Green two-wheeled mobility

-Material Hygiene and life cycle analysis of an electric scooter

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and Management

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Abstract

In the last years electric vehicles gained importance as a more sustainable alternative to traditional vehicles. The introduction of an electric powertrain leads to lower air-pollution emissions but it also involves the introduction of new materials in the product life cycle, e. g., the rare earths and lithium contained in the motor and in the batteries. Those materials have an environmental impact and they need to be disposed properly.
The aim of this thesis is to have a quantitative knowledge of the environmental balance linked to the use of a different powertrain. Furthermore, this study explores how this balance can be modified improving the recycling and the end of life management.
Specifically in this thesis, an average electric scooter has been chosen as a case study. The electric scooter is used as object of comparison with a traditional internal-combustion-engine scooter. The choice of a two-wheeled mean of transport is linked to the low level of facilities involved.
This report first includes a definition of the case of study; this section also presents a description of the technologies taken into exam. It is also presented the result of interviews with dismantlers to depict the current process of EoL management of a scooter.
The central part of thesis deals with different recycling scenarios. With the help of the Material Hygiene mind-set, a qualitative analysis and different recycling scenarios are proposed. The recycling scenarios involve the component of the electric powertrain that are peculiar of the electric vehicle. They mainly are the electric motor and the lithium battery pack.
The last part of the analysis encompasses a Life Cycle Assessment of an average electric scooter to give a quantitative meaning to the life cycle comparison and to assess the environmental benefits of the proposed recycling scenarios.
To perform the Life Cycle Assessment a software, SimaPro 7.3, is used. This software lets the user insert the bill of materials of the product and it associates to each material its environmental loads according to the database EcoInvent v.2.2.

Keywords: electric scooter, lithium battery, permanent magnet, neodymium, Material Hygiene, Design for Disassembly, Life Cycle Assessment, LCA

FOREWORD

Several people contributed to the development and the implementation of this thesis. In this section, the author would like to acknowledge them.

First of all the author would like to thank the professors that supervised this work. Professor Mario Guagliano that made this experience possible accepting to supervise this thesis from Italy and Professor Conrad Luttropp that guided the author through the dumpy roads of the EcoDesign, always ready to share his experience and to provide help. Moreover, a special thanks to all the other people that took part to this work such as the interviewed companies and to all the staff of KTH that helped the author through the daily life of a student writing his master's thesis abroad.

Dario Braconi

Milan, September 2014

Riassunto

Negli ultimi anni i veicoli elettrici sono emersi come un’alternativa sostenibile ai veicoli tradizionali. L’introduzione di un gruppo propulsore elettrico permette emissioni inquinanti più basse ma comporta anche l’introduzione di nuovi materiali nel ciclo di vita del prodotto, e.g., le terre rare e il litio contenuti rispettivamente nel motore e nelle batterie. Questi materiali hanno un impatto ambientale e hanno bisogno di essere trattati correttamente.

Lo scopo di questa tesi è di avere una comprensione quantitativa del bilancio dal punto di vista ambientale legato all’adozione di sistema di propulsione elettrico. Inoltre, è indagato come questo bilanco possa essere influenzato migliorando il riciclaggio e la gestione dell’ultima fase di vita del prodotto.

Nello specifico, in questa tesi, uno scooter elettrico è stato scelto come caso di studio. Lo scopo è di comparare questo scooter con uno tradizionale considerando il ciclo di vita del prodotto. Il mezzo di trasporto a due ruote è stato scelto perché considerato più semplice da modellare in quanto privo di componenti non inerenti al trasporto (es. aria condizionata, hi-fi, etc.).

Questo report anzitutto include una definizione del caso di studio, questa sezione presenta anche una descrizione delle principali tecnologie coinvolte nel prodotto studiato. In questa parte del lavoro è anche riportato il risultato di interviste a rottamatori di scooter per illustrare l’attuale iter di rottamazione di uno scooter.

La parte centrale della tesi tratta i differenti scenari di riciclaggio. Sfruttando la mentalità Material Hygiene vengono proposte un’analisi qualitativa e differenti scenari di riciclaggio. Gli scenari di riciclaggio coinvologono il progettista a livelli differenti. Questi scenari riguardano i componenti del sistema di propulsione elettrico. Essi sono principalmente il motore elettrico e le batterie al litio.

L’ultima parte dell’analisi riguarda il Life Cycle Assessment di uno scooter elettrico al fine di dare un significato quantitativo al confronto tra i cicli di vita delle due alternative. Inoltre, il life cycle assessment ha lo scopo di verificare e quantificare i benefici di impatto ambientale collegati all’adozione degli scenari di riciclaggio proposti.

Per svolgere il Life Cycle Assessment è stato usato un sofware, SimaPro 7.3. Questo software permette all’utente di inserire l’elenco dei materiali di un prodotto e di associare a ciascun materiale il proprio impatto ambientale. Il software ha a disposizione per la modellazione i database di impatto ambientale EcoInvent 2.2.

Parole chiave: scooter elettrico, batteria al litio, magnete permanente, neodimio, Material Hygiene, Design for Disassembly, Life Cycle Assessment, LCA

NOMENCLATURE

Abbreviations

EV	Electric vehicle
PTW	Powered two-wheeler
MH	Material Hygiene
GHGs	Greenhouse Gasses
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ELV	End of Life of Vehicle
EoL	End of Life
ICE	Internal Combustion Engine
ICE-scooter	Internal Combustion Engine scooter
E-motor	Electric motor
E-scooter	Electric scooter
BLDC motor	Brushless DC motor
WEEE	Waste Electrical and Electronic Equipment

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1 INTRODUCTION

'We will not stop till every car in the road is electric' –Elon Musk. This statement has been pronounced by the CEO of Tesla Motor, one the most famous mass-produced and purpose-designed electric vehicle automaker [1.W]. Despite the strong advertising content of the previous quote, what is true is that in future more and more electric vehicles will share road infrastructures with traditional vehicles.

An electric vehicle, either a car or a scooter, is often presented as a greener alternative to the traditional mobility. This is true just considering the use-phase emissions but many factors have to be inspected to depict a complete framework.

With electric vehicles, new materials like permanent magnets, used in the brushless motors, or lithium, used in the batteries, are introduced in the life cycle of the product.

'*The main interest of EcoDesign is to examine the conditions for and to provide help in creating a sustainable future by improving recycling, energy savings and products well suited for its purpose' –Conrad Luttropp [2.W].* With these words, it is possible to understand the outlook that has been used to perform the whole study. There are no easy solution nor easy answer to obtain an environmentally effective design. This study has been conduct to have a clearer view of the electric mobility as an environmentally effective alternative to internal combustion engine mobility.

1.1 Background

This study is linked to three wide areas. The first one is two-wheeled mobility; the second one is the introduction of electric vehicles as a more sustainable mean of transport and the third one is EcoDesign and the Material Hygiene as methods towards a more sustainable approach to product development.

Cities are becoming more populated, and scooters are gaining captivation as an alternative to cars [1]. Nevertheless, traditional scooters, especially the ones equipped with the two-stroke engine, are supposed to be, with their exhausted gases, one of the main causes of air pollution. According to Environmental Protection Administration, Government of Republic of China, an average two-stroke engine scooter produces from three to seven times more pollutants, exhaust pollution per kilometer, than an average 2000 c.c. car [2].

After an examination of either electric cars or electric scooters history, it is interesting to notice how they do not represent a *new* product. Both of them, in fact, were considered an alternative to internal combustion engine vehicles before 20s. During the 90s different driving forces, such as oil-price raising and environmental concern, led to rediscover of the electric vehicles. In the last fifteen years, manufactures spent many efforts to produce electric vehicles comparable to traditional vehicles. Several of the major automakers have electric cars available among their in-production models.

One of the most powerful *design tool* towards a greener product is EcoDesign. The main purpose of EcoDesign is to design a more sustainable product without noteworthy tradeoffs regarding the product properties and price.

In this study, great importance is given to the work carried out by the EcoDesign group at KTH. The Ten Golden Rules [3] are seen as a starting point. In this report, a specific field of EcoDesign gains great relevance: the Material Hygiene as a mindset for recycling of products [4].

1.2 Motivation

This master's thesis has been written within the EcoDesign group at KTH. This work would become part of different research works regarding the life cycle management, the material management and the recycling of electric vehicles in comparison with traditional vehicles.

The research motive behind this thesis is to perform a comparison between the life cycle management of a traditional and an electric vehicle with specific focus on material and energy flows linked to the different powertrain alternatives.

The mind-set used for this work is Material Hygiene as a tool towards an improved material management of a product.

The vehicle chosen for the comparison is a scooter. The scooter seems more suitable as a case study. The comparison is mainly focused on material and energy flows involved in the powertrain alternatives, and the scooter is a mean of transport that inherently enhances the powertrain. The weight of the powertrain is a consistent percentage of the total weight of a scooter. Furthermore, an average scooter does not include the facilities of an average a car. There are fewer materials involved (no conditioning liquid, fewer electronic devices, etc.) and the bill of materials of the product is less "diluted" by components not related to the powertrain. In addition, considering the significant amount of data to analyse the choice to the two-wheeled vehicles is more suitable for the scope of a master's thesis.

1.3 Purpose

One purpose of this thesis is to perform a life cycle analysis of the material and energy flows of an electric scooter in comparison with an internal combustion engine scooter. As it comes out intuitively, there is a balance, between the advantages (e.g. the zero-emission tail pipe, the higher efficiency at low speed…) and the disadvantages (e.g. higher manufacturing impact, new materials involved…) that the electric vehicle brings regarding the material and energy flows.

Another aim of this paper is to consider the life cycle material management of an electric scooter in order to depict, evaluate and assess recycling scenarios for an electric scooter. The recycling opportunities for the new materials encompassed in the life cycle are then added to the overall balance already showed as first purpose of this thesis. The target is to weight the effect of an improved material management and to draw considerations for the product development.

In other words, this thesis aims to answer to the following research questions:

1. *"What is the quantitative balance, from an environmental point of view, between the benefits and the drawbacks of an electric scooter, regarding the material and the energy embraced in the product lifecycle?*
2. *"What are the recycling opportunities for the new materials involved in the life cycle of an electric scooter and what are the quantitative benefits linked to these recycling scenarios? Furthermore, which is the role of the designers on those scenarios?"*

The choice of the scooter as case study, leads to another research question explored in this thesis:

3. *"What is the standard procedure for the disposal of a scooter?"*

1.4 Scope

This master's thesis involves many different fields: two-wheeled vehicles, electric mobility, EcoDesign, recyclability and industrial design. The goal, anyhow, is to have a concrete answer to the research questions of the previous section.

The vehicle chosen for the comparison between the two-powertrain technologies is a scooter. The scooter considered is an average electric scooter from the European market. The market boundaries and the specification of the model chosen are specified further in the paper.

The data employed for the life cycle analysis comparison are from manufacturers, scientific literature, private databases and personal consultancies. The level of technologies described, the two average models of scooters, represents models already familiar to the scooter market since at least one year. Although the recycling scenarios for the new materials are referred to the state-of-art of the industrial technologies or to processes available only on lab-scale. The data used for the recycling scenarios are from recycling companies, patent analysis, scientific literature and private databases. The aim is to assess the recycling opportunities of the product according to the available technologies whether or not these technologies are then used in industrial processes. The recycling/reusing chain of a product, needs a certain volume of disposed units to be affordable, this is currently impossible for electric scooter, and electric vehicles in general, since their relatively recent appearance in the vehicle market.

1.5 Thesis structure

This thesis is outlined through a scheme, see Figure 1.1. The scheme tries also to let the reader understand the process flow followed by this work.

After the introduction, the second chapter regards the definition of the methods. The third chapter explains the case study, there the electric scooter is better defined also in terms of technical specification and regional boundaries. The fourth chapter describes the recycling background and the research efforts to depict it. It contains information about the directives and the disposal of scooters. The fifth chapters treats the Material Hygiene both the theoretical background and the case study. This chapter leads to the definition of recycling scenarios for the E-scooter. The sixth chapter presents the literary review regarding other comparison between electric and traditional alternative. The seventh chapter describes the theoretical background of the LCA and the way that the method has been applied to the E-scooter. The eighth chapter reports the analysis and the interpretation of the results of the LCA. The ninth chapter encompasses discussions and conclusions. The scheme outlines the fact that the workflow is divided in two stages, the first one of data collection, powered by the material hygiene mind-set, that ends up with the proposal of recycling scenarios. The second stage is the implementation of the LCA of an electric scooter and the interpretation of its results.

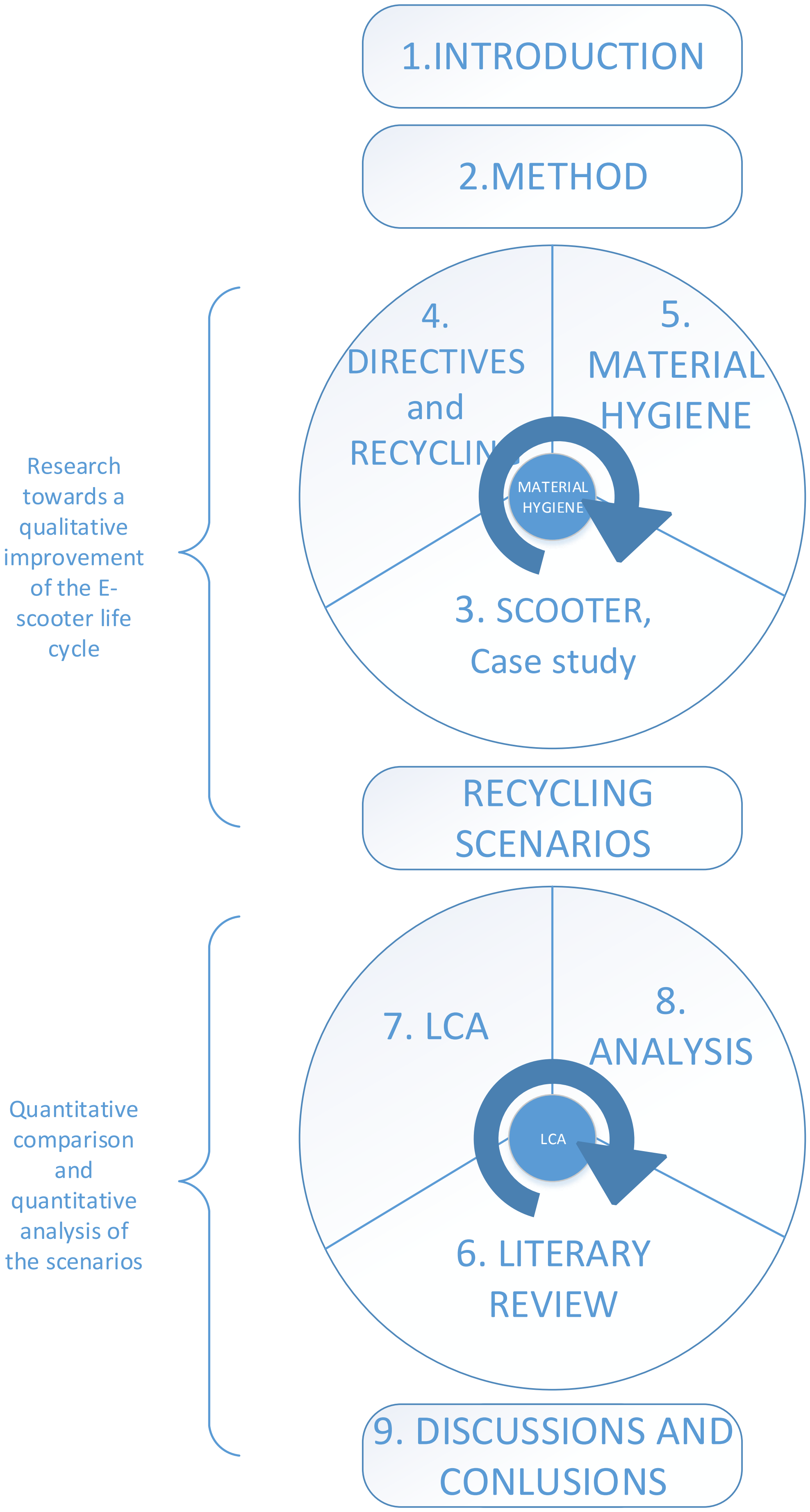


Figure 1.1, Thesis outline

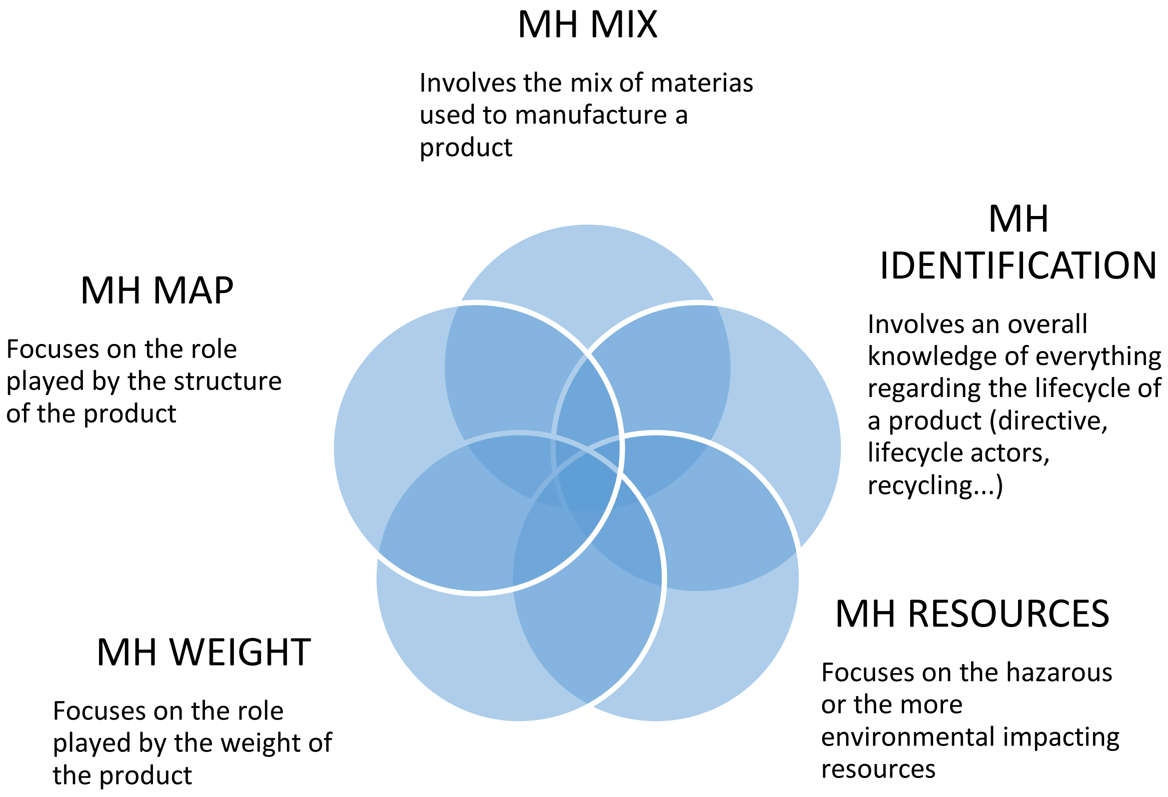
2 METHOD

This chapter presents the methods used in this thesis. Furthermore, this chapter describes also the general approach, the mind-set, used to draw the outline of the work.

2.1 Material hygiene, a mind-set

Material Hygiene, MH, as a way to analyse and improve the material management of a product, represents the most import method encompassed in this work. Although, material hygiene has to be considered more as a work approach or a general mind-set than a proper method. Material Hygiene, in fact, denotes a tool for EcoDesign to collect, understand and merge information and data regarding a specific product toward a more efficient management of the material lifecycle of the just-defined product. MH can also be used to describe a high level of material efficiency through the whole life cycle. In this sense, it is possible to state that an efficient material management of a product increases its MH.

The mind-set defines five factors that actively influence the product MH. See Figure 2.1, see Chapter 5.



MH MIX

Involves the mix of materias used to manufacture a product

MH IDENTIFICATION

Involves an overall knowledge of everything regarding the lifecycle of a product (directive, lifecycle actors, recycling...)

MH MAP

Focuses on the role played by the structure of the product

MH RESOURCES

Focuses on the hazarous or the more environmental impacting resources

MH WEIGHT

Focuses on the role played by the weight of the product

Table 2.1, Material Hygiene factors

The activity of collecting and understanding information and data is part of the mind-set but it can actually be accomplished with different methods. The methods to use are not part of the mind-set, and they are left at author's discretion and experience. Furthermore, the product in itself and the goal of the study influence the choice of those methods. The methods used in this paper, encompassed in the material hygiene mind-set are: database research, interviews, patent analysis, and a Design for Disassembly method.

2.2 Data collection

As first an initial literature research is performed thorough KTHB Primo [3.W], the scientific search engine of the Royal Institute of Technology. Then, other, more specific, scientific databases are used, e.g. the IMechE Journal database [4.W], the MechanicalENGINEERINGnet database [5.W] and the Engineering Village [6.W]. These databases are designed for engineering with the possibility to define very specific queries.

A peculiar way of conducting the research, especially after the first less detailed study phase, has been the "snowballing" method [5]. This method consists in finding new articles through reading reference lists of already read papers. This process increases the knowledge of the subject as a snowball rolling down a hill increases its volume.

This study involves also the use of interviews with experts or companies related to the life cycle of scooter. This thesis reports interviews with dismantlers and manufactures to have a general framework of the disposal of scooters. The outline of the interviews is reported further in this work, see Chapter 4.

The data collection and the interviews are used according to Material Hygiene mind-set, and specifically to MH identification, to depict the current EoL framework of an E-scooter, see Chapter 4.

The data collection has been used also to collect the information for the literary review on vehicle alternative comparisons of chapter 6, see Chapter 6.

2.3 Methods used to propose recycling scenarios

This study aims to assess effective ways to increase the MH of an E-scooter. The chosen way to do so is to propose recycling scenarios for those materials that are currently not recycled. Hence, this study treats both recycling technologies and disassembly processes. To interpret and encompass these recycling technologies into realistic recycling scenarios a patent research and functional analysis has been conducted. There are different ways of conduct this kind of analysis. The method used in this work involves four steps:

1. Identify components (or phases) of the invention and their functions;
2. Identify at which step of the process flow each component performs its function;
3. Draw a flow diagram to show the relationships between the components (or phases) of the recycling treatment and to depict the overall process.
4. Considering separately the input/output flows of disposed product/recycled material and material/energy needed by the process.

This method is an adaptation made by the author of the functional analysis method developed in the course "methods and tools for systematic innovation" held at Polytechnic of Milan by Cascini [6].

The recycling scenarios deal also with Design for Disassembly and disassembly procedures. The method used to depict disassembly flows is the graphic tool developed by Luttropp [7] for Design for Disassembly structure, DfDs, the part of Design for Disassembly that treats the product structure. The method is graphical. It defines the concept of describing joints as resting load cases. Each of these resting loads can be graded, with an ordinal scale, regarding the information, the equipment, the force and the time needed to “wake up” the resting load. Once each resting load is waken up the module or the structure is disassembled.

2.4 LCA, life cycle assessment

The method chosen to answer to the quantitative research questions of this paper is the Life Cycle Assessment, LCA. A quantitative meaning to the comparison between the powertrain technologies is a primary goal of this work. The reasons of the choice of the LCA as method for this work are:

- LCA is a renowned method for quantitative analysis of the life cycle of a product, also in the product development and in the choice between alternatives [8].
- The LCA is a method spread in the academic and industrial world since more than 20 years.
- The LCA has an ISO standard (ISO14040) that assures a strong level of repeatability.
- Several software help to run LCAs. The software used in this work to run the LCA is SimaPro7.3 and the data used are mainly from EcoInvent data v2.2 (2010)
- The LCA is designed to give an overall interpretation of the lifecycle of a product. It does not provide just mere quantitative mass balance but it provides directly a measure of the environmental impact.

Other methods that could accomplish the task of a quantitative flow analysis are Material/Energy Flow Analysis or Material/Energy Flow Accountings [9]. These methods mostly consist in two steps: a system definition and a mass/energy balance. These methods provides only mass/energy balances. Furthermore, system definition and mass/energy balance are actually part of a LCA. LCA, in fact, encompasses a boundary definition step and the Life Cycle Inventory that mainly consists in a mass/energy inventory regarding the whole life of the product. As last, these methods do not have an ISO and they are not as well defined as the LCA. LCA seems more robust and gives a complete understanding of life cycle. With the LCA the answer to the research question is more meaningful.

Reliability is discussed for the LCA in relation with the quality of the data within the idea of “garbage in-garbage out” model. The quality of the results of a method cannot be better than the quality of the input data that the method uses. In other words, LCA as a model of analysis is strictly related to the quality of the data and to the goal of the assessments. The matter is further deepened in the LCA chapter and in the discussions.

Validity is discussed in relation with the spatial (European region) and temporal boundaries (time horizon of the data involved). This matter too is further deepened in the LCA chapter and in the discussions.

The second purpose of LCA is to give a validation to the qualitative recycling scenarios depicted in Material Hygiene analysis. Associating an environmental impact to the different recycling solutions let the author have a quantitative understanding of the work done within the material management research. The reliability of this validation is debated in the discussion chapter.

3 ELECTRIC SCOOTER, A CASE STUDY

This chapter introduces the electric scooter as case study. The following paragraphs present a definition of the scooter and a description of the market. The description of the market is important since each market has a product with different features. The market chosen is the European market. The chapter presents also a description of the components and the basic design of a scooter.

3.1 Scooter, a definition

The case of this study is the scooter in its two main powertrain technologies, electric and thermic. First, it is important to give a definition of scooter. The Oxford dictionaries defines the scooter as follows:

> *'A light two-wheeled open motor vehicle on which the driver sits over an enclosed engine with their legs together and their feet resting on a floorboard.'*-Oxford Dictionaries [7.W]

The previous definition involves also a brief description of the standard structure of a scooter.

Another useful efinition is the one of the European vehicle category. In this case study, it is considered L1 and L2 category scooters:

> *' A two-wheeled vehicle with an engine cylinder capacity in the case of a thermic engine not exceeding 50 cm^3 and whatever the means of propulsion a maximum design speed no exceeding 50 km/h [8.W]. '*

> *'A two-wheeled vehicle with an engine cylinder capacity in the case of a thermic engine exceeding 50 cm^3 and whatever the means of propulsion a maximum design speed exceeding 50 km/h [8.W].'*

3.2 Description of scooter market

In this report, the market borders are the European ones. This choice is explained in the next paragraphs and is due to the electric scooter market features.

The circulating park of PTWs in Europe amounted in 2011 to over 36 million of units. In the last decade, the number of motorcycles and mopeds increases of over 6 million of unit. Year by year the number of PTWs in Europe were increasing until 2010 when, because of the economic crisis, the vehicle market fell. Considering the last ten years, the average number of scooters and motorcycles registered in Europe each year was approximately 2100000 [10].

The European country which produces more motorcycles and scooters is Italy with over 400000 units followed by Germany, 110000, and Spain 95000. What need to be specified is that some European brands have their production sites in India or China whilst some manufacturers are Japanese so their production amount in Europe is almost negligible [11, 12].

Considering the top ten sold PTWs of the 2012 [10], seven out of ten models are L1 or L2 category vehicles. The main manufactures of PTWs up to 125 cc of cylinder capacity are the Italian Piaggio and Vespa, both part of the Piaggio Group and the Japanese Honda Motors and Yamaha Motors. The top sold scooters in Europe sell over 14000 units each.

To give a quick idea of the electric scooter market the Navigant Research Leaderboard Report [9.W] concerning electric scooters states that the electric scooter market in Europe is around the 2% of the traditional one. What comes out from the report is that the two main market areas are Asia Pacific and Western Europe. The two markets, however, have different features. Asian market account more than 99% of the global sales. The E-scooters sold in Asia Pacific are low-cost vehicles with relatively few features. To participate in the Asian market these models have to be price-competitive to the internal combustion engine scooters. The Western European market is the second world market, even if its volume is dramatically smaller than the Eastern one. The features of models sold in Europe are different. The market challenge with traditional scooter is played on another level. In Europe, E-scooters have more features and they can compete as performance with traditional ones. Although, the electric scooters present in the European market are significantly more expensive than the ICE ones. In this case plays a role also the green perceived value of the customer and its sensitivity to less GHG emitting and noise polluting vehicles.

A brief review of the manufactures showed by the report has been performed, see Table 3.1. The idea is to point out the differences between an average model for the Asian market and one for the European market. It is worth specifying that Japan is not part of Asian market in this analysis. Japanese market features are similar to Western European.

COMPANY	TARGET MARKET	COUNTRY	PRODUCES also ICE scooters
Jiangsu Xinri E-Vehicle Co. [10.W]	ASIAN	CHINA	NO
Vmoto [11.W]	BOTH	AUSTRALIA	NO
SYM [12.W]	EUROPEAN	TAIWAN	YES
Vectrix [13.W]	EUROPEAN	USA	NO
Terra motors [14.W]	EUROPEAN	JAPAN	NO
Govecs [15.W]	EUROPEAN	GERMANY	NO
Yamaha [16.W]	EUROPEAN	JAPAN	YES
Peugeot [17.W]	EUROPEAN	FRANCE	YES
iO Scooter [18.W]	BOTH	AUSTRIA	NO
BV Nimag (Nimoto) [19.W]	EUROPEAN	NETHERLANDS	YES

Table 3.1, Top ten E-scooter manufacturers

It is possible to point out the principal design differences between the two markets, see Table 3.2.

ASPECT	EU MARKET MODEL	ASIAN MARKET MODEL
Battery technology	Lithium	Lead acid
Battery recharging time	3-5 h	6-8 h
Weight	100-120 kg	120-140 kg
Maximum speed	50-65 km/h	45 km/h

Table 3.2, European/Asian market comparison

There are differences also concerning other specifications like brake technology, energy recovery technologies, average distance range, etc. These specifications often differ from model to model [10.W, 11.W, 12.W, 13.W, 14.W, 15.W, 16.W, 17.W, 18.W, 19.W]. Hence, without losing generality it is possible to assert that the main difference stays in the battery technologies. Lead batteries from one side let the price be lower but from the other they have less performance features.

Since the aim of this report is to make a technology comparison between a traditional scooter and an E-scooter and to evaluate future waste scenarios of new technologies, the average model for the E-scooter is chosen from the European market. The idea is to give more significance to the technology competition than to the price one.

Once chosen the representing technology, it seems worth to propose a comparison between performances and price of *European* electric scooter and the traditional scooter, see Table 3.3. The data for the electric scooter are taken from the models designed for the European market listed in the Table 3.1. The data for the traditional scooter are from the top two model of the European market [10]. To give more meaning to the economic comparison, considering the average cost in Europe [20.W] of a litre of petrol (2.04 $) and of a kWh (0.26 $), a fuel cost is provided with the hypothesis of 50000 km use life expectance, although the comparison is not complete since no maintenance is accounted.

ASPECT	E-SCOOTER	ICE-SCOOTER
Recharging spot	Home/work plugs	Gas stations
Recharging time	3-5 h	<10 min
Weight	100-120 kg	90-100 kg
Maximum speed	50-65 km/h	60 km/h
Range	65 km	250 km
Average consumption	3.3 kWh/100km	3.3 l/100km
Price	5400 $	2700$
Fuel cost over 50000 km	345 $	3341 $

Table 3.3, Performance comparison

3.3 Components and design differences

This section shows the scooter as a mechanical system composed by mechanical components. It seems reasonable to present this description to let the reader better understand the topic of the next chapters.

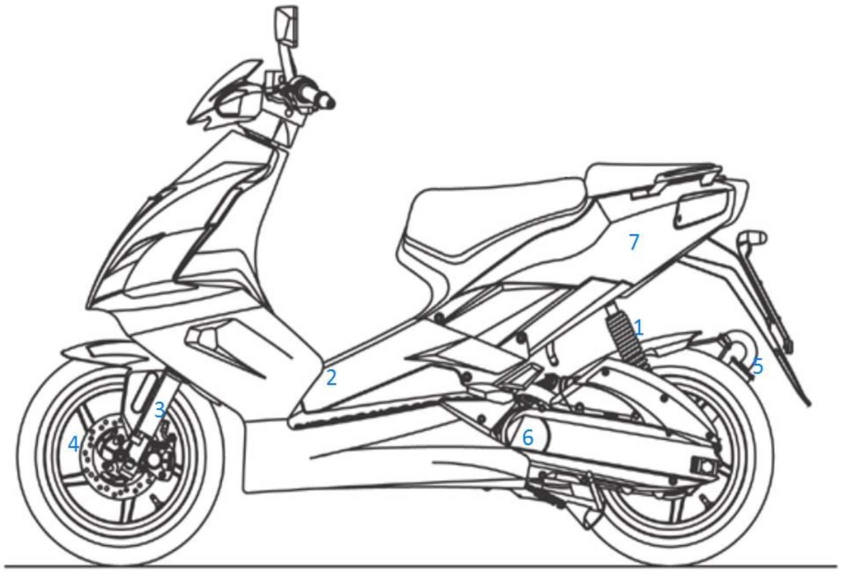
This section reports the sketch of an average scooter, see Figure 3.1. The model presented is the Aprilia SR 50, the same used in the LCA further in the paper, see Chapter 7.

At this point seems worth to list the principal components that constitute a traditional scooter, the components can be collected in functional groups, see Figure 3.2. The functional groups defined are four: the electronic & electrical system, the motion systems, the structure and the powertrain. This division is made by the author, other solutions are possible. The groups are linked among each other.

The electronic & electrical system involves the electric system and its power source, the battery. The electronic control manages all the electric devices such as turn indicators, horn, lights, etc.

The motion systems group encompasses the steering system, the wheels, the tyres, the suspensions, the braking system, the transmissions and their subsystems.

The structure group includes the parts designed to give structural solidity to the mean of transport. The principal parts are the polymeric body, the steel frame, the chassis and the seat.



#Number	Component
1	Rear dumper
2	Battery
3	Fork
4	Brake
5	Silencer
6	Engine
7	Fuel tank

Figure 3.1, Internal-combustion-engine scooter sketch (Aprilia SR 50)

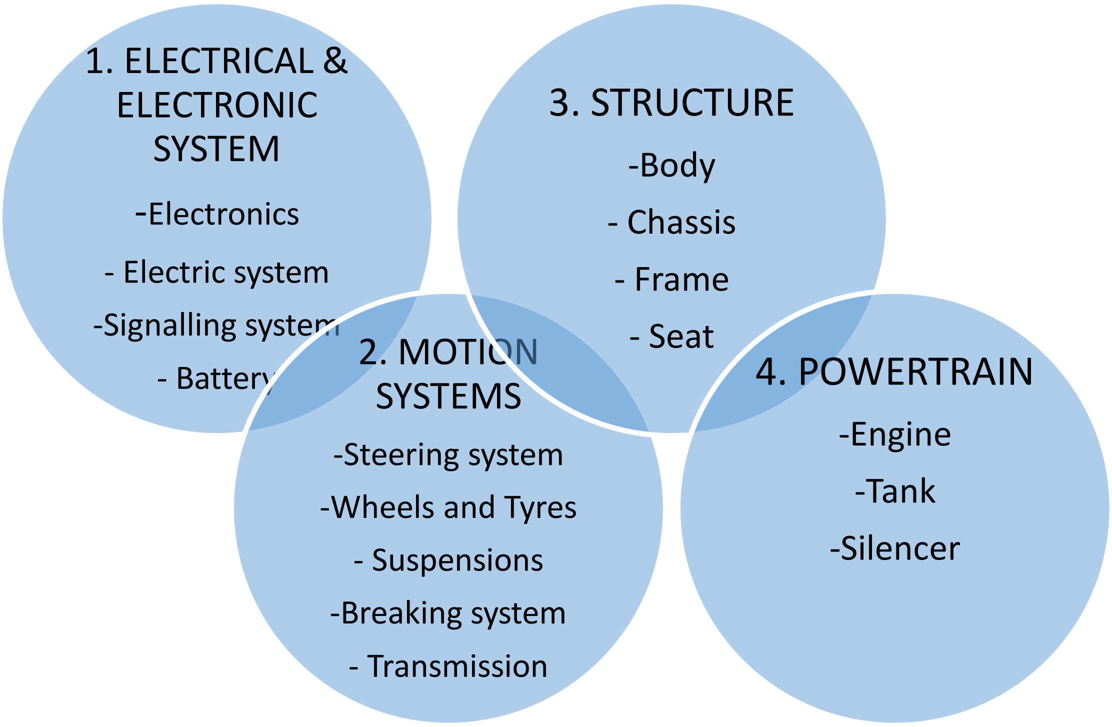


Figure 3.2, Components and functional groups of an ICE-scooter

The last group is the thermic powertrain. The components that take part to this group represent the power source to the motion. It involves the engine, the tank and the silencer.

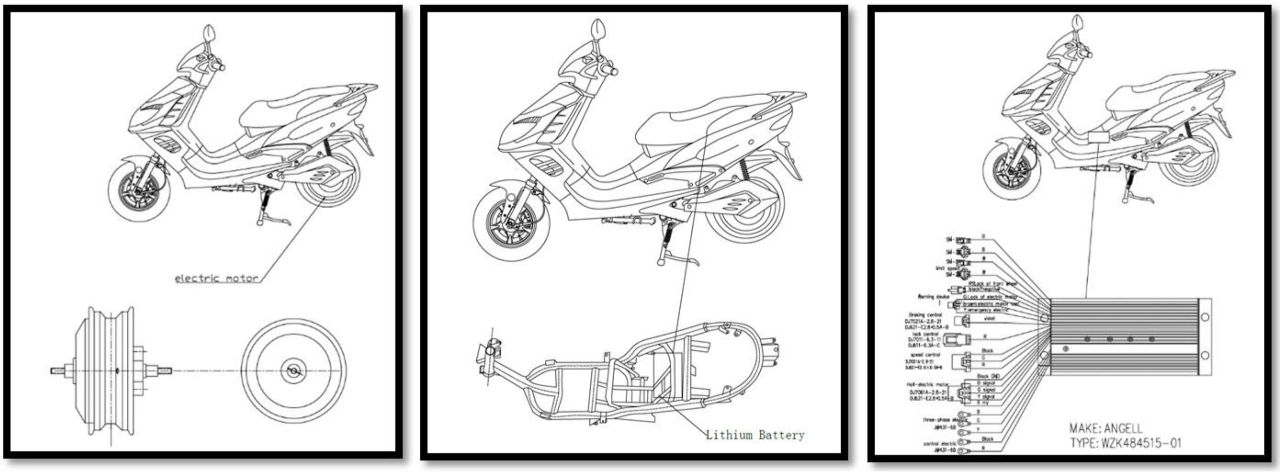


Figure 3.3, Powertrain components of an E-scooter (Penelope MotoriniZanini)

The picture above is taken from the approval certificate of the model Penelope, an electric scooter sold by the Italian company MotoriniZanini. This scooter is presented as reference for the LCA, see Chapter 7.

A strong assumption made in this case study, regarding the comparison between the two alternatives, is that, for simplicity’s sake, the powertrain is the only difference between the two technical solutions, see Figure 3.4. The first consequence of this assumption is to not consider the transmission. The ICE solution inherently need a complex transmission. The Electric solution, instead, is usually simpler. This study considers a wheel hub motor that have a theoretical 100% transmission efficiency since it does not actually need a transmission. Hence, the assumption seems correct.

The electric powertrain group consists in three component: the lithium battery, the electronic controller and the hub wheel motor.

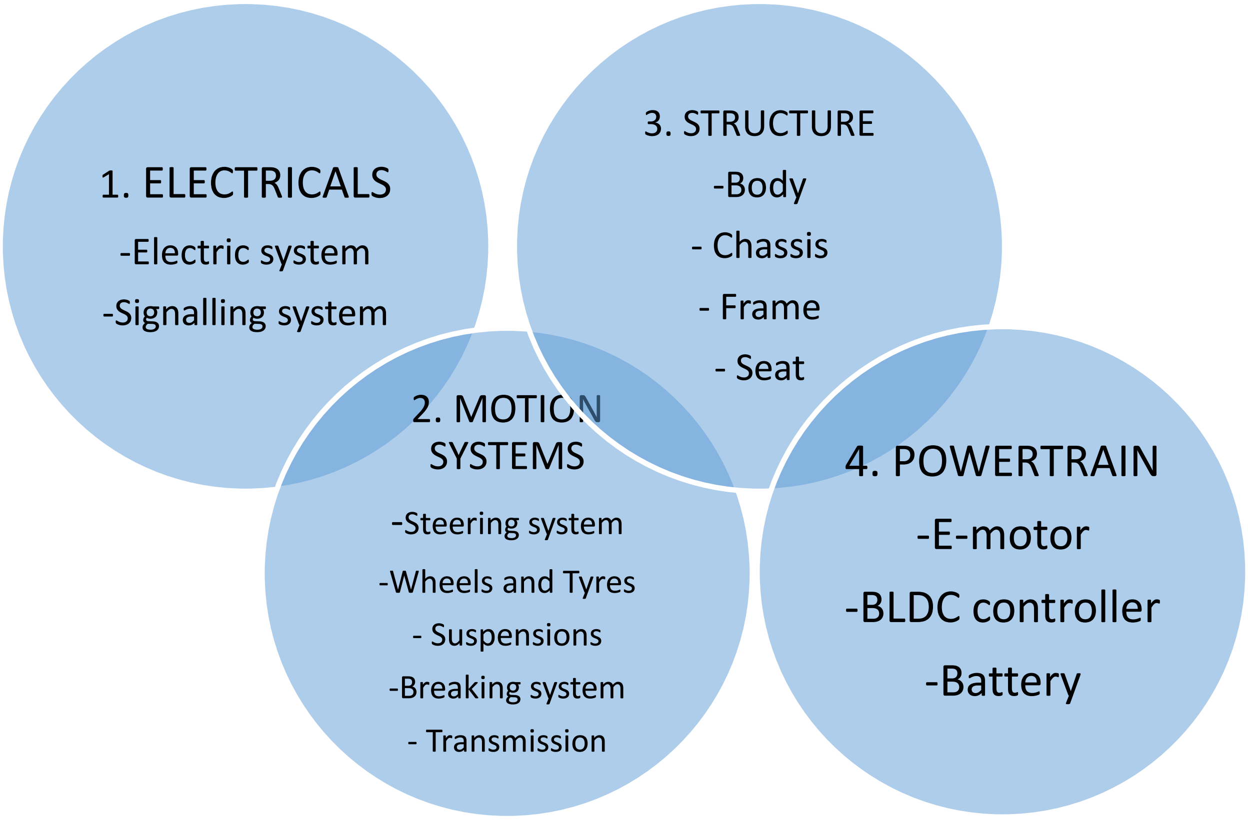


Figure 3.4, Components and functional groups of an E-scooter

The electronic and electrical system group is also changed. The electronic controller is considered part of the E-powertrain since it is crucial for the E-motor functionality. Furthermore, it is considerably different from a traditional scooter electronic system. The traditional scooter uses the fuel tank as energy storage and thermic engine as source of power. The lithium batteries and the electric motor substitute the previous components in the electric scooter. The relations among the different functional groups changes (e.g. the battery that powers the electricals is in the powertrain, etc.) but these assumptions do not affect the results of the study. The idea is to consider in the same functional group the new components. They are "outsider" parts for the traditional automotive engineering and they are the ones adding new challenges regarding a proper dismantle and recycling. It seems worth to have a clearer vision of these new objects. The next paragraphs describe in short the physical operation of lithium batteries and the brushless electric motors.

3.4 The new components: lithium battery

Sony sold the first lithium-ion battery in 1991. Since then the lithium-ion battery technology has had a great development. Next paragraphs present a brief description of this technology. The reference for this section is the work of Dingguo and Xia [18], this section treats the lithium battery as follows:

- Electrochemical process description;
- Components;
- Performance and comparison;

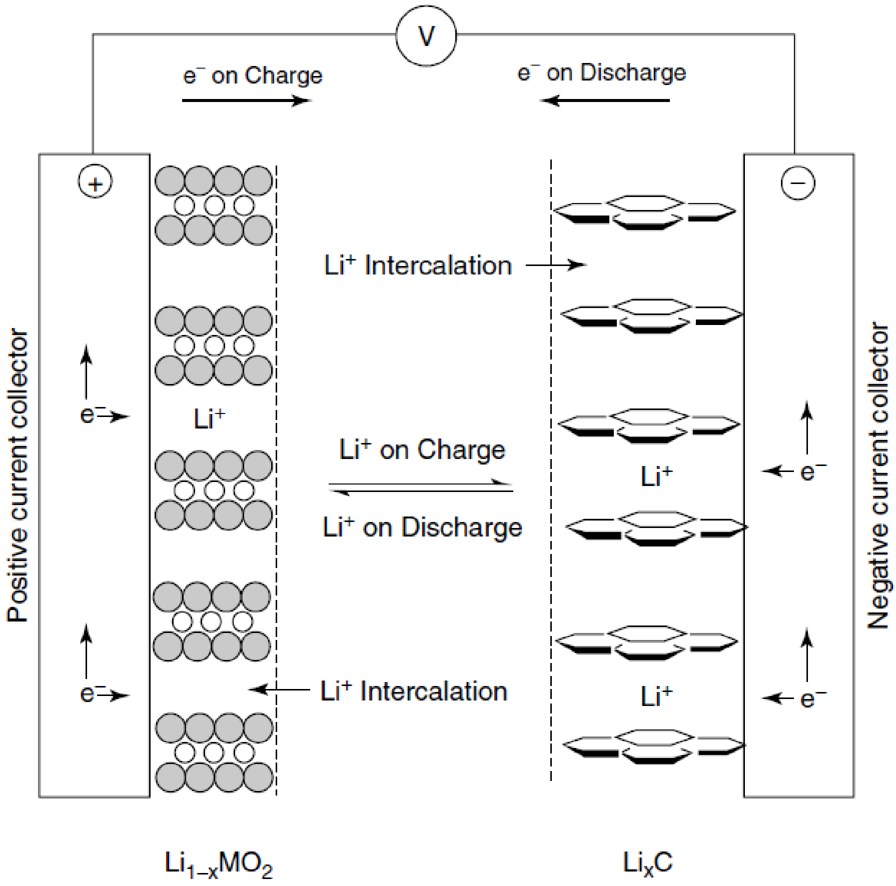


Figure 3.5, Physical operation of a lithium-ion battery [18]

The three main actors of the electrochemical process are the anode, the cathode and the electrolyte. During the useful phase of a battery, the discharge, the Li ions, Li+, convey the current from the negative to the positive electrode passing through the electrolyte and the separator. When an external electric source is applied, the Li ions are forced to go in the opposite direction. During the discharge the positive electrode is oxidized and the negative electrode is reduced. The opposite happens during the charge phase, see Figure 3.5.

The classical designs are the wound Li-ion cells and the flat-plate prismatic Li-ion cells. The first design is more common for small batteries while the other is the most used for big batteries, such as vehicle batteries.

Except the shape design, it is possible to identify some common components. The anode, the cathode, the separator, the endplates and the current collectors.

The anode is usually made out of graphite. The graphite accepts Li ions between its layers in the form of LiC_6. Carbonaceous anodes present a good acceptability for Li ions. Different choices are available between the different kinds of carbonaceous anodes on the market. Non-carbonaceous anodes are nowadays object of study.

The cathode can be made out of three materials: a layered oxide (e.g. $LiCoO_2$), a polyanion (e.g. $LiFePO_4$) or a spinel (e.g. $LiMnO_2$). The principal features that a good cathode should have are high cyclabilty, high energy efficiency, high Columbian efficiency and high capacity of storing lithium. Each of the three technologies has its benefits and its drawbacks, see Table 3.4

Material	**Pro**	**Cons**
$LiCoO_2$	• Easy to make • High capacity 140 mAh g-1	• Expensive • Environmental risk
$LiMnO_2$	• Low capacity 120 mAh g-1 • Storage losses at high temperature	• Environmental friendly • Not expensive
$LiFePO_4$	• Low conductivity	• High capacity 170 mAh g-1 • Non toxicity • Temperature stable • Not expensive • High accessibility of Iron

Table 3.4, Comparison among cathode technologies [18]

In the electric vehicle market, it is possible to find all the three alternatives. Nevertheless, the second and the third technology, since they are less expensive and with less environmental risks, will likely be the more common in the future. Furthermore, there is the prospect to increase the conductivity of $LiFePO_4$ by reducing particle size or by specific coatings [19].

The separator is a membrane positioned between the two electrodes into the electrolyte. It has to prevent the contact of the two electrodes; in the meanwhile, it has to function as electrolyte basin to let the free ionic transport go on. The common materials used are natural or synthetic polymers.

The current collector is the component that links the electrodes with the external electric circuit. They usually have a thin-foiled shape. Aluminium is largely used as current collector due to its high mechanical strength, ductility, low density, good electrical and thermal conductivity. Copper is another suitable alternative.

The principal physical quantities to describe energetic characteristic of an electric battery are specific energy of cathode and anode materials. Specific energy of a material describes the energy (Wh) stored in a mass unit (kg). To describe working characteristics the most important peculiarities are discharge rate capability, cycle life, storage performance, temperature effects on performance. The discharge rate capability describes the product of electricity and time (mA) stored in a mass unite (g). The cycle life represents the ability of a battery to cycle without losing properties. Table 3.5 shows a comparison among different battery technologies for electric vehicles [20], see Table 3.5.

Battery tech.	Specific energy	Cycle life	Energy efficiency
Lead acid	35-50	500-1000	80%
NiCd	40-60	800	75%
NiMH	75-95	750-1200	70%
Li-ion	114	1000	-
Na/S	100	-	-

Table 3.5, Comparison among battery technologies [20]

3.5 The new components: electric motor

The electric motor is the unit that provides power to electric scooter. The electric motor is part of the electric powertrain that also encompasses the power electronics and the controller. There are different technologies for electric motors are available. Although, the most suitable motor for electric vehicles is the brushless DC motor. The main feature of this motor is the great specific power. Great specific power means a lighter motor once the power is decided [21]. Within this thesis the terms electric motor, E-motor, BLDC motor always denote the brushless DC motor.

The brushless DC motor is actually an AC motor. It is called DC because the motor *needs* the alternative current to be variable in frequency and a DC power supply provides that current.

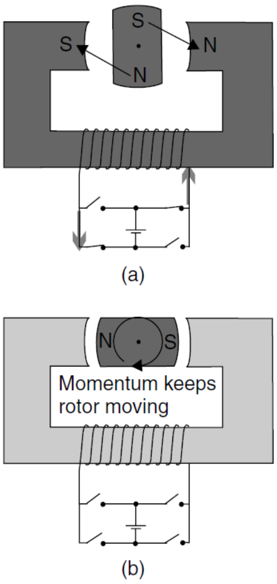


Figure 3.6, Physical operation of a BLDC motor [21]

The Figure 3.6 shows the physical operation, see Figure 3.6. The current flows through the stator and it gives a momentum to the rotor. The rotor is made of a steel structure and permanent magnets. The rotor turns clockwise. When the rotor reaches the stator poles, the current in the stator switches off. The rotor keeps turning because of the inertia. In the meanwhile, the power supply changes the stator current flow in reverse. The rotor turns clockwise again. The process continues and the motor keeps transferring mechanical power to the rotor. The principal components of the motor are the stator, consisting in a steel core and copper windings, the rotor, consisting in a steel core and NdFeB permanent magnet, the inverter and the sensors.

Roughly simplifying the framework, the permanent magnet is the component that provides one of the most import features of the brushless DC motor: the power density. As already stated is the power density of this motor that leads to the weight reduction, a crucial feature for vehicles.

4 RECYCLING: DIRECTIVES AND OPPORTUNITIES

This chapter resumes the author efforts to depict the framework in which the end of life of an electric scooter takes place. The work consists in three main part: a brief analysis of the European directives involving the EoL of vehicles and the disposal of batteries and accumulators, an investigation performed through interviews regarding the EoL of scooters and a description of the current recycling management of the electric powertrain.

4.1 Waste management and recycling directives in EU

This section presents the main lines of the EU directives regarding recycling and EoL of vehicles, the directives treated are:

- Directive 2008/98/EC on waste management;
- Directive 2000/53/EC on ELV;
- Directive 2006/66/EC on batteries and accumulators;

In the European Union the Directive 2008/98/EC covers the general issue of the waste management and recycling. This Directive depicts a legal framework for the treatment of waste among the countries of the Union. The purpose is to protect both the environment and human health through the right handling of waste [13].

An important point touched by the Directive is the “waste hierarchy”, see Figure 4.1. The “waste hierarchy” is a central issue of the waste management. This issue is also significant for the product development. In fact, it is during the “conceptual design” of a product, in the early life of it, where market analysis are performed and the first resources are allocated, that the engineer or the designer has the most powerful means to design a product recycle-friendly [3].

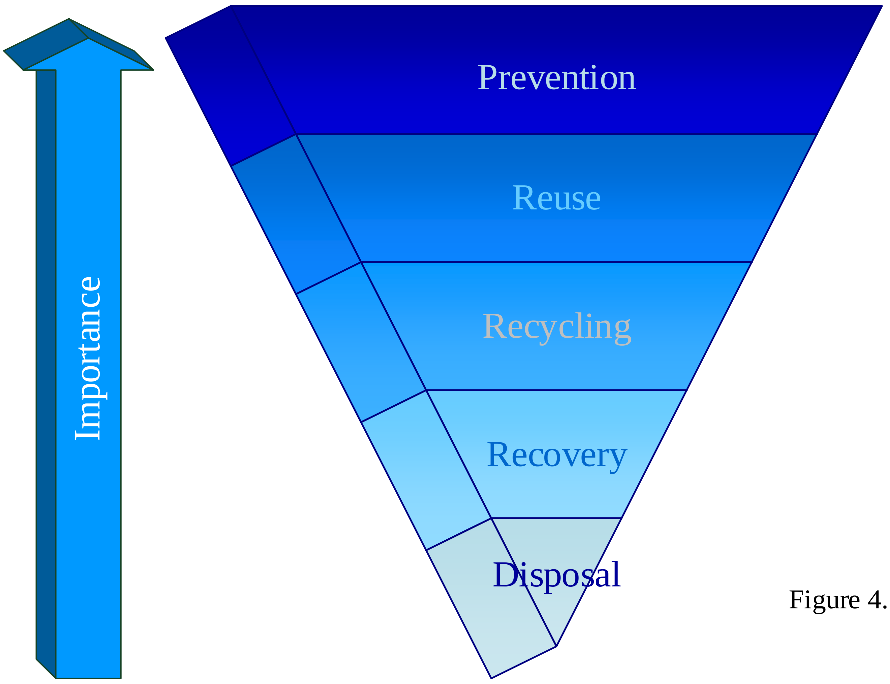


Figure 4.1, the waste hierarchy

Another important role is acted by the Commission Communication of 21 December 2005 “aking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste” [14]. This communication represents a list of guidelines for the members of EU towards a more effective and sustainable waste management. The objectives to achieve were encompassed in seven points

1. Implementation and enforcement of existing EU waste legislation
2. Simplification and modernisation
3. Introducing life-cycle thinking in waste policy
4. Waste prevention
5. Improving the knowledge base
6. Development of recycling standards
7. Further elaboration of the EU’s recycling policy

In 2000 the EU approved a directive about the end of life of vehicles [15]. The directive concerns vehicles with at least three wheels, so, scooters, and two-wheeled vehicles in general, are not affected. The directive pointed out some goals to be persecuted during the following years. Interesting to underscore is the recovery/reuse weight ratio and the recycle/reuse weight ratio thresholds to reach in the future, see Table 4.1. The mainlines of the directive are:

- Limit waste production
- Organise waste collection
- Organise waste treatment
- Prioritise the reuse and recovery of waste
- Facilitate dismantling through information on components and materials
- Evaluate progress made through implementation reports

year	%of recovery/reuse	%of recycle/reuse
2006	85	80
2015	95	85

Table 4.1, recovery/recycle goals for ELV

A concern proper of vehicles is the disposal of spent batteries and accumulators. Traditional vehicles contain lead batteries. Lead batteries, as a well-known technology, have an efficient collection and recycling chain [16]. It is interesting to underscore, though, that electric vehicles contain lithium batteries. Lithium batteries as a relatively new technology do not have an efficient recycling chain.

The European directive concerning the spent batteries and accumulators is the directive 2006/66/EC [17]. This directive brings an important change from legislation point of view. The new directive, in fact, regards all kind of batteries and accumulators, and not only the hazardous ones (the batteries containing mercury, lead or cadmium). Interesting are the collection and recycling rate thresholds that each Member State shall achieve in the next years, see Table 4.2, 4.3.

year	%of collection
2012	25
2016	45

Table 4.2, collection goals for batteries

year	%of coll.(PbA)	%of coll.(NiCd)	%of coll.(Oth.)
2011	65	75	50

Table 4.3, recycle goals for batteries

4.2 End of life of scooters

The end of life of scooters is an interesting case study. As written in the previous paragraphs the European directive ELV regards only vehicles with at least three wheels. Hence, about the disposal of scooters there is not legal responsibility of the manufacturers as for the cars.

The investigation of this field of study is performed in three parts. First is reported the position of the ACEM, the body representing both the major manufactures and the national two-wheeler associations. Then information from the yearly environmental reports of several manufacturers are presented. Finally, the result of interviews with vehicle disposal companies are reported to depict how scooters are currently handled. This section mainly involves the ICE-scooter. The E-scooter is "too new" to have enough material for a proper investigation.

4.2.1 Scooter manufacturers and recycling

The ACEM [21.W], the Motorcycle Industry in Europe, is an Association constituted by 18 national associations and 14 powered-two-wheeler, PWT, manufactures. ACEM was instituted in 1994 by merging two professional bodies the COLIMO (Comité de Liason de l'Industrie du Motocycle) founded in 1962 and ACEM (Association des Constructeurs Européens de Motocycles) founded in 1990. The ACEM manufactures give jobs to more than 127000 people and the yearly turnover of the members of ACEM amounted to 26 billion € in 2010. The ACEM manufacturers hold up to 95% share of the European PTW market. The ACEM gives its own answer to End-of-life issue regarding the PTW [22.W]. ACEM asserts that the End-of-life of PTWs represents a non-existing issue in the EU waste management discussion. The reasons that ACEM presents to justify the previous statement are:

- In the EU states there are no reported case of illegal dumping of dismissed PTWs.
- Old PTWs are still an object of value. Vintage scooters are articles suitable for collection.
- The second hand spare parts are object of a well-established market. This also contributes to limit the waste.
- PTWs are designed for easy accessibility and maintenance.
- PTWs rider groups and sport associations promote the reuse market.
- ACEM analysis shows that the 75% by weight of an average PTW is reused through high-value recycling as spare parts. The 25% is disposed as waste.
- An ACEM survey reveals that almost any PTW is returned to the dealer/manufacturer circuit for the disposal.
- An ACEM survey reveals that the ratio of dismissed PTWs over dismissed cars treated by the dismantling companies is 1 to 150/400. The difference is two orders of magnitude.

A review of the environmental reports of the two most valuable scooter manufacturers in Europe has been conducted. According to ACEM among the top 10 sold motorcycle models three are manufactured by Piaggio Group and four by Honda. The environmental report of Honda and Piaggio are analysed for what concerns the waste management of their products.

From the review of the 2013 Honda environmental report, some interesting features emerge [11]. First, there are interesting statements among the "environmental issues for Japan". Honda motor co. declares to reduce waste per unit of revenue by 5% by fiscal year 2014. More specifically Honda motor co. declares to maintain the zero landfill strategy and to involve its manufacturing holdings. The Company is also aiming to increase the effective recycle of motorcycle up to 95%. In the report there is also a section dedicate to waste management and recycling, the most important issues are:

- Regarding the 3Rs (reduce, reuse, recycle) Honda motor co. claims to adopt a 3R pre-assessment system during the first stages of the product development. Classical measures are making lighter vehicles, use recycled materials, disassemble-friendly design and product labelling. The 3R pre-assessment system has been adopted for the design of PTWs since 1992.

- Size and weight reduction is taking into account. The reduced gear oil capacity by 20% and the reduced use of radiant coolant by 20% of the PCX scooter is the result of the weight reduction purposed design.
- As already stated in the “environmental issues for Japan” the aim is to reach the threshold of 95% of recyclability rate for motorcycle, calculated with the Japanese directive.
- An interesting issue of Honda motor co. is the “voluntary initiatives to recycle motorcycles”. Since 1st October 2004, Honda and other Japanese manufactures started a voluntary recycling initiative that continues until today. It represents the first voluntary attempt of this kind in the motorcycle industry. The results of the initiative during the 2013 were that 1724 products, the 58% of the total amount collected, were Honda products. The recycling rate for these products was 92.4% on weight, an increase of 4.6% points in respect to the previous year.

Figure 4.2, Recycled pigmented polypropylene parts of a Piaggio scooter [12].

In the paragraph is presented a brief analysis of the 2013 corporate social responsibility report of Piaggio [12]. The main aspect to underscore are:

- In 2007, Piaggio performed a recycle analysis of its products according to the ISO 22628. The average recycling rate was around 90%, higher than the 85% required by the car directive at that time.
- In the vehicle is endorsed the use of recycled pigmented polypropylene for the parts like footboards, seat, etc., see Figure 4.2. The report states that the plastic body represents the 10% of the whole scooter weight. The pigmented polypropylene, that could be recycled, represents the 70% of the plastic body.
- “Re-Produced” project. The “Re-Produced” project involves the recycling of plastic materials usually used for thermal recovery. A new material called Plasmix is made out of the plastic waste.

4.2.2 A waste management investigation

To depict a framework of the end-of-life of the scooters several interviews through phones and emails have been conducted. The companies chosen are from the centre-north of Italy. The reason is the high level of diffusion and use of the two wheelers in that area. According to ACEM, the European association of motorcycle manufactures, Italy is historically the European country with more two wheelers registered and that produces more motorcycles and scooters. Piaggio Group, the main European two-wheeler producer, is Italian.

The companies involved in the investigation are three dismantle companies and one manufacturer [23.W, 24.W, 25.W, 26.W]. The choice to include a manufacturer is to reach a wider framework of the topic.

The most frequently asked question were:

1. What is the normal procedure for the acceptance of a scooter? What is the difference with a car?
2. Which is the disassembly process flow?
3. Have you ever treated an electric scooter? How would you treat it, in case?

To the first question, the answer was very similar among the four parties. The normal procedure is to receive the powered two wheeler, PTW, like a standard car. The first operation is to accept the vehicle and to release a certification to hold harmless the last owner. From that moment on, the scooter ends its life as a mean of transport and starts the new one as waste. For the car, the dismantler is obliged to accept to dispose the vehicle without any costs but taxes and the transportation. For the PTWs the decision is up to the dismantler. Usually the same rule is applied. This is also linked to the profitable market of the spare parts [23.W, 25.W]. It can happen that the reason of the disposal is an accident and the scooter is so damaged that the only residual value is represented by the materials to recycle. The dismantler in that case can apply an extra charge [26.W].

The process for the disassembly is divided in three steps, see Figure 4.3:

- hazardous component treatment;
- disassembly of valuable parts;
- safe stock.

The hazardous component treatment consists in the removal of batteries, fluids, oils and fuel. Before this treatment, the scooter is a hazardous waste. It contains fluids with high environmental risk. The first step is the removal of the battery and the safe stock of it. The safe stock is in a tin container to avoid any fluid loss. The second step is the removal of the fuel. The fuel can be easily reused. The third step is the removal of the engine oil, transmission oil and brake fluid. These fluids have to be safe stocked in tin containers. There could be a fourth step for the removal of the oil filter. It depends if the engine meant to be reused or disposed. For disposed batteries and waste oils, there are national disposal unions. The lead of the batteries is recycled. The 95% of the lead in the vehicle battery market is secondary [27.W]. The oils are recycled or thermic recovered [28.W].

The second stage is the disassembly of valuable parts. The scooter parts have different levels of value. The most valuable are the spare parts for the spare part market. The spare parts represent a high level of reuse of disposed material.

"The spare part market represents the only remunerative reuse/recycle method of the entire disposal chain of a vehicle" – Autodemolizioni Busche [23.W].

With this statement, a dismantler wanted to underscore that often the value of a vehicle for the recycled material market is not even enough to cover the manual work for the disassembly whilst the spare market is a profitable market. After this step, there is the disassembly of the cost-effective material for recycling. These materials can be divided in metals, polymers and tyres. The more important metals for recycling are copper, aluminium and magnesium. For the polymers there are two option the recycling or the thermal recovery. The tyres too have a specific recycle union for their recycling or their thermal recovery [29.W].

The dismantler after the disassembly performs a volume reduction of the different materials. The dismantler performs also a volume reduction of what remains from the second stage. Each group of materials waits in a safe stock until it leaves the dismantle company for following recycle/recovery treatments. In addition, the residual car body is stocked waiting for shredding/sorting treatment.

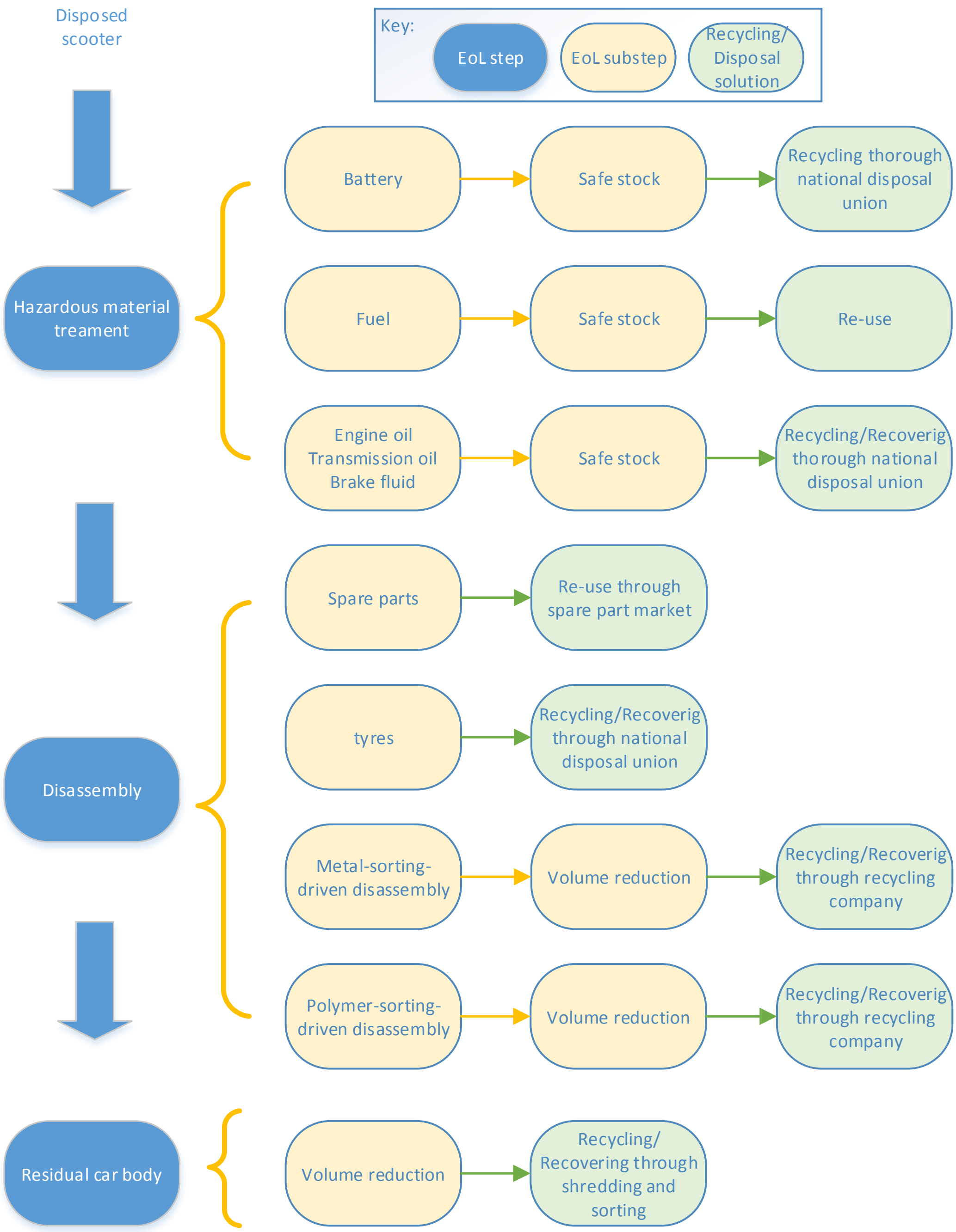


Figure 4.3, the E-scooter disposal process flow

Among the three dismantlers interviewed, no one has ever treated an electric scooter. To the question “What would you do if?”, the answers have been similar. The main differences between the two designs are the lithium battery and the electric motor. The lithium battery is removed in the first stage as a standard battery. Therefore, from the dismantler point of view the removal is conducted in the same way.

“The electric motor actually increases the value of an electric scooter compared to a traditional scooter, at least because of the copper. It would probably be easier to sell than a thermic engine” –Ecostrada [26.W].

This statement underscores the fact that the E-scooter actually includes more valuable materials than a traditional scooter. In the most probable scenario depicted, the dismantler disassembles the E-motor during the second stage of the process flow and sells it to a metal recycle company. At the moment the interviewed dismantlers do not treat printed board circutis, PCBs, part of the controllers of an E-motor. The PCBs contain small amounts of precious materials like gold. They state that whether it is economical worth they would treat them [23.W].

4.3 Disposal of the electric powertrain

This section explains how the management of the electric powertrain takes place.

4.3.1 Lithium battery waste management

As already mentioned in the third chapter, there is a European directive [17] regarding the spent battery management. This directive involves also the management of spent lithium batteries. An important issue of the directive is that the waste management of batteries is under producers’ responsibility. EU member countries have to set up the waste collection but it is up to producers to run the collecting system and take care of the proper disposal.

The lithium battery is a relatively new technology. The collection system has been implemented in all European countries. The treatment implants, instead, are not equally distributed. In Italy, for example, there are still not plants for the proper disposal of lithium accumulators. Nowadays, the batteries are collected and then they are sent to mainly Germany and Switzerland for the disposal and recycling [27.W].

According to Georgi-Maschler, T. et al. [21] the collection rate of lithium batteries in the EU in 2007 was just the 3% whilst in Germany in 2008 9%. The collection rate of a disposed product is the ratio between the disposed units and the sold units of that product over a certain period. However, the collection rate is expected to increase rapidly since the main share of lithium batteries was sold in the last 10 years.

The recycle chain of disposed lithium batteries is still not well defined. There are different technologies and process flows applied all around the world to treat these batteries, see Table 4.4. Company websites and scientific literature have been the main tools to collect information.

Company	**Location**	**Technology**	**Li recovery**	**Other metals**	**References**
Batrec	Switzerland	Pyrometallurgical	NO	Steel, Ni, Co	[22, 23, 24, 30.W]
Retriev Tech.	USA	Hydrometallurgical	YES	Al, Cu, Co	[22, 23, 24, 31.W]
Recupyl	France	Hydrometallurgical	YES	Steel, Cu, Co	[22, 23, 24, 32.W]
Umicore	Belgium	Pyrometallurgical	NO	Ni, Cu, Co, Slag	[22, 23, 24, 33.W]

Table 4.4, Li-ion battery recycling companies

During the last ten years, a strong driving force towards the recycling has been the value of some materials. Considering the average composition of a lithium battery, see Table 4.5, with the cobalt cathode the price in terms of materials is between 4000-6000€/ton [22]. The 80% of the total price is actually the cobalt, that by itself has a value between 3000-4000€/ton. This is why most processes are mainly focused on the recycling of valuable metals like cobalt or nickel.

Battery component	**Mass-%**
Casing (Aluminum)	20-25
Cathode ($LiCoO_2$)	25-30
Anode (graphite)	14-19
Electrolyte	10-15
Copper electrode foil	5-9
Aluminum electrode foil	5-7
Separators (polymers)	-

Table 4.5, Average composition of a lithium battery with cobalt cathode [22]

Nevertheless is possible to underscore some driving forces that are gaining more importance in the lithium recycle framework:

- Regulations: European directive 2006/66/EC is giving energy to collection and recycling. The directive states that from September 2011 the recycle content of a lithium battery has to be at least the 50%. The regulations states also that the collection level to be reached within September 2016 is 45%.
- Lithium market increasing: The lithium market has enormous potentiality. At the moment lithium batteries are the most suitable for portable technologies, such as laptop or smartphones, and for the full electric vehicles. Hence, from this point of view is important to improve the recycle chain to avoid the introduction of virgin material in the market.

4.3.2 Permanent magnet waste management

The NdFeB permanent magnet is an unknown component for the traditional vehicle life cycle. The neodymium has a considerable environmental impact, the mining of neodymium leads to radioactive dust [25], a complete review of the neodymium life cycle, the same used for the LCA, see chapter 7, is reported in the appendix, see Appendix A.1. Furthermore, neodymium is a peculiar case of one-country resource, since over the 90% of neodymium comes from China [26]. Considering the increasing need of brushless electric motors, the environmental impact of rare earth element mining and the China control over the world reserves the recycling of this material becomes crucial [27, 28].

The permanent magnets are made of an alloy of neodymium, iron and boron. The most important material of the alloy is the rare earth neodymium. Neodymium, as all the other rare earths, is mainly mined in China. According USGS national minerals information, China owns the 40% of the world rare earth element reserves and the 91% production market share [34.W]. There are different mining sites in China. The biggest ones are Sichuan and Bayan-Obo in the Inner Mongolia [29]. According different studies Bayan-Obo is actually, the most prolific, holding around the 50% of the Chinese production [30].

As already stated in the previous paragraph the recycle of rare earth elements, REEs, is becoming crucial. However, the level of recycling is still very low. The implementation level of the recycling technologies is still at a lab-scale [31]. Nowadays, the level of recycling is less than 1% [32]. Jones et al. [33] discriminate among three different recycling perspectives. The first is the direct recycle of pre-consumer WEEE manufacturing scrap, the urban mining as the possibility to see the urban waste as a source of REEs, and the landfill mining of residues containing WEEEs scrap.

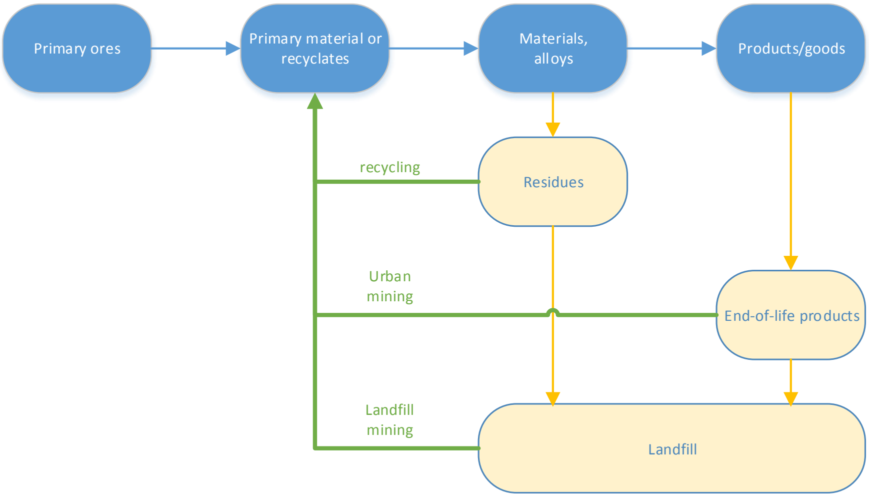


Figure 4.4, different recycling opportunities [33]

Focusing on permanent magnet, K. Binnemans et al. [34] define three different flows. One is for magnet manufacturing; one is for disposed WEEE and another one for large magnets from wind turbines and electric vehicles. The manufacturing actually produces a large amount of scrap, almost the 30%, but the recycling is effective. For long time, though, the recycling during the production was the only kind of recycling of REEs [35].

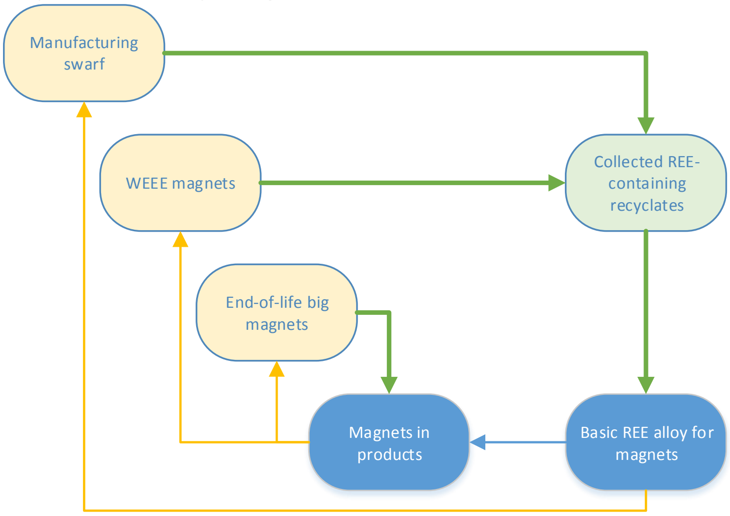


Figure 4.5, different recycling flows for permanent magnets [34]

Also involving the case of electric scooter, a very interesting approach is the direct reuse of magnets in their original shape. K. Binnemans et al. think that this could represents the best alternative for large electric motors used in wind turbines, industrial machines and electric vehicles. However, this kind of reuse is not currently available. The number of electric vehicles or E-scooters is not enough to build a proper reuse chain. First, there must be a strong penetration of the vehicle market by the EVs, and then there will be another time gap linked to the long service period of these devices.

Hard disk drives, HDDs, present in the WEEE are at moment the widest source of permanent magnets. Currently, the procedure does not include a disassembly pre-step for HDDs. The WEEEs are usually shredded. After the shredding is very hard to sort ferrous powder and NdFeB powder because of the strong magnetic properties of the neodymium. The following sorting operations consist in a series of physical treatments. It let sort mainly ferrous materials, aluminum, copper and plastics. The most advanced procedures can separate valuable materials like lead, nickel or precious metals trough smelting. In these processes, REEs still are not treated. They become part of the smelter slags, not recoverable in the nowadays recycle processes. The pre-step for the disassembly remains an issue. Further information on the recycling opportunities of neodymium are presented in the appendix, see Appendix A.2.

5 MATERIAL HYGIENE

The Material Hygiene is a mind-set developed by the EcoDesign staff at KTH. This mind-set helped and suggested the whole research topic of this report.

5.1 Material Hygiene, the mind-set

Material Hygiene is a mind-set aimed to improve the recycling of materials throughout the product life cycle. The name of Material Hygiene has been chosen as an "evocative" name. The authors wanted to recall a metaphor for the treatment of provisions. Meat and vegetable lifecycle requires to preserve a cold chain to maintain high hygienic standards from the producers to the last users, to keep information about the origin of a product throughout the whole food life, etc. [4]. In the same way, the material hygiene aims towards a purpose-recycled mind-set that attempts to preserve a high level of effective recyclability during the whole product life cycle. The definition of Material Hygiene proposed by the KTH EcoDesign research group is:

> *MH is to, in every step of the product life cycle to act towards larger amounts of useful material from recycling, on the same quality level as virgin material.*

MH represents a tool to keep the recycling to a high level. High levels of recycling mean high effectiveness of material use. Furthermore, the MH mind-set should be encompassed in the early stages of the product development where there is more design freedom, see Figure 5.1.

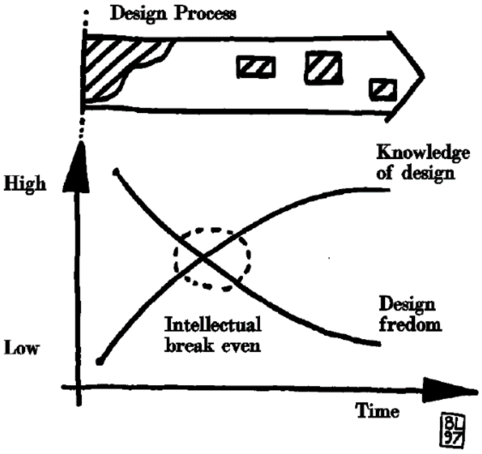


Figure 5.1, Design freedom in product development [3]

MH represents a tool for material management. As a tool, MH aims to build a virtuous chain of material production/consumption/recycling.

Concerning the waste management, the three procedures of dismantling, shredding and sorting are often seen as alternatives. MH underlines the difference and the conflict between these procedures. The shredding and the downstream sorting, the most common process flow at the moment for WEEE, is the cause of the loss of valuable resources. The dismantling and the upstream sorting represents an alternative process flow at a higher MH level. MH always considers reuse and remanufacturing.

MH, as an evolution of the ten golden rules for Ecodesign, defines more areas of interest. The next paragraphs show these factors.

- **MH mix**. The first issue is the use of materials. MH first position is to decrease the material involved in the project. However, this first statement leads to different consequences. More materials involved in the material mix could lead to lower weight, crucial parameter for automotive consumptions. Another strong design issue is to keep materials as separate as possible towards an easier sorting. More materials involved in the material mix could lead to a more disassemble-friendly product.

- **MH identification**. MH aims to let, not only the material chain, but also the information chain unbroken throughout the lifecycle of the product. The analysis of this information chain runs on two levels. The first level aims to figure out what kind of information is transmitted. The second level aims to figure out how the person/machine on charge of the product interprets this information. For metal sorting, for example, the information transmitted by the material is usually a physical property. The responsible of sorting, e.g. a density-based filter, reads the physical "information". For other materials, like hazardous fluids, a pre-treatment is required.
- **MH resources**. Often in the bill of materials of product, there are hazardous materials. These materials have to be handled with care. There are different approaches to deal with these materials. Lead batteries, e.g., have to be recycled according to a specific directive. The recycle chain of lead is one of the more efficient among the metal recycling chains. The RoHS [36] is a directive that states weight percentage thresholds for some hazardous materials. RoHS, as MH, involves material management. Nevertheless, the main difference between RoHS and MH is that RoHS attempts to keep out some materials of the product lifecycle while MH attempts to keep some other materials in the lifecycle product as long as possible.
- **MH weight**. As already said, weight could be crucial in automotive. Sometime, although, weight or material saving can go against an easy disassembly. More weight can lead to a disassemble-friendly product. For MH is not just important the amount of material that you save in the first life phase of a product but it is also important what you can recover afterwards.
- **MH map**. The MH map is a pre requisite of the MH mind set. A more efficient recycling or disassembly of a product is often achievable with small design changes. A clear idea of the basic product structure is crucial.

According to the MH there are six principal actors that play an active role in the material management of a product:

- **Designers**. They have a primary impact on the material mix choice and the Design for Disassembly solutions.
- **Purchasers** of the manufacturing companies. They have a primary impact on the material mix choice. They have to balance, together with designers, the cost of materials with the recycling thresholds imposed by the EU directives.
- **Retailers**. According to EU directives WEEE and ELV, retailers have to support the recycling costs. They have the opportunity and the duty to keep the MH chain unbroken. Recycling costs might decrease with an effective material management.
- **Consumers**. They have the opportunity and the duty to preserve the MH chain with a proper handling of the disposed products.
- **Recyclers**. They have a primary impact on the value of the recycled material. Their work acts downstream the work of the designers, since the efficiency of the recycling is dependent to the disassembly-friendly design of a product. Although, current recycling processes have a strong potential: recycling degree of technology is still far from the manufacturing.
- **Managers and Owners** of manufacturing companies. Since their dominant position on the strategic choices of the company, they have to understand fully the value of disposed material.

The five factors indicate five areas that directly influence the Material Hygiene of a product. In the same way, the six actors indicate six stakeholders that affect the material management throughout the life cycle. It possible to relate these two lists considering the role played by the most important actors on each factor, see Table 5.1.

	Designers	Recyclers	Users	Managers
MH MIX	+++	++	-	+
MH RESOURCES	++	++	++	++
MH IDENTIFICATION	++	++	+	+
MH WEIGHT	++	++	-	-
MH MAP	+++	+	-	-

Table 5.1, Relation between MH factors and MH actors

5.2 Material Hygiene, E-scooter as case study

The aim of this section is to assess different ways to increase the MH of an electric scooter. The first step related to the analysis of the E-scooter is to point out the qualitative flow of material involved in the life cycle. The chapter 4 shows the current level of recycling of the studied product. The first goal of the material hygiene is to get a high level of material efficiency through a proper material management. The qualitative graph hypothesized by the author is meant to clarify the purpose of a proper material management. In the graphs is also reported the qualitative balance of an ICE-scooter for comparison.

5.2.1 Material flow qualitative analysis

The first goal of the material flow quantitative analysis is to resume all the information collected in the previous chapter, see Chapter 4. The knowledge already presented about the current waste management of a scooter lets the author have a clearer idea of which are the materials and the components which require a higher material hygiene. The material flow analysis allows a graphical understanding of the aim of the Material Hygiene.

The material use is higher in the first phase, materials are, in fact, needed to manufacture and assemble the product. The material use of the electric alternative is assumed higher due to the new materials involved in the powertrain.

During the use phase, the material consumption of the two alternative is similar. The electric vehicle has to change the lithium batteries, heavy and containing different rare materials, the thermic scooter incurs in more maintenance of the “hot” components. In addition, the lead battery of the traditional scooter, is expected to last less than the lithium battery of an electric scooter.

The end of life of E-scooters does not include the recycling of permanent magnet and lithium. Other materials like aluminium and steel are recycled. The recycle rate of E-scooter is lower than the one of an ICE-scooter. Therefore, the “use” of material in the end of life of E-scooter is less effective.

In the qualitative comparison proposed, see Figure 5.2, the materials involved in the manufacturing and maintenance are considered “embedded” in the product lifecycle. Recycling in end of life is a way to keep these materials still embedded in the system.

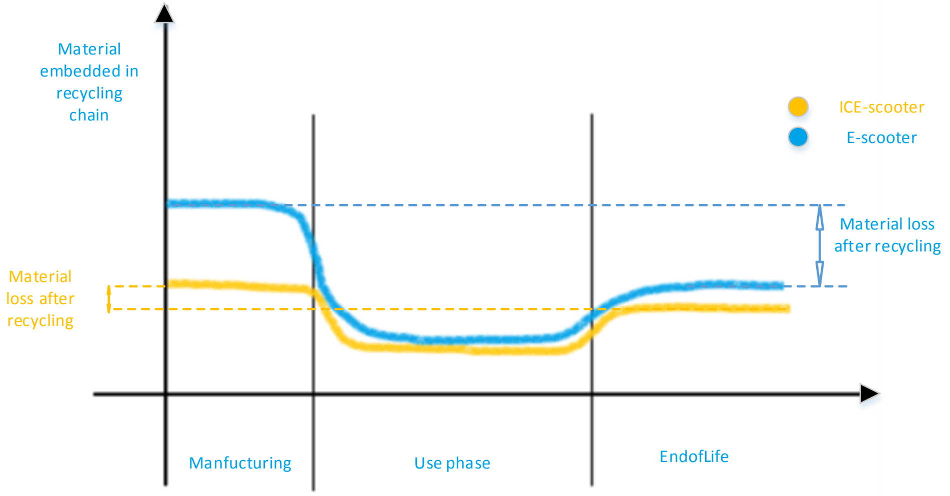


Figure 5.2, Qualitative material flow comparison

An efficient waste management means high recycling/reusing rates of the disposed product. High recycling rates improve the material use of the E-scooter. What just stated is one of the, already mentioned, purposes of this master's thesis. See Figure 5.3.

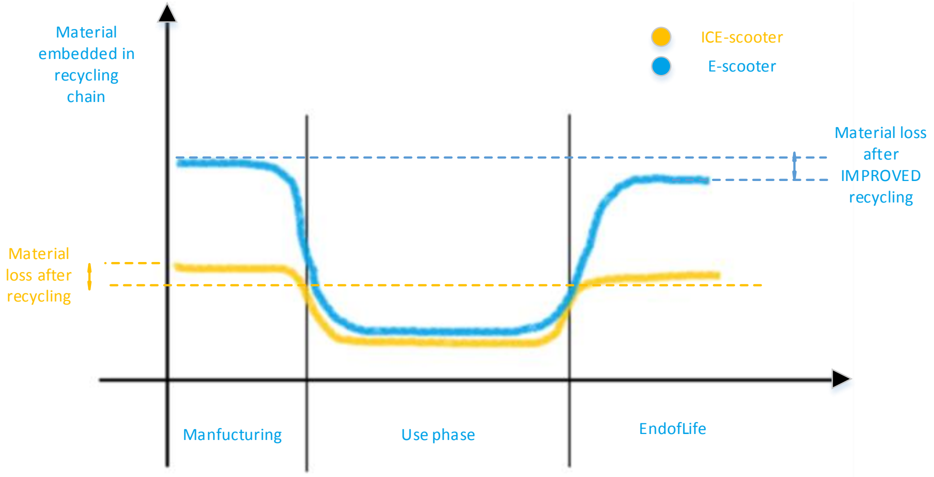


Figure 5.3, Qualitative material flow comparison after improved recycling

5.2.2 The method

To achieve an improvement on material use different recycling scenarios regarding the electric powertrain are hypothesised. The electric powertrain, in fact, is the *new* mechanical system that currently is not involved in a recycle chain, according to the investigation of chapter 4, see Chapter 4. The method consists in:

- Decide which are the MH actors more involved in the recycling scenario according to the scope of this work.
- Define which components and materials are the target of the improved material management.
- Depict the final scenarios according to the chosen materials and the scope of MH actors.

The principal features that the designed recycling scenarios have to embody are:

- Reasonableness. The recycling scenario has to be plausible. There must be scientific evidences of the feasibility of this process;

- Measurability. The recycling scenario has to be quantifiable. The level of detail has to allow the author to assess the overall impact assessment of the scenario;
- High level of material use. The recycling scenario's first aim is to have a high level of material use.

The three stakeholders more involved by this study are the managers of the companies, the recyclers and the designers.

The managers of the companies share the biggest responsibility to improve the recycling of their products according with a larger market penetration of the electric vehicles. Nowadays, neodymium magnets, for example, are not recycled because the amount of disposed electric cars or scooters is still too low to build up an efficient recycling chain. Nevertheless, it is responsibility of the owners to understand the value of the material. A feature of the MH is that

> '*Owners and company executives should see material as a second, different kind of share capital. If material is seen as a bank loan then the losses in recycling can be regarded as interest charge'* (J. Johansson on MH, 2006).

To assess the statement that the material embedded in the life cycle of the product is a shared capital, the author presents a bill of materials on electric scooter see Table 5.2. The data are from the literature and from the manufactures. This bill of material is a part of the inventory of the LCA of an electric scooter presented in the next chapters, see Chapter 7.

Together with the raw bill of materials is presented also a rough estimation of the price of each material involved. The total value computed, 343 $, is representative of the value as disposed E-scooter. The traditional scooter, with the same material prices $/t, has a total raw material value of 93$. This comparison shows the higher inner value of the E-scooter. The permanent magnet value considers it suitable for direct reusing.

material	weight (kg)	price $/t	$/product	$%	references
steel	40.8	380	15.50	4.52%	[35.W]
copper	7.68	6995	53.72	15.65%	[35.W]
nickel	0.141	19300	2.72	0.79%	[35.W]
aluminium	25.1	1823	45.76	13.33%	[35.W]
polyethylene	4.94	1639	8.10	2.36%	[36.W]
polypropylene	12.3	1406	17.29	5.04%	[36.W]
polyvinylchloride	2.06	440	0.91	0.26%	[37.W]
synthetic rubber	4.96	410.55	2.04	0.59%	[38.W]
alkyd paint	0.459	-	-	-	-
lead	0.04	2084	0.08	0.02%	[35.W]
gold	0.000512	40053000	20.51	5.97%	[39.W]
zinc	0.739	2073	1.53	0.45%	[35.W]
silver	0.0016	602500	0.96	0.28%	[39.W]
LiMnO	3.91	20000	78.20	22.78%	[40.W]
NdFeB	0.48	200000	96.00	27.96%	[41.W]
others	2.39	-	-	-	-
total	106		343.32	100.00%	

Table 5.2, Bill of materials of an E-scooter

According to Autodemolizioni Brusche, one of the company interviewed, the labour cost of a complete dismantling, considering also the treatment of the hazardous fluids, of a vehicle is around 70€ (c.ca 95$). As already stated, without the market of the second hand spare parts the recycling of an ICE scooter is not economical worth.

The E-scooter introduces new challenges and new environmental loads but it also has a higher inner value that could lead to economical-worthy recycle chain.

This work focuses on three materials. The NdFeB magnets, the lithium manganese oxide and the copper. These three materials share over 60% of the EoL value of the product while they constitute just the 11% of the total weight. The NdFeB is not recycled at the moment. The recycling of the lithium manganese oxide is a rare exception of in the normal procedures that usually do not recycle lithium. The copper is recycled, but it is usually recycled downstream a shredding procedure through handpicking or automatic separation. Since the increased amount of copper in the electric alternative (almost seven times more than the traditional scooter), also a more efficient recycling procedure for copper is matter of study.

Once pointed out which are the most valuable materials on which the stakeholders should focus. The recycling scenarios are described within the scopes of the two stakeholders more involved in recycling procedures: the recyclers and the designers. For this work has been considered scope of the recyclers all the recycling procedures that act downstream the disposal and are not specifically design-dependant. These scenarios are linked to state of art of the recycling technologies and are linked the idea that the

"Current recycling process has a lot of potential for industrialization; still recycling is far from reaching the level of manufacturing" (J. Johansson on MH, 2006).

From this point of view, the recycling processes proposed are:

1. Lithium battery recycling flow. The lithium battery recycling flow depicted comes downstream a patent analysis of the most used technologies on the market for the disposal of lithium accumulators. The cathode material recycled according to process step is the lithium manganese oxide ($LiMnO_2$). There is another cathode technology common nowadays, $LiFePO_4$, although, the choice has been made because more reliable data were available for $LiMnO_2$ cathode, especially for the LCA.
2. Neodymium recycling flow. The recycling flow for permanent magnet of electric motor that is hypothesised comes downstream a patent analysis. It is important to point out that whilst the patents linked to the lithium battery are used on industrial scale, nowadays the patents linked to the recycling of permanent magnets are just used on a laboratory scale.

For this thesis has been considered scope of the designers all the recycling procedures that are strongly design-dependant. A classic example of *design-dependant procedure* is the disassembly. The recycling scenario proposed linked to the disassembly is:

3. Permanent magnet reuse flow. The reuse flow for permanent magnet consists in sequence of steps for the disassembly of the wheel hub motor and the extraction of the permanent magnets. The principal method used is the disassembly graphical model defined by Luttropp.

The third material involved in the study is the copper. Both the battery (in the anode) and the electric motor (in the stator windings) have considerable amount of copper. Two copper recycling scenarios are modelled together with the previous scenarios. More specifically is considered the possibility to recycle copper within the lithium battery recycling flow 1 and it is considered to disassemble the copper windings of the E-motor together with the permanent magnets during the reuse flow 3.

It is worth to discuss also the recycling of the electronic controller for the electric motor. The valuable part of the electronic controller are the print circuit boards, PCBs. The PCBs contain precious metals like gold. Nevertheless, electric vehicles and scooters are one out of the thousands of products that use that component. The share of disposed PCBs from the vehicle market is negligible in respect to the ones from the electronic system market. Furthermore, since the great penetration market of electronic devices in the last decade different companies developed remunerative recycling processes already well established. For this reasons no recycling scenario is proposed for the electronic controller. The assumption is that it is disassembled, see Chapter 4, and recycled according to already existing procedures, see Chapter 7, section 7.2.4.

5.3 Material Hygiene, recycling scenarios

5.3.1 Lithium cathode recycling scenario

The author selected four technologies that should represent the top industrial standards available nowadays. The list of these technologies, and of the companies that use them, comes after literature review [22, 23, 24]. This section contains the patent analysis of the four process flows. Then, a plausible process flow is proposed. The table 5.3 resumes the features of the companies selected, see Table 5.3.

Company	**Location**	**Technology**	**Li recovery**	**Other metals**	**References**
Batrec	Switzerland	Hydrometallurgical	NO	Steel, Ni, Co	[22, 23, 24, 30.W]
Retriev Tech.	USA	Hydrometallurgical	YES	Al, Cu, Co	[22, 23, 24, 31.W]
Recupyl	France	Hydrometallurgical	YES	Steel, Cu, Co	[22, 23, 24, 32.W]
Umicore	Belgium	Pyrometallurgical	NO	Ni, Cu, Co, Slag	[22, 23, 24, 33.W]

Table 5.3, Lithium battery recycling companies

Batrec [37]

The technology is modelled as a process flow, see Figure 5.4. The method used to neutralize lithium reactivity in standard atmoshpere is the use of CO_2 as inert gas. The process involves also a method for the proper storage and transport of the lithium batteries. The metal recovered are chrome-nickel steel, cobalt, non-ferrous metals, manganese oxide and plastic.

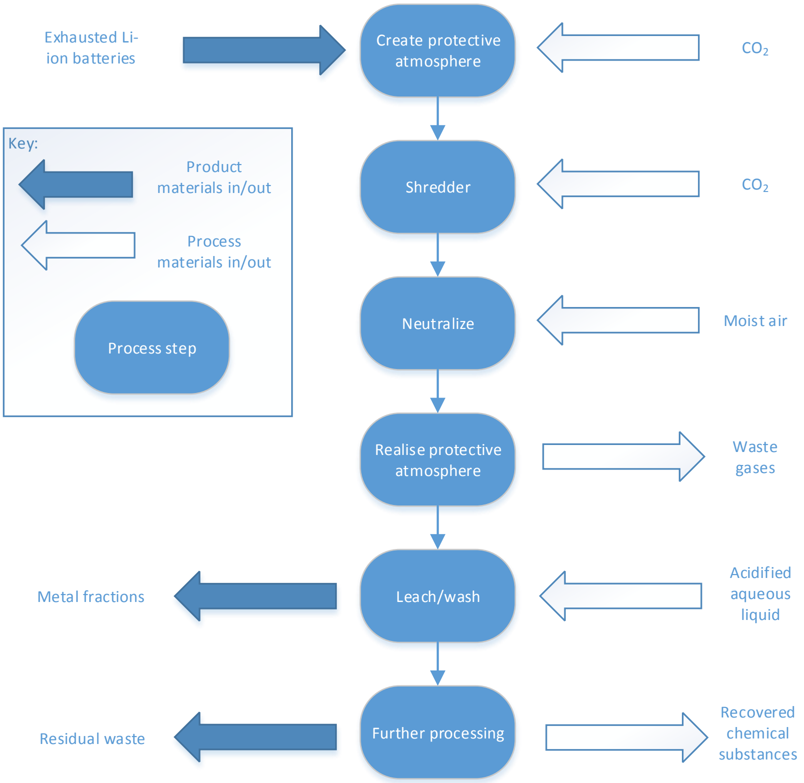


Figure 5.4, Batrec recycling process flow

Retriev Tech. [29.W]

The company claims to be able to recycle any size or type of lithium battery. An important step is the neutralization of lithium reactivity through a cryogenic treatment. This treatment is effective but it is very energy consuming. In the last years, an alternative process involving mechanical shredding and lithium brine has been proposed and implemented. The rest of the process flow is then a mixture of mechanical treatment and hydrometallurgical process. In the last stages through the adding of Na_2CO_3 and a further washing and drying, lithium carbonate is obtained. Other materials recovered are cobalt, steel and copper. See Figure 5.5

Recupyl [38]

Recupyl collects and recycles primary and secondary lithium batteries. The company uses a patented hydrometallurgical recycling process, see Figure 5.6. The material recovered are steel, copper, cobalt and lithium. The following part of the paragraph describes shortly the patent owned by Recupyl. The safe inactivation of lithium is realized through an inert atmosphere of argon and carbon dioxide. Then mechanical and magnetic filters sort recyclable metals such as steel and copper. Lithium hydroxide and water are added to obtain a lithium solution plus solid cobalt. In the next step, solid/liquid are separated in two streams. The liquid containing lithium in solution is processed to obtain precipitated lithium carbonate. Interesting to notice is that this process generates hydrogen. The process recycles gas from the inert atmosphere employed in the early stages to keep the oxygen percentage under the inflammable range of hydrogen. The stream for the solid part leads to the recycle of cobalt and more lithium.

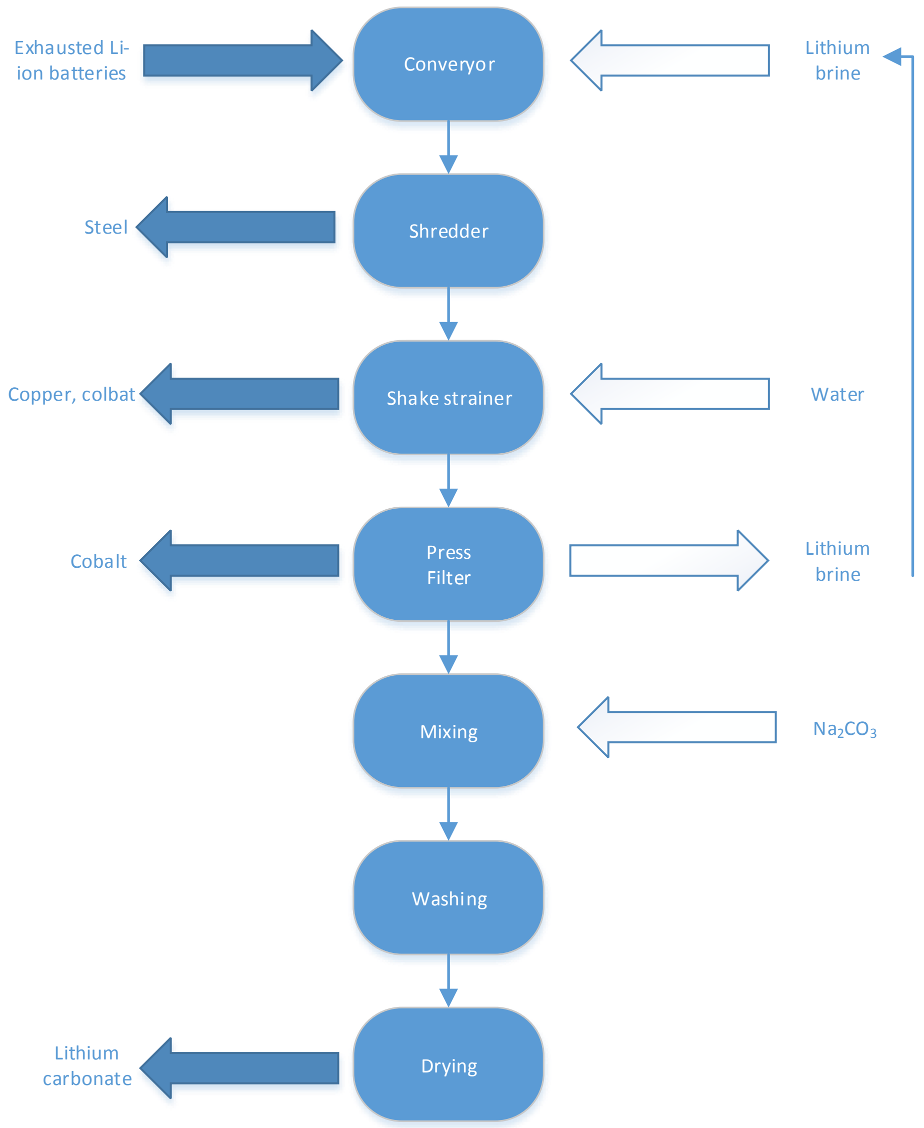


Figure 5.5, Retriev tech. recycling process flow

Umicore [39]

The following paragraphs present a brief description of the process flow. The description comes from an analysis of both Umicore website and the U.S. patent owned by the company describing the recycle technology, see Figure 5.7. Large batteries, like vehicle batteries, are first dismantled in Hanau, Germany. The rest of the process takes place in Hoboken, Belgium. The core of the process is the pyrometallurgical furnace. The exhausted lithium batteries together with coke, limestone and sand are fed into a vertical shaft furnace. Oxygen enriched air blows from the bottom of the furnace. The furnace works in three different stages: preheating zone, plastic pyrolysing zone and metal smelting zone. The temperature steps are from 300 °C to 1450°C. At the end of the process, there are two products: a slag and an alloy. The slag mainly contains aluminum, silicon, calcium and iron. In the slag is present also all the lithium held in the batteries. Currently the lithium is not recovered. The slag can be used in the construction industry. The alloy contains iron, copper and cobalt.

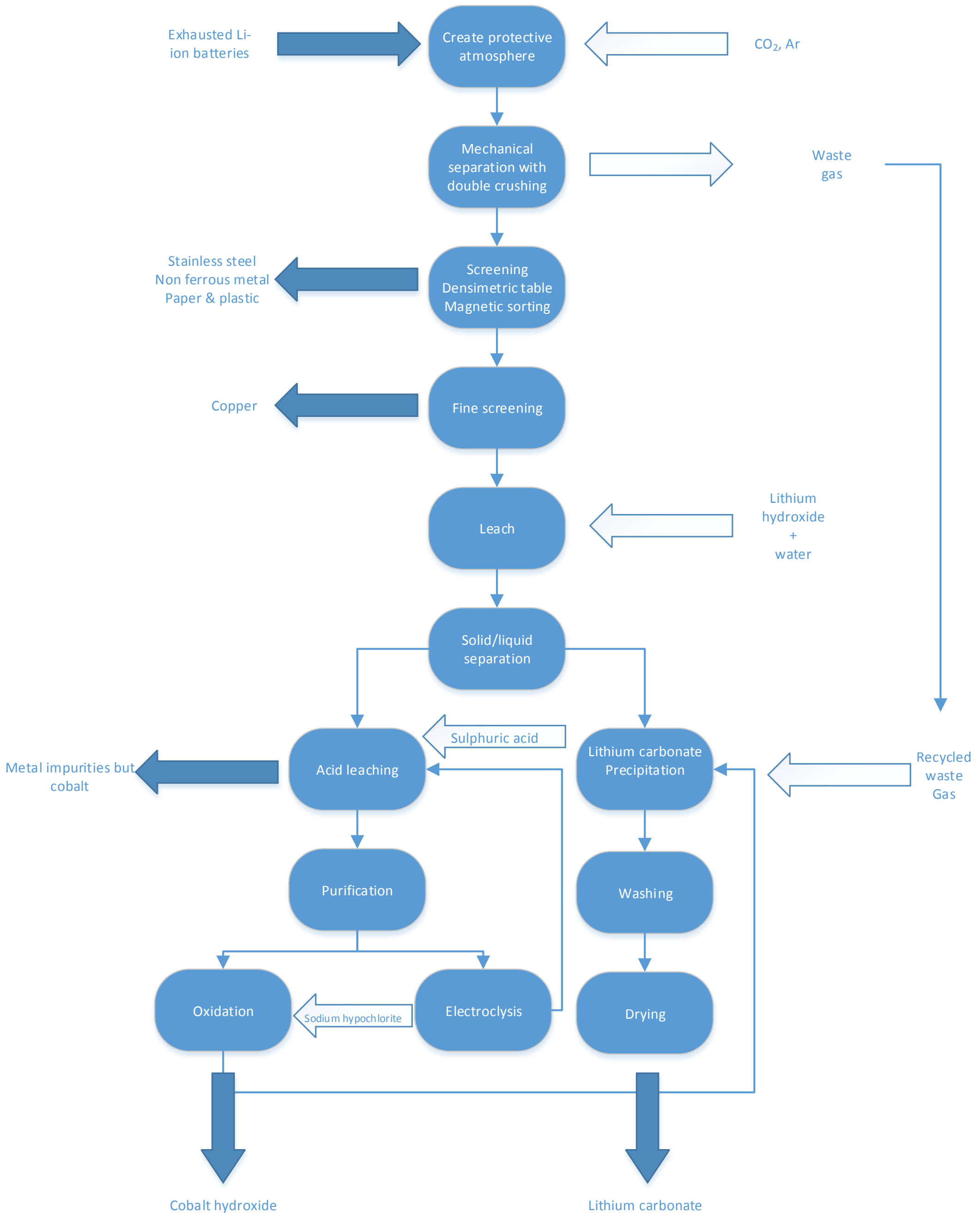


Figure 5.6, Recupyl recycling process flow

According to the processes analysed the most effective process for the recovery of lithium is the hydrometallurgical method together with a mechanical crushing step. The combination of hydrometallurgical and crushing processes is crucial. The mechanical process is important because gives the possibility to the recyclers to separate polymers and several metals, such as steel and copper, whilst the hydrometallurgical step leads to the recycling of the most precious materials like cobalt and lithium. The lithium causes explosive reaction with the standard atmosphere therefore an *inactivation* treatment has to be performed before or during the mechanical crushing. The hydrometallurgical process needs different chemicals, mostly acids, to be implemented.

The pyrometallurgical process is easier to implement. The most of the phases take place in the furnace. The fact that the disposed product is treated by pyrolysis makes the inactivation treatment unnecessary. Although, the pyrolysis does not allow the recycling of polymers and lithium because they are burnt during the process. The aim of MH is to look for a higher material efficiency, the pyrolysis, in comparison with the hydrometallurgical treatment, seems not to satisfy that requirement.

A recycling process for lithium based on a crushing step and a mechanical step is proposed. The outline of the proposed process consists in a hydrometallurgical flow with a crushing pre-step that could lead to a more complete recycling. The crushing pre-step is crucial for the separation of materials like polymers and copper. Before the crushing step is necessary to inactivate the lithium. This is done through a protective atmosphere of CO_2. After the crushing takes place a step of filtering to sort metals, such as steel and copper, and polymers. Afterwards, a hydrometallurgical treatment, the most suitable is acid leaching, is suggested with downstream a drying stage to obtain lithium manganese oxide powder. The author proposes just a simple outline of the process, also because it is out of the scopes of this thesis get into more details. The recycling scenario suggested respects the aimed features:

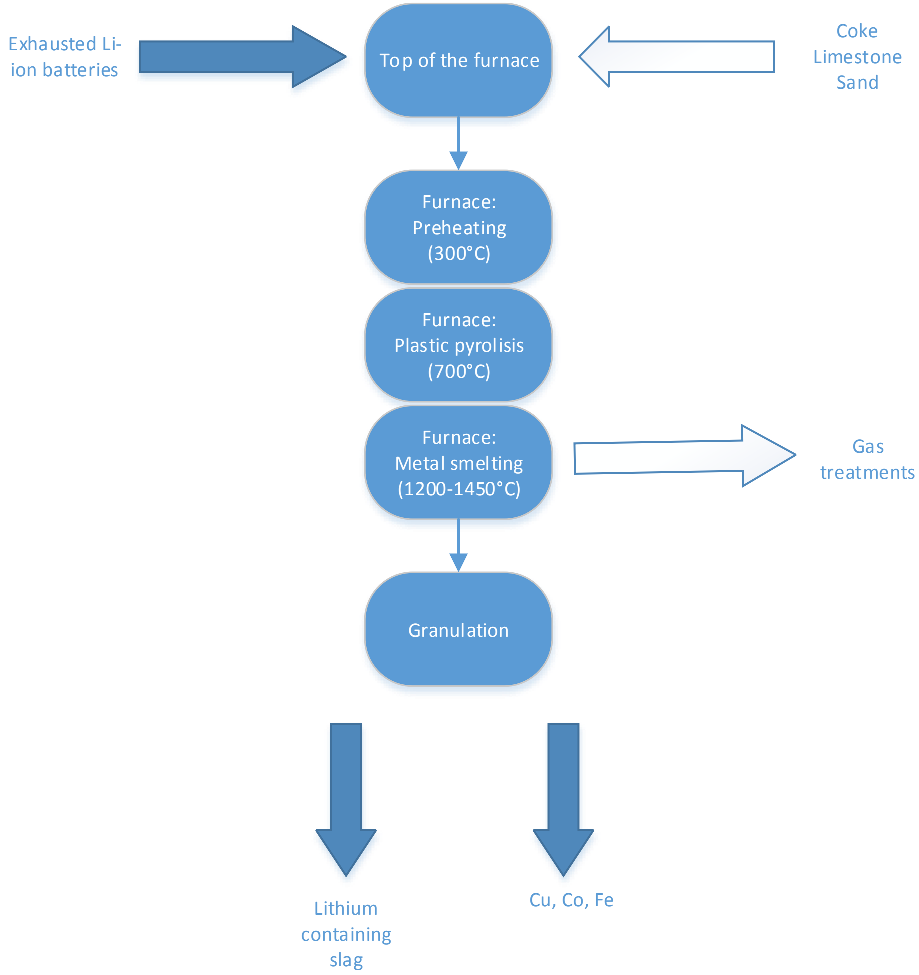


Figure 5.7, Umicore recycling flow process

- Reasonableness. The patent analysis seems to satisfy this condition;
- Measurability. The process depicted, see Figure 5.8, seems detailed enough. Furthermore, this process has actually been assessed in a LCA, see Chapter 7.
- High level of material use. With the recycling of lithium and copper this feature seems to be achieved.

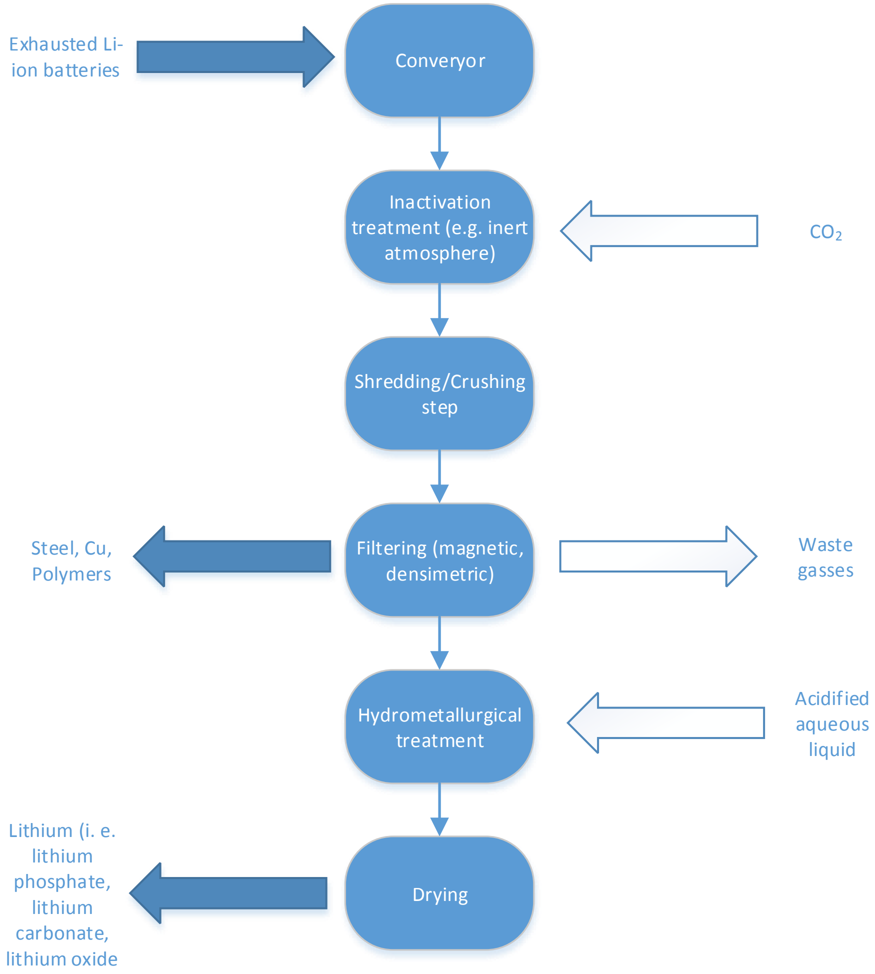


Figure 5.8, Recycling process flow proposed for lithium

5.3.2 Permanent magnet recycling scenario

According to the framework of the scooter disposal of the chapter 4, the E-motor is normally sorted and sold to some metal recycling company. The options for the E-motor are two. If the E-motor is big enough, in other words it contains enough copper to justify a disassembly pre-step, is dismantled and the copper windings are sorted out [40] otherwise it is shredded creating "meatballs" where the recovery of copper is less effective. In both cases, the permanent magnet follows the ferrous materials along the whole process. To increase the Material Hygiene of an E-scooter the permanent magnet has to be recycled. The approach used for the first scenario consists in the implementation of a process that does not requires a manual disassembly. No disassembly step means higher removal rate, a crucial parameter for recyclers. The recycling of neodymium is considered according the patent and the research work of the researchers A. Wallace and A. Walton [41, 42, 43]. The process is named hydrogen decrepitation, see Figure 5.9. The process flow is relatively simple. It exploits the hydrogen decrepitation, the fact that in hydrogen atmosphere the Nd rich boundary phase, between the bigger grains of NdFeB in permanent magnet, expands in volume. The permanent magnet breaks up and becomes powder. The demagnetization that let powder fall apart from the ferrous material is obtained by heating. The recycling rate is more than 90%. The details of the physical operation of the machine are descripted in the patent and in research work of Wallace and Walton. The hydrogen decrepitation is not important in itself but it represents a technical feasible solution for the recycling of permanent magnet. The goal of recycling neodymium is achieved. The rare earth is in the state of solid powder.

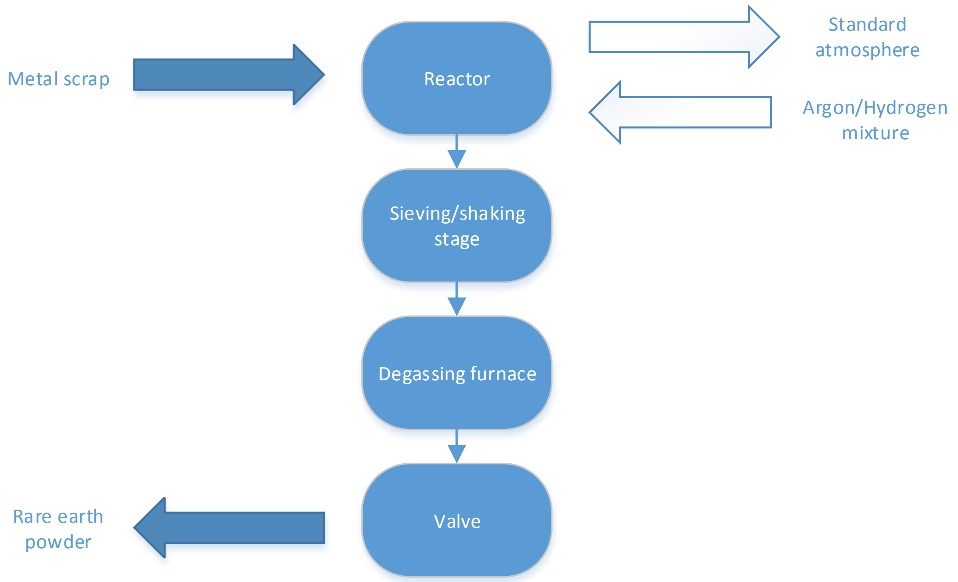


Figure 5.9, Recycling flow process for neodymium

The rare earth can then be inserted again in the process flow of NdFeB permanent magnet (for further information about the NdFeB life cycle see Appendix A.1). The recycling scenario suggested respects the aimed features:

- Reasonableness. Also in this case the analysis of an existing patent gives plausibility to this scenario;
- Measurability. The process depicted, see Figure 5.9, seems detailed enough. Furthermore, this process has actually been assessed in a LCA, see Chapter 7.
- High level of material use. The process achieves the goal of recycling the neodymium.

5.3.3 Permanent magnet reusing scenario

To reuse the permanent magnet is necessary to disassemble the electric motor. Furthermore, this disassemble pre-step is important towards a more effective recycling of the copper in the stator. This scenario involves a manual disassembly pre-step. The manual disassembly pre-step before recycling is a tricky topic for recyclers since involves skilled workers and design-dependant solutions that generally decrease the removal rata of a material. Nevertheless, the pre-step involves significant benefits towards a high level of material reuse and recycling.

According to what said about the MH it is very important to have a solid idea of the structure of the product analysed. MH map factor mainly embodies this concept. Towards a higher knowledge of the product, the figure below presents the CAD [44] of a wheel hub motor. The wheel hub motors can have different design solutions, nevertheless, is possible to identify one common prerogative [27.W]: the physical operation and the parts are the same of a classic BLDC motor but unlike it the rotor is external and stator is internal.

The method used to achieve an effective understanding of the motor structure and to propose a disassembly process is the one designed by Luttropp [7]. Luttropp developed the method as a tool for “Design for Disassembly structure”, DfDs, the part of Design for Disassembly, DfD, that deals with product structure. The method is graphical. It defines the concept of describing joints as resting load cases. Each of these resting loads can be graded, with an ordinal scale, regarding the information, the equipment, the force and the time needed to “wake up” the resting load. A graph is presented below. The implementation of the graph is qualitative.

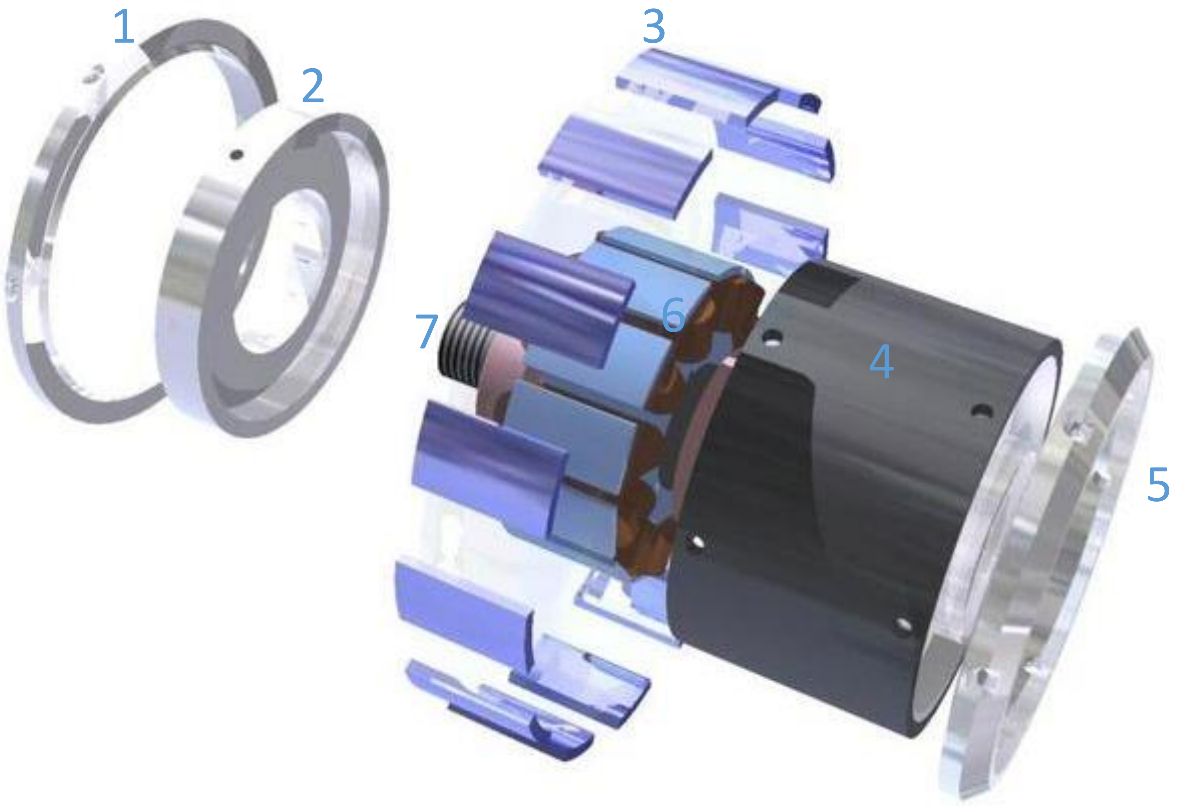


Figure 5.10, CAD of a wheel hub motor [44]

Number	Component	Description
1	Closing ring	It hosts screws. It holds the left endcap on the rotor
2	Left endcap	
3	Permanent magnet	Are glued to the internal part of the rotor
4	Rotor	It is linked to the two endcaps and the rest of the wheel
5	Righ endcap	
6	Stator	The stator with ferrous material and copper windings. it is stiffly mounted on the shaft (hub shaft)
7	Hub shaft	It is linked to the rotor by the resting load of the bearings

Table 5.4, Components of a wheel hub motor

Considering the joint evaluation, the most critical joints are the forcing joint (2.75 index), the magnetic field (3.0 index) and the glued joint (3.0 index). For the forcing joint, the use of a powered tool seems the plausible solution. For the magnetic field of the magnet that keeps it attached to the rotor, a demagnetization step should be included. There are two different approaches to demagnetization: the thermal and the electromagnetic. The thermal is easier and less expensive but has drawbacks such as the melting and vaporization of the glued bond between the magnet and the rotor that could lead to toxic vapour [34]. Thermal demagnetization would also preclude a hypothetical worker to work downstream. The electromagnetic solution seems more suitable [29]. The glued joint that attachs the magnet to the rotor is considered the main weakness towards an efficient disassembly.

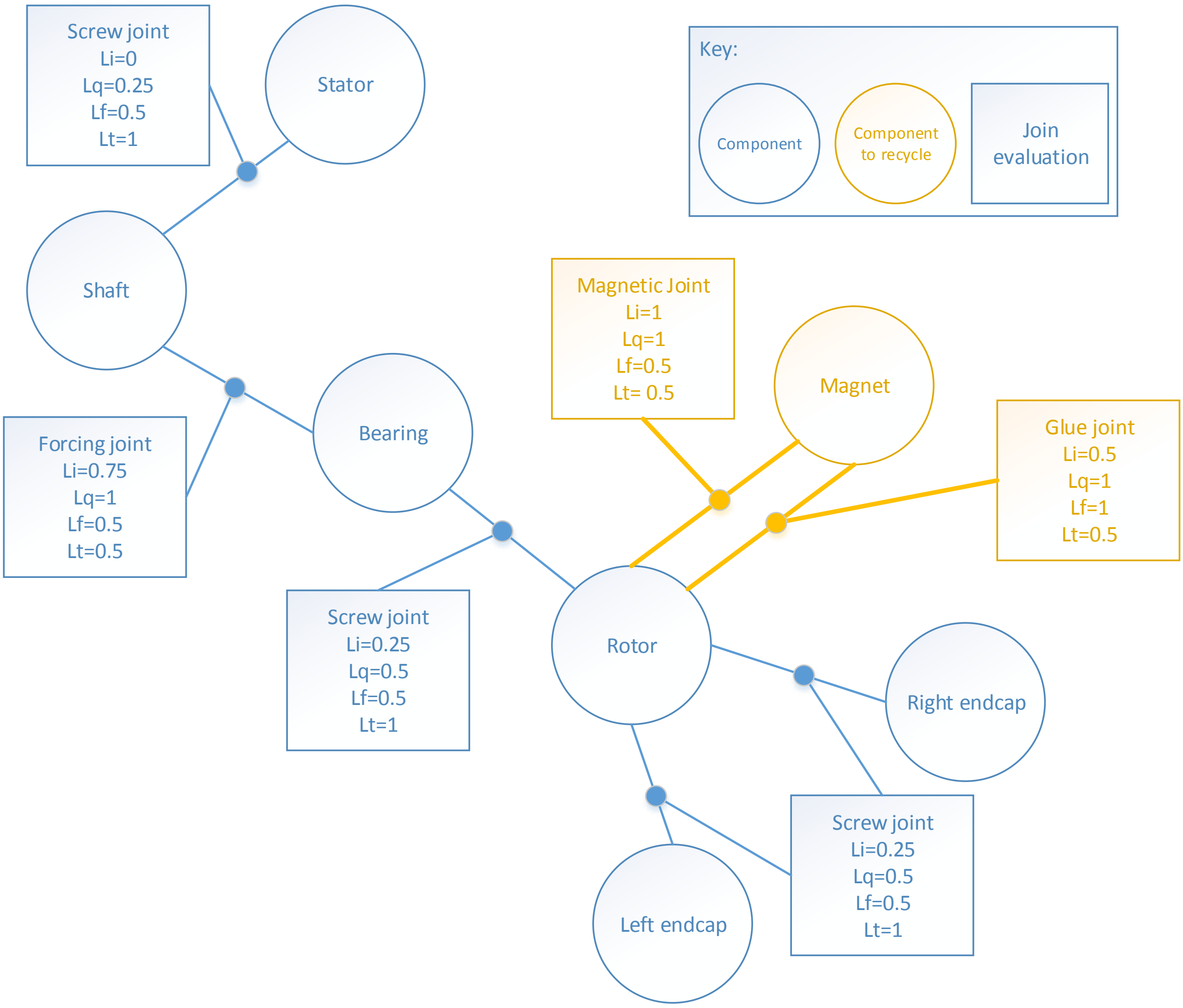


Figure 5.11, Motor disassembly scheme and resting loads

Index	**Topic**	**Meaning**
Li	Information	0-Easy to understand, 1-almost impossible to understand
Lq	Equipment	0-No tools needed, 1-special tools needed
Lf	Force	0-Just fingers needed, 1-power tools needed
Lt	Time	0-less than 10 s, 1-more than 30s needed

Table 5.5, Resting load index

The reuse is an available solution for permanent magnet of a certain dimensions [29]. The hypothetic reuse shown in this section is a four-step disassembly process:

1. **Disassembly of the end cap**; the assumption for the disassembly of the end cap is the unscrewing of the screw joints that connect end cap to the rotor.
2. **Extraction of the stator/shaft component**; the forcing joint between the shaft and the rotor might request a considerable force. A power tool that holds the rotor and pull out the stator and the shaft is needed.
3. **Electromagnetic demagnetization**; the permanent magnet needs a demagnetization step. The process designed involves an electromagnetic demagnetization. The electromagnetic demagnetization physical operation consists in electromagnetic pulse with the same magnetic field magnitude and opposite polarity. The electromagnetic demagnetization process is based on the patent US 2011/0100981 [45]. The invention selected, and the

process flow for the demagnetization, are not important in themselves but, as for the hydrogen decrepitation, they represents the feasibility of the process.

4. **Tool-aided magnet extraction;** the assumption made is that a skilled worker can extract a magnet with the help of a tool. The resting load of the glue joint is considered weak. This assumption has been made because the deterioration of the glue bond at the last stage of the use life of BLDC motors is one the causes of failure for these components [46].

This process flow is an example of the disassembly for reuse of a permanent magnet. The magnet needs to be magnetized again before being reused. The magnet is attached to the rotor with a glued joint. Glued joints may cause problems to the disassembly since the resting load linked to this kind of joints changes case by case according to the state of deterioration of the adhesive layer. To have a standardize disassembly pre-step it would be better to use different joint designs like screws or a supporting collars of magnetically non-conductive material.

. The recycling scenario suggested respects the aimed features:

- Reasonableness. For this scenario the Luttropp DfDs graphical tool seems to depict the disassembly step with plausibility;
- Measurability. The steps described in this section seems detailed enough. Furthermore, this process has actually been assessed in the LCA, see Chapter 7.
- High level of material use. This process ensures a high level of material use. This scenario, compared to the other regarding the permanent magnet, appears more environmental friendly since does not involve chemical treatments, brings to the reuse of permanent magnets and encompasses the disassembly of the stator that could lead to sort the copper windings.

5.3.4 Copper recycling scenario

The copper amount in the electric alternative is seven times bigger than in the ICE-scooter. As already stated the copper is usually recycled but the effectiveness of this recycling can be improved.

In the E-scooter, the greatest amounts of copper are in the battery and in the motor, according to these two components the hypothesised recycling scenario are:

- Copper recovery in lithium battery recycling process. The assumption made is to consider that the crushing/sorting process is also able to sort copper. This assumption seems coherent with the patent analysis performed;
- Copper recycling after the E-motor disassembly pre-step. The assumption made is that the disassembly of the E-motor to take out the permanent magnet gives also the opportunity to sort out the copper windings of the stator. This assumption seems plausible since, once the stator pull out from the motor the extraction of the windings is a relatively simple operation for tool-aided operator [47].

The importance of an efficient sorting of copper from other metals is important also because copper is a contaminant if present in other metals especially steel. To sort copper downstream a shredding process, even if economically worth, leads to losses of copper (more than 10%) that remains mixed up with ferrous materials. This causes a high environmental load since the recycled ferrous materials have to be diluted with primary steel to decrease the average amount of copper. A case study involving this recycling matter is present in the work of Johansson [4].

6 LITERARY REVIEW

This chapter shows the result of a literary review regarding quantitative comparisons between electric and traditional vehicles. The chapter reports both comparisons of cars and scooters. The author thinks that these notions are useful to understand the LCA of the next chapter and to comprehend better its results.

6.1 Comparison between an electric and a traditional car.

There have been in the scientific literature some examples of comparison between electric and traditional cars. The electric mobility as an alternative mobility has to face this comparison trying to solve or at least reduce the traditional mobility concerns.

Thomas [48] performed the comparison between electric and traditional vehicle from the emissions point of view. It states that the electric vehicle is still an oil-dependent technology and that the GHGs can be reduced only by 25%.

Boureima et al. [49] performed a comparative Life Cycle Assessment between a gasoline car and an electric car. The result of the study states that the electric car represents the greener alternative considering all the impact (GHGs, human health, acidification). However, this study appears too optimistic. Some assumptions that may have affected the result are the choice, as average electric car for the study, of the model “Tesla” by Tesla motor. The car Tesla is actually a high performance roadster that costs around 80000 $ [42.W]. Furthermore, the bill of material of the electric car is not accurate enough especially regarding the electric motor and the lithium battery.

In a LCA comparison [50] performed by EMPA, a research institute of the ETH, the internal combustion engine vehicle results worst as fossil fuel consumption and global warming potential, whilst the electric vehicle has worst effects on the human health, the ecosystem and the metal depletion. The main reason for the negative features of the electric vehicle is the amount of further energy and materials needed to manufacture the battery and the brushless motor. Nevertheless, in this study is underscored that to reduce the impact of an electric vehicle two main conditions are required. First, increasing the fragment of electricity produced by renewable sources in the electricity production mix and, second, increasing of the amount of recycled materials at the end of the life of the product.

A study conducted by H. Ma et al. [51] involves the comparison between the life cycle of a traditional and electric vehicle. The report estimates the global warming potential, through the parameter carbon dioxide grams per kilometre, of the two vehicle. The report states that for both the vehicle the life phase in which more GHGs are produced is the use phase. The results confirm the idea that the electric vehicle has a lower global warming potential.

Bartolozzi et al. [52], regarding the private transport in Tuscany, have conducted a comparison among different mobility alternatives. The method used was a complete life cycle assessment and the results were that the electric vehicle is better than the traditional one regarding the abiotic depletion, the acidification, the global warming and the ozone. The electric vehicle is more affecting, though, regarding eutrophication, human toxicity, aquatic and terrestrial Eco-toxicity.

6.2 Comparison between an electric and a traditional scooter.

The scientific literature concerning the comparison between electric and traditional scooters is quite poor.

Bishop, at the University of Oxford, performed a comparison between the operation costs of a traditional scooter and an electric scooter [53] and the environmental impact linked to the use phase. The result of the investigation is that the electric scooter produces 54% less GHGs and it used 35% less energy during its use phase. The result of the comparison between the operational costs is that the E-scooter operational cost results higher because of the cost for the replacement of the battery.

An important work, used also as reference for the Life Cycle Assessment of this reports, is the "Life Cycle Assessment of two wheel vehicles" performed by ESU-services Ltd. [54] and then implemented in the ecoinvent data 2.2. The complete life cycle assessment of an electric scooter and a traditional one are performed. The overall impact of the E-scooter according to the Ecoindicator99 is lower than the one of the ICE-scooter. The model, tough, has some strong assumptions. The Life Cycle Inventory, LCI does not include the permanent magnet and the bill of materials is obtained through a weight ratio with an electric car.

7 LCA, ANALYSIS OF E-SCOOTER LIFECYCLE

This chapter aims to answer quantitatively to the research questions declared in the purpose of the report. The method chosen is the Life Cycle Assessment. This chapter presents a section to introduce the theory of LCA method and a second part that describes the Life Cycle Assessment of an E-scooter.

7.1 LCA, description of the method

The method used in this report to answer this question is the life cycle assessment (LCA). Next paragraphs present a description of the method. The book “the hitch hiker’s guide to LCA” is the main reference used for this section [55].

The LCA is a method to assess the whole life cycle of a product. LCA meaning is relatively easy to understand intuitively. Another way to call this method is from “cradle to grave” analysis. In few words, the LCA is an assessment method that quantify all the life phases of a product, from the production, the “cradle” up to the disposal, the “grave”. LCA is actually more than this, it is also a procedure that lets us deal with complex problems.

The international standard ISO 14040:2006 [56] describes the method in detail. The procedure used to perform the LCA of this method tries to follow the standard approved procedure. Nevertheless, it can happen that the procedure used differs from the ISO. Anyway, each assumption has been commented and justified.

The LCA consists in a sequence of steps:

1. Definition of goal and scope of the LCA
2. Life Cycle Inventory, LCI
3. Life Cycle Impact Assessment, LCIA
    a. Classification
    b. Characterization
    c. Optional steps (Normalization, Grouping, Weighting, etc.)

The main feature of the goal should be a proper description of the reason why the study is performed. The main reason is usually the question that leads to perform the study.

The scope of the Life Cycle Assessment depicts the way to achieve the goal. In other words, it represents how to answer the question that causes the LCA. Hence, the scope should define the system boundaries, the allocation methods and the data quality.

The Life Cycle Inventory, LCI, represents a list of all the materials and the processes involved in the lifecycle of the product investigated. To collect this data is possible to use different resources. The more reliable are the resources provided by the manufacturers. Other sources of information and data are literature and personal consulting. In the LCI there is always a ranking between the data. Those data that influence directly the goal and scope of the LCA have the highest ranking and they shall have the highest reliability.

The Life Cycle Impact Assessment, LCIA, is the stage of the LCA that gives actually a meaning to the great amount of data collected during the previous phase of the method. The LCIA translates each amount of material and emission to indexes that can be understood by the readers of the study. The LCIA involves compulsory and optional steps. Classification is compulsory. It represents the first step. The classification defines the different impact categories. The impact categories are defined according to a classification method. The two classification methods adopted in this LCA are CML2001 e Ecoindicator’99. CML2001 has been developed by The Centre of Environmental Science at Leiden University in the Netherlands it defines eight different impact categories, see Table 7.1. Ecoindicator’99 is a ready-made LCIA method. It was specifically created for designers.

The ECOINDICATOR ’99 finds eleven impact categories that may be grouped in three main impact areas, see Table 7.2.

Impact category	Unit	Description
Abiotic depletion	Kg Sb eq.	It refers to the consumption of natural resources
Eutrophication	Kg 1.4 DCB-eq.	It accounts all the effects of macronutrients in ecosystems
Acidification	Kg SO_2-eq.	It refers effects of acidifying substances
GWP100	KgCO_2-eq.	It quantifies the global warming potential within 100 years
Ozone layer depletion	KgCFC11-eq.	It quantifies the stratospheric ozone layer depletion
Human toxicity	Kg 1.4 DCB-eq.	It concerns effects of toxic substances on human environment
Fresh water ecotoxicity	Kg 1.4 DCB-eq.	It refers effects of toxic substances on fresh water ecosystems
Marine CML2001aquatic ecotoxicity	Kg 1.4 DCB-eq.	It refers effects of toxic substances on marine w. ecosystems
Terrestrial ecotoxicity	Kg 1.4 DCB-eq	It refers effects of toxic substances on terrestrial ecosystems
Photochemical oxidation	Kg ethyl.-eq.	It computes formation of reactive sub.s, mainly ozone

Table 7.1, impact categories of CML2001 and their characterization [57]

Impact category	Unit	Description
Carcinogens	DALY/kg	Carcinogenic effects due to emissions
Respiratory organics	DALY/kg	Respiratory effects resulting from summer smog
Respiratory inorganics	DALY/kg	Respiratory effects resulting from winter smog
Climate change	DALY/kg	Health damage resulting from climate changes
Radiation	DALY/kg	Health damage resulting from radioactive radiation
Ozone layer	DALY/kg	Health damage resulting from increased UV radiation
Ecotoxicity	PAF*m^2*yr/kg	Damage to ecosystem quality due to UV ecotoxic subst.
Acidification/Eutroph.	PDF*m^2*yr/kg	Damage to ecosystem quality due to acidification
Land use	PDF*m^2*yr/m^2	Damage due to occupation and conversion of land
Minerals	Surplus energy/kg	Decreasing ore grades
Fossil fuels	Surplus energy/MJ	Results of lower quality resources

Table 7.2, impact categories of EI99 and their characterization [57]

With the classification, each substance is classified in impact categories. The characterization quantifies the contribution of each substance to its impact categories. To do this operation the amount of material or emission is translated into an equivalent unit. The impact categories defined by CML2001 are translated in kg of equivalent impacting substances. This translation does not imply complex calculations. This leads to fewer uncertainties but the results are less intuitive. The global warming potential, e.g., is translated in KgCO_2-eq. The impact categories of EI99 are based on complex unit. They have more uncertainties but they are more intuitive. The climate changes are quantified as disability adjusted life years/kg. This unit describes the deaths and the diseases caused by climate changes. The other unit of EI99 acronyms are PDF, potential disappeared fraction and PAF, potential affected fraction. Optional steps for the LCIA are the normalization, the grouping and the weighting. The ones involved in this report are grouping and normalization. The grouping summarizes more impact categories in three more easy-to-understand categories: human health, ecosystem quality and resources. It is available only for the EI99. The normalization is a step that relates (i.e. divides by) the results of the characterization to the predicted values of impact categories for the region (spatial boundaries) taken into exam by the study. The predicted value of an impact category for a region is the magnitude of that impact category considering all the technosphere of that region.

The database is a very important part of the LCA. For this study the data concerning the background system and part of the data concerning the foreground system (see next chapter for background/foreground) are from the EcoInvent 2.2 database [43.W]. Performing an LCA is a time-consuming operation if not made with the proper tools. The software SimaPro 7.3.3 by PréConsultants is the tool selected for running this LCA. SimaPro 7.3.3 is an all-included software. SimaPro 7.3.3 has step to implement different data and gives the user the possibility to calculate inventories, networks and impact assessments.

7.2 LCA of an electric scooter

7.2.1 Goal

This life cycle assessment has two main goals. The first is to perform a comparison between an average traditional scooter and average E-scooter encompassing the environmental impact of the permanent magnets in the E-motor and the lithium in the Li-ion battery cathode. The second is to analyse the effect of the recycling of those two "new" materials on the overall environmental impact of the scooter, according to the recycle models depicted in the previous chapter, see Chapter 5. This LCA is an attempt to answer to the research question of this thesis:

"What is the quantitative balance between the benefits and the drawbacks of an electric scooter, from an environmental point of view? Furthermore, what are the benefits on the just-defined balance of an improved material management?"

In addition, this LCA attempts to perform a comparison phase by phase between the two alternatives.

7.2.2 Scope

According to the purposes described in the previous paragraphs, this LCA aims to give an overall understanding of the electric mobility and of the environmental weight of the recycling of new materials. Hence, a scientific audience and more in general a public audience is the target of this work.

The product system studied is the scooter in its two different alternative powertrains. The main function of the product is the private transportation in urban area. The products are supposed to be design for the European market. The selection of the market leads to consequences according to the design of the product, such as the average weight, the battery technology, the life expectancy. The electric production mix considered for the use phase is the European one. The product is studied in all its life phases. The life phases are the manufacturing, the use phase that encompasses the maintenance and the operation and the waste scenario. For the ICE scooter the only fuel considered is petrol (not biofuels) since the aim is to compare the fossil fuel consumption of the two alternatives.

The functional unit chosen is one pkm, so the transportation of one person for one kilometer of European roads. To have an easier comprehension of the LCA the system has been divided in foreground and background system. The foreground system includes the life phases of the product. The data for these process are implemented according literature and manufacturer data. The foreground encompasses the most important data of the LCI and the most sensible. These data are the ones that effect more the results of the LCA. The foreground system describe also the life cycle of neodymium . The background system describes all the resources and the materials that represent the inputs and the outputs for the foreground system. The background system, as first analysis, includes also the data for the recycling according with the cut-off model.

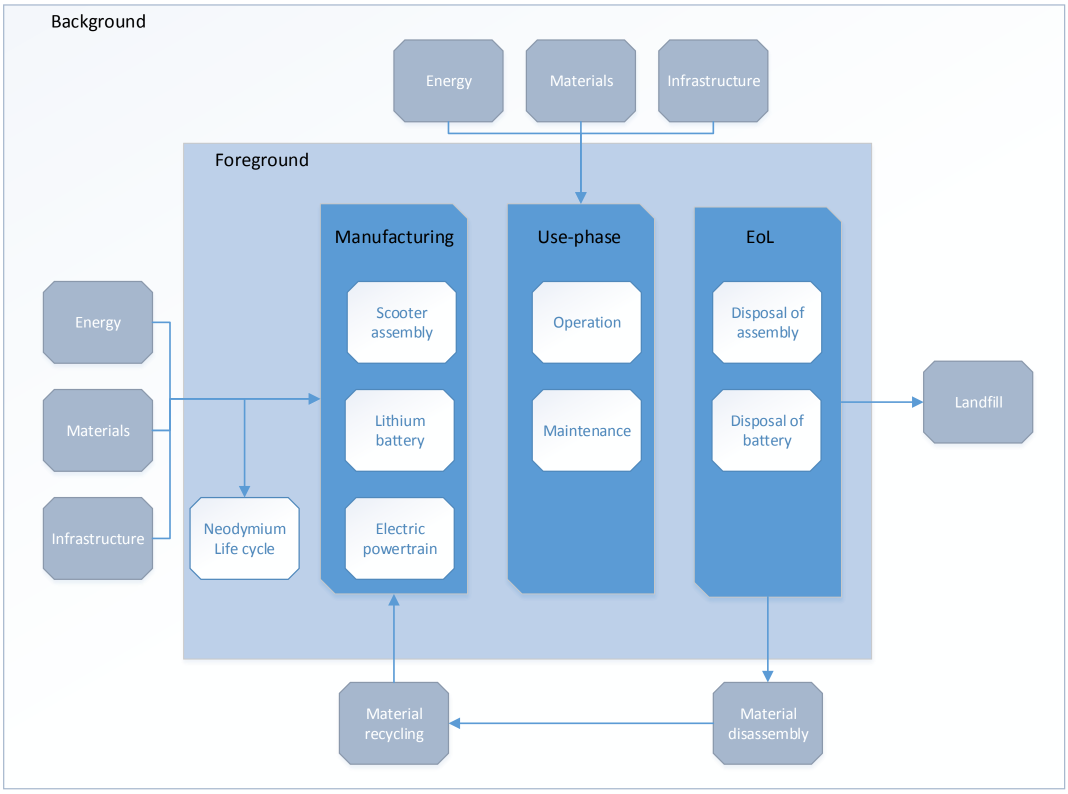


Figure 7.1, Background and foreground system

Regarding the data quality, the data come from the literature and manufacturer. Since the main goal of the LCA is the comparison, the main concern is to have a proper definition of the life cycle of those components that are different between the two alternatives. The data quality describing the recycling scenarios are affected by wide uncertainties since some of the process described are still on lab-scale. The impact assessment are computed with the software SimaPro 7.3.3.

7.2.3 Life Cycle Inventory, LCI

The life phases of the product represent the structure of this LCI. This allows making comparison between the different life cycle phases and the different components.

The following paragraphs describe all the models used. The functional unit is the transport of 1 person for 1 kilometre. The scooters are considered with a capacity utilization of 1.1 (average value) since two people actually can ride them. The LCI presented in this section encompasses each life phase according to the following list:

- Production phase
    - Scooter structure
    - Electric powertrain
- Use phase
    - Maintenance
    - Operation
- Disposal
    - Cut-off model
    - System expansion and substitution model

The approach used for the structure LCI of this LCA mainly takes into account documents from the manufacturers. The Aprilia SR 50 CAT PD by Aprilia (Piaggio Group) [58], a top-sold scooter of the early two thousands, has been used for the LCI of the ICE scooter. The model Penelope from MotoriniZanini [59] has been used for the LCI of the E-scooter.

Assembly	Weight (kg)
Rear dumper	1
Battery (PbA)	2
Body	20
Wheels	12.4
Fork	5
Brake	4
Tyres	5
Cooling system	1
Electric system	1.4
Handlebar	1
Silencer	5
Engine and transmission	24
Seat	1.2
Tank	0.6
Chassis	11
Screws, bearings, etc.	1.5

Table7.3, assembly of Aprilia SR 50 CAT [58]

For the Aprilia model the analysis of the technical drawings [44.W], personal consulting [60, 61] and the list of the weighted components, see Table 9.3, brought to the definition of a bill of materials. Nevertheless, some other manufacturer data are used. To define the amount of polymers and, the proportion between the polypropylene and the polyethylene, is used the information provided by Piaggio. To maintain the model chosen representative for the whole ICE-scooter category a weight ratio has been applied referring the weight of Aprilia SR 50 CAT PD to the average weight of the top sold scooters in Europe in 2012 according to ACEM. The Honda environmental report of 2013 is used as reference for the consumption of energy and natural resources linked to the production of a single scooter, see Appendix B.2. Since the list of all the weighted components of Penelope was not available, the approach used is to subtract the weight of the thermic powertrain and to add the weight of the electric powertrain (battery, E-motor and BLCD controller of Penelope) to the previous assembly. The resources consumption data are assumed the same that for the other model since the battery and the E-motor have their own resource allocation. In addition, a weight ratio has been applied to adapt the weight of Penelope scooter to the average weight of scooters produced by the top ten E-scooter manufacturers according to the Navigant Search Border. Paint, Chromium, Nickel and Zinc are estimated using a weight ratio with an average ICE-car from the EcoInvent database 2.2.

Vehicle	Weight(kg)	Weight ratio vs ICE car
Aprilia SR 50 CAT	96.1	0.072
Average ICE-scooter	93	0.07
Penelope	100	0.075
Average E-scooter	106	0.08
ICE car, EcoInvent 2.2	1320	1

Table 7.4, weight ratios

The bill of materials of the two scooters:

Material	E-s, w%	ICE-s, w%	References
Steel	25.89	49.43	Aprilia SR [58]
Copper	0.56	1.17	Aprilia SR [58]
Aluminium	17.11	20.31	Aprilia SR [58]
Polymers	14.81	20.95	Piaggio group [12]
Chromium	0.15	0.17	Ecoinvent [43.W]
Nickel	0.09	0.10	Ecoinvent [43.W]
Paint	0.42	0.47	Ecoinvent [43.W]
Zinc	0.36	0.41	Ecoinvent [43.W]
Lead		1.54	[20]
Sulphuric acid		0.31	[20]
Synthetic rubber	4.57	5.14	Aprilia SR [58]
Li-ion battery	22.64		Penelope [59]
E-motor	11.32		Penelope [59]
BLDC controller	2.08		Penelope [59]
Total	100	100	

Table 7.5, percentage bill of materials of the two scooters

The previous ICE-scooter inventory already encompasses the ICE-powertrain. This section describes the electric powertrain. In the model analysed, the scooter Penelope, the E-drivetrain is composed by three components. The Li-ion battery, the BLDC controller and the E-motor. The Lithium battery weights 24 kg according to Penelope model. The Li-ion is described through the process of Ecoinvent 2.2 */battery, LiIo, rechargeable, at plant.* The dataset represents a battery with a $LiMnO_2$ cathode. According to the technology description of chapter 4, this choice is reliable. It is worth to underscore that these batteries are cobalt free. The E-motor considered weights 12 kilograms. It is a hub wheel motor produced in China by the Chinese manufacturer Angell. The power of the motor is 1500 W. Since there were not data available from the manufacturer, the assembly is taken from the literature [62], see Table 7.7 . Then, also from literature, a bill of material for the brushless DC motor is proposed [63], see Table 7.8 and see Appendix B.2. The brushless DC motor controller, BLDC controller, considered weights 2.2 kg. The model is a close-box controller that controls the electric components of the scooter. As the hub wheel motor, the Chinese manufacturer Angell produces it. The only information provided by the producer is that the housing is made of aluminium. Therefore, the process used in LCA is an adaptation, considering the aluminium housing, of the EcoInvent 2.2 process */Electronics for control unit/RER U*, see Appendix B.2. The neodymium permanent magnet is modelled according to the LCI performed by Sprecher et al. [25]. The life cycle flow of the permanent magnet reported in the LCI is depicted in the appendix, see Appendix A.1.

Component	W%
Stator core	27.4
Stator winding	12.6
Housing	24.0
Rotor	18.3
Magnets	4.0
Attachment band	0.6
Shaft	6.3
Miscellaneous	6.8
Total	100

Table 7.6, components of a BLDC motor [62]

Material	W%
Steel	49.59
Aluminium	25.65
Stainless steel	6.72
Copper	13.43
NdFeB	4.0
Synthetic	0.61
Total	100

Table 7.7, materials of a BLDC motor [63]

For the use phase encompasses maintenance and operation. Concerning the maintenance, for both the models, it has been estimated a life expectance of 50000 km. For the ICE-scooter is considered as reference the EcoInvent process */maintenance, scooter.* The process considers that maintenance accounts the sostitution of the 5% of metals and 15% of polymers of the original bill of materials of the scooter. The process is updated according to the bill of materials proposed by the author. The ICE scooter needs, also, two lead acid batteries for 50000 km. The E-scooter follows the same approach. The E-scooter needs 0.5 lithium battery pack for 50000 km [59]. The maintenance is computed in respect to pkm. The operation are described through the two EcoInvent 2.2 models */operation, scooter* and */operation, electric scooter*. The two models contain the emissions due to the operation of the two scooters. The electric scooter has emissions due to the wearing of components (brakes, tyres, transmission…) and due to the production of electricity used to charge the batteries. The consumption considered is 3.3 kWh/100 km The traditional scooter has emissions due to the wearing of the components and to the combustion. The consumption considerd is 3.3 litres of fuel every 100 km. The emissions due the combustion are averaged between the two and the four-stroke engine. The operation is computed in respect to pkm. The infrastructure consumption is described trough the EcoInvent 2.2 processes for roads. The infrastructure processes to make, maintain and control a road are the same between the two models.

The description of the waste scenario represents a complex subject. According to the principles of the LCA the disposal of materials has to be accounted in the life cycle of a product. It is true, tough, that materials are recycled. Recycling generates a problem regarding where to account processes. The problem is whether they are accountable to the first product lifetime and in which measures. The simplest approach to this matter is the cut-off method. The cut-off method is the same used by Ecoinvent 2.2. This approach cuts off the life cycle of the recyclable materials before the end of life. Processes linked to the recycling are not accounted on the disposal. Nevertheless, the input resources, the resources accounted during the manufacturing, for those materials suitable for recycling, are considered a mix of primary and secondary materials, according to statistical market data. So, as an example, considering 1 kg of copper for the manufacturing phase, according to the cut-off model, a certain share, the 20% for Ecoinvent 2.2, is of secondary copper and actually accounts for the recycling. The cut-off method, however, is not meaningful for those materials that do not have a proper recycle market. Since the aim of this LCA is to evaluate the effect of recycling of the “new” materials in the life cycle of the electric vehicles, another method to describe the allocation process of these materials is needed. The method chosen is the system expansion and substitution just for those materials that usually are not recycled but, in this specific case, could be recycled through one of the recycling process described in the chapter 5. This method expands the product system to include the recycling processes for the involved materials. However, according to the method the waste scenario accounts as avoided products all the effective (after applying a recycle/recovery rate) recycled materials and the recovered energy. The system expansion and substitution is particular suitable for product development and more specifically for scenario comparisons. The theoretical background behind this section is the “Hitch hiker’s guide to LCA”.

A first waste scenario, following a cut-off approach, is assessed. This scenario is described by the waste treatment already present in the EcoInvent 2.2, the */disposal, scooter*. It accounts the transport to the scrap yard, the disposal of the lead battery, the incineration of polymers, half of the synthetic rubber and of the zinc. All the other materials are considered recycled so, according to the cut-off model, they do not have to be accounted on the product lifecycle. For the E-scooter, the process considered is similar to the ICE-scooter one. The differences involve those components that require a specific disposal. For the Li-ion battery is hypothesized that half the amount is treated by pyrolysis and half by hydrometallurgy processes, the most diffused treatments at the moment. These treatments, usually just recover valuable metals like nickel or cobalt. The lithium is not recovered. The model already considered this since the lithium used for the production of the $LiMnO_2$ cathode is primary lithium. The neodymium of the electric motor is not recovered as well. However, the lithium battery has to be disposed anyway as the directive states. The neodymium, instead, takes part to the recycling flow of ferrous materials. The final results is that it joins other metal oxides in the slag of the steel recycling process. The BLDC controllers are usually processed. The disposal process is described by the Ecoinvent 2.2 process */disposal of electronics for control units*. All the other materials of the E-motor of an electric scooter are considered recycled, according to the end of life framework, see Chapter 4. The figure 7.2 shows the cut-off model, see Figure 7.2. The product system is the one managed by the performer of the LCA.

The second modelling approach adopted for waste scenario is the system expansion and substitution model. This scenario involves those materials that could become part of recycling processes in the future. The system expansion and substitution model designs four recycling scenarios, according with chapter 5, see chapter 5:

1. Recycling of lithium manganese;
2. Recycling of NdFeB alloy;
3. Reuse of NdFeB permanent magnet;
4. High-level recycling of copper;
5. Recycling of gold;

The recycling of the battery represents a first scenario. The process flow modelled is the one of chapter 5. Therefore, in the EcoInvent2.2 process defining the disposal of the Li-ion battery with a hydrometallurgical treatment have been added a crushing process and the inert atmosphere production process. The energy for the crushing is considered equivalent to crush 1 kg of electronic scrap (process from the EcoInvent2.2 database). Lithium oxide manganese becomes avoided product with a recovery rate of 90% [24]. The inputs required by the treatment (the inputs and their quantities) are from the patent analysis, e.g. quantity of CO_2, or the EcoInvent2.2 process for chemical treatment, e.g. chemical plant. The emissions are default emissions defined by the software for hydrometallurgical treatment.A table describing the process implemented in the LCI realized with the software SimaPro 7.3 is reported, see Table 7.8. It is useful also because it outlines how the software works.

Another recycling scenario is the one regarding the permanent magnets. There are two scenarios involving Neodymium. The first method uses the hydrogen decrepitation to sort the magnet and steel. The magnet obtained is in the state of a powder. According to the model of Sprecher et al. this powder can newly take part to the process flow of permanent magnet production at level of the milling of the powder, see Appendix A.1. The process implemented for the recycling thorough hydrogen decrepitation of hydrogen in SimaPro 7.3 is reported, see Table 7.9. The amounts of hydrogen and argon are from the patent analysis.

In relation to what depicted in the Material Hygiene chapter, see Chapter 5, the best scenario for the permanent magnet is the reuse. This solution consists in a manual disassemble with a demagnetization step, a new magnetization and a direct reuse. As for the previous step the manual disassembly and the demagnetization step is not accounted. This scenario include a reuse rate of 0.9 to account magnetic property loss of the NdFeB alloy.

Waste treatment specification: Lithium ion battery hydrometallurgical/mechanical treatment, 1 kg				
1. Avoided product				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	LiMnO	Lithium Manganese Oxide, at plant	kg	0.154707
2. Known input from nature (resources)				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Water	Water, unspecified origin	m^3	0.00072
3. Known input form technosphere (material/fuels)				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Chemicals	Chemicals, at plant	Kg	0.025
Material	Sulphuric acid	Sulphuric acid, liquid, at plant	Kg	0.025
Material	Carbon dioxide	Carbon dioxide, liquid, at plant	Kg	0.005
Auxiliaries		Electricity, medium voltage, from grid	KWh	0.14
Auxiliaries		Transport, lorry	tkm	0.5
Auxiliaries		Chemical plant	P	0.000000004
Emissions to air				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
		Heat, waste	MJ	0.504
		Sulphuric dioxide	kg	0.0000045
Emissions to water				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Copper	Copper, ion	Kg	0.00000016
Material	Fluoride	Fluoride	Kg	0.0000003
Material	Nickel	Nickel, ion	Kg	0.00000016
Known outputs to technosphere				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Disposal		Inert waste disposal	Kg	0.202
Disposal		Plastic mixture disposal	Kg	0.0605
Processing	Electronic goods	Shredding, electronic scrap	Kg	1

Table 7.8, Lithium manganese oxide, recycling process on SimaPro 7.3

Waste treatment specification: NdFeB, hydrogen decrepitation treatment, 1 kg				
1. Avoided product				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Permanent magnet powder	NdFeB flakes, at plant	kg	0.9
3. Known input form technosphere (material/fuels)				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Hydrogen	Hydrogen, at plant	Kg	0.025
Material	Argon	Argon, at plant	Kg	0.025
Auxiliaries		Electricity, medium voltage, from grid	KWh	0.1
Auxiliaries		Transport, lorry	tkm	1.5
Auxiliaries		Iron scrap plant	P	0.000000004

Table 7.9, NdFeB, recycling process on SimaPro 7.3

According to the bill of materials of an E-scooter, the copper has an important share of the total amount. The Li-ion battery contains a large amount of copper, according to the EcoInvent2.2 model */battery, LiIo, rechargeable, at plant* about the 15% of weight is copper. Copper in lithium

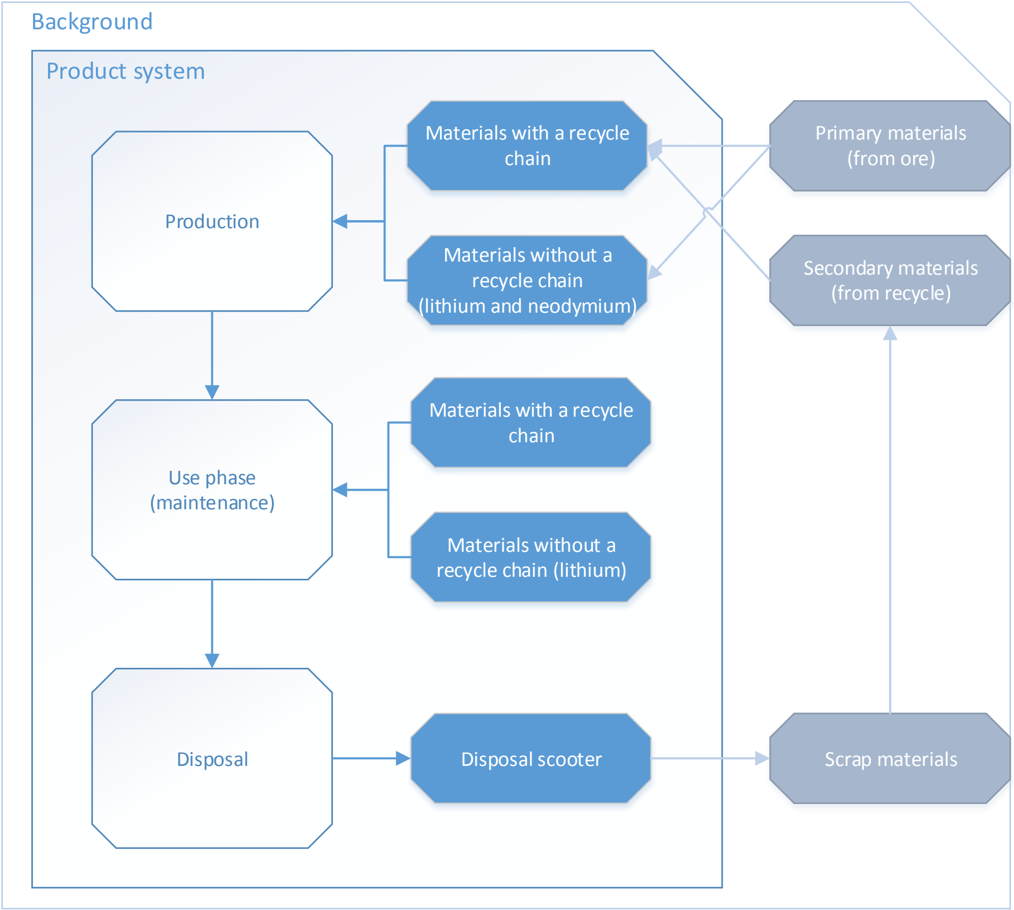


Figure 7.2, Cut-off model

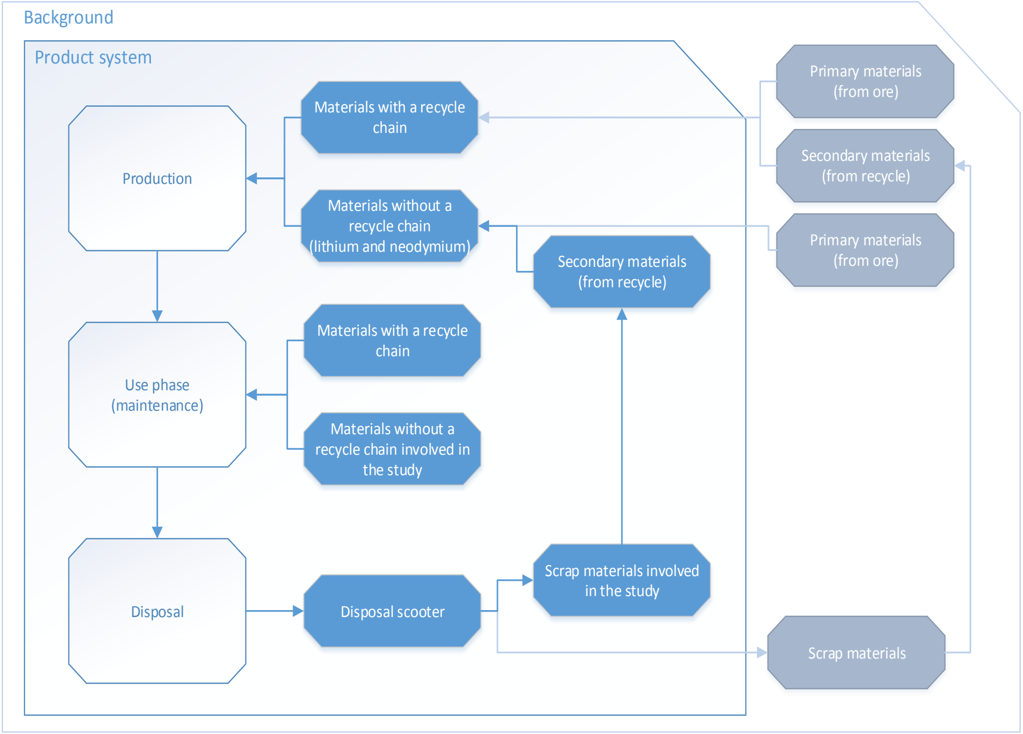


Figure 7.3, system expansion and substation model for lithium and NdFeB recycle chain

battery is in the anode and in the current collector, see Chapter 4. The recycling of copper from lithium battery is not a standard procedure. Among the process flow analysed the hydrometallurgical processes claim to recover also copper. An extra system expansion and substitution model is implemented for the recycling of copper from battery and motor.

This report focuses more its attention to lithium and neodymium since their higher weight share in the bill of materials. Since the original cut-off model of the EcoInvent 2.2 database does not consider any recycling of precious metals for the electronic control, a system expansion and substitution scenario is depicted. The material recycled is gold. To describe this model anyway is used the default process */gold, secondary, at precious metal refinery*.

7.2.4 Life cycle impact assessment, LCIA

The impact assessment methods chosen for this LCIA are CML2001 and ECOINDICATOR99.

Specifically from CML2001 the categories chosen are abiotic depletion, GWP100 and water ecotoxicity. From ECOINDICATOR99 the categories chosen for this assessment are radiation, land use and the three groups: human health, ecosystem quality and resources. Those impact categories have been chosen for different reasons. Abiotic depletion and GWP100 embody two important concerns of the contemporary industrial world since they are related, respectively, to the resource scarcity and to the climate changes. The water ecotoxicity has been selected since it emerges, together with the GWP100, as the most affecting impact categories out of the normalization step, performed during the LCIA. It means that the relative weight of its magnitude related to the system regional boundaries is the greatest among all the other impact categories. Land use is chosen because it is representative of the benefits linked to the recycling. Recycle a metal reduces the need of primary metal, hence, reduces the land needed for the mining of that metal. Radiation points out an interesting weakness of the E-scooter. The human health, the ecosystem quality and resources give an overall look to the comparison.

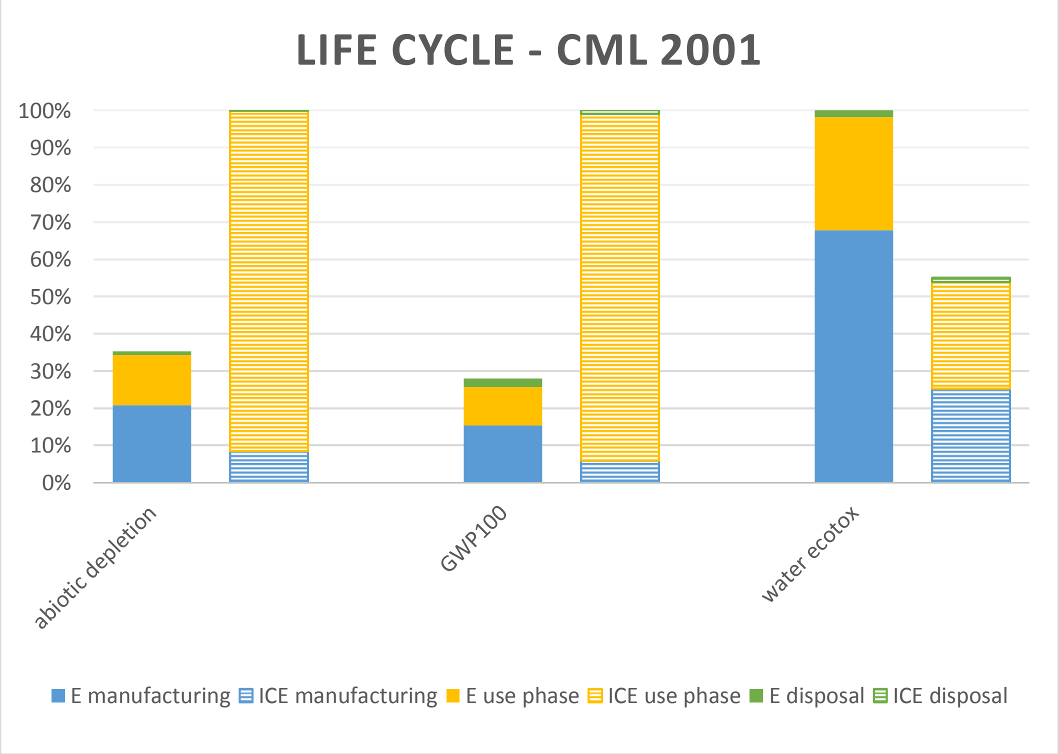


Figure 7.4, lifecycle comparison with the contribution of each life phase CML2001

The first field assessed is a life cycle comparison between the two alternatives. The two life cycles are presented according to the cut-off model. Each impact category has its own unit, as specified in the previous section, here the difference are showed as percentage spread see Figure 7.4 and 7.5. The result is that, according to main part of the impact categories, the ICE scooter has a higher environmental load than the E-scooter and the reason is the high relative weight of its use phase. Nevertheless, the manufacturing of the E-scooter is more impacting than the one of the traditional scooter. The analysis and the interpretation of the results is reported in the next chapter, see Chapter 8.

To answer to the second field of research, the one regarding the weight of the recycling, is reported the comparison, not considering the use-phase, among the environmental impact of the ICE-scooter, the environmental impact of the E-scooter considering the recycling of new materials ($LiMnO_2$, NeFeB and Au recycling) and the environmental impact considering a higher level of copper recycling, see Figure 7.6 and Figure 7.7. This last comparison aims to be a quantitative validation to the waste scenario depicted according to the Material Hygiene mind-set. In the graphs, the impact is reported out of 100% and the patterned area represents the reduction due to the recycling scenario. The results of this comparison are that a high level of recycling of copper brings to higher environmental benefits than the recycling of the other new materials involved in the study. Further analysis is reported in the next chapter, see Chapter 8.

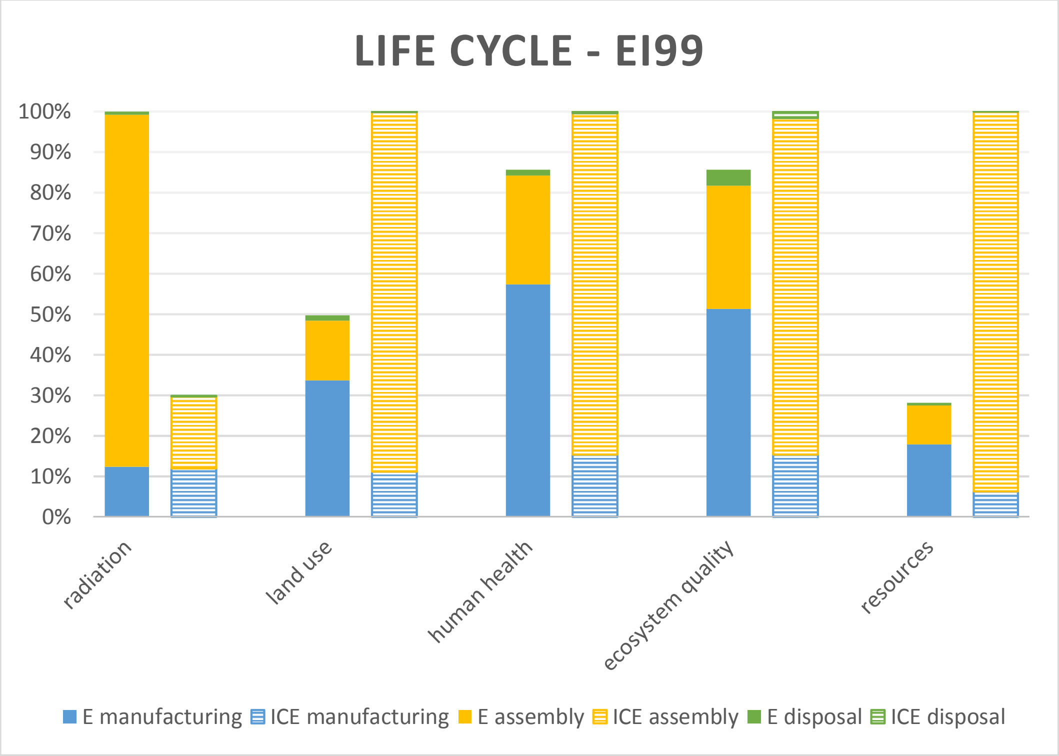


Figure 7.5, lifecycle comparison with the contribution of each life phase, EI99

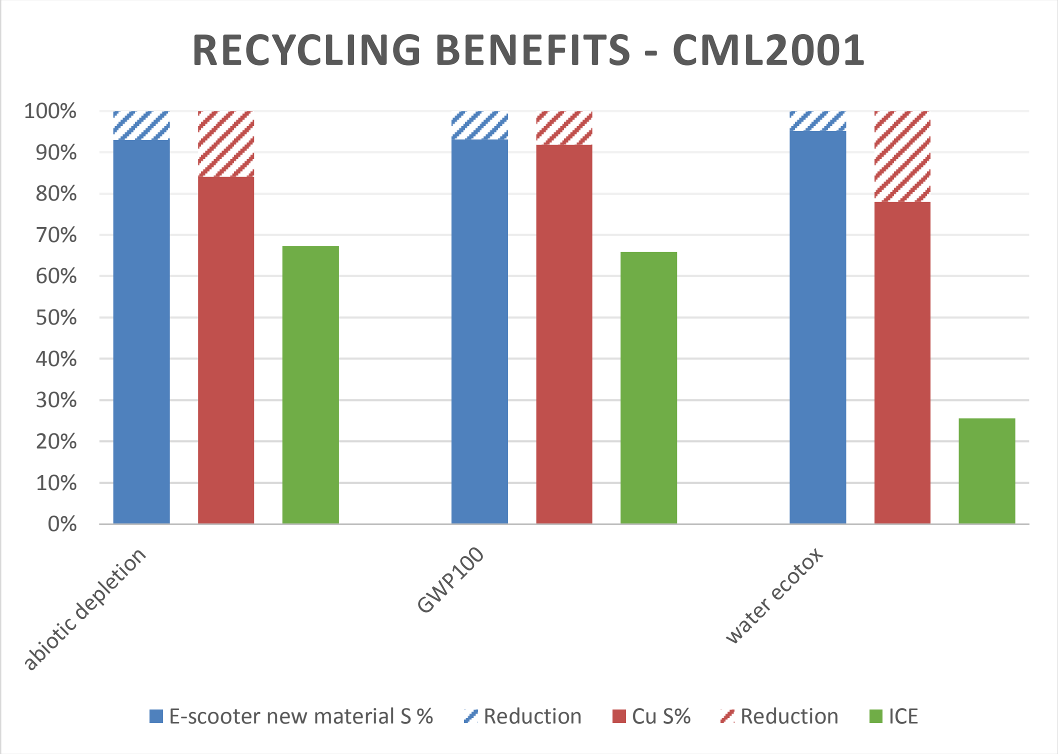


Figure 7.6, improved recycling of E-scooter CML2001

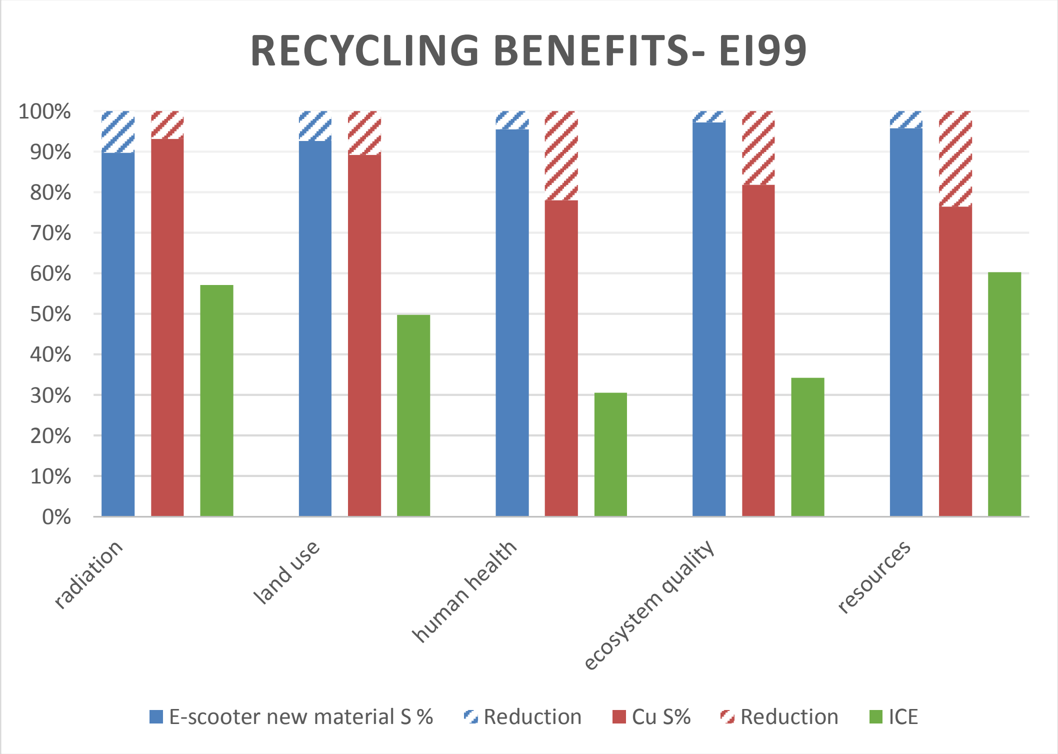


Figure 7.7, improved recycling of E-scooter EI99

7.2.5 Uncertainties

Two level of data analysis is presented:

- Data uncertainties
- Sensitivity and contribution analysis

The uncertainties for the data are inserted by the author according with the *Pedrigree matrix* of SimaPro software. Each data is assessed regarding six rules or criteria plus so-defined basic uncertainty factor. The square geometric standard deviation is calculated using the formula:

$$SD_{g95} = exp^{\sqrt{[\ln(U_1)^2]+[\ln(U_2)^2]+[\ln(U_3)^2]+[\ln(U_4)^2]+[\ln(U_5)^2]+[\ln(U_6)^2]}}$$

The factors from U1 to U6 refer to the score in the table reported in the appendix, see Appendix B. They take into consideration reliability, completeness, temporal correlation, geographical correlation, further technological correlation and sample size.

The sensitivity analysis is a way to assess how the assumptions influence the results. To perform this analysis the author changes some assumptions and see how the results change. This LCA has a specific goal. The representativeness and the robustness of the model are very difficult to evaluate since the electric motor is still a *young* product on the market and the recycling scenarios proposed are not currently implemented in an existing recycling chain. Although an analysis has been performed involving the relative weight of the use phase in respect with the other life phases. A sort of sensitivity analysis has already been performed regarding the comparison between the two end of life model of cut-off and system expansion and substitution. These two model describes in fact the same thing changing the assumption. A sensitivity analysis has been performed in the next chapter. The contribution analysis is a way to assess what is the contribution of a single material /component/life phase to the whole life cycle of a product. A contribution analysis is performed in the next chapter.

8 ANALYSIS OF RESULTS AND INTERPRETATION

This chapter analyses the results gained through the LCA and proposes an interpretation to them.

8.1 Analysis

This section presents an analysis of the results according to the research questions of this work.

8.1.1 Life cycle analysis and contribution analysis

impact assessment	unit	less impacting	Spread
abiotic depletion	kg Sb eq	E-scooter	64.7%
GWP100	kg CO2 eq	E-scooter	72.1%
marine w ecotox	kg 1,4-DB eq	ICE-scooter	44.9%

Figure 8.1, Impact assessment according CML2001

impact assessment	unit	less impacting	Spread
radiation	DALY	ICE-scooter	70.2%
land use	PDF*m2yr	E-scooter	50.3%
human health	DALY	E-scooter	14.3%
ecosystem quality	PDF*m2yr	E-scooter	14.4%
resources	MJ surplus	E-scooter	71.8%

Figure 8.2, Impact assessment according EI99

According to this study, the E-scooter results more environmentally sustainable according to six indicators out of eight. The principal reason of these results is the use of fossil fuel for the internal combustion in the use phase. Fossil fuels, in fact, are one of the closest resources to depletion. The impact of the fuel extraction and use is also affecting human health and ecosystem quality more than the use of new materials in E-scooters. The fuel mining and extraction accounts more land use than the mining of the materials like neodymium and lithium up to the whole life cycle. The radiation assessment of the E-scooter is 70% higher than the traditional one. The reason is the European electric mix and its share of electricity produced by nuclear power plants. The need of electric energy from grid is considerably higher for the E-scooter than for the traditional one. All the electric energy used by the E-scooter for the transportation is, in fact, taken from the European electric grid. The reason of the higher water ecotoxicity is the large amount of copper (battery anode and BLDC motor) and in a smaller part of the precious metals in the BLDC controller. The mining of these metals, especially copper, leads to the disposal of sulfidic tailing that has a strong impact on water ecosystems. The disposal of sulfidic tailings leads to a lower pH in the water [64].

In the MH analysis, a qualitative graph regarding the material and the energy consumption of the product was presented. This section proposes a quantitative graph resulted from the LCA. The abiotic depletion indicator is chosen to give a quantitative proposal of the material consumption flow. The abiotic depletion accounts as consumed materials the metals and polymers used in the manufacturing and the fuel consumed during the use phase.

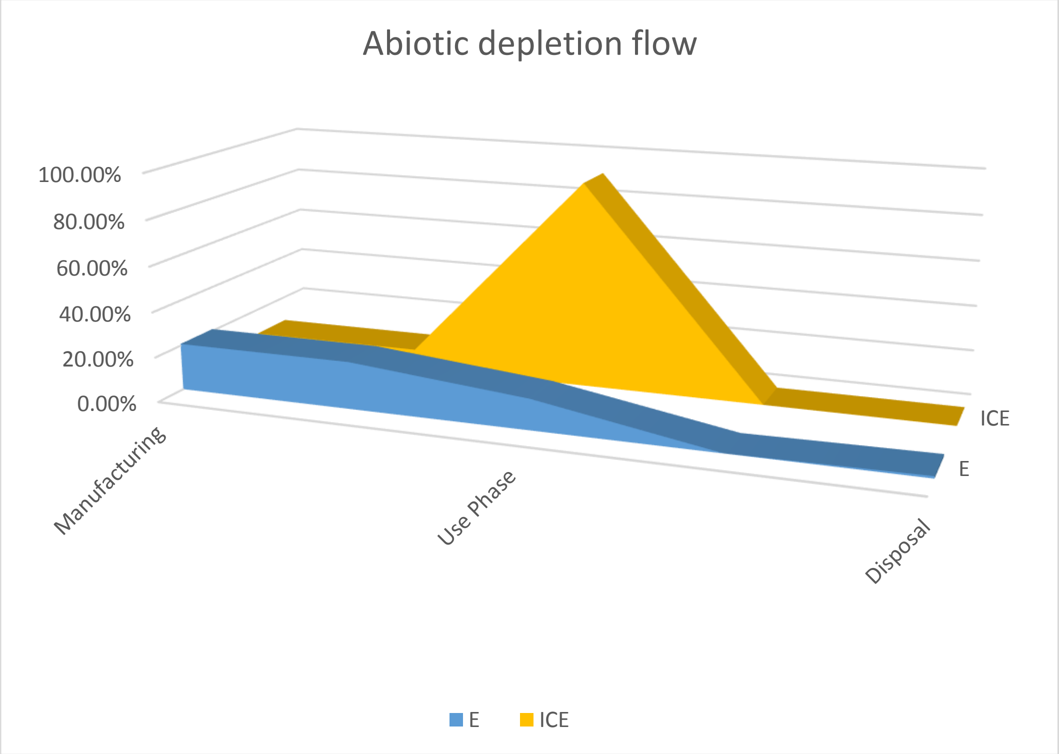


Figure 8.1, Abiotic depletion life cycle flow

The disposal does not account any recycling, according to the cut-off model. Hence, it does not consider the approach that a material recycled is embedded in the life cycle as in the qualitative graph of chapter 5, see Figure 5.2, Chapter 5. Nevertheless, it is believed that the figure helps the reader anyway. The results are similar to what predicted in the qualitative analysis. The GWP100 is chosen to give a quantitative meaning of the energy flow through the life cycle. For both the impact categories is possible to see how different the proportions of the life phases are between the two alternatives. For the traditional scooter the impact of the use phase accounts for more than the 80% of the whole life cycle. This is due to the fuel consumption. For the E-scooter the most

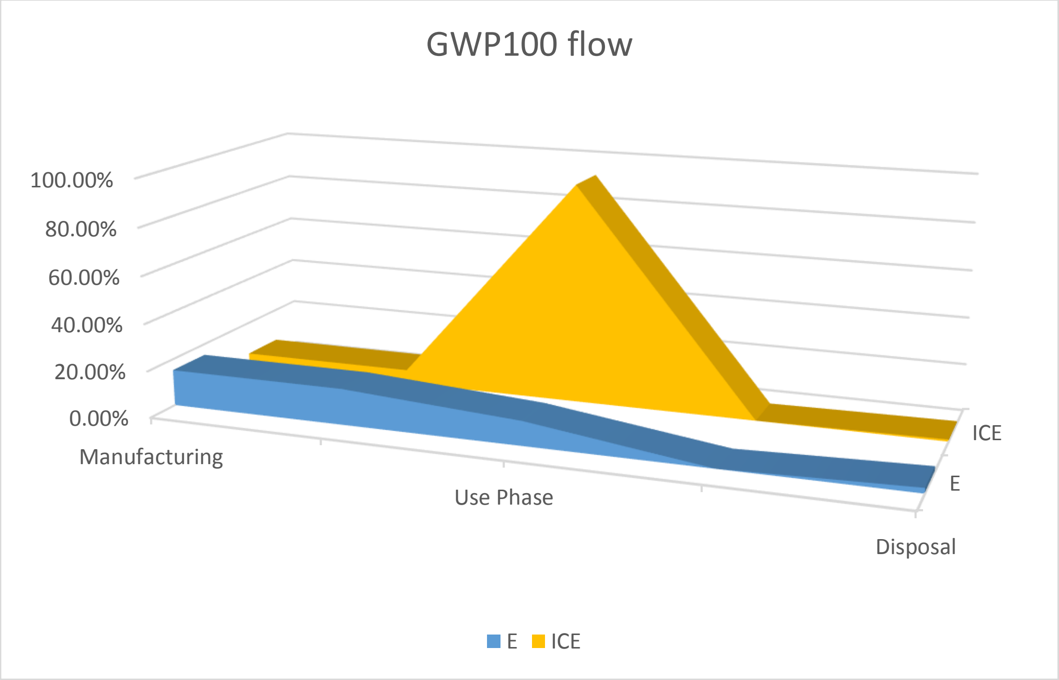


Figure 8.2, Global Warming Potential life cycle flow

affecting life phase is the manufacturing. The manufacturing of an E-scooter actually has a heavier environmental load than the manufacturing of the ICE-scooter. This shows the relative strong weight of the new materials.

A contribution analysis is performed to assess the relative weight of the different components for the most important indicators across the different life phases.

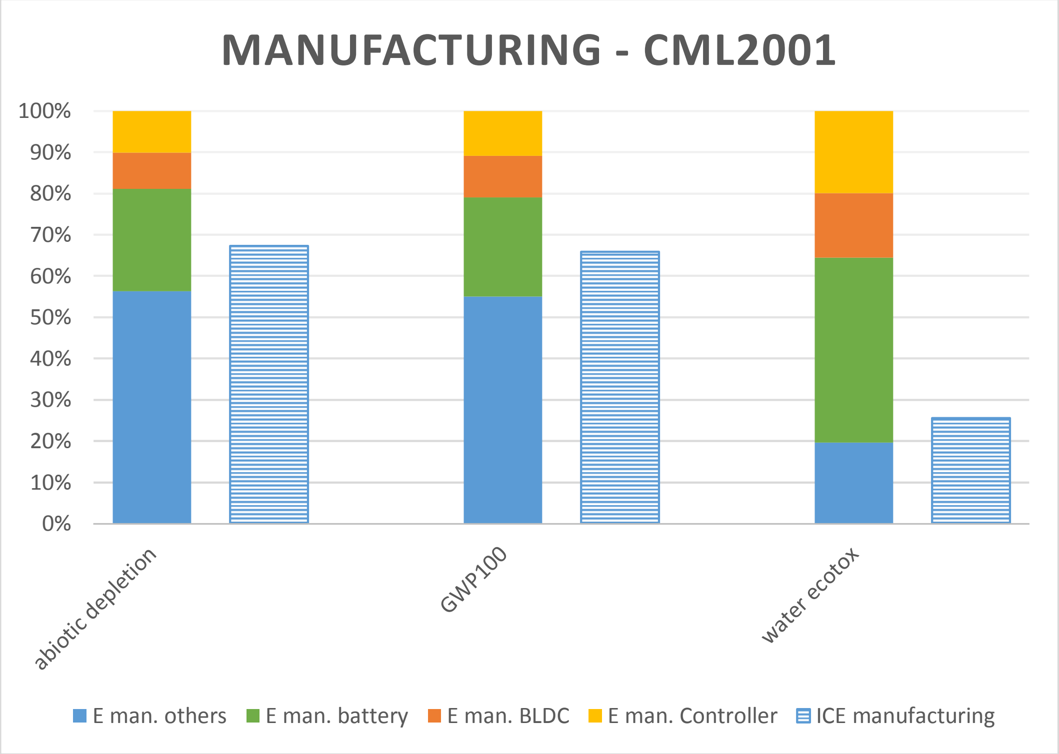


Figure 8.3, Manufacturing impact assessment CML2001

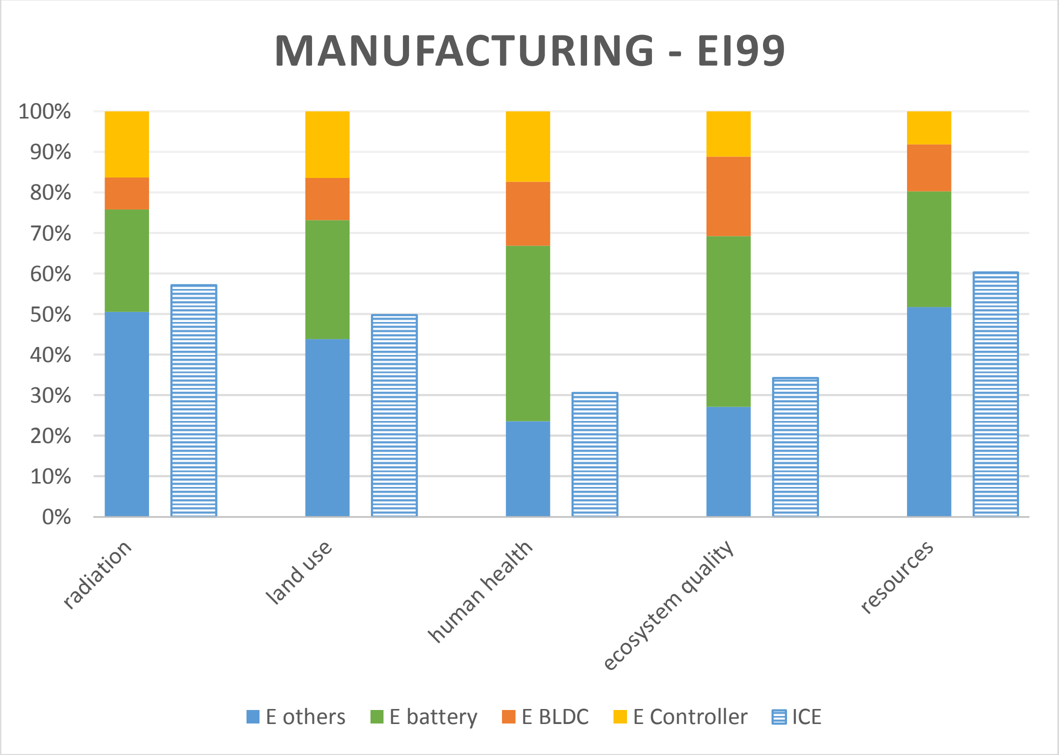


Figure 8.4, Manufacturing impact assessment EI99

The lithium battery is the heaviest among the three E-powertrain components and is the one that gives the greatest contribution to the environmental impact. The battery is the component with largest amount of copper. In those impact categories such as human health, ecosystem quality (EI99) or water ecotoxiciy (CML2001) where the copper has considerable environmental load the relative share of the battery increases. Other materials with a considerable environmental load for the battery assembly are the aluminium (GWP) and the lithium manganese oxide (GWP and land use). The pie charts below reports a comparison between the contribution analyses of two indicators of CML2001. The comparison is reported to show the influence of each material on each indicator. The Ecotoxicity of copper linked to the sulfidic tailings makes the amount of the copper in the battery accounts for the 25% of the whole E-scooter environmental impact on Water ecotoxicity.

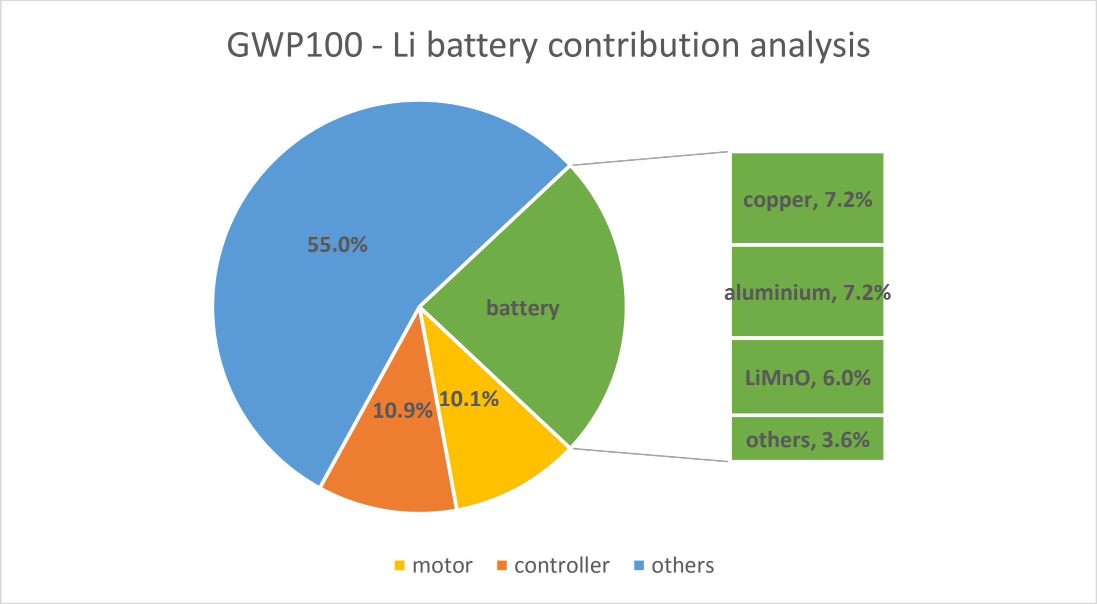


Figure 8.5, Lithium battery contribution analysis - GWP100

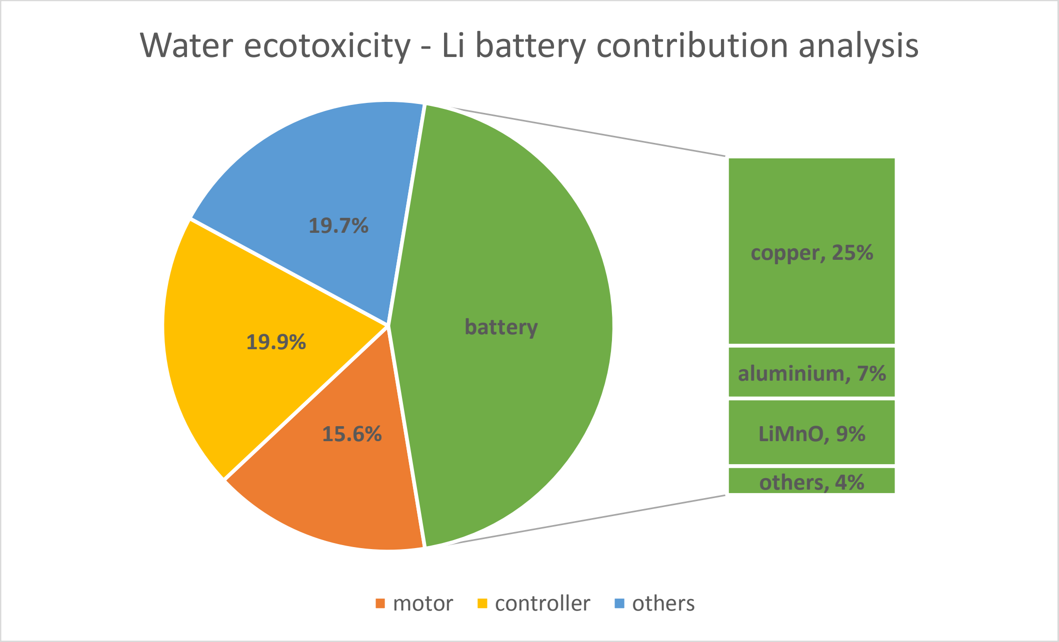


Figure 8.6, Lithium battery contribution analysis – Water ecotoxicity

The BLDC motor contains copper as well. Considering other impact categories but the ones affected strongly by the copper, the materials with a higher environmental load are aluminium and the magnetic alloy NdFeB. For the abiotic depletion and the GWP, the aluminium and the NeFeB share respectively around the 40% and the 20% of the total environmental load of the E-motor. The NeFeB has an important relative environmental impact. In a mass ratio, it accounts for just the 0.5%. In the GWP100, tough, it gives a contribution of 2%.

The gold is the more affective material throughout all the impact categories of the BLDC controller. The specific impact of gold according to the CML2001 and EI99 is the most affecting. This is the reason why the controller that accounts just for the 2% of the weight of the scooter always shares more than the 5% of the environmental load.

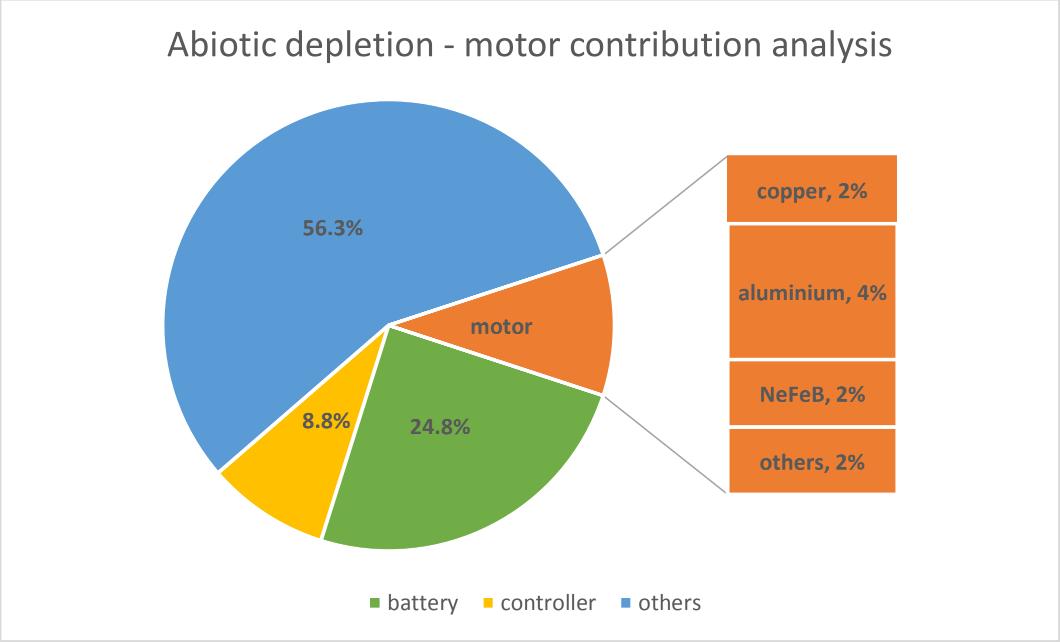


Figure 8.7, Electric motor contribution analysis – Abiotic depletion

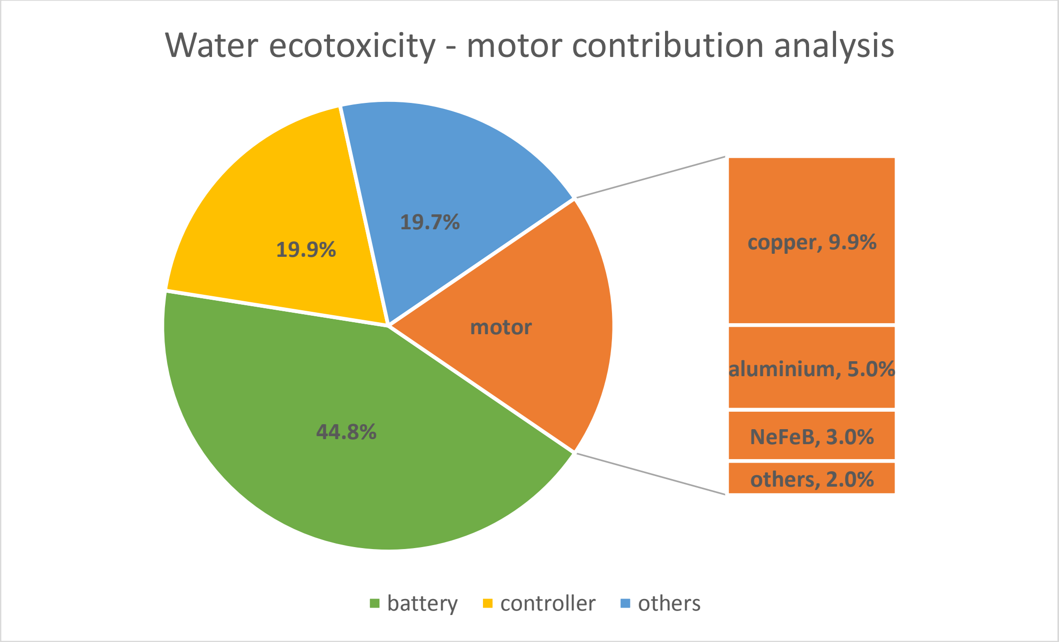


Figure 8.8, Electric motor contribution analysis – Water ecotoxicity

It is possible to perform a contribution analysis also of the other life phases. The weight of the bill of materials is less important since some parts are not considered involved by the maintenance.

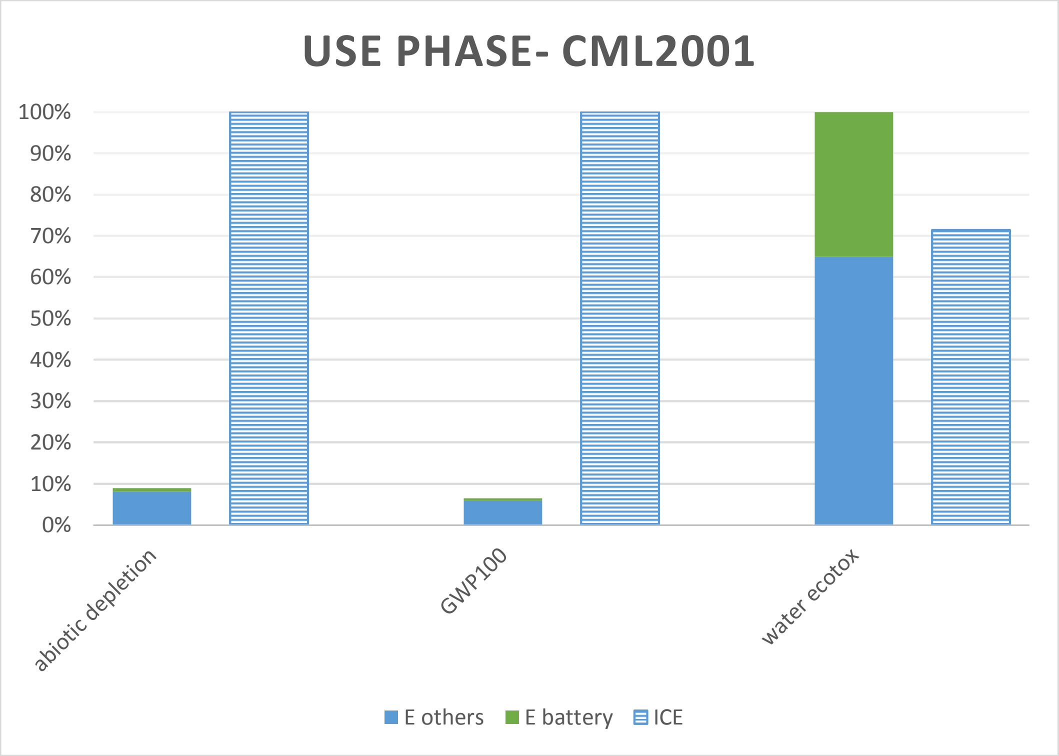


Figure 8.9, Use phase impact assessment CML2001

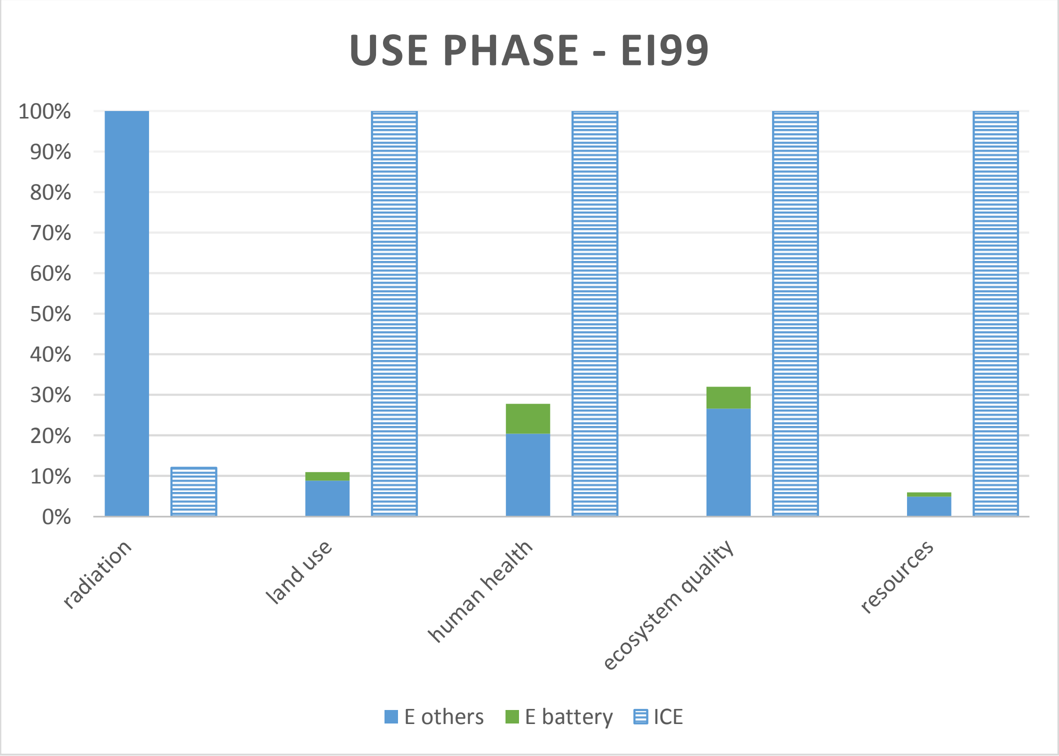


Figure 8.10, Use phase impact assessment EI99

The ICE scooter results by far the less environmentally sustainable throughout almost all the categories. The environmental load of the fossil fuels is very high. In certain impact categories such as GPW and abiotic depletion there is a spread between the two alternatives of more than 80%. The only two categories where the E-scooter results with a higher environmental load are the radiation, for the same reason already explained in the previous paragraphs, and the water ecotoxicity. The water ecotoxicity is strongly affected by the lithium battery. It is possible to see, in fact, that is the contribution of the lithium battery the crucial contribution to let the indicator value overtake the ICE scooter one.

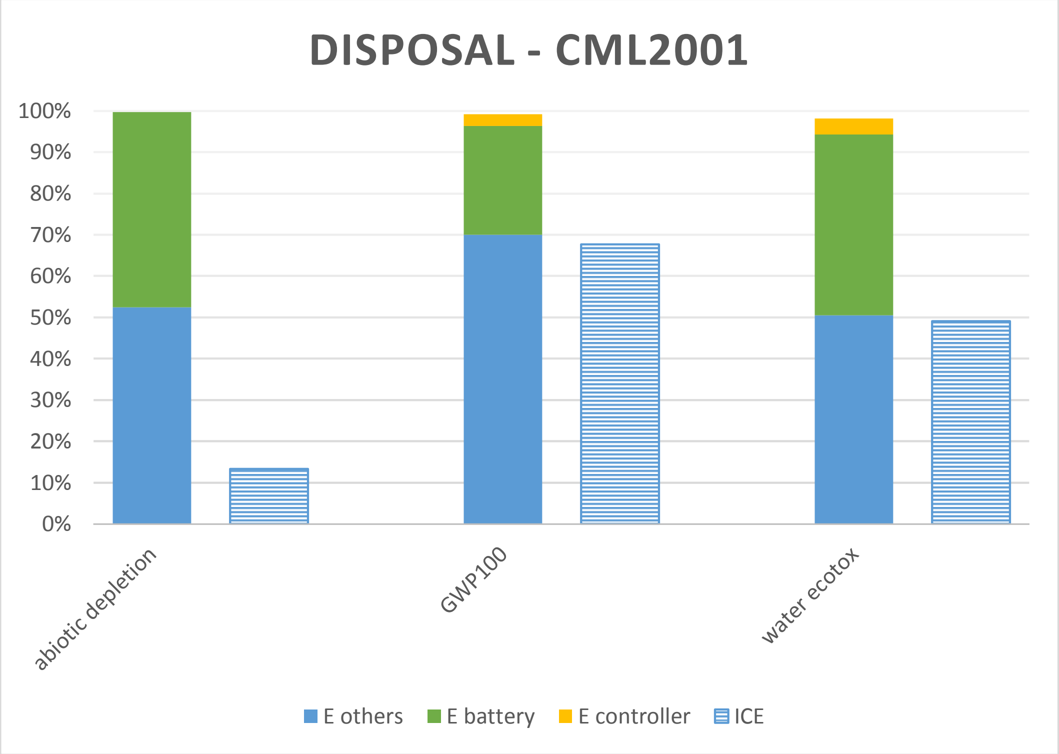


Figure 8.11, Disposal impact assessment CML2001

The author also proposes a comparison between the EoL phases of the two scooters according the cut-off model.

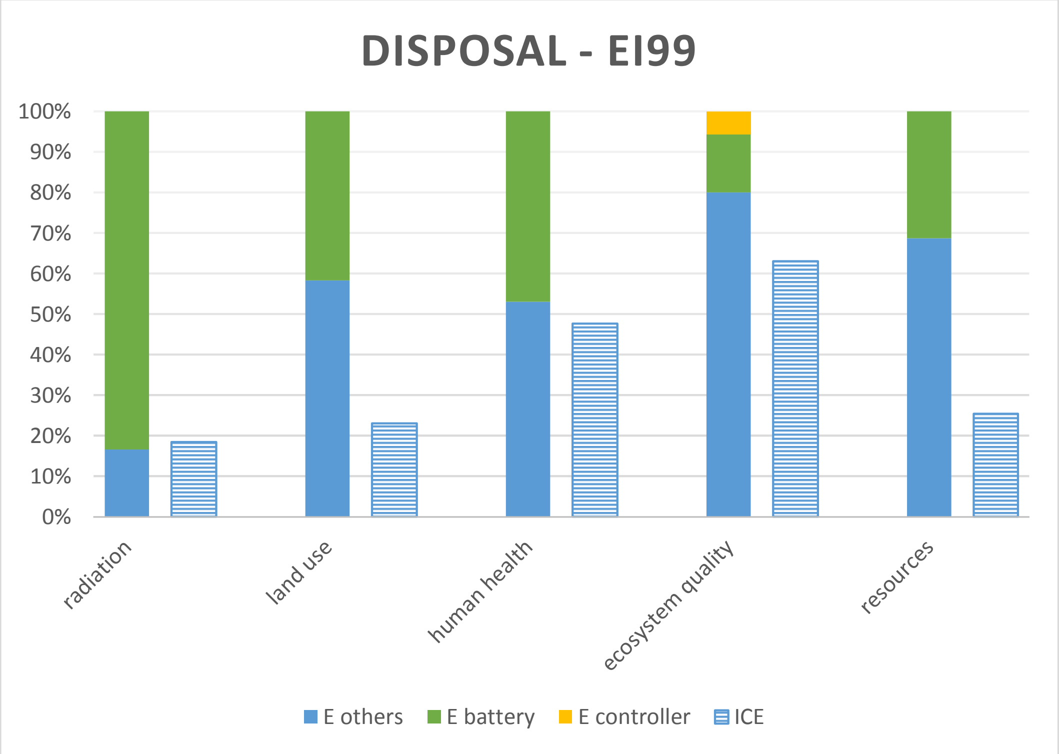


Figure 8.12, Disposal impact assessment EI99

This model accounts just for the resources used for the collection, the dismantling and treatment of lithium battery and electronic controller without considering any recycling. The E-scooter since accounts those components that actually need more treatments than the others is, of course, more affecting. Nevertheless, the relative weight of this life phase is under 5%.

8.1.2 Benefits of recycling scenarios

This section reports the assessment of the recycling of the “new materials”. This time the model adopted is the system expansion and substitution model for all the material involved in the scenarios. The waste scenarios assessed are:

1. Lithium manganese oxide recycling with a mixture of mechanical and hydrometallurgical processes;
2. NdFeB magnet recycling using a hydrogen decrepitation treatment;
3. NdFeB magnet reuse with a manual disassembly step, a demagnetization step and tool-aided extraction step of the permanent magnet;
4. The recycling of gold according to the default process */gold, secondary, from electronic* from the print wiring board of the electronic for control units.
5. A best case scenario, summary of the best solutions for the three materials
6. A scenario involving a high level of recycling of copper modelled according to system expansion and substitution. This scenario represents the will of the recyclers to collect a high percentage (90%) of the copper of the battery anode and of the motor windings. The third scenario that encompasses the manual disassembly of an electric motor is crucial towards this goal.

impact assessment	**unit**	**scenario1**	**scenario2**	**scenario3**	**scenario4**	**scenario5**	**scenario 6**
abiotic depletion	kg Sb eq	-5.31%	-2.06%	-2.06%	-1.02%	-7.06%	-15.89%
GWP100	kg CO2 eq	-5.71%	-0.78%	-1.57%	0.00%	-6.94%	-8.18%
marine w ecotox	kg 1,4-DB eq	-1.82%	-0.60%	-0.90%	-2.13%	-4.76%	-22.02%

Table 8.3, benefits of recycling scenarios – CML2001

impact assessment	**unit**	**scenario1**	**scenario2**	**scenario3**	**scenario4**	**scenario5**	**scenario 6**
Radiation	DALY	-11.48%	0.00%	0.00%	0.00%	-10.29%	-6.76%
land use	PDF*m2yr	-3.34%	-2.85%	-3.34%	-0.93%	-7.40%	-10.77%
human health	DALY	-1.67%	-0.83%	-1.46%	-1.67%	-4.52%	-21.97%
ecosystem quality	PDF*m2yr	-1.20%	-0.80%	-1.20%	-0.80%	-2.77%	-18.18%
resources	MJ surplus	-3.03%	-0.85%	-0.85%	0.00%	-4.20%	-23.53%

Table 8.4, benefits of recycling scenarios – EI99

The reductions are calculated comparing the manufacturing and the disposal of the whole E-scooter to the manufacturing and disposal of the E-scooter with improved recycling scenarios. The impact of the use phase is not linked to the material management but to the electricity production mix. The impact of the use phase is the same for all the scenarios. This is why it is not accounted in this comparison. This comparison focuses on the material management: production-consumption.

Among the three new components, the most affecting in terms of recycling is lithium manganese oxide. Lithium manganese oxide is also the most abundant in the bill of materials among the three “new” materials (gold, NeFeB alloy and lithium manganese oxide).

The neodymium has a very high specific impact, especially regarding mining. The reuse solution, for example, causes the same land use reduction than the lithium manganese oxide recycle. Although, the weight amount of lithium manganese oxide is eight times bigger than the NdFeB alloy.

An electric scooter contains a large amount of copper. According to the model depicted, an E-scooter has almost 8 Kg of copper mainly held in the battery anode and in the E-motor stator. The proper recycling of the copper results as the most affecting among the recycling procedures. The cut-off model considers that the 22% of copper comes from the recycle streams. This data comes from market analysis conducted by EcoInvent2.2. In the system expansion and substitution scenario the recycling rate of copper is considered 90%, value not difficult to reach if a disassemble step for the E-motor is considered and the battery disposal companies encompasses a process to recover the copper in the anode and in the current collectors. After this assessment, it is possible to analyse the benefits of a best case scenario encompassing the recycling of lithium manganese oxide, the recycling of gold, the reuse of permanent magnets and that increases the recycling of rate of copper. The benefits are considered as percentage spreads in comparison with the current end of life scenario that does not involve the electric powertrain, see Table 8.5 and 8.6

impact assessment	unit	Best case scenario
abiotic depletion	kg Sb eq	-22.5%
GWP100	kg CO2 eq	-15.1%
marine w ecotox	kg 1,4-DB eq	-26.7%

Table 8.5, benefits of the best-case scenario – CML2001

impact assessment	unit	Best case scenario
radiation	DALY	-17.1%
land use	PDF*m2yr	-18.1%
human health	DALY	-22.6%
ecosystem quality	PDF*m2yr	-20.9%
resources	MJ surplus	-27.7%

Table 8.6, benefits of the best-case scenario – EI99

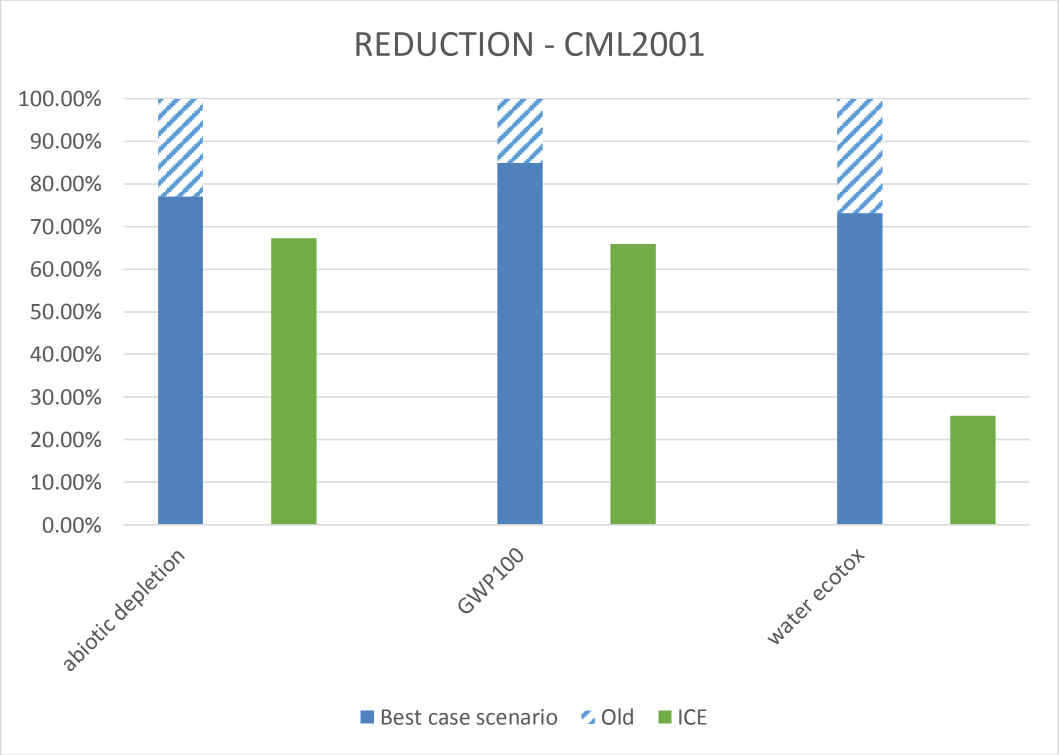


Figure 8.13, Benefits of the best-case scenario – CML2001

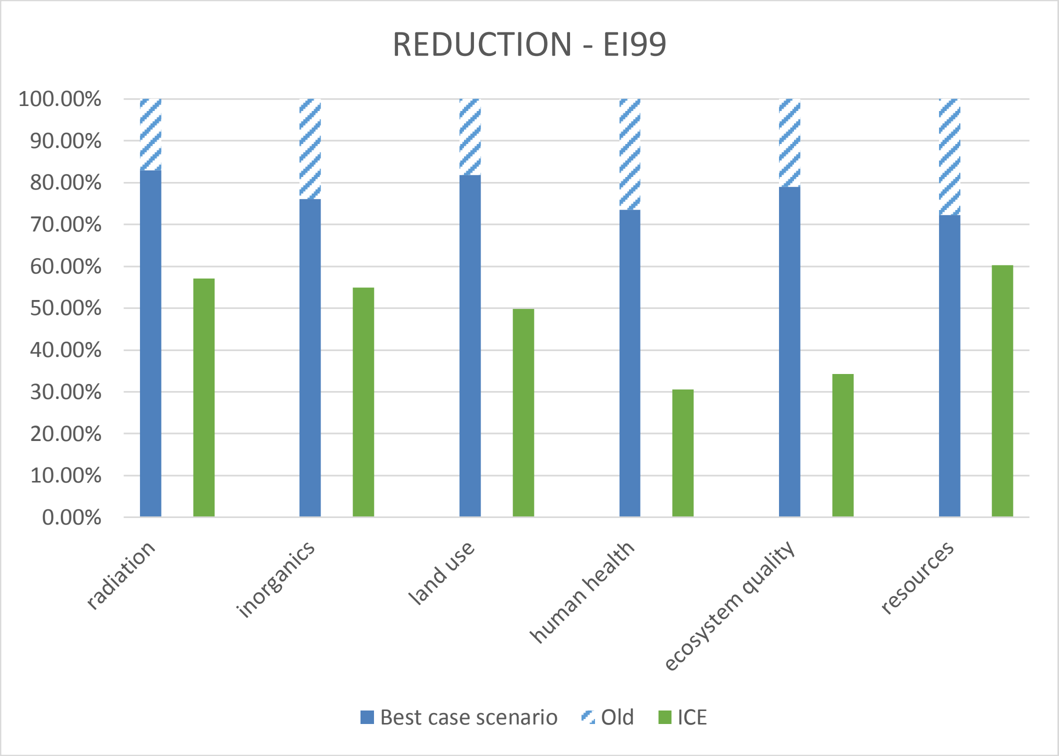


Figure 8.14, Benefits of the best-case scenario – EI99

Considering a comparison with the manufacturing of the ICE scooter, see Figure 8.13 and 8.14. It see possible to show that with a more efficient material management some parameters are considerably improved. The abiotic depletion (CML2001) and the resources (EI99) of the two alternatives have a spread lower than 10%. For other indicators, such as water ecotoxicity, even if the impact reduces of more than 20% the spread with the traditional scooter is still wide. In this sense is meaningful to state that it is the indicator for the ICE-scooter that is very low, since the ICE-scooter assembly has a very low amount of copper and not lithium, gold and neodymium at all, and not the indicator for the E-scooter that is that high. In this sense what is meaningful is the reduction percentage over 20%.

8.1.3 Sensitivity analysis

A sensitivity analysis has been performed according to the variation of the hypothesised use phase of a scooter. The use-phase according to the contribution analysis of the life cycle is the phase that lets the E-scooter be more environmental friendly than the ICE-scooter. Nevertheless the use phase is linked to an assumption. Reducing the expected kilometres of the use-phase the manufacturing of the E-scooter weights more in respect with the manufacturing of the ICE-scooter.

The most important breakeven points between the life cycles of the two alternatives are:

- 2799 km, for the abiotic depletion. So, according to the model, it is worth to drive an electric scooter for more than 2800 km to have a more sustainable life cycle compared to the traditional scooter according to material and fossil fuel depletion.
- 1982 km, for the GWP100.

According to this values the results obtained seem enough robust. 2800 is less than 10% of the proposed life expectance of the product

Another analysis is approached to assess which should be the life expectance of an electric scooter to have the use phase to weigh more than the manufacturing phase:

- 76800 km, for abiotic depletion.
- 73500 km, for GWP100.

According to the model result, over 75000 km the use phase of the scooter accounts more than its manufacturing.

The author proposes also an evaluation of the uncertainties related to the representativeness of this LCA. The uncertainties are calculated in relation with two aspects: the results of the overall LCA according to the cut- off model and the uncertainties according to the recycling process proposed. The model used to assess the uncertainties is the model proposed by SimaPro 7.3, see Appendix B.1. A table reports the evaluation of the different factors according six areas of evaluation. 1 corresponds to no uncertainty 5 to maximum uncertainty, see Table 8.7.

	Life cycle analysis with cut-off model	**Recycling scenarios**
Reliability	3	4
Completeness	2	3
Temporal correlation	2	3
Geographical correlation	2	3
Further technological correlation	3	4
Sample size	3	4

Table 8.7, Uncertainty factors

The GEOMETRIC standard deviation, covering the 95% confidence interval, of the two model results:

- Life cycle analysis with cut-off model: SD_{g95}= 1.24. It means that the computed valued for the LCIA have a 95% confidence interval of -19.3% and +24%.
- Recycling scenarios: SD_{g95}= 1.59. It means that the computed valued for the recycling scenarios have a 95% confidence interval of -37% and +59%.

An LCA, especially involving product development and choice among alternatives has always to deal with great amount of uncertainties. The author believes the life cycle analysis results, even considering the huge uncertainties, are satisfactory, since some indicators (GWP100, abiotic depletion) have spreads far wider than 24%.

It was easy to guess that the recycling scenarios had great uncertainties. Nevertheless, this thesis's scopes were to propose and assess recycling scenarios to have an overall understanding of the benefits and not to provide certain answers. In this sense, the results of the recycling scenarios show that there is room for reducing the EoL environmental impact of an Electric scooter and that the designer's choices (DfDs) play an important role.

8.2 Interpretation

This section embraces the interpretation of the results showed before. The considerations involves the E-scooter life phases and its comparison with the ICE-scooter, the E-scooter weakness emerged in the comparison and the role of the new materials, especially the neodymium, towards a higher level of material managements.

8.2.1 E-scooter life phases and design goals

What comes out from the quantitative analysis concerning the life cycle of an electric scooter is that the manufacturing phase is the most impacting phase among the others. This result leads to different interpretations. The environmental impact of the manufacturing is mainly due to two factors: the production processes and the material lifecycle of the new components encompassed in the E-scooter assembly. In a product where the production phase is such heavy in respect with the others, a high level of recycling is an effective way to improve the overall environmental impact. From this point of view, the result of the qualitative analysis is more coherent with the recycling thresholds imposed by the European directives in the last decades. For the traditional vehicles, where the use phase accounts for over the 90% of the lifecycle environmental load, the imposed recycling thresholds can lead to a contradiction. The contradiction is that to obtain high level of recycling rate the designers have to use more recyclable and sometimes heavier materials (metals instead polymers or composites), but heavier materials increase the fuel consumption rate, and the fuel consumption rate plays a crucial role in the use phase impact. This contradiction is an historical concern of vehicle manufacturers [65]. In the E-scooter the concern caused by the manufacturing let the designer focus more freely on compliance with the recycling thresholds. The conflict between the weight and energy consumption obviously remains but this time an effective recycling improves the most impacting life phase and worsens the second most impacting and not vice versa as happens for the traditional vehicles. In this sense, the results of this study can set more clear design goals.

8.2.2 E-scooter weaknesses

The E-scooter results less environmental sustainable for the radiation and the water ecotoxicity.

The radiation is linked to the European electricity production mix and to its share of electricity produced by nuclear power plants. The improvement of this indicator is not related to any specific feature of the product. A way to reduce the indicator is to increase the share of renewable energies in the electricity production mix. This solution does not only reduce GHG emissions but also radiation emissions. However, this scenario is out of the scopes of this work.

The water ecotoxicity is a general problem of metal mining. A higher level of recycling decreases the ecotoxicity. The copper gives the greatest contribution to the ecotoxicity. The recycling of copper from the lithium battery and the disassembly step of the stator are improvements toward a reduction of the ecotoxicity.

8.2.3 NdFeB, a Trojan horse for MH

The study shows that the recycling of copper is crucial for environmental sustainability. The dismantling of the stator of the motor or the crushing and hydrometallurgical treatment of the battery to sort the copper are steps that give an effective contribution to reduce the environmental impact (around 10%).

The NdFeB represents less than the 0.5% of total weight of an E-scooter. Nevertheless, considering the reuse scenario hypothesized in the chapter 5 the land use decrease of 3.5% and the GWP100 of more than 2%. Furthermore, a reused permanent magnet accounts for almost the 25% of whole value of a disposed E-scooter.

The two forces that drive recycling are usually thresholds decided by international directives or economic reasons. The reuse of permanent magnets can be an economic reason. A disassembly-purposed design (e.g. no use of glue bondage) of wheel hub motors can reduce the disassembly time and make the reuse of NdFeB magnets remunerative. Within this boundary, the designer plays a dominant role since he is the main responsible for the disassembly of product. In this sense, the NdFeB could be the economic motive to justify the systematic disassembly of the E-motor. A disassembly pre-step plays an important role towards a high rate of recycling of the copper windings. From this point of view the permanent magnet could be an economic *Trojan horse* that starts a virtuous combination based on the disassembly pre-step that leads to the complete sorting of the material of the disposed component, see Figure 8.15 and 8.16. This pre-step, in fact, leads to the sorting of both the most valuable material (magnet) and the most environmental impacting material (copper) of the component. The disassembly step has also a positive influence on the overall impact assessment of E-motor compared to the other recycling scenario proposed for the magnet, the hydrogen decrepitation, see Figure 8.17.

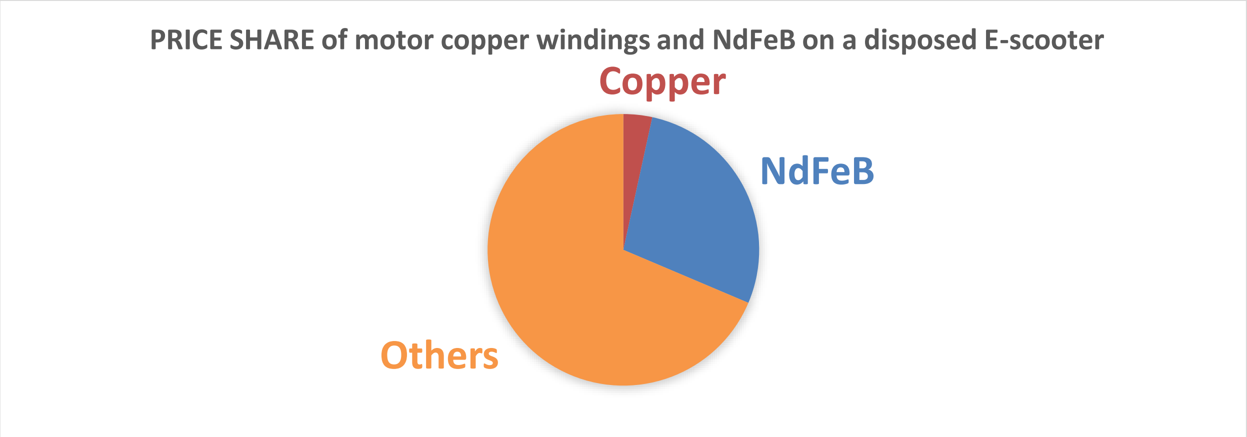


Figure 8.15, Prices share of valuable materials in a wheel hub motor

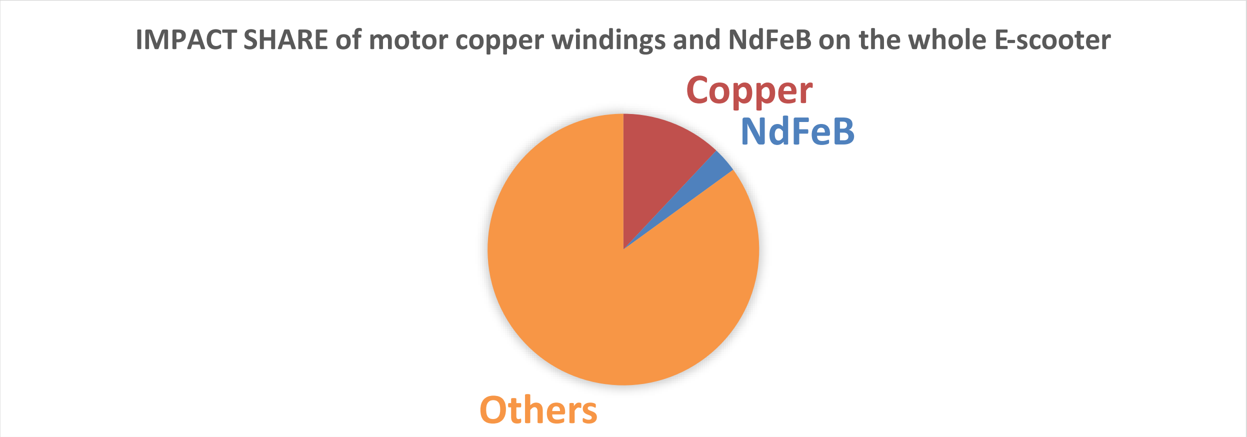


Figure 8.16, Impact share of valuable materials in a wheel hub motor

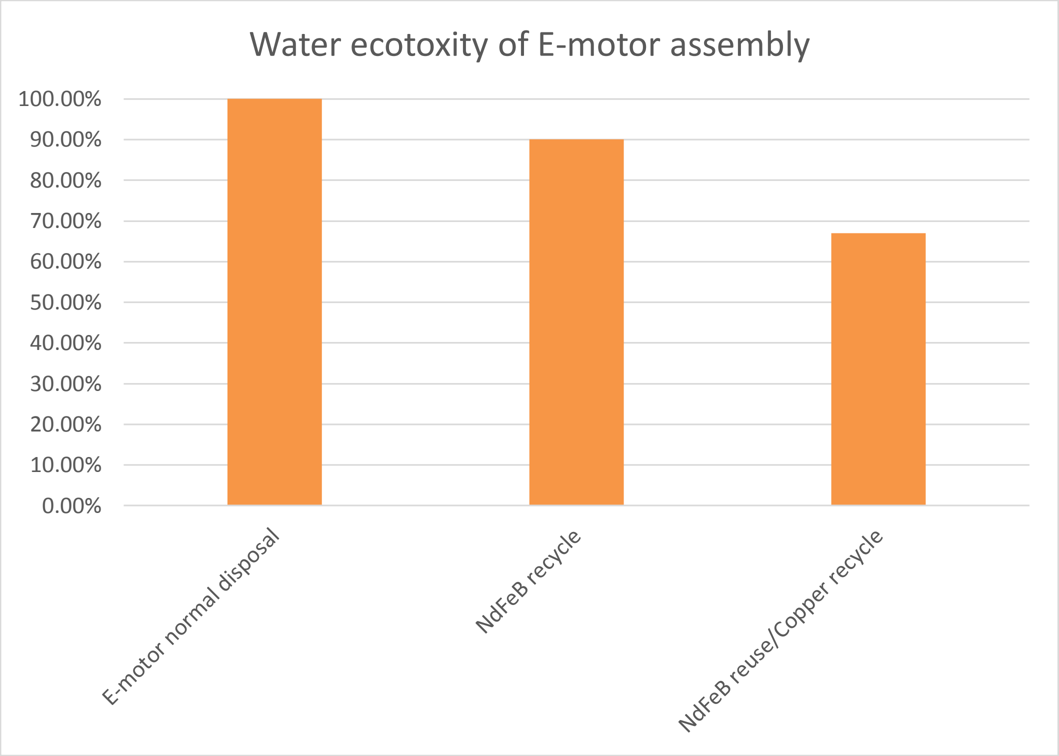


Figure 8.17, Water ecotoxicity of a wheel hub motor with different recycling approaches

9 DISCUSSION AND CONCLUSIONS

In this chapter, the author discusses the methods and the results of this master's thesis and draws the conclusions.

9.1 Discussions

The method used in this work are literature research, interviews, Material Hygiene as a mind-set, patent analysis, disassembly model and LCA.

The literature research has been used to depict the way the recycling takes place and to get familiar with all the works regarding the comparison between the two alternatives. The field of research is very wide, especially regarding the recycling opportunities linked to the components of the electric powertrain, nevertheless it seems to satisfy the needs of this work.

The interviews to the dismantler companies have been done to identify the EoL management of the scooter. The companies interviewed let the author depict a sufficient framework of the traditional scooter disposal. The fact the all the companies selected were Italian is considered a point of strength that gives the work reliability since, as already said, Italy holds a primary position regarding two-wheeled production and selling. For what concerns the electric scooter disposal, the framework is not completely represented since the substantial lack of electric vehicles treated by disposal companies. Nevertheless, the information collected let the author hypothesise a plausible dismantle process that encompasses the sorting of the electric powertrain. The recycling of the different E-powertrain materials takes place in further steps.

The Material Hygiene as a mind-set has been used as a way to coordinate all the data and the information recruited during the first stages of this thesis. The Material Hygiene has been also used to direct the efforts towards a concrete goal. The Material Hygiene, as said, works more as a mind-set than as a proper method (proper methods are disassembly model, etc.), in this sense it has helped to interpret the results and to give specific understanding of the matter, such as, for example, the value analysis of the disposed scooter.

The patent analysis and the disassembly model play a role within the proposal of recycling scenarios. These methods had the task to let the author reach an adequate understanding of the recycling technologies or the product structure to describe plausible process flows or disassembly steps. Furthermore, those recycling and disassembly steps had to be in a manner that allowed the author to perform a LCA, to obtain a quantitative interpretation. Within these boundaries, the methods appear satisfactory. It is important to state that these recycling scenarios, especially the ones involving chemical processes might be recycling standards in the future but they also might be not. It is believed that to design a concreate and effective chemical recycling process could be, by itself, the topic of a master's thesis since it requires many specific competences out of the boundaries of this work. Nevertheless, the proposed scenarios worked properly to have the understanding of the weight of recycling of the "new" materials in the lifecycle and to assess the influence of the mechanical designers (Design for Disassembly) in respect to the influence of the recycling technologies.

The Life Cycle Assessment has been chosen as method to have a quantitative knowledge of the life cycle of the two alternatives and to validate and give quantitative meaning to the scenarios. Within these boundaries, the LCA seems to be satisfactory. The limit of this method stays fundamentally in the limit of the chosen data, which in a certain sense stays in the limit of the chosen topic. The point is that the wider are the boundaries of the study, and in this case study the boundaries are wide both for the product design (*average* electric scooter) and for the time boundaries (*plausible* recycling scenarios), wider are the data uncertainties. Data cannot represent each case and the method can lose reliability. Nevertheless, the work investigated a field, in some sense, unexplored, at least, for what concerns such a wide understanding of the material management of a complex and relatively new product as the E-scooter. The numerical results are considered satisfactory and useful to depict the role of the electric vehicle as an alternative for private transportation and the benefits achievable with a proper material management. They also point out the benefits achievable by a proper DfD and the contribution of disassemble-friendly design

9.2 Conclusions

This master's thesis had two aims. The first one was to perform a lifecycle comparison of a traditional scooter and an electric scooter, regarding the energy and material flows and their environmental load, pointing out the relative weight of the electric powertrain. The author, within the boundaries of the chosen methods, gave a consistent answer to this question. The E-scooter represents a green alternative considering the whole life cycle even if the its manufacturing needs more resources than the ones required by the traditional two wheeler.

The second aim was to assess how an efficient material management could improve the environmental load of an electric scooter. Regarding this topic, the results provide a reasonable answer. The interpretation of this results leads to some considerations. Some recycling processes, such as the lithium recovery process and the neodymium recycling with hydrogen decrepitation, represent a plausible option for recycling but they actually involve several different parties such as recycling technology developers, recycling companies, threshold directives, etc. These variables do not allow the author to draw specific conclusions about the future of this opportunity. Nevertheless, there is the evidence of environmental benefits for this scenario. The disassembly of NdFeB permanent, as way to get the E-motor completely sorted out and to have a higher copper recycling rate, represents a very interesting opportunity both from economic and environmental opportunities strictly related to designers' working scope.

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APPENDIX A

This appendix shows the results of a literature research regarding the permanent magnet life cycle. The lifecycle is the same used for the LCA. There is also a section involving the recycling opportunities for the rare earths.

A.1 Permanent magnet life cycle

The permanent magnets are made of an alloy of NdFeB. The most important material of the alloy is the rare earth neodymium.

The process flow towards the mining of neodymium consists in different steps [25]. The first operation aims to extract the rare earth materials. It takes place with traditional mining technique. The ore has 4.1% of rare earth oxide, REO, and 30-35% of iron. After the mining, the REO containing materials (bastnasite and monazite) are separated from iron and brought to the beneficiation site. The ore has also 0.04% of ThO_2. The beneficiation consists in a mechanical, magnetic and chemical process. The beneficiation results is a 61% REO-containing mineral.

The next operation is acid roasting. The acid roasting removes all not-water soluble materials. The acid roasting is a preparation step for the acid leaching. The acid leaching process let the solution have a higher level of purity. After the acid leaching with the help of soda the REO salt precipitates and then is washed and dried. The last steps it solvent extraction that gives a REO with a purity up to 99.99%. The process flow just described has been hypothesized by Sprecher et al., see Figure A.1. It is the same implemented in the life cycle assessment of this thesis.

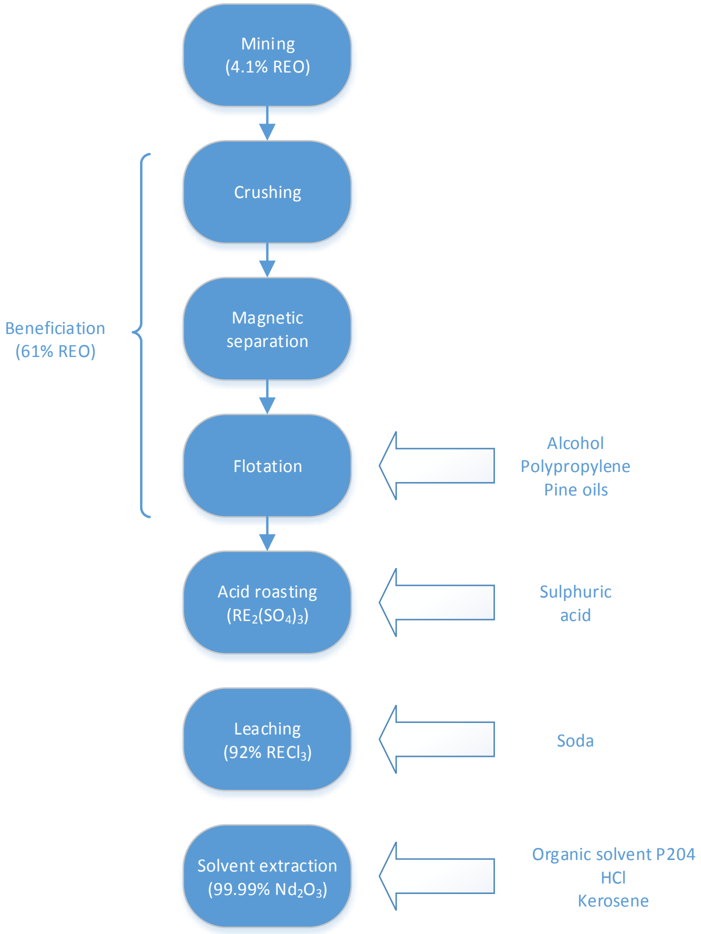


Figure A.1, Nd mining

Sprecher et al. hypothesized also the NdFeB production route. The scheme is reported after this paragraph, see Figure A.2. Also this process has been implemented in the life cycle assessment. The first step for the production of the magnet usually dissolves the REO in molten salt and then electrolyzes to obtain pure liquid neodymium. The next process leads to the making of the NdFeB alloy. A mixture of the three materials, Nd, Fe and B is molten in a furnace. To have a fast cooling the molten alloys is poured over a rapid rotating copper wheel. Hydrogen decrepitation exploits structural properties of the NdFeB flakes. The contact with a hydrogen atmosphere causes the alloy to fall apart in a fine powder. This process reduces the energy needed for the following process the jet milling. The jet milling is the last process to reduce the size of the powder of the alloy before the sintering. The final size of the particle is 5-7 μm. Before the sintering, the last processes are the aligning, made through a magnetic pulse, and the pressing. The sintering takes place in a vacuum chamber at the temperature of 1000°C to let the alloy particles liquefy. The next operations are the grinding and the slicing with traditional mechanical methods. A further operation is the nickel coating made through electroplating. At last, the magnetizing and the testing take place.

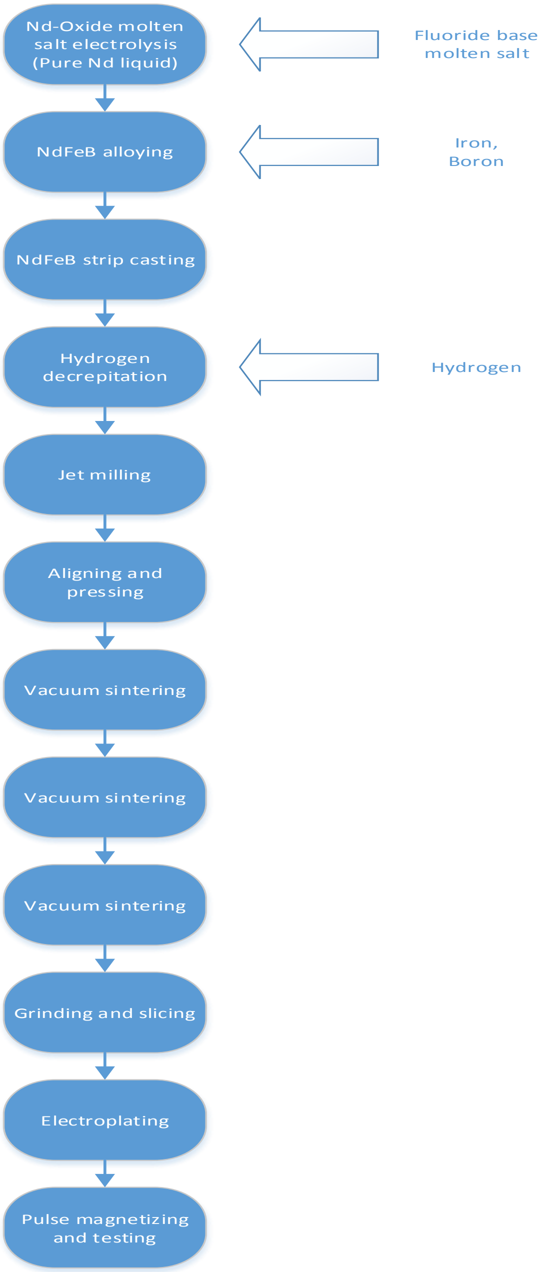


Figure A.2, NdFeB production chain

A.2 Recycling opportunities for permanent magnets

Considering the complex architectures of the devices using permanent magnets a turning point could be a sorting method downstream a shredding step, like the magnetic step that let the recyclers sort ferrous and non-ferrous metals. Nowadays, there is not available method for this kind of downstream shorting for REEs. However, if this process will become available a high concentration of oxygen and impurities will be present in the recovered material not allowing a direct re-processing. It is from this point of view that all the other methods, currently just present at a lab-scale, could become part of the recycle chain. A panoramic view upon these methods is reported in a table, see Table A.1 [34]

Table A.1, Solution for the recycling of permanent magnet [34]

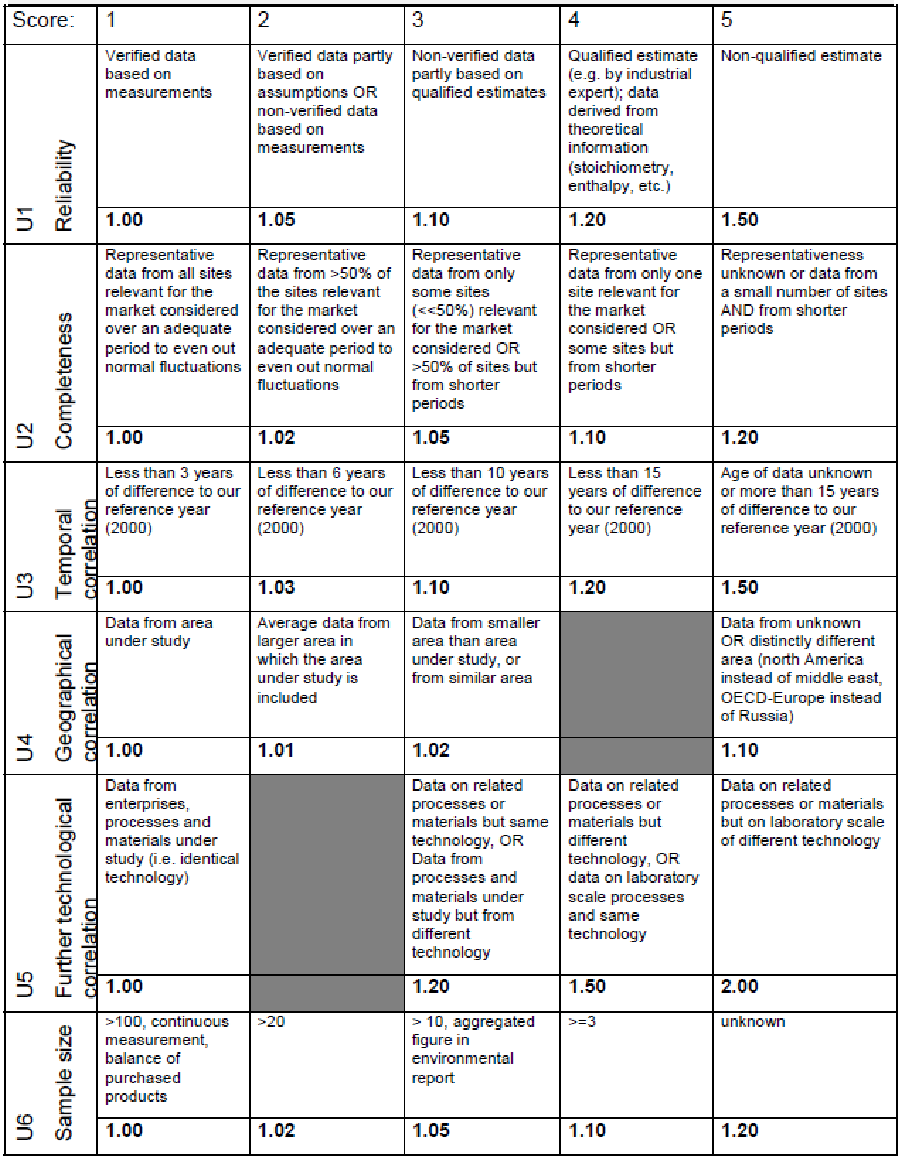
Method	Pro	Cons
Direct re-use	• Most economical and environmental friendly: no use of chemicals or energy • No waste generate	• Only for specific products like wind turbine or vehicle electric motors • Not enough volume today
Mechanical dismantle	• Less energy-consuming than pyrometallurgical and hydrometallurgical processes • No waste generated	• Too much related to specific architectures
Reprocessing after hydrogen decrepitation	• Less energy-consuming than pyrometallurgical and hydrometallurgical processes • No waste generated	• Too much related to specific architectures • No suitable with for magnets with big compositional variations
Hydrometallurgical methods	• Generally applicable to all kind of magnet composition • Same processing step from primary ore	• Complex process flow • Large consumption of chemicals • Large consumption of water
Pyrometallurgical methods	• Generally applicable to all kind of magnet composition • Less steps than the hydrometallurgical methods • Obtaining of REEs in liquid state	• Large energy consumption • Electroslag refining and glass slag method generate large amount of waste.
Gas-phase extraction	• Generally applicable to all types of magnet compositions • No generation of waste water	• Large chlorine gas consumption • Aluminum chloride is very corrosive

This appendix contains integrations to the LCA chapter, see Chapter 7.

B.1 Uncertainties

The uncertainties have been valued according to the table proposed by SimaPro 7.3. See Table B.1. The factors are then input for the equation:

$$SD_{g95} = exp^{\sqrt{[\ln(U_1)^2]+[\ln(U_2)^2]+[\ln(U_3)^2]+[\ln(U_4)^2]+[\ln(U_5)^2]+[\ln(U_6)^2]}}$$



Score:	1	2	3	4	5
U1 Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
	1.00	**1.05**	**1.10**	**1.20**	**1.50**
U2 Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	**1.02**	**1.05**	**1.10**	**1.20**
U3 Temporal correlation	Less than 3 years of difference to our reference year (2000)	Less than 6 years of difference to our reference year (2000)	Less than 10 years of difference to our reference year (2000)	Less than 15 years of difference to our reference year (2000)	Age of data unknown or more than 15 years of difference to our reference year (2000)
	1.00	**1.03**	**1.10**	**1.20**	**1.50**
U4 Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area		Data from unknown OR distinctly different area (north America instead of middle east, OECD-Europe instead of Russia)
	1.00	**1.01**	**1.02**		**1.10**
U5 Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials but same technology, OR Data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00		**1.20**	**1.50**	**2.00**
U6 Sample size	>100, continuous measurement, balance of purchased products	>20	> 10, aggregated figure in environmental report	>=3	unknown
	1.00	**1.02**	**1.05**	**1.10**	**1.20**

Table B.1, Uncertainty factor table

B.2 LCI of an E-scooter

This section reports the LCI as they have been reported in the LCA run with the software SimaPro 7.3. The LCI defines the components and the manufacturing processes of the BLCD motor, see Table B.3, of the BLDC controller, see Table B.4, and of the whole E-scooter, see Table B.5.

Product: BLDC motor, 1 kg				
1. Known input form technosphere (material/fuels)				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Steel	Steel, at plant	Kg	0.4959
Material	Chromium steel	Chromium steel 18/8, at plant	Kg	0.0672
Material	Copper	Copper, at storage	Kg	0.1343
Material	Permanent magnet	NdFeB magnet, at plant	Kg	0.04
Material	Aluminium	Aluminium, product mix	Kg	0.2565
Material	PVC	PVC, at plant	kg	0.0061
Processing	Steel	Sheet rolling, steel	Kg	0.4959
Processing	Copper	Wire drawing	Kg	0.1343
Auxiliaries		Manufacturing plant	p	0.000000004

Table B.2, LCI of BLDC motor on SimaPro 7.3

Product: BLDC controller, 1 kg				
1. Known input form technosphere (material/fuels)				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Steel	Steel, at plant	Kg	0.06
Material	Polyethylene	Polyethylene, HDPE	Kg	0.3219
Material	Aluminium	Aluminium, product mix	Kg	0.4
Material	Cable	Cable, ribbon cable	Kg	0.032
Material	PCB	Printed circuit board, mixed, at plant	Kg	0.14
Processing	Steel	Sheet rolling, steel	Kg	0.06
Processing	Aluminium	Sheet rolling, aluminium	Kg	0.4
Processing	Injection moulding	Injection moulding	Kg	0.32
Auxiliaries		PCB plant	p	0.000000004

Table B.3, LCI of BLDC controller on SimaPro 7.3

Product: E scooter, 1 unit				
1. Known input form technosphere (material/fuels)				
Process type	**Materials**	**EcoInvent 2.2 dataset**	**Unit**	**Amount**
Material	Steel	Steel, at plant	Kg	6.93
Material	Reinforcing steel	Steel, at plant	Kg	20.51
Material	Chromium	Chromium, at storage	Kg	0.16
Material	Nickel	Nickel 99%, at storage	Kg	0.093
Material	Aluminium	Aluminium, product mix	Kg	18.18
Material	Polyethylene	Polyethylene, HDPE	Kg	1.82
Material	Polypropylene	Polypropylene, at plant	Kg	11.92
Material	Polyvinylchloride	Cable, ribbon cable	Kg	1.92
Material	Synthetic rubber	Synthetic rubber, at plant	Kg	4.85
Material	Paint	Alkyd paint, at plant	Kg	0.45
Material	Zinc	Zinc, primary, at plant	Kg	0.38
Processing	Steel	Sheet rolling, steel	Kg	14.31
Processing	Steel	Section bar rolling, steel	Kg	7.91
Processing	Copper	Wire drawing, copper	Kg	0.59
Processing	Polymers	Injection moulding	Kg	15.7
Auxiliaries		Natural gas, burnt in furnace, at plant	MJ	39.67
Auxiliaries		Electricity, medium voltage, at grid	kWh	23.17
Auxiliaries		Light fuel oil, burnt in furnace, at plant	MJ	12.63
Auxiliaries		Diesel, burnt in furnace, at plant	MJ	9.09
Auxiliaries		Tap water, at user	Kg	215
Auxiliaries		Ethylene, at plant	Kg	1.24
Auxiliaries		Transport, lorry	tkm	5
Auxiliaries		Transport, freight	tkm	1870
Auxiliaries		Road vehicle plant	p	0.000000193
Component		LiMnO battery	Kg	24
Component		BLDC motor	Kg	12
Component		BLDC controller	kg	2.2

Table B.4, LCI of E-scooter on SimaPro 7.3

The calculation of the energy allocation for the manufacturing of an average scooter is calculated using the approach proposed by Leuenberger, M. & Frischknecht, R., [54]. The assumption is that the energy needed to manufacture an E-scooter is the same of an ICE-scooter, except for the electric powertrain that has its own energy allocation. The data are from the Environmental report of Honda [11]. The report presents the total amount of electricity from grid, natural gas, oil based fuel and diesel consumed during 2013. These data are to be multiplied by the percentage share of sales due to motorcycles. Then, the obtained values are divided by the annual production of motorcycles by Honda. These last values are finally divided by a factor two to account just for the production of scooters (50cc). The process is reported in a table, see Table B.6. The same approach has been used for the Annual report of Piaggio [12], see Table B.7. The results are different. The choice of one or the other of the results does not affect the comparison between the alternatives. In fact, the original assumption is that the energy allocation for the manufacturing is the same for the ICE-scooter and the E-scooter. The model adopts the values from Honda to be comparable with the work of Leuenberger, M. & Frischknecht, R. that uses as reference the Honda Annual Report of 2008.

HONDA						
Consumption Honda 2013	Japan	N.America	S.America	Europe	Asia	Total
Electricity demand (1000*MWh)	1560	1820	322	151	1610	5463
Natural gas demand(1000*GJ)	85	6410	240	526	2093	9354
Oil based fuel demand(1000*GJ)	806	273	336	7	1556	2978
Diesel(1000*GJ)	8	301	41	7	1788	2145
Sales	**Sales (¥_10^6)**	**Sales(%)**				
Motorcycle	1339549	13.51				
Totale sales	9915065	100				
Annual Production	**Total**	**Japan**	**Others**			
Motorcycle	15926000	184000	15742000			
Consumption per motorcycle fleet production	**Total**					
Electricity demand (1000*MWh)	738.06					
Natural gas demand(1000*GJ)	1263.75					
Oil based fuel demand(1000*GJ)	402.33					
Diesel(1000*GJ)	289.79					
Consumption per scooter (50cc)	**Total**					
Electricity demand (kWh)	23.17					
Natural gas demand(MJ)	39.67					
Oil based fuel demand(MJ)	12.63					
Diesel(MJ)	9.09					

Table B.5, Energy consumption for manufacturing according to Honda 2013 data.

PIAGGIO					
Consumption Piaggio 2013	**Italy**	**Spain**	**India**	**Vietnam**	**Total**
Electricity demand (1000*kWh)	45887	913	26198	13979	86977
Natural gas demand(1000*GJ)	282.27	0.17	-	-	282.45
Oil based fuel demand(1000*GJ)	-	-	17.81	1.04	18.85
Diesel(1000*GJ)	0.07	3.80	75.18	31.32	110.37
Consumption per scooter (50cc)	**Total**				
Electricity demand (kWh)	112.87				
Natural gas demand(MJ)	366.55				
Oil based fuel demand(MJ)	24.46				
Diesel(MJ)	143.24				

Table B.6, Energy consumption for manufacturing according to Piaggio 2013 data.

B.3 LCIA, impact of metals involved in recycling scenarios

This appendix section reports the LCIA of NdFeB, $LiMnO_2$ and Copper. The comparison involves both the primary and the secondary (from recycle) metals. The results of the LCIA are a balance between the amount of a certain material in the LCI and its specific impact assessment. In this section are reported the specific impact assessment to have a wider view of the LCI. The gold is not reported since it has by far the greatest environmental load, around three order of magnitude more affecting than copper. See Figure B.1, B.2 and B.3.

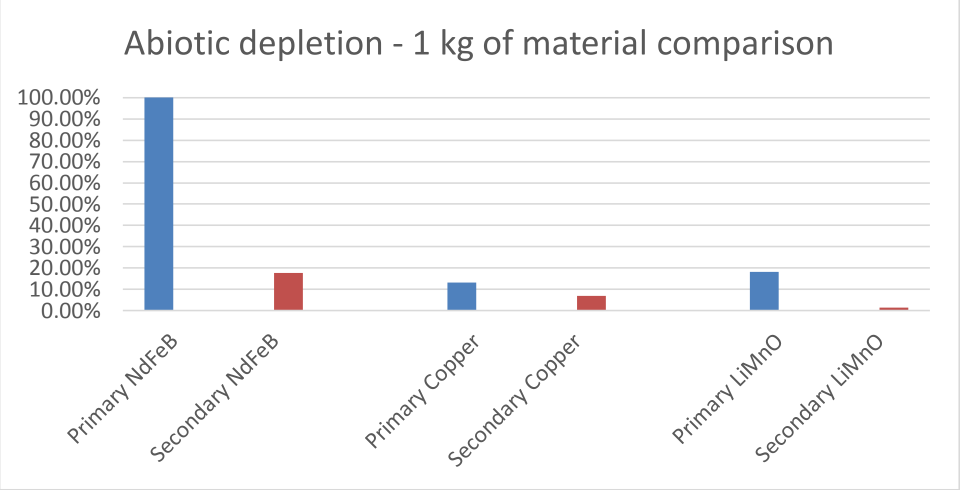


Figure B.1, Specific abiotic depletion of materials

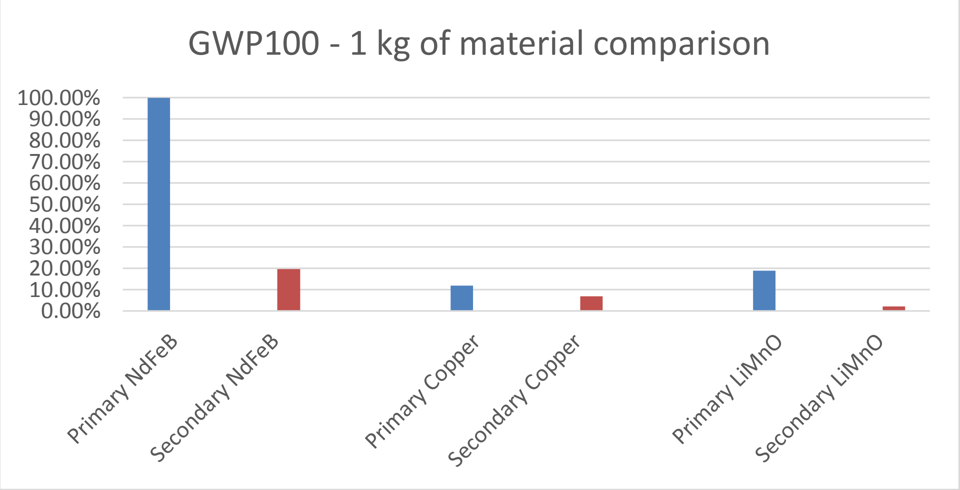


Figure B.2, Specific GWP100 of materials

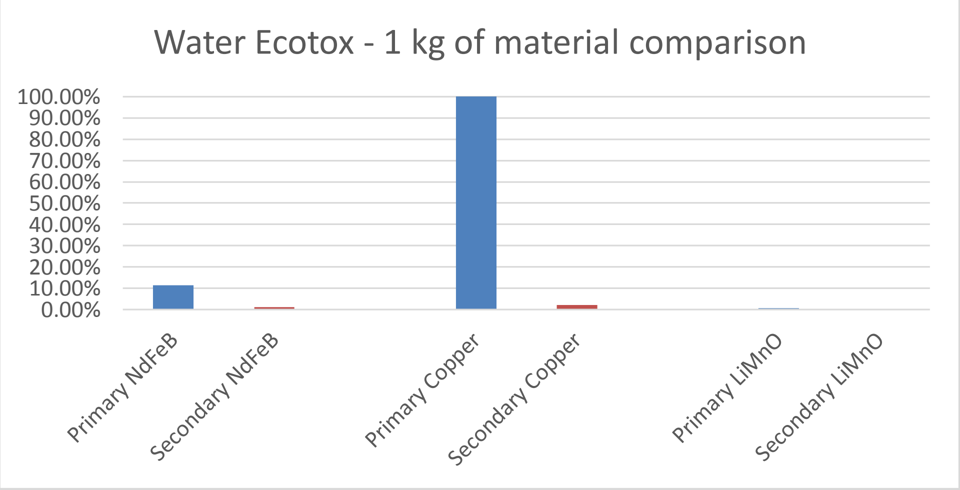


Figure B.3, Specific Water Ecotoxicity of materials