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ANALYSIS OF THE APPLICATION OF CIRCULAR ECONOMY PRINCIPLES IN THE SECTOR OF THE COMMERCIAL VEHICLES

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Abbrevation	Meaning
AC	Alternating current
BEV	Battery electric vehicles
CE	Circular economy
CNG	Compressed natural gas
CVs	Commercial vehicles
DC	Direct current
EC	European Commission
EEA	European Enviroment Agency
EFs	Emission factors
EoL	End-of-life
EV	Electric vehicles
FCEV	Fuel cell electric vehicles
GHG	Greenhouse gases
GTT	Gruppo Torinese Trasporti
GWP	Global Warming Potential
IEA	International Energy Agency
KPI	Key performance indicator
LCA	Life Cycle Assessment
LIB	Lithium-ion battery
NMVOC	Non methane volatile organic compounds
OICA	International Organization of Motor Vehicle Manufacturers
PHEV	Plug-in hybrid electric vehicles
ROTW	Rest of the world
SDGs	Sustainable development goals
T&B	Trucks and Buses
VOCs	Volatile organic compounds

Introduction

Climate change, environmental degradation, pollution, biodiversity loss, depletion of resources: these are only few words that reflect the world's actual situation, that is evolving and getting worse over time. The solution is to shift towards a clean, sustainable, low-carbon, resource-efficient and competitive economy: it is essential to move towards Circular Economy (CE). On July 2021, all 27 EU Member States adopted a package of proposal to reach carbon neutrality in 2050, setting the intermediate target of emissions reduction by 55% by 2030 than the levels of 1990.

Therefore, electrification is considered one of the keys of CE to reach the target of decarbonization proposed by the European Green Deal for 2050: from statistics made by EU at a global scale, in 2028 there will be almost 50 -200 millions of electric vehicles and 900 million in 2040, from 4 million in 2018 (European Commission, 2019b).

In this scenario, this thesis was focused on the electrification in the sector of commercial vehicles (CV) and was supported by CNH Industrial, a global leader for design, manufacturing, and distribution in the international market of agriculture vehicles, construction vehicles, commercial and specialty vehicles and powertrains.

The first part of the thesis presents a methodology to measure and evaluate the circularity and sustainability in the automotive sector, through the comparison of three automotive companies (CNH Industrial, Volvo and Daimler), using mainly the public information available on their 2020 Sustainability Reports. The second part presents a special focus on hybrid and electric buses: the impacts and GHG emissions generated by the actual urban bus fleet of Turin were estimated and some alternative scenarios of increased electrification were proposed and discussed.

Although the electric mobility can be considered the solution to reach carbon neutrality because it guarantees zero emissions of pollutants during the use phase, it is important to consider what is hidden behind this scenario. The Lithium-ion batteries (LIBs) represent the invisible emissions that characterize electric vehicles. In this context, the higher demand of electric vehicles will translate into a large number of spent LIBs: the global battery market is expected to grow by 25% per annum to 2600 GWh in 2030 due mainly to the demand from electric mobility, that will grow from 142 GWh in 2018 to 2333 GWh in 2030 (Zhao et al., 2021). For that reason, in the third part of the thesis, the impacts related to entire life of three types of LIBs adopted for electric buses were estimated, including two alternatives recycling scenarios, adopted at industrial scale, for their end-of-life management (e.g., pyrometallurgy and hydrometallurgy).

1 The concept of Circular Economy

The Circular Economy (CE) concept is opposite to the traditional linear economy model, adopted since the industrial revolution and based on "take-make-consume-dispose", assuming that resources are almost unlimited: raw materials are used to make products and, after their use, they become waste.

It is difficult to associate the CE concept to a specific date or to a specific author but, certainly, it is not new: in 1966, the economist Kenneth Boulding published the article "The economics of the coming spaceship Earth". In this article, he defines two types of economy that are the "cowboy economy" and the "spaceman" economy: the cowboy is the symbol of the "illimitable plains" and it is associated to an open economy, based on the continuous consumption; the figure of spaceman is associated to the concept that the earth, being like a single spaceship, has not unlimited reservoirs and, thus, this is associated to a closed and auto regenerative economy, based on recycling of the outputs. Boulding considers the economy of the future similar to the "spaceman economy" and he believed that: "The closed earth of the future requires economic principles which are somewhat different from those of the open earth of the past" (Boulding, 1966).

According to the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013), from the 1970s, the CE concept was developed by different school of thought:

- **Cradle to cradle**: this philosophy eliminates the concept of the waste because all the products used in industrial and commercial processes become nutrients, reusing them in their biological and technical metabolism. The key principles are: "Waste equals to food"; the maximization of renewable energy using ("Use current solar income") and the managing of water maximizing the quality ("Celebrate diversity");
- **Performance economy:** Walter Stahel developed in 1976 a "close loop" economy, aiming to the extension of the product life, long life goods, reconditioning activities and waste prevention;
- **Biomimicry:** this philosophy was developed by Janine Benyus in 1997, author of "Biomimicry: innovation inspired by nature" in which she suggests to study and emulate nature's model to solve human problems;
- **Industrial ecology:** this approach is referred to the "study of material and energy flows through industrial systems" and, thus, she sustains a close-loop system in which the waste are reused as input;
- **Natural capitalism:** this philosophy was developed by Paul Hawken, Amory Lovins and L.Hunter Lovins in 1999 in the book "Natural Capitalism: Creating the Next Industrial Revolution" and it is based on an economy system described by the overlapping of business and environmental interests;
- **Blue Economy:** this philosophy promotes the idea of "using the resources available in cascading systems, (…) the waste of one product becomes the input to create a new cash flow";
- **Regenerative design**: in the 1970s, the American Professor John T. Lyle developed the idea that the concept of regeneration, adopted earlier for the agriculture, can be applied to all the compartments and probably this approach laid the foundation for the Circular Economy.

1.1Circular Economy: definition

It is useful to introduce a definition of CE but, considering the large number of studies about this topic, it is not univocal. A representative definition of CE could be provided by the Ellen MacArthur Foundation: "A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (Ellen MacArthur Foundation,2013).

1.2 The first Circular Economy Action Plan

In July 2014, the European Commission (EC) proposed a Circular Economy Package made of: measures to create a resource efficiency Europe; targets to improve waste management and resource efficiency; new proposals to update waste legislation, promoting the reuse and the recycling (European Commission, 2014). On December 2015, as part of it, the EC adopted the first Circular Economy Action Plan to promote the transition of the Europe towards the CE, that will enhance the Europe competitiveness creating innovative and more efficient business models, new jobs, and social opportunities.

The objective is to shift the Europe towards a Circular Economy, giving a value to the end-of-life products to reduce and minimize significantly the waste: this transition "requires changes throughout value chains, from product design to new business and market models, from new ways of turning waste into a resource to new modes of consumer behaviour" (European Commission, 2014).

The starting point to implement the CE is the design of products, in a way that their life can be extended as long as possible through remanufacturing, reparation, recycling, reusing, upgrading instead of becoming a waste. In this way, it generates less dependency from natural resources, reducing the environmental impact and creating a new business model, that is sustainable also from the cost's perspective. In Figure 1, is represented the CE conceptual diagram: it is a loop and the different phases are interconnected, putting products into different uses after their end-of-life, minimizing the residual waste.

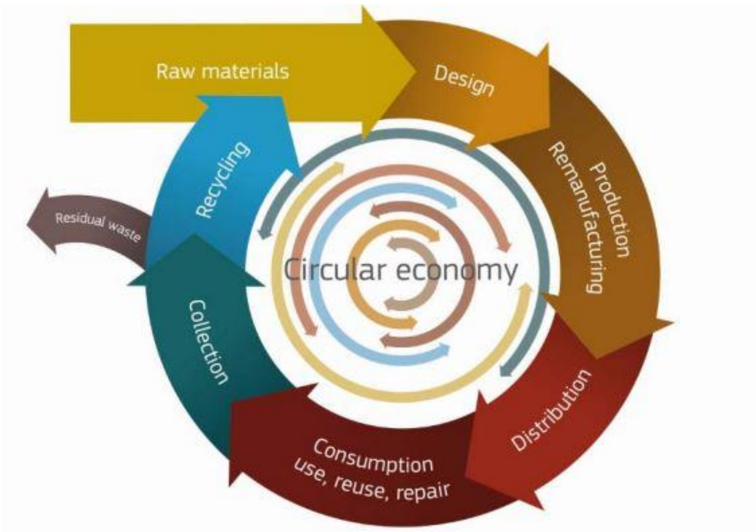

Figure 1. Circular economy conceptual diagram (European Commission,2014)

To better understand the principles of CE, it is useful to introduce some definitions, provided according to the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013):

- *Remanufacturing*: a product is disassembled to the component level and restored (replacing components where necessary) to "as new" condition with the same performance and warranty as a new product;
- *Refurbishment*: a process of returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making 'cosmetic' changes to update the appearance of a product, such as cleaning, changing fabric, painting, or refinishing.

Any subsequent warranty is generally less than issued for a new or a remanufactured product, but the warranty is likely to cover the whole product (unlike repair). Accordingly, the performance may be less than as-new;

- *Reuse*: the use of product again for the same purpose in its original form or with little enhancement or change;
- *Recycling*: it is the process of reducing a product all the way back to its basic material level, thereby allowing those materials to be remade into new products. It is a recovering of material for the original purpose or for other purposes, excluding energy recovery;
- *Downcycling*: a process of converting materials into new materials of lesser quality and reduced functionality;
- *Upcycling*: a process of converting materials into new materials of higher quality and increased functionality.

According to the Ellen MacArthur Foundation, CE is based on three principles:

- Design out waste and pollution: waste and pollution originated at the design phase, in which are determined most of the environmental impacts. The concept is the rethinking of the product already from the design stage, in a perspective of creating less waste and pollution;
- Keep products and material in use: the design of the products must guarantee the reusing, repairing and remanufacturing, becoming a secondary raw material;
- Regenerate natural system: the action is to improve the environment, returning valuable nutrients to the soil and other ecosystem to enhance natural resources.

A better design of the product in fact can allow the long durability of it or the possible reparation, an easier upgrading or remanufacturing and an easier recycling; but attention must be paid to the environmental impact of the raw materials' production: it is important to promote sustainable sourcing (European Commission, 2015b).

Another key aspect of CE implementation is the consumption because must be guaranteed the availability of information to the costumers in order to choose the most sustainable product (e.g. Ecolabel identifies products that have a reduced environmental impact throughout their lifecycle) and to support innovative forms of consumption (e.g. sharing products); in addition, the waste management is also a key of CE through the reusing, recycling or energy recovering instead of landfilling, promoting the "secondary raw materials" market (European Commission, 2015b).

The Circular Economy Action Plan presents, in the Annex, 54 actions to implement by 2018, in different general sectors that are production, consumption, waste management, market for secondary raw materials and in different specific sectors that are plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based materials, innovation and investments, monitoring (European Commission,2015a).

Furthermore, on 4 July 2018 entered into force the following four Directives, as part of the Circular Economy Package, that every Member State should have implemented within a two-year period:

- Directive (EU) 2018/849 of the European Parliament and of the Council of 30 May 2018 amending Directives 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment
- Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste
- Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste

- Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste.

These Directives proposed targets about landfilling, reusing, and recycling, such as:

- A common EU target for recycling 65% of municipal waste by 2035;
- A common EU target for recycling 70% of packaging waste by 2030;
- Separate collection obligations are strengthened and extended to hazardous household waste (by end 2022), bio-waste (by end 2023), textiles (by end 2025).

1.3 The European Green Deal

The European Green Deal was proposed by the EC in December 2019 to implement the United Nation's 2030 Agenda, which contains the Sustainable Development Goals (SDGs), and to plan a strategy that will transform the Europe (and also its neighbour countries) adopting a resource-efficient and competitive economy, reaching the following goals:

- no net emissions of greenhouse gases in 2050
- decoupling of economic growth and resource use
- protect, conserve, and enhance the EU's natural capital
- protect the health and well-being of citizens from environment-related risks and impacts
- restore biodiversity and decreasing pollution

To achieve these goals, the EU Green Deal operates through 50 actions to propose new Directives or to enforce the existing Directives and legislations: it is necessary to intervene in all sectors, rethinking "policies for clean energy supply the economy, industry, production and consumption, large-scale infrastructure, transport, food and agriculture, construction, taxation and social benefits" (European Commission, 2019a).

In Figure 2 is represented a scheme of the European Green Deal's goals.

Figure 2. European Green Deal's goals. (European Commission, 2019a)

One of the most important goal of the European Green Deal is reaching of the carbon neutrality in 2050 because this target requires actions in different sectors, that are (European Commission, 2019):

- energy: the action is to decarbonise the energy sector because the production and the use of energy contribute for more than 75% of the EU's greenhouse gas emissions (European Commission, 2019a). The goal is to use renewable energy sources, increase the energy efficiency and innovative systems (e.g., smart grids, smart infrastructures, energy storage systems);
- buildings: the action is to renovate building to reduce the energy use because actually 40% of our energy consumption is by buildings; in fact, they requires a huge amount of energy and mineral resources (European Commission,2019a);
- industry: the action is to promote innovation and green economy into industry because, actually, European industry uses only 12% of recycled materials (Eurostat).The economy of the industries is still too linear: the resource extraction and processing of materials contribute for the half of total greenhouse gases emissions and more than 90% of biodiversity loss (European Commission, 2019). The aim is to promote the circular economy practices into industries through the "New Circular Economy Action Plan" proposed in March 2020, to encourage also strategic forms of collaborations through the implementation of the Strategic Action Plan on Batteries and supporting the European Battery Alliance in order ensure a safe, circular and sustainable battery value chain for all batteries, including the batteries for electric vehicles;
- mobility: the action is to promote alternative and more sustainable forms of mobility and transport fuels because transports are the cause for 25% of emissions and, to achieve carbon neutrality on 2050, is needed the 90% of the reduction in emissions. For this reason, the European Commission planned to revise the legislation on CO_2 emission performance standards for cars and vans and to increase the efficiency of the public transport system (European Commission,2019a).

Among the other goals of the EU Green Deal there are the "Farm to Fork Strategy" to create a clean food system; the "Biodiversity Strategy" to preserve and restore the ecosystem and biodiversity; a zero-pollution ambition for a toxic-free environment. In Figure 3 is represented the timeline of the EU Green Deal actions.

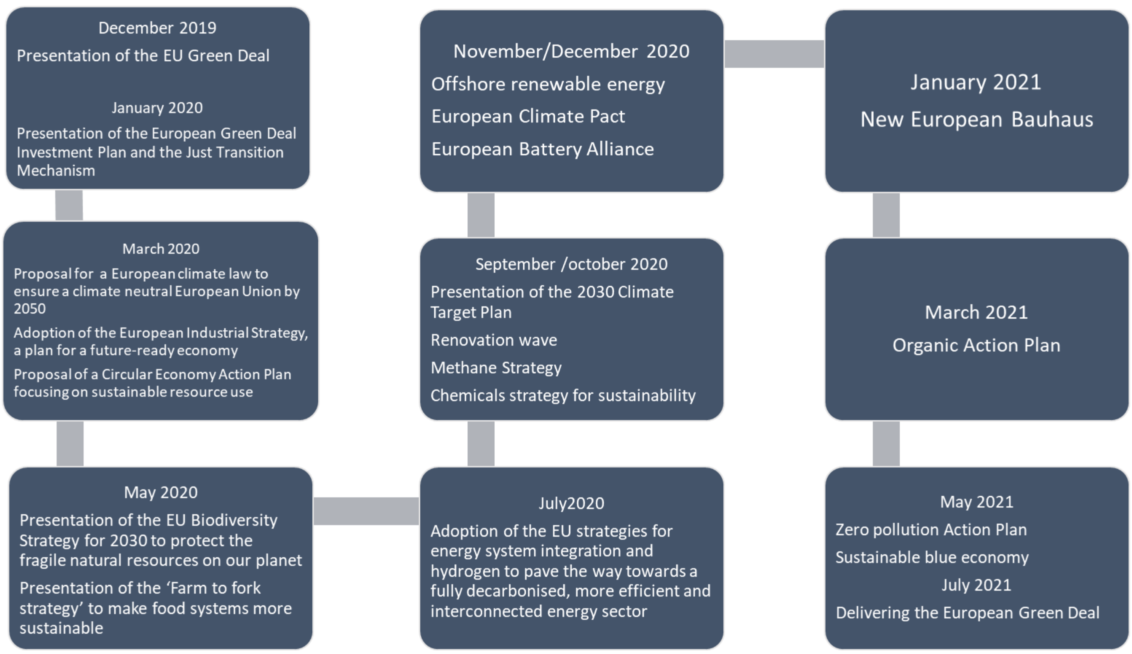

Figure 3. Timeline of the European Green Deal Actions

On July 2021, all 27 EU Member States adopted a package of proposal to reach carbon neutrality in 2050, setting the intermediate target of emissions reduction by 55% by 2030 than the levels of 1990. In the transport sector, have been defined the following goals:

- 55% reduction of emissions from cars by 2030
- 50% reduction of emissions from vans by 2030
- zero emissions from new cars by 2035

1.4 The new Circular Economy Action Plan

The new Circular Economy Action Plan was presented by the European Commission in March 2020, and it is part of the 50 actions of the European Green Deal road map.

It promotes "the transition of the EU towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate in the coming decade" (European Commission,2020b).

The aim is to enhance the actions presented in 2015 and to create a more sustainable, cleaner, and competitive Europe considering as fundamental elements the economic actors, the consumers, citizens and civil society organizations: this plan allows to implement CE globally, reaching the 2030 Sustainable Development Goals promoted by United Nations.

As is reported in the new Circular Economy Action Plan (European Commission, 2020b), the Commission established the following goals:

- improving product durability, reusability, upgradability and reparability, addressing the presence of hazardous chemicals in products, and increasing their energy and resource efficiency;
- increasing recycled content in products, while ensuring their performance and safety;
- enabling remanufacturing and high-quality recycling;
- reducing carbon and environmental footprints;
- restricting single-use and countering premature obsolescence;
- introducing a ban on the destruction of unsold durable goods;
- incentivising product-as-a-service or other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycle;
- mobilising the potential of digitalisation of product information, including solutions such as digital passports, tagging and watermarks;
- rewarding products based on their different sustainability performance, including by linking high performance levels to incentives.

The new CE Action Plan aims to revise legislations for different topics, that are:

- Electronics and ICT
- Batteries and vehicles
- Packaging
- Plastics
- Textiles
- Construction and buildings
- Food, water and nutrients.

This thesis is focused on electric mobility: for this reason, it is described only the part of the new Circular Economy Action Plan about batteries and vehicles.

The new CE Action Plan plans a new regulatory framework for batteries, considering both the Batteries Directive (Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators) and the European Battery Alliance, implementing the following actions:

- improving the collection and recycling of batteries, through instruction for customers and providing the valuable material recovery;
- promoting an alternative use of non-rechargeable batteries (if it is present);
- promoting sustainable requirements for batteries based on the carbon footprint of battery manufacturing, sourcing of raw materials, reusing, repurposing, and recycling.

Concerning vehicles, the Commission planned to revise the Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles, to promote circular solutions for end-of-life vehicles, establishing rules on mandatory recycled content for certain materials of components and improving recycling efficiency. Another goal is also to promote the "Sustainable and Smart Mobility", reducing raw materials consumption, using sustainable transport fuels, and reducing pollution by increasing occupancy rates.

All the revision of the legislations in the different sectors mentioned above have the target to reduce waste, promoting the recycling and, furthermore, another target is to reach a better separated waste: in fact, the Commission proposed to improve the separate waste collection systems (e.g., symbols for key waste types, accessibility of separate collection points, bin colours for different waste types). Another important goal are the creation of secondary raw materials market and the reduction of EU waste to third Countries. Implementing CE means reaching the carbon neutrality because if circularity actions will be implemented, they will have an important impact on climate change mitigation and adaptation, reducing the greenhouse gases emissions.

2 Circular economy application: the automotive sector

Measuring the CE application for an entire company is a relatively new topic: there is not a unique method, and the main idea of this thesis is going beyond the only measures of material flows and products, investigating all the aspects of a company that can be affected by CE.

In this chapter are implemented the principles of CE specifically for the automotive sector and are investigated methods to measure circularity for an entire company. At first, is presented an existing tool to measure circularity in a company, the Cyrculytics, developed by Ellen MacArthur Foundation; in the second part of this chapter, is developed a method to compare and measure the application of CE principles and performances considering the three global leader companies to produce commercial vehicles.

2.1 Cyrculytics: a tool to measure circularity

Cyrculytics is a tool developed by Ellen MacArthur Foundation to measure circularity (CE performances) into a company and it is aligned with the Ellen MacArthur Foundation's circular economy principles. The idea of Cyrculytics is to go beyond the measure of only material flows and products, considering the implementation of CE for different aspects and supporting company to monitor and improve the transition towards CE.

Cyrculytics adopts 36 indicators to measure the CE performances of an entire company: they are subdivided into 2 categories and 11 themes. Each category includes a certain number of themes, and each theme consist of quantitative and quantitative indicators, that lead to the final score (from A to E). In Table 1 are resumed the categories and the themes considered in Cyrculytics; for each theme are defined different indicators in form of questionnaire (the indicators are not reported in this work). Before the themes indicators, the company has to submit some general information about their activity (e.g., Company name, Region if business activity, Company description, Industry classification).

Table 1. Categories and themes of Cyrculytics (Ellen MacArthur Foundation, 2020).

	Category 1: Enablers	**Category 2: Outcomes**
Topic	It measures the critical aspects to enable company-wide transformation	It measures how circular a company is today
Themes	**Strategy and planning:** have you placed the circular economy at the heart of your strategy?	**Products and materials:** are the materials you procure and the products you design supporting a circular economy?
	People and skills: have you employed people with the skills required to transition to a circular business model?	**Services:** are the services you provide supporting a circular economy?
	Operations: have you invested sufficiently in your systems, processes, and assets to support the change?	**Plant, properties and equipment assets:** are you procuring and decommissioning your plant, property, and equipment assets in ways that support a circular economy?
	Innovation: are you innovating towards new circular economy products, systems or services?	**Water:** if you operate in a water-intensive industry, are you using water in a circular way?
	External engagement: are you promoting your circular economy initiatives and influencing those in your business sphere, such as clients or your supply chain?	**Energy**: are you procuring renewable energy and (if you are an energy provider) producing renewable energy to support a circular economy?
		Finance: if you are a financial institution, are you intentionally financing companies and projects that support a circular economy?

As it is shown in Table 1, Cyrculytics considers several aspects of implementation of CE through the different themes to have a complete view of application of CE, considering internal policies, investments, customers, supply chain, initiatives, water and energy use, products and service design outcomes, assets, and finance.

The logic of the method can be resumed as following (Ellen MacArthur Foundation,2020):

- each qualitative indicator response option is translated into a quantitative 'score' from 0 to 100;
- for each quantitative indicator is inserted a percentage input from 0 to 100;
- for each indicator is given a weight that collectively adds to 100 per theme and through these weights is calculated a weighted average score (from A to E) for each theme;
- for each theme is given a weight and these weights are used to calculate a weighted average score (from A to E), that is the score of each category;
- finally, for each category is given a weight of 50 to calculate the final score, that varies from A (highest score) to E (lowest score).

It is important to specify that the indicators displayed depends on the type of company and, consequently, the total number of indicators can be less than 36. In Figure 4 is shown the Cyrculytics' method logic.

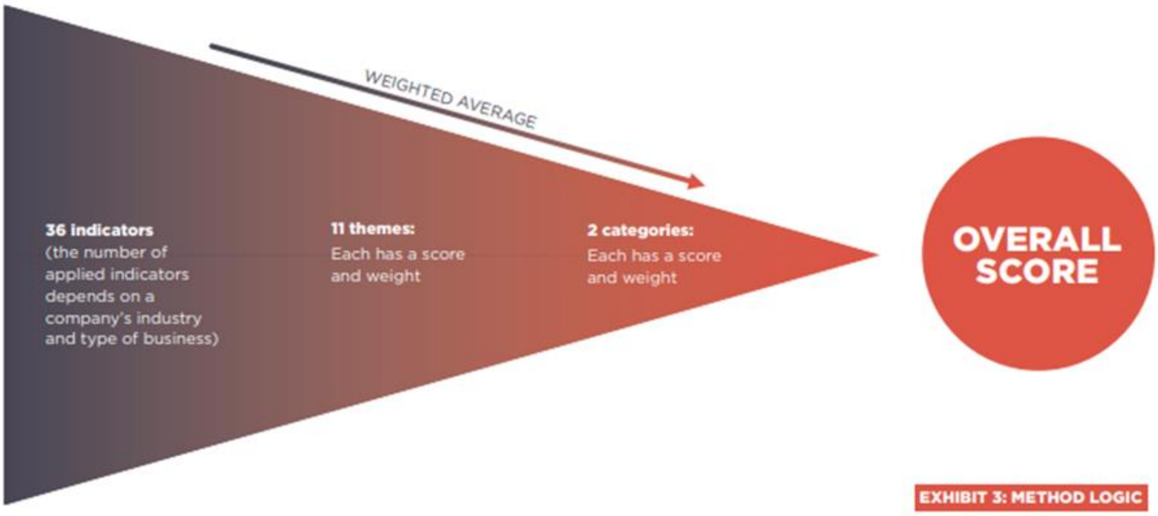

Figure 4. Scheme of Cyrculytics' method logic (Ellen MacArthur Foundation,2020).

Each company can take part to Cyrculytics through a platform used to submit responses. When the score is given by Ellen MacArthur Foundation through a scorecard, they are not published and not shared with third parties, unless the company authorizes the publication of the score: the idea is that the information submitted will be aggregated to multi-company averages in anonymous form to generate industry benchmarks.

As mentioned above, Cyrculytics can be applied for different type of companies, including automotive sector but the results are not public, and they cannot be employed for this thesis to compare the CE performances of different automotive companies. Consequently, in the next section is developed an alternative to method to perform the comparison.

2.2 CE measurement for the automotive sector

2.2.1 The CLEANS method development

This section presents a method, named CLEANS, to measure and evaluate circularity and sustainability of the automotive sector, considering specifically the commercial vehicles belonging to the three categories: vans, trucks, and buses. The acronym was obtained highlighting some letters of the key words of this method: CircuLar Economy sustAiNability aSsessment. The analysis was made comparing 3 different companies, considered as case studies, that operate at a global level: CNH Industrial, Daimler AG and Volvo group.

This method was developed following a top-down approach (Figure 5), considering and including the main concepts of CE to classify the data inventoried and evaluate the circularity and sustainability performances. The development of the here presented approach can be resumed into the following steps:

1. definition of the significant macro-areas considered in the assessment, using as reference the principles and the concepts of the European Green Deal and the Circular economy Action Plan. They are:
    - Environment performance indicators;
    - Actions;
    - Strategy;
    - Targets.
2. identification of the different categories to consider in the evaluation of CE and sustainability performances, which are:
    - air emissions;
    - water management;
    - waste management;
    - energy consumption;
    - CO_2 emissions;
    - resource conservation;
    - air emissions reduction;
    - protecting biodiversity;
    - digitalization;
    - sustainable design criteria;
    - improved environmental performances;
    - sustainable end-of-life management;
    - internal policy;
    - suppliers;
    - partnerships;
    - expenditure and investments;
    - Research & Developments;
    - Certifications;
    - carbon neutrality;
    - sustainable policy.

These categories were subdivided between the four different macro-areas defined above;

3. for each category were defined their boundaries, depending on the specific evaluation made for the entire company (i.e., considering the production phase and the relative connected activities, or for the final products) and then, for some categories, were formulated different aspects;
4. circularity and sustainability assessment of the case studies based on the public data listed in their 2020 Sustainability Report.

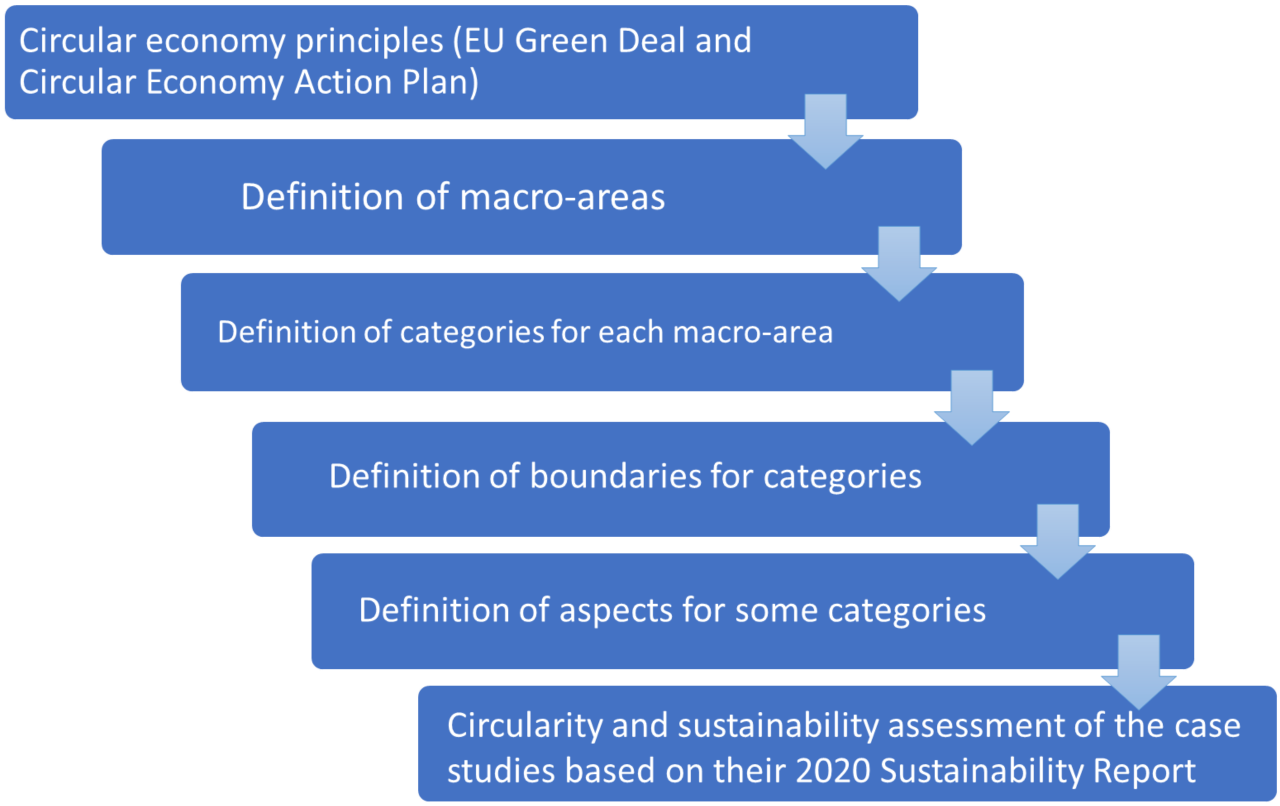

Figure 5. Concept of the CLEANS methodology applied to the top-down evaluation of the circularity of a company.

The aim of the CLEANS method is to measure and compare the circularity and sustainability performances of an automotive company, going beyond the material flows and products. The starting point of the method development were the European Green Deal and the New Circular Economy Action Plan, considering the main principles and targets. Consequently, were initially defined the four macro-areas, which reflect the fields of investigation to evaluate CE application, that are: "Environment performance indicators"; "Actions"; "Strategy" and "Targets". Then, for each macro-area, were identified the specific categories together with their boundaries, depending on the specific evaluation made for the entire company: if the assessment was performed considering the production phase and the relative connected activities, the specific categories were included into the "company" boundaries; if the assessment was performed for the final products (e.g., vehicles, engines), the specific categories were included into the "products" boundaries. The macro-areas, categories and boundaries were organized as following:

- "Environmental performance indicators" macro-area consists of the categories: air emissions; water management; waste management; energy consumption; CO_2 emissions. These categories were included into the "company" boundaries;
- "Actions" macro-area consists of the categories: resource conservation; air emissions reduction; protecting biodiversity and digitalization, which were included into the "company" boundaries. Furthermore, for this macro-area were defined the following categories, included into the "products" boundaries, that are: sustainable design criteria; improved environmental performances and sustainable end-of-life management.
- "Strategy" macro-area consists of the categories: internal policy; suppliers; partnerships; expenditure and investments; Research and Development; certifications. These categories were included into the "company" boundaries.

- “Targets” macro-area consists of the categories: carbon neutrality; resource conservation; sustainable policy. These were included both into “company” and “products” boundaries.

Then, for some categories, were defined specific aspects, on the basis of which the data were collected and the assessment was performed, comparing the different case studies.

Specifically, as regard the “Environmental performance indicators” macro-area, the formulated aspects are:

- VOC, NOx and SOx for “Air emissions” category;
- total water consumption for “Water management” category ;
- total waste generated; hazardous waste; waste disposed; waste recovered/recycled for “Waste management” category.

As regard the “Actions” macro-area (boundaries: company), the formulated aspects are:

- optimization of waste management; optimization of water management; optimization of energy consumption and use of renewable resources; reduction of raw materials use for “Resource conservation” category;
- reduction of GHG and CO_2 emissions; reduction of ozone depleting substances for “Air emissions reduction” category;
- index to evaluate biodiversity; initiatives for “Protecting biodiversity” category;
- specific actions for “Digitalization” category

As regard the “Actions” macro-area (boundaries: products), the formulated aspects are:

- environmental compatibility; recyclability/recoverability; elimination of critical substances; environmental impact reduction and improved efficiency during use phase for “Sustainable design criteria category”;
- emissions reduction; fuel consumption reduction for “Improved environmental performances” category;
- remanufacturing; recovery and recycling for “Sustainable end-of-life management” category.

As regard the categories of “Strategies” and “Target” was not considered necessary the definition of aspects to perform the evaluation.

In Figure 6 is reported the scheme of the macro-areas, categories and boundaries considered. The figures that include aspects for each category will be reported in the next sections.

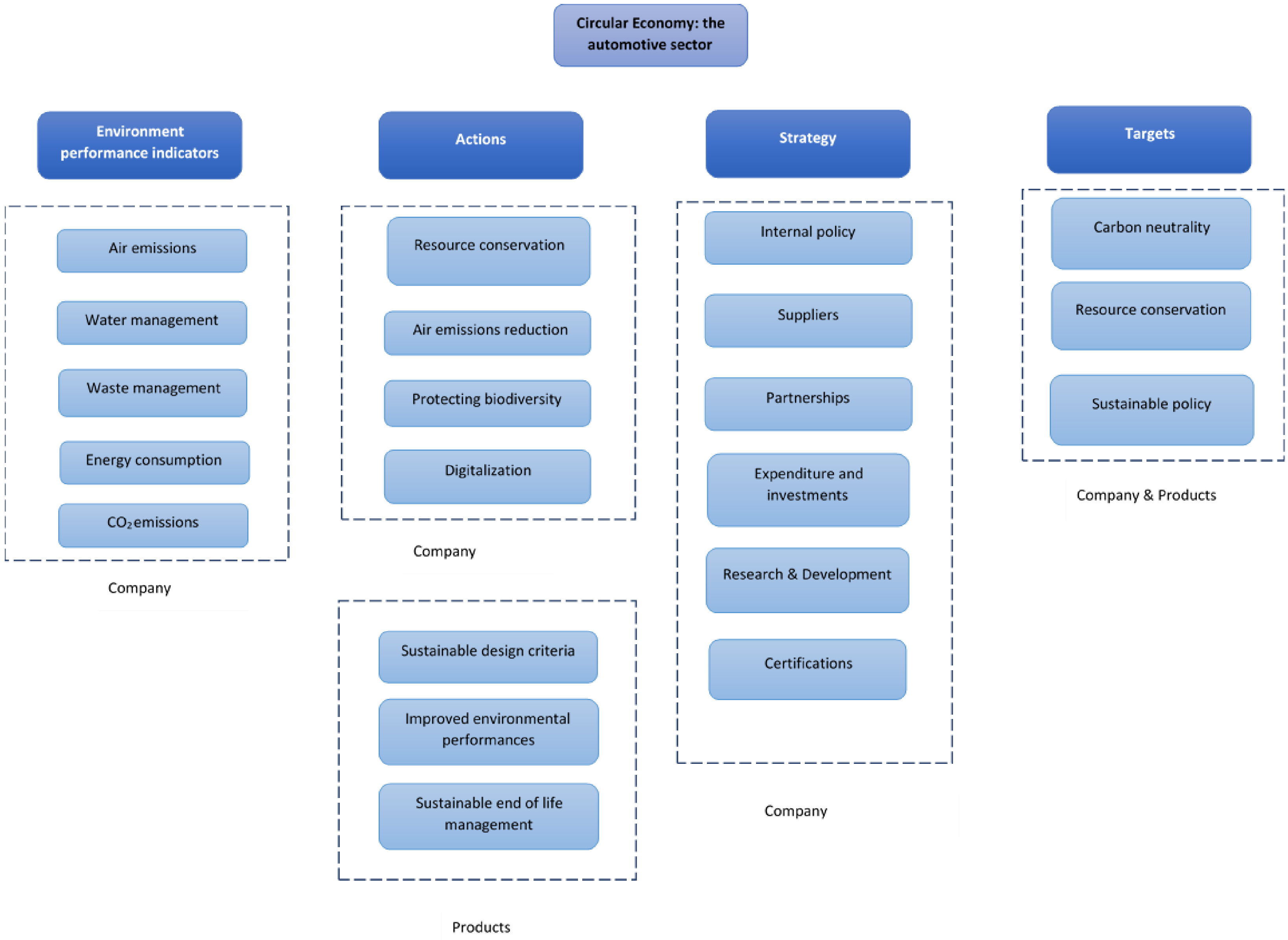

Figure 6. Macro-areas and categories considered in the CLEANS *methodology.*

The circularity assessment of the case studies was based on the public data listed in their 2020 Sustainability Report and, for that reason, the evaluation could not be completely exhaustive. The only exception is for CNH Industrial, the host of this thesis, for which were obtained some additional information through direct surveys. Furthermore, it is important to notice that, in this assessment, were considered only the information directly related to circularity and sustainability, excluding the other topics included in the Sustainability Reports, such as human rights, occupational safety and people engagement.

It is important to specify that each company's Sustainability Report follows the GRI Standards (Global Standards for Sustainability Reporting) and SASB Standards (Sustainability Accounting Standards Board) and it means that are reported the same information; however, the Sustainability Report does not have a standard form: consequently, the same aspects can be reported and organized differently and with a different level of detail for each company.

2.2.2 Companies: general information and markets

The general information related to the considered case studies (Table 2) showed that the three companies operate through different brands in several countries, and they all produce commercial vehicles (CVs). Regarding this segment, CNH Industrial and Daimler produce vans, trucks and buses, while Volvo group produces trucks and buses. Daimler also manufactures passenger vehicles through its brand Mercedes-Benz; CNH Industrial and Volvo group also produce construction vehicles and engines.

Focusing on CNH Industrial, the company supporting this thesis, it operates in 180 countries through 12 brands; it owns 66 manufacturing plants and 57 Research and Developments (R&D) centres. The global footprint of CNH industrial is shown in Figure 7. CNH Industrial is specialized on production commercial and specialty vehicles, agriculture vehicles, construction vehicles and powertrain (through the brand FPT).

Table 2. General information of investigated companies

Company	Segments	Products	Location of operations	Brands
CNH Industrial	Commercial & Specialty vehicles (C&SV)	Vans, trucks, buses, firefighiting vehicles, defense vehicles, quarry and construction vehicles, C&SV components	North America, Europe, South America, Rest of the world (Australia, China, India, South Africa, Uzbekistan)	CASE IH Agriculture, Steyr traktoren, CASE Construction, New Holland Agriculture, New Holland Construction, IVECO, IVECO ASTRA, IVECO BUS, Heuliez BUS, IVECO Defence vehicles, FPT
	Agriculture	Vehicles (e.g. tractors, harvesters, row crop, cultivators, ploughs, balers), agriculture components and equipment		
	Construction	Vehicles (e.g. excavators, forklifts, skid steer loaders), construction components and equipment		
	Powertrain	Engines, transmissions, drive shafts		
Daimler AG	Passenger vehicles	Cars	North America, Europe, South America, Africa, Asia, Australia & Pacific	Mercedes-Benz, Mercedes-amg, Mercedes- Maybach, Mercedes-EQ, Mercedes-me, Freightliner, Mitsubishi-FUSO, Western star, Thomas buily buses, Bharatbenz, Setra, Mercedes-Benz bank, Mercedes-Benz financial services, Daimler truck financial, Athlon
	Commercial vehicles	Vans, trucks, buses		
Volvo Group	Commercial vehicles	Trucks, buses	North America, Europe, South America, Asia, Africa & Oceania	Volvo, Volvo Penta, Terex trucks, Renault Trucks, Prevost, Nova bus, Mack, Arquus
	Construction	Excavators,haulers, construction equipment		
	Marine and industrial engines	Marine generator sets, propulsion,auxiliary		

Figure 7. Global footprint of CNH Industrial (CNH Industrial, 2021)

Because the three companies have in common the trucks and buses production, the market relatively only to these vehicles was considered to perform a consistent analysis. All the three companies sold less vehicles in 2020 than 2019 due to the COVID pandemic.

CNH Industrial sold in 2020 a total of 141,874 trucks and buses (132,095 trucks and 9,779 buses); in 2019 the Company sold a total of 153,780 trucks and buses (143,388 trucks and 10,392 buses). In Figure 8 is reported the total trucks and buses sales share for 2020: most units are sold in Europe, with a 81% share.

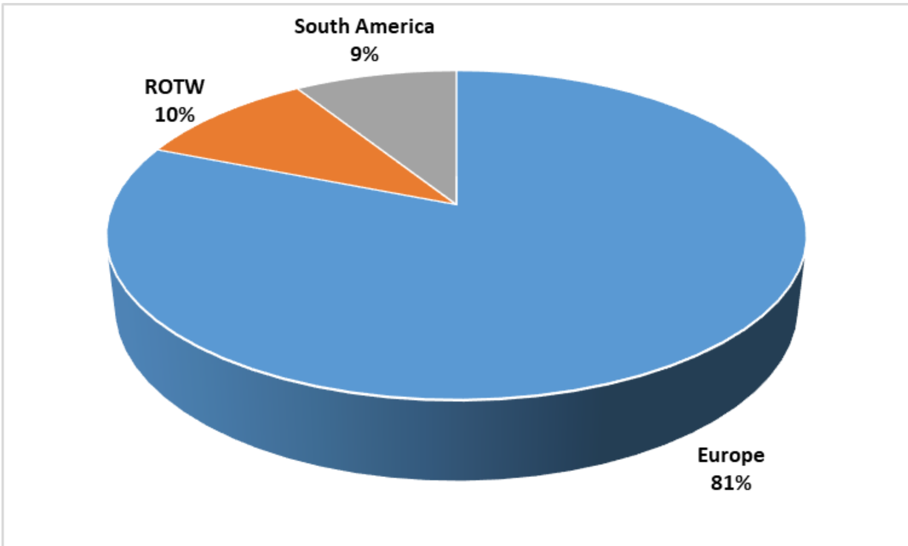

Figure 8. CNH Industrial trucks and buses sales share 2020

Daimler sold in 2020 a total of 378,400 trucks and buses (358,300 trucks and 20,100 buses); in 2019 the Company sold a total of 521,100 trucks and buses (488,500 trucks and 32,600 buses). Volvo Group sold in 2020 a total of 173,056 trucks and buses (166,841 trucks and 6,215 buses); in 2019 the Company sold a total of 242,500 trucks and buses (232,769 trucks and 9,731 buses).

In Figure 9 are reported CNH Industrial, Daimler and Volvo trucks and buses sales share for 2020 and it is possible to notice that the geographic areas of the market are different for the three companies. As regard trucks, for CNH Industrial most sales occurred in Europe (about 80%), followed by a share of 9% in South America and 10% in the rest of the world (ROTW); for Daimler, most sales occurred in North America (39%),followed by Asia (27%) and Europe (17%) (Daimler, 2020a); for Volvo group,most sales occurred in Europe (48%), followed by North America (19%), Asia (16%), South America (11%) and Africa and Oceania (6%) (Volvo group, 2020).Regarding buses, for CNH Industrial, the share was 14% in South America and 7% in the ROTW; for Daimler, the market is different than trucks, in fact most of sales occurred in Europe (37%) and Latin America (35%) (Daimler, 2020a);also for Volvo group the buses market is different than trucks, in fact most sales occurred in North America (26%) and in Europe (25%) (Volvo group, 2020).

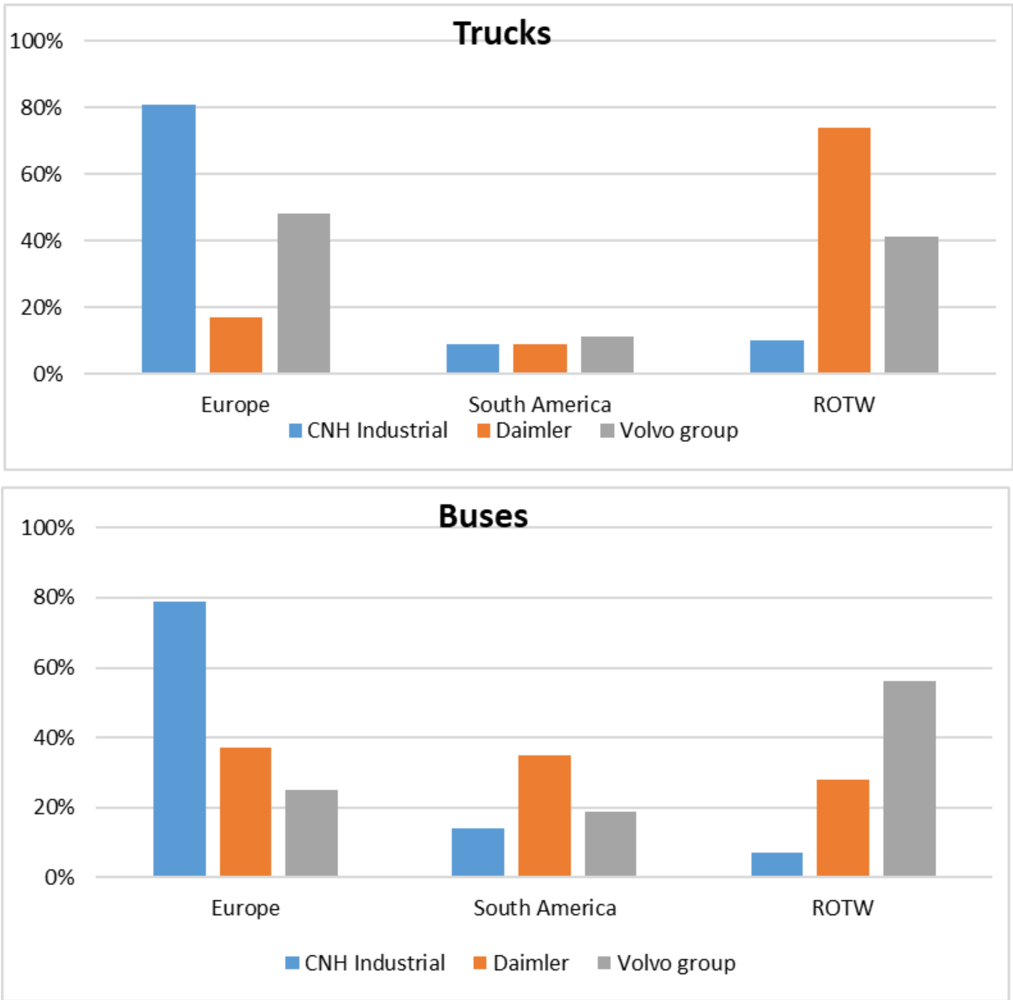

Figure 9. CNH Industrial, Daimler and Volvo trucks and buses sales share 2020

2.2.3 Environmental performance indicators

The first category considered and examined is called “Environmental performance indicators” to evaluate and compare quantitatively the entire companies’ circularity. This category includes the following environmental categories, examined at a company level (boundaries: Company):

- air emissions
- water management
- waste management
- energy consumption
- CO_2 emissions

For these categories, were defined different aspects (Figure 10), on the basis of which the three case studies performances were compared.

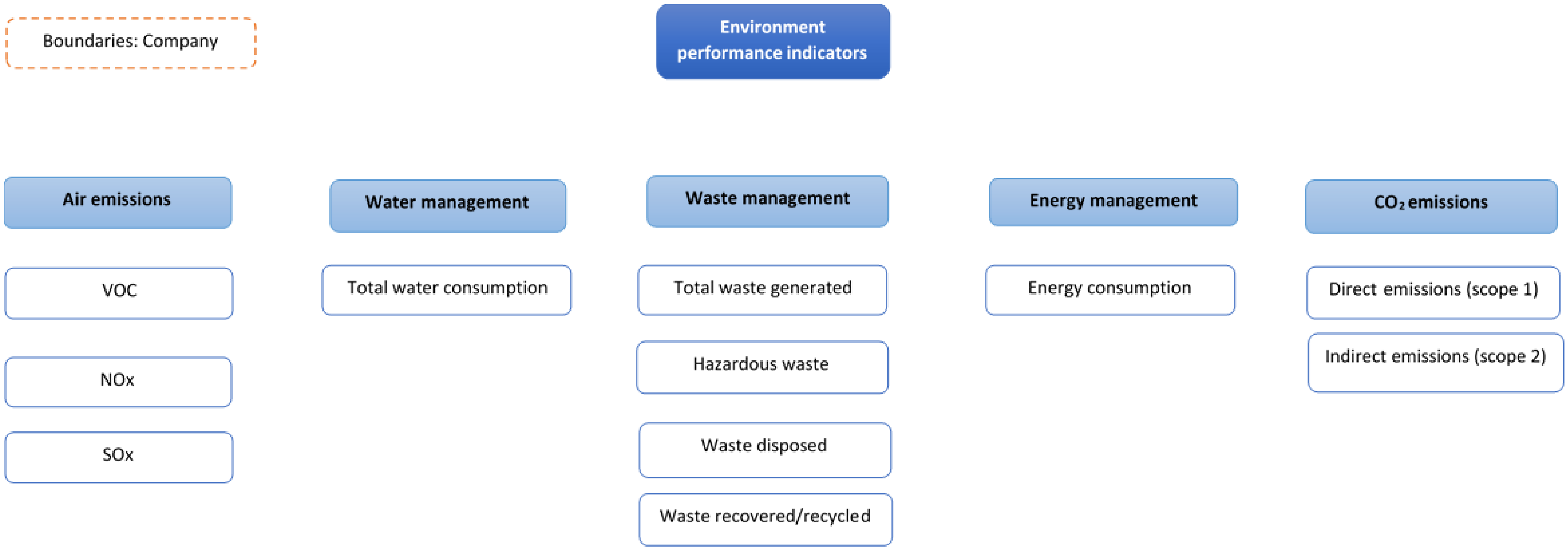

Figure 10. Defined aspects (white blocks) for each category of the environment performance indicators macro-area

Method

The evaluation was structured in the following steps:

1. **Data inventory**: collection of the quantitative data for all the aspects from the three companies' 2020 Sustainability Reports. In the Appendix are reported the complete data, also including quantities on aspects that are not considered for the evaluation.

2. **Key performance indicators (KPIs)**: in each Sustainability Report are defined KPIs relatively to the data collected, but, for each company, they are different and it is not possible to compare them consistently. As an example, CNH Industrial's KPIs are calculated respect to the total number of manufacturing hours, defined as the hours of presence of hourly employees within the manufacturing scope required to manufacture a product; Daimler's KPIs are calculated respect to the number of vehicles produced for category; Volvo group's KPIs are calculated over net sales. For that reason, the CLEANS method defined alternative KPIs, obtained through the normalization of the data collected in the data inventory over the number of trucks and buses (T&B) sold in 2020. As mentioned before, T&B were considered as the only CVs because they are the only vehicles produced by all the three companies. The defined KPIs were calculated through the following equation:

$$KPI = \frac{quantity}{T\&B\ sold\ in\ 2020}$$

   The trucks and buses sold quantities in 2020 for the three companies are:
   - CNH Industrial: 141,874 units
   - Daimler AG: 378,400 units
   - Volvo Group: 173,056 units

The KPIs were calculated for the defined aspects, expressing the quantities in the same unit of measurement.

In Table 3 are reported the unit of measurements of the comparable quantities. The KPIs were calculated dividing the numerical quantities reported in Table 3 over the number of T&B sold in 2020. As regard air emissions, KPIs were calculated for VOC, NOx and SOx; as regard water management was compared the total water consumption; as regard waste management, KPIs were calculated considering the quantities of total waste generated, hazardous waste, waste disposed and waste recovered/recycled (the recovery and the recycling are considered aggregate because CNH Industrial reports only waste recovery data, Daimler only waste recycling data and Volvo group reports both); regarding energy consumption, the KPIs were calculated considering as quantity the total energy consumption; concerning CO_2 emissions, KPIs were evaluated considering the direct and indirect emissions.

Table 3. Unit of measurements for the aspects considered by the three companies

	CNH Industrial	Daimler	Volvo group
Air emissions	VOC (Kg)	VOC (tons)	VOC (tons)
	NOx (tons)	NOx (tons)	NOx (tons)
	SOx (tons)	SO2 (tons)	SOx (tons)
Water management	Total water consumption (thousand of m^3)	Total water consumption (thousand of m^3)	Total water consumption (Mega-liters)
Waste management	Waste generated (tons)	Waste generated (thousand of tons)	Waste generated (tons)
	Hazardous waste (tons)	Hazardous waste (thousand of tons)	Hazardous waste (tons)
	Waste disposed (tons)	Waste disposed (tons)	Waste disposed (tons)
	Waste recovered/recycled (%)	Waste recovered/recycled (%)	Waste recovered/recycled (%)
Energy consumption	Total energy consumption (GJ)	Total energy consumption (GWh)	Total energy consumption (GWh)
CO_2 emissions	Direct emissions- scope 1 (tons)	Direct emissions- scope 1 (tons)	CO2eq emissions scope 1 (thousand of tons)
	Indirect emissions (scope 2) – market-based (tons)	Indirect emissions (scope 2) – market-based (tons)	CO2eq emissions scope 2- market based (thousand of tons)

3. **Environmental performances evaluation**: through the obtained KPIs calculation it is possible to compare, consistently, the environmental performances of the three companies.

Results

In this section are presented the obtained values of KPIs for three companies to evaluate the companies' environmental performances and to make the comparison. The Table that contains all the results is reported in the Appendix.

In Figure 11 are reported the obtained values for air emissions: as regard VOC emissions, the highest value is obtained for Daimler (17.13 Kg VOC/ T&B sold in 2020), the lowest value is obtained for Volvo Group (7.75 Kg VOC/ T&B sold in 2020) and for CNH Industrial was calculated a value of 9.24 Kg VOC/ T&B sold in 2020; regarding NOx, also in this case, the highest value was calculated for Daimler (3.57 Kg NOx/ T&B sold in 2020) and the lowest values is reached by Volvo Group (1.18 Kg NOx/ T&B sold in 2020), CNH Industrial values is between the other two, with 2.16 Kg NOx/ T&B sold in 2020; concerning SOx, the highest value is reached by CNH Industrial (0.27 Kg SOx/ T&B sold in 2020), the lowest value is obtained for Volvo Group (0.032 Kg SOx/ T&B sold in 2020) and for Daimler is obtained a value of 0.106 Kg SOx/ T&B sold in 2020. It is possible to say that, as regard air emissions, Volvo group presents the lowest KPI values in all cases. It can be noticed that as concern VOC emissions, Daimler presents a KPI that is almost the double than the other two; the KPI calculated for SOx of Volvo group is much lower than the other.

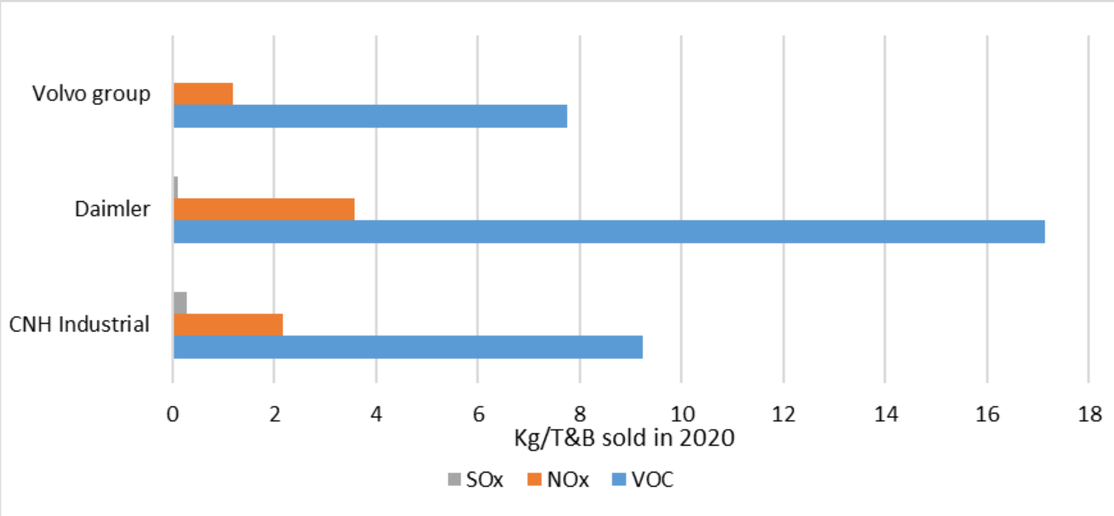

Figure 11.Air emissions KPIs-results

In Figure 12 are reported the obtained KPI values for total water consumption: it is possible to notice that for Daimler and Volvo Group is obtained a similar value (31 m^3/ T&B sold in 2020 for Daimler and 30 m^3/ T&B sold in 2020 for Volvo Group) but for CNH Industrial is obtained a KPI of 9 m^3/ T&B sold in 2020, a value that is about one third of the other two. Therefore, it is possible to say that CNH Industrial has the most efficient water management.

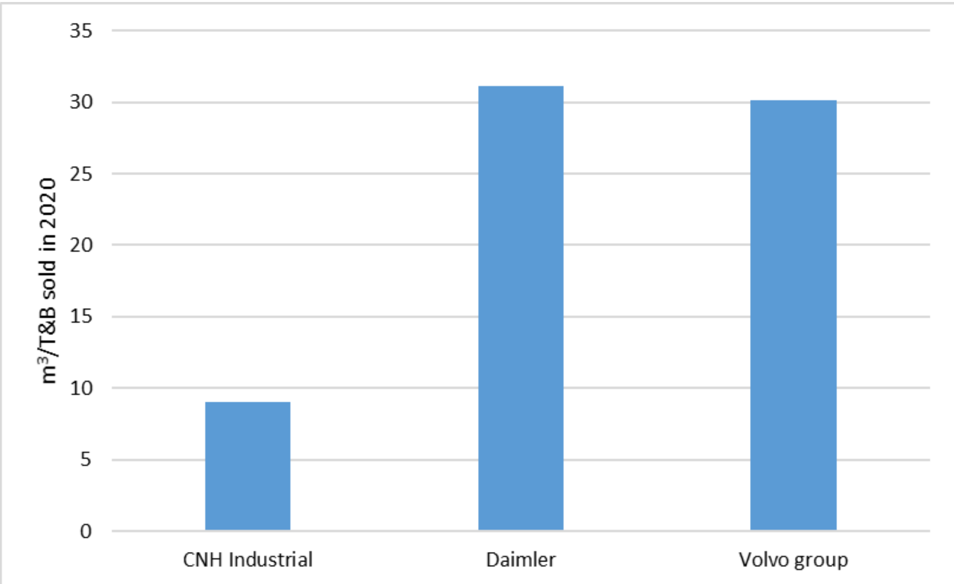

Figure 12. Total water consumption KPI

In Figure 13 are represented the obtained KPIs values as concern the waste management: as regard total waste generated, Daimler presents the highest value, with 2,708.8 Kg/T&B sold in 2020, for Volvo group is obtained a KPI of 1,609 Kg/T&B sold in 2020 and for CNH Industrial is obtained the lowest value, that is 1,225.3 Kg/T&B sold in 2020; as concern the waste disposed, the lowest value is obtained for Daimler (63.4 Kg/T&B sold in 2020), the highest value is obtained for Volvo (106.1 Kg/T&B sold in 2020) and for CNH Industrial is obtained a value of 75 Kg/T&B sold in 2020; as regard the hazardous waste production, CNH Industrial is the most efficient, with a KPI of 102.8 75 Kg/T&B sold in 2020, Volvo group presents the highest value of 299 Kg/T&B sold in 2020 and Daimler is in the middle position with 200 Kg/T&B sold in 2020. As regard the waste recovering and recycling, as explained above, these two practices were considered aggregated and the KPIs values were obtained dividing the waste recovered or recycled over the T&B sold in

2020. For Daimler, that reports only the % of recycling, is obtained a KPI of 2,654.6 Kg of recycled waste/T&B sold in 2020; for Volvo Group, that in the Sustainability Report, provides a the percentage of waste recycled, composted or destined energy recovery, is obtained a KPI of 1,496 Kg of waste recycled, composted or destined to energy recovery/ T&B sold in 2020; for CNH Industrial, that provides only the % of recovered waste, the KPI obtained is 1,139 Kg of waste recovered/ T&B sold in 2020. In conclusion, as regard this category, it is possible to say that Daimler applies the best management of waste, because it reaches the highest KPI value for recovery/recycling: it means that that the company promote alternative management of waste, since the percentage of recycling is the 98%.

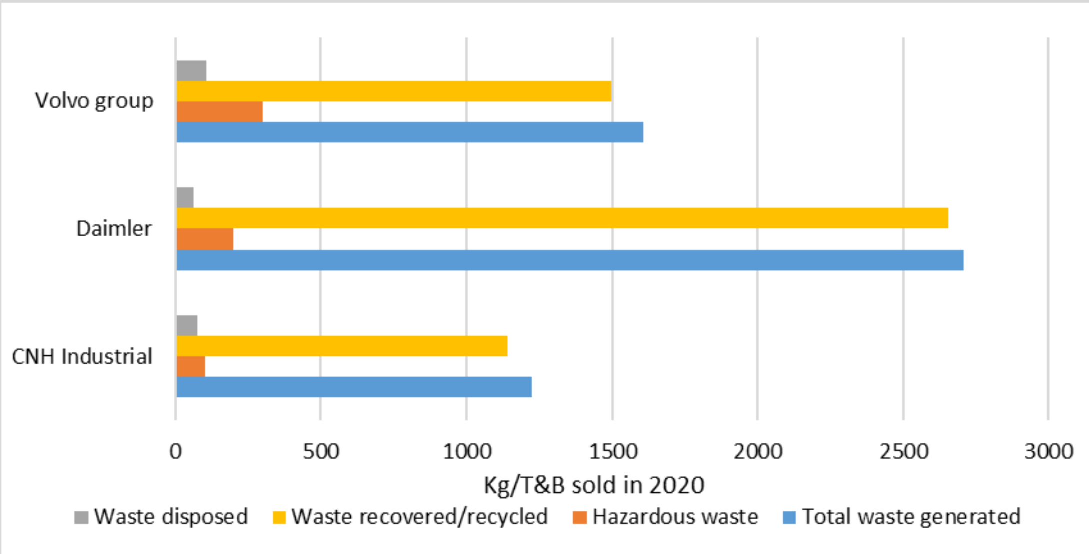

Figure 13. Waste management KPIs

In Figure 14 are reported the KPI values obtained for the energy consumption: the highest value is obtained for Daimler, with a KPI of 26 MWh/T&B sold in 2020; the values for CNH Ind. And Volvo are almost the same (10 MWh/T&B sold in 2020).

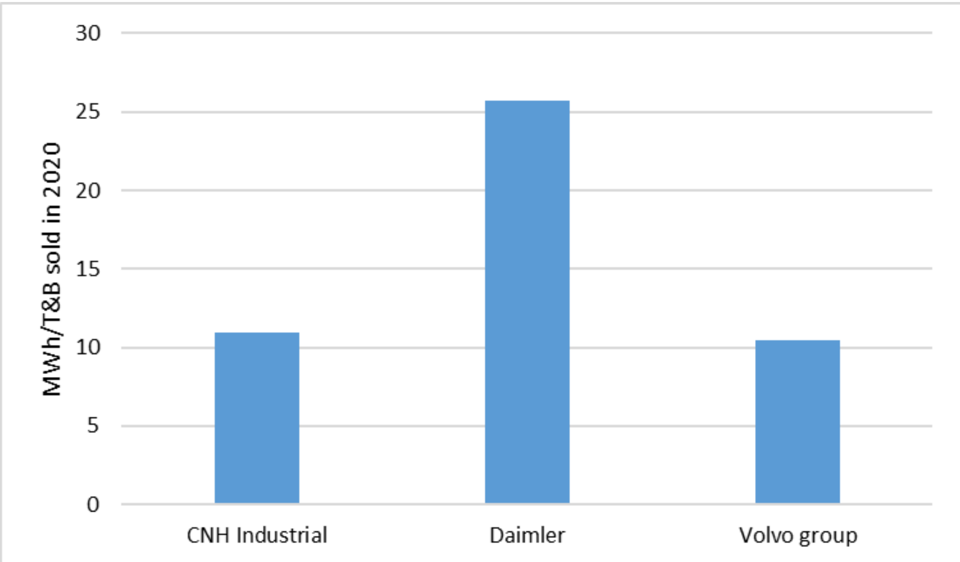

Figure 14. Energy consumption KPI

In Figure 15 are presented the obtained values for CO_2 emissions: the highest values are reached by Daimler both for direct and indirect emissions (direct: 2.71 tons/T&B sold in 2020; indirect: 2.74 tons/T&B sold in

2020); for Volvo and CNH Ind presents is obtained a similar value for direct emissions (1 tons/T&B sold in 2020 for Volvo and 1.1 tons/T&B sold in 2020 for CNH Ind.); concerning the indirect emissions, the lowest value is reached from Volvo (0.561 tons/T&B sold in 2020) and for CNH Ind. is obtained a KPI of 0.93 tons/T&B sold in 2020. In conclusion, it is possible to notice that Daimler presents the highest CO_2 emissions and the other two are almost at the same level.

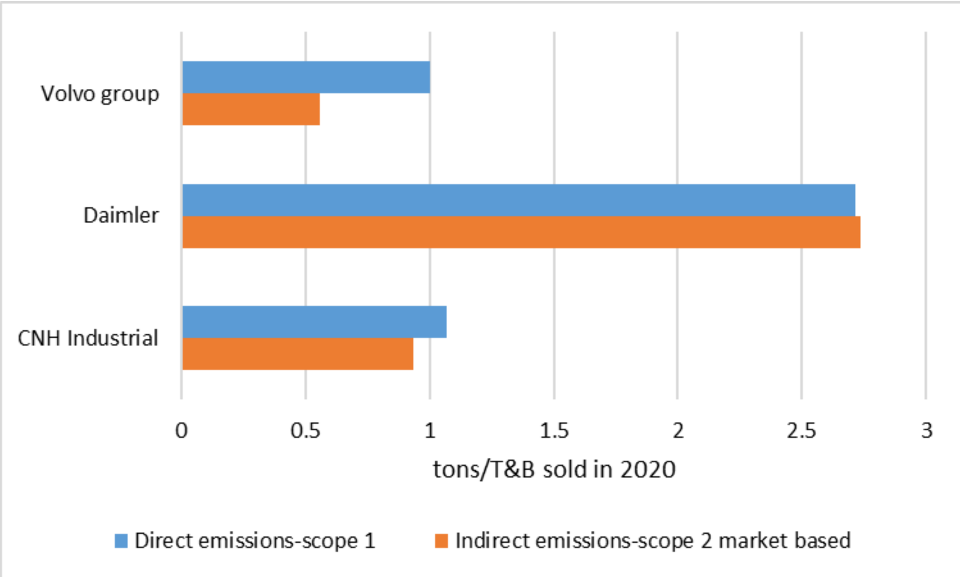

Figure 15. CO2 emissions KPIs

To summarize the results obtained for the different aspects, an overall performance report was compiled according to the following legend:

- Position 1: most efficient company for that specific aspect. It means that the company presents the lowest KPI value for the specific aspect. The only exception is for the waste recovered/recycled, in which the most efficient company presents the highest KPI value;
- Position 2: the company presents a KPI for a specific aspect that is in the middle between the companies in the first and in third positions;
- Position 3: less efficient company for that specific aspect. It means that the company presents the highest KPI value for the aspect (or the lowest in the case of waste recovered/recycled).

If the companies' KPI values for a specific aspect differed less than 0.5, they were considered at the same positions.

In Figure 16 are represented the companies' positions for the specific aspects. As regard air emissions, the most efficient was always Volvo Group; regarding the total water consumption, the company that presented the lowest KPI values was CNH Ind; as regard waste management, CNH Ind. occupied the first position for the total waste generated and hazardous waste, Daimler occupied the first positions for waste disposed and waste recovered/recycled; concerning the energy consumption, CNH Ind. was the most efficient; concerning CO_2 emissions CNH Ind. and Volvo occupied the first position both for direct and indirect emissions.

In conclusion, it is possible to say that CNH Ind. and Volvo both scored the first positions for six aspects; Daimler occupied the first position only for two aspects.

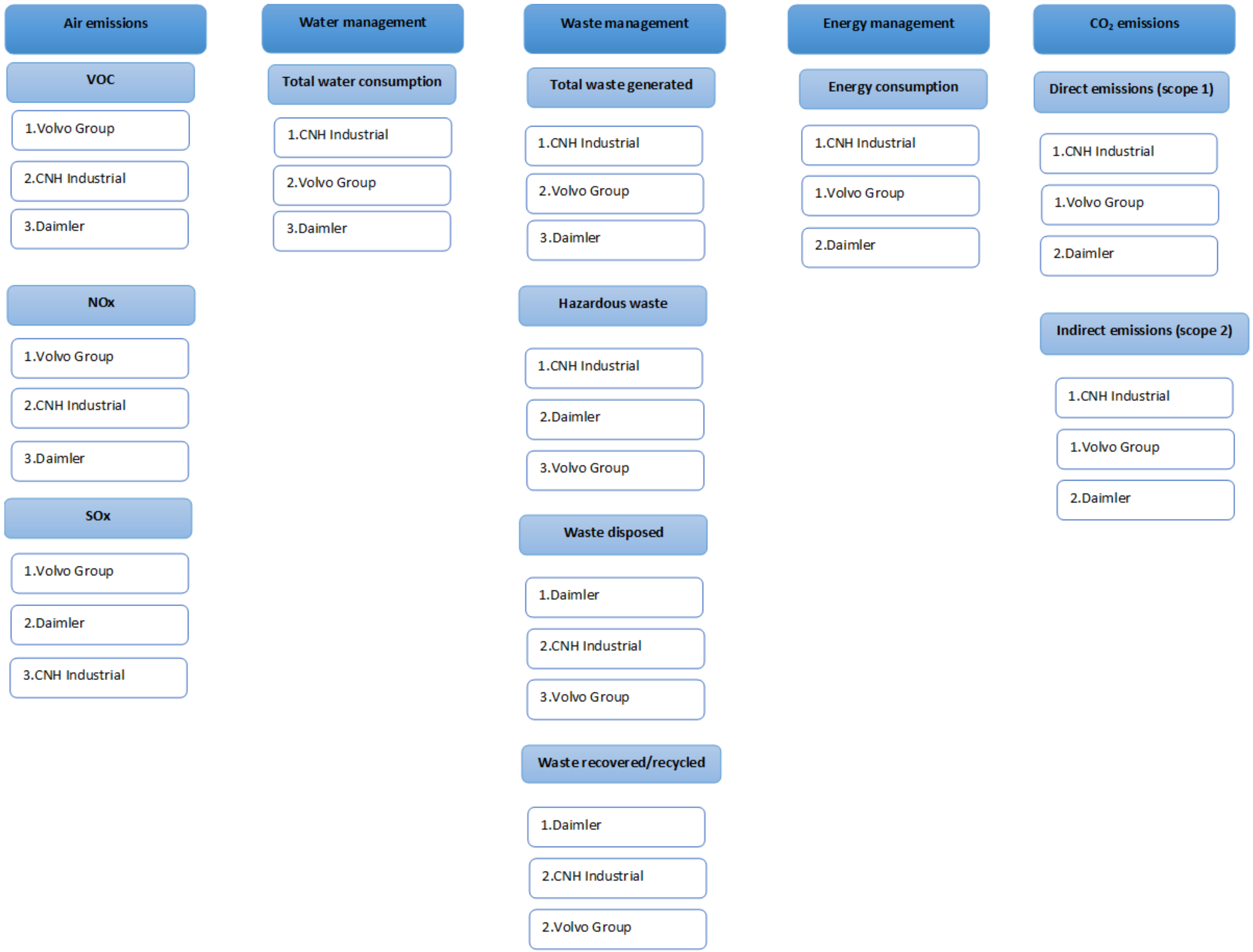

Figure 16. Environmental performance indicators-company positions

After the KPIs evaluation for all the aspects, the aggregated values for the categories were calculated: all the aspects are summed to obtain a unique value for each category. The only exception was for the "Waste management" category, that was obtained adding all the KPI values of the considered aspects and subtracting the KPI values for the waste recovered/recycled. The aggregated KPI values obtained are represented in Figure 17: the highest values were obtained for Daimler in all categories. It can be explained through the fact that the market for this company is different than the other two; in fact, considering the sales of 2020, it was reached a number of 378,400 units for trucks and buses and 378,400 for the vans: considering also the vans and calculating the KPI values on the number of trucks, buses and vans sold in 2020, the KPI values for Daimler halved (Figure 23). Considering the single categories, as air emissions, energy management and CO_2 emissions, CNH Ind. and Volvo reached almost the same results; as regard water management, for CNH Ind. was calculated the less aggregated KPI, Volvo and Daimler presented about the same value; regarding waste management, CNH Ind. was at the highest position (with the less aggregated KPI), followed by Daimler and then by Volvo.

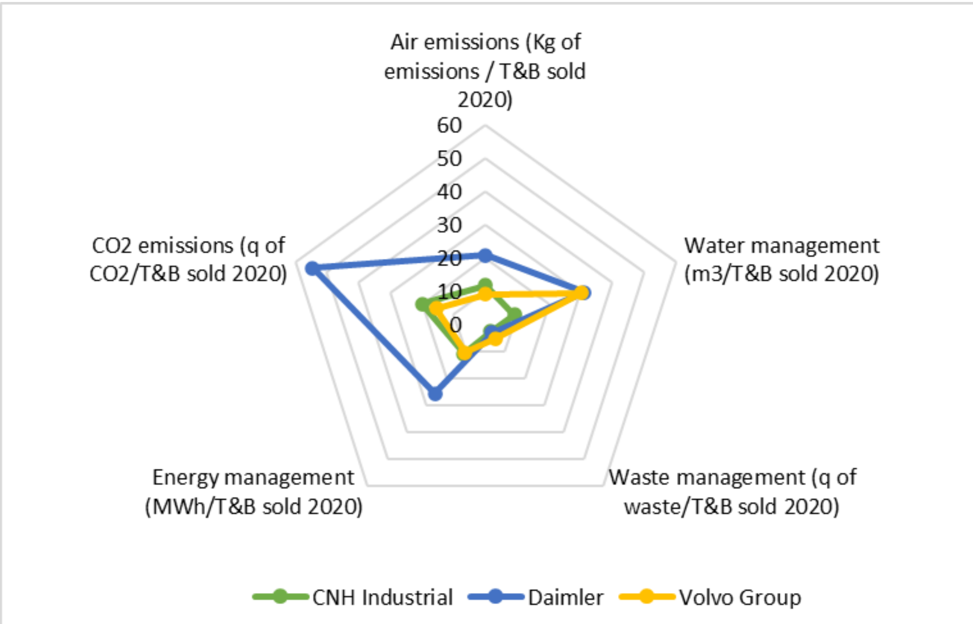

Figure 17. Aggregated KPIs for each category

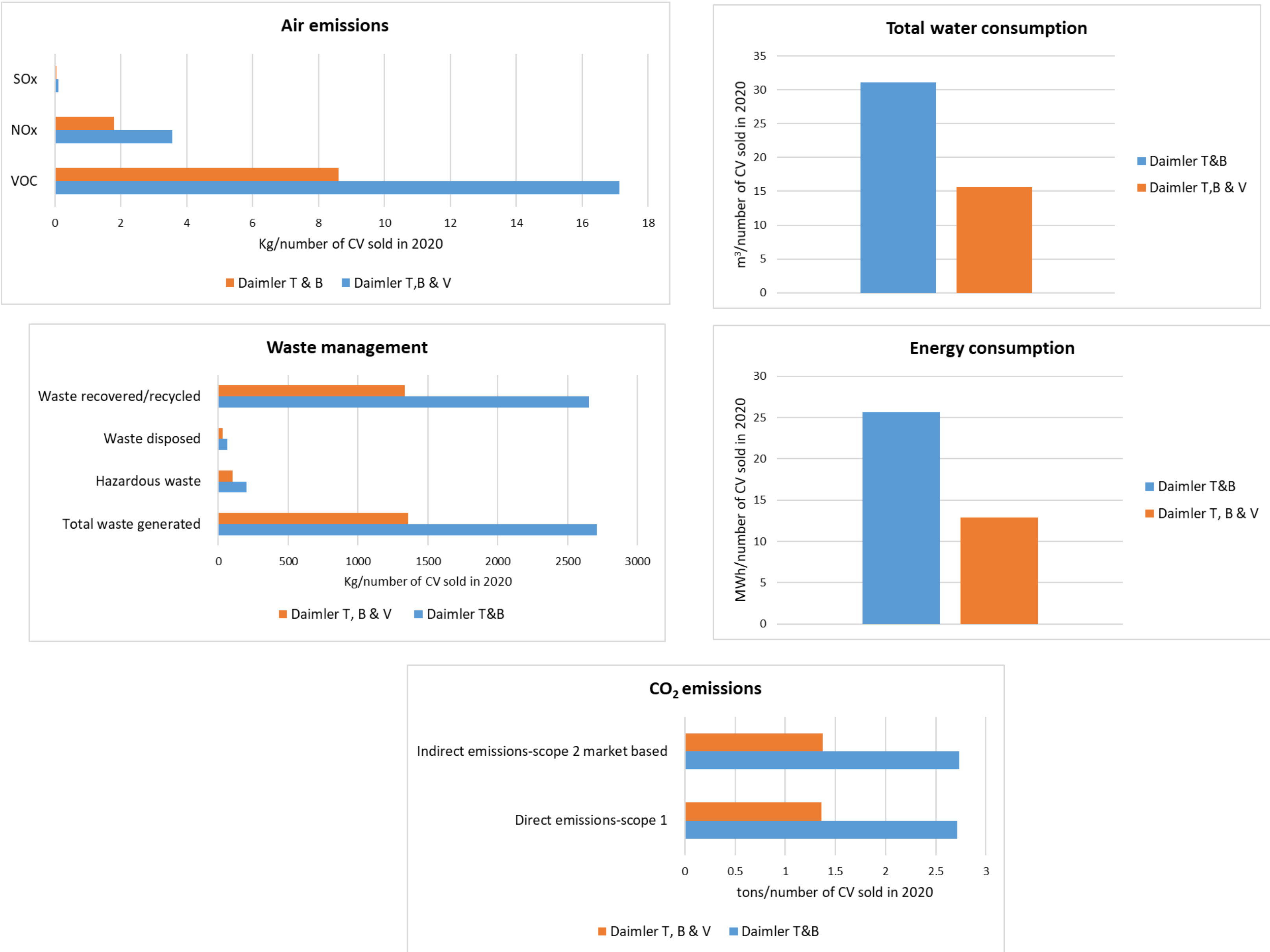

Figure 18. KPIs calculation for Daimler considering T&B sold in 2020 and Trucks, Buses and Vans sold in 2020 (T, B &V).

2.2.4 Actions

2.2.4.1 Actions (company level)

Method

Considering CE principles, at a company level were evaluated the actions that lead to resource conservation, air emissions reduction, biodiversity protection and digitalization as regard the various activities conducted by the company, such as production and distribution. Digitalization is a fundamental element to integrate CE principles and it includes all actions that involve technology solutions that allow, for example, to reduce environmental impacts or to improve efficiency of the processes. For each category, were defined the aspects to collect and compare information (Figure 19). Only for digitalization are not defined common aspects because are reported directly the actions implemented by the three companies.

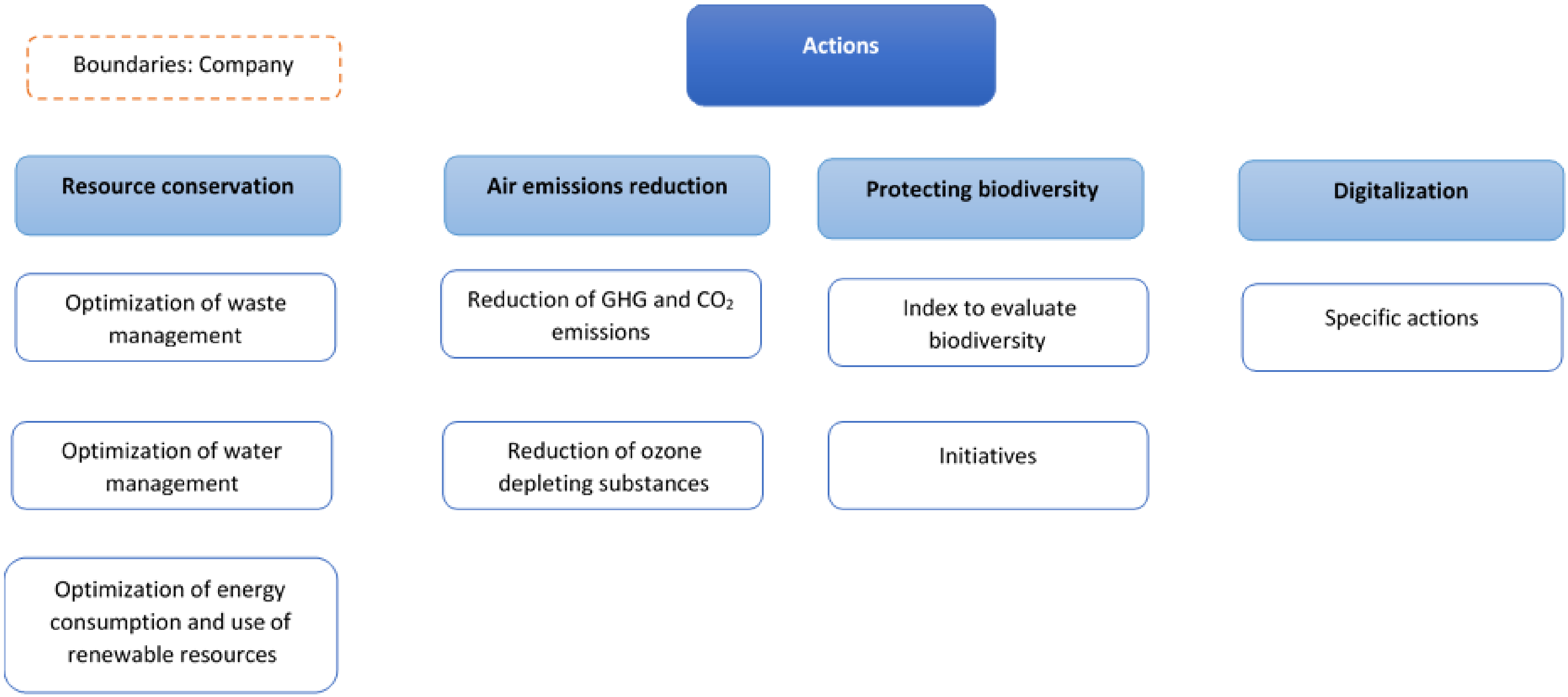

Figure 19. Categories and aspects considered for actions macro-area (boundaries: Company).

For each aspect defined in Figure 19, the data inventory is in the Appendix.

Results

As regard the “Resource conservation” in the Appendix are reported the actions implemented by companies to preserve natural resources and consequently to reduce company’s environmental impacts. The information were collected from Sustainability Reports 2020 and for each action is reported one example of application. It is possible to notice that all companies make efforts to optimize waste, water and energy management and to use less volumes of raw materials: for example both CNH Industrial and Daimler work on packaging to reduce waste, adopting reusable materials and metal containers instead of wooden packaging; to reduce energy consumption LEDs are adopted and it is promoting the use of renewable resources; regarding water reduction, CNH Industrial and Daimler adopt close-loop system to recycle water; to use less volume of raw materials, all the three companies try to use recyclable materials and secondary raw materials for products.

Concerning “Air emissions reduction”, all the three companies try to control the energy consumption, reducing GHG emissions and, in particular, CO_2 emissions; both CNH Industrial and Daimler reduce the ozone-depleting substances; Volvo group and CNH Industrial operate also in the logistic area, adopting more efficient transport modes (e.g., intermodal transport).

As regard “Protecting biodiversity” category, CNH Industrial adopts the Biodiversity Value Index (BVI) to measure plants’ impacts on protected areas. The company adopts also the Biodiversity Risk Evaluation method (BRE), that is articulated in three steps: the first is the evaluation of the protected areas, areas with high biodiversity value and protected species available in that region; the second step is the impact of plant activities on biodiversity, in terms of use of resources and polluting emissions and the third step is the evaluation of the level of environmental consciousness among plant employees and stakeholders in the region (CNH Industrial,2020). Daimler also adopts an index, the Biodiversity Index (BIX) to evaluate the impact of plants to biodiversity and, as regard initiatives, the company also creates semi-natural habitats at plants (e.g., for local birds and insects). CNH Industrial is studying at Burlington Plant (USA), through the participation at Citizen Science Program, the number and the migrations pattern of monarch butterflies. As regard Volvo Group, are not provided information about biodiversity in the Sustainability Report 2020.

Concerning “Digitalization”, it is a fundamental element to implement CE principles and allows to obtain a system that is more sustainable, efficient, and transparent towards customers and suppliers. Technology is one of the keys to reduce impacts and emissions and this transition can involve both the entire company and final products. CNH Industrial developed the Service Delivery Platform (the Company’s own ‘cloud’) that allows access to specific services and stores operational data for all connected machines, delivering advantages in: agriculture, through the collection of real-time data for better informed decision-making; in construction, enhancing productivity and reducing emissions; in commercial vehicles, in which IVECO customers have access to an innovative algorithms that cut fuel consumption by up to 15% and also reduce carbon footprints and total cost of ownership; in engines, because customers can depend on ever-more personalized services that improve efficiency and extend engine life (CNH Industrial, 2020). Daimler and Volvo group are also implementing technology: in particular, Volvo group implemented a new digital service, called “Efficient Load Out” that enables the connection of trucks and excavators, which increase efficiency and reduces transport emissions because, utilizing the system, the excavator operators receive a notification when there is a truck nearby for loading (Volvo group, 2020).

2.2.4.2 Actions (products level)

Method

In this section are reported the actions implemented by the three company to the final products, that are vehicles and engines. The categories analysed are:

- Sustainable design criteria
- Improved environmental performances
- Sustainable end of life management

As mentioned in the previous chapter, CE principles are refurbishment, reuse, recyclability and recovering, thinking in a circular way from the design phase. Therefore, the aim is to produce a final product using as few virgin materials as possible and considering the performances during use phase: in the case of a vehicle, it is important to reduce as much as possible the emission of pollutants in the atmosphere. Road vehicles in fact are large source of greenhouse gases emissions and in particular of CO_2 In addition, it is important to manage the end of life of the vehicles in a circular optics, promoting the refurbishment, recyclability and recovery. All these actions can contribute to the decarbonization target promoting by EU Green Deal for 2050. Consequently, were defined the different aspects for the three categories considered and they are reported in Figure 20. As “Sustainable design criteria”, were considered for the final products (vehicles) different characteristics: the environmental compatibility, the recyclability/recoverability, the elimination of the critical substances and the environmental impact reduction and the improved efficiency during use phase because they are all aspects that are considered during the design phase. For the “Improved environmental performances” category, were collected information about the emissions reductions and fuel consumption reductions technologies. For the “Sustainable end of life management” category, the aspects defined were remanufacturing and recovery and recycling. The Tables with the information collected for the defined aspects are reported in the Appendix.

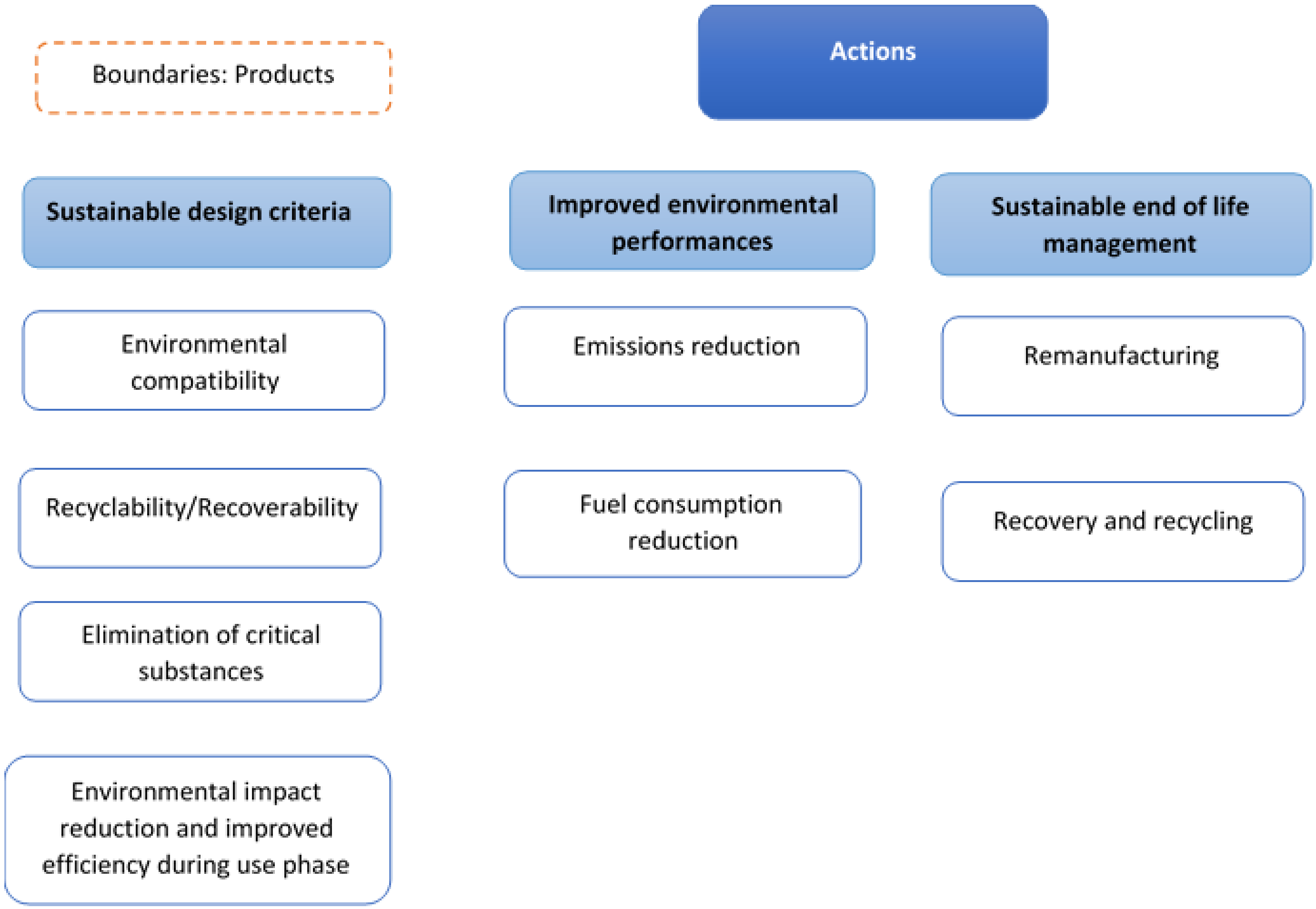

Figure 20. Aspects considered for actions macro-area categories (boundaries: Products)

Results

As regard the category "Sustainable design criteria" in the Appendix are reported the complete tables for each company. All the three companies adopt the Life Cycle Assessment (LCA) that allows to evaluate the potential environmental footprint of the products, such as carbon footprint during the entire life (from the extraction of raw materials to end of life). Regarding the recyclability/recoverability they use material that can lead to a highest rate of recyclability of vehicles (e.g., IVECO New Daily and Daimler A 250e recyclability are over 95% and a typical truck produced by Volvo group is around 85% recyclable). Another aspect that is considered during the design phase is the elimination of the critical substances, that are the hazardous substances potentially harmful to environment and human health, such as cobalt, tungsten and tantalum. During the design phase is fundamental to guarantee the reduction of the environmental impact and the improving of efficiency during the use phase that is realized through the implementation of alternative propulsion systems, such electric or hybrid, or through alternative fuels, such as biofuels.

Concerning the "Improved environmental performances", all the three companies adopt, to reduce the pollutant emissions in the atmosphere, the Selective Catalytic reduction, the Diesel particulate filter, biofuels or alternative powertrains (electric or hybrid) and Diesel Euro VI engines; to reduce the fuel consumption, they all adopt hybrid systems that allow to save a certain percentage of fuel. Emissions and electric/hybrid technologies for commercial vehicles will be studied and explained in the next chapters.

Concerning the "Sustainable end of life management" of vehicles category, this is in line with CE principles because the idea is to minimize waste and to refurbish, recycle and recover material, saving virgin materials and extending the vehicle or the component life as much as possible. All the three companies implement remanufacturing on worn components of vehicles, that have the same performances as new and allow to avoid extraction of raw materials. The companies also perform the recovery and recycling: the vehicles are made with recyclable materials, leading to reach a high rate of vehicles' recyclability.

Electric vehicles can be a solution to reach the decarbonization target set by the EU Green Deal: this propulsion system allows to avoid pollutant emissions in the atmosphere during the use phase and, for that reason, the electric vehicles market is growing. It is supposed that the future mobility will be totally electric. It is obvious that an electric vehicle does not emit chemical substances in the atmosphere during its use phase but it is important to consider the emissions and the environmental impacts generated during the Lithium-ion battery manufacturing, that are not negligible aspects. It is important to consider that batteries for commercial vehicles have large capacity and the impacts can be very high. This aspect will be examined in the last part of this thesis. Because of large impacts, it is considered appropriate to make a focus on Lithium-ion batteries end-of-life management (Table 4): CNH Industrial end-of-life batteries management is all performed by the supplier and, therefore, there are no specific information on the remanufacturing or reuse. For some electric bus batteries, is performed the recycling by a third party since the battery returns to the supplier. Daimler performs refurbishment on Lithium-ion batteries through the reprocessing of them; reuse as energy storage unit; recycling to recover valuable materials. Volvo group is performing research about refurbishment; it has a partnership with Stena to give a second life to batteries, using them as energy storage or recycling.

Table 4. Focus on lithium-ion batteries end of life management adopted by the three companies

Focus on lithium-ion batteries end of life management			
Company	**Remanufacturing**	**Reuse**	**Recycling**
CNH Industrial	Supplier management	Supplier management	Supplier management. Some lithium-ion batteries of electric buses are sent by the supplier to a recycling plant (Sarpi Veolia)
Daimler	Defective batteries are reprocessed for reuse in vehicles. After being reprocessed in line with the requirements of series production, the batteries are closely inspected to ensure that their function and quality are the same as those of a new part.	Batteries that are no longer suitable for reuse in a vehicle — for example, because their residual capacity is too low — can be reprocessed for use in a stationary energy storage unit. These energy storage systems can offset fluctuations in electricity production from renewable sources, smooth out load peaks, and serve as backup power sources for an uninterrupted energy supply. Many energy storage systems of this kind, with a total capacity of more than 95 MWh, are already operating in Germany.	Only after it is no longer possible to reuse a battery it is recycled in order to recover valuable raw materials. Today they are already able to go far beyond the recycling quotas that are prescribed for drive batteries by law. The battery housings, the cables, and the busbars can be recycled without any difficulty.
			Recycling the high-voltage battery modules, where most of the rare materials are embedded, is somewhat more complicated. The processes already exist, but they still need to be refined so that the valuable raw materials inside the battery cells can be recovered in as pure a state as possible. Mercedes-Benz is actively involved in the research and development of new recycling technologies for vehicle batteries.
Volvo group	No information provided	Volvo Buses collaborates with Stena Recycling's Battery Loop to reuse batteries for a second life storing renewable energy. After the batteries are removed from Volvo's buses, they are reused as energy storage units in buildings and charging stations for a number of years.	When the batteries have served its second life, there is still value left in the battery components and they are recycled by Stena

The "Actions" macro-area allowed to evaluate the CE application and sustainability, going beyond the material flows and products: the idea was to collect and compare information about the actions that the companies implement to become more circular. As regard the "company" boundary, it is possible to conclude that all the three case studies adopt solutions to reduce air emissions, optimize water and waste management, use renewable sources for energy production, use less quantity of raw materials. Furthermore, for all companies, digitalization is considered an instrument to improve the environmental performances and the efficiency of the operations. Regarding the "products" boundary, CNH Industrial, Daimler and Volvo integrate the CE principles into their products, through the implementation of the sustainable criteria at the design stage: vehicles are designed to be recyclable at the end of their life and to be compatible with the environment. The three companies in fact adopts the LCA study for products to evaluate the potential environmental footprint of the products (such as carbon footprint during the entire life). In general, concerning the use phase, the analysis presented a transition towards alternative powertrains, such as hybrid and electric vehicles to reduce emissions in the atmosphere. Finally, as regard the EoL management, all the three companies implement remanufacturing on worn components and they guarantee a high recyclability rate of vehicles, reducing the quantity of the total emissions.

2.2.5 Strategy

Method

The third macro-area considered is "Strategy" and were collected information adopted by companies to move towards CE: are analysed all the elements on which the company policy is based and that influence the transitions towards more sustainable practices. For this category, were collected information about the different categories and it is not considered necessary the aspects definition.

Results

The first category examined are the “Internal policies” adopted to promote sustainable practices. In Table 5 are reported this information and it is possible to notice that all company adopts the environmental policy, to use the resources more efficiently and to reduce impacts of operations.

Table 5. Internal sustainability policies adopted

Internal policy (sustainability)		
CNH Industrial	**Daimler**	**Volvo group**
Environmental policy	Environmental and energy policy	Environmental policy
Health and safety policy	Health and safety policy	Health and safety policy
Energy policy		

The second category examined is “Suppliers” and the complete information are reported in the Appendix. Supply chain is a key element to guarantee sustainability of the processes and to reduce environmental impacts. CNH Industrial performs a supplier selection to integrate environmental and social sustainability standards into supplier management: in fact, one of the requirements, also for Daimler AG, is the presence of environmental and health and safety systems in the working area, preferably certified by a third party (such as ISO 14001 or EMAS) that demonstrates the satisfaction of the suppliers’ environmental criteria. Moreover, all the three companies are member of the Responsible Mineral Initiative to guarantee conflict-free and transparency for mineral sourcing.

The third category considered are “Partnerships” between companies and third parties, that are strategic to integrate CE principles and to improve sustainability practices. In the Appendix are reported some partnership accordance (referring to sustainability) of the three companies. Regarding the decarbonization of the truck sector, the Volvo Group, Daimler Truck AG, IVECO, OMV and Shell are working together to develop a market of hydrogen trucks in Europe. Another important sector for partnerships is the development of the electric vehicles and the Lithium-ion batteries management: CNH Industrial is collaborating with Microvast to design and assemble in-house the Li-ion batteries (CNH industrial,2020); Daimler AG collaborates with Andritz to reuse batteries for hydroelectric power plants (Daimler, 2020b); Volvo group collaborates with Stena Recycling’s Battery Loop to give a second life for the used electric vehicles’ batteries (Volvo group,2020).

The other two categories considered to measure circularity were the “environmental expenditure and investments” and the “R&D investments:” it is possible to measure quantitatively how much the company invests to integrate and implement more sustainable practices. R&D in fact it is one of the keys for a company to improve and to develop new solutions to operate in a more circular way. These two aspects are reported differently in the three Sustainability Reports: CNH Industrial describes them in the most detailed manner, reporting the different expenditures and investments and the R&D investments specifying the fields; Daimler AG reports the aggregated data and Volvo Group’s Sustainability Report does not report this information considering only the environmental aspects.

The last category examined for this macro-area is “Certifications”, that are voluntary instruments to operate in a clearer way towards customers and suppliers. In Table 6, certifications are grouped into 4 categories: environment, quality, safety and energy. It is possible to notice that all the three companies have the ISO

14001 environmental certification; CNH Industrial applies also to most of the plants, the principles of World Class Manufacturing program, that promotes a continuous improvement of the production performances, to eliminate all types of waste and loss through the rigorous application of specific methods and standards (CNH Industrial, 2020). In particular, 3 plants reached the gold awards, 15 plants reached the silver awards, and 28 plants reached the bronze awards. All the companies adopt a quality management system in compliance with ISO 9001; a safety management system in compliance with OHSAS 18001/ISO 45001 and they all adopt a system to improve energy performances, that leads for example reducing GHG emissions, through the ISO 50001 certification.

Table 6. Companies' certifications.

Certifications				
Company	**Environment**	**Quality**	**Safety**	**Energy**
CNH Industrial	ISO 14001	ISO 9001	OHSAS 18001/ISO 45001	ISO 50001
	World Class Manufacturing (WCM) for most of plants			
Daimler	ISO 14001	ISO 9001	OHSAS 18001/ISO 45001	ISO 50001
	EMAS			
Volvo group	ISO 14001	ISO 9001	OHSAS 18001/ISO 45001	ISO 50001

"Strategy" macro-area allowed to collect and compare information about the policies that the companies adopt to integrate CE principal both internally and with third parties. All the three case studies adopt the environmental policy internally, to integrate the sustainability in their systems. As regard the external communication, the analysis revealed that they select suppliers evaluating their sustainability performances; the companies obtained the environmental certification ISO 14001; they are working together on alternative mobility solutions.

2.2.6 Targets

Method

The last macro-area considered for the principles implementation towards CE are targets, that can be grouped into 3 categories: carbon neutrality, resource conservation and sustainable policy both at a company and products levels. The goals represent the ambition and the efforts of companies to improve their sustainability practices for the next years, trying to reach the objectives set by the EU Green Deal. In the Appendix are reported the targets for the next years. The information were extracted from the three Sustainability Reports 2020 and are reported targets that are considered significant to vehicles (for example are not reported targets about occupational safety and people engagement).

Results

In general, all companies established targets until 2030. In table 7 is resumed the result of the targets investigation for the different boundaries considered.

Table 7. Target aspects for the three companies

Target aspects	Boundaries	CNH Industrial	Daimler	Volvo Group
Carbon neutrality	Company	yes	yes	no
	Products	yes	yes	yes
Resource conservation	Company	yes	yes	yes
	Products	no	no	no
Sustainable policy	Company	yes	yes	no
	Products	no	no	no

As regard carbon neutrality, all companies present targets on vehicles (products) that share common goals:

- Expansion of alternative propulsion (electric/hybrid) vehicles to reduce environmental impacts and improve efficiency
- Increase the recyclability of vehicles
- Fuel emissions reduction for Diesel/CNG vehicles

Concerning carbon neutrality but at a company level, the Volvo's Sustainability Report are not provided information. CNH Ind. and Daimler have set specific targets to reduce CO_2 emissions and energy consumption during the production phases.

Regarding resource conservation targets found for the three companies, they were all classified only into company boundaries. In general, the objectives aim to:

- Optimize the waste management
- Optimize the water management
- Optimize the energy management
- Increase the share of secondary material

As regard sustainable policy, for Volvo Group were not found targets that can be inserted into this aspect. CNH Ind. aims to enhance sustainability awareness, to monitor CO_2 emissions and to execute sustainability audits among suppliers; Daimler aims to review 70% of all the production raw materials use that pose a high risk of human rights violations and to define any necessary remediation measures

2.2.7 Guidelines

At the end of this analysis, it is important to understand if there are some guidelines that constitute a reference for the circularity and sustainability of an automotive company.

The first general guidelines, that are the main reference for the Sustainability Reports analysed, are the Sustainable Development Goals proposed by the United Nation: they are 17, for a total of 169 targets. In Table 8 are reported only the targets that are considered significant for an automotive company, the symbols, the targets and an example of a company application.

Table 8. Sustainable Development Goals considered significant for an automotive company (United Nations, 2021)

Goal	Symbol	Target	Example of application
Goal 6: Clean water and sanitation		6.3 Improving water quality	Water saving and water reuse/recycling
		6.4 Increasing water efficency	
Goal 7 : Ensure access to affordable, reliable, sustainable and modern energy for all		7.2 increasing the share of renewable energy	Electricity derived from renewable resources
		7.3 Double the energy efficiency	
Goal 12 : Ensure sustainable consumption and production patterns		12.5 Reducing waste generation through prevention, reduction, recycling and reuse	Waste recovering at Company plants
			Reyclability of products
Goal 13: Take urgent action to combat climate change and its impacts		13.2 Integrate climate change measures into policies, strategies and planning	GHG emissions reduction at a company level Development of alternative propulsion systems for vehicles

The second general guideline is the EU Green Deal, discussed in the previous chapter.

The third guidelines, that are more specific for commercial vehicles, are the EU regulations referred to:

1. Passenger vehicles and vans: by 2030, the CO_2 emissions of cars should be reduced by 37.5 percent relative to the base values of 2021; those of vans should be reduced by 31 percent (European Commission, 2020a).
2. Heavy-duty commercial vehicles: must reduce their CO_2 emissions by 15 percent on average relative to the reference period 2019/2020 by 2025 and by 30 percent on average by 2030 (European Commission, 2020a).
3. Directive 2000/53/CE: it is valid for passenger cars and vehicles for freight transport with a gross vehicle weight not exceeding 3.5 tons (M1 and N1 categories of Directive 70/156/CE). For all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85 % by an average weight per vehicle and year (European Parliament, 2000).

2.2.8 Final considerations

At the end of this analysis, it is possible to make some final considerations of this developed method to evaluate and measure circularity and sustainability for the automotive sector, specifically for the CV sector.

Strengths:

- It allows to measure circularity and sustainability for the automotive sector using public information of a company;
- It is possible to compare different companies through the development and application of the different categories on each company;
- It provides quantitative measures and qualitative information;
- It allows to categorize the information provided in the Sustainability Reports of a company;
- It allows to compare, through quantitative index, the environmental performances of companies in a consistent mode;
- It highlights the common features and solutions adopted by different companies.

Weaknesses:

- Using only public information, the circularity and sustainability evaluation could be not exhaustive;
- It does not provide qualitative indices;
- If it is applied to a different sector (not automotive), probably some categories, the relative aspects and the KPIs should be changed;
- It is useful to compare different company and not to measure in an absolute mode a company sustainability and circularity.

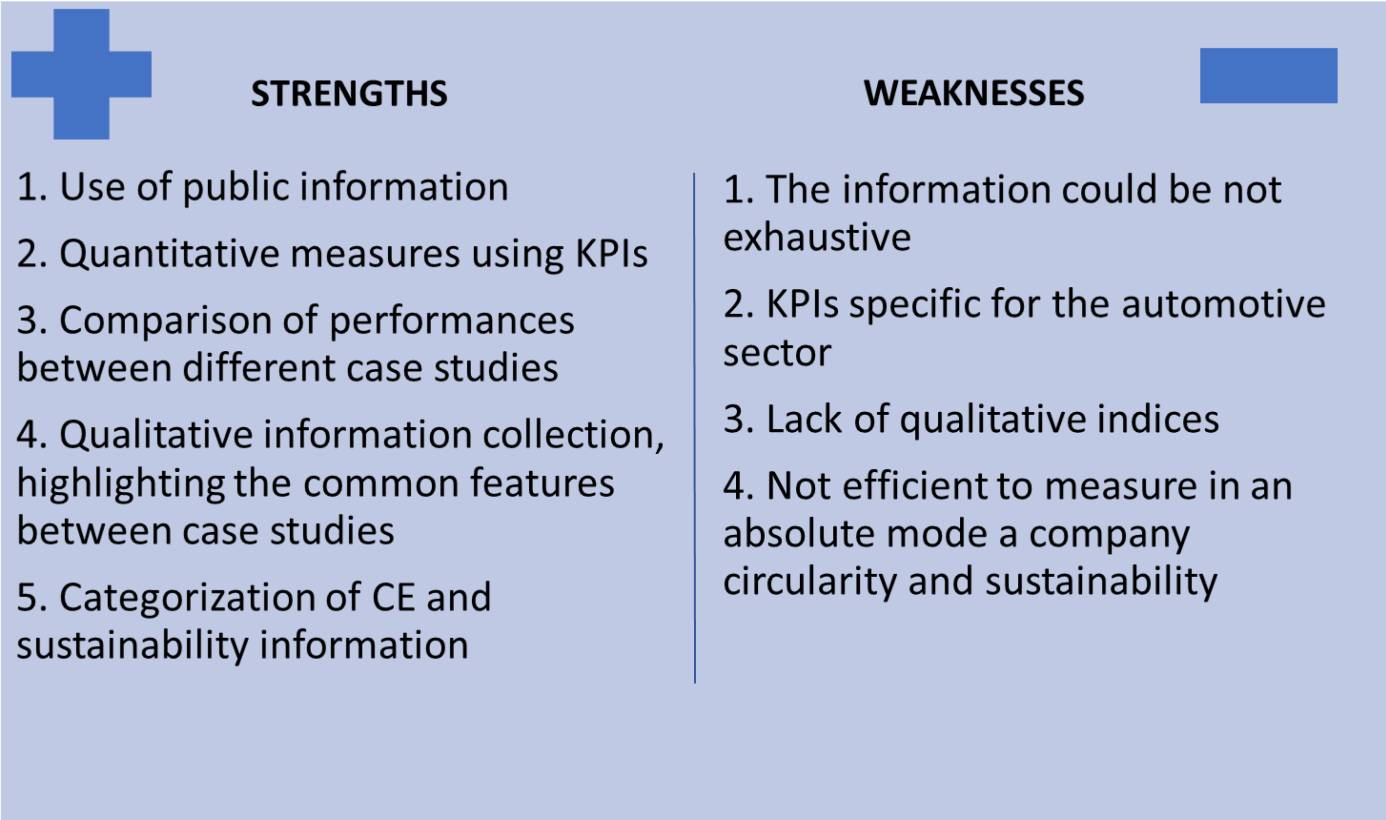

Figure 21. Strengths and weaknesses of CLEANS method

3 The electric mobility

As shown in the previous section, the transition towards electric mobility is an application of CE principles related to decarbonization targets. In this chapter is described the transition towards electric mobility focusing on the commercial vehicles sector: in the first part are illustrated who are the global leader countries regarding the automotive manufacturing market and for the commercial vehicles at a global and European level; in the second part of this section is described the transition towards electrification and the main future perspectives.

3.1 The automotive manufacturing market

In this section was analysed the global automotive manufacturing market for commercial vehicles, with a focus on the light commercial vehicles, heavy trucks, and buses production. This description is important to understand who are the global leading countries in the sector of the CVs manufacturing.

3.1.1 The World Automotive Industry

In this section, was analysed the World Motor Vehicle Production 2020 published by OICA (International Organization of Motor Vehicle Manufacturers). In the Appendix are reported the numbers of vehicles produced in different Countries, subdivided by cars and commercial vehicles (the commercial vehicles category considers the sum of light commercial vehicles, heavy trucks, and buses). It is possible to notice that there is a decreasing trend in the global motor vehicle production from 2019, caused by the impact of COVID-19 pandemic. In Europe and in America the production decreased by almost 22%; in Asia about 10% but in China the drop was only of 2% (OICA, 2020b).

In Table 9 is reported the top 13 motor vehicles producing countries of 2020 and in Figure 22 is represented the percentage of share of Global Motor Vehicle Production in 2020: China is the leader of the production, with approximately the 32% of share of the global production, followed by USA with the 11.4%, Japan with the 10.4%, Germany with 4.8%, South Korea with 4.5% and India with 4.4% (OICA, 2020b).

As it is possible to observe in Figure 22, Asia (excluding China)-Oceania contributed almost with the 25% of global share production, followed by Europe that contributed with the 22% of global share production. North America contributed with the 17%, followed by South America with 3% and Africa with only 1% (OICA, 2020b).

Table 9. Top 13 motor vehicle producing countries. Data elaborated from OICA (OICA, 2020b)

Position	Country/Region	Total production 2020	% of global production 2020
1	China	25225242	32
2	USA	8822399	11.4
3	Japan	8067557	10.4
4	Germany	3742454	4.8
5	South Korea	3506774	4.5
6	India	3394446	4.4
7	Mexico	3176600	4.1
8	Spain	2268185	2.9
9	Brazil	2014055	2.6
10	Russia	1435335	1.8
11	Thailand	1427074	1.8
12	Canada	1376623	1.8
13	France	1316371	1.7

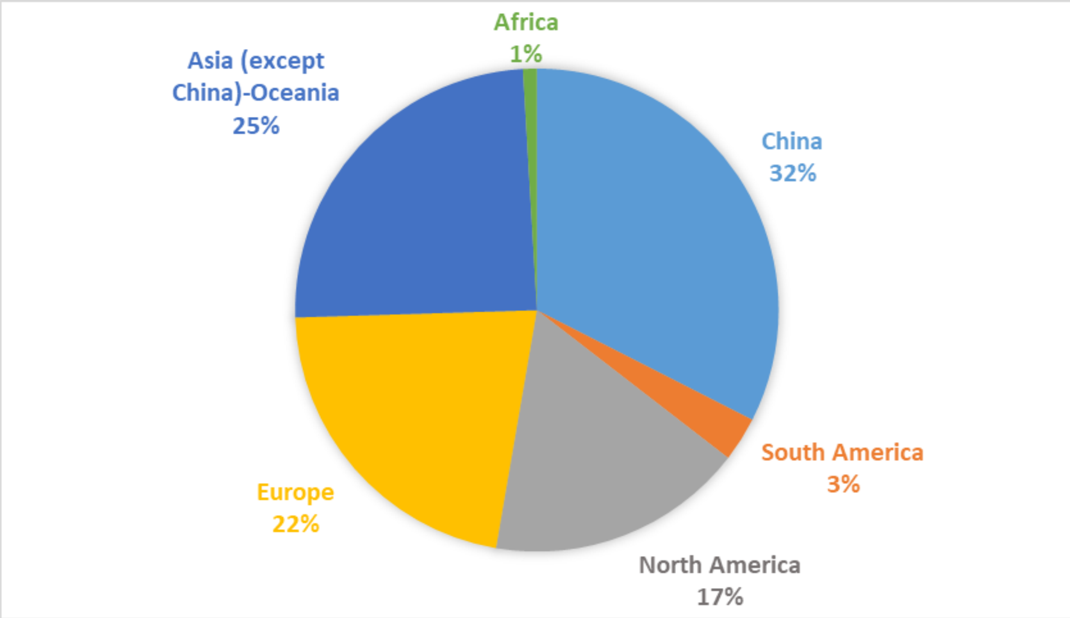

Figure 22. Percentage of share of Global Motor Vehicle Production 2020. Data elaborated from OICA (OICA, 2020b)

To compare the 2020 situation with the previous years is reported, in Figure 23, a graph that represents the percentage of share of world motor vehicle production for the years 2004-2019: it is possible to notice that China, in the last years, is the global leader of the motor vehicles production reaching almost 26.1 million vehicles in 2019, followed by Europe with 22.1 millions of vehicles. The situation is changed from the year 2004, in which China represented only the 9% of the total share (5.5 million vehicles) and Europe was the leader with the 32% of the total share (20.7 millions of vehicles). In 2009 Europe continued to be the leader with 16.7 millions of vehicles produced (27% of global share motor vehicles production) and China increased the share world production to 23%; since 2014 China became the leader with the 27% of share of global motor vehicle production (24.2 million vehicles), followed by Europe with 20.7 million vehicles that represented the 23% of global share production (ACEA, 2020c).

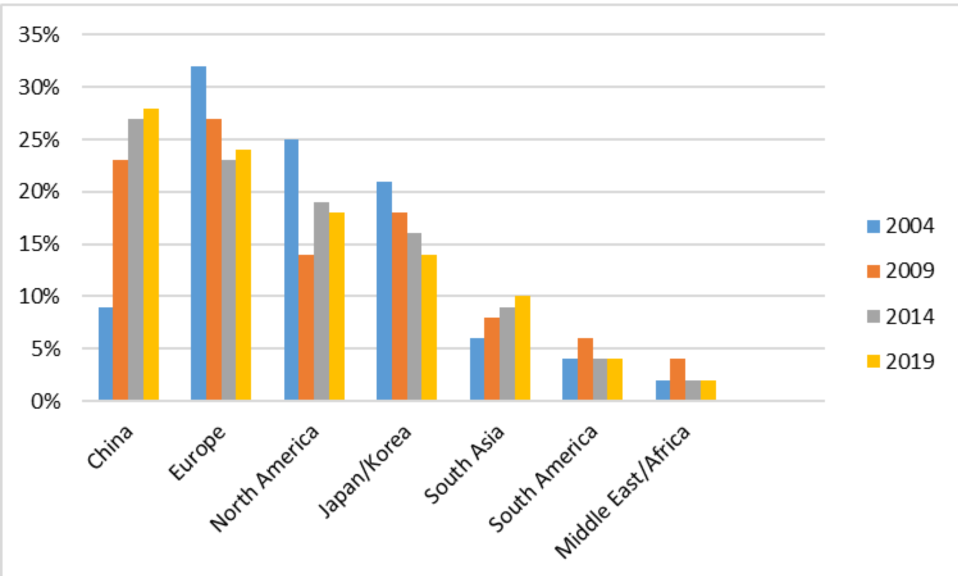

Figure 23. Percentage of share of Global Motor Vehicle Production 2004-2019 (ACEA, 2020c)

3.1.2 The global commercial vehicles production

In 2020, were produced almost 21.8 million of commercial vehicles (-11% than 2019), thereof 17.2 million of light commercial vehicles, 4.3 millions of heavy trucks and 219.267 buses (OICA, 2020a).

The North America is the leader of light commercial vehicles with 56% of total production (9.8 million light commercial vehicles produced), followed by China with 2.5 millions of light commercial vehicles produced and Europe with 12% of the global share (2 109 940 million light commercial vehicles produced); China is the global leader of heavy trucks production with 2 976 459 million produced (70 % of global share), followed by North America with 383 044 millions of heavy trucks produced and by Europe with 225 470 million; China is also the leader of the bus production with 103 355 buses produced (47% of the global share) followed by Europe with 39 916 buses produced. (OICA, 2020a).

3.1.3 The European Commercial Vehicles production

In the European Union were produced almost 2.3 million of commercial vehicles in 2020, that represents a loss of 15% than 2019: also in this case, that decreased is caused by COVID-19 and were produced 2 109 940 light commercial vehicles, 225 470 heavy trucks and 39 916 buses (OICA,2020a). In particular, concerning the light commercial vehicles, were produced 430 616 of them in Spain, 388 653 in France, 277 067 in Italy and 227 082 in Germany; concerning the heavy trucks, the leader among EU 15 is Italy with 47 937 vehicles produced, followed by Spain with 30 070 vehicles and Belgium with 30 070 vehicles; concerning buses, the data available are that a total of 39 916 of buses were produced, thereof 6037 in Poland, 5070 in Czech Republic, 941 in United Kingdom, 335 in Italy 335 of them and 333 in Belgium (OICA, 2020a).

In order to analyse better the EU situation, is reported in Figure 24 the commercial vehicle production for the years 2012-2019 European Union were produced almost 2.7 million of commercial vehicles in 2019: it is possible to notice that the most of production is due to light commercial vehicles (LCV) and from 2012 to 2019 there is an increase of it, passing from 1 528 233 million in 2012 to 220 111 8 million in 2019; the production of medium commercial vehicles (MCV) oscillated passing from 114.420 in 2012 to 106.536 in 2019; the graph presents an increase of heavy commercial vehicles (HCV) production, passing from 328.303 in 2012 to 428.667 in 2018 (the peak of production) to 387.571 (ACEA, 2020a).

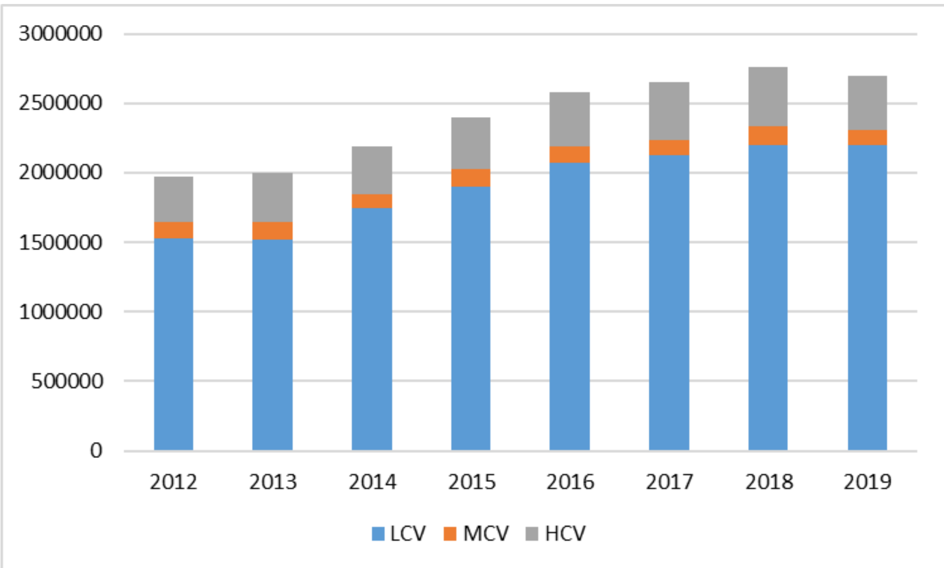

Figure 24. Commercial Vehicle production in the EU for the years 2012-2019 (ACEA, 2020a)

3.2 The transition towards electric mobility

3.2.1 Road vehicles emissions

In this section are described the road vehicles emissions, that are main reason of the transition towards electric mobility. Road transport is one of the main sources of greenhouse gases and pollutants in the atmosphere, damaging human health and the environment (EEA, 2016). In fact, these emissions occur in highly populated areas, like cities and towns, causing a decrease of air quality and negatively affecting people and environment, causing the increase of the global atmosphere temperature and climate change (EEA, 2016).

Considering the combustion reaction of a traditional carbon-based fuel (e.g., Diesel, petrol) present in the engine of the vehicle, the fuel burns in presence of oxygen and, if the reaction was complete (ideal situation), the products would be only Carbon Dioxide and water, but the real combustion is incomplete, leading to formation of different kind of pollutants (in addition to Carbon Dioxide and water). Therefore, the main chemical compounds emitted by road vehicles are (EEA, 2016):

- **Carbon Dioxide (CO_2)**, that derives inevitably from a carbon-based fuel combustion, and it is the main product along with water (EEA,2016). It is the main greenhouse gas because of its influence on climate change (EEA,2016).
- **Carbon Monoxide (CO)**, that is produced when a carbon-based fuel is burnt incompletely, that means when the carbon in the fuel is only partially oxidised (EEA,2016). Although it is colourless and odourless, it is highly toxic for human health, and it contributes to the formation of ground-level ozone and smog (EEA, 2016).
- **Hydrocarbons (HC)**, that are produced from either incomplete or partial combustion and are toxic for the human health (EEA,2016). In particular, the volatile organic compounds (VOCs) contribute to the formation of ground-level ozone and photochemical smog in the atmosphere (EEA,2016).
- **Nitrogen oxides (NOx)**, that are chemicals formed by reaction between nitrogen and oxygen and are produced when fuel is combusted in the engine in the presence of air (EEA,2016). NOx includes the nitric oxide, that is not dangerous for human health at typical concentration in the atmosphere, and nitrogen dioxide (NO_2), that is toxic. NOx are responsible of acidification and eutrophication of water and soils.
- **Particulate matter (PM)**, that are very small particles, mostly of unburnt Carbon and are formed by incomplete combustion (EEA,2016). PM is a mixture of both primary PM, that is the fraction emitted directly into the atmosphere, and secondary PM, formed by the release of precursor gases (sulphur dioxide, nitrogen oxides, ammonia and some VOCs) (EEA,2016). PM is one of the most dangerous pollutant for human health because it can enter into respiratory system, leading to cancer (EEA,2016).
- **Sulphur Dioxide (SO_2)**, that derives from the incomplete combustion, and it is harmful for the respiratory system.
- **Ammonia (NH_3)**, that derives from the combustion reaction, and it is highly toxic.

3.2.2 Climate change and the electrification

Climate change is the most globally discussed environmental issue and because it is caused by the increase of greenhouse effect due to human activity, there is the need to reduce the greenhouse gases emissions. It is important to explain that the greenhouse effect is a natural atmosphere phenomenon that allows to regulate the temperature through the presence of the greenhouse gases that absorb the 70 % of infrared radiation and then the heat is reflected to the Earth's surface. However, when the concentration of the greenhouse gases in the atmosphere increases, the quantity of the heat, that is absorbed and then reflected, increases and it causes a rise of the global atmosphere temperature. The human activity leads to an increase of greenhouse gases emissions and, consequently, the global average temperature is increasing over time:

in 2020 it is increased by almost 1.27°C above pre-industrial levels (from 1850-1900, assumed as a baseline for global temperature) and this is the second warmest year after 2016 (Berkeley Earth, 2021).

As mentioned above, the European Green Deal aims to reach the carbon neutrality in 2050 and proposed to reduce greenhouse gases emissions by at least 55% by 2050, compared than the levels of 1990: this goal requires actions in all the economy sectors. Regarding this topic, the EU Commission presented the "2030 Climate Target Plan" in September 2020 and launched the "European Climate Pact" on December 2020, to involve people and organisation to contribute to the decarbonization.

Since the exhaust gases of road vehicles contain the different kind of harmful pollutant mentioned in the previous section, the tendency is to move towards electric mobility that would be the key to reach the carbon neutrality because the engine is completely electric and exhaust gases are not generated.

It is important to specify that Carbon Dioxide (CO_2) is a natural component of the atmosphere, and it is not harmful: it is part of the Earth's carbon cycle and it is important for the plant's life, allowing the photosynthesis, and it is breathed out by humans and animals. However, it is a product of the combustion, and, for this reason, it is produced from the coal's combustion, when a carbon-based fuel burns (diesel, gasoline), from the solid waste burning, from chemical reactions. Among the greenhouse gases, that are H_2O, CO_2, N_2O, CH_4 and SF_6, Carbon Dioxide is considered the main gas because of its largest contribution: it is the primary gas emitted through human activities and the uncontrolled production of it (e.g., use of the fossil fuels, deforestation, burning of oil, coal and natural gas) causes the global temperature rise because of the increase of the "greenhouse effect". The anthropic CO_2 emissions is only a small part of the total, including emissions from natural sources, but it is enough to change the Earth's natural balance and to cause the temperature increase.

Focusing on the main GHG gas, in Figure 25 are represented the global energy related CO_2 emissions from 1990 to 2020, considering data reported by IEA: it is possible to notice a general increase over years but in 2020 was emitted 31.5 $GtCO_2$ and the graph presents a decrease of about 5.8% than 2019, the largest annual percentage decline since 1990: it is caused by Covid-19 pandemic that, with the lockdown measures and travel restrictions, reflected its effect mainly in road transport, with the consequence that the global oil demand fell down by 50% contrarily to the previous years, in which transports contributed almost for 60% of oil demand (IEA, 2020b).

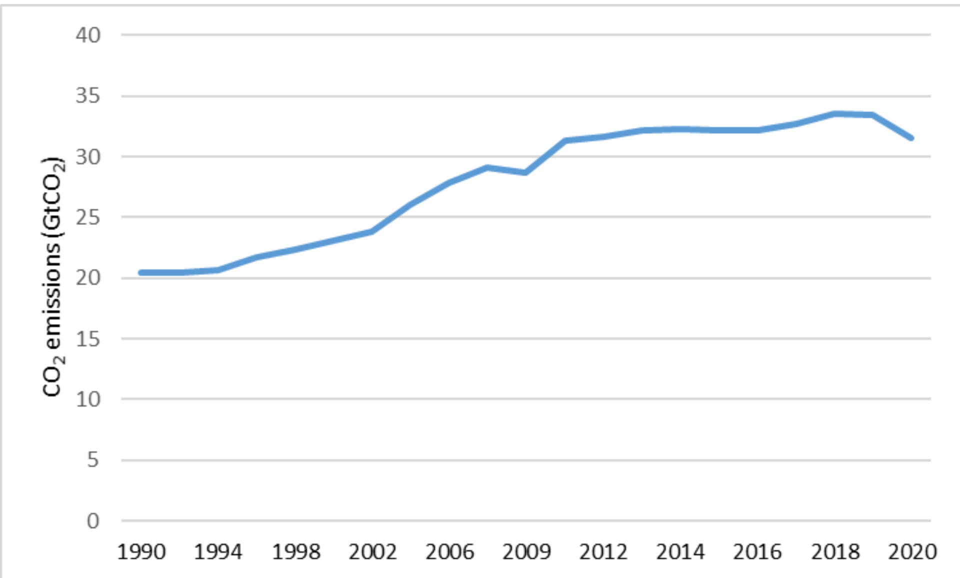

Figure 25. Global energy related CO_2 emissions,1990-2020 (IEA, 2020b).

As mentioned above, the transition to low-carbon alternative fuels and electric mobility is adopted to reduce the greenhouse gases (GHG) emissions caused by the traditional transports: as it is reported in the Synthesis Report of the IPCC Fifth Assessment Report (AR5), the total GHG emissions in 2010 was about 49 Gt CO_2eq and, as it is represented in Figure 26, the main contribution to GHG emissions are due to electricity and heat production, with a share of 25%, followed by Agriculture, Forestry and other Land use (share of 24%) and industry, with a share by 21%; transportation is responsible for about the 14% of the global greenhouse gases emissions, followed by other energy (share of 10%) and buildings, with a share of 6% on the total (IPCC, 2014).

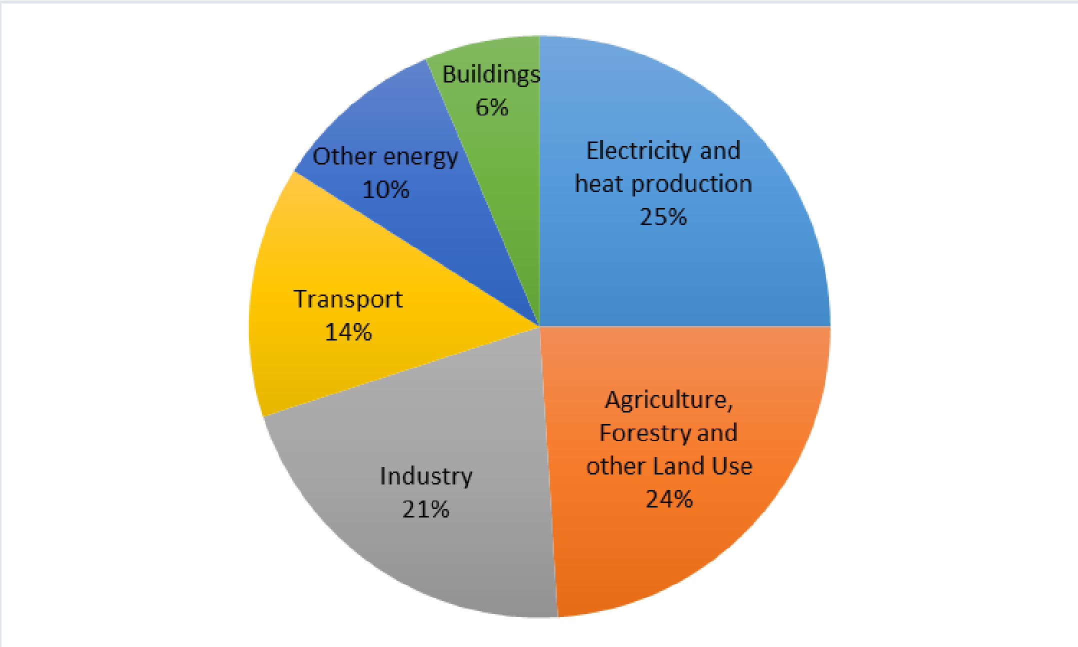

Figure 26. Share of anthropogenic greenhouse gases emissions by economic sectors (IPCC, 2014).

CO_2 is the major pollutant emitted by transport because is the main product of the combustion reaction: the 24% of direct CO_2 emissions derives from fuel combustion and road vehicles (cars, trucks, buses and two and three wheelers) contribute for three-quarters of transport CO_2 emissions, while a minimal part (but continuously rising) is given by aviation and shipping (IEA, 2020c). In Figure 27, it is shown that transports are at the second place for contribution of CO_2 with the 24.6% of share of emissions after electricity and heat producers.

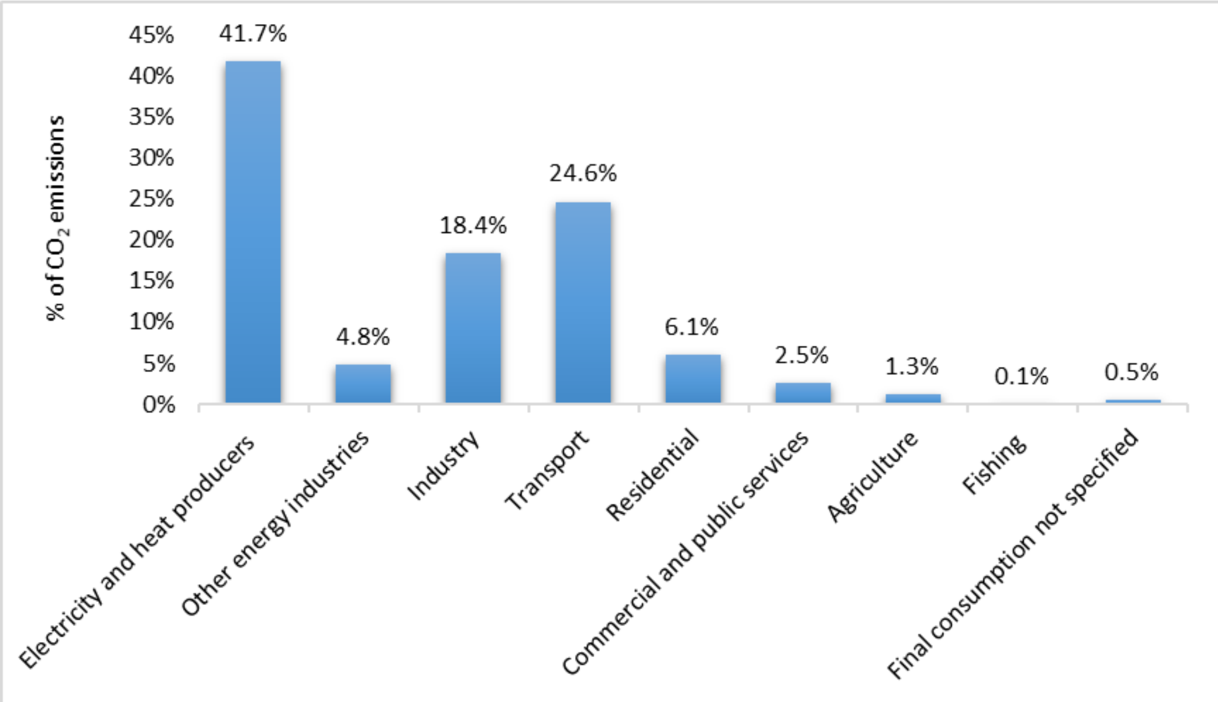

Figure 27. % of CO_2 emissions contribute by sector (IEA, 2020b)

Analysing data on global CO_2 emissions emitted by transport in 2018 published by IEA, it is possible to build a graph with the contribution of CO_2 emissions given by the different sectors (Figure 28), referring to the year 2018: in particular, IEA reported that the total emission of CO_2 in 2018 from transports was about 8.1 $MtCO_2$ and in the Table 10 are reported the values of CO_2 emissions for the different sectors. The highest percentage is due to road passengers' vehicles, flowed by road freight that represent the second main contribution.

Table 10. Global CO2 emission from transport in 2018 (IEA,2020b).

	CO2 emission (MtCO2)
road passengers vehicles (cars, motorcycles, buses and taxis)	3600
road freight (trucks and lorries)	2400
aviation	900
shipping	900
rail	100
other (transport of oil, gas, steams and other materials via pipelines)	200
Total CO2 emissions	**8100**

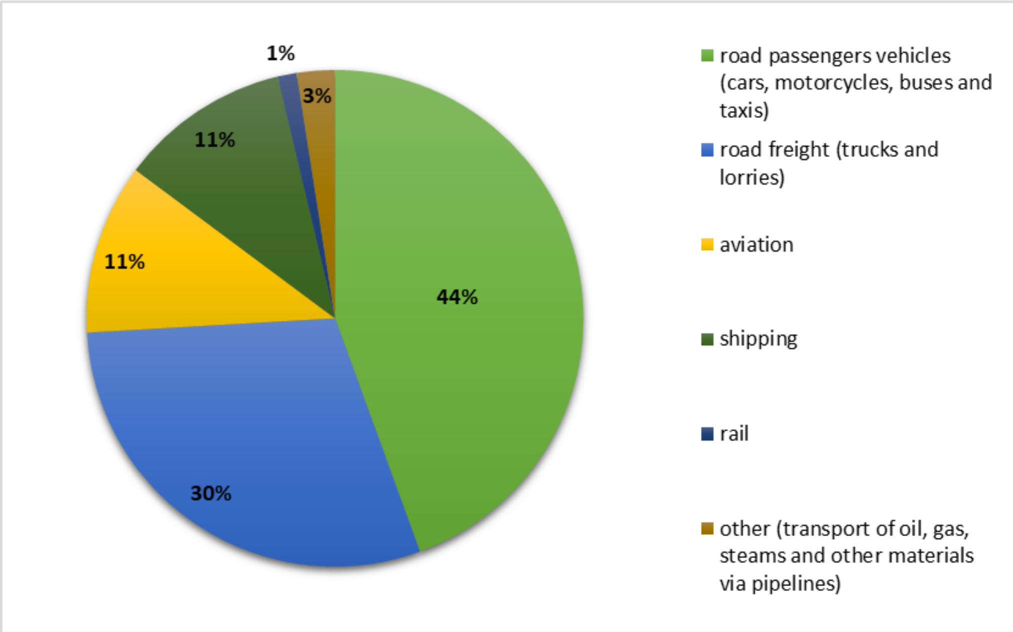

Figure 28. Global CO_2 emission from transport for 2018 (Elaborated from IEA)

The IEA proposes the Sustainable Development Scenario, that outlines how the world can achieve the Sustainable Development Goals (SDGs) and it is in compliance with the Paris Agreement: as is represented in Figure 29, it predicts the increase of electrification in all sectors and the most interested sector will be transport, conducing to the 30% CO_2 annual reduction in 2070 through the spread of electric vehicles, first in light-duty vehicles (cars and commercial vehicles) and urban buses, and later in medium- and heavy-duty buses and trucks.

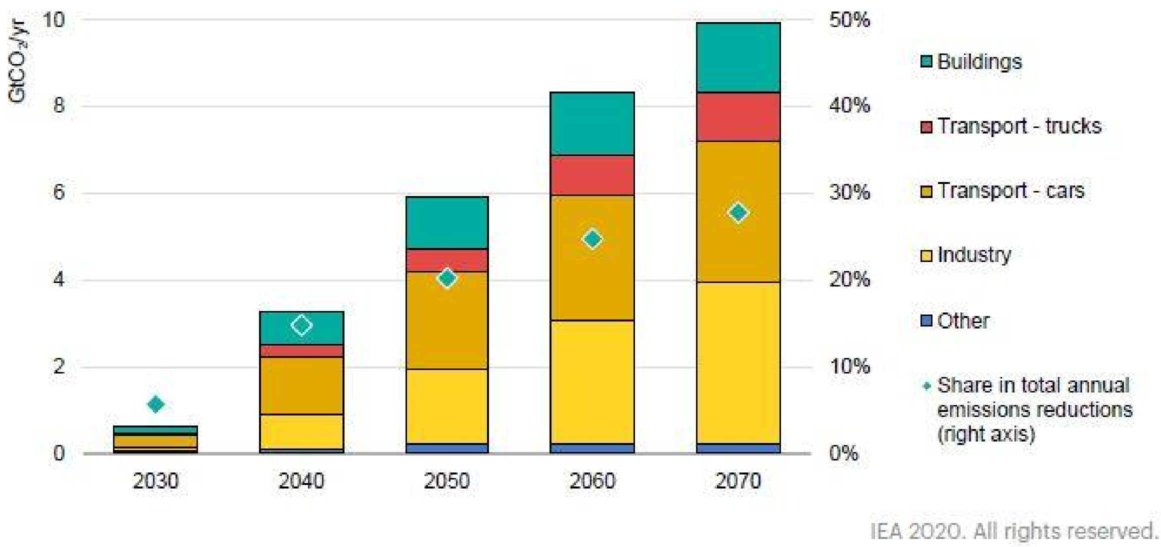

Figure 29. Global CO_2 emissions reductions from electrification by sector in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2030-70 (IEA, 2020c)

In Figure 30 is reported a graph that represents the global CO_2 emissions in transport by mode in the Sustainable Development Scenario 2020-2070 elaborated by IEA: in this scenario, the global direct CO_2 emissions from fossil fuel used in the transport sector will fall by almost 90% from 8.1 Gt in 2019 to 1 Gt by 2070 through mainly the implementation of electrification, biofuels and low-carbon fuels (hydrogen and synthetic hydrocarbons); the residual emissions in 2070 will come mainly from road freight (e.g. trucks, buses, light commercial vehicles), maritime shipping and aviation: for these sectors, the emissions will fall by three-quarters from 2020 but it will represent the highest contribute because it is difficult to implement zero-carbon technologies in these categories of transport (IEA,2020a).

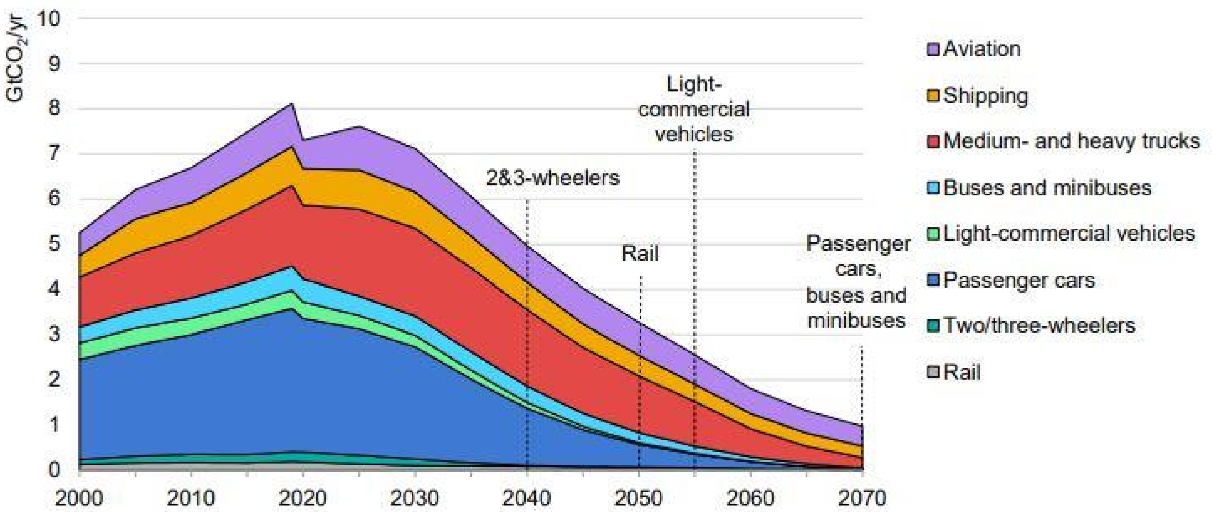

Figure 30. Global CO_2 emissions in transport by mode in the Sustainable Development Scenario 2020-2070 (IEA, 2020a)

The main perspective for IEA is in fact that by 2040 electric passengers cars and two/three-wheelers will play a significant role, reducing drastically the carbon emissions; light commercial vehicles will switch rapidly to electricity or, when longer hours if operation are required, to hydrogen-powered fuel cells; concerning buses and minibuses, by 2070 about two-thirds will be battery electric and one-fourth powered by hydrogen; heavy-duty trucks constitutes a problem for electrification because they have to cover long distances and it is due the lack of availability of charging infrastructures, high power charging and/or large batteries capacity requirements (IEA,2020a). For that reason, IEA predicts that about 20 million electric LCVs, 5.5 millions of electric buses and 3.9 million will circulate worldwide by 2030 (IEA,2021).

3.2.3 Trend and developments in electric-light commercial vehicles

Global electric light-commercial vehicle (LCV) stock numbers about 435 000 units: as it is showed in Figure 31, China is the global leader and most of the registrations was for the electric LCV in 2020, followed by Europe where new electric LCV registrations in 2020 were about a third of the total and only 5% below those in China, with a jump of 40% than 2019; the registrations on the rest of the world were about 19000 units, mostly in Korea and Canada (IEA, 2021).

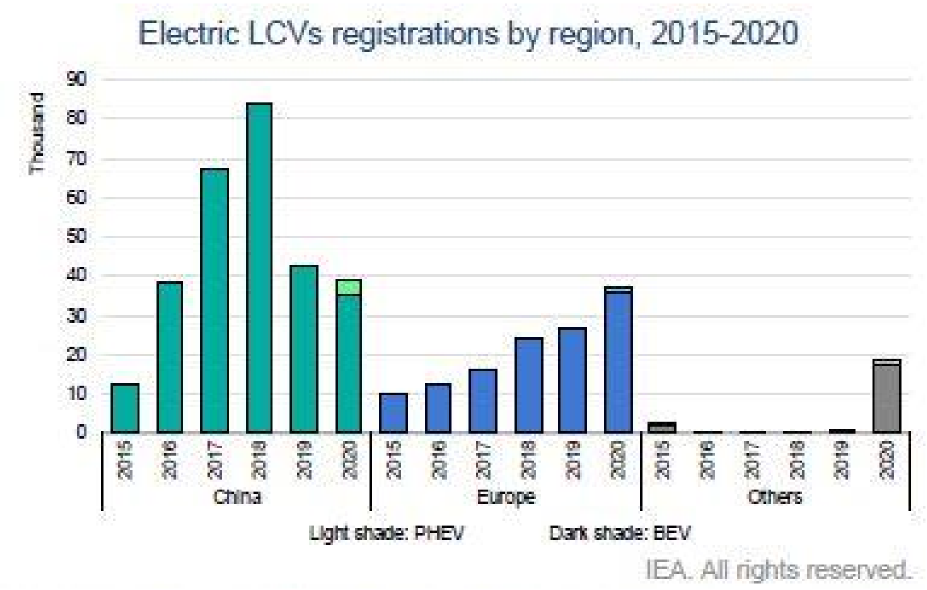

Figure 31. Electric LCVs registrations by region, 2015-2020. PHEV=plug-in hybrid vehicles; BEV=battery electric vehicles (IEA, 2021)

In Figure 32 are reported the actual electric vans global sales and the future perspectives according to the Sustainable Development Scenario for the years 2020-2030: it can be noticed that it is expected a substantial increase of sales for battery electric vehicles (BEV) and a moderate increase of sales for plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV) (IEA,2021).

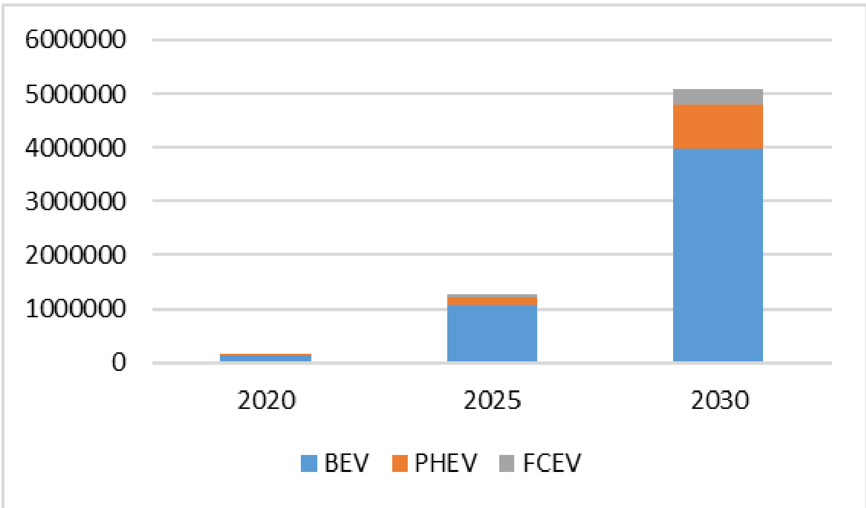

Figure 32. Electric vans global sales, 2020-2030 for the Sustainable Development Scenario (IEA,2020b)

3.2.4 Trend and developments in electric-heavy duty vehicles (HDV)

Diesel is the primary fuel for the HDV and its consumption rose from 38% in 2000 to 45% in 2019 and to reduce the GHG emissions, will need a transition to low carbon alternatives fuels and powertrains, adopting electrification via battery, plug-in and hydrogen fuel-cell electric vehicles, advanced biofuels and synthetic fuels (IEA,2020b).

The market of the electric urban buses is spreading rapidly thanks to availability for charging, buses' frequent stops and the ambition to reduce the local pollution and CO_2 emissions.

Global electric bus stock numbers about 600 000 units in 2020 and the electric heavy-duty trucks (HDT)stock was 31 000: China is the leader of the electric bus market with registration of 78000 new vehicles while in

Europe electric bus registrations were 2100 (+7% than 2019), followed by North America with 580 new electric bus registrations (IEA,2021).

Global electric HDT registrations were 7 400 in 2020 (+10% than 2019): also in this case, China is the global leader with 6 700 new registrations in 2020, followed by Europe with 450 new registrations and USA with 240 vehicles (IEA, Global EV Outlook , 2021). These data are showed in Figure 33.

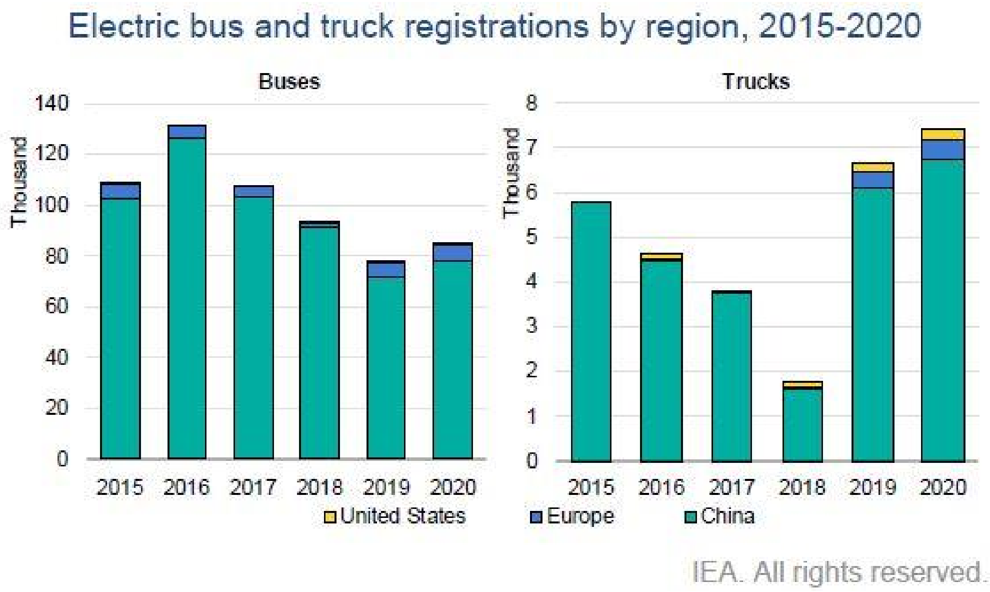

Figure 33. Electric bus and truck registrations by region, 2015-2020 (IEA,2021).

As it is showed in Figure 34, in the years 2020-23 there will be a growth in the electric HDV segments: China has the most the most variety in available electric bus models and this trend is predicted also in the future, United States will have the most availability in medium-freight truck and Europe will offer the widest selection of models for heavy-freight truck (IEA,2021).

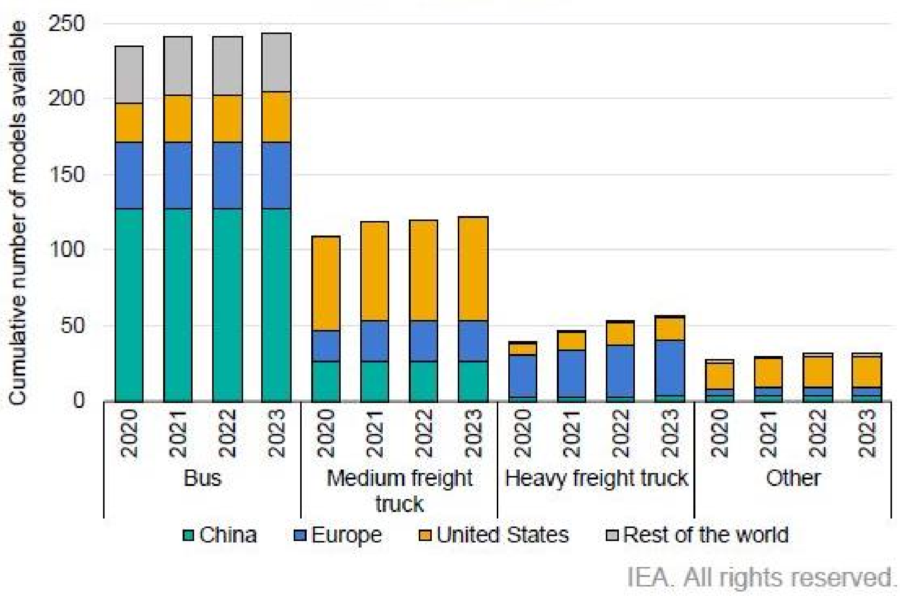

Figure 34. Number of announced electric HDV models available by segment, 2020-2023 (IEA,2021).

In Figure 35 are reported the actual electric buses global sales and the future perspectives according to the Sustainable Development Scenario for the years 2020-2030: it can be noticed that it is expected a substantial increase of sales for battery electric vehicles (BEV) and a moderate increase of sales for plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV) (IEA,2021).

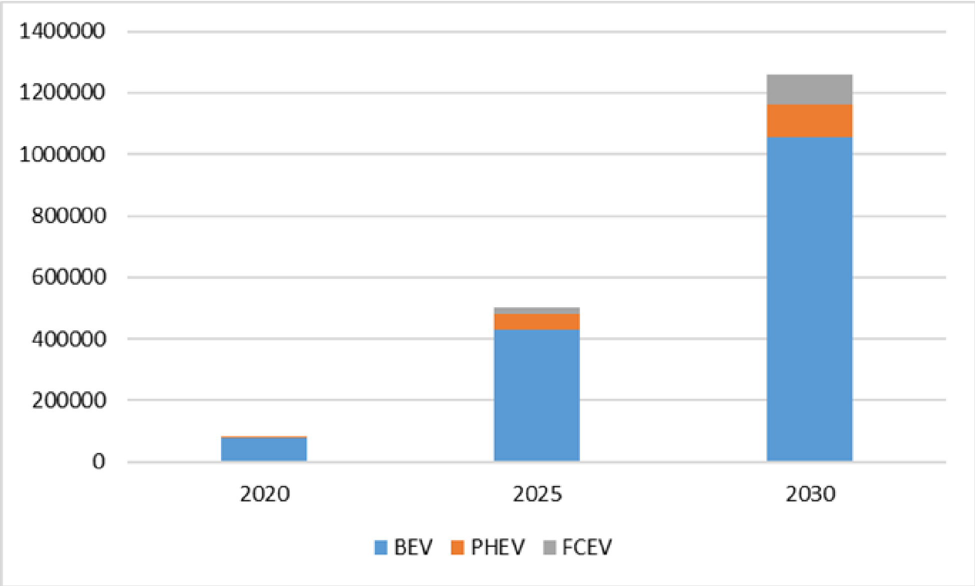

Figure 35. Electric buses global sales, 2020-2030 for the Sustainable Development Scenario (IEA,2020b)

In Figure 36 are reported the actual electric trucks global sales and the future perspectives according to the Sustainable Development Scenario for the years 2020-2030: it can be noticed that it is expected an increase of sales for battery electric vehicles (BEV) for plug-in hybrid electric vehicles (PHEV) and a moderate increase for sales of fuel cell electric vehicles (FCEV) (IEA, 2020b).

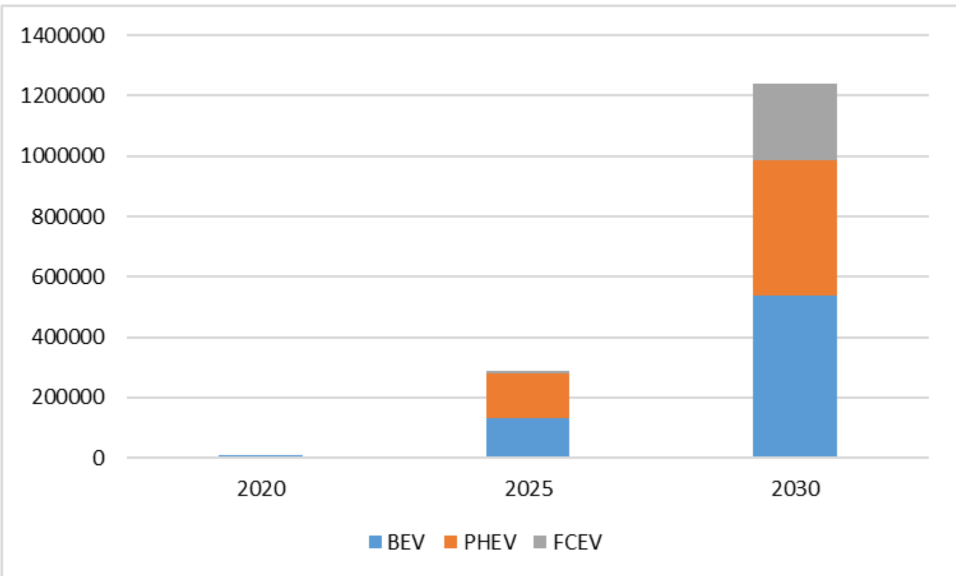

Figure 36. Electric trucks global sales, 2020-2030 for the Sustainable Development Scenario (IEA,2020b)

It can be noticed that the future perspectives for electric trucks global sales are less than vans and buses, due to the technical problems related to the electrification for heavy-duty trucks mentioned above (they have to cover long distances and it is due the lack of availability of charging infrastructures, high power charging and/or large batteries capacity requirements). However, for trucks, there will be more investments for plug.in hybrid and fuel cell technologies.

4.The Li-ion batteries

In this chapter are presented and explained the Lithium-ion batteries, used as energy source for the electric and hybrid vehicles. This information are useful for the next part of this work, that is focused on hybrid and electric bus.

The first Li-ion batteries (LIB) were commercialized by Sony in 1991, including $LiCoO_2$ (LCO) in the cathode and a non-graphitic carbon anode; actually LIBs are the most popular storage devices, used as power source for mobile phones, tablets, notebook computers, video cameras and electric vehicles (Kim et al., 2021).In recent years, the request for electric vehicles (EV), that includes also hybrid and plug-in hybrid vehicles, has increased significantly because the use electricity instead of gasoline allows to reduce the greenhouse gases emissions (Lowe et al.,2010).

The large use of LIBs in different sectors is due to their excellent performances (high specific density, no memory effect, low-self discharge and long cycle life) as it is represented in Figure 37, in fact they are actually the best options for the electrical energy storage for high-energy and high-power applications (e.g. transport, stationary storage): they have in particular also a huge potential for use in off-grid power supply systems, especially in combination with solar home systems (Zubi et al,2018). The largest market are electronic devices, characterized by light weight, such as laptops that use a battery with capacity between 50 and 100 Wh and tablets that use a battery of a range between 15 and 35 Wh; there are applications also in aerospace and medical devices (Zubi et al., 2018).

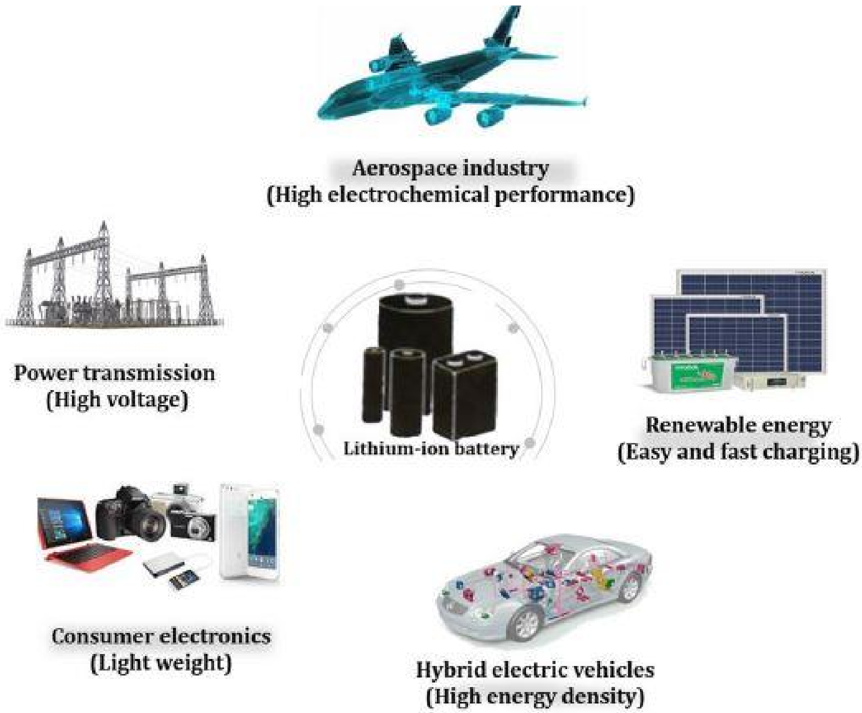

Figure 37. Application of LIBs (Makuza at al. 2021)

Definitions

In this section are reported some useful definitions for Lithium-ion batteries.

- Battery cell: basic unit of the Li-ion battery that exerts electric energy by charging and discharging and it is made by cathode, anode, separator and electrolyte inserted in a case;

- Battery module: a battery assembly put into a frame by combining a fixed number of cells (connected in series and/or in parallel) to protect the cells from external shocks, heat or vibration;
- Battery pack: final shape of the battery system installed into the electric vehicle and it is composed by various modules and various control and protection systems (e.g. battery management system, cooling system);
- Battery management system: Electronic system associated with a battery, which monitors and/or manages its state, calculates secondary data, reports that data and/or controls its environment to influence the battery's safety, performance and/or lifetime;
- Energy density: Chargeable electric energy per weight of battery pack expressed in Wh/Kg;
- Power density: Proportion of dischargeable electric energy to charged energy;
- Cycle life: The number of charging/discharging cycles in battery's entire life;
- Volumetric energy density: Amount of stored energy related to the battery cell, module, pack or system volume expressed in Wh/L;
- State of charge (SoC): it is the capacity cell denotes the capacity that is currently available as a function of the rated capacity and it varies form 0% (cell completely discharged) and 100% (cell fully charged)
- State of health (SoH): it is a measure that reflects the general condition of a battery compared to its ideal conditions and it is measured in % (100% means that battery's conditions match the battery's specifications). Typically, a battery's SoH will be 100% at the time of manufacture and it will decrease over time and use;
- Memory effect: it refers to a decrease in energy capacity after the battery has been discharged shallowly. The battery remembers the smaller capacity and thereafter can no longer charge fully (Lowe et al.,2010). Li-ion batteries do not have this memory effect, so the battery can always be recharged even before its stored energy has been depleted (Lowe et al., 2010)

4.1 Structure of a Li-ion Battery

As explained above, the cell is the elementary unit of the battery pack, and the module is formed by the combination of different cells connected in series/parallel. Consequently, the battery pack is composed by different modules connected in series/parallel and it is provided of an electronic control at modules level. In Figure 38 are showed the components of a battery pack.

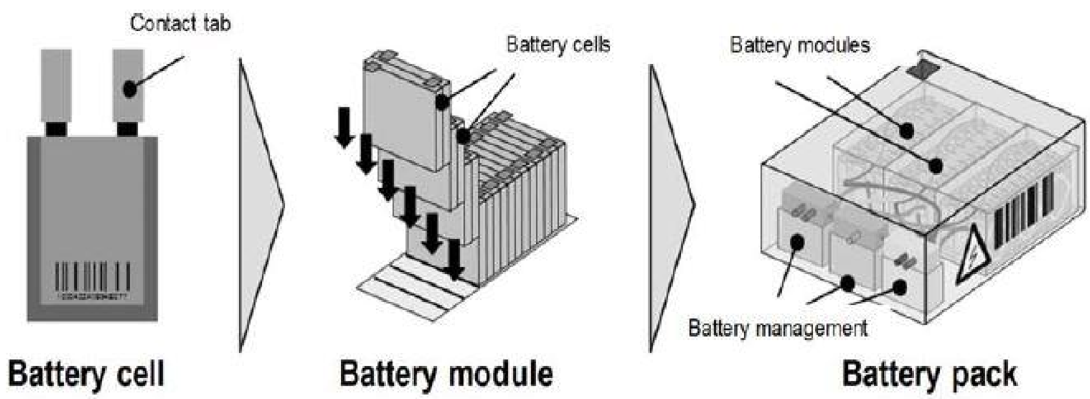

Figure 38. From battery cell to battery pack (Kampker et al., 2016)

In Table 11 are reported LIBs advantages and disadvantages, according to Zubi (Zubi et al., 2018):

Table 11. Advantages and disadvantages of LIBs Elaborated from (Zubi et al.,2018)

Strengths	Weaknesses
Outstanding specific energy and power	High initial costs
Long calendar and cycle lives	Advanced battery management system required
High roundtrip efficiency	Safety concerns; thermal runaway incidents
Low operation and maintenance requirements	Material bottleneck concerns; lithium and cobalt
Satisfactory operating temperature ranges	Currently weak recovery and recycling schemes
High reliability	Complete discharge damage the batteries
Technological diversity and several chemistries	
Intensive global Research & Development efforts	
Chemistries with eco-friendly materials available	
Reasonable self-discharge rate	
Relatively fast recharge	
No memory effect	

In Figure 39 is represented the comparison of different electric energy storage technologies, that allow to convert electric power to another form of energy for storage and then, when is required, this energy is reconverted to electricity (Zubi at al., 2018). These systems are capacitors, that have limited applications due to low specific energy; flywheels; electrochemical systems (e.g., lead-acid, lithium-ion, nickel-cadmium, nickel metal hydride, sodium-sulphur, vanadium redox, zinc-bromine, nickel-hydrogen, nickel-zinc, molten salt and metal-air batteries, fuel cells) (Zubi et al., 2018).

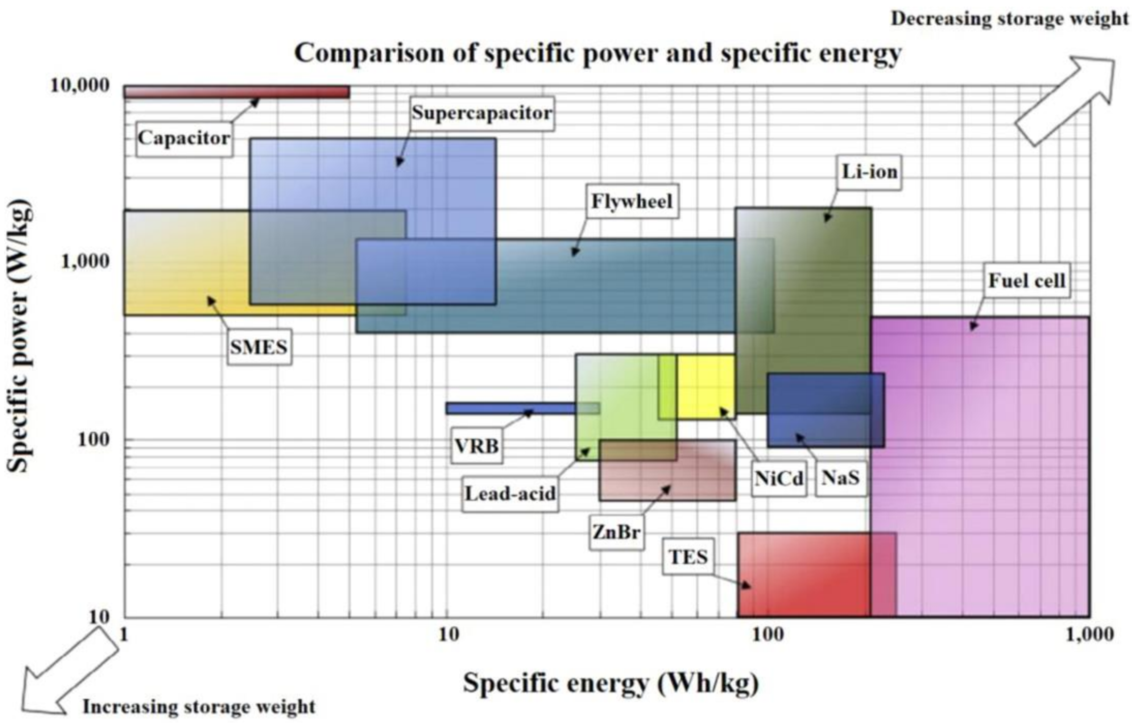

Figure 39. Comparison of specific energy and power for different electric energy storage technologies. Acronyms: SMES (superconducting magnetic energy storage), VRB (vanadium redox battery), ZnBr (zinc-bromine battery), NaS (sodium-sulphur), TES (thermal energy storage) (Zubi et al.,2018).

Among these electric energy storage technologies, the most commercialized rechargeable batteries are Lead-acid, Li-ion, Nickel metal hydride (NiMH) and nickel-cadmium (NiCd) (Zubi et al., 2018); in particular, as it is shown in Figure 40, the advantage of Li-ion batteries is that they are smaller size and lighter weight than the others, presenting an higher specific energy density and an higher volumetric energy density.

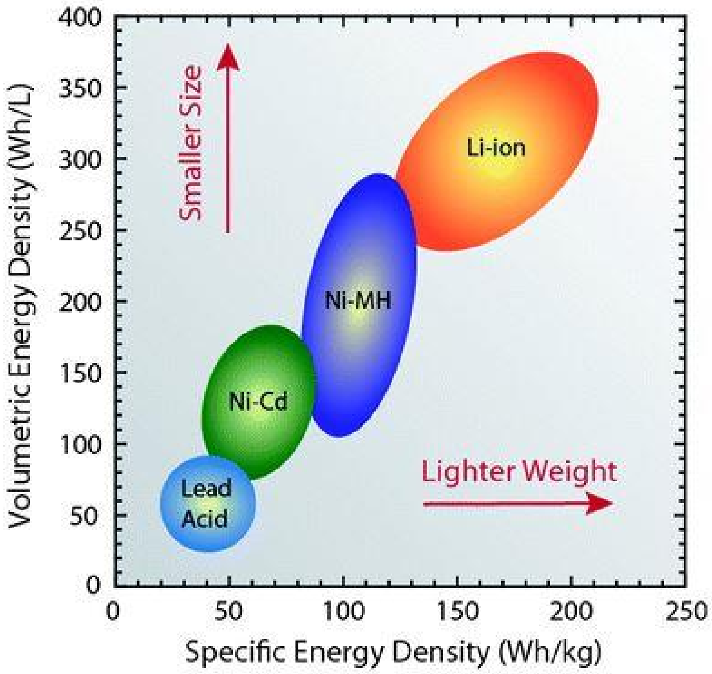

Figure 40. Specific energy density and volumetric energy density for different commercial types of batteries (https://www.epectec.com/batteries/cell-comparison.html)

A typical Li-ion battery (LIB) cell is composed by 5 principal elements:

- Cathode
- Anode
- Electrolyte
- Separator
- Current collector

During the charge the Lithium ions move, through electrolyte, from the cathode to anode and during the discharge lithium ions move from the anode to cathode. In Figure 41 and in Figure 42 are represented the different components of a Lithium-ion battery cell.

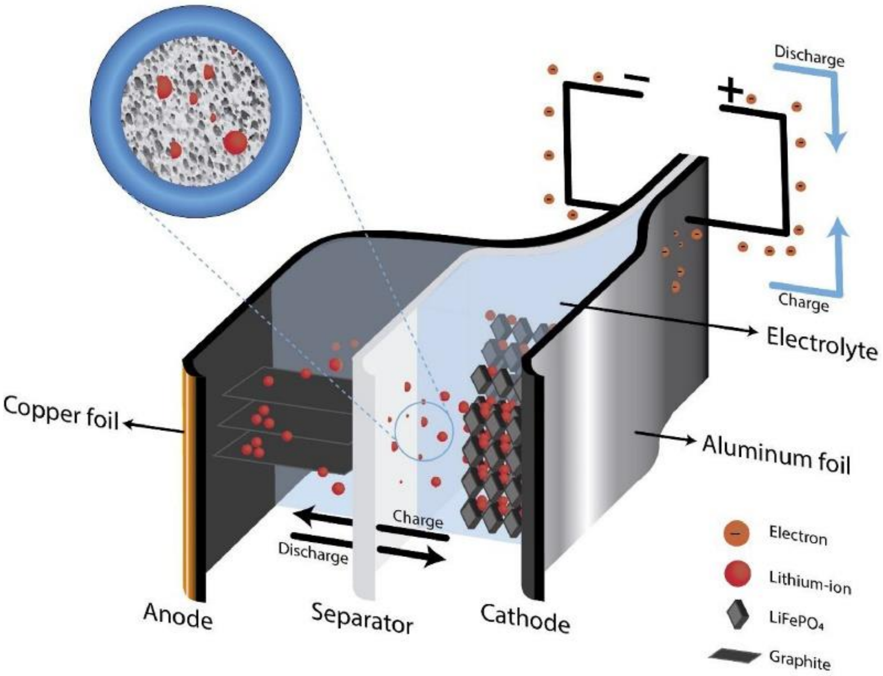

Figure 41. Li-ion battery cell's structure (Costa et al.,2021)

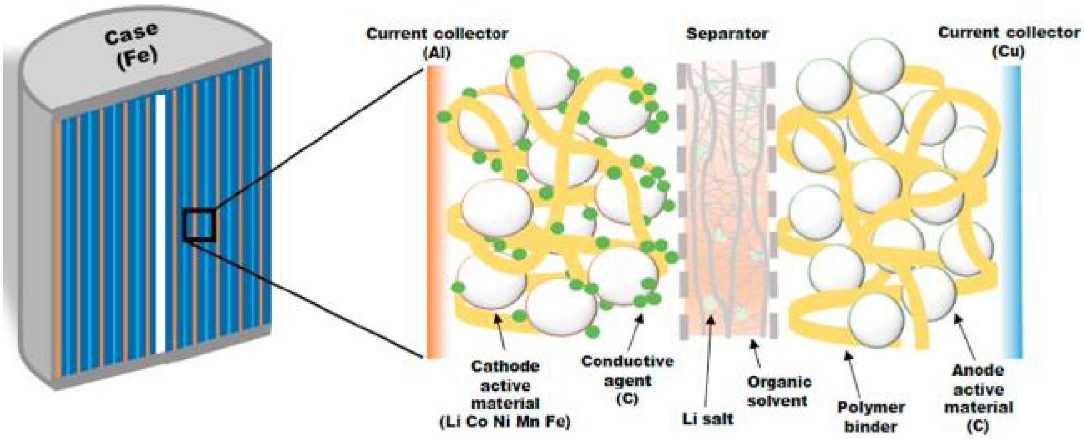

Figure 42. Schematic diagram of the LIB components and their constituent elements at issue (Kim et al., 2021)

4.1.1 Electrodes

The anode and the cathode are respectively the negative and the positive electrodes of the LIB cell. In particular, the cathode is an aluminium metallic conductive foil covered with an electrochemically intercalated active material and the anode is formed by a copper foil coated with graphite (Makuza et al., 2021).

The electrodes are formed by a mixture of three components, that are: the conductive material, the active material (different for the anode and the cathode) and the binder solution (usually the same for the electrodes); these three elements are mixed into a paste coating the electrode side of the current collector (Costa et al., 2021).

In Table 12 are reported the typical different active materials, responsible of the Lithium intercalation and reservoir, used for the anode and the cathode: for the cathode are commonly adopted Lithium metal oxides and phosphates (Lithium cobalt oxide, Lithium iron phosphate, Lithium Nickel Manganese Cobalt oxide, Lithium Nickel Cobalt Aluminium oxide) and for the anode the most common are graphite and silicon (Costa et al., 2021) or non-graphite materials, such as Lithium titanate (LTO, $Li_4Ti_5O_{12}$) (Zubi et al.,2018). LTO is an expensive option, but it guarantees an higher cycle life and it can operates at lower temperatures than the typical carbon- based anode (Woody at al.,2020). Typically, for the anode it is used carbon because of its features: it is abundant, low cost, high coulombic efficiency, and long cycle life (Makuza et al., 2021). The choice of the cathode material will influence nominal voltage, cycle life, self-discharge rate, specific energy, specific power, energy density, power density, operating temperature range, and cost of the battery (Woody et al., 2020).

Table 12. Anode and cathode active materials with theoretical voltage and specific capacity, lithium precursor and synthesis method (Costa et al.,2021)

	Active material	Theoretical voltage (V)	Theoretical specific capacity ($mAh.g^{-1}$)	Lithium precursor	Synthesis method
Cathode	$LiCoO_2$	3.8	274	$LiOH.H_2O$	solid-state
	$LiFePO_4$	3.4	170	Li_2CO_3	solid-state
	$LiMnO_2$	3.3	285	LiBr	solid-state
	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	3.7	280	$LiOH.H_2O$	Co-precipitation
	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	3.7	279	$LiOH.H_2O$	Co-precipitation and solid-state
Anode	Graphite	0.2	372	-	Natural
	Silicon nanowire	0.5	4200	-	vapour–liquid–solid method

The active material used for the cathode determines the commercial names of LIBs:

- LCO (Lithium Cobalt dioxide), that are easy handling, high capacity and good stability (Mohanty et al., 2021);
- LFP (Lithium Iron phosphate), that are low priced, steady, environmental, low capability, low ion transmission (Mohanty et al.,2021);
- LMO (Lithium Manganese oxide), that are easy preparation, ecological, cheap, low capacity than LCO but long life (Mohanty et al.,2021);
- NMC (Lithium Nickel Manganese Cobalt oxide), that specifically are named, for instance, NMC111, NMC811 and NMC 622, based on the transition metal composition ratio (Kim, et al., 2021). They are low-cost, stable, high power and a higher Ni content allows to extract higher Li without structure destruction (Mohanty et al.,2021);
- NCA (Lithium Nickel Cobalt Aluminium oxide)

In Table 13 is reported the percentage of composition of different types of Li-ion batteries: it is possible to notice that NMC (111) is composed by the same quantity of Cobalt, Nickel and Manganese; NMC (811) is composed by a proportion of Nickel, Manganese and Cobalt that is 8:1:1; NMC (622) is composed by Nickel, Cobalt and Manganese with a proportion of 6:2:2.

The cell performance is affected by the proportion active material (AM), conductive material (CM) and binder solution (BS): it affects mainly ionic conductivity, porosity and conductivity and, in particular, higher BM/CS ratios increases the interfacial resistance; higher AM guarantees, at the cathode, an high battery capacity and, at the anode, it guarantees the Lithium-ion storage capacity (Costa et al.,2021).

The most used conductive material in LIB is carbon black: it allows the electrical contact between the current collector and the active material particles because of its high electrical conductivity and large surface area, improving the cycle life of the battery (Costa et al.,2021).

The binder material is usually polymeric (e.g., PVDF and copolymers, polypropylene (PP)) and it is useful to bind particles within each electrodes and to a conductive additive, ensuring the entire electrode is conductive (Woody et al., 2020). The binder solution acts as a support for the electrode structure through the bonding of AM e CM and the adhesion to the current collectors: it is in a low content into the electrode (2%-5%) but it determines its performance and, for this reason, it should be electrochemically inert to allow the ionic conduction (Costa et al.,2021).

Table 13. Composition of different Li-ion batteries (Gaines et al.,2018)

	NMC(111)	NMC(622)	NMC(811)	LCO	NCA	LMO	LFP
Active cathode material	34.1%	31.8%	31.1%	35.3%	30.4%	40.1%	32.2%
Elemental composition of active cathode material							
Li	7.86%	7.82%	7.79%	7.09%	7.22%	3.84%	4.40%
Co	20.21%	12.07%	6.02%	60.21%	9.20%	…	…
Ni	20.13%	36.07%	47.93%	…	48.87%	…	…
Mn	18.84%	11.26%	5.61%	…	…	60.77%	…
Al	…	…	…	…	1.40%	…	…
Fe	…	…	…	…	…	…	35.40%
P	…	…	…	…	…	…	19.63%
O	32.95%	32.78%	32.66%	32.69%	33.30%	35.39%	40.57%
Graphite	19.0%	20.7%	20.6%	18.5%	22.0%	13.8%	16.6%
Carbon black	2.3%	2.1%	1.7%	2.4%	2.1%	2.7%	2.2%
Binder: PVDF	2.9%	2.9%	3.6%	3.0%	2.9%	3.0%	2.7%
Copper	16.4%	16.8%	15.7%	16.1%	16.9%	15.7%	14.5%
Aluminum	8.2%	8.4%	8.0%	8.1%	8.4%	7.9%	7.5%
Electrolyte: $LiPF_6$	2.2%	2.2%	2.6%	2.2%	2.3%	2.2%	3.3%
Electrolyte: EC	6.20%	6.30%	7.20%	6.00%	6.30%	6.10%	9.40%
Electrolyte: DMC	6.2%	6.3%	7.2%	6.0%	6.3%	6.1%	9.3%
Plastic: polypropylene	1.9%	1.9%	1.8%	1.8%	1.9%	1.8%	1.7%
Plastic: polyethylene	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.2%
Plastic: polyethylene terephthalate	0.3%	0.3%	0.4%	0.3%	0.3%	0.3%	0.4%

4.1.2 Current collectors

The anode and the cathode active materials are coated on the current collectors that allows the passage of electrons trough the external circuit and supports the electrode materials: for the anode, the current collector is made by copper and for the cathode is made by aluminium because of their electronic conductivity and stability (Costa et al.,2021). In particular, the copper it is used for the anode because it does not intercalate Li at low voltage (Makuza et al.,2021). The current collectors (Aluminium foil and Copper foil) lead to the battery cell terminals (Zubi et al.,2018).

4.1.3 Separator and electrolyte

The separator is typically a micro porous membrane made by polypropylene (PP) or polyethylene (PE) and it avoids the direct contact of anode and cathode, preventing a short circuiting and blocking the free electrons' travel in the cell (Makuza et al.,2021). In fact, the separator it is fundamental for the cell's safety thanks to the "shutdown" effect: if the cell heats excessively accidentally (sign of thermal runaway) , the separator melts due to the high temperature and fills its micro pores to stop lithium-ion flow between anode and cathode (Lowe et al., 2010) and this function damages the cell irreversibly but avoids negative consequences (Zubi et al.,2018). The main requirements of the separator are: high ionic conductivity, uniform porous structure, good wettability, excellent chemical stability, low thickness, limited shrinkage and low electric conductivity (Costa et al.,2021).

The electrolyte fills the separator, promoting the movement of ions from the cathode to the anode during the charging and from the anode to the cathode when discharging (Makuza et al.,2021) and it is a mixture of Lithium salt and organic solvents (Zubi et al.,2018). It is typically a high-grade Lithium salt (e.g. lithium hexafluorophosphate $LiPF_6$, lithium tetrafluoroborate $LiBF_4$, lithium bis (trisfluoromethanesulfonyl)mide LiTFSI, lithium perchlorate ($LiClO_4$), lithium hexafluoroarsenate ($LiAsF_6$)), dissolved in dipolar aprotic organic alkyl carbonate solvents, such as ethylene carbonate / dimethyl carbonate (EC/DMC) (Costa et al., 2021), Ethyl methyl carbonate (EMC), Diethyl carbonate (DEC), Propylene carbonate (PC) (Lowe et al,2010) .The organic solvents are useful to increase the solubility of Lithium, that results in higher battery performance because of better mobility of Lithium ions (Lowe et al.,2010). The electrolyte is useful to guarantee the electrons flow through the external circuit (preventing self-discharge), in fact it is ionically conductive but insulates the flow of electrons (Woody et al.,2020). Elecrolyte's choice is related to the cycle efficiency, temperature of operation and specific capacity (Makuza et al.,2021). In particular, Lithium polymer ion batteries, in which the cell casing is not high resistance (Zubi et al.,2018), contains gel electrolyte (that combines the characteristics of solid and conventional electrolyte) to prevent electrolyte leakage from the laminate pouch and to guarantee high thermal stability (Costa et al.,2021). Materials used to create this gel electrolyte are Polyethylene oxide (PEO), Polyacrylonitrile (PAN), Poly vinylidene fluoride (PVDF), Poly methyl methacrylate (PMMA) (Lowe et al.,2010).

The reactions occur at electrode/electrolyte interface and its selection is essential for the LIB performance, in fact it should have wide electrochemical window, low viscosity, good wettability towards separator and electrode, high flash point and high ionic conductivity (Costa et al., 2021). Another important reaction occurs during battery operation, forming the undesired solid electrolyte interface (SEI) that can decompose the electrode (Costa et al.,2021).

In Table 14 are reported the common materials used for LIBs and in Figure 43 are represented the percentage of components of LIBs.

Table 14. Common materials used in Li-ion batteries (Woody et al.,2020)

Cathode	Anode	Electrolyte salt	Electrolyte solvent	Separator	Binder	Current collectors	Conductive additives
LCO	C	$LiFP_6$	EC	PP	PVDF	Al (cathode)	black carbon
LMO	LTO	$LIBF_4$	DMC	PE	SBR	Cu (anode)	
LFP		$LiAsF_6$	DEC	ceramics		Al (LTO anode)	
NCA		$LiClO_4$	EMC				
NMC			PC				

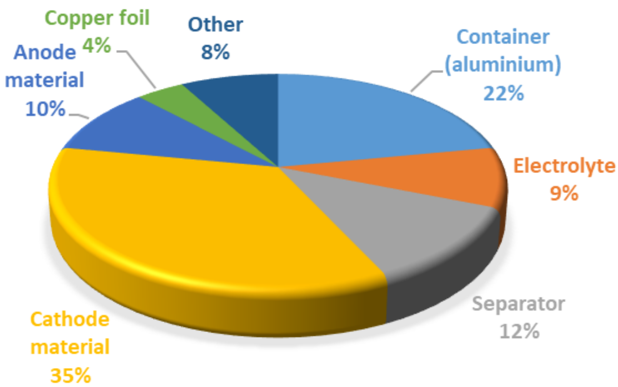

Figure 43. Components of a generic LIB (Mohanty et al.,2021)

4.2 Operation of LIBs

The LIB cell is governed by two different redox reactions (in this case it is described a rection for the LCO ($LiCoO_2$) cathode and graphite anode) that occurs in the charge/discharge cycles:

$$Cathode\ half\ reaction: LiCo_2 \leftrightarrow xLi^+ + Li_{1-x}CoO_2 + xe^-$$

$$Anode\ half\ reaction: 6C + xLi^+ + xe^- \leftrightarrow Li_{1-x}CoO_2 + Li_xC_6$$

$$Total\ reaction: LiCoO_2 + 6C \leftrightarrow Li_{1-x}CoO_2 + Li_xC_6$$

During the discharge, electrons flow from the anode to the cathode through an external circuit powering a device and, at the cathode, the metal oxide is reduced because it gains electrons from the external circuit (Woody et al.,2020). Li, at the anode, is oxidized from 0 to 1 oxidation state (Li to Li^+) and the Lithium ions migrate through the electrolyte from anode to the cathode (that is reduced), where they are intercalated into Lithium Cobalt oxide (through the reaction 2) and the Cobalt is reduced from +4 to +3 oxidation state: in this way, it is provided the electric current used for the specific work. In Figure 48 is represented the flow of electrons and Lithium ions and the reactions at each electrode that occur during the discharge phase.

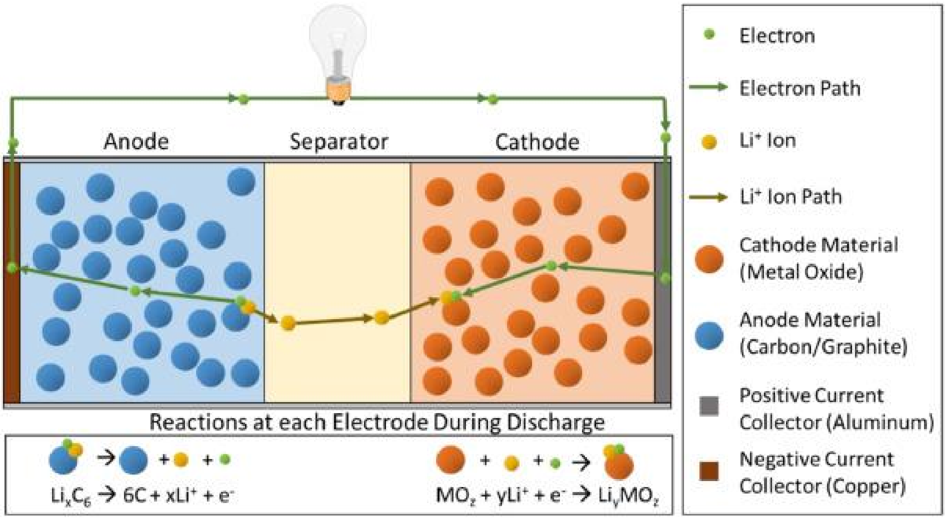

Figure 44. Flow of electrons and Lithium ions and reactions at each electrode during battery discharge. As the battery discharges, Li in the anode (x) decreases and Li in the cathode (y) increases. X corresponds to the battery state of charge and the relationship between x and y depends on the ratio of active material between anode and cathode. Different metal oxides (MOz) are used as cathode material (Woody et al., 2020)

During the charge phase, the oxidation reaction occurs at the cathode (it loses negative electrons): Li ions leave the Lithium cobalt oxide, travelling from cathode to anode and they are reduced to neutral Li and intercalated into graphite.

In both cases, during charge and discharge, the electrodes travel through the current collector to reach the external circuit and the Li ions travel through the separator/electrolyte system and, in particular, the electrolyte ensures the ionic conductivity and mobility, not only between the electrodes, but also inside the electrodes (Costaet al., 2021).

Li-ion battery cells can assume two different configurations (Figure 45):

- cylindrical cells: the layers are rolled and sealed a metal can and the typical size is 18mm diameter and 65 mm height (Zubi et al.,2018)
- stack cells: the anode, cathode and separator are enclosed in a laminate film and their edge are heat-sealed (Lowe et al.,2010); in particular, polymer Li-ion are stack cells with a polymer casing (that makes the cells more flexible) (Zubi et al.,2018). The stacked case often uses gel to prevent electrolyte from leaking.

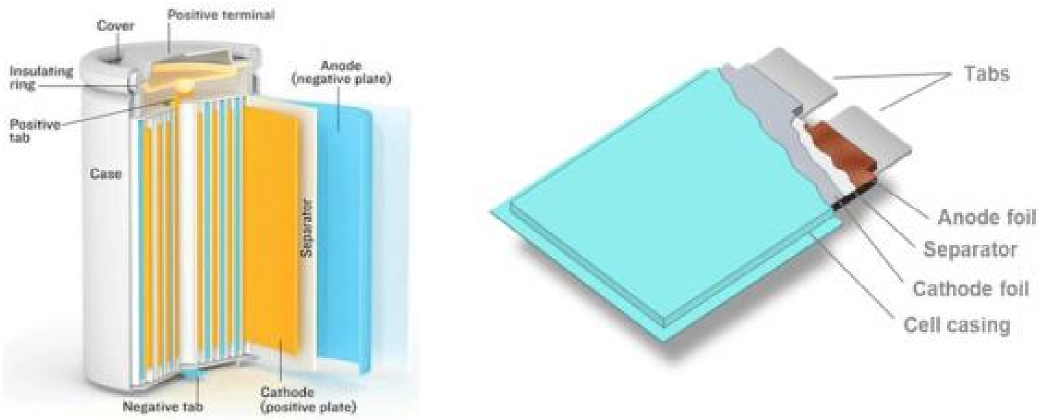

Figure 45. Li-ion batteries cells configurations (cylindrical cell and stack cell) (Zubi et al.,2018)

4.3 Lithium-ion batteries key properties

The most important features of the Li-ion battery are the specific energy and power, durability, and safety. The specific energy depends on the cathode and anode chemistry, covering a range from 90 to 250 Wh/Kg: the NCA has the highest specific energy and the LFP are the worst; the maximum power that a Li-ion battery could provide depends on the voltage, density of Lithium ions, solid electrolyte interphase, diffusion coefficient of the electrodes and their conductivity and the specific power, that is described within the power to energy (P/E) ratio (Zubi et al., 2018). The durability is another important feature: batteries can degrade in different proportions depending on the use, in fact it is accelerated by low or high operation temperatures, overcharge, deep discharge and high amperage; in particular, the external condition (specifically the temperature) cause calendar and the charge and discharge conditions cause cycle ageing (Zubi et al.,2018). The loss of cyclable Lithium causes capacity fade and loss of power because of side reactions; the loss of electrode active materials is due to dissolution, structural degradation and particle isolation (Zubi et al.,2018). The cycle life indicates the number of full cycles that a battery can deliver under standard operating conditions before its key performances drop to 80% of initial values and, depending on the application, a battery can be considered obsolete at a higher or lower value than the 80% (Zubi et al., 2018). Safety is another important feature because batteries contain Lithium, oxygen and a flammable electrolyte and one of the most relevant problem is the thermal runaway because, if a battery cell is excessively heated (for instance through prolonged overcharge or short circuiting) to the level of decomposing its metal oxide, the battery could burst into flames because of the reaction of free oxygen with Lithium and also, the formation of dendrites over time could build a conductive bridge, resulting in short-circuit and eventually thermal runaway. The safety must be controlled at inherent level, choosing the best battery chemistry (e.g. LFP is thermically stable than LCO), at cell design level by elements that prevent short circuits between cathode and anode, through the Battery Management System (BMS) that avoids overcharge and short-circuits through voltage and current controls, providing safe operating conditions (Zubi, Lopez, Carvalho, & Pasaoglu, 2018).

In Figure 46 are represented the main characteristics of commercial Li-ion batteries. In Table 15 are resumed the main technical features of Li-ion batteries.

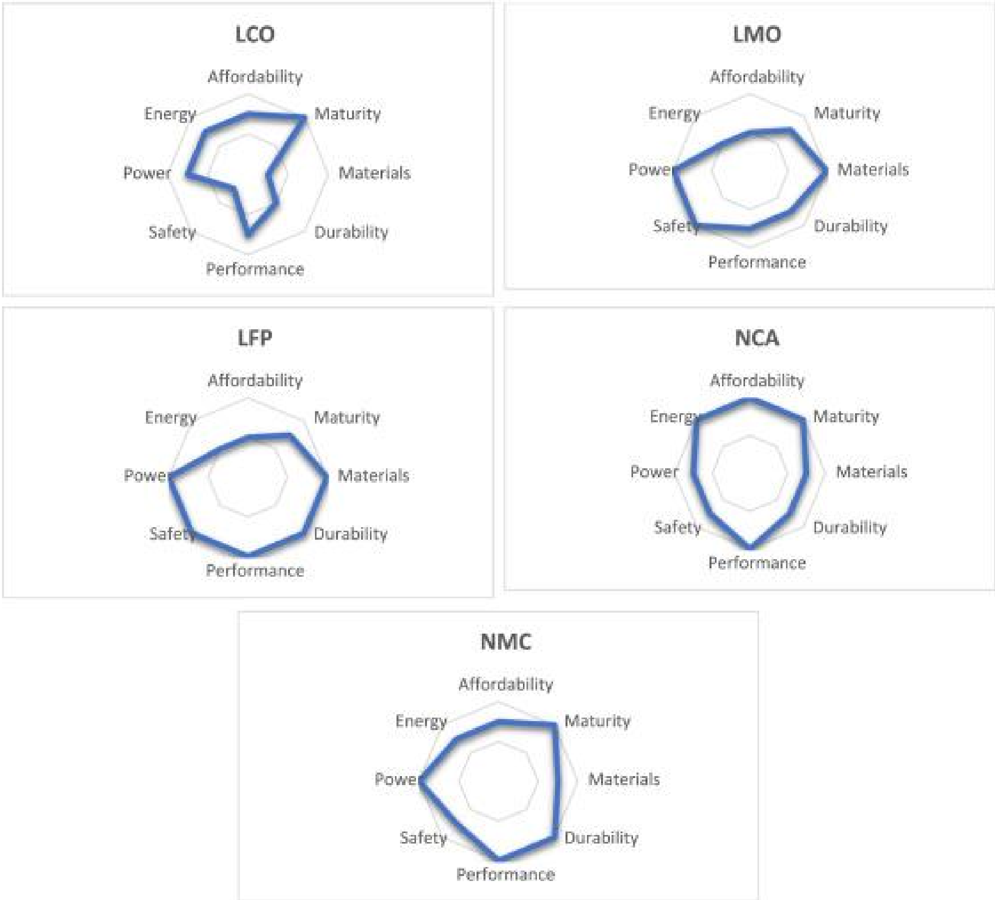

Figure 46. Main characteristics of commercial Li-ion batteries (Zubi et al., 2018)

Table 15. Main technical features of commercial Li-ion batteries. Elaborated from (Zubi et al.,2018; Battery University, 2021)

Specifications	LCO	LMO	LFP	NCA	NMC
in use since	1991	1996	1999	1999	2004
Anode	graphite	graphite or LTO	graphite	graphite	graphite
Cathode	LiCoO2	LiMn2O4	LiFePo4	LiNiCoAlO2	LiNiMnCoO2
Voltages	3.6 V nominal; typical operating rage 3-4.2 V/cell	3.7V (3.8 V) nominal; typical operating range 3.0–4.2V/cell	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cel	3.60V nominal; typical operating range 3.0–4.2V/cell	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher
Charge (C-rate)	0.7-1 C, charges to 4.2 V(most cells); 3 h charge typical. Charge current above 1C shortens battery life.	0.7–1C typical, 3C maximum, charges to 4.20V (most cells)	1C typical, charges to 3.65V; 3h charge time typical	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells	0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2.50V cut off. Discharge current above 1C shortens battery life.	1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)	1C typical; 3.00V cut-off; high discharge rate shortens battery life	1C; 2C possible on some cells; 2.50V cut-off
Cycle life	500-1000 full cycles	1000-1500 cycles	up to 2000 full cycles	1000-1500 full cycles	1000-2000 cycles
Energy density	150-190 Wh/Kg	100-140 Wh/Kg	90-140 Wh/Kg	200-250 Wh/Kg	140-200 Wh/Kg
Thermal runaway temperature	150 °C	250°C	200°C	150 °C	210 °C
Used in	mobile phones, tablets,laptops, aviation	e-bike, power tools and medical deivices	e-bikes, power supply systems	electric vehicles (Tesla)	electric vehicles, plug-in hybrid electric vehicles mainly, portable electronics, power tools and medical devices
Comments	The main disadvantage is its low unherent safety and due to the low thermal stability of cobalt-oxide, thermal runaway could be initiated already at 150 °C. Limited load capabilities (specific power). Cobalt is expensive	Low internal resistance, low energy denisty.Due to the higher thermal stability of manganese oxide, LMO batteries are inherently safer. Furthermore, the battery is cobalt-free and relies on abundant and eco-friendly materials.	The main advantages are durability, inherent safety (one of safest Li-ion) and reliance on abundant, eco-friendly materials. The battery tolerates operation with a wide SOC window (15–100%), and the cell displays constant voltage within this range, which implies constant performance	Typically, NCA cathodes use a blend of 80% nickel, 15% cobalt and 5% aluminium, and therefore the reliance on cobalt is relatively moderate when compared with LCO batteries. Outstanding specific energy, high specific power	They have lower energy density.The proportions of nickel, manganese and cobalt could be varied to influence the battery characteristics and provide tailored solutions for specific applications. Increasing the share of nickel favours the specific energy aspect, while increasing the share of manganese increases specific power.Provides high capacity and high power

4.4 Battery management system (BMS)

Li-ion pack batteries are equipped with the Battery Management System (BMS) useful to manage and monitor the functionality and performance aspects, such as voltage, current, state of charge (SOC), state of health (SOH), state of function (SoF), state of safety (SoS); it is based on measurable outputs like temperature, voltage and current (Zubi et al., 2018; Woody et al.,2020). BMS considers as input the current, the voltage, the temperature sensors, the vehicle control (in case of EVs) and the digital inputs; the outputs are thermal management modules including fans and electric heaters, balancing modules including capacitors and switch arrays to equalize batteries, managing voltage, digital outputs such as charging indicators and failure alarms (Woody et al.,2020). The BMS, to derive SoH, considers internal resistance, capacity, voltage, self-discharge, number of charge–discharge cycles, ability to accept a charge, age of the battery, temperature of battery during its previous uses, total energy charged and discharged. It can perform the battery balancing and controls also capacity, power consumption, remaining operating time and charging cycles. One of the most important value is the control of the SoC because in electric or hybrid vehicles, batteries are connected in series to have a sufficient voltage but, even a small difference between the cells, can deteriorate the system; consequently, the solution is an equalization system for the SoH of each cell of the battery: the BMS in fact controls the SoH of the single cells and the charge applied to each cell in the battery pack during the charging phase because the overload can destroy the cell and an excessive discharge can lead to permanent decrease of the maximum charge that can be stored (ENEA, 2011). The balancing is based on the presence of an external circuit (to balance the cells) and there are two balancing methods:

- the passive balancing: the external circuit is a resistor, and it is used to dissipate the excess energy on resistors connected in parallel to each single cell and to level the distribution of the state of charge values of the various cells into the battery system. It is the cheapest and easiest method and there are switches that, when a cell has reached the 100% SoC, create a by-pass for the charge current and the energy is dissipated to the resistors if also the weaker cells has reached the complete SoC (ENEA, 2011)
- the active balancing: energy is drawn from the most charged cell and transferred to the least charged cells and there is no dissipation of energy. This method allows to have a higher energy efficiency because the energy of the most charged cells is redistributed to the least charged cells through capacitors, inductors or transformers (ENEA, 2011).

Summarizing, the BMS operates at cell, module, and pack levels and allows the "preventing damage to cells and battery packs, ensuring proper operational voltage and temperature ranges, balancing SoC differences between cells, guaranteeing safe operation, extending battery service life as long as possible, and maintaining batteries in a healthy condition that will fulfill the vehicle requirements" (Woody et al.,2020).

5. Hybrid and electric buses: emissions assessment

Because of the spread of electrification for the bus sector, in this chapter are examined the hybrid and electric city buses produced and distributed by CNH Industrial. In the second part, is performed the annual emissions assessment for the Turin urban bus fleet, considering also different supposed scenarios of increasing electrification.

5.1 CNH Industrial: Hybrid and Electric buses

As described in the chapter 2, CNH Industrial is one of the global leaders for the commercial vehicles production. In particular, for this thesis, were considered the hybrid and electric technologies implemented for city buses.

CNH Industrial is specialized in manufacturing of urban buses, inter-city buses, coaches and minibuses and it commercializes them through two brands:

- **IVECO Bus**: it is one of the European leaders for buses production (urban, inter-city, coaches and minibuses) and it is present in more than 40 countries (CNH Industrial, 2021). Buses are all produced in European plants: in France (town of Annonay), in which are produced urban buses and tourism coaches; Czech Republic (town of Vysoké Mýto), that is the second biggest European manufacturer of automotive and collective passenger transport vehicles; Italy (town of Suzzara), in which are produced vans and minibuses (CNH Industrial, 2021).
- **Heuliez Bus**: it is the French leader for urban buses, and it is spreading also in Spain, Switzerland, Belgium, Luxembourg, and the Netherlands (CNH Industrial, 2021). The production takes place in France (town of Rorthais).

Although the two brands are different, the solutions, technologies and components adopted are basically the same and this means that the buses are the same but are distributed through two different brands. For that reason, are described in detail only the IVECO hybrid and electric city buses. In Table 16 are resumed the current line-up of different models and types of buses produced by IVECO Bus: for this thesis were analysed only the hybrid and electric city buses but, for completeness, are reported also the other models. In Table 17 are reported the correspondent city buses produced by Heuliez Bus.

Table 16. Iveco Bus models (IVECO, 2021)

Brand	Model	Engine	Type
Iveco Bus	Crossway Line 10.8 m/ 12 m / 13 m	Diesel Euro VI	Intercity
	Crossway POP 10.8 m /12 m/ 13	Diesel Euro VI	Intercity
	Crossway PRO 10.8 m /12 m/ 13 m	Diesel Euro VI	Intercity
	Crossway Line POP 12 m/13 m	Natural power (CNG)	Intercity
	Crossway Low entry Line 10.8 m /12 m/13 m	Diesel Euro VI	Intercity
	Crossway Low entry City 10.8 m /12 m/13 m	Diesel Euro VI	Intercity
	Crossway Low entry 12 m (CI, CII) & 13 m (CII)	Natural power (CNG)	Intercity
	Urbanway 10 m	Diesel Euro VI	City
	Urbanway 12 m	Diesel Euro VI	City
	Urbanway 18 m	Diesel Euro VI	City
	Urbanway 10.5 m	Natural power (CNG)	City
	Urbanway 12 m	Natural power (CNG)	City
	Urbanway 18 m	Natural power (CNG)	City
	Urbanway Hybrid High Value 12 m	Hybrid (electric+Diesel Euro VI)	City
	Urbanway Hybrid Hugh Value 18 m	Hybrid (electric+Diesel Euro VI)	City
	Urbanway In-Motion-Charging 18 m	Electric	City
	Crealis 12 m/ 18 m	Diesel Euro VI	City
	Crealis 12 m/ 18 m	Natural power (CNG)	City
	Crealis Hybrid High Value 12 m/ 18 m	Hybrid (electric+Diesel Euro VI)	City
	E-WAY 9.5 m/ 12 m / 18 m	Electric	City
	Evadys	Diesel Euro VI	Coach
	Daily LINE	Diesel Euro VI	Minibus
	Daily LINE	Natural power (CNG)	Minibus
	Daily Start	Diesel Euro VI	Minibus
	Daily Tourys Plus	Diesel Euro VI	Minibus

Table 17. Heuliez Bus models

Brand	Model	Engine	Type
Heuliez Bus	GX 137 9.5 m / 10.7 m	Diesel Euro VI	City
	GX 137 9.5 m / 10.7 m	Electric	City
	GX337 12 m	Diesel Euro VI	City
	GX 337 12 m	Natural power (CNG)	City
	GX 337 HYB 12 m	Hybrid (electric + Diesel Euro VI)	City
	GX 337 12 ELEC	Electric	City
	GX 437 18 m	Diesel Euro VI	City
	GX 437 18 m HYB	Hybrid (electric + Diesel Euro VI)	City
	GX Linium 12 m/ 18 m	Diesel Euro VI	City
	GX Linium 12 m/ 18 m	Natural power (CNG)	City
	GX Linium 12 m/ 18 m	Hybrid (electric + Diesel Euro VI)	City
	GX Linium 12 m/ 18 m	Electric	City

5.1.1 Hybrid vehicles: a general description

In general, the hybrid propulsion technology is equipped by an internal combustion engine (gasoline or Diesel engine) and an electric motor, that uses the energy stored in an accumulator (Lithium-ion batteries or supercapacitors). The main advantages are the fuel consumption reduction and the emissions reduction because the electric motor helps the internal combustion engine particularly during situations of less efficiency, such as the start phase, the overtaking, the low velocity phases, and moments of highest loading. It possible to classify the hybrid system considering the hybridization level and the configuration.

Considering the different hybridization levels, the various types of systems are:

- **Full hybrid**: the vehicle can be powered from the internal combustion engine and from the electric motor; they can work simultaneously or independently, and the vehicle can travel in full electric mode for few kilometres. The combustion engine is used also, if needed, for the battery recharge and, during the braking and deceleration phases, the electric motor acts as electricity generator to recharge the battery pack.
- **Plug-in hybrid**: it is variation of the full hybrid because it works as a full hybrid, but it has larger battery, allowing to vehicle to travel in full electric mode for more kilometres. For that reason, the battery can be charged through an external electrical socket or charging point.
- **Mild hybrid**: this system uses an internal combustion engine and a small electric motor; the latter is not connected to the wheels, and it means that vehicle can't travel in full electric mode but the transmission is always given by the internal combustion engine. Consequently, the battery is smaller than a full hybrid, but the energy is recovered, as a full hybrid, during the braking or deceleration phases. The electric motor acts as a boost for the combustion engine, allowing to reduce fuel consumption and emissions.

Considering the different configurations, the various types of hybrid systems are:

- **Parallel hybrid drivetrain**: this system uses both the internal combustion engine and the electric motor to power the vehicle; it is not required an external recharging of the battery because it occurs, thanks to the internal combustion engine, through the conversion of the kinetics energy of the vehicle into electricity: the principle is that the excess of energy, that is generated during braking and deceleration phases, is captured and converted into electricity instead of being dissipated as heat. The internal combustion engine and the electric motor can work together or separately. This configuration is shown in Figure 47.
- **Series hybrid drivetrain**: this system uses only the electric motor for the traction of the vehicle and the internal combustion engine is not connected to the wheels, but it generates the electric current to power the electric motor or to recharge the battery; a generator, that is powered by the internal combustion engine, generates electricity, that is transferred to the battery pack, which in turn powers the electric motor; as an alternative, the generator can power directly the electric motor with the battery pack . Therefore, the electric motor is the only responsible for the vehicle's traction and the required energy is obtained from batteries or the internal combustion engine or both, when needed a large quantity of energy. Also in this case, it is not required an external recharge source for the battery. This configuration is shown in Figure 48.
- **Series-parallel drivetrain**: this configuration is a combination of the parallel hybrid system and the series hybrid system. The internal combustion engine can be used for the vehicle's traction (as parallel system) or it can be disconnected from the wheels, allowing the electric motor to power the vehicle (as series system). This configuration is shown in Figure 49.

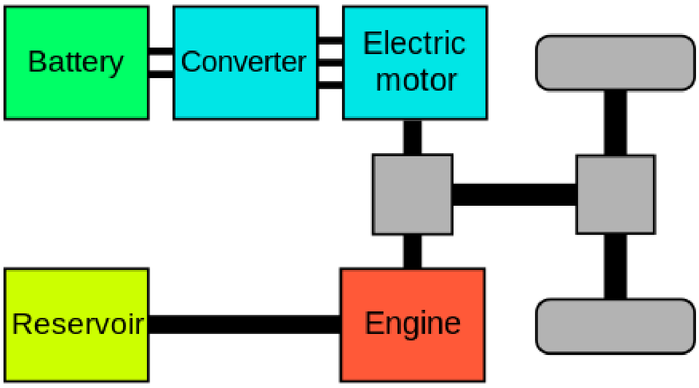

Figure 47. Parallel hybrid drivetrain (Wikiwand)

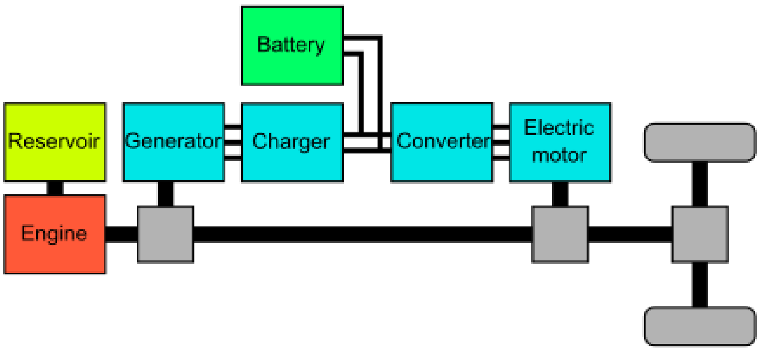

Figure 48. Series hybrid drivetrain (Wikiwand)

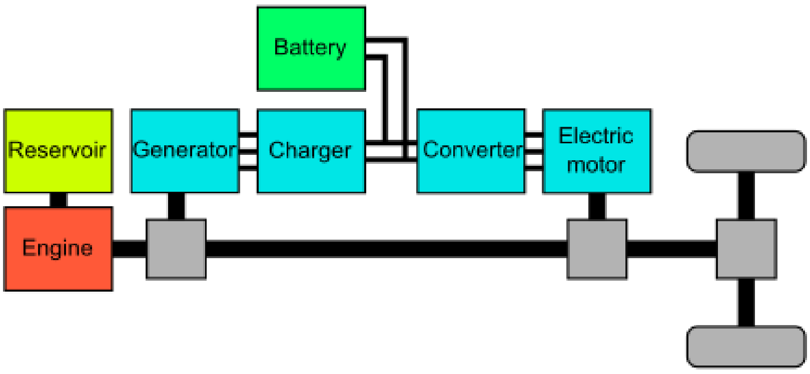

Figure 49. Series-parallel hybrid drivetrain (Wikiwand)

5.1.2 Hybrid buses: the IVECO Urbanway and the Crealis

In this section are described the hybrid urban buses produced by IVECO, the Urbanway Hybrid High Value, and the Crealis Hybrid High Value, both available with a length of 12 m or 18 m. The equivalent model produced by Heuliez bus of the Urbanway are the GX337 HYB (12 m long) and the GX437 HYB (18 m long); the corresponding of the Crealis is the GX Linium Hybrid.

The models mentioned above are part of the current line-up of buses and they represent the evolution of the old products (phased out), that in this section were not described. The phased-out buses are Iveco Citielis Hybrid 12 m and 18 m; Iveco Urbanway Full Hybrid 12 m and 18 m; Iveco Crealis Full Hybrid 12 m and 18 m;

Heuliez GX Full Hybrid 12 m and 18 m. Considering the first generation hybrid running park, were sold 1265 vehicles.

The Urbanway Hybrid High Value, shown in Figure 50, is the evolution of the Urbanway Full Hybrid. It is an urban bus equipped with the serial hybrid technology, realized through the combination of the Euro VI Diesel engine (Tector 7 engine) and an ultracapacitor for the 12 m version and a Lithium-ion battery (Li-NMC type) or an ultracapacitor for the 18 m version. The serial hybrid system means that there is not realized a mechanical connection between the internal combustion engine and the traction, that is ensured constantly by the electric motor. The battery or the ultracapacitor is the electric engine power during the acceleration phase.

Figure 50. IVECO Urbanway Hybrid High Value-18 m version (IVECO, 2021)

Therefore, this technology combines sustainability and efficiency, because the electric generator realizes the traction, giving a reactive acceleration at the start-up, a gradual speed increase and consistent power to travel as efficient commercial speeds, optimizing the efficiency of the engine and allowing to fuel consumption and emissions reduction.

These buses present the following features (IVECO, 2021):

- “Arrive & Go” function, through which the bus travels in full electric mode below 20 Km/h, that means near the stop, and allows the vehicle to travel in all-electric mode at low speed, even without stopping. In particular, the Diesel engine stops 30 meters before stops, travelling in full electric mode, and restarts after about 30 meters;
- electric energy recovery during braking and descent, that contributes to the battery recharging;
- fuel consumption reduction by up to 40% compared to a conventional bus;
- CO_2 emissions reduction by about 33% per Km and NOx emissions by 40% per Km than a conventional diesel bus;
- noise reduction in Full Electric mode by 7 dB less than Diesel;
- electric traction without emissions and vibrations.

In Table 18 are reported the main technical information for the two models of Urbanway Hybrid High Value.

Table 18. Technical feature of IVECO Urbanway Hybrid High Value (IVECO, 2021)

	Crealis Hybrid High Value 12 m	Crealis Hybrid High Value 18 m
Length	12485 m	18395 mm
Width	2550 mm	2550 mm
Height	3291 mm	3291 mm
Wheelbase	6120 mm	5355/6675 mm
Max legal permissible gross vehicle weight	19950 Kg	30000 Kg
Max permissible front axle load	7500 Kg	7500 Kg
Max permissible rear axle load	13000 Kg	13000 Kg
Hybrid Engine	Electric	Electric
	Internal combustion engine: Tector 7 Diesel Euro VI 210 KW/286 CV	Internal combustion engine: Tector 7 Diesel Euro VI 210 KW/286 CV
Generator	Start the engine without starter or flywheel	Start the engine without starter or flywheel
	Permanent magnet brushless generator coupled to the engine	Permanent magnet brushless generator coupled to the engine
	Power 140 kW	Power 200 kW
Electric engine	Permanent magnet electric motor	Asynchronous brushless electric engine
	Power: 120 kW, peak: 195 kW	Power: 160 kW, peak: 200 kW
	Torque: intermittent 1524 Nm, peak 2134 Nm	Torque: intermittent 3800 Nm, peak 5100 Nm
Energy accumulators	Utracapacitors EDLC: 0.82 kWh, 500-750 VDC, 200 kW	1st option. Battery Li NMC: 31.8 kWh, 665 V, 200 kW
		2nd option. Ultracapacitor EDLC : 0.82 kWh, 500-750 VDC, 200 kW
Engine	Hi-SCR exhaust gases treatment system	Hi-SCR exhaust gases treatment system
	Diesel heater filter	Diesel heater filter
	Fire detection of engine compartment	Fire detection of engine compartment
Fuel tank	230 Liters	340 Liters
AdBlue tank	54 liters	90 Liters

The Urbanway Hybrid High Value 18 m has the option of a NMC battery: it presents a capacity of 32 KWh and a weight of 520 Kg. The producer is BAE Systems, and the cells are produced by LG.

It is important to specify that the Iveco Citielis HYB, a phased-out product, has a different battery than the new model: it presents in fact a LFP battery with 11.6 KWh of capacity and a weight of 385 Kg. The battery producer is BAE Systems, and the cells producer is A123 Systems.

In Figure 51 is represented the Urbanway Full Hybrid operation: the maximum velocity that the bus can reach is about 70 Km/h; when it reaches a velocity below 20 Km/h, it works in full electric mode up to the stop. For that reason, in this phase, the generator stops and during the deceleration, the energy is recovered and stored into the battery. After the stop, the bus continues to travel in the electric mode, through the power supplied by the batteries; then, and above 20 Km/h or after 30 m, the generator starts and the system works in hybrid mode, using the power supplied by generator and the battery.

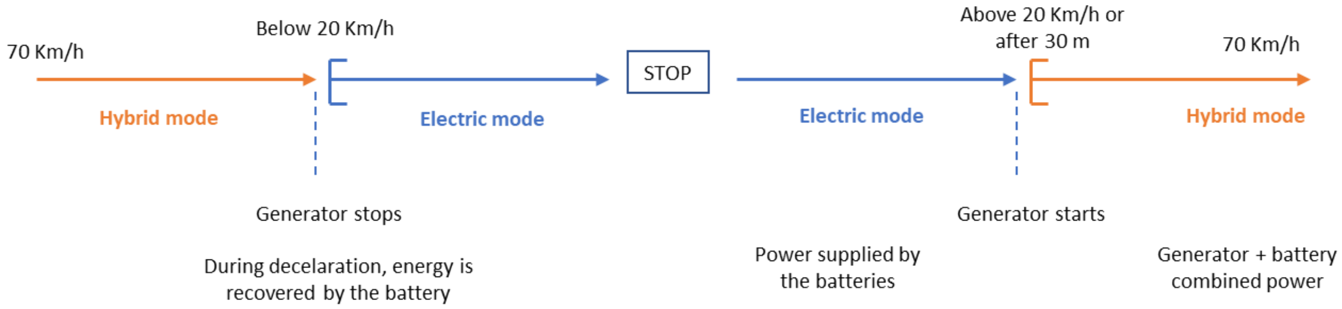

Figure 51. Urbanway Full Hybrid system operation (IVECO, 2021)

To treat the exhaust gases, IVECO adopts the HI-SCR technology (Figure 52), developed by the CNH Industrial's brand FPT, that allows to obtain the emission levels of Euro VI. This system does not present the exhaust gases recirculation technology and presents different advantages:

- combustion process optimization and consequent fuel consumption reduction;
- presence of Diesel Oxidation Catalyst, that oxidizes CO and HC (obtaining CO2 and H_2O) and transforms NO into NO_2;
- presence of a Diesel Particulate Filter (DPF), that reduces the Particulate Matter (PM) emissions;
- Selective Catalytic Reduction (SCR) to reduce by 97% of NOx trough AdBlue injection, that is a solution formed by 32.5 % of Urea and 67.5 % of deionized water. The AdBlue reacts with exhaust gases forming ammonia (NH_3) and then, through a reduction reaction, the NOx are converted into N_2 and water;
- Clean-up catalyst, that eliminates the residual ammonia.

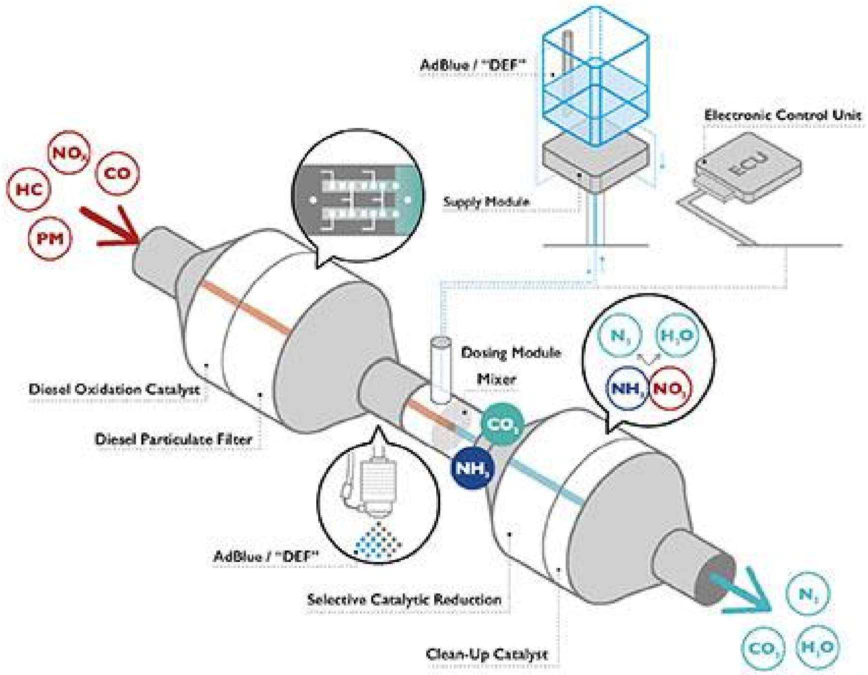

Figure 52. HI-SCR technology (IVECO, 2021)

Another city bus that IVECO produces with hybrid system is the Crealis Hybrid High Value (Figure 53), that is specifically a Bus Rapid Transit (BRT), that means a trolley bus, and it is available in the versions of 12 m and 18 m. It is the evolution of the Crealis Full Hybrid, and it can be considered an evolution of the Urbanway Hybrid High Value; it is an alternative to tramways, travelling on dedicated high-speed lines. The hybrid architecture and the technical solutions are the same described for Urbanway Hybrid High Value.

Figure 53. IVECO Crealis Hybrid High Value 18 m (IVECO, 2021)

In Table 19 are reported some main features of the Crealis Hybrid High Value.

Table 19. Technical feature of IVECO Crealis Hybrid High Value (IVECO, 2021)

	Crealis Hybrid High Value 12 m	Crealis Hybrid High Value 18 m
Length	12485 m	18395 mm
Width	2550 mm	2550 mm
Height	3291 mm	3291 mm
Wheelbase	6120 mm	5355/6675 mm
Max legal permissible gross vehicle weight	19950 Kg	30000 Kg
Max permissible front axle load	7500 Kg	7500 Kg
Max permissible rear axle load	13000 Kg	13000 Kg
Hybrid Engine	Electric	Electric
	Internal combustion engine: Tector 7 Diesel Euro VI 210 KW/286 CV	Internal combustion engine: Tector 7 Diesel Euro VI 210 KW/286 CV
Generator	Start the engine without starter or flywheel	Start the engine without starter or flywheel
	Permanent magnet brushless generator coupled to the engine	Permanent magnet brushless generator coupled to the engine
	Power 140 kW	Power 200 kW
Electric engine	Permanent magnet electric motor	Asynchronous brushless electric engine
	Power: 120 kW, peak: 195 kW	Power: 160 kW, peak: 200 kW
	Torque: intermittent 1524 Nm, peak 2134 Nm	Torque: intermittent 3800 Nm, peak 5100 Nm
Energy accumulators	Utracapacitors EDLC: 0.82 kWh, 500-750 VDC, 200 kW	1st option. Battery Li NMC: 31.8 kWh, 665 V, 200
		2nd option. Ultracapacitor EDLC : 0.82 kWh, 500-750 VDC, 200 kW
Engine	Hi-SCR exhaust gases treatment system	Hi-SCR exhaust gases treatment system
	Diesel heater filter	Diesel heater filter
	Fire detection of engine compartment	Fire detection of engine compartment
Fuel tank	230 Liters	340 Liters
AdBlue tank	54 liters	90 Liters

The Full Hybrid buses will reach the phase out in December 2021 to be replaced by Urbanway and Crealis Mild Hybrid with 1 KWh battery.

5.1.3 Electric vehicles: a general description

In general, the electric vehicles are powered by an electric motor instead of the internal combustion engine and the principle is that the electric energy is transformed into mechanical energy to run the vehicle. The electric motor uses the energy stored in a battery pack, that is transferred to the first through an inverter, that transforms the direct current (DC) of the traction battery pack to alternating current (AC). This system recovers energy, like the hybrid system, during deceleration and braking: in this phases, the electric motor acts as a generator and recharges the battery. The batteries are Lithium-ion type, they are usually grouped into different packs to reach the energy required and they must be externally charged: the on-board charger allows recharge, controlling the current flow (voltage and current) from the grid to the battery. It takes the incoming AC supplied via the charge port and converts it to DC power for charging the traction battery. The recharge can occur in two ways: using the direct current, in this case the on-board charger is bypassed, and the current is sent directly to the battery through the Battery Management System; using the alternating current of a charging station, in this case the current flows through the charging cable to the on-board charger, which converts the AC current to DC and sends it to the battery via the Battery Management System. In Figure 54 are shown the different elements of an electric vehicle.

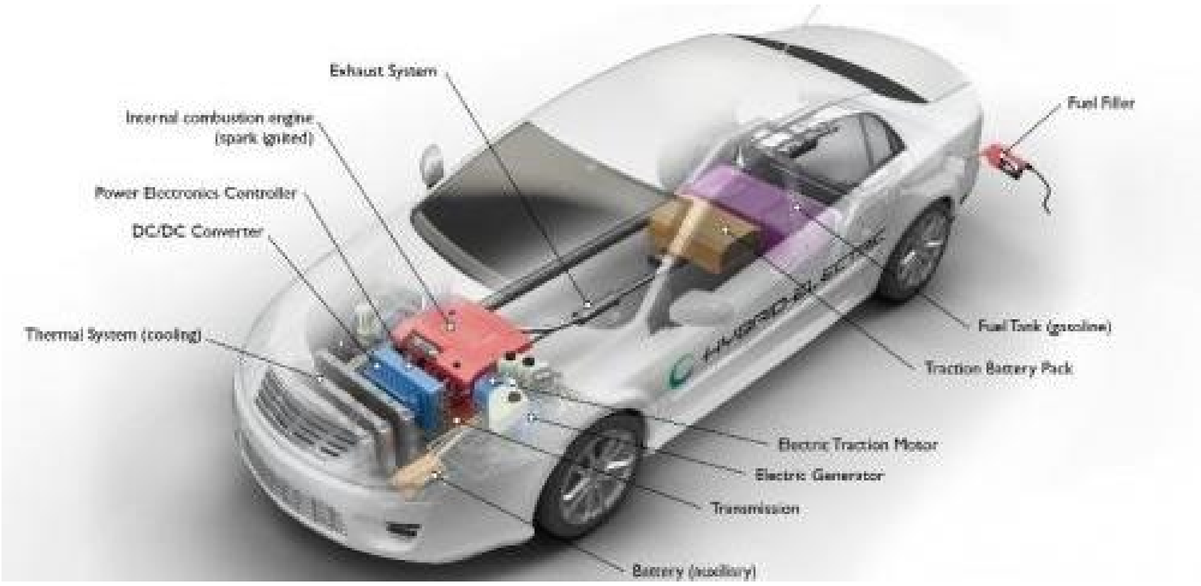

Figure 54. Electric vehicle scheme (U.S. Department of energy.)

5.1.4 Electric buses: the IVECO E-WAY

In this section are described the electric urban buses produced by IVECO, the E-WAY Full Electric, available both in standard version, with a length of 9.5 m or 12 m, and articulated version, with a length of 18 m. The equivalent model produced by Heuliez bus are the GX137 ELEC (9.5 m or 10.8 m long), the GX337 ELEC (12 m long) and the GX437 ELECT (18 m long). In Figure 55 is represented the IVECO E-WAY Full Electric.

Figure 55. IVECO E-WAY Full Electric (IVECO, 2021)

The IVECO E-WAY is 100% electric and it means that, during travelling, it guarantees zero emissions because of the absence of the internal combustion engine, that is responsible, due to the combustion reaction, for the pollutant emissions in the atmosphere. In Table 20, 21 and 22 are reported the main technical features for the three models.

Table 20. IVECO E-WAY 9.5 m technical features (IVECO, 2021)

	E-WAY 9.5 m
Length	9510 mm
Width	2330 mm
Height	3350 mm
Wheelbase	4130 mm
Max passenger capacity (number)	68
Gross kerb weight	10572 Kg
Electric motor	brand: Siemens
	power: 160 KW
	torque: 2500 Nm
Battery	Lithium ion batteries with NMC cells
	energy: 210 KWh (option 245 KWh)
	brand: Forsee Power (ZEN 4)
Charge system	Overnight charge

Table 21. IVECO E-WAY 12 m technical features (IVECO, 2021)

	E-WAY 12 m
Length	12060 mm
Width	2550 mm
Height	3350 mm
Wheelbase	6120 mm
Max passenger capacity (number)	86
G.V.W max permitted weight	20000 Kg
Electric motor	brand: Bae System
	power: 120/190 KW
	toque:1000 Nm (continuous) / 2100 Nm (max)
Battery first option	Lithium ion batteries with NMC cells
	energy: 350 KWh
	brand: Forsee Power (ZEN 35)
	charge system: overnight charge
Battery second option	Lithium ion batteries with LTO cells
	energy: 73 KWh
	brand: Forsee Power (Pulse 15)
	charge system: opportunity fast charging via off board pantograph

Table 22. IVECO E-WAY 18 m technical features (IVECO, 2021)

	E-WAY 18 m
Length	17970 mm
Width	2550 mm
Height	3350 mm
Wheelbase	5355/6675 mm
Max passenger capacity (number)	130
G.V.W max permitted weight	30000 Kg
Electric motor	brand: Bae System
	power: 160/200 KW
	torque: 2100 Nm (continuous) /2405 (max)
Battery first option	Lithium ion batteries with LTO cells
	energy: 102 KWh
	brand: Forsee Power (Pulse 15)
	Opportunity fast charging via Off board pantograph
Battery second option	Lithium ion batteries with NMC cells
	energy: 250 KWh
	brand: Forsee Power (Flex 7)
	charge system: opportunity fast charging

It is important to show the E-WAY battery layout: considering the IVECO E-WAY 12 m long, it is equipped with Li-ion NMC battery of 350 KWh capacity. This total capacity is divided into 8 battery packs (Figure 56): six of them are on the roof and two in the tailgate (Sustainable bus, 2020).

Figure 56. IVECO E-WAY layout (IVECO BUS, 2018)

From the Tables 20 to 23, it is possible to notice that the producer of the electric motor is Siemens for the 9.5 m version and Bae System for the 12 m and 18 m version. As regard batteries, the producer is always Forsee Power that offers different solutions:

- 9.5 m version: it is equipped with a 210 KWh Lithium-ion NMC battery pack (ZEN 4 model), the recharge is performed during night at depot and the bus can travel about 250 Km;
- 12 m version: there are two batteries options. The first is that the bus is equipped with a 350 KWh Lithium-ion NMC (Nickel-Manganese-Cobalt) high energy battery pack (ZEN 35 model) and the recharge is performed during night at depot. It can travel about 350 Km with a single charge. Under controlled conditions, this bus presents a high efficiency because, during a test performed on October 2019, it travelled for 12 hours (from 10 a.m. to 9:41 p.m.) at an average speed of 46 Km/h, maintaining heating and air conditioning turned off, and it covered 527 Km with a single charge, presenting a 4% remaining charge in the battery (Sustainable Bus, 2019). The second battery option is a 73 KWh Lithium-ion LTO (Lithium-Oxyde-Titanate) high power battery pack (Pulse 15 model), that offers less autonomy (less Km with a single charge) but a longer life and it can be charged rapidly via an off-board pantograph for a time of 15 minutes from 15 to 25 times a day (Forsee Power, 2021);
- 18 m version: there are two batteries options. The first is that the bus is equipped with a 102 KWh Lithium-ion LTO (Lithium-Oxyde-Titanate) high power battery pack (Pulse 15 model) and it can be charged rapidly via an off-board pantograph for a time of 15 minutes from 15 to 25 times a day (Forsee Power, 2021).The second battery option is a 250 KWh Lithium-ion NMC (Nickel-Manganese-Cobalt) high energy battery pack (Flex 7 model) that presents both an high autonomy and a fast recharge, in fact it travels up to 120 Km on a single charge and it allows to perform occasional fast recharges several times a day (50% recharge in 15 minutes up to 20 times a day), and thus optimize on-board energy (Forsee Power, 2021).

To sum up, Forsee Power battery systems are available in three different models:

- **ZEN 35 high energy (night charge):** this battery pack is Li-ion NMC type and it presents a slow charging system, in fact it must be charged for several hours during night at the depot, through a cable plug, after the bus has finished for the day. Because of the high specific energy density of 125 Wh/Kg, this system can store a large amount of energy and, consequently, it allows to reach high autonomy in Km, indeed it can run for a whole day on a single charge. The battery presents an optimal mechanical design for bus roof and back integration; to reach the energy of 250 KWh, are connected in parallel 10 scalable modular systems of 35 KWh (Forsee Power, 2021). The cells' producer is LG and the life is about 8 years: considering that a bus life is about 15 years, the battery must be substituted once. In Figure 57 are represented the modules of ZEN 35 and in Table 23 are resumed the main features.

Figure 57. Forsee Power ZEN 35 (Forsee Power, 2021)

Table 23. Forsee Power ZEN 35 features. SOC: state of charge, BOL: beginning of life (Forsee Power, 2021)

Forsee Power ZEN 35-high energy battery pack		
Chemistry	Li-ion NMC battery	
Voltage	Minimal	440 V
	Nominal	642 V
	End of charge	739 V
Energy/Capacity	Nominal energy (1C, BOL, 25°C)	350 KWh
	Nominal capacity (1C, BOL, 25°C)	543 Ah
	Minimum capacity available (1C, BOL, 25°C)	340 KWh
	Minimal capacity (1C, BOL, 25°C)	530 Ah
Power	Maximum continuous power in discharge (SOC 50%, 25°C)	174 KW
	Recommended continuous power in charge / discharge (SOC 50%, 25°C)	105 KW
	Peak power in discharge (SOC 50%, 25°C)	254 KW
Current	Maximum continuous current in discharge (SOC 50%, 25°C)	270 A
	Recommended continuous current in charge / discharge (SOC 50%, 25°C)	162 A (C/3)
	Peak current in discharge (SOC 50%, 25°C)	396 A (1C)
Energy	Specific energy	125 Wh/Kg
	Energy density	157 Wh/L
	Power density	42 W/Kg
Mechanical characteristics	Weight	2800 Kg
Charging system	Overnight charging	
Cycle life	8 years	

- **Pulse 15 high power (opportunity charge)**: this battery pack is Li-ion LTO type (the Lithium Titanate is used in place of Carbon in the anode) and it presents a fast charging system, in fact it must be charged rapidly in the city through an off-board pantograph during the day. The charge lasts some minutes (about 15 minutes) from 15 to 25 times a day. Because of the high-power density of 488 W/Kg, this system is able to release high amount of energy quickly: the battery life is high, about 15 years and, consequently, considering a that the bus life is about 15 years, it has not be changed. However, the autonomy is less than ZEN batteries. The battery presents an optimal mechanical design for bus roof and back integration and, to reach the total energy of 73 KWh in the 12 m version, are connected in parallel 5 scalable modular systems of 14.6 KWh; to reach the total energy of 102 KWh in the 18 m version, are connected in parallel 7 scalable modular systems of 14.6 KWh (Forsee Power, 2021). The cells' producer is Toshiba. In Figure 58 are represented the modules of Pulse 15 and in Table 24 are resumed the main features.

Figure 58. Forsee Powe Pulse 15 (Forsee Power, 2021)

Table 24. Forsee Power Pulse 15 features. DOD: depth of discharge (Forsee Power, 2021)

Forsee Power Pulse 15-high power battery pack		
Chemistry	Li-ion LTO battery	
Voltage	Minimal	414 V
	Nominal	635 V
	End of charge	745 V
Energy/Capacity	Nominal energy	73 KWh
	Nominal capacity (C/3, BOL, 25°C)	115 Ah
Power	Continuous power in charge / discharge	286 KW
	Peak power in charge / discharge (pulse 10 s, 4% DOD)	572KW
Current	Peak current in discharge (pulse 10 s, 4% DOD)	900 A
	Continuous current in charge/discharge	450 A
Density	Specific energy	56 Wh/Kg
	Energy density	58 Wh/L
	Power density	488 W/Kg
Mechanical characteristics	Weight	1300 Kg
Charging system	Fast charging system	
Cycle life	15 years	

- **Flex 7 energy and power (ultra-fast charge)**: this battery pack is Li-ion NMC type and it is a compromise between the ZEN and the Pulse. It presents a relatively high specific energy (88 Wh/Kg) and high-power density (219 W/Kg): this battery allows an opportunity charging several times a day, reaching 50% of recharge in 15 minutes up to 20 times a day. The battery presents an optimized weight and volume for high vehicle's capacity and the total energy of 250 KWh is reached connecting, both in series and in parallel, different scalable modular systems. The battery's life is about 10 years: considering that a bus life is about 15 years, the battery must be substituted once. In Figure 59 are represented the Flex 7 and in Table 35 are resumed the main features.

Figure 59. Forsee Power Flex 7 (Forsee Power, 2021)

Table 25. Forsee Power Flex 7 features (Forsee Power, 2021)

Forsee Power Flex 7 - energy & power battery module		
Chemistry	Li-ion NMC battery	
Energy/Capacity	Nominal energy	250 KWh
Energy	Specific energy (BOL)	88 Wh/Kg
	Energy density (BOL)	130 Wh/L
	Power density (BOL)	219 W/Kg
Cycle life	10 years (>10000 cycles)	
Charging system	Opportunity charging	

In Figure 60 are represented the specific energy and the power density of ZEN 35, Pulse 15 and Flex 7: it is possible to notice that ZEN have the highest specific energy, ensuring an high autonomy in Km on a single overnight charge at depot; the Pulse 15 present the highest power density and, as a consequence, they provide the less autonomy in Km but they can be recharged rapidly in the city through a pantograph and they present the longest life (about 15 years); the Flex 7 present intermediate values of specific energy and power density, in fact they combine both an higher autonomy than Pulse 15 and a fast recharge. The most used are the ZEN model.

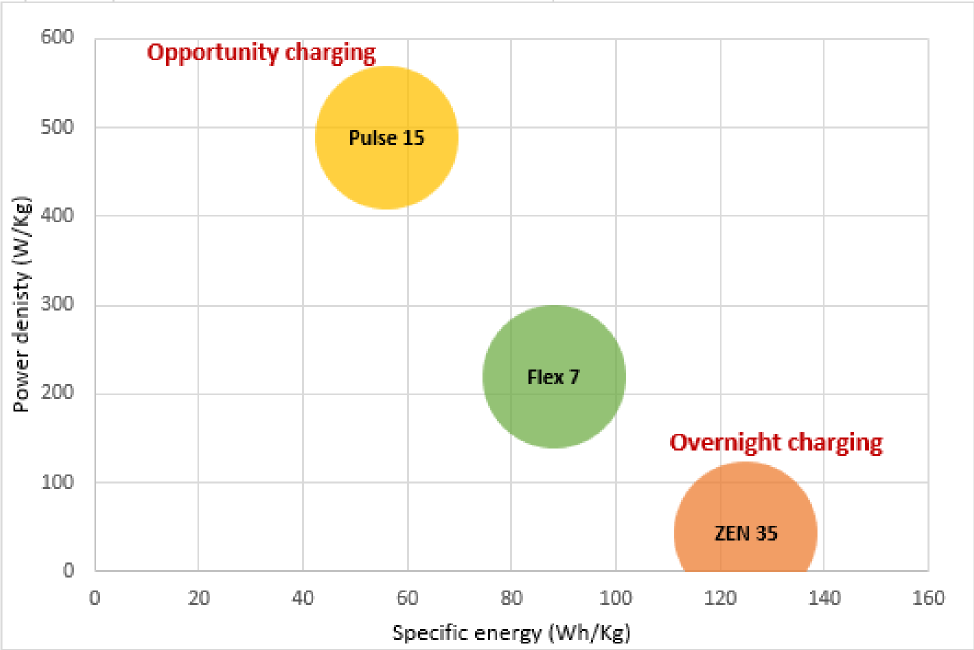

Figure 60. Specific energy and Power density of ZEN 35, Pulse 15 and Flex 7 (Forsee Power, 2021; IVECO BUS,2018)

5.2 Buses emissions assessment: the city of Turin

In this section, are evaluated the emissions generated by only the use phase (road travel) of Turin city buses. In this emissions assessment were excluded the production phases of buses and the end-of-life management. At the beginning, there is a description of the actual Turin bus fleet; then, are reported the explanation and the results for the annual emissions evaluation relative to the actual bus fleet; then are supposed different bus fleet scenarios, which tends, increasingly, towards electrification.

The emissions were evaluated in terms of single pollutants emitted, considering, as explained in the chapter 3 (3.2.1 section), the main products of exhaust gases, that are: CO_2, CO, HC, NO_x, PM (including black carbon and organic carbon), SO_2 and NH_3, that all derive from the combustion reaction of the fuel (Diesel). In addition, are considered also N_2O, Pb and non-methane volatile organic compounds (NMVOCs), that are all combustion products.

5.2.1 Turin public transport: the urban bus fleet

In this section is analysed the urban bus fleet of Turin updated to April 2021 and, in particular, the information were extracted from the datasheet published and released by the company that manages the local public transport in Turin, GTT (Gruppo Torinese Trasporti). In this document, are reported quantities and technical information about the urban bus fleet, considering only urban buses and excluding intercity buses, trams and coaches.

The urban buses in Turin can be subdivided into three segments:

- City buses with a length between 8 m and 10 m;
- City buses with a length of 12 m;
- Articulated city buses with a length of 18 m.

In the following Tables (26-27-28) are reported the Turin urban bus fleet relatively to the three categories defined above: for each category, are reported the model of buses, the length, the year of registration, the fuel type, the fuel consumption, the mass at medium load and the number of vehicles that constitute the city bus fleet.

Table 26. City bus fleet of Turin (8-10 m) – technical features (GTT, 2021)

Model	Length (m)	Year of registration	Fuel	Fuel consumption	Fuel consumption- unit of measurement	Mass at medium load (Kg)	Number of vehicles
EPT-CACCIAMALI "ELFO" ELETTRICO	7.5	2003	Electric	95	KWh/100 Km	9875	23
BYD K7 ELETTRICO	8.7	2019	Electric	67	KWh/100 Km	11050	8
BMC NEOCITY	8.5	2019/2020	Diesel Euro 6	32.2	L/100 Km	11472.5	6
MAN A47 LION'S CITY NL283 E4	10.5	2006	Diesel Euro 4	36	L/100 Km	13750	5
						Total	**42**

Table 27. City bus fleet of Turin (12 m) – technical features (GTT, 2021)

Model	Length (m)	Year of registration	Fuel	Fuel consumption	Fuel consumption- unit of measurement	Mass at medium load (Kg)	Number of vehicles
IVECO 491E.12.24 CNG CITYCLASS	12	2001/2002	CNG (EEV)	60	Kg/100 Km	15547.5	100
IRISBUS 491E.12.29 - CITYCLASS E3	12	2005	Diesel Euro 3	55	L/100 Km	15220	35
IRISBUS 491E.12.29 - CITYCLASS E4	12	2006	Diesel Euro 4	51	L/100 Km	15220	15
IRISBUS 491E.12.27 CNG - CITYCLASS	12	2006/2008	CNG (EEV)	56	Kg/100 Km	15796	88
IRISBUS CITELIS 12.29 DIESEL EEV	12	2009/2010	Diesel EEV	50.9	L/100 Km	15537	100
IVECO CITELIS 12.29 DIESEL EEV	12	2012/2013	Diesel EEV	50	L/100 Km	15423.5	81
BYD K9UB ELETTRICO	12	2017	Electric	104	KWh/100 Km	16207.5	20
MERCEDES CONECTO E6	12	2019	Diesel Euro 6	42.9	L/100 Km	14722	41
MERCEDES CONECTO CNG	12	2019/2020	CNG Euro 6	44.4	L/100 Km	15455	48
BYD K9UB ELETTRICO	12	2021	Electric	91	KWh/100 Km	16884	50
						Total	**578**

Table 28. Articulated city bus fleet of Turin (18 m) – technical features (GTT, 2021)

Model	Length (m)	Year of registration	Fuel	Fuel consumption	Fuel consumption- unit of measurement	Mass at medium load (Kg)	Number of vehicles
VAN HOOL AG 300 - DE SIMON URS	18	1999/2000	Diesel Euro 2	68	L/100 km	21770	60
VAN HOOL AG 300 - DE SIMON URS	18	2001/2002	Diesel Euro 3	74	L/100 km	22460	25
IRISBUS 491E.18.31 CNG CITYCLASS	18	2002/2004	CNG (EEV)	67	Kg/ 100 km	23120	70
IRISBUS 491E.18.31 CNGCITYCLASS	18	2005	CNG (EEV)	67	Kg/ 100 km	23120	27
IRISBUS CITELIS 18m DIESEL EEV	18	2010	Diesel EEV	64.1	L/100 km	23937.5	8
IRISBUS CITELIS 18m CNG	18	2010	CNG (EEV)	64.16	Kg/ 100 km	24097.5	4
IRISBUS CITELIS 18m CNG	18	2010	CNG (EEV)	64.16	Kg/ 100 km	24097.5	4
IRISBUS CITELIS 18m DIESEL EEV	18	2011/2012	Diesel (EEV)	65.9	L/100 km	22893	70
IRISBUS CITELIS 18m DIESEL EEV	18	2013/2014	Diesel (EEV)	65.9	L/100 km	22893	5
Merceds Connecto G E6	18	2019/2020	Diesel Euro 6	59.4	L/100 km	22019	47
						Total	**320**

Considering the total number of buses for the three categories, the total number of city buses for Turin is 940.

In Figure 61 are represented the total number of city buses subdivided by emissions profile: it possible to notice that the largest quantity is represented by CNG buses, with a 36% of the total share; at the second place there are the Diesel EEV (Enhanced - Environmental Friendly Vehicle, of which the emissions are between Euro 5 and Euro 6), with a share of 28%; at the third place there are the electric buses with a share of 11% and a minority is represented by Diesel Euro 2 (share of 7%), Diesel Euro 3 (6%) and Diesel Euro 4 (2%)

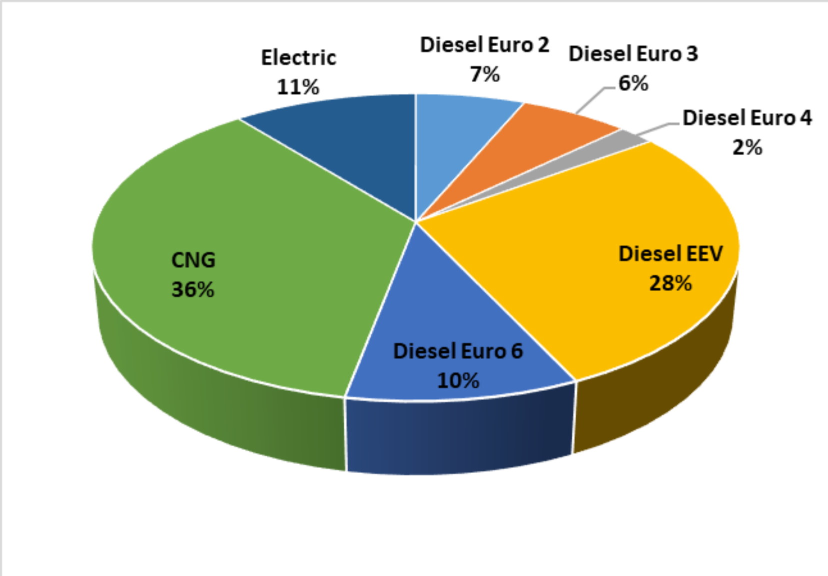

Figure 61. Turin city buses categorization by emission profile

5.2.2 Annual emissions assessment for the Turin urban buses fleet

In this section, is performed the annual emissions assessment relatively to the urban city buses that circulate in Turin. The evaluation was articulated in several steps, and it is different for the Diesel buses, for CNG buses and for the electric buses.

Diesel buses: the emission factors (EFs) evaluation

In this section is explained the methodology applied to calculate the emission factors (EFs) for the Diesel buses. The EF, in this case, is the ratio of the quantity of a certain pollutant released in the atmosphere and the Km. This evaluation was performed through the following steps:

1. Estimation of the emission factors (EFs) for the different pollutants emitted in relation to the different categories of buses considered and to the emission profile. For this evaluation, was used the ISPRA database 2018 of EFs for the Italy road transport and it provides EFs in t pollutant/TJ, distinguished for the following categories:
    - Urban buses midi (Diesel) < 15 t
    - Urban buses standard (Diesel) 15-18 t
    - Urban buses articulated (Diesel) > 18 t

    Considering the Turin urban buses fleet relatively to the emission profiles and the mass at medium load, the categories defined by ISPRA were associated to the different urban buses' segments defined above:

    - Urban buses midi (Diesel) < 15 t were associated to Diesel city buses with a length between 8 m and 10 m. The Diesel buses that are grouped in this segment present in fact an average mass at medium load of 13 tons;
    - Urban buses standard (Diesel) 15-18 t were associated to Diesel city buses with a length of 12 m. The Diesel buses that are grouped in this segment present in fact an average mass at medium load of 16 tons;

- Urban buses articulated (Diesel) > 18 t were associated to articulated Diesel city buses with a length of 18 m. The buses that are grouped in this segment present in fact an average mass at medium load of 23 tons;

The EFs values provided by ISPRA were transformed in g pollutant / Kg fuel, through a calculated conversion factor for each category associated to the different emission profiles:

$$EF\left[\frac{g\ pollutant}{Kg\ fuel}\right] = 42.7 \cdot EF\ \left[\frac{t\ pollutant}{TJ}\right]$$

2. Conversion of the EFs in g/Km for each pollutant, obtained considering the bus fuel consumption for the different categories.
In Table 29 for, the different categories, are reported the fuel consumptions relatively to the different Diesel emission profiles: for each category, were considered only the Diesel types that are present in the Turin bus fleet (for example for the category urban buses midi < 15 t, the Turin urban bus fleet is composed only by Diesel Euro 4 and Diesel Euro 6 buses). Considering a Diesel density of 835 Kg/m^3, in Table 29 are reported the fuel consumptions in Kg fuel/Km, obtained starting from the values in L fuel/100 Km, reported from Table 26 to 28.

Table 29. Fuel consumption for Diesel buses.

Category	Diesel emission profile	L fuel /100 Km	Kg fuel /Km
Urban buses midi < 15 t	Diesel Euro 4	36	0.30
	Diesel Euro 6	32.3	0.27
Urban buses standard 15-18 t	Diesel Euro 3	55	0.46
	Diesel Euro 4	51	0.43
	Diesel Euro 5 (EEV)	50	0.42
	Diesel Euro 6	42.9	0.36
Urban buses articulated > 18 t	Diesel Euro 2	68	0.57
	Diesel Euro 3	74	0.62
	Diesel Euro 5 (EEV)	64.1	0.54
	Diesel Euro 6	59.4	0.50

Therefore, it is possible to calculate the EFs for the pollutants considered:

$$EF_{Diesel}\ \left[\frac{g\ pollutant}{Km}\right] = EF\ \left[\frac{g\ pollutant}{Kg\ fuel}\right] \cdot fuel\ consumption\ \left[\frac{Kg\ fuel}{Km}\right]$$

All the calculated EFs are reported in the Appendix. It is important to notice that ISPRA database contains also values of EFs in g/Km for the different categories, but they are generic values and the assumptions made for that calculation, such as the fuel consumptions used, are not indicated: for that reason, was considered appropriate to calculate the EFs for this specific case, using the Turin bus fleet fuel consumption. In addition, to compare the obtained values of EFs and the values provided by ISPRA database, was calculated the relative difference and it is possible to notice, from the Tables reported in the Appendix, that the values are similar.

In Figure 62 are represented the obtained EFs of CO_2 for the category urban buses midi < 15 t: it is possible to notice that the Diesel Euro 4 emits a value of CO_2 that is about 100 units higher than the Diesel Euro 6 profile.

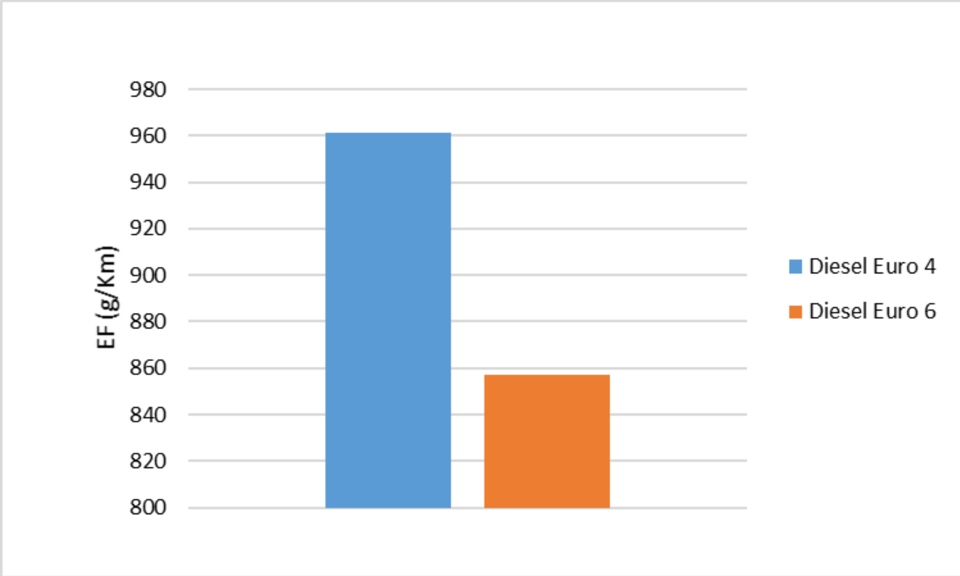

Figure 62. EFs of CO_2 for urban buses midi < 15 t Turin bus fleet

In Figure 63 are represented the obtained EFs values obtained for the category urban buses midi < 15 t. In this case, the EFs were evaluated for the rest of pollutants considered, except the CO_2: it is possible to notice that, among these substances, the most emitted are the NOx and CO. Also in this case, as the CO_2, there is a huge difference among the Diesel Euro 4 and the Diesel Euro 6 profiles: NOx emission factor for Diesel Euro 4 is about 6 g/Km and for Diesel Euro 6 is about 0.5 g/Km; CO emission factor for Diesel Euro 4 is about 1.3 g/Km and for Diesel Euro 6 is about 0.24 g/Km. As concern the other pollutants, the emissions are almost the same but lower for the Diesel Euro 6. In Figure 64 are reported the EFs obtained excluding NOx and CO, to have a detail of lower emissions: among them, PM 10 is the most emitted pollutant, followed by PM 2.5 and VOCs. It is interesting to notice that Diesel Euro 6 emit more N_2O and more NH_3 than Diesel Euro 4.

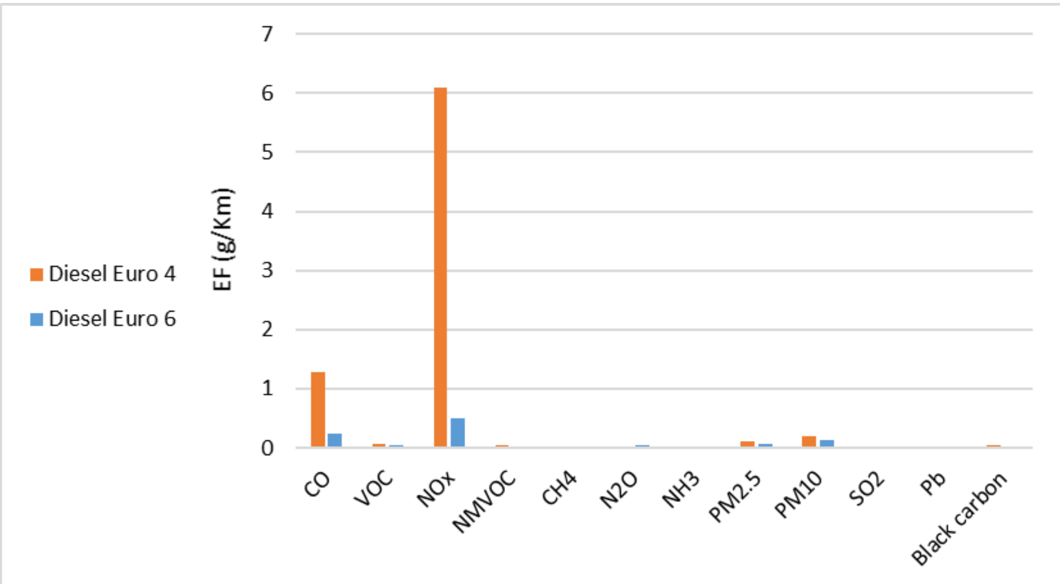

Figure 63. EFs for urban buses midi < 15 t Turin bus fleet.

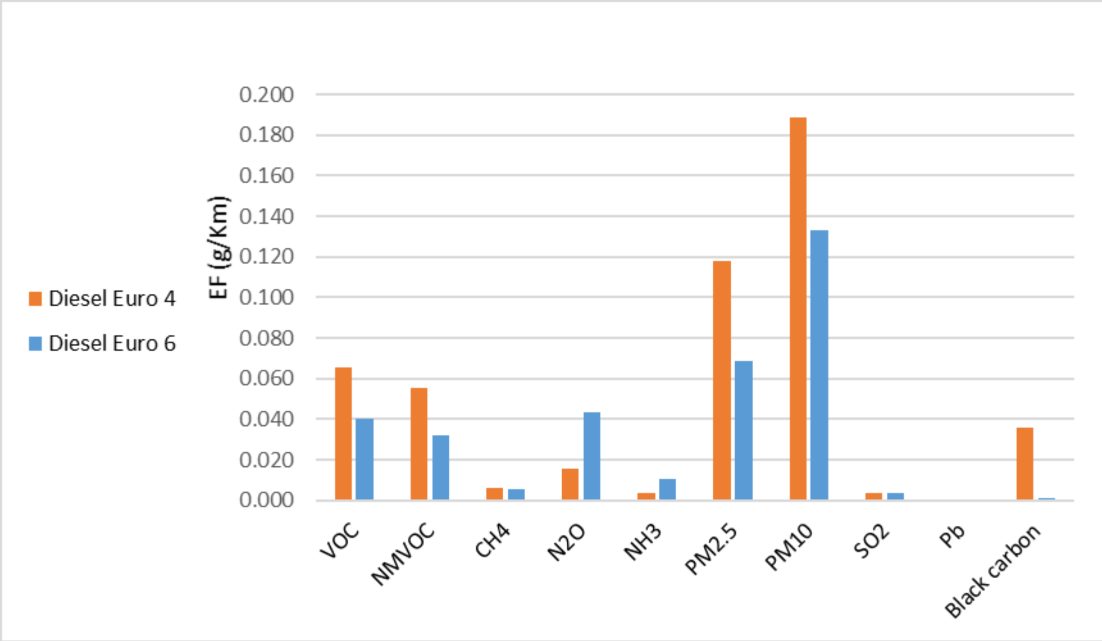

Figure 64. EFs for urban buses midi < 15 t Turin bus fleet-focus on specific pollutants

In Figure 65 are represented the calculated EFs of CO_2 for urban standard buses 15-18 t category: although the Turin bus fleet does not include Diesel Euro 1 and Diesel Euro 2, they are considered to compare the different emissions profile. It is possible to notice that from Diesel Euro 1 to Diesel Euro 6 there is an important decrease of CO_2 emissions, passing from about 1,673 g/Km to 1,141 g/Km.

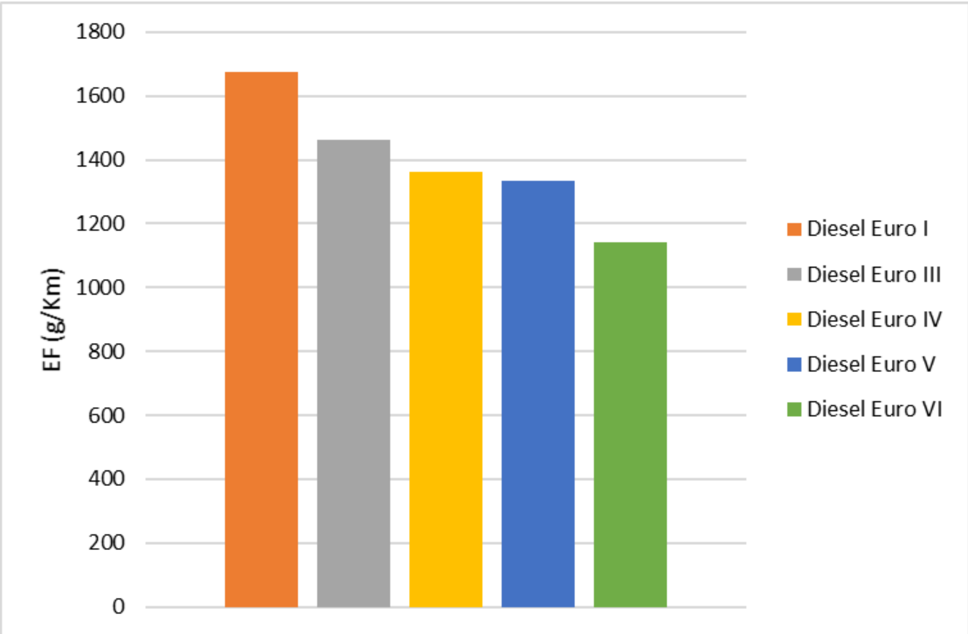

Figure 65. EFs of CO_2 for urban standard buses 15-18 t Turin bus fleet

In Figure 66 are represented the obtained EFs values for the category urban standard buses 15-18 t, considering the rest of pollutants (except the CO_2). It is possible to notice that the highest EFs were calculated for NOx and the difference for Diesel Euro 6 is remarkable than the other emission profile, passing from 9 g/Km for Diesel Euro 5 to 0.57 g/Km for Diesel Euro 6. Regarding CO and VOC, also in this case there are considerable differences: for CO, the EF of Diesel Euro 5 is about 3.1 g/Km and for Diesel Euro 6 is about 0.3 g/Km; for VOCs, the EF for Diesel Euro 3 is about 0.74 g/Km and for Diesel Euro 6 is 0.04 g/Km (similar to Diesel Euro 4 and Euro 5). In Figure 67 is represented a focus on the lower EFs: the graph shows a decline as regard NMVOCs, PM and Black carbon emissions, passing from Diesel Euro 1 to Diesel Euro 6. As in the previous case, there is an increase of N_2O emissions for Euro 6.

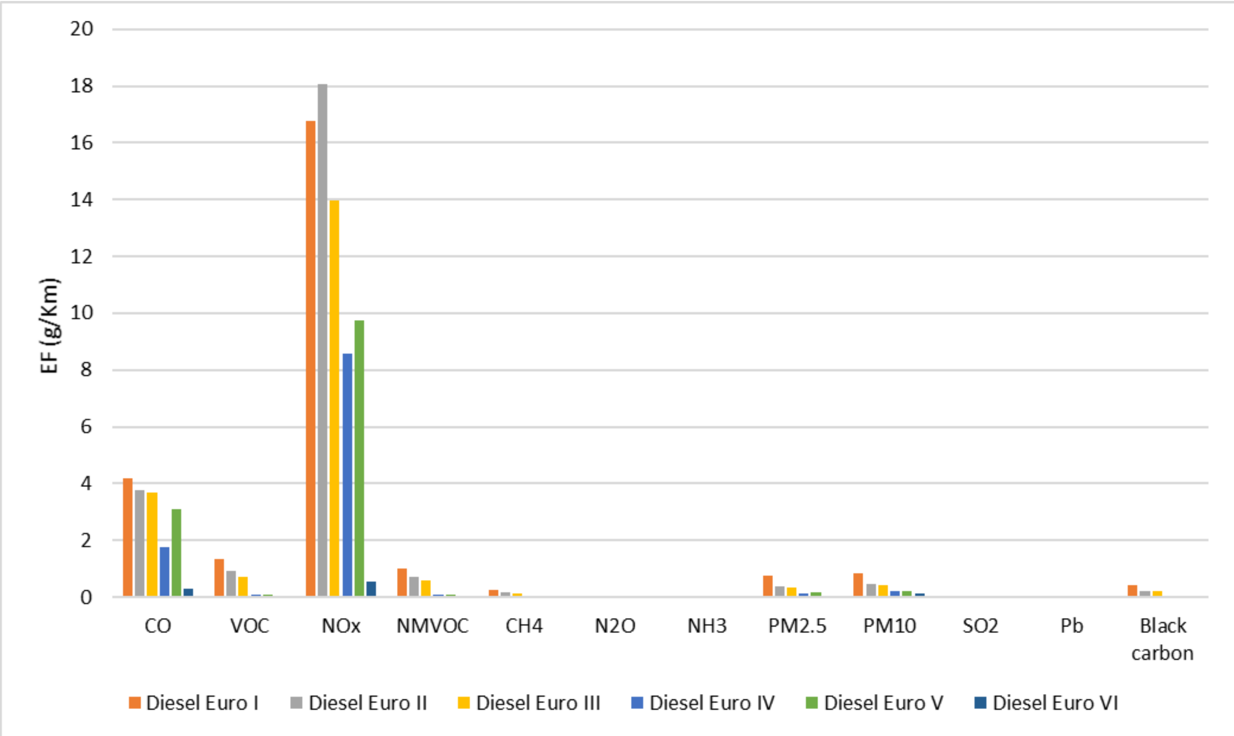

Figure 66. EFs for urban standard buses 15-18 t Turin bus fleet

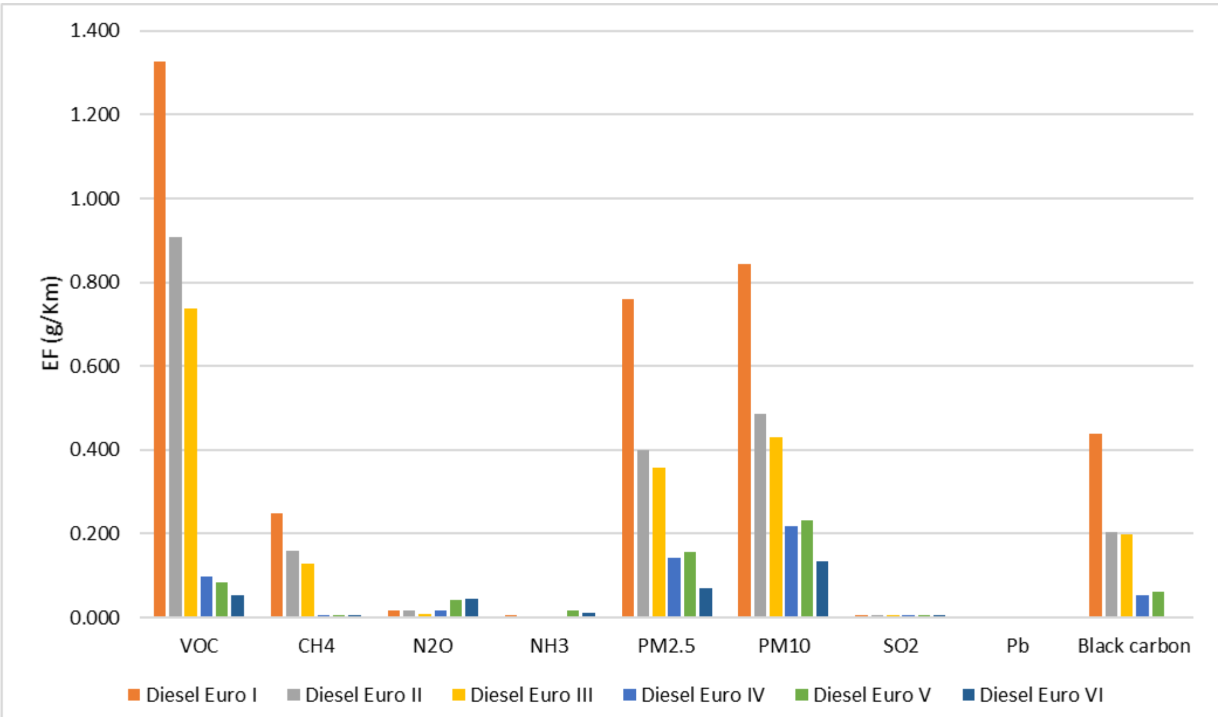

Figure 67. EFs for urban standard buses 15-18 t Turin bus fleet-focus in specific pollutants

In Figure 68 are shown the obtained EFs of CO_2 for articulated urban buses > 18 t category: for Diesel Euro 2, Diesel Euro 3 and Diesel Euro 4 is almost the same (1,964 g/Km) and there is a decrease to 1,708 g/Km for Diesel Euro 5 and to 1,580 g/Km for Diesel Euro 6.

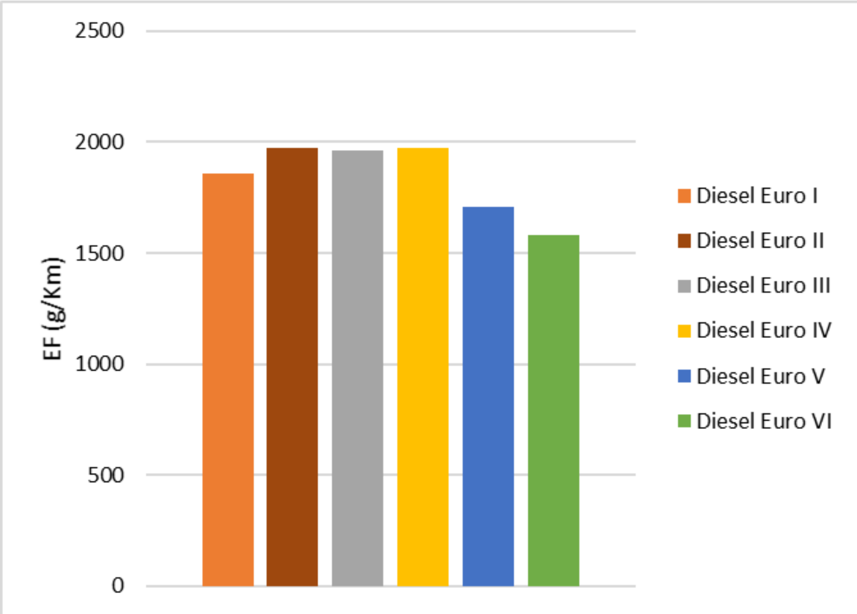

Figure 68. EFs of CO_2 for articulated urban buses > 18 t Turin bus fleet

In Figure 69 are shown the EFs obtained for the articulated urban buses > 18 t category (excluding the CO_2): as in the previous cases, the most emitted pollutants are NOx, CO and VOCs. Considering Diesel Euro 5 and Diesel Euro 6, there is a huge decrease of NOx emissions, passing from 10 g/Km to 0.5 g/Km; as regard CO, the EF is about 4 g/Km for Diesel Euro 5 and 0.36 g/Km for Diesel Euro 6. The decrease for VOCs and NMVOCs in almost the same, passing from about 1 g/Km for Diesel Euro 1 to 0.1 g/Km for Diesel Euro 6. As shown in Figure 70, the PM 2.5 and PM 10 emissions decrease a lot, passing from a value of about 1 g/Km for Diesel Euro 1 to 0.16 g/Km for Diesel Euro 6 but there is an increase of N_2O emissions.

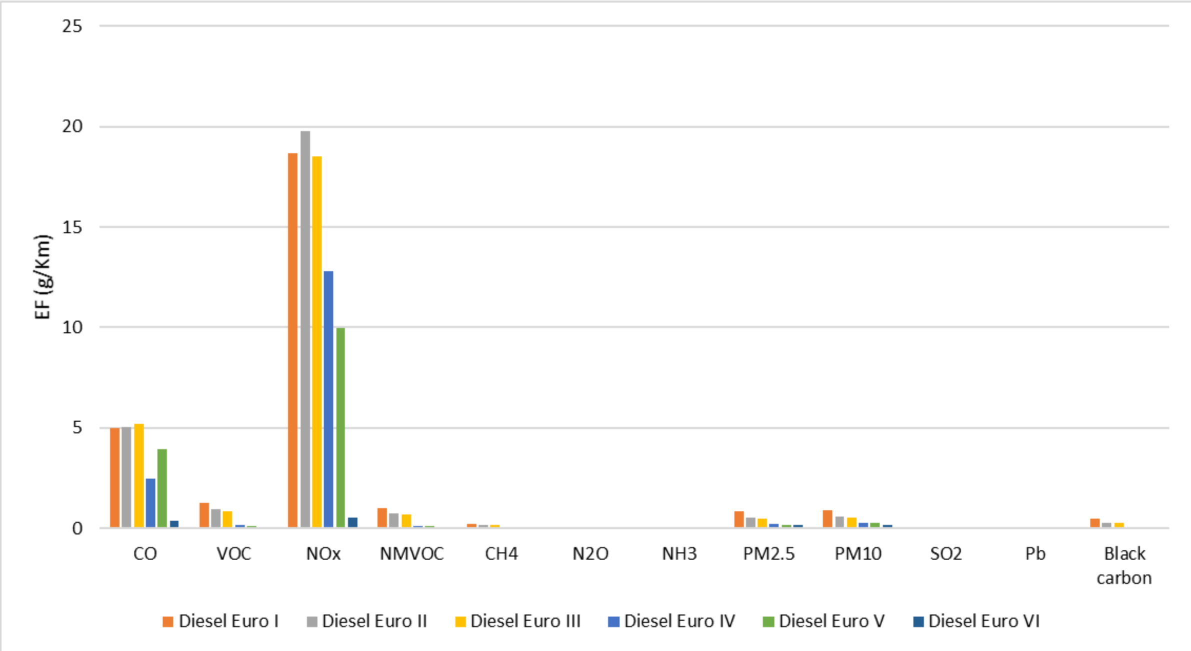

Figure 69. EFs for articulated urban buses >18 t Turin bus fleet

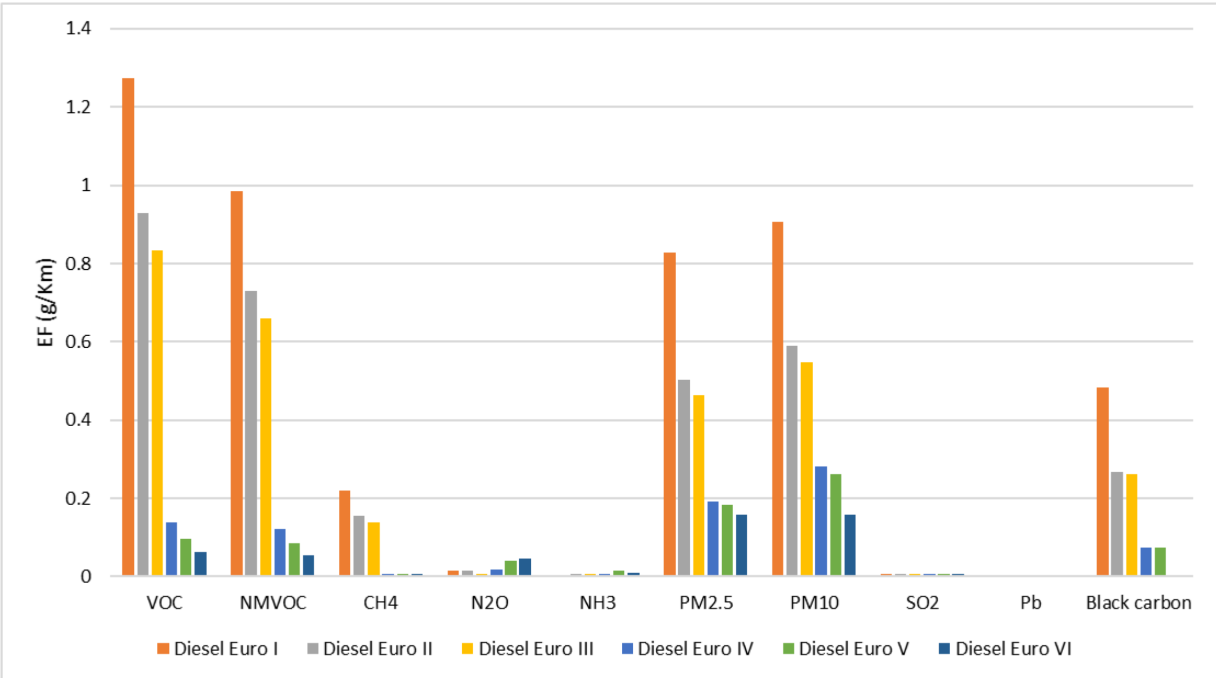

Figure 70. EFs for articulated urban buses >18 t Turin bus fleet-focus on specific pollutants

In general, from the obtained EFs, it possible to consider that the category that emits mostly all the pollutants are the buses that have an average weight highest than 18 tons, due to the highest fuel consumption, followed by urban standard buses with an average weight between 15 and 18 tons and, at the end, urban midi buses with a weight less than 15 tons. The lowest emissions are reached from Diesel Euro 6 profiles and, obviously, the most emitted pollutant in the atmosphere is the CO_2 because it is the main product of the combustion reaction: considering, for example, Diesel Euro 6, the EF is about 1,580 gCO_2/Km for articulated urban buses (> 18 t); the EF is about 1,141 gCO_2/Km for urban standard buses (15 t -18 t) and about 857 gCO_2/Km for urban midi buses (< 15 t). After the CO_2, the most emitted pollutants are NOx, and also in this case, it is important to notice that Diesel Euro 6 buses emit much lower than the other emission profile. At the third place is positioned the CO and then there are VOCs, NMVOCs, PM 2.5 and PM 10. The lowest emissions, but also important, are represented by CH_4, SO_2, N_2O, black carbon and Pb. All the calculations and the values obtained are reported in the Appendix.

For each category and, therefore, for each emission profile, the pollutant emissions were calculated in gCO_2eq/Km, considering the GWP 100, that is a quantity (that exists only for gases that contributes to the greenhouse effect) that expresses how much energy the emission of 1 ton of a greenhouse gas will absorb over 100 years, in relation to the emissions of 1 ton of CO_2. In Table 30 are reported the GWP 100 for the different greenhouse gases: the values for CO_2, N_2O and CH_4 are extracted from the IPCC Fifth Assessment Report (IPCC, 2014); the values for CO and NMVOC are calculated by Collins et al. (2002). This evaluation is made to estimate the greenhouse effect that derives from Diesel emissions of buses and to represent in a consistent form this impact.

Table 30. GWP 100 for GHGs

Pollutant	GWP 100
CO2	1
N2O	265
CH4	28
CO	2.1
NMVOC	3.4

In this evaluation, were considered as greenhouse gases: CO_2, N_2O and CH_4 but also the CO and NMVOCs because of their indirect effects, related to the ozone formation or destruction, enhancement of stratospheric water vapour, changes in concentrations of OH radical: the latter is the most relevant phenomenon, because the changes (a decrease) of OH radical concentrations lead to an increase of CH_4 lifetime and to secondary aerosol formation. The calculation of the indirect GWPs presents higher uncertainty than the direct GWPs because, in many cases, they depend on location and time of emission. For each considered pollutant, was calculated the EF expressed in term of CO_2 equivalent:

$$EF\left[\frac{g\ CO_2eq}{Km}\right] = GWP100 \cdot EF\left[\frac{g}{Km}\right]$$

The total emissions expressed as CO_2 eq were obtained through the addition of the different calculated emission factor, applying the following equation (i are the different greenhouse gases considered in Table 72):

$$Total\ EF\left[\frac{g\ CO_2eq}{Km}\right] = \sum_i GWP100_i \cdot EF_i\left[\frac{g}{Km}\right]$$

In Table 31,32 and 33 are reported the EFs in gCO_2eq/Km calculated for the three categories to have an estimation of their emissions on the greenhouse gas effect; as expected, the main contribution derives from CO_2 because is the main product of the combustion, but it is interesting to notice the proportion: for example, N_2O has a GWP100 that is 265 highest than CO_2 but the impact is less because the related emission (in g/Km) is much lower than CO_2. The same concept is valid for the other gases considered.

Table 31. EFs in gCO2eq/Km for urban midi buses (< 15 t) category

Pollutant	GWP 100	Diesel Euro IV (gCO2eq/Km)	Diesel Euro VI (gCO2eq/Km)
CO2	1.0	961.3	857.0
N2O	265.0	4.1	11.6
CH4	28.0	0.2	0.2
CO	2.1	2.7	0.5
NMVOC	3.4	0.2	0.1
Total (gCO2 eq/ Km)		968.5	869.4

Table 32. EFs in gCO2eq/Km for urban standard buses (15-18 t) category

Pollutant	GWP 100	Diesel Euro I (gCO2 eq/Km)	Diesel Euro II (gCO2 eq/Km)	Diesel Euro III (gCO2 eq/Km)	Diesel Euro IV (gCO2 eq/Km)	Diesel Euro V (gCO2 eq/Km)	Diesel Euro VI (gCO2 eq/Km)
CO_2	1	1673.0	1593.5	1460.5	1360.6	1333.5	1141.4
N_2O	265	4.8	4.5	2.1	4.3	10.9	11.8
CH_4	28	7.0	4.5	3.6	0.2	0.2	0.2
CO	2.1	8.9	7.9	7.7	3.7	6.5	0.7
NMVOC	3.4	2.2	2.4	2.0	0.3	0.2	0.1
Total (gCO2 eq/ Km)		1695.9	1612.9	1475.9	1369.2	1351.3	1154.2

Table 33. EFs in gCO2eq/Km for urban standard buses (>18 t) category

Pollutant	GWP 100	Diesel Euro I (gCO2 eq/Km)	Diesel Euro II (gCO2 eq/Km)	Diesel Euro III (gCO2 eq/Km)	Diesel Euro IV (gCO2 eq/Km)	Diesel Euro V (gCO2 eq/Km)	Diesel Euro VI (gCO2 eq/Km)
CO2	1	1858.0	1964.2	1964.1	1972.9	1708.5	1580.1
N2O	265	4.0	4.2	2.1	4.9	10.9	12.4
CH4	28	6.2	4.4	3.8	0.2	0.2	0.2
CO	2.1	10.5	10.5	10.9	5.1	8.3	0.8
NMVOC	3.4	3.4	2.5	2.2	0.4	0.3	0.2
Total (gCO2 eq/ Km)		1881.9	1985.7	1983.2	1983.5	1728.2	1593.6

CNG buses: emission factors evaluation

The evaluation of emission factors for CNG buses is similar to the procedure employed for Diesel buses. It is possible to resume the calculation into the following steps:

1. Estimation of the emission factors (EFs) for the different pollutants emitted. For this evaluation, was used the ISPRA database 2018 of EFs for the Italy road transport and it provides EFs in t pollutant/TJ: the only category considered is CNG EEV because is the only type that is present in the Turin bus fleet. The EFs values provided by ISPRA were transformed in g pollutant / m^3 fuel, through a calculated conversion factor:
$$EF\left[\frac{g\ pollutant}{Kg\ fuel}\right] = 38.17 \cdot EF\left[\frac{t\ pollutant}{TJ}\right]$$

2. Conversion of the EFs in g/Km for each pollutant: this calculation was done for the different types of CNG buses of the Turin bus fleet because they have different fuel consumption and, as a consequence, it was necessary to estimate different EFs for each model of buses. The models and the fuel consumptions considered are reported in Table 34.

Table 34. Fuel consumption of Turin bus fleet CNG buses

Model	Kg fuel /100 Km	m^3 fuel /Km
Iveco CNG cityclass 12 m	60	0.9
Irisbus CNG cityclass 12 m	56	0.84
Mercedes Conecto CNG EEV 12	44.4	0.666
Irisbus CNG cityclass 18 m	67	1.005
Irisbus Citelis 18 m CNG	65.9	0.9885

Therefore, it was possible to calculate the EFs for the pollutants considered and for each model of bus:

$$EF_{CNG}\left[\frac{g\ pollutant}{Km}\right] = EF\left[\frac{g\ pollutant}{m^3\ fuel}\right] \cdot fuel\ consumption\left[\frac{m^3\ fuel}{Km}\right]$$

All the calculated EFs are reported in the Appendix. Also in this case, as Diesel buses calculation, were compared the obtained values of EFs in g/Km and the values provided by ISPRA database.

In Figure 71 are represented the EFs obtained for CNG buses: it is possible to notice that the buses have almost the same emissions except the Mercedes Conecto, with an EF of 1,486 g/Km.

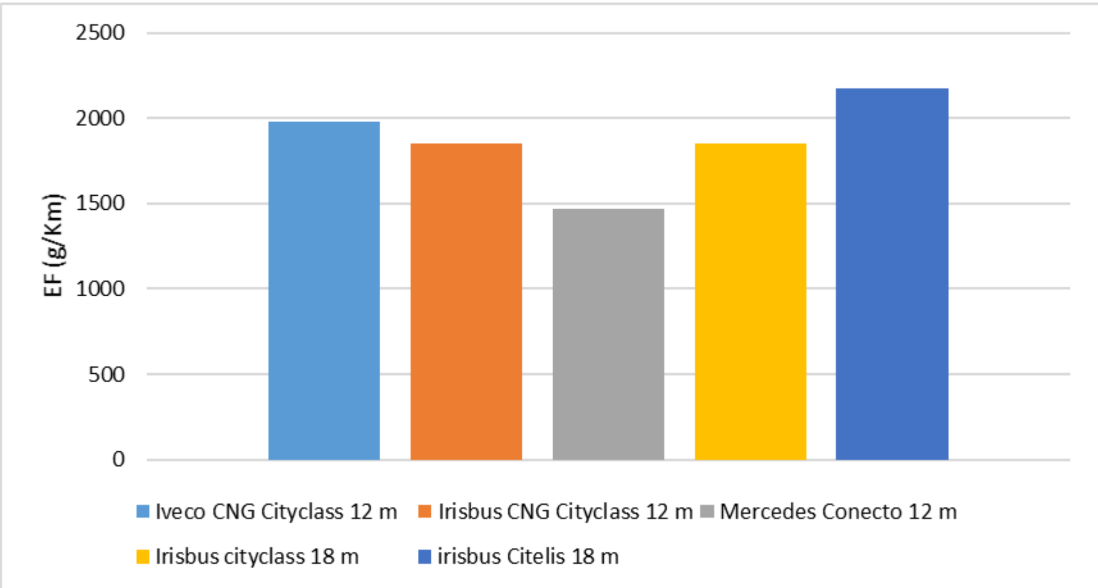

Figure 71. EFs of CO_2 for CNG Turin buses

In Figure 72 are represented the obtained EFs for the rest of the pollutants: also in this case, the most emitted are NOx; CO, VOCs and CH_4 present almost the same values of emission; NMVOC, PM 2.5, PM 10 and Pb are lower than the other considered pollutants. In particular, the values obtained for CH_4 are higher than Diesel buses and it occurs because CNG is a fuel gas composed mainly by methane. Furthermore, it is interesting to notice that CNG buses do not emit N_2O, NH_3, SO_2 and black carbon.

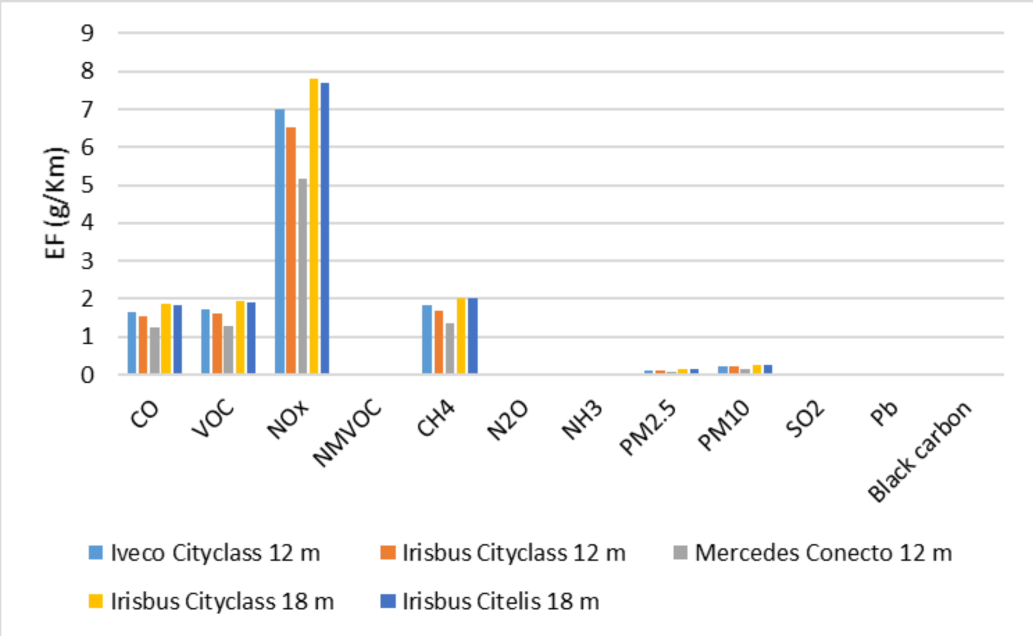

Figure 72. EFs for CNG Turin buses

3. As the Diesel buses, were calculated the EFs in terms of CO_2eq in gCO_2eq/Km using the same equations above, to have an idea of CNG buses impact: comparing the values for CNG buses reported in Table 35 and the values obtained for Diesel buses, it possible to notice that CNG has an highest impact than Diesel because of the increase of CH_4 emissions, due to the nature of the fuel.

Table 35. EFs in gCO2eq/Km for CNG buses

Pollutant	GWP 100	Iveco Cityclass 12 m (gCO2eq/Km)	Irisbus Cityclass 12 m (gCO2eq/Km)	Mercedes Conecto 12 m (gCO2eq/Km)	Irisbus Cityclass 18 m (gCO2eq/Km)	Irisbus Citelis 18 m (gCO2eq/Km)
CO2	1	1980.21	1848.19	1465.35	2211.23	2174.93
CH4	28	50.99	47.59	37.73	56.94	56.01
CO	2.1	3.49	3.25	2.58	3.89	3.83
NMVOC	3.4	0.09	0.09	0.07	0.10	0.10
Total (gCO2 eq/ Km)		2034.78	1899.13	1505.74	2272.17	2234.86

Electric buses: EFs calculation

Regarding electric buses, it is obvious that, because they do not use a fuel but work through an electric motor and the energy stored in the battery, during the travel, they do not emit pollutants. For that reason, were not calculated emission factors relatively to pollutants considered for Diesel and CNG buses. However, in the case of electric buses, it is necessary to consider the impact of greenhouse gases emissions for the electricity generation because, as it is explained in the previous chapter, these buses must be charged to travel. To calculate this impact, that is an EF in gCO_2eq/Km, was used the value of greenhouse gas emission intensity of the electricity generation for Italy (the reference year is 2019) provided by EEA, that is 233 gCO_2eq/KWh (this value is different for the various countries). The calculation was performed for each model of electric bus present in the Turin bus fleet, considering the bus consumption, using the following equation:

$$EF_{electric}\left[\frac{gCO_2eq}{Km}\right] = consumption\left[\frac{KWh}{Km}\right] \cdot GHG\ emissions\ intensity\ of\ electricity\ generation\left[\frac{gCO_2eq}{KWh}\right]$$

In Table 36 are reported the obtained values.

Table 36. EFs (g CO2eq/Km) calculated for the electric buses

Model	Consumption (KWh/100 Km)	Consumption (KWh/Km)	Greenhouse gas emission intensity of electricity generation (2019)- Italy (gCO2 eq/KWh)	EF(g CO2 eq/Km)
EPT-CACCIAMALI "ELFO" ELECTRIC	95	0.95	233	221
BYD K7 ELECTRIC	67	0.67	233	156.11
BYD K9UB ELECTRIC	104	1.04	233	242.32
BYD K9UB ELECTRIC	91	0.91	233	212.03

Annual emissions assessment: the actual scenario

After the calculation of the emission factors for all the type of buses that constitute the Turin bus fleet, it was performed the emission assessment relatively to buses considering an entire year. For this calculation, it was assumed that each bus travels in a year an average of 50,000 Km. Considering Diesel and CNG that emits pollutants during their travels because of exhaust gases, are calculated the emissions in Kg of pollutant in a year for all the buses, using the EFs calculated above. The evaluation was performed applying the following equation singularly for all the buses:

$$pollutant\ emission\ [Kg] = EF\left[\frac{g}{Km}\right] \cdot 50{,}000\ Km \cdot number\ of\ vehicles$$

This calculation was performed for all the buses (except the electric because they contribute zero to the single pollutant emissions) and the complete results are reported in the Appendix.

In this way, were obtained the total pollutant emissions in a year for the different bus categories. At the end, the total emissions generated by Turin urban buses, relatively to the different pollutants, were obtained through the addition of the values calculated for the three buses categories:

$Total\ pollutant\ emission_i\ [t] = \sum_j \frac{pollutant\ emission_i[Kg]}{1000}$, where i are the different pollutants considered (e.g., CO_2, N_2O, CO, VOC, etc.) and j are the three buses categories considered (8-10 m, 12 m and 18 m). In Table 37 are reported the calculated values of emissions.

Table 37. Total annual pollutant emissions evaluation for Turin urban bus fleet

Pollutant	Total annual emissions (t)
CO	102.12
VOC	33.97
NOx	358.04
NMVOC	5.78
CH_4	29.85
N_2O	0.84
NH_3	0.29
PM 2.5	7.48
PM10	10.78
SO_2	0.15
Pb	0.01
Black carbon	2.38
CO_2	69016.27

Then, the annual emissions were converted in terms of CO_2 eq applying the following equation (i are the different pollutants considered):

$$Total\ emissions\ [tCO_2eq] = \sum_i GWP100 \cdot total\ annual\ \ pollutant\ emission\ (t)\ _i$$

In Table 38 are reported the total annual emissions expressed as tCO_2eq but the value obtained considers only Diesel and CNG buses, excluding the electric buses contribution.

Table 38. Total annual emissions expressed as tCO_2eq-Diesel and CNG buses contribution

Pollutant	GWP 100	Emission (tCO2eq)
CO2	1	69016.27
N2O	265	223.35
CH4	28	835.90
CO	2.1	214.44
NMVOC	3.4	19.64
Total		**70309.60**

It was considered necessary to also include the contribution of electric buses because of their greenhouse effect impact during charging phase. It was calculated through the following equation:

$$emission\ electric\ buses\ [tCO_2eq] = EF_{electric}\left[\frac{gCO_2eq}{Km}\right] \cdot 50000\ Km \cdot number\ of\ vehicles$$

In Table 39 are reported the emissions obtained.

Table 39. Emissions as CO2eq calculated for the electric buses

Model	Number of vehicles	EF (g CO2 eq/Km)	Emissions (t CO2 eq)
EPT-CACCIAMALI "ELFO" ELECTRIC	23	221.35	254.55
BYD K7 ELECTRIC	8	156.11	62.44
BYD K9UB ELECTRIC	20	242.32	242.32
BYD K9UB ELECTRIC	50	212.03	530.08
Total			**1089.39**

At this stage, the total annual emission expressed as tCO_2eq generated by the Turin urban bus fleet is:

$$Total\ annual\ emission = 70309.60\ tCO_2eq + 1089.39\ tCO_2eq = \mathbf{71,399\ tCO_2eq}$$

5.2.3 Evaluation of alternative scenarios

Due to tendency of electrification, in this section is performed an evaluation of emissions supposing alternative scenarios through the substitution of Turin urban bus fleet with hybrid and electric buses: at the end, the values of emissions obtained were compared with the actual situation examined above. The analysed scenarios are:

1. Scenario 1HYB: Diesel Euro 2, Diesel Euro 3 and Diesel Euro 4 buses are substituted by hybrid buses, that represent the 15% of the total bus fleet;
2. Scenario 2HYB: Diesel Euro 2, Diesel Euro 3, Diesel Euro 4 and Diesel EEV are substituted by hybrid buses, that represent the 43% of the total bus fleet;
3. Scenario 3HYB: Diesel Euro 2, Diesel Euro 3, Diesel Euro 4, Diesel EEV and Diesel Euro 6 are substituted by hybrid buses, that represent the 53% of the total bus fleet;
4. Scenario 1EL: Diesel Euro 2, Diesel Euro 3 and Diesel Euro 4 buses are substituted by electric buses, that represent the 26% of the total bus fleet;
5. Scenario 2EL: Diesel Euro 2, Diesel Euro 3, Diesel Euro 4 and Diesel EEV are substituted by electric buses, that represent the 54% of the total bus fleet;
6. Scenario 3EL: Diesel Euro 2, Diesel Euro 3, Diesel Euro 4, Diesel EEV and Diesel Euro 6 are substituted by electric buses, that represent the 64% of the total bus fleet.

Hybrid buses: EFs evaluation

The hybrid bus considered were the Iveco Urbanway Hybrid High Value 12 m and 18 m described in the section 5.1. For these buses, were calculated the EFs using the same method adopted for Diesel buses: the only difference is the fuel consumption, that for these buses is reduced by 30% than Diesel Euro 6. Consequently, for the Iveco Hybrid High Value 12 m, the fuel consumption is 33.4 L/100 Km; for Iveco Hybrid High Value 18 m, the fuel consumption is 41.58 L/100 Km. In particular, to calculate the EFs in g/Km were used the same EFs values (expressed in t/TJ) provided by ISPRA for Diesel Euro 6 buses because the studied hybrid buses have a Diesel Euro 6 engine. Were considered the values provided for category 15-18 tons as regard the Iveco Hybrid High Value 12 m and the values provided for category > 18 tons as regard the Iveco Hybrid High Value 18 m. In Figure 73 and 74 are represented the EFs calculated for the hybrid buses.

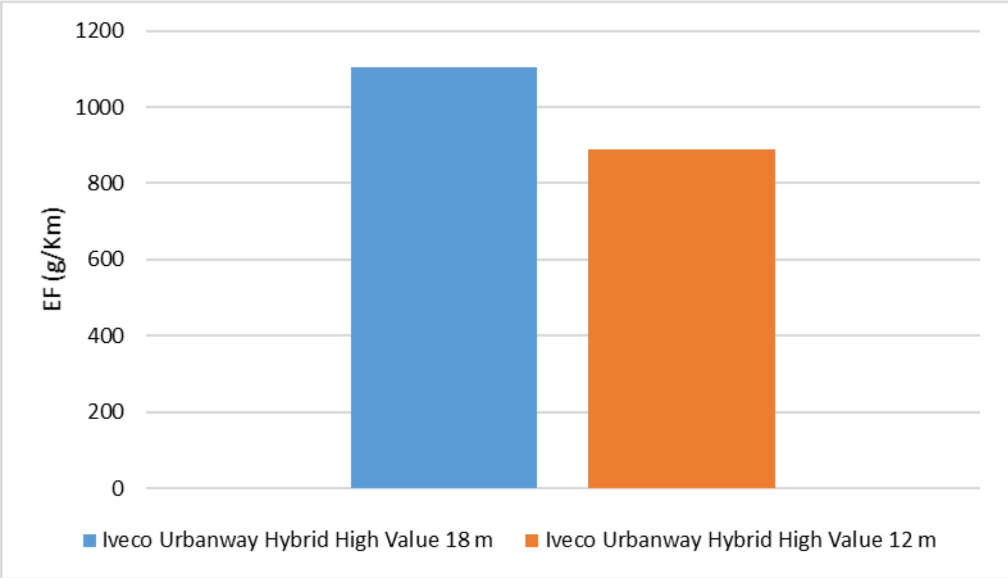

Figure 73. CO2 EFs calculated for hybrid buses

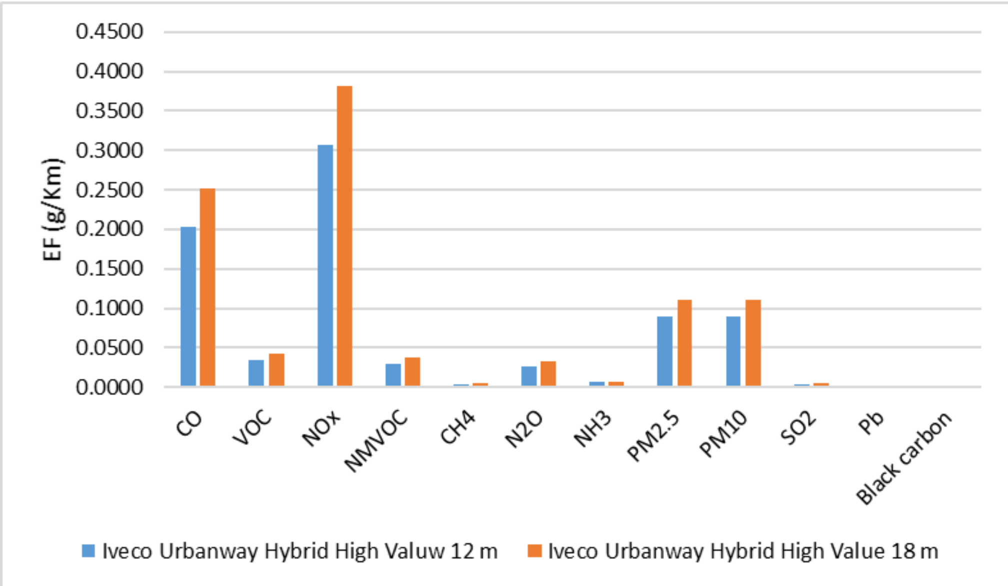

Figure 74. Pollutant EFs calculated for hybrid buses

Scenario 1HYB

In this scenario, Diesel Euro 2, Diesel Euro 3 and Diesel Euro 4 buses were substituted by hybrid buses, that represent the 15% of the total bus fleet, that means a total of 140 hybrid buses (55 buses of 12 m and 85 buses of 18 m). The scenario is represented in Figure 75.

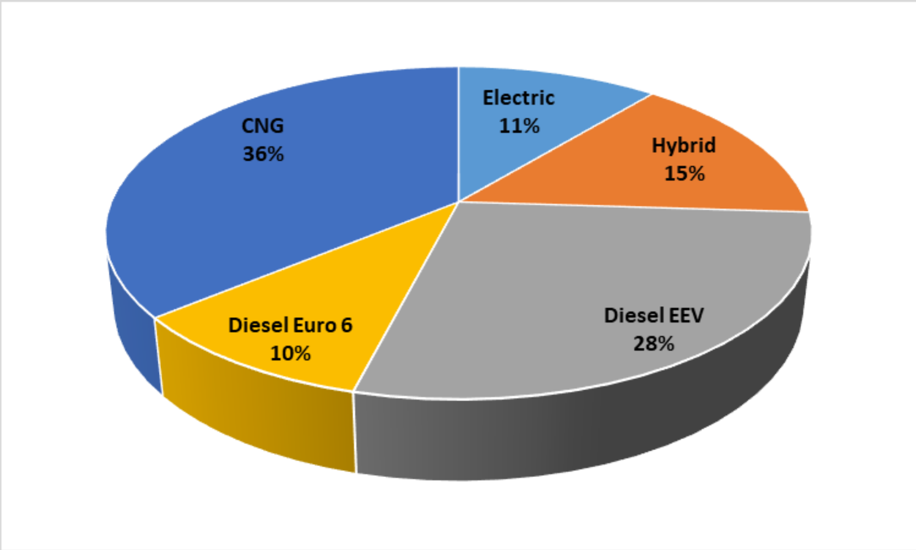

Figure 75. Scenario 1HYB: 15% of hybrid buses

It was evaluated the total pollutants emission in a year, using the same method and assumptions adopted for the actual scenario. In Table 40 are reported the value of annual emissions obtained for the scenario 1HYB. The single values of emissions for the hybrid buses considered are reported in the Appendix.

Table 40. Total annual pollutant emissions evaluation for Scenario 1HYB

Pollutant	Total annual emissions (t)
CO	74.10
VOC	29.04
NOX	245.64
NMVOC	1.91
CH4	29.01
N2O	0.97
NH3	0.31
PM2.5	5.34
PM10	8.08
SO2	0.13
Pb	0.01
Black Carbon	0.87
CO2	64000.64

In Table 41 are calculated the total annual emissions for the scenario 1HYB, also including the contribution of the electric buses.

Table 41. Total annual emissions for the scenario 1HYB

Pollutant	GWP 100	Scenario 1HYB (tCO2eq)
CO2	1	64000.64
N2O	265	256.10
CH4	28	812.37
CO	2.1	155.60
NMVOC	3.4	6.49
Total		**66320.60**

Scenario 2HYB

In this scenario, Diesel Euro 2, Diesel Euro 3, Diesel Euro 4 and Diesel EEV buses were substituted by hybrid buses, that represent the 43% of the total bus fleet, that means a total of 404 hybrid buses (236 buses of 12 m and 168 buses of 18 m). The scenario is represented in Figure 76.

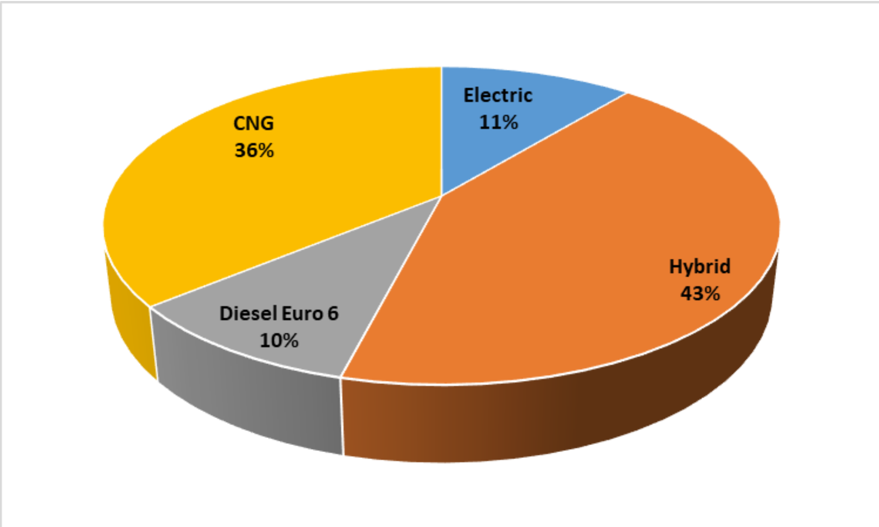

Figure 76. Scenario 2HYB: 43% of hybrid buses

It was evaluated the total pollutants emission in a year, using the same method and assumptions adopted for the actual scenario. In Table 42 are reported the values of annual emissions obtained for the scenario 2HYB. The single values obtained for the hybrid buses considered are reported in the Appendix.

Table 42. Total annual pollutant emissions evaluation for Scenario 2HYB

Pollutant	Total annual emissions (t)
CO	32.37
VOC	28.37
NOX	120.34
NMVOC	1.32
CH4	28.97
N2O	0.80
NH3	0.18
PM2.5	4.43
PM10	6.16
SO2	0.10
Pb	0.01
Black Carbon	0.03
CO2	57488.66

In Table 43 are reported the total annual emissions for the scenario 2HYB, also including the contribution of the electric buses.

Table 43. Total annual emissions for the scenario 2HYB

Pollutant	GWP 100	Scenario 2HYB (tCO2eq)
CO2	1	57488.66
N2O	265	211.33
CH4	28	811.19
CO	2.1	67.98
NMVOC	3.4	4.49
Total		59673.04

Scenario 3HYB

In this scenario, Diesel Euro 2, Diesel Euro 3, Diesel Euro 4, Diesel EEV and Diesel Euro 6 buses were substituted by hybrid buses, that represent the 53% of the total bus fleet, that means a total of 498 hybrid buses (283 buses of 12 m and 215 buses of 18 m). The scenario is represented in Figure 77.

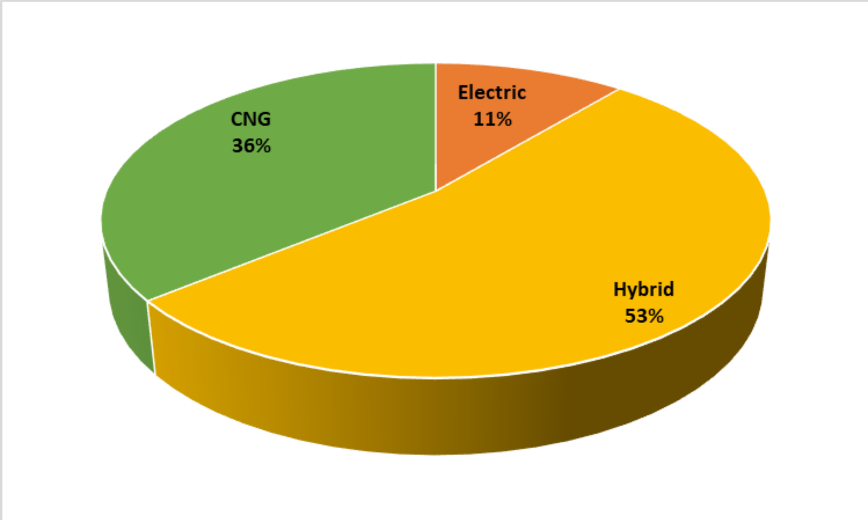

Figure 77. Scenario 3HYB: 53% of hybrid buses

It was evaluated the total pollutants emission in a year, using the same method and assumptions adopted for the actual scenario. In Table 44 are reported the value of annual emissions obtained for the scenario 3HYB. The single values obtained for the hybrid buses considered are reported in the Appendix.

Table 44. Total annual pollutant emissions evaluation for Scenario 3HYB

Pollutant	Total annual emissions (t)
CO	31.88
VOC	28.29
NOX	119.37
NMVOC	1.26
CH4	28.96
N2O	0.72
NH3	0.16
PM2.5	4.37
PM10	5.95
SO2	0.10
Pb	0.01
Black Carbon	0.03
CO2	55869.42

In Table 45 are reported the total annual emissions for the scenario 3HYB, including also the contribution of the electric buses.

Table 45. Total annual emissions for the scenario 3HYB

Pollutant	GWP 100	Scenario 3HYB (tCO2eq)
CO2	1	55869.42
N2O	265	191.40
CH4	28	810.90
CO	2.1	66.96
NMVOC	3.4	4.27
Total		**58032.34**

Scenario 1EL

In this scenario, Diesel Euro 2, Diesel Euro 3 and Diesel Euro 4 buses were substituted by electric buses, that, added to the electric buses already present in the actual fleet (101), represent the 26% of the total bus fleet, that means a total of 241 (23 buses of 7.5 m, 13 buses of 8.7 m, 120 buses of 12 m and 85 buses of 18 m). It is important to specify that the Turin bus fleet does not include electric buses with a length of 18 m and, for that reason, for scenario 1EL, 2EL and 3EL, to perform the substitution, was adopted the Iveco E-WAY 18 m, that presents a consumption of 1.2 KWh/Km. The scenario is represented in Figure 78.

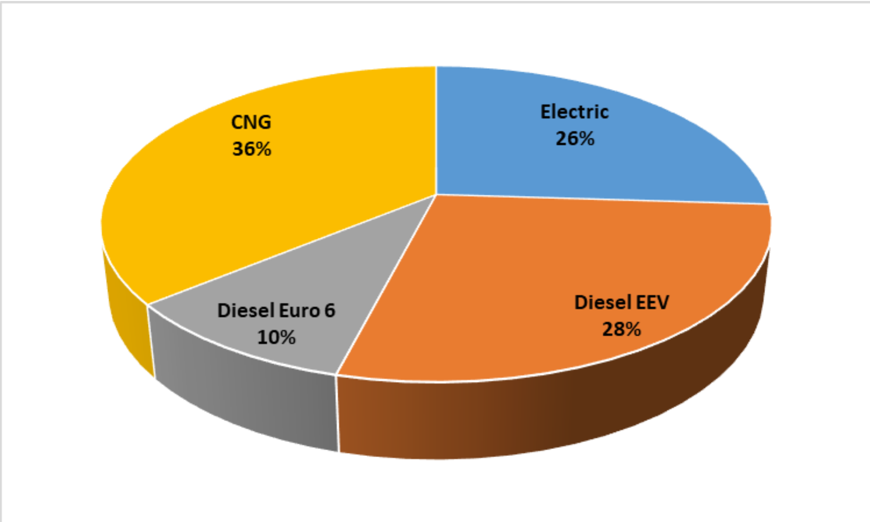

Figure 78. Scenario 1EL: 26% of electric buses

For each type of electric bus, was evaluated the emission factor, expressed as gCO_2eq/Km, and the total emissions, expressed as tCO_2eq, making the same assumption and equation adopted for the actual scenario. The obtained results are reported in Table 46.

Table 46. EFs and emissions for Scenario 1EL-electric buses

Model	Number of vehicles	Consumption (KWh/Km)	GHG emission intensity of electricity generation (2019)-Italy (gCO2 eq/KWh)	EF (g CO2 eq/Km)	Emissions (t CO2 eq)
EPT-CACCIAMALI "ELFO" ELECTRIC (7.5 m)	23	0.95	233	221.35	254.55
BYD K7 ELECTRIC (8.7 m)	13	0.67	233	156.11	101.47
BYD K9UB ELECTRIC (12 m)	70	1.04	233	242.32	848.12
BYD K9UB ELECTRIC (12 m)	50	0.91	233	212.03	530.08
Iveco E-WAY (18 m)	85	1.2	233	279.6	1188.30
Total					**2922.52**

Then, it was evaluated the total pollutants emission in a year caused by Diesel and CNG gases, using the same method and assumptions adopted for the actual scenario. In Table 47 are reported the value of annual emissions obtained for the scenario 1EL.

Table 47. Total annual pollutant emissions evaluation for Scenario 1EL

Pollutant	Total annual emissions (t)
CO	72.47
VOC	28.76
NOX	243.18
NMVOC	1.67
CH4	28.98
N2O	0.76
NH3	0.26
PM2.5	4.62
PM10	7.36
SO2	0.10
Pb	0.01
Black Carbon	0.86
CO2	56851.92

In Table 48 are reported the total annual emissions for the scenario 1EL, including also the contribution of the electric buses.

Table 48. Total annual emissions for the scenario 1EL

Pollutant	GWP 100	Scenario 1EL (tCO2 eq)
CO2	1	56851.92
N2O	265	200.22
CH4	28	811.57
CO	2.1	152.18
NMVOC	3.4	5.68
Total		**60944.09**

Scenario 2EL

In this scenario, Diesel Euro 2, Diesel Euro 3, Diesel Euro 4, Diesel EEV and Diesel Euro 6 buses were substituted by electric buses, that, added to the electric buses already present in the actual fleet (101), represent the 54% of the total bus fleet, that means a total of 505 (23 buses of 7.5 m, 13 buses of 8.7 m, 301 buses of 12 m and 168 buses of 18 m). The scenario is represented in Figure 79.

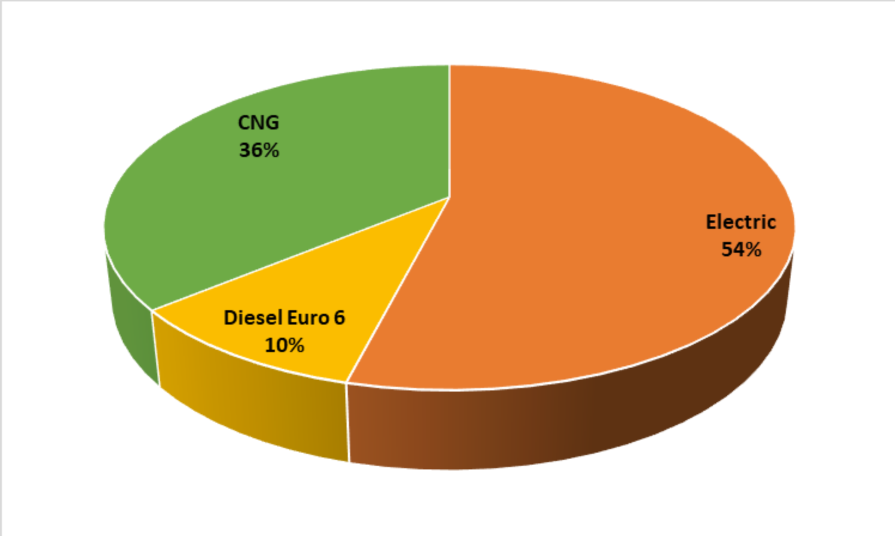

Figure 79. Scenario 2EL: 54% of electric buses

For each type of electric bus, was evaluated the emission factor, expressed as gCO_2eq/Km, and the total emissions, expressed as tCO_2eq, making the same assumption and equation adopted for the actual scenario. The obtained results are reported in Table 49.

Table 49. EFs and emissions for Scenario 2EL-electric buses

Model	Number of vehicles	Consumption (KWh/Km)	GHG emission intensity of electricity generation (2019)-Italy (gCO2 eq/KWh)	EF (g CO2 eq/Km)	Emissions (t CO2 eq)
EPT-CACCIAMALI "ELFO" ELECTRIC (7.5 m)	23	0.95	233	221.35	254.55
BYD K7 ELECTRIC (8.7 m)	13	0.67	233	156.11	101.47
BYD K9UB ELECTRIC (12 m)	251	1.04	233	242.32	3041.12
BYD K9UB ELECTRIC (12 m)	50	0.91	233	212.03	530.08
Iveco E-WAY (18 m)	168	1.2	233	279.6	2348.64
Total					**6275.86**

Then, it was evaluated the total pollutants emission in a year caused by Diesel and CNG gases, using the same method and assumptions adopted for the actual scenario. In Table 50 are reported the value of annual emissions obtained for the scenario 2EL.

Table 50. Total annual pollutant emissions evaluation for Scenario 2EL

Pollutant	Total annual emissions (t)
CO	56.07
VOC	28.36
NOX	201.87
NMVOC	1.32
CH4	28.96
N2O	0.58
NH3	0.20
PM2.5	3.86
PM10	6.27
SO2	0.07
Pb	0.01
Black Carbon	0.56
CO2	49761.73

In Table 51 are reported the total annual emissions for the scenario 2EL, including also the contribution of the electric buses.

Table 51. Total annual emissions for the scenario 2EL

Pollutant	GWP 100	Scenario 2EL (tCO2 eq)
CO2	1	49761.73
N2O	265	154.97
CH4	28	810.77
CO	2.1	117.75
NMVOC	3.4	4.49
Total		**57125.56**

Scenario 3EL

In this scenario, Diesel Euro 2, Diesel Euro 3, Diesel Euro 4 and Diesel EEV buses were substituted by electric buses, that, added to the electric buses already present in the actual fleet (101), represent the 59% of the total bus fleet, that means a total of 599 (23 buses of 7.5 m, 19 buses of 8.7 m, 372 buses of 12 m and 215 buses of 18 m). The scenario is represented in Figure 80.

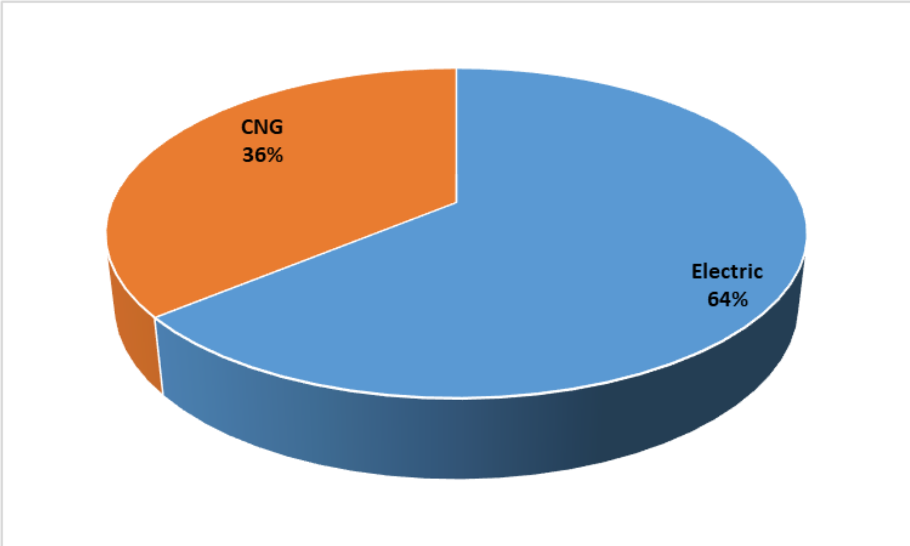

Figure 80. Scenario 3EL: 59% of electric buses

For each type of electric bus, was evaluated the emission factor, expressed as gCO2eq/Km, and the total emissions, expressed as tCO2eq, making the same assumption and equation adopted for the actual scenario. The obtained results are reported in Table 52.

Table 52. EFs and emissions for Scenario 3EL-electric buses

Model	Number of vehicles	Consumption (KWh/Km)	GHG emission intensity of electricity generation (2019)-Italy (gCO2 eq/KWh)	EF (g CO2 eq/Km)	Emissions (t CO2 eq)
EPT-CACCIAMALI "ELFO" ELECTRIC (7.5 m)	23	0.95	233	221.35	254.55
BYD K7 ELECTRIC (8.7 m)	19	0.67	233	156.11	148.30
BYD K9UB ELECTRIC (12 m)	322	1.04	233	242.32	3901.35
BYD K9UB ELECTRIC (12 m)	50	0.91	233	212.03	530.08
Iveco E-WAY (18 m)	215	1.2	233	279.6	3005.70
Total					**7839.98**

Then, it was evaluated the total pollutants emission in a year caused by Diesel and CNG gases, using the same method and assumptions adopted for the actual scenario. In Table 53 are reported the value of annual emissions obtained for the scenario 3EL.

Table 53. Total annual pollutant emissions evaluation for Scenario 3EL

Pollutant	Total annual emissions (t)
CO	26.30
VOC	27.34
NOX	110.93
NMVOC	0.44
CH4	28.86
N2O	0.00
NH3	0.00
PM2.5	1.91
PM10	3.49
SO2	0.00
Pb	0.00
Black Carbon	0.00
CO2	31383.66

In Table 54 are reported the total annual emissions for the scenario 3EL, including also the contribution of the electric buses.

Table 54. Total annual emissions for the scenario 3EL

Pollutant	GWP 100	Scenario 3EL (tCO2 eq)
CO2	1	31383.66
N2O	265	0.00
CH4	28	808.14
CO	2.1	55.24
NMVOC	3.4	1.48
Total		**40088.50**

5.2.4 Comparison of the different scenarios

In this section was performed the comparison between the actual annual emissions scenario and the six scenarios supposed.

In Figure 81 are represented the values of annual CO_2 emissions obtained for the different scenarios, considering the travelling phase: the highest is the actual scenario, with about 70,000 tons; considering the scenario 1HYB,2HYB and 3HYB, that suppose the transition towards hybrid buses, it is possible to notice a gradual decrease and the same trend is for scenario 1EL, 2EL and 3EL, that represent the transition towards electric buses. Comparing scenarios that involve hybrid buses (scenario 1HYB,2HYB and 3HYB) and scenarios that involve electric buses (scenarios 1EL, 2EL and 3EL), obviously, the decrease of CO_2 is higher for electric because, increasing the number of them, there are less pollutant emissions during travelling phase, but, scenario 1EL (26 % of electrics with the presence of Diesel EEV, Euro 6 and CNG) emits more CO_2 than scenario 3HYB (53 % of hybrids with only the presence of electrics and CNG). Comparing the correspondent scenarios of hybrid and electric percentage substitutions, that means comparing scenario 1HYB with scenario 1EL;

scenario 2HYB with scenario 2EL and scenario 3HYB with scenario 3EL, it is that CO_2 emissions are always lower for the scenarios that involve electrics.

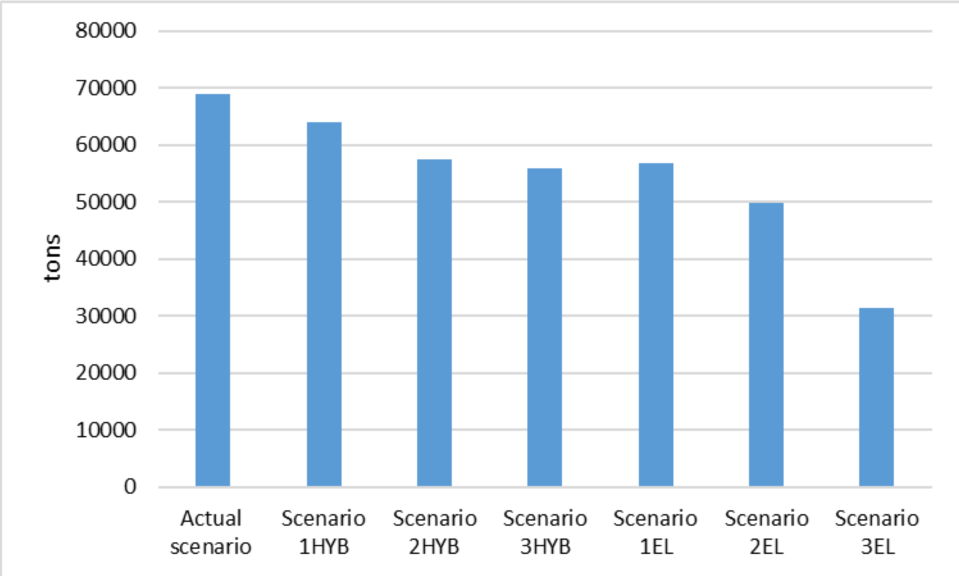

Figure 81. Comparison of scenarios: CO2 emissions

In Figure 82 and in Figure 83 are shown the values of pollutant emissions obtained: in Figure 82, it is possible to notice that NOx are the most generated pollutant in all cases and the highest value is reached from the actual scenario; scenario 2HYB, 3HYB and 3EL presents almost the same quantity but less NOx than scenario 1HYB; scenario 1EL is similar to scenario 1HYB and this means that, considering only CO and NOx emissions, there is no difference between transition towards hybrids or electrics because, considering the best hypothesis (scenario 3HYB and scenario 3EL), the values are almost the same. The values for VOC and CH_4 are almost the same for all scenarios.

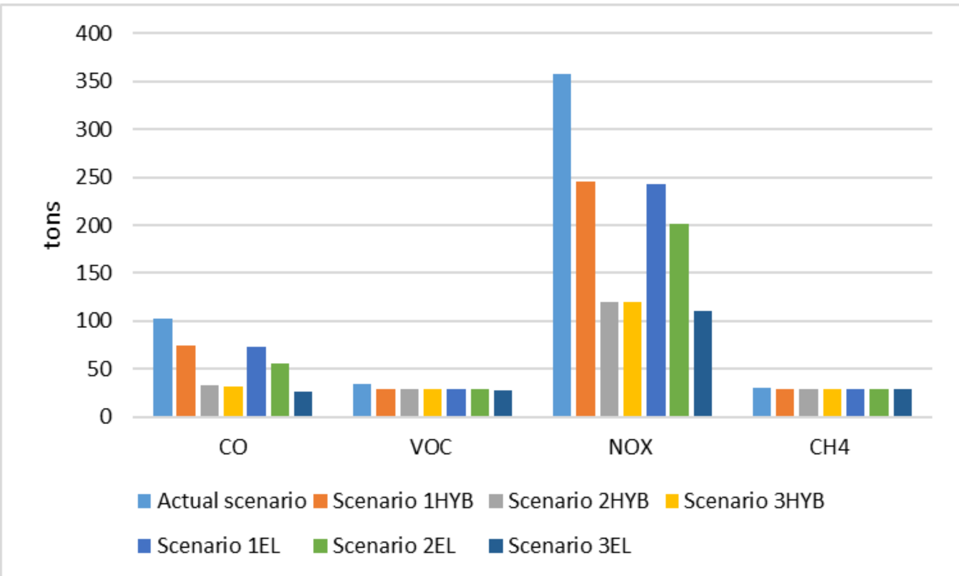

Figure 82. Comparison of scenarios: CO, VOC NOx, CH_4, emissions

In Figure 83 it is possible to notice that, among the pollutants considered in this graph, the most emitted are PM10 and PM2.5 with highest value for the actual scenario; as regard NMVOC, not considering Diesel Euro 2, Euro 3 and Euro 4, the emissions decrease a lot. For scenario 3EL, that includes only electric and CNG, there are not emissions of N_2O, NH_3, SO_2 and Black carbon.

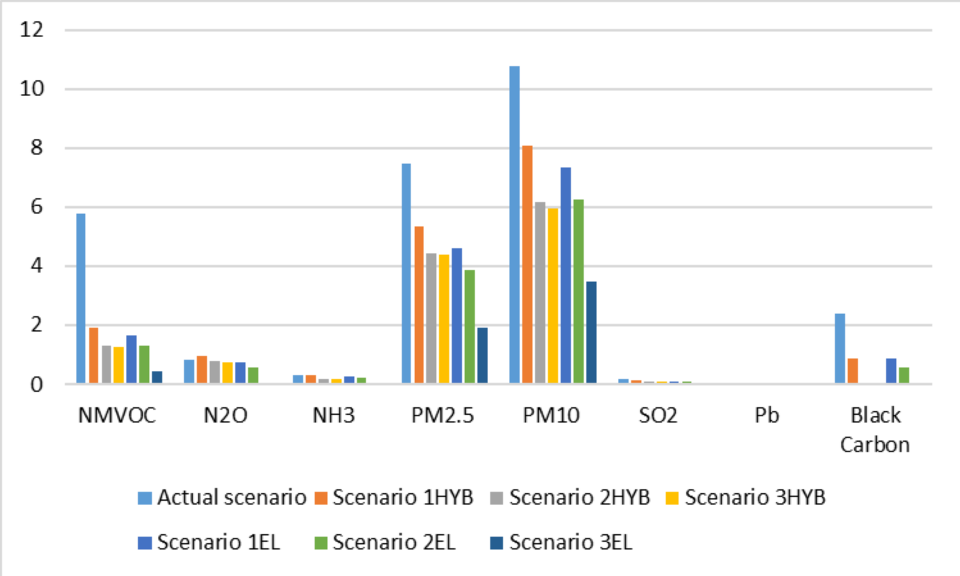

Figure 83. Comparison of scenarios: NMVOC, N_2O, NH_3, PM2.5, PM10, SO2, Pb, Black carbon emissions

In Figure 84, are represented the total annual emissions in tCO_2eq and this means that also the contribute of greenhouse gas effect of the energy used for electric buses charging was included. It is possible to notice that the graph presents the same trend of CO_2 emissions (Figure 81): consequently, the energy used for the electric buses charging impacts much less than CO_2 emissions due to Diesel and CNG.

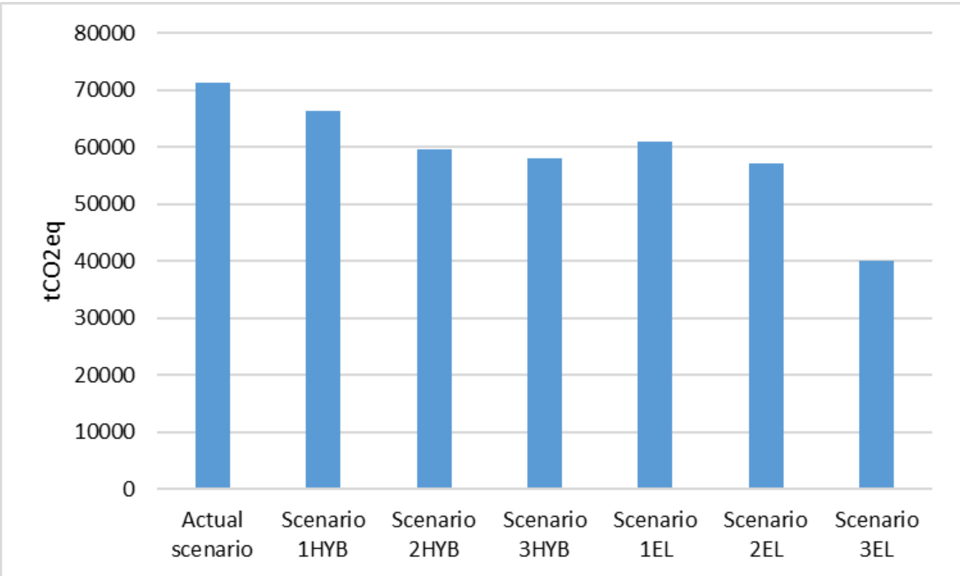

Figure 84. Comparison of scenarios: emissions as tCO_2eq

In Table 55 are reported the percentage of reduction in terms of CO_2 emissions because is the most emitted pollutant and it impacts mostly on total emissions.

Table 55. CO_2 reduction for different scenario than the actual scenario

Scenario	CO2 (t)	% reduction
Actual scenario	69016.3	
Scenario 1HYB	64000.6	7.3
Scenario 2HYB	57488.7	16.7
Scenario 3HYB	55869.4	19.0
Scenario 1EL	56851.9	17.6
Scenario 2EL	49761.7	27.9
Scenario 3EL	31383.7	54.5

In Table 56 are reported the percentage of reduction in terms of CO_2 eq emissions, also including the charging phase of electric buses.

Table 56. Emissions as tCO_2eq for different scenario than the actual scenario

Scenario	tCO2eq	% reduction
Actual scenario	71399.0	
Scenario 1HYB	66320.6	7.1
Scenario 2HYB	59673.0	16.4
Scenario 3HYB	58032.3	18.7
Scenario 1EL	60944.1	14.6
Scenario 2EL	57125.6	20.0
Scenario 3EL	40088.5	43.9

In conclusion, analysing the results reported in Table 56 and 57, it is possible to say that, considering only the use phase of buses (excluding emissions that involve bus and batteries production), supposing that each bus travels 50,000 Km in a year, the best scenario is the 3EL, with the 64% of electric buses because it guarantees always less emissions with a reduction by 54% of CO_2 emissions than the actual scenario and a reduction of 44% in terms of CO_2 eq. Scenario 3HYB, with 54% of hybrid buses, present a reduction of CO_2 emissions and in terms of CO_2 eq that is about 20%.

6.Li-ion batteries impacts assessment

In this section, is performed an impact assessment of LIBs types used in the IVECO buses analysed in the chapter 5: In particular, were considered:

- NMC 111, adopted for the IVECO electric buses;
- NMC 622, adopted for the IVECO hybrid buses;
- LFP, adopted for the IVECO phased out hybrid buses.

This evaluation considered the entire life of the batteries, starting from the materials extractions, the battery production, the use phase and the end-of-life management, as shown in Figure 85. In particular, this assessment was based on existing Life Cycle Assessments (LCAs):

1. In the first part, was performed an impact assessment with a "cradle-to-gate" approach, collecting data about material extraction and processing and battery manufacturing for the three batteries investigated basing on existing LCAs;
2. In the second part, was performed an impact assessment considering two alternative scenarios of LIBs recycling, that are pyrometallurgy and hydrometallurgy.

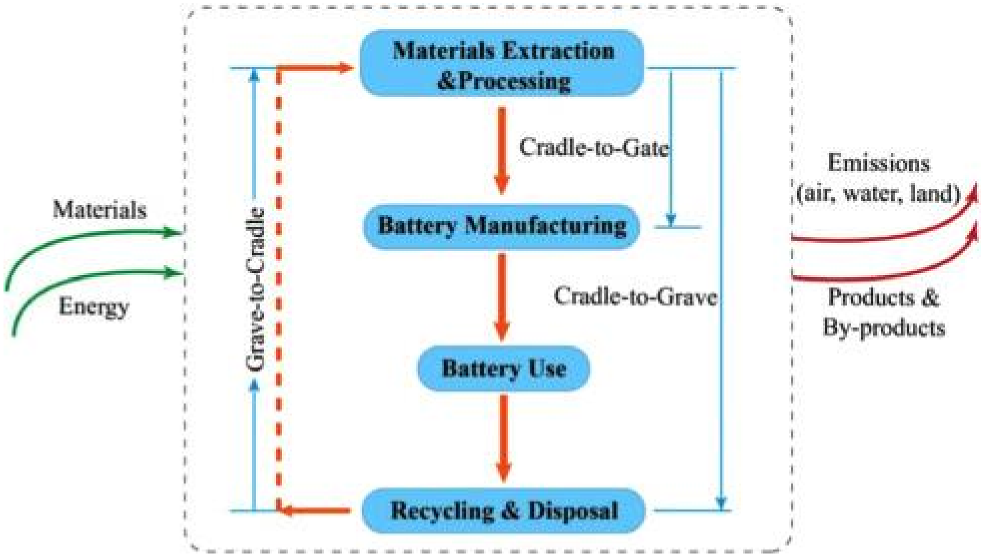

Figure 85.Generic boundary, process and energy/materials flow for the three types of LCAs (Yang et al., 2021)

6.1 Li-ion batteries production

At first, were considered the materials extractions and refining and the battery manufacturing, performing a cradle-to-gate analysis. The Functional Unit (FU) adopted for this evaluation is 1 tons of battery.

Phase 1: Materials extractions and processing and battery and components manufacturing

Methods and materials

In phase 1 were evaluated the impacts related to materials extraction and processing and battery and components manufacturing to produce 1 ton of NMC 111, NMC 622 and LFP battery. As regard the materials extraction and processing, initially, referring to Table 13, in which was reported the composition for cells of different Li-ion batteries (Gaines et al.,2018), were calculated the mass percentage of materials for NMC 111, NMC 622 and LFP cell composition. In particular, the materials considered for this analysis are: Li, Co, Ni, Mn, Al, Fe, P, for the cathode; Graphite for the anode; Aluminium and Copper as current collectors. The total active cathode material that composes the three batteries' cell is present in different percentages: for NMC 111, it constitutes the 34.1% of a single cell; for NMC 622, it represents the 31.8% of a single cell and for LFP, it represents the 32.2% of a cell (Gaines et al., 2018). The results of the calculated mass percentage of these elements for the three types of batteries and the results are reported in Figure 86. It is possible to notice that the NMC111 and NMC 622 are composed by the same elements but in different proportion mainly as regard Ni, Co and Mn; the LFP cathode's active material is composed by Li, Fe and P; the graphite constitutes about the 20% in mass of the cell for the NMC and the 17% for the LFP; the indication "other material " in the graph's legend is the material not investigated in that analysis. In the Appendix are reported the detailed results.

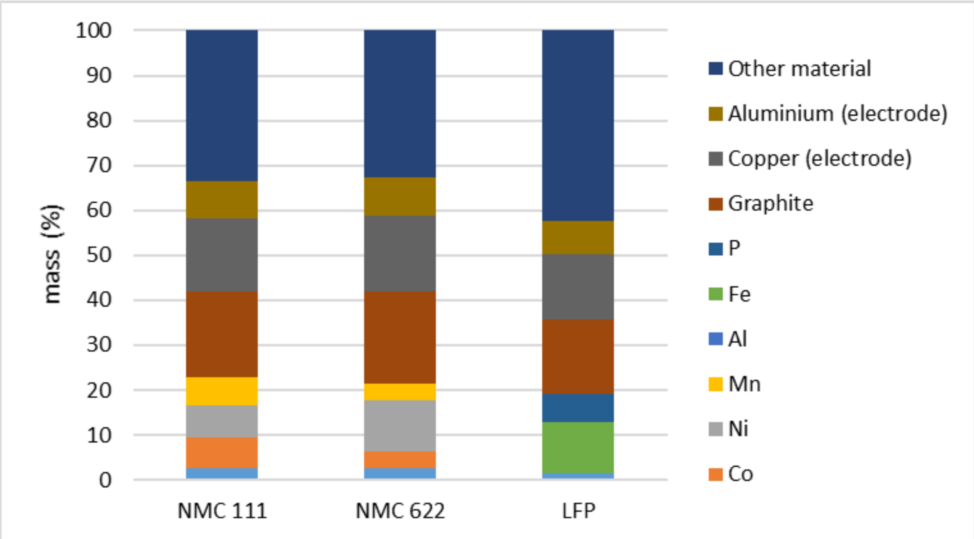

Figure 86. Cell composition for the NMC111, NMC 622 and LFP.

After this calculation, it is possible, considering these results for the cathode active material and the different percentages of the other elements that compose the battery cell, to evaluate the quantity of the considered material to be extracted to produce 1 tons of battery. The results of this calculation were reported in the Appendix. Then, are calculated the GWP impacts relative to mining, purification and refining of Li, Co, Ni, Mn, Al, Fe, P, Aluminium and Copper that compose the batteries' cells, using the GWP associated to the cathode materials and current collectors calculated in a LCA analysis performed by Nuss et al. (2014) and adopting the GWP associated to graphite calculated by Manjong et. al (2021). To perform this evaluation, it was used the following equation:

$$Impact_{extraction\ and\ refining}\ [KgCO_2eq] = Kg\ of\ extracted\ material \cdot GWP[KgCO_2eq/Kg]$$

The GWP are calculated for the three types of batteries.

As regard the GWP associated to battery components and manufacture, it was calculated considering the impact of production provided by Yang et al (2021), that is the same for the three types of batteries and it is equal to 6,160 $KgCO_2eq$.

At the end, was performed the total impact calculation in $KgCO_2eq$ adding the values of emissions obtained for the material extraction and refining (extr and ref) and the value of emissions associated to battery and components manufacture (B&C manufacture):

$$Impact_{prod}\ [KgCO_2eq]\ =\ Impact_{extr\ and\ ref}\ [KgCO_2eq] + Impact_{B\&C\ manufacture}\ [KgCO_2eq]$$

Results

In Figure 87 are reported the obtained results as regard the impact of material extraction and refining for 1 ton of battery, using the values provided by Nuss et al (2014) and Manjong et al. (2021) for the investigated elements (reported in the Appendix): it is possible to notice that the highest impact is obtained for 1 ton of NMC622 with a value of 3,305.1 KgCO_2eq, followed by NMC11 with a value of 3,202.3 KgCO_2eq; the LFP presents a value of emissions that is about 1.5 times less than the other two and it is 1,989.7 KgCO_2eq. In conclusion, the impacts calculated were directly related to the three mass percentage compositions (Figure 86): the lowest impact is due to LFP materials extraction and refining because it presents less quantity of investigated materials on its composition. Analysing the impact relatively to the single elements, it is possible to notice that, in all cases, are due to Graphite (798 KgCO_2eq for NMC 111, 869 KgCO_2eq for NMC 622 and 697 KgCO_2eq) and the Aluminium for the electrode (672.4 KgCO_2eq for 1 t of NMC 111, 688.8 KgCO_2eq for 1 t of NMC 622 and 615 KgCO_2eq for 1 t of LFP). The quantity of Li is less for LFP and the relative impact is 100.6 KgCO_2eq; for the NMC111 is calculated the highest impact for Li, with a value of 190.3 KgCO_2eq; for NMC 622 is calculated a Li impact extraction of 176.56 KgCO_2eq. The impact relatively to Copper is almost the same for the three batteries: for NMC 111 is about 459.20 KgCO_2eq, for NMC 622 is about 470.4 KgCO_2eq and for LFP is about 406 KgCO_2eq. As regard the NMC batteries, the main difference between NMC111 and NMC 622 is the impact, that derives from the different quantity, of Ni and Co: for the NMC 622 the calculated impact associated to Ni extraction is about 745.6 KgCO_2eq, for the NMC111 is about 1.7 times less, with a value of 446.18 KgCO_2eq/t of battery; in the contrary, as regard the Co, the impact is highest for NMC 111 (572 KgCO_2eq) and for the NMC622 is 1.8 times less (318.6 KgCO_2eq). As regard Mn extraction, the highest impact is due to NMC 111, with a calculated value of 64.2 KgCO_2eq, followed by NMC111 that, due to less quantity of Mn, presents an impact of 35.8 KgCO_2eq. As regard the LFP, the impact of Fe extraction is about 11.4 KgCO_2eq and for P is about 6.32 KgCO_2eq.

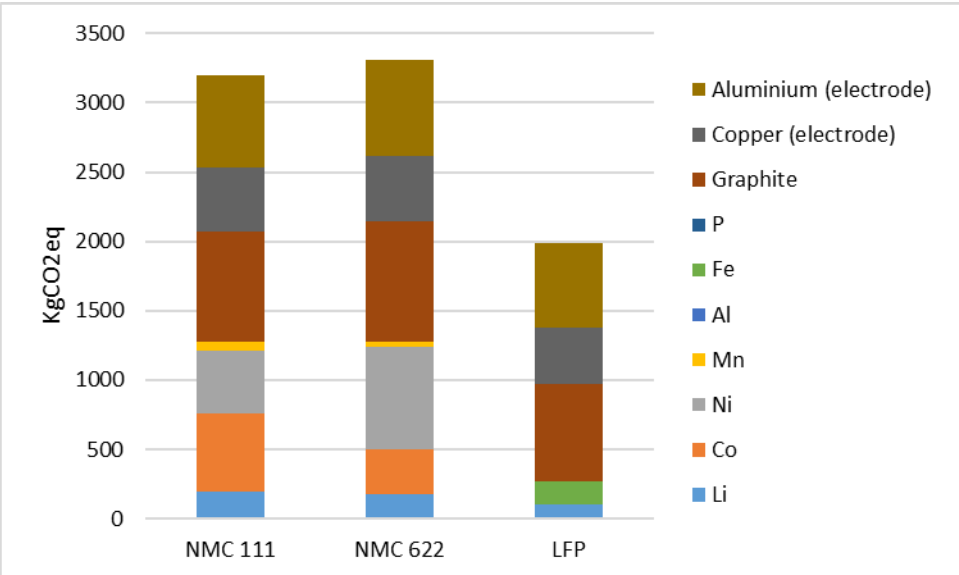

Figure 87. Impact of materials extraction and refining per 1 ton of battery

In Figure 88 are represented the percentages relatively to the impact of materials extraction and refining to produce 1 ton of battery: it is possible to notice that the highest impact is due for the cathode production, that represents about 85% of total emissions for the NMC type and about the 80 % of total emissions for LFP production. As regard the anode production, it represents about the 40% of total impacts for the NMC and the 55% for the LFP.

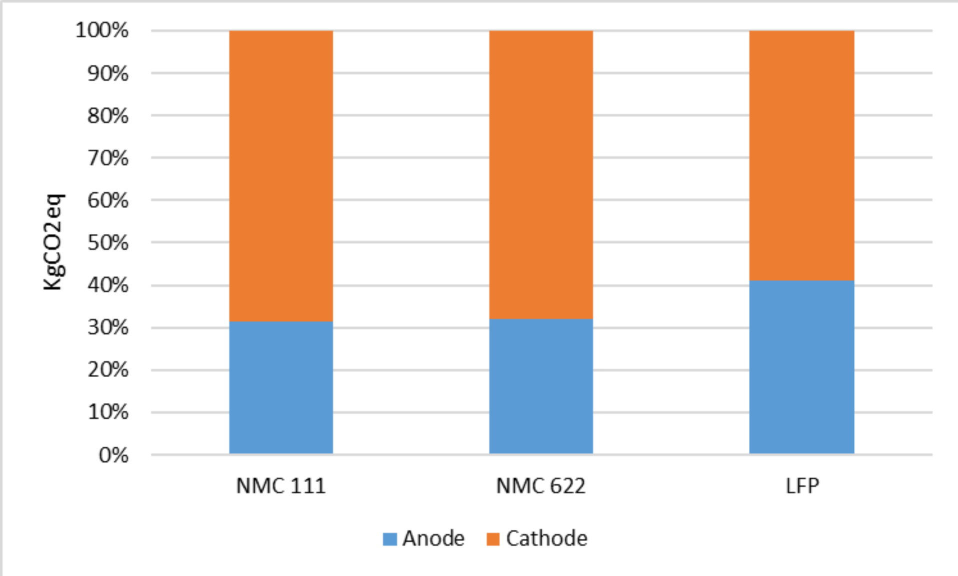

Figure 88. % of impacts of total anode and cathode materials extraction and refining per 1 ton of battery

In Figure 89 are reported the obtained values for the total impact of 1 ton if battery production, considering the extraction and refining phases of materials and the impact associated to the battery components and manufacture, that is the same for the three types (6,160 $KgCO_2eq$). The highest total impact is due the different composition of the batteries: the highest is calculated for NMC622 with a value of 9,465 $KgCO_2eq$, followed by NMC 111, with a calculated total value of 9,362.3 $KgCO_2$ and the lowest is calculated for LFP, that presents a total impact of 8,149. 8 $KgCO_2eq$.

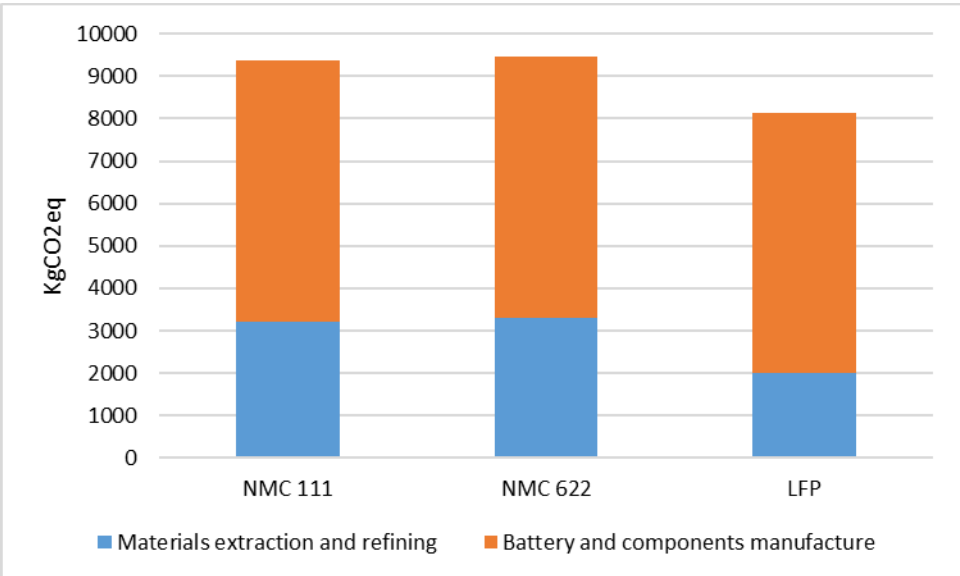

Figure 89. Total impact for 1 ton of battery production.

6.2 Li-ion batteries recycling

In this section are evaluated the impacts relatively to emissions of EoL batteries recycling, considering the two alternative scenarios:

1. Pyrometallurgic treatment
2. Hydrometallurgical treatment

6.2.1 End of life batteries options

Typically, a LIB is considered end of life when its capacity decrease of 20% (it means that the battery has the 80% of the initial battery capacity) (Woody et al.,2020) and and there are three main options for an EoL battery depending on different conditions, quality and State of charge, that are: remanufacturing, repurposing and recycling (Chen et al., 2019). In Figure 90 are represented the circularity strategies for EoL batteries (Alamerew et al., 2020).

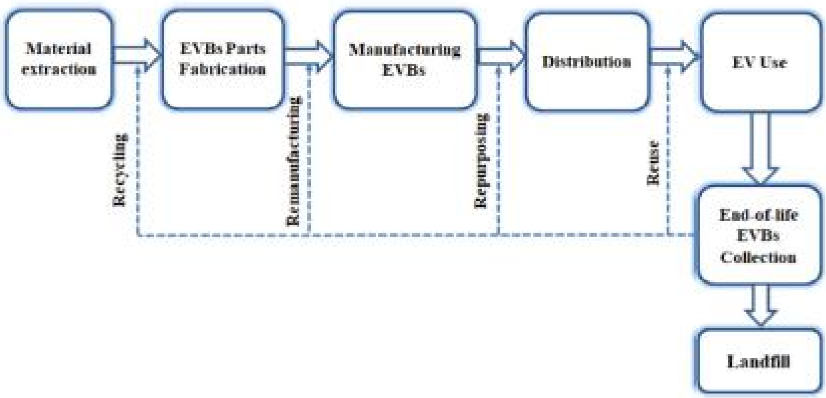

Figure 90. Circularity strategies for retired batteries (Alamerew et al., 2020)

Referring to Figure 94, the remanufacturing allows to maximize the value of LIBs but it is stringent in terms of quality requirements because, using them in their original automotive applications, they must have specific State of Charge and specific requirements about power, energy and cycle life and according to the United States Advanced Battery Consortium (Chen, et al., 2019). The remanufacturing phases are: battery diagnosis, partial disassembly of battery packs, replacement of damaged cells or modules within the battery pack and then reassembly into new battery pack to be used for an electric vehicle (Chen, et al., 2019)

The repurposing is an option that gives to the LIB a “second life”, replacing of damaged cells or modules and reconfiguring the modules or the pack (including establishing a new BMS) for a use in a less stressful application (e.g., stationary storage, peak shaving integrating solar) (Chen, et al., 2019).

The recycling is the option that allows to recover the mainly the cathode material, that accounts of 40% average of the material value in a typical LIB and represents, also economically, the highest value in LIBs (also economically) (Chen, et al., 2019). The recycling implementation in fact can be a solution to avoid the LIBs disposal: they in fact contain toxic material (heavy metals such as Ni and Co) and, furthermore, the materials extraction, such as Li and Co, are connected to various problems, that involve political risks, security risks, conflicting land use, scanty supply, irregular distribution on the Earth, unethical mining practices source due to the scarcity of these resources and theirs high demand (Costa et al., 2021; Makuza et al., 2021). In this context, is important to recover valuable metals from LIBs that can be employed to synthetize a new cathode, avoiding the extraction of virgin materials (Makuza et al., 2021). The recycling of lithium and other metals are 10% globally and it means that the remaining 90% ends up to landfill (Costa et al., 2021).

In the specific case of IVECO Bus, the life of a LIB is about 7/8 years and, considering that the life of a bus is about 15 years, it must be substituted once; these batteries are not used for less stressful application, such as secondary storage, and, for that reason, is analysed only the recycling scenario. When a LIB of IVECO Bus reaches its EoL, it returns to the battery's supplier, that assume the EoL battery management (the EoL battery management is not under the control of CNH Ind.); then the supplier gives the EoL battery to a third recycling company (Sarpi Veolia). There is not information provided by CNH Ind. about the recycling technique because the control is under a third company. As regard the hybrid buses, the EoL battery is sent to the supplier but in this case the final management is evaluated case by case. Also, in this case there are not information provided by CNH Ind. because the EoL battery control is under the supplier. In Figure 91 is represented a scheme with the management of EoL buses batteries.

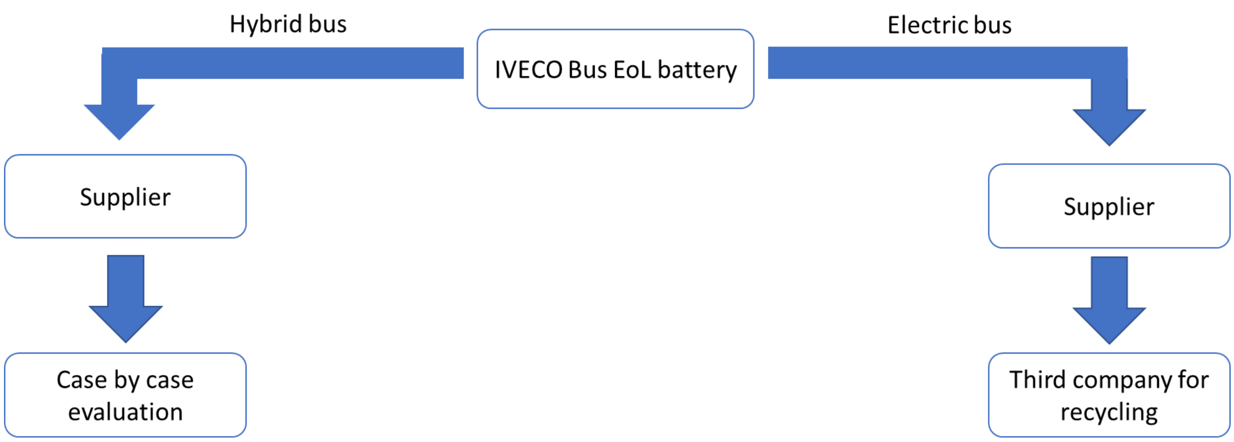

Figure 91. CNH Industrial's EoL batteries management for hybrid and electric buses

In general, a LIB recycling is articulated in the following phases:

- **Discharging, disassembly and comminution**

The spent LIBs have a remain capacity and, for this reason, they are discharged to avoid the detonation caused by short-circuiting or self-ignition and they are discharged in electrolyte solutions such as NaCl and Na_2SO_4 (Mohanty et al., 2021). Then, is conducted the disassembly to separate cell packing and to get access to the modules (that contain active materials) (Ali et al.,2021); this operation is usually manually with knives and saws (Kim et al., 2021). In this way, are obtained the cathode plate, anode plate, the separator and battery packaging materials and then, the battery active materials are separated from the current collectors (Wang et al., 2021). Then, the LIBs modules, that contains the valuable raw materials, undergo to a comminution phase performed with hammer crushing, wet crushing, shear crushing, impact crushing and cutting milling (Ali et al.,2021) to liberate the electrode materials.

- **Physical separation**

Then, it is performed a physical separation, that includes size separation, magnetic separation, density separation and froth flotation to increase the purity of products: trough these phases are separated the different materials that are plastics, separator and pouch, steel frame, Aluminium, Copper and black mass (Ali et al, 2021). In particular, the black mass include positive and negative electrodes contents and it undergo to a pyrometallurgic or hydrometallurgical process to recover valuable metals (Ali et al., 2021).

- **Recycling technique**

At this point it is possible to adopt two different techniques to recover the valuable metals from the black mass:

1. **Pyrometallurgy**: this method allows to recover materials from the black mass in the form of metal alloy. The LIB, after the dismantling of the battery pack to individual cells (Wang et al., 2021), is smelted in a furnace at high temperature (800-1000 °C) and the metal oxides are turned into an alloy of Co, Cu, Fe and Ni (Ali et al., 2021) with a carbon reductant; Li, Al, Si, Ca, and some of Fe remain in the slug (Wang et al.,2021). Finally, the obtained metals alloy is separated to individual metals through a solvent based extraction post-process (often hydrometallurgy) to produce high purity nickel and cobalt salts that can be used for battery applications (Abdelbaky et al., 2021); the plastics, organic solvents and graphite are not recovered and are burned to supply energy for the recycling process (Wang et al.,2021).
   The advantages of this process are:
   - Applicable to all LIB chemistries (Ali et al.,2021)
   - High recovery of metals (Ali et al., 2021) but low selectivity
   - Simple and mature process (Chen et al., 2019)
   - Sorting and size reduction are not necessary (Chen et al.,2019)
   - the output consists in "elemental building blocks" that can be used to synthetize new cathode material (Chen et al.,2021)

   The disadvantages of this method are that (Wang et al.,2021):

   - the valuable Li cannot be effectively recycled
   - the electrolyte, separator, and anode graphite are not recycled
   - it generates emission of hazardous gases
   - it requires and high energy consumption and generates CO_2

2. **Hydrometallurgy**: through this technique, the material recovery is performed through a leaching in acids or basis, that dissolves the metals present in the EoL batteries; then a subsequent concentration and purification phases allows to separate metal ions (Chen et al.,2019). The ions in solution can be separated trough different technologies, such as ion exchange, solvent extraction, chemical precipitation or electrolysis (Chen et al.,2019).
   The advantages of this methods are:
   - applicable to all LIB chemistry (Ali et al., 2021);
   - generation of high purity materials (Chen et al., 2019);
   - most constituents of LIB can be recovered (Chen et al., 2019);
   - low temperature operation and lower CO_2 emissions compared to a pyrometallurgical process (Chen et al., 2019).

   The disadvantages of this method are:

- the need of sorting and crushing, that adds costs (Chen et al.,2019);
- the challenge of separating some elements (Co, Ni, Mn, Fe, Cu, and Al) in the solution, due to their similar properties, which can lead to higher costs (Chen et al.,2019);
- wastewater treatment is required and it leads to higher costs (Chen et al.,2019)

In Figure 92 are resumed the two options described.

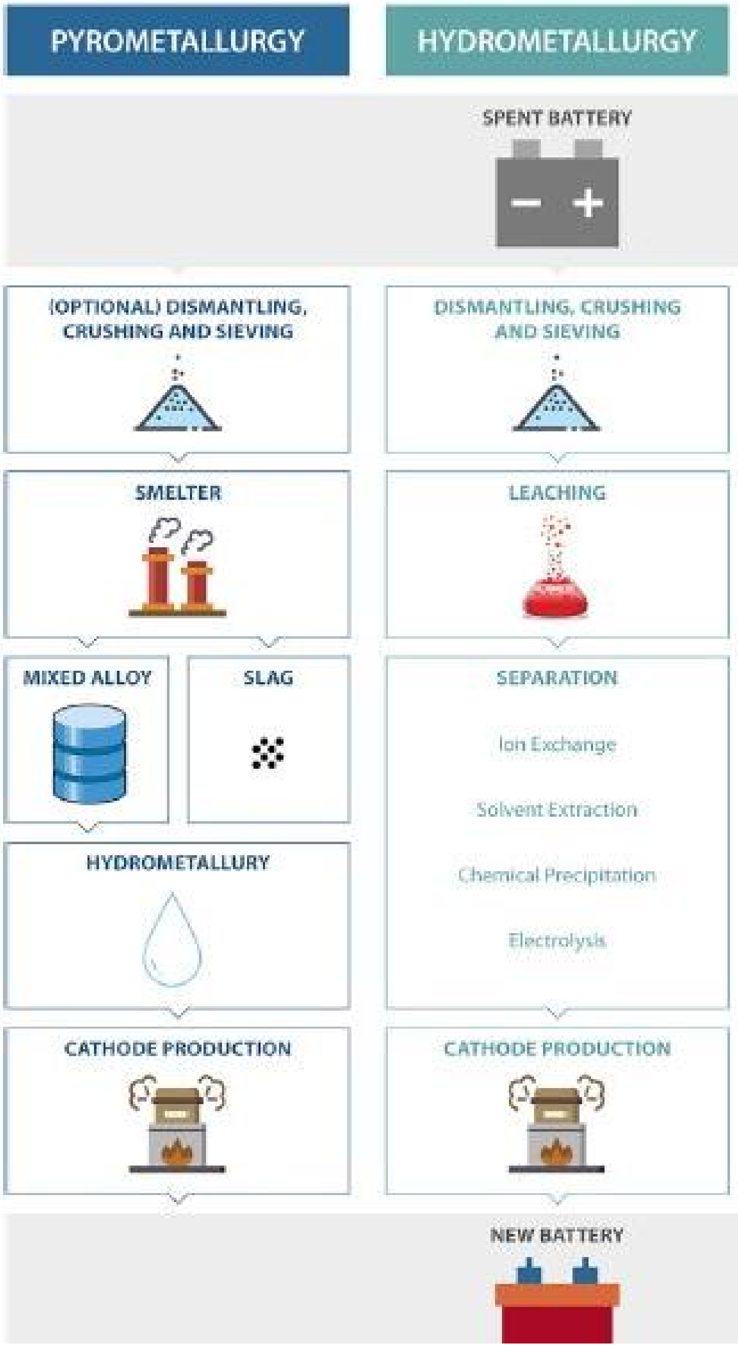

Figure 92. LIBs recycling options (Chen et al.,2019)

6.2.2 Recycling impact assessment and material flow analysis

Methods and materials

As mentioned above, in the phase 2, was performed the evaluation of emissions related to EoL batteries recycling, considering the two alternative scenarios of pyrometallurgy and hydrometallurgy treatment. Furthermore, through a material flow analysis was performed the calculation of materials recovery from the two recycling options.

As a first step, were calculated the Kg of recovered materials for 1 ton of battery for the two recycling alternatives, using the following equation:

$$Kg\ of\ recovered\ material = recovery\ efficiency\ [\%] \cdot Kg\ of\ extracted\ material$$

The evaluation was performed considering the recovery of the cathode active materials, that represent the highest value of a LIB in terms of metals, for the two scenarios. The Kg of recovered materials were calculated considering the recovery rate for the two techniques:

- as regard pyrometallurgic process, recovery rates for Co and Ni are obtained from the study of Makuza et al. (2021), performing an average between the different recoveries efficiencies associated to different pyrometallurgic techniques, and from Rajaeifar et al. (2021) is obtained the recovery rate for Fe. Considering that pyrometallurgy does not recover Li and Mn, the recovery rates are: 93.62% for Co, 91.97% for Ni and 64.5% for Fe.
- concerning hydrometallurgical process, the calculated recovery rates are obtained performing an average between the recovery efficiencies provided in the study of Lai et al. (2021), that consider different leaching agents (organic and inorganic acids). As regard NMC, the calculated recovery rates are: 94.79% for Li, 87.89% for Co, 90.1% for Ni and 86.14% for Mn; as regard LFP, the calculated average recovery rates are 96.6% for Li and 95.85 for Fe.

Then, were calculated the $KgCO_2eq$ saved through recycling, applying the following equation:

$$KgCO_2eq\ saved = Kg\ of\ recovered\ material\ \cdot\ GWP[KgCO_2eq/Kg]$$

The total emissions due to recycling process for 1 ton of battery is calculated applying the following equation:

$$Recycling\ emissions\ (KgCO_2eq\ ) = GWP_{recycling}\left[\frac{KgCO_2\,eq}{Kg}\right] \cdot 1\ ton\ of\ battery - KgCO_2eq\ saved$$

The GWP associated to recycling process is provided by Abdelbaky et al.(2021): it is 2.1 $KgCO_2eq/Kg$ for the pyrometallurgical process and 1.8 $KgCO_2eq$/ Kg for the hydrometallurgical process (that requires thermal and mechanical treatments stages prior to hydrometallurgy).

Results

Performing the material flow analysis, was calculated the quantity of material revered for each type of batteries considering the two different scenarios. The results were represented using the software STAN.

- **Pyrometallurgy - NMC 111**
  In this section, are reported the results obtained from the material flow analysis for NMC111 batteries (Figure 93-96) considering the pyrometallurgy scenario.

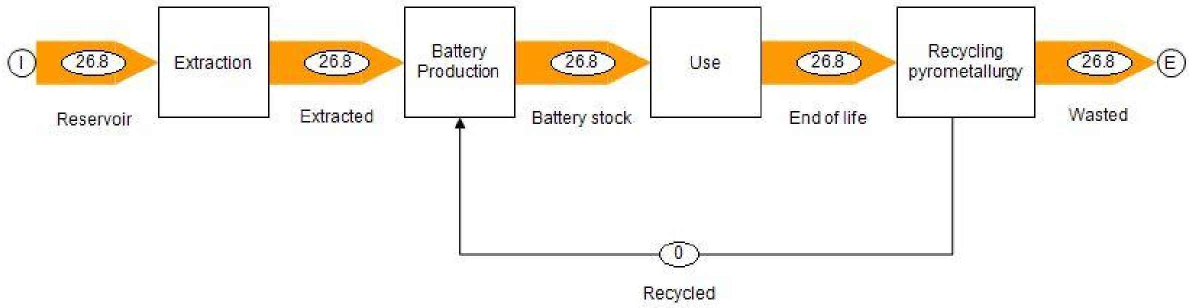

Figure 93. Kg of Li recovered and wasted for 1 t of NMC111- pyrometallurgy

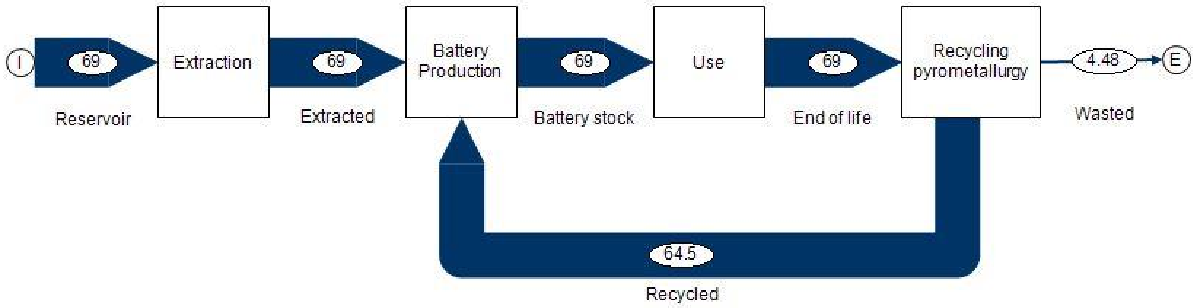

Figure 94. Kg of Co recovery for 1 t of NMC111-pyrometallurgy

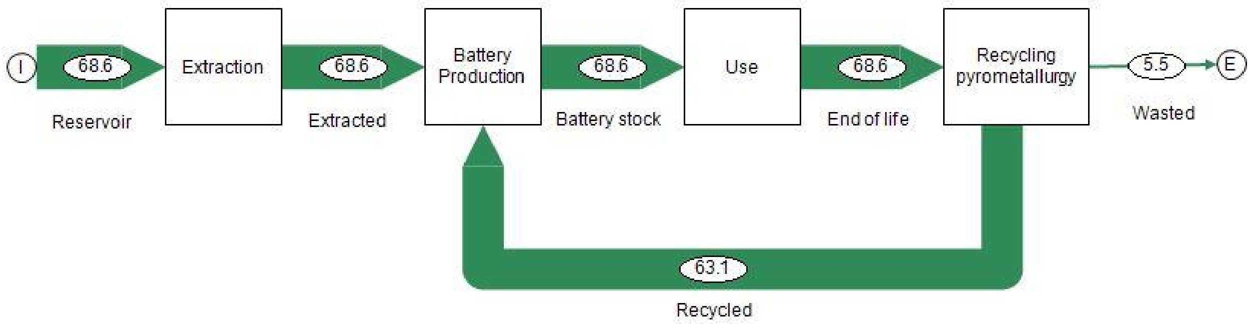

Figure 95. Kg pf Ni recovered and wasted for 1 t of NMC111-pyrometallurgy

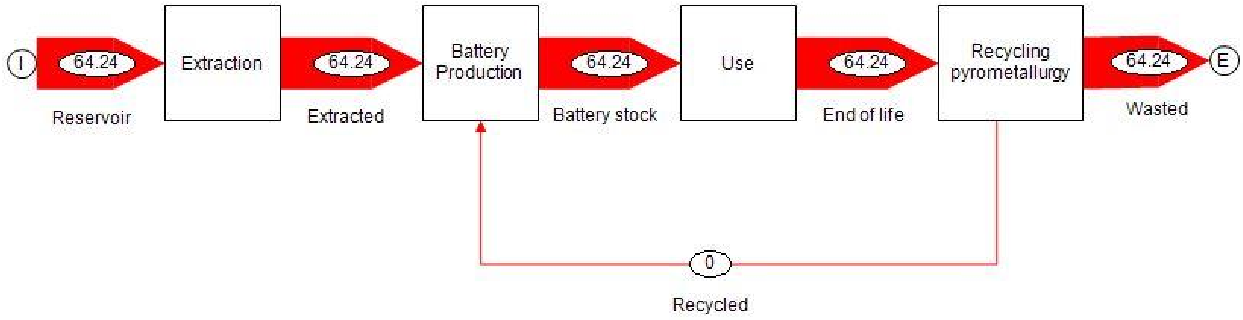

Figure 96. Kg of Mn recovered and wasted for 1 t of NMC111-pyrometallurgy

- **Pyrometallurgy-NMC 622**
  In this section, are reported the results obtained from the material flow analysis for NMC622 batteries (Figure 97-100) considering the pyrometallurgy scenario.

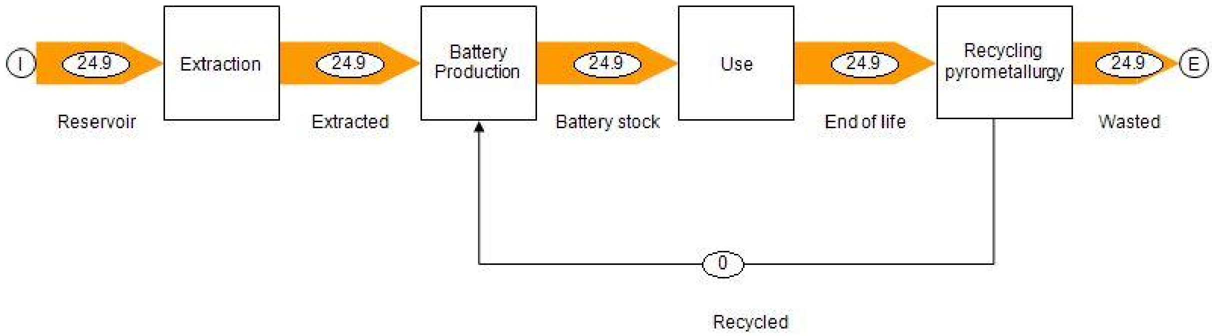

Figure 97. Kg of Li recovered and wasted for 1 t of NMC622-pyrometallurgy

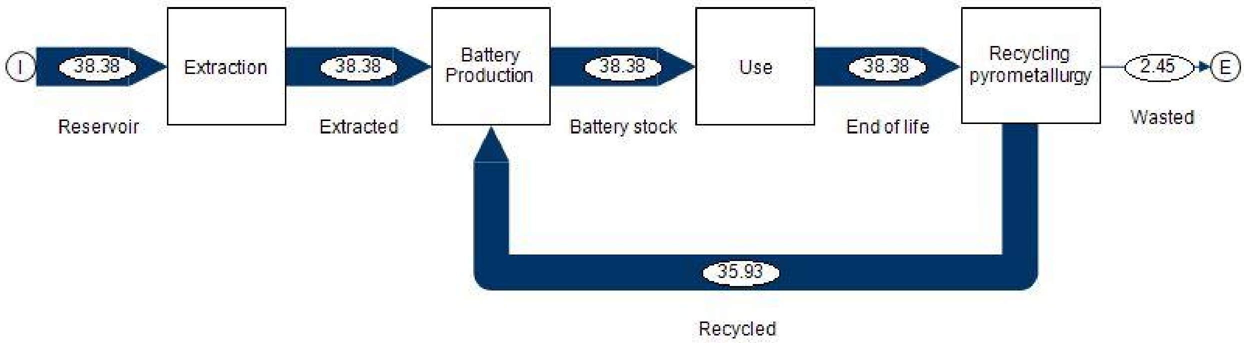

Figure 98. Kg of Co recovered and wasted for 1 t of NMC622-pyrometallurgy

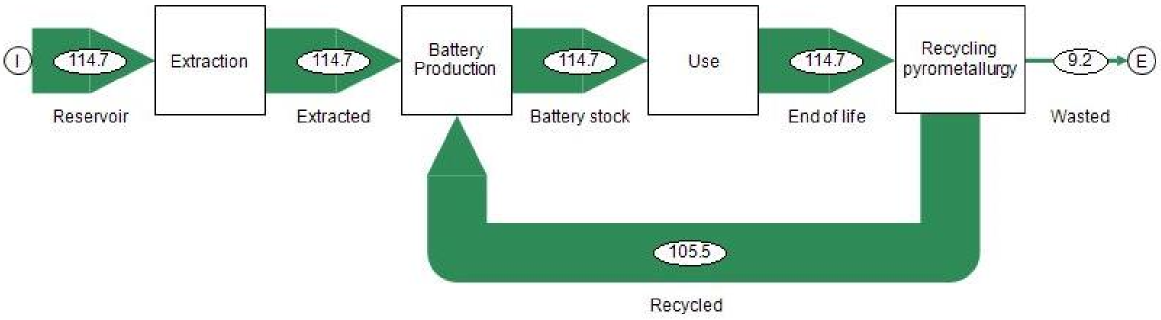

Figure 99. Kg of Ni recovered and wasted for 1 t of NMC622-pyrometallurgy

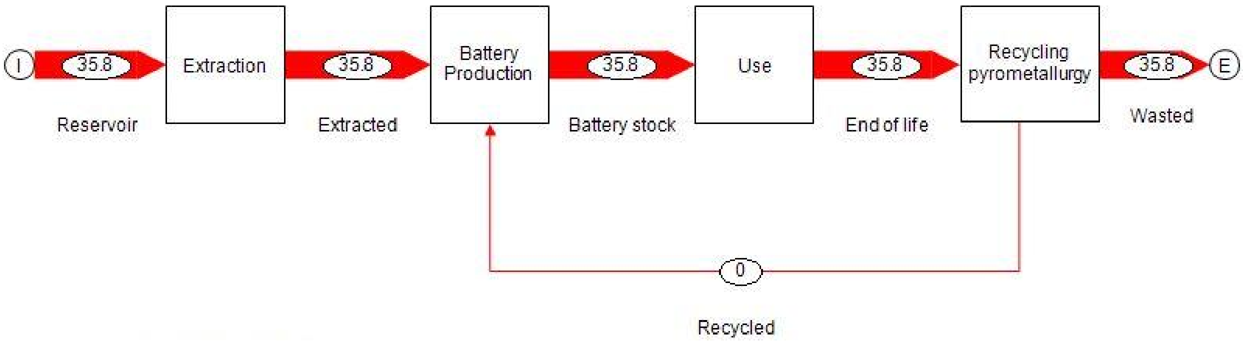

Figure 100. Kg of Mn recovered and wasted for 1 t of NMC622-pyrometallurgy

- **Pyrometallurgy-LFP**
  In this section, are reported the results obtained from the material flow analysis for LFP batteries (Figure 101-103) considering the pyrometallurgy scenario.

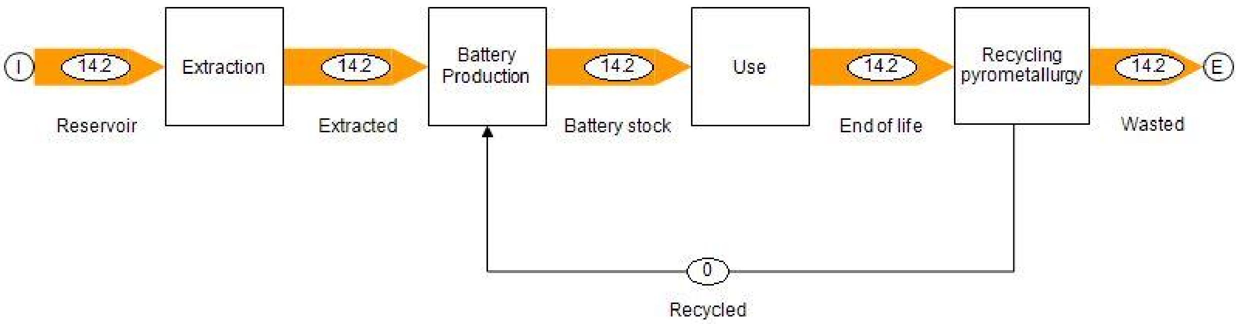

Figure 101. Kg of Li recovered and wasted for 1 t of LFP-pyrometallurgy

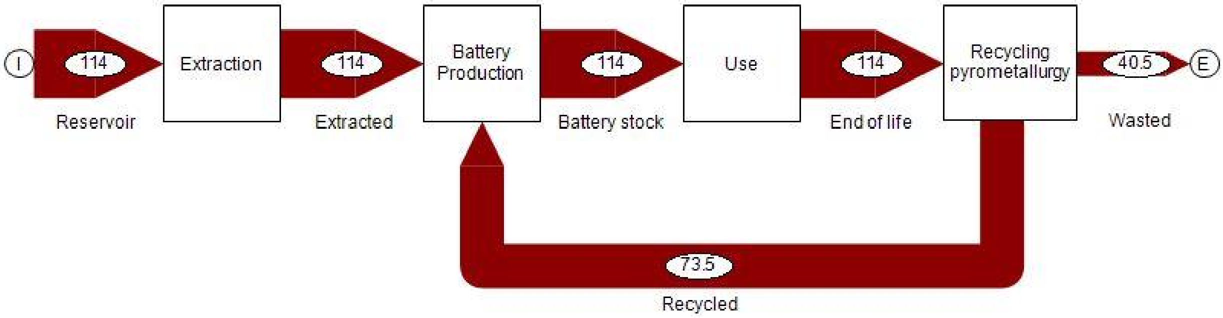

Figure 102. Kg of Fe recovered and wasted for 1 t of LFP-pyrometallurgy

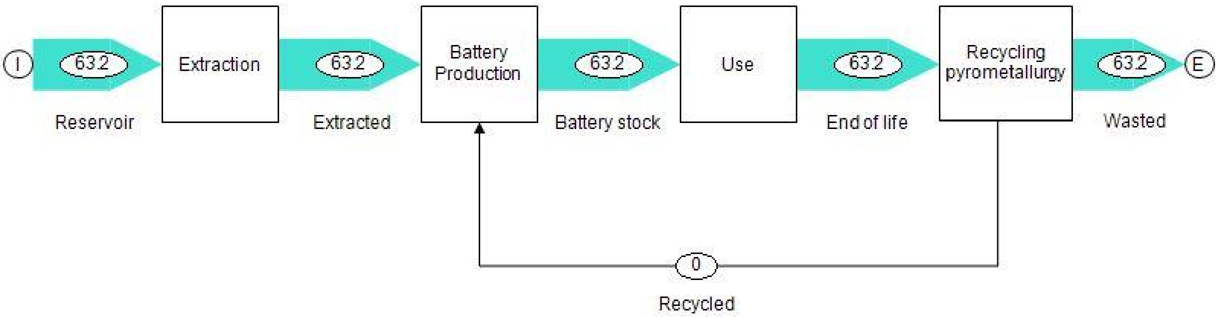

Figure 103. Kg of P recovered and wasted for 1 t of LFP-pyrometallurgy

- **Hydrometallurgy-NMC 111**
  In this section, are reported the results obtained from the material flow analysis for NMC622 batteries (Figure 104-107) considering the pyrometallurgy scenario.

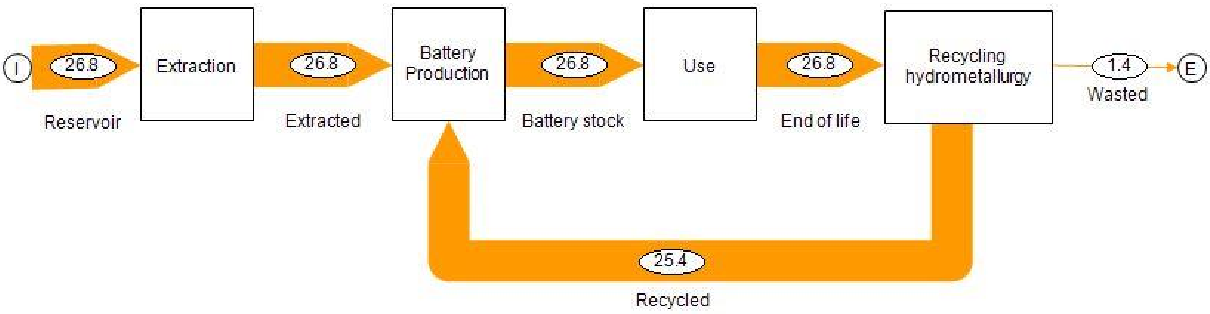

Figure 104. Kg of Li recovered and wasted for 1 t of NMC111-hydrometallurgy

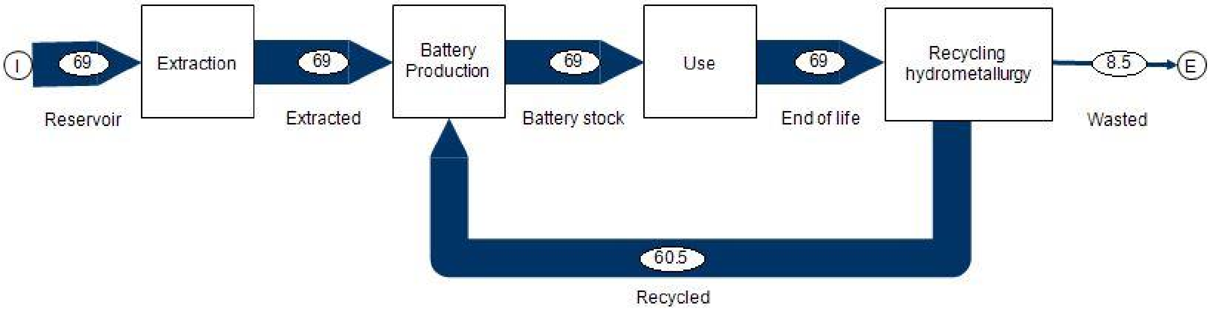

Figure 105. Kg of Co recovered and wasted for 1 t of NMC111-hydrometallurgy

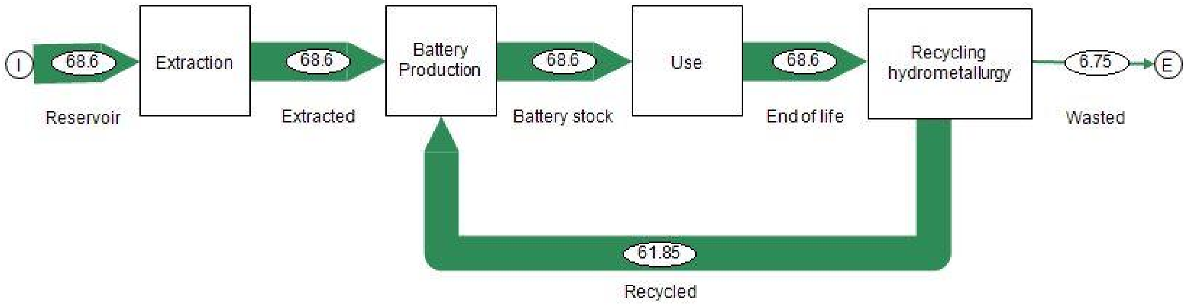

Figure 106. Kg of Ni recovered and wasted for 1 t of NMC111-hydrometallurgy

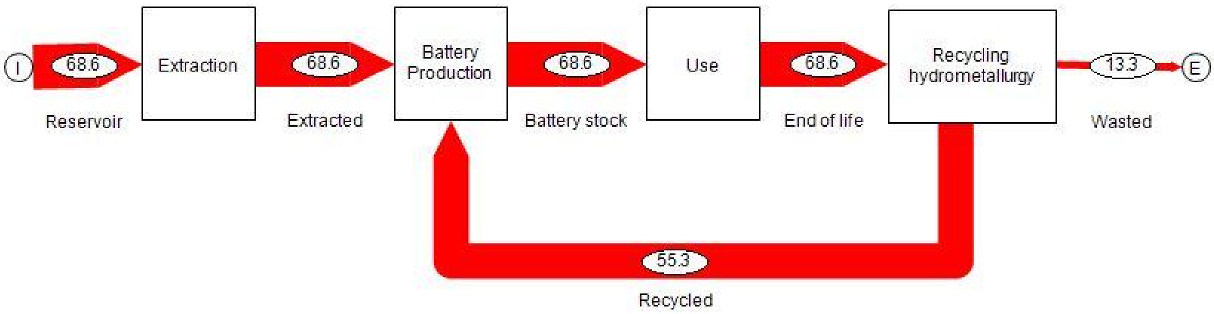

Figure 107. Kg of Mn recovered and wasted for 1 t of NMC111-hydrometallurgy

- **Hydrometallurgy-NMC 622**
  In this section, are reported the results obtained from the material flow analysis for NMC622 batteries (Figure 108-111) considering the pyrometallurgy scenario.

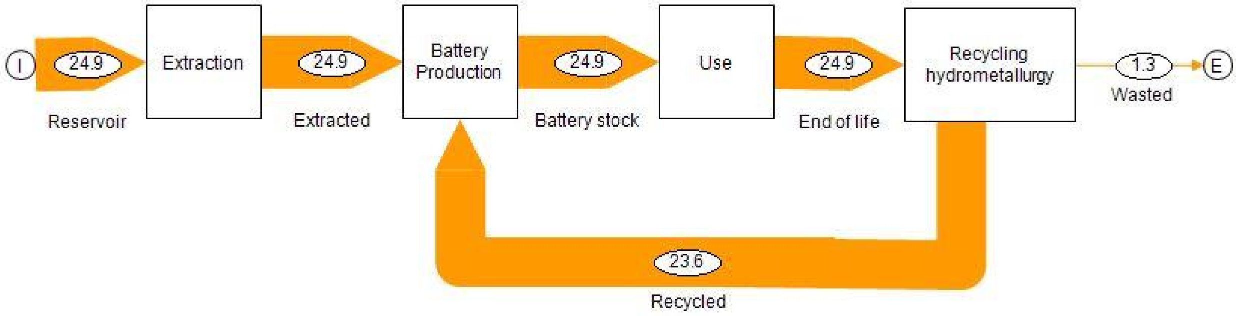

Figure 108. Kg of Li recovered and wasted for 1 t of NMC622-hydrometallurgy

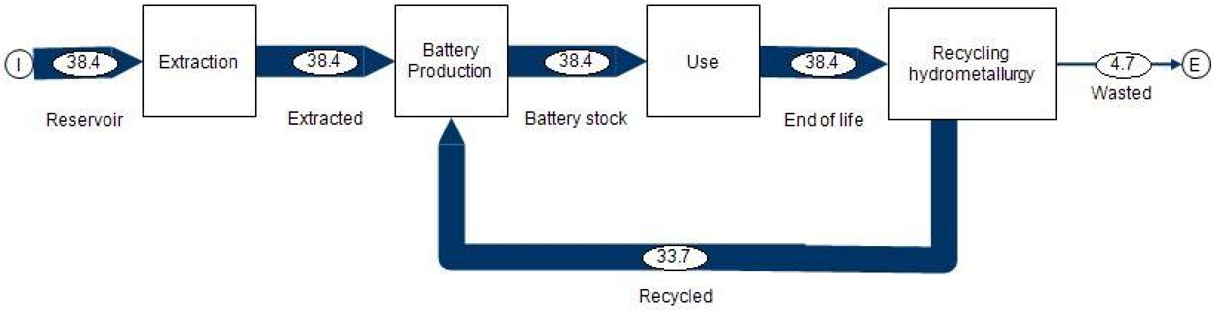

Figure 109. Kg of Co recovered and wasted for 1 t of NMC622-hydrometallurgy

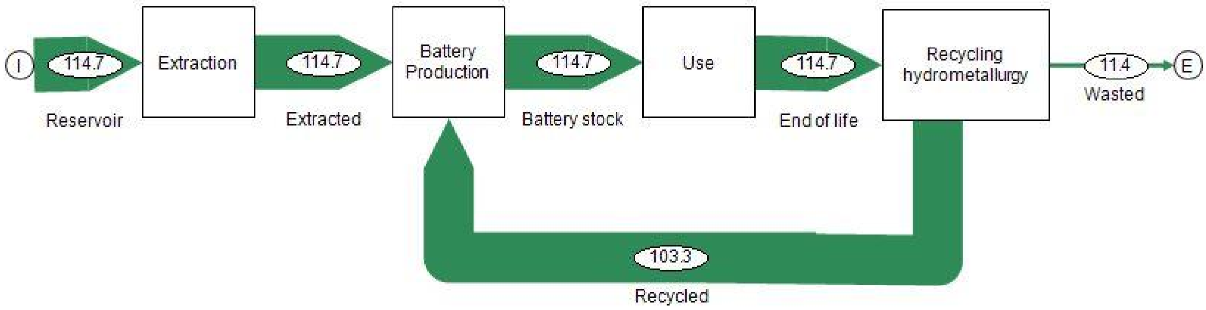

Figure 110. Kg of Ni recovered and wasted for 1 t of NMC622-hydrometallurgy

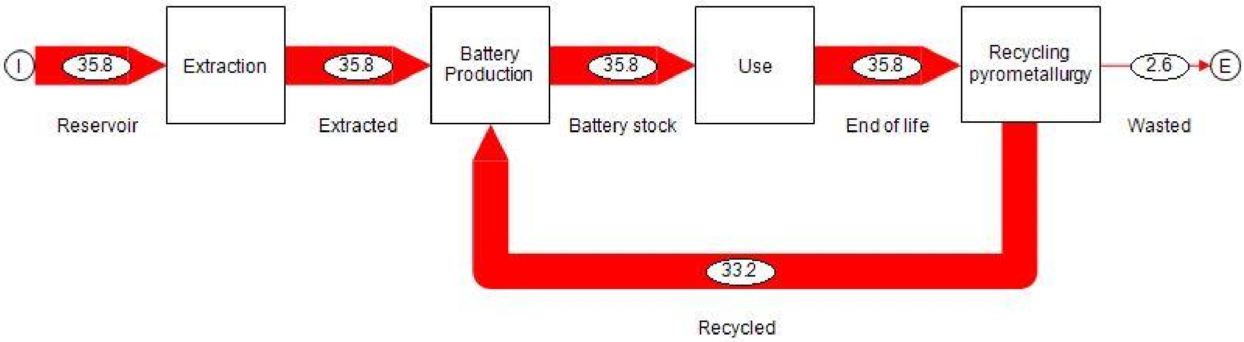

Figure 111. Kg of Mn recovered and wasted for 1 t of NMC622-hydrometallurgy

- **Hydrometallurgy-LFP**
  In this section, are reported the results obtained from the material flow analysis for NMC622 batteries (Figure 112-114) considering the pyrometallurgy scenario.

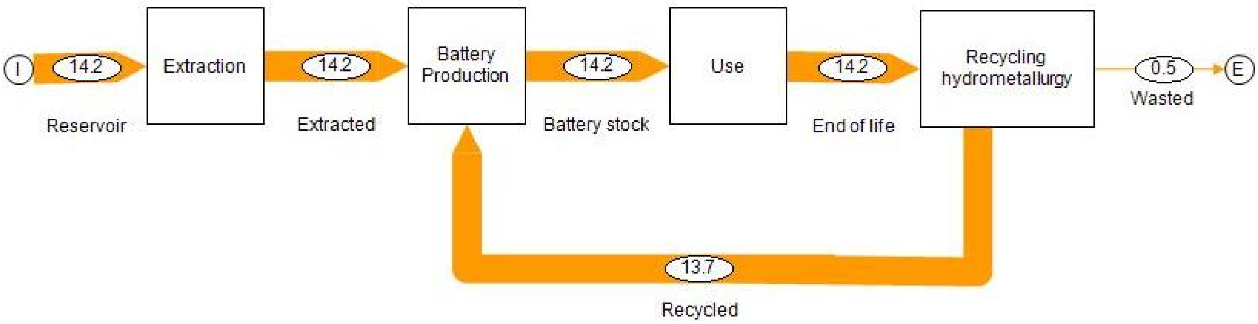

Figure 112. Kg of Li recovered and wasted for 1 t of LFP-hydrometallurgy

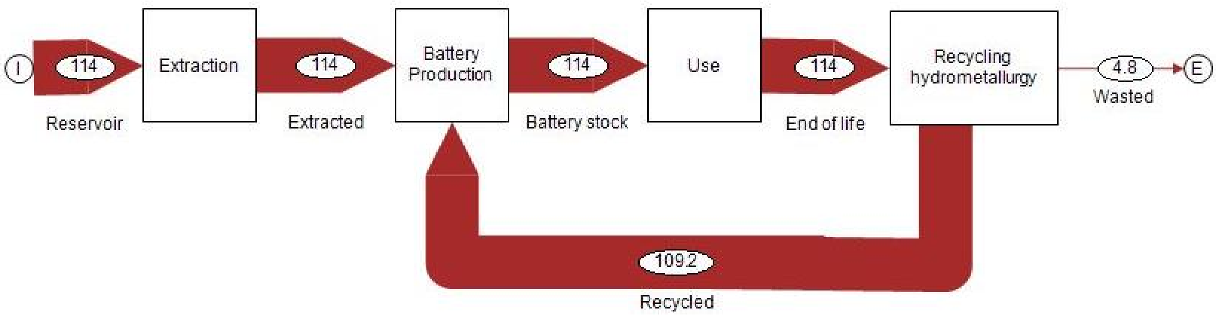

Figure 113. Kg of Fe recovered and wasted for 1 t of LFP-hydrometallurgy

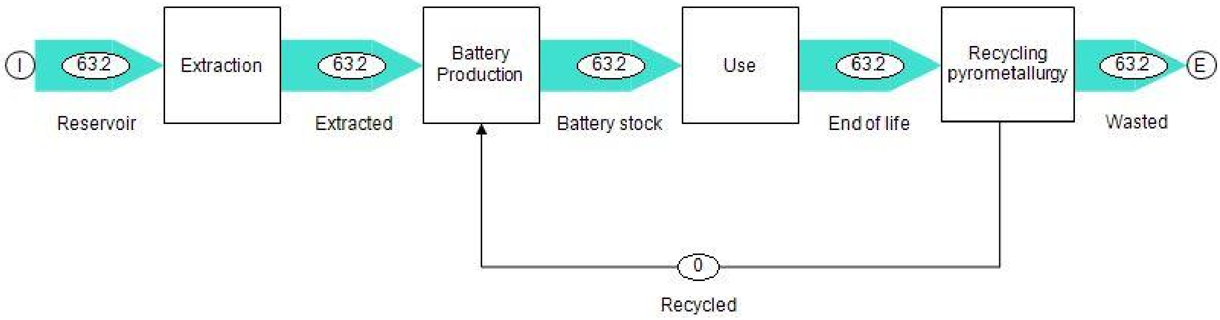

Figure 114. Kg of P recovered and wasted for 1 t of LFP-hydrometallurgy

In general, from the material flow analysis results, it is possible to notice that through the pyrometallurgy is not possible to recover Li and Mn and, consequently, they are totally wasted; as regard LFP, adopting pyrometallurgy, is not possible to recover Li and P. On the contrary, hydrometallurgy allows to also recover Li in LFP: as a consequence, the impact in of hydrometallurgy is less than pyrometallurgy because it has a less GWP and it allows to recover more materials. Pyrometallurgy is less selective, although it presents an high recovery efficiency; adopting hydrometallurgy is possible to recover more valuable material because it includes the recovery of Li and Mn.

In Figure 115 are reported the total recycling impacts: in general, the impacts to pyrometallurgy are higher because the process requires more energy and because it recovers less materials; the highest impacts, in both cases, are due to LFP because the pyrometallurgy not allows to recover most of cathode materials (Li and P) and the hydrometallurgy not allows to recover P. The impact of pyrometallurgy for the LFP is 1,989 KgCO_2eq per t of battery and the calculated impact associated to hydrometallurgy is 1,539 KgCO_2eq per t of battery. The impacts for 1 t of NMC111 and NMC622 are similar: for NMC 111, the calculated impact for pyrometallurgy is 1,154 KgCO_2eq and the calculated impact for the hydrometallurgy is 660 KgCO_2eq; for NMC 622, the calculated emissions associated to pyrometallurgy are 1,116 KgCO_2eq and for hydrometallurgy are 650 KgCO_2eq. In particular, the calculated values for NMC 622 are less than NMC 111 because, adopting the same recovery efficiencies, is recovered more materials through the two techniques of recycling and this translated into a major KgCO_2eq saved relatively to materials extractions.

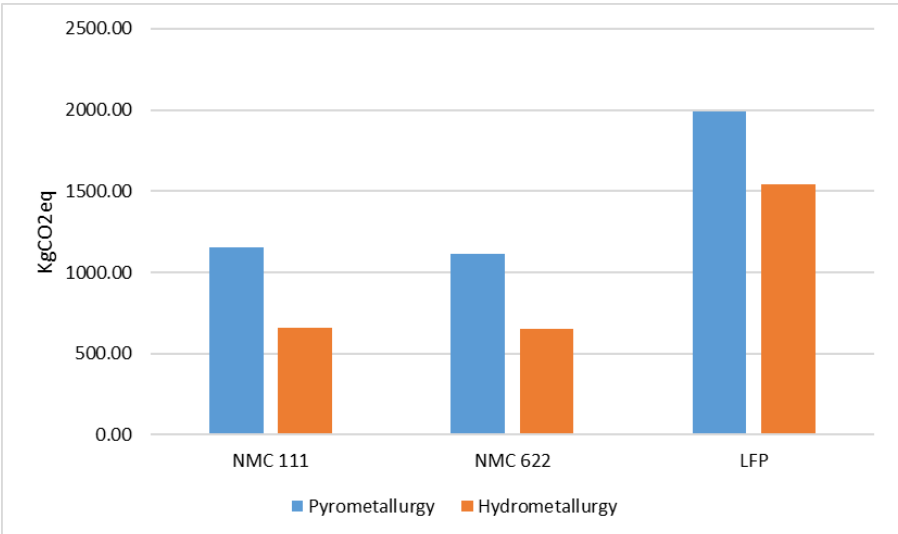

Figure 115. Recycling impacts for LIBs per ton of battery

6.3 Total impact

At the end, was calculated the total impact, adding the emissions due to phase 1 (minerals extraction and refining and battery and components manufacture) and phase 2 (recycling). In this way, was performed a "cradle-to-grave" evaluation for 1 t of battery. These results were obtained considering only the two phases mentioned above and not considering other boundaries conditions, such as the transport phase and the energy mix of a specific country. In Figure 116 are represented the obtained values: in general, the scenario with pyrometallurgy recycling emits more than hydrometallurgy because of the different energy consuming and the difference between the number and quantities of materials recovered. The impact of NMC is similar: as regard pyrometallurgy scenario, is calculated for NMC111 a value of total emissions that is 10,516 $KgCO_2eq$ per t of battery and for NMC622 is obtained a total emission of 10,581 $KgCO_2eq$ per t of battery; for LFP, the value obtained considering the pyrometallurgy scenario is 10,139 $KgCO_2eq$ per t of battery and considering hydrometallurgy is obtained a value of 9,688 $KgCO_2eq$ per t of battery. The LFP emissions to produce 1 ton of battery are less than NMC due to the different compositions and the relative associated impacts (GWP) to its components, that are lower than the NMC.

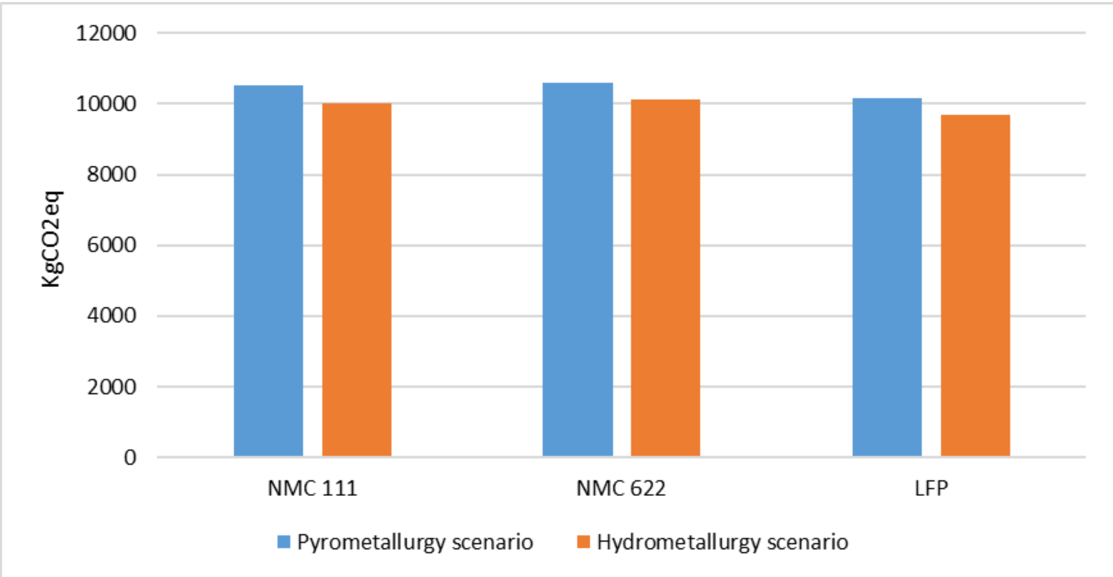

Figure 116. Cradle to grave total emissions associated to 1 t of LIB considering phase 1 and phase 2

In Figure 117 and 118 are represented the detailed contribution to total emissions to produce 1 ton of battery considering the pyrometallurgy and the hydrometallurgy scenario: the most contribution, in both cases is due to the battery components and manufacture, that represents about the 60% of total emissions; for NMC, the 30% of total emissions is associated to materials extraction and 10% to recycling; for LFP the 20% is associated to material extraction and about 20 % to recycling process. This difference between LFP and NMC is due, as mentioned above, to the different compositions and to the different recycling efficiencies.

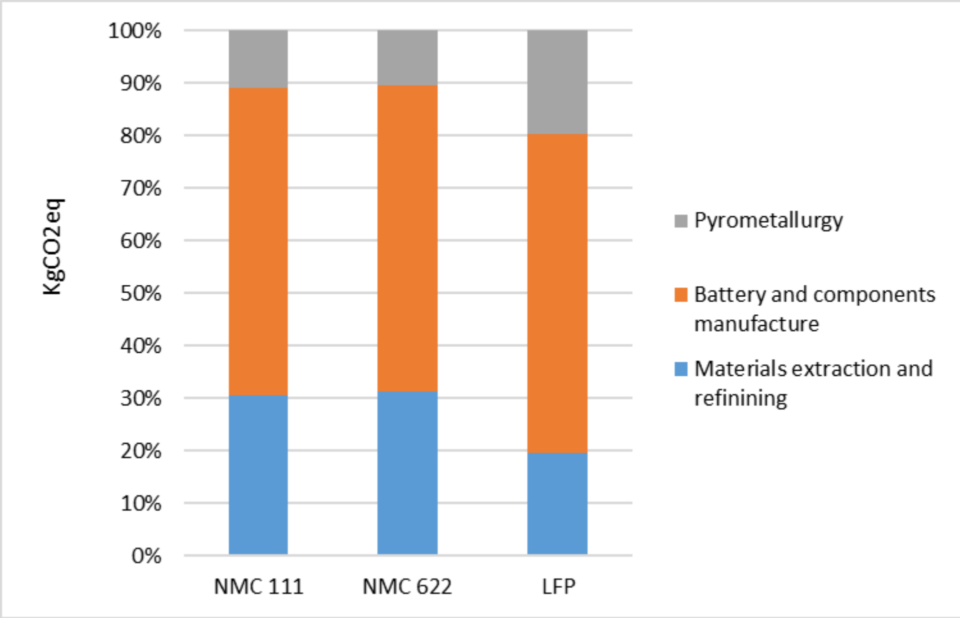

Figure 117. Detailed Cradle to grave total emissions associated to 1 t of LIB considering phase 1 and phase 2-pyrometallurgy scenario

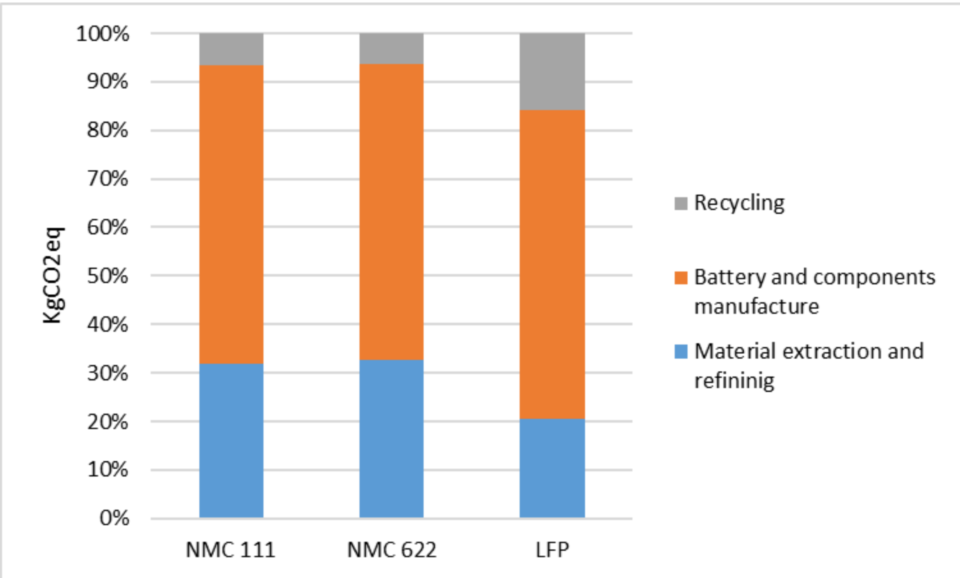

Figure 118. Detailed Cradle to grave total emissions associated to 1 t of LIB considering phase 1 and phase 2-hydrometallurgy scenario

Conclusions

Circular economy is relatively new concept and there is not a unique and a standard method to measure its application for a company. This thesis gives a contribution on this topic, presenting a method to evaluate the circularity and to compare the circular economy performances of three different companies in the automotive sector, based on public information, mainly provided by 2020 Sustainability Reports. Circularity, for a company that operates in the automotive sector, can be analysed through different aspects, that apparently are not directly related to mobility. To perform a complete evaluation, it is important to examine the environmental performances, the actions implemented by the company to become more circular, the strategies adopted and the targets established for the near future. Aiming to compare different companies, considering all these mentioned features, it is possible to have an overview on circular economy application and to measure it quantitatively, through the definition of KPIs that measure the environmental performances, and qualitatively, by collecting and classifying information.

Nowadays, due to resource depletion and to increasing greenhouse gases emissions, there is a transition towards electric mobility. As regard the public transports, the number of electric buses is rising, substituting the ones powered by conventional fuels. Considering the use phase, it is certain that moving towards electric buses can be convenient: in a scenario where the Turin city buses fleet is constituted by 64% of electric buses, it was estimated, considering the Italian energy mix, that the CO_2 eq emissions could be reduced by 43% compared to the actual scenario, in which the electric buses represent only 11% of the total circulating fleet.

However, to provide a complete evaluation on the impacts related to electric buses, it necessary to evaluate the emissions related to the core of electric vehicles, that is the Lithium-ion batteries. For a bus, the LIB lasts about 8 years and, considering the bus lifetime is around 15 years, it must be substituted once. For that reason, it is important to evaluate the best scenario of management of an end-of-life battery, considering that it contains valuable components that can be recycled to produce a new battery or in another sector. In this thesis, the performed global warming potential impact assessment involved three types of batteries that can be used in an electric and hybrid buses, e.g., NMC111, NMC622 and LFP; the calculation was conducted adopting as functional unit 1 ton of battery, considering the phases of minerals extraction, battery and components manufacturing and two types of recycling processes, pyrometallurgical and hydrometallurgical. The results revealed that in all cases 60% of a LIB's total impact was due to battery and components manufacturing. However, considering the end-of-life phase, it was possible to recover a high quantity of valuable materials from the cathodes because of the high recovery efficiencies of the recycling processes. From the results of the performed material flow analysis, combined to the environmental assessment, it was possible to conclude that in the considered boundaries the best method was hydrometallurgy, which allowed to recover the highest amount of active cathode materials, and lead to lower GHG emissions than pyrometallurgy.

At the end of this thesis, it is possible to conclude that:

- to have a complete overview of CE application for an automotive company, the evaluation must involve different areas of investigation (even if they are not apparently related to mobility) and not only the material flows and the environmental performances;
- the transition towards buses electrification can lead to a substantial saving of GHG emissions compared with the actual situation, in which the electric buses represent a small percentage;
- the most significant impact for a Lithium-ion battery is due to the manufacturing process but, through recycling (particularly via hydrometallurgy), it is possible to recover a high quantity of valuable metals of the cathode that can be employed to synthetize a new battery, avoiding the extraction of virgin materials and scarce metals.

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