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The environmental impact of electric vehicles: a comparative LCA-based evaluation framework and its application to the Italian context

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INDEX

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List of Abbreviations, Acronyms, Symbols and Signs

BEP	Break Even Point
BEV	Battery Electric Vehicle
BMS	Battery Management System
CE	Charging Efficiency
CO_2	Carbon Dioxide
EL	Energy Loss
EoL	End of Life
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GHG	Green House Gas
GWP	Global Warming Potential
HV	Hybrid Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
LC	Life cycle
LCA	Life-Cycle Assessment
LDV	Light Duty Vehicle
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric Vehicle
PTW	Pump-to-Wheel
REE	Rare-Earth Element
RES	Renewable Energy Source
TTW	Tank-to-Wheel
WTP	Well-to-Pump
WTT	Well-to-Tank
WTW	Well-to-Wheel
USD	United State Dollar
%	Percent
€	Euro
g	gram
gCO_2-eq	grams of CO_2 equivalent
J	Joule
L	litre
MJ	Megajoule
kg	kilogram
km	Kilometre
Wh	Watt hour
kWh	Kilowatt hour
TWh	Terawatt hour

List of Figures

List of Tables

Abstract

In the last years it has been observed a progressive shift from the traditional mobility (fuel-powered vehicles) toward the so-called e-mobility, which has as primary objective that of favouring a (more) sustainable mobility. The achievement of a complete shift toward the electric mobility represents one of the biggest challenges that the present together with future generations will need to face. One of the most important topics tightly linked with this alternative form of mobility is that of the greenhouse gas emissions produced along vehicle's life cycle, and as demonstrated by this thesis work, an electric vehicle can be claimed to be "zero-emissions" as much as it is the energy mix used for its production and its use phase.

The main aim of the present thesis work is to develop an emission-model that is able to calculate the CO_2 emissions produced along the entire vehicle's life cycle, so to estimate electric vehicle emission values and to compare such results with those of traditional fuel-powered vehicles.

At the beginning, of such work, a brief history overview about the inventions and innovations of the first road-vehicles with respect to the different vehicle typologies has been performed. The milestones that promoted and that still promote the diffusion of electric vehicles across all countries have been evaluated. Successively the scenarios for the countries with the highest market penetration for electric vehicles have been presented and the actions that governments across the world are trying to implement in order to boost the diffusion of e-mobility.

It has been analysed which is the actual condition related to the emissions coming from the transportation sector and which are the measures and policies that are being introduced by different national governments so to tackle and reduce these emissions in the upcoming years.

Then, numerous LCA studies, industrial reports, scientific papers and research papers have been analysed with the aim of investigating the state-of-art on the emissions associated to electric vehicles, adapting a "cradle-to-grave" approach. It has been dedicated particular attention to the study of the main cycles (battery, electric energy/fossil fuels and vehicle) and the life cycle phases of an electric and traditional vehicle.

Grounded on such literature review, have been developed the CO_2 emission-models to track all the emissions coming from the entire vehicle's life cycle for electric and traditional vehicles.

The models have been, successively, applied to the analysis conducted on several scenarios evaluated and to the comparison of the emission results among the 2 vehicle typologies, so to quantify the gap in terms of emissions. To deepen more into such evaluation have been performed 3 sensitivity analysis to estimate how the variation of some parameters has an impact over the entire vehicle's life cycle emissions.

It has been demonstrated that emissions associated to electric vehicles increase as it increases the weight of the vehicle and of the battery. There is still a significant portion of emissions arising from the manufacturing of the battery pack and this represents the main gap to be filled with respect to internal combustion engine vehicles. The CO_2 emission results allowed also to evaluate how

increasing the vehicle segment both for electric and traditional vehicles there is a progressive shift toward higher values of break-even points.

Considering the Italian scenario, it has been proved that the increasing RES penetration is positively impacting on the overall environmental footprint produced by electric vehicles. Furthermore, the development of a "*100% made in Italy*" electric vehicle would strongly reduce the overall emissions associated to the whole life cycle.

To conclude such thesis work it is provided a section with comments on the emission-models and the obtained results, together with some general observations about the future development of e-mobility in the upcoming years.

1. Electric Vehicles' overview

1.1 Introduction

Electric mobility is a general term that is used when referring to electric-powered drivetrains designed to shift vehicle design away from the use of fossil fuels and carbon gas emissions. It compromises all street electric vehicles that are not only relying on an ICE but are additionally powered by an electric motor and primary get their energy from the power grid. This broad definition allows to include several different typologies of vehicles such as purely electric (BEVs) or hybrid ones (HVs and PHEVs) with a combination of an electric engine and an ICE.

In the last 30 years e-mobility has demonstrated positive market trends and gained a consistent interest at global scale for its positive contribution in lowering the environmental footprint in terms of GHG emissions and for favouring a more sustainable approach toward the transport sector.

In 2018 the transport sector accounted for a portion that ranged between the 23% to 25% of GHG emissions and especially for anthropogenic emissions of CO_2 at worldwide level (IEA, 2018a). Electric mobility, in this scenario where climate change, air and land pollution, global warming and increased level of CO_2 emissions are affecting in a drastic way our society, represents a possible solution for achieving a (more) sustainable mobility and reducing society's environmental impact. Due to the decarbonization processes being introduced by governments, electric mobility can open the way toward a greener future and with resilience allowing to achieve policy's objectives.

The development of e-mobility in recent years has come together with many correlated factors such as: several car manufacturing companies started investing into this alternative form of mobility, new models being introduced on the market, technology development, batteries with an higher capacity and autonomy range, battery's production costs are decreasing year after year, the charging infrastructure becoming more solid and spread at global level, a slow but continuous vehicle's price reduction, the increasing amount of incentives introduced for a wider adoption of this alternative form of mobility and the combination of such vehicles with new economic paradigms such as circular and sharing economy. Such technological development can also strongly help in reducing the transport sector heavy reliance on fossil fuels and so leading in a market shift from ICEVs toward a broader adoption of EVs.

Together with electric mobility is becoming also important the combination of cleaner form of energy production, such as renewable energy sources (RES) that allow to produce electricity without emissions of GHG. The combination of such clean sources and electric vehicles can further contribute to better reduce the amount of emissions during the operation phase of any electric vehicle.

1.2 Brief history of automobile

Transportation can be defined as "*the ability and level of ease of moving people, goods and services*" and it has always played a crucial role in human history. Specially in the last 250 years this is demonstrated by the huge amount of inventions and innovations that have characterised this sector and shaped the evolution of mankind as well. The major improvements into the automobile sector, taking into consideration compact passenger vehicles and light duty vehicles, in the last 2 and half century are due to new technological developments, new models and vehicles with higher efficiency and speed.

The beginning of the automobile era has been very concentrated on the search of a reliable technology that could suitably propel the vehicle. It is possible to analyse the history of the automobile dividing it into several eras, mainly based on the different means of propulsion systems implemented.

The first notion of a mechanical-powered vehicle can be attributed to Leonardo Da Vinci (1452 – 1519) that in 1478 designed a self-moving car that was powered by large coiled springs located in cylindrical drum-like casings. Da Vinci's vehicle can be considered as the ancestor of the modern car. It was the very first internally stored-energy propelled vehicle and that was probably most suited for battle's purposes rather than civil transportation.

Fig. 1 Da Vinci's spring-driven stage car (studies in the Codex Atlanticus)

Another predecessor of modern vehicles can be considered the model by the Flemish Ferdinand Verbiest (1623 – 1688), who was a member of a Jesuit mission in China and built in 1672 a steam powered vehicle as a toy for the Chinese Emperor. This can be considered the first working model of a powered vehicle ever built.

The former prototype of "*modern automobile*" was developed by Nicolas-Joseph Cugnot (1725 – 1804) a French inventor who built in 1769 the first vehicle that was powered by a steam engine. The vehicle was around 6-meter-long, able to carry a load of $4\ tons$ (it was intended for transporting cannons) and to proceed with an average speed of $6\ km/h$ and it had a limited range of autonomy of some minutes. There are some reports of preliminary driving tests that show how such vehicle had low efficiency and many problems associated to weight balance, to the ability of promptly turning when needed and to the breaking system, in fact the vehicle is also awarded as the first mechanical vehicle to crush on a wall, due to such issues of manoeuvrability. However, the invention of such kind of vehicle represents the beginning of the mechanical-powered vehicle era.

This technology continued to be studied under the 18th and 19th century, but it did not become a practical solution until the contribution of the British engineer Richard Trevithick (1771 – 1833) who developed the use of high-pressure steam around 1800. Almost 50 years later, in 1864 Innocenzo Manzetti (1826 – 1877) an Italian inventor, built a road-steamer that can be considered as the first steam engine vehicle able to circulate on roads. The steam engine was a major solution for vehicles during the 19th century due to the characteristics of being powerful, fast and reliable but the main drawbacks were associated to its long start-up time that could require up to 45 minutes and short km range that could be covered due to the need of water refilling.

The second technology developed to power vehicles was a hydrogen-oxygen-powered ICE with electric ignition, implemented in 1807 by the Franco-Swiss, François Isaac De Rivaz (1752 – 1828). The first attempts to develop the combustion engine were performed using liquid fuels which did not provide good results, proving a lack of suitable fuels, so that the first engine was developed using such gas mixture. The engine developed by De Rivaz, had no timing mechanism and the introduction of fuel mixture and ignition had to be performed manually. He tried to improve his model in the following years but however it never become a successful commercial solution.

The third technology implemented was that one of EVs, powered by a battery, which saw its birth in the early 19th century. The preliminary studies of the implementation of such motive power are attributed to the Hungarian priest and engineer Ányos Jedlik (1800 – 1895) who built the first prototype of electric motor comprehensive of stator, rotor and commutator.

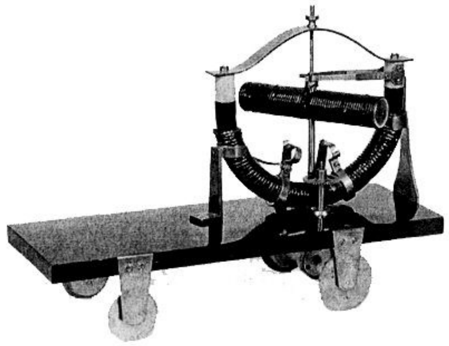


Fig. 2 Jedlik's electric car

The wave of innovations within this field come together with the progresses that were made in both physic and chemistry, giving contribution to electrodynamic. In the following years the first prototypes of EVs were introduced in 1835 by the Dutch professor Sibrandus Stratingh (1785– 1841) of University of Groningen and by the Scottish entrepreneur Robert Anderson (1804 – 1894) between 1832 and 1839. In the same period are also reported some experiments made by the American Thomas Davenport (1802 – 1851) who was able to build an electric locomotive toy that represented the first American DC electric motor.

Fig. 3 Stratingh's small electric car

The improvements that boosted the adoption and diffusion of this electric technology come from the increase amount of energy that was able to be stored within batteries, the increments of batteries' size in terms of power and capacity. Those developments are mainly due to the French physicist Gaston Planté (1834 – 1889) who invented the lead–acid battery in 1859 and the French chemical engineer Camille Alphonse Faure (1840 – 1898) that in 1881 significantly improved the design of the lead-acid battery. In 1884 the English inventors and engineers Thomas Parker (1843 – 1915) and Paul Bedford Elwell (1853 – 1899) built the first production electric car, using their own designed high-capacity rechargeable batteries, that were relying on lead-acid batteries as accumulators.

In many countries such as: Belgium, France, Germany, Great Britain and United State by the end of 19th century, EVs were present and being implemented by many companies that started their commercial production and favoured their diffusion. As to demonstrate the broad adoption of EVs is the fact that in 1897 the whole New York city's taxi fleet was wholly made by these vehicles. In those years of continuous improvements were also set new speed records as by the Belgian Camille Jenatzy ($1868 - 1913$) that in 1899 drove his electric "Jamais Contente" at the astonishing speed of $105.88\ km/h$. It was the first time ever that a land vehicle broke the $100\ km/h$ limit.

Fig. 4 Jenatzy at the victory parade on 1 May 1899 after the 100 km/h record-breaking run on 29 April 1899.

During the first decade of the 20th century EVs experienced the period of major success. In the United States it was estimated that 40% of the market share was covered by EVs, almost the same amount by the steam engine vehicles and the remaining part by ICEVs. EVs had the characteristics of being silent, odourless (no emissions), reliable, simple to drive and easy to start, on the negative side they were the most expensive technology on the market and low ranging as distance able to be covered (within 30 to 60 km).

By the end of 19th century another typology of vehicle made its first appearance on the market, it was that of HV. The first hybrid car, the "*System Lohner-Porsche Mixte*" was built in 1899 by the German automotive engineer Ferdinand Porsche ($1875 - 1951$). It was the first kind of vehicle that used a gasoline engine to supply power to an electric motor (Helmers and Marx, 2012). This technology did not really become a viable solution due to the simultaneous introduction of Ford assembly line that made gasoline powered cars more affordable compared to the latter. The hybrid technology will see its rise again in the second late half of the 20th century. It was necessary to wait almost 100 years to see the first commercial HV models to be realised on the market, the "Toyota Prius" in 1997 in Japan, followed by the "Honda Insight" in 1999.

The solution offered by ICEVs drastically changed when in 1870 the German Siegfried Marcus ($1831 - 1898$) invented the first gasoline powered combustion engine and improved his work in the following years, with the introduction of the two-cycles combustion engine. In the upcoming years many German inventors introduced on the market their models of vehicles, among them it is possible to list Karl Benz ($1844 - 1929$) that in 1885 introduced his first automobile and Gottlieb Daimler ($1834 - 1900$) and Wilhelm Maybach ($1846 - 1929$) that in 1889 designed their automobile.

Fig. 5 The second Marcus' car of 1888

It is possible to highlight among all 4 main factors, that allowed to develop and boost the solution offered by ICEVs.

- The development due to the German engineer Nikolaus August Otto ($1832 - 1891$) of the compressed charge four-stroke gasoline internal combustion engine (which is still nowadays the most diffused form of modern automotive propulsion system).

- The innovation in 1892 of the German engineer Rudolf Diesel ($1858 - 1913$) of the compressed charge four-stroke diesel internal combustion engine, which was able to increase the level of efficiency of combustion engines.

- The introduction of the assembly line implemented for the first time within the Ford motor company, operated by the American Henry Ford ($1863 - 1947$).

- The discoveries of new petrol depots in $1920s$ in Texas, that allowed to reduce the price of oil and stimulated investments toward this fossil fuel extraction and nonetheless made petrol-powered cars cheaper to operate over long distances, compared to other typologies.

The market of vehicles was deeply shaped by those factors that contributed to make the ICEs the most adopted vehicle solution and allowed them to take the leading market position. Another important factor to be mentioned has to do with building and operating costs that in case of ICEVs were lower compared to EVs and steam-engine vehicles. The "Ford model T", equipped with an ICE, which started to be produced in 1913 became the first vehicle to be mass produced and only 15 years later accounted more than 15 million units sold.

During the second half of the 20th century another technology of propulsion system emerged, the one of fuel cell vehicles (FCV). The preliminary studies of such alternative to electric and combustion engine vehicles are dated back in 1801 with Humphry Davy ($1778 - 1829$) and the expansion of his work due to the chemist and physic William Grove ($1811 - 1896$) that in 1842 proved that an electric current could be produced by an electrochemical reaction between hydrogen and oxygen over a platinum catalyst. The operating principle was based on the usage of a fuel cell instead of a battery to power the on-board electric motor. Groove's work was improved and expanded by the English engineer Francis Bacon ($1904 - 1992$) that between 1939 to 1959 created and experimented on various Alkaline fuel cells. The first vehicle that was able to operate with this technology was made in 1959, a modified Allis-Chalmers farm tractor equipped with $15\ kilowatt$ fuel cell. The first commercial road vehicle was the "Chevrolet Electrovan" made by General Motors in 1966. In the last years the FCVs have been studied and improved by the spaceship programs and by General Electric, but still remain a technology that has not yet achieved a maturity level similar to other vehicles' typologies (Guarnieri, 2012).

1.2.1 Revamping of EVs

As mentioned in the above paragraph, electric mobility has been a viable solution for the transportation sector for more than 100 years. The adoption of such electric technology has seen in its early beginning a consistent penetration on the global car market. Demonstrating its strong position was the achievement of a 40% market share of road-vehicles in the USA and European countries in the first decade of 1900.

When the ICE made its appearance on the market, it rapidly took the leading role in the first 2 decades of 20th century, this come together with a reduction of production costs (e.g. assembly line introduced by Ford Motor Company) and fuel price reduction, due to mass discoveries of new petrol depots in the USA. Those factors consequently led ICEVs in $1900s$, to have a cost of around $650\ USD$ while EVs were priced around $3000\ USD$. The combination of such factors allowed ICEVs to take the biggest share on the transport sector and to become the most diffused and preferred propulsion system implemented on vehicles. As a matter of fact, investments into EVs suffered a dramatic reduction and the development of the technology almost stopped, so by the early $1920s$ the heyday of EVs had passed.

It was needed more than half century to spot again signals for revamping the EV technology. It was in 1966 when electric versions of some General Motors' gasoline-car were proposed in electric mode. Following this trend also the spaceship programmes (e.g. NASA) started to develop the electric technology to implement their robots that had to land on the Moon. In $1990s$ General Motors started to introduce its EV concept of a two-seater that was named "Impact" and were produced almost 1.000 units. It is possible to see that e-mobility has seen a major rise in the last 3 decades, with a growing number of companies such as: BMW, BYD, Fiat, Nissan, Renault, Tesla and Toyota among others, getting interested and that slowly started to invest again into EVs.

1.3 Sustainability milestones

The development of e-mobility has seen the biggest increase during the late $1990s$ when governments started to realize how critical had become the environmental situation and how EVs could represent a suitable solution to this scenario.

Nowadays the transportation sector accounts yearly for the global 23% of CO_2 emissions, 50% of energetic consumption derived from oil and for the 20% of global energetic consumption (IEA, 2018b).

Already in 1972 with the "*Rome club*" a primary sustainability milestone was introduced for governments, concerning how climate change would affect our society. Those meetings among national governments continued in the following years and one of the most important agreement was the "*Kyoto protocol*" of 1997 among 184 nations that signed the ratification paper and committed to the reduction of GHG emission in comparison to the levels of 1990.

With the growing concern and awareness of sustainability problems, governments also started to develop a set of goals and targets that countries must achieve in order to prevent the amount of emissions and pollution generated and to reduce the environmental footprint.

In this scenario, the European Union has issued in 2008 the "*Climate and Energy Package*" also known as *"20-20-20"* in which are set the targets that would help in reducing human impact on Earth and the environmental impact, promoting a more sustainable lifestyle (EU, 2016a).

For this reasons, European countries need to achieve by 2020 those 3 fundamentals goals.

- To reduce at least 20% of GHG emissions resulting from energy consumption in the EU-27, compared to 1990 levels.
- To achieve a 20% share of energy from renewable sources of total energy consumed. In addition, reaching a minimum of 10% biofuels in the total consumption of petrol and diesel in the EU.
- To achieve a 20% improvement in energy efficiency (reduction of energy consumption) of the EU, compared to projections for 2020.

A second important set of goals has been introduced with the Paris agreement of 2015, adopted by all United Nations Member States that signed for the "*2030 Agenda for Sustainable Development*" in which 17 goals have been identified (169 objectives and 243 targets) (United Nations, 2015). The aim of this set of goals is to act for people and the planet, now and into the future with the specific goal of keeping and containing temperature's uprising below $2°C$, and if possible below $1{,}5°C$, compared to the pre-industrial levels (Ambrosetti, 2018). Among these goals there are some that aim to tackle the environmental pollution and as consequence trying to reduce the impact of mankind on Earth.

In 2016 it has been issued the *"2030 Climate and Energy Framework"* proposed by the European Union which is considered to be the development of the *"20-20-20"* package (EU, 2016b). The new objectives were posed to achieve:

- 40% reduction in GHG emissions (from 1990 levels);
- 32% share for RES;
- 32.5% improvement in energy efficiency measures.

In order to translate into practice such targets and goals set by the European Union and United Nations, each country can translate those directives into national directives that afterward need to be implemented within national boundaries.

On June 2017 a campaign, called *"EV 30@30"* for the support of electric mobility has been promoted by the Clean Energy Ministerial at its 8th meeting. The aim of such campaign is promote the shift toward the adoption of electric vehicles in the transport sector with the plan to reach a 30% share of electric cars within 2030 and this initiative is mainly supported by Canada, China, Finland, France, India, Japan, Mexico, Netherlands, Norway, Sweden and United Kingdom (CEM, 2017).

During the 9th Clean Energy Ministerial in May 2018 it has been launched a program called "*The Global EV Pilot City Programme*" as one of the implementing actions of the *"EV30@30"* campaign. The aim is to create a network of 100 cities over a period of 5 years to work together in order to increase the promotion of EVs, to facilitate information sharing and the replication of best practices (IEA, 2019).

1.4 The present situation of e-mobility

For the reasons mentioned above, the role that electric mobility is having nowadays is fundamental to represent a turning point with this global picture. E-mobility, that basically consists in the substitution of a traditional engine with an electric one, allows the reduction of CO_2 emissions associated to the operation of a vehicle and so to reduce the environmental impact and promote a better life condition reducing air and environmental pollution.

In order to favour the adoption of such "clean" technology in the last years many have been the improvements that were carried out in this sector. It was possible to observe a consistent increase number of battery technologies being introduced on the market that allowed higher level of efficiency, increments with the capacity size, increase in the energy density that allowed to store more energy and reduction of costs associated to battery production.

Among those factors it is also possible to evaluate 5 main drivers at global level that will provide a relevant contribution to the diffusion of e-mobility and influence the future of EVs.

1. The increase availability of new electric models introduced in market, in this sense is becoming essential the role played by big oil companies and car manufacturers that are turning their investments toward electric mobility and increasing the market offer, those investments are expected also to reduce the price of such vehicles.

2. The incentive scheme that will be crucial for enabling the EV market penetration in the initial stages of development. Each country can provide direct or indirect incentives.

3. The development of the charging infrastructure will play a significant role in the development of the EV market, reducing the problems associated to the availability and location of chargers. At worldwide level the number of available charging stations is increasing consistently year after year.

4. The application of anti-pollution measures that will strongly decrease sales of traditional ICEVs and ban the circulation of those latter, in order to reduce air pollution. Those measures have already been implemented in many countries but the vast majority of these will start to be applied in the next 5 years.

5. Introduction on the market of new paradigms and business model.

1.5 Different types of vehicles

In order to better proceed with the analysis is important to give a preliminary introduction of the main different technologies covered within the automobile sector and to highlight the way of working of each one.

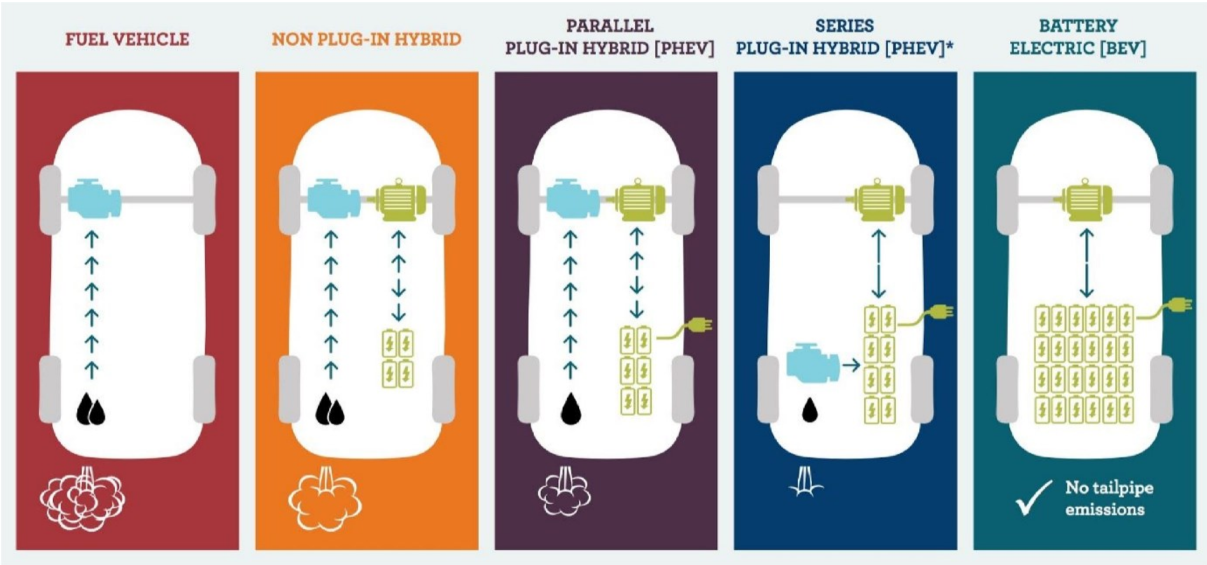


Fig. 6 Vehicle types

ICEVs

ICEVs represent the most diffused configuration of propulsion system with which cars are equipped nowadays. Among all the different typologies of vehicles this ensures high levels of performance. The main component characterising this model is a heat engine, working with a derivate of petrol such as gasoline or diesel, which converts the chemical energy associated to the fuel into mechanical energy that is then transferred to the wheels of the car that are then set in motion. The main configurations for the operation of the engine are the 4-stroke or either the 2-stroke piston engine. ICE configuration is the still representing the largest portion on the vehicle transportation sector, they rely on a huge variety of models on the market and have a relatively low price compared to other typologies of vehicles. ICEVs rely on a mature technology, they can cover long distances with a single tank and can rely, as well, on a well-developed refilling infrastructure at worldwide level. The issues that characterise such kind of vehicles are mainly attributed to fuel price volatility and the amount of exhausted gases that give contribution to the level of CO_2 emissions, that represents a serious problem for human health and the environment.

HVs

HVs (without plug) are one of the alternative typologies to ICEVs, they represent the second most diffused category of vehicles circulating on the streets, counting more than 10 million units sold worldwide. They are now perceived as a core segment of the automobile market of the future. Those vehicles are equipped with two different engines, an ICE and an electric engine made by batteries (that usually have a size of few kWh). HVs are characterized by the fact that they do not need to be charged. For starting the vehicle, the electric engine gives the ignition and starts the car, electric engine is the one also working when the car is proceeding with low speed. When higher speed is reached and more power is needed, the vehicle begins to operate with the combustion engine. The main characteristics of such typology are the combination of optimised ICE and a regenerative brake system that contributes to provide energy to the battery pack. The batteries have the possibilities to be charged in different ways, either by spinning an electric generator when the combustion engine is operating, this combination is known as "*motor-generator*", or in another case by converting the kinetic energy into electric energy through systems like regenerative breaks, when breaking or during deceleration phases. For these reasons, HVs are more suitable for circulating within cities, where speed should be kept slow. The presence of the electric powertrain allows at the same time to reduce fuel consumption and to better perform. Fuel consumption is in the order of $3.5L/100\ km$ and so contributing in reducing the amount of emissions with respect to the same car typology that operates with only an ICE. Nowadays, the cost of an HV is slightly higher compared to ICEVs. The 2 main car manufacturing companies, Toyota and Honda, retain the highest market share.

PHEVs (Parallel)

Parallel Plug-in Hybrid Electric Vehicles represent a consistent share of HVs, with more than 1.8 million stock units totalled in 2018 at worldwide level. What differentiate this typology with respect to the previous, is the possibility of connecting the vehicle in order to charge it, to an external power source. Charging can occur both at home or either where there is a proper electrical socket and as for HVs with the adoption of regenerative brake system that converts the kinetic energy associated to the deceleration phase into electric energy to be stored within batteries. PHEVs have the same structure of HVs in the sense that have a hybrid drivetrain, relying on an electric motor and an ICE as well. This peculiar configuration of PHEVs allows to have both engines working in parallel and providing power in alternative or combined way. The battery package can vary according to the different chemistry used, but usually the size is up to $10\ kWh$ ensuring an increased level of autonomy in EV mode, allowing to cover $60 \div 70\ km$. When the charge of the battery is depleted or when higher power is needed the vehicle turns its operations relying instead on the combustion engine. With this configuration and the increased size of the battery, PHEVs demonstrate better characteristics for both short distances (or within cities), that can be covered in electric mode and for long distances that can be performed with the ICE modality, providing good results and level of efficiency in both cases. This double and enriched configuration allows to reduce the amount of tailpipe generated and exhaust gases. The drawbacks associated to such PHEV are the complicated engine requirements for a proper level of maintenance, petrol refuelling costs and engine noise. For what concern the cost of such typology of vehicles they are more expensive than similar HVs and ICEVs and the main markets are China and the USA.

PHEVs (Series)

Series Plug-in Hybrid Electric Vehicles can be considered as a way between HVs and BEVs due to their operating configuration. When referring to such typology it is used the acronym EREV (Extended-Range Electric Vehicle) because the main difference with respect to HVs is the presence of an auxiliary power unit (APU) also known as range-extender, that usually is an ICE. The reason for the implementation of such component is to drive an electric generator that charges the batteries and supply the electric engine, this arrangement is known as series hybrid drivetrain. As result the traction for the vehicle comes only from the electric engine, that benefiting from the range-extender can reach higher level of autonomy. This category of vehicles have then a higher level of autonomy compared to BEVs but at the same time have higher costs due to the necessity to be equipped with the range-extender. Compared to ICEVs and HVs they produce a lower amount of emissions and have higher purchasing cost as well.

BEVs

Battery Electric Vehicles (BEVs) are increasing year by year their presence on the market, overpassing 3 million unit stock and over 1 million units sold at global scale in 2018 (IEA, 2018b). BEVs are not equipped with an ICE and so are the “pure” electric solution for what concern the traction system of a vehicle. The propulsion system is based on the energy generated by an electric engine which is supplied by the battery pack that stores electric energy. BEVs are equipped with rechargeable batteries that can vary according to the different typologies of chemistry implemented, the 2 main ones are Lithium Ion (Li-Ion) and Lithium Polymers (Li-Po) configurations. Even the size of the battery pack can vary among the different models present on the market, ranging from $24\ kWh$ up to $100\ kWh$ for Tesla’s models. Related to the battery size is the autonomy, which vary according to the different models, but the actual range covered is between $100\ km$ up to $400\ km$ for Tesla’s models. It is possible to charge the batteries as discussed for the previous cases, with the regenerative brake system that recovers the kinetic energy and transforms it into electric energy to be stored in the batteries or either with the possibility of connecting the car to the electric grid, it can be with AC or DC and even performed with different power levels. Another important aspect to be mentioned is the weight of the battery pack, that is heavier compared to an ICE and in this sense poses also a limit due to the higher traction that is needed compared to traditional vehicles. The main characteristics of such vehicles are their ability to quickly and smoothly accelerate, are silent vehicles and so eliminating noise pollution, do not require high level of maintenance and operation costs are very low and most important of all do not produce any GHG at tailpipe. Another relevant characteristic for such vehicles is their higher engine’s efficiency, while the endothermic engine has an efficiency of $17 \div 19\%$ representative of real-world driving conditions (EEA, 2018a), the electric engine is able to achieve an efficiency of 36%, and this value can be further improved in the next years (ENEL e Ambrosetti, 2017) (Helmers and Marx, 2012). Finally, BEVs are the only typology of vehicles that do not produce any kind of emission during their operations.

1.6 Global market scenario

The year 2017 can be considered as a milestone for electric mobility, with BEVs and PHEVs selling more than 1 million units globally and the quantity of stocks overcoming the threshold of 3 million units. The 2018 values are even higher with 2.1 million units sold representing 64% increase from previous year and an overall stock that has passed the 5 million units. The share for the global sales of light vehicle market consists in a 2.2% of new vehicles sold worldwide making also all EVs gaining a 3% share in the mix since 2017. Globally, BEVs accounted for the 69% while PHEVs for the remaining 31% of new sells in 2018 (IEA, 2019).

In this scenario the biggest market is by far China that moved from more than 500.000 units sold in 2017 to 1.2 million units in 2018. It has more than double quantity of Europe and the USA which respectively are the second and third biggest market. Europe in 2018 registered more than 400.000 units sold of EVs with an increase of 33% compared to previous year, while the USA had 360.000 units sold among which 66% were BEVs and 34% PHEVs, an overall 81% more than 2017 (it was the highest growth rate since 2013) (EV-volumes, 2019).

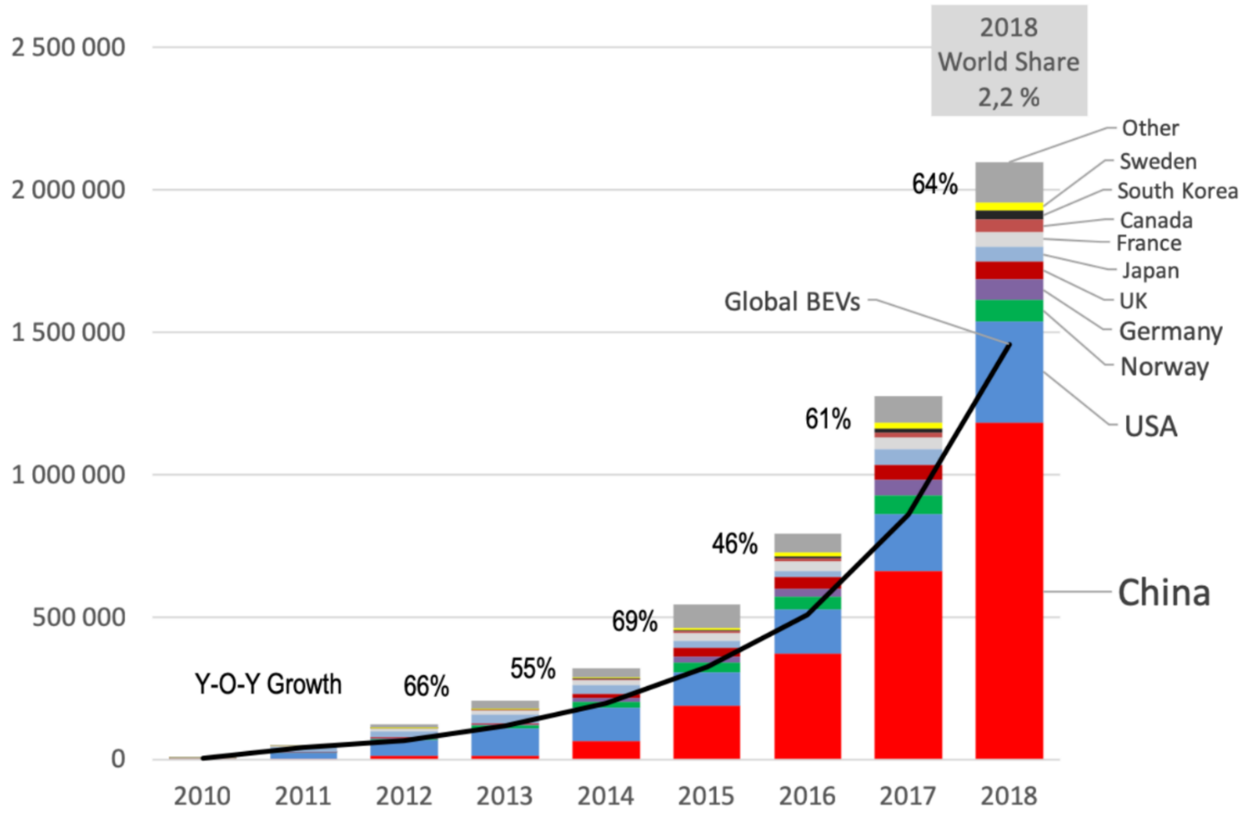


Fig. 7 Global BEVs and PHEVs - Light Vehicles
[Source: Adapted from EV-volumes.com]

Looking at *Fig.7* it is possible to highlight the positive trends that EVs are experiencing in the last years and how countries are strongly investing in their adoption and diffusion. With this current growth rate trajectory, it is reasonable to think of achieving a 4.5 million units sold in 2020. Also the number of available electric models is expected to further increase in the next years, passing from the 155 at the end of 2017 to the 289 by 2022 (Bloomberg, 2018). An important aspect has to be mentioned with respect to the strong disparities that still exist among countries and those are mainly influenced by the development and presence of the charging infrastructure and the availability of incentives. The charging infrastructure, both domestic and the one available in working and public places, is essential to contribute to the spread and use of EVs.

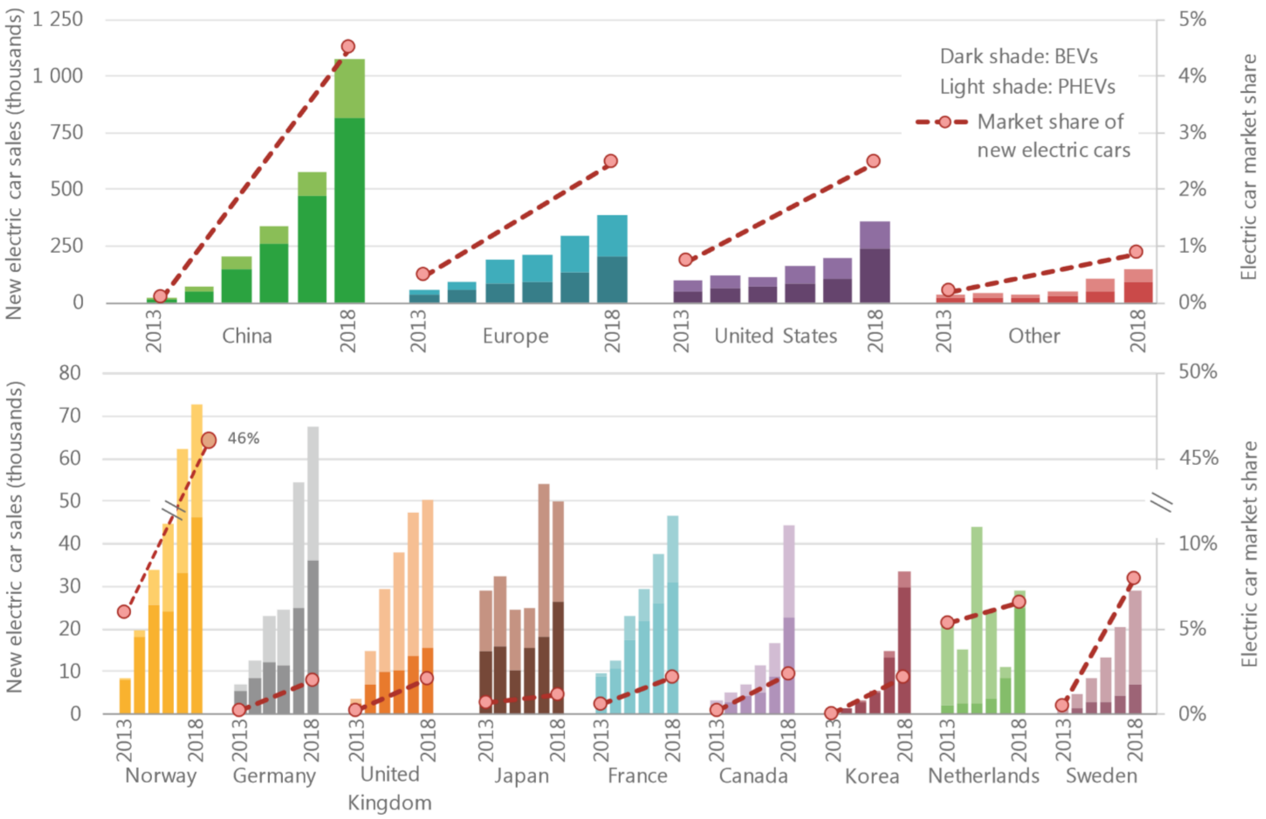


Fig. 8 Electric car sales and market share in the top-ten countries for sells
[Source: Adapted from GEVO, 2019]

An important aspect that must be considered when evaluating countries' market situation is the relative market share of EVs with respect to the whole number of vehicles circulating in that country. Although their consistent numbers, countries like China and the USA have still low values of market share (lower than 2%) but are the ones showing consistent advancements in EV penetration and on the manufacturing side. Norway, for example, is the country that within the last 8 years has drastically increased the number of EVs in the country, due to the national incentives that favoured the acquisition of such vehicles and invested in the development of the charging infrastructure. Nowadays, Norway has a 32% Plug-in EV share, making it by far the country with the highest global share, supported by more 200.000 stock units. It is also the first country where the number of EVs has almost exceed the number of ICEVs and it has also been the first country to introduce the ban for petrol-powered cars starting from 2025 (Ambrosetti, 2018). Potential bans are pushing both buyers and automakers away from ICEVs. Those bans are the consequences for urban air quality concerns that have quickly become central pillars of many countries' policy. It is expected that in 2030 countries such as Denmark, Iceland, Ireland, Israel, Netherlands and Slovenia will adopt bans for ICEV while progressively to 2040 also France, Portugal, Spain and United Kingdom will adopt the same ban for petrol-powered vehicles (IEA, 2019).

Within Europe countries that have higher market share for EVs are Iceland, Sweden, Ukraine, Belgium, Switzerland, Finland and Luxemburg. Strong progresses are being made also by UK, France, Germany and Netherland that are increasing their numbers.

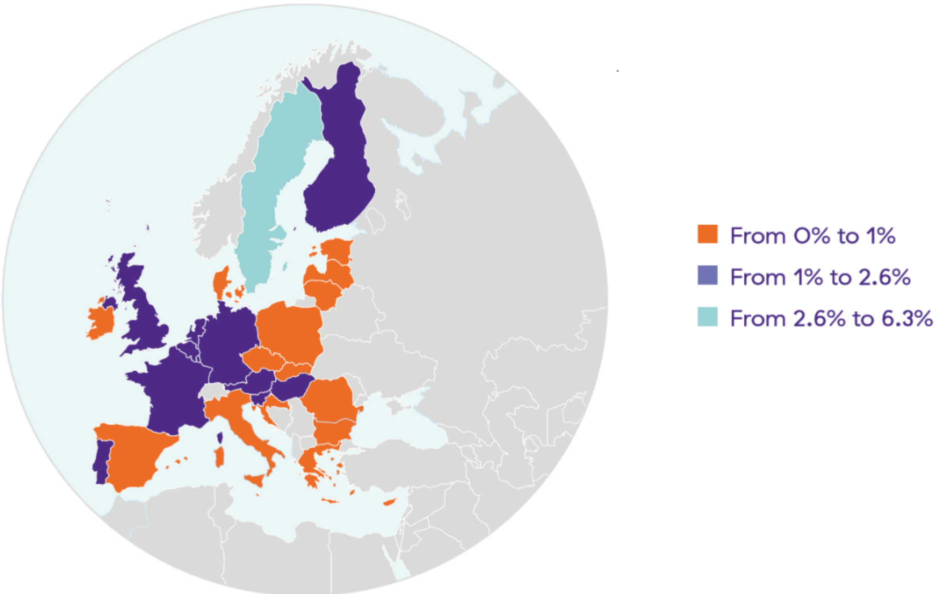


Fig. 9 Market share of e-Cars in the European Union, 2017
[Source: Adapted from The European House – Ambrosetti elaboration on United]

The growth of electric mobility is also shaping another important sector that is the one of materials supply for battery manufacturing. As mentioned above, the 2 main configurations of batteries are Lithium – Ion (Li-Ion) and Lithium – Polymers (Li-Po). Nowadays for sustaining Lithium – Ion battery manufacturing capacity the demand for the components that make up the batteries will increase from almost 0.7 $million\ metric\ tons$ in 2018 to over 10 $million\ metric\ tons$ in 2030. The main issues are connected to the manufacturing production capacity that will need to increase the pace to sustain the value chain, and mostly to the amount of Cobalt, Lithium and Copper that will significantly increase in the next years (Bloomberg, 2018).

A second relevant aspect connected to electric mobility that affects how it will evolve in the upcoming years is the increasing electricity demand required for charging EVs. Electricity is becoming more and more the fuel of the future. In 2017 the global electricity consumption for all EVs was estimated in the order of 54 $terawatt - hours$ (TWh), whose major part (91%) being required from China. The overall electricity demand for e-mobility increased by 21% compared to 2016 (IEA, 2018b). In order to better cope with the electricity demand that will significantly increase in the next years, it will become essential the role of renewable energy sources and the possibility of properly connecting vehicles to the electric grid.

2. Environmental concern

2.1 Present scenario

In last years with the development of electric mobility and specifically with the emerging of BEVs, it has become clear that this alternative form of propulsion system can help in reducing the environmental impact generated by the transport sector. BEVs provide several environmental benefits compared to traditional ICEVs, firstly and most important, not having a combustion engine means to not produce any tailpipe emissions and exhausted fumes and secondly to reduce dependence from petroleum. During their use phase BEVs do not produce, directly, any kind of emissions and in doing so they contribute in lowering air pollution within cities and providing a strong reduction of harmful tailpipe pollutants such as particulate matter, hydrocarbons, carbon monoxide, carbon dioxide, ozone and various oxides of nitrogen.

When referring to GHG emissions is important to highlight that also BEVs produce a given quantity of emissions during their life cycle phases, that have some variabilities associated to the energy mix generation and several aspects related to the different phases of both vehicle and fuel cycles'.

GHG emissions are mainly associated to the energy mix that is used for the extraction and manufacturing phase of vehicle's components and the different power sources that are used to charge the vehicle during the use phase. In this way, BEVs carbon emissions vary significantly from country to country, with respect also to the national or even the regional energy mix. Having in mind that the significant contribution for emissions comes from the above mentioned phases, the only way in which it is possible to label BEVs as pure "*zero-emission vehicles*" is if the electricity comes entirely from RES, which do not produce any amount of emissions during their use phase (the only emissions, but almost null, come from the power plant production and installation). Thus, it became essential to ensure a complete transition toward RES in order to have a complete decarbonisation and the achievement of a zero-emission mobility. For these reasons, the sustainability of the transport sector will be reached in parallel with the decarbonisation of the energy generation sector. But, the large adoption of BEVs will require additional electricity generation and consequently, there will be an increase in energy demand and GHG emissions from vehicle's use due to the electricity production sector.

Another aspect that must be considered when referring to BEVs and their environmental impact, is their strong dependence on some Rare-Earth Elements (REEs) that are required for the manufacturing phase of some components, specially the battery package. The demand for Lithium, heavy metals and other elements such as Neodymium, Boron and Cobalt that are required for the manufacturing of the battery package and the powertrain are expected to strongly increase in the next future as sales of BEVs are expected to increase as well. Technological improvements of battery chemistries, the reuse of batteries for storage applications and the development of a recycling industry for BEV's batteries will lead to improvements in their sustainability and in a dependence's reduction from REEs.

2.2 Metals and Rare Earth Elements

Increased sales of BEVs are posing the problem of the increased demand for some materials required for vehicle's manufacturing and production. Among those materials, play a critical role metals such as Boron, Cobalt, Copper, Lithium, Nickel, Neodymium and some Rare Earth Elements that are used for the manufacturing of the electric engine and batteries. REEs are a group of 17 chemical elements, among these, 12 despite their label are not especially scarce but are available only in small amounts dispersed on the Earth's crust. This is making it difficult to mine them because are rarely found in concentrations high enough to allow for profitable economic extraction. Problems associated with the dependence of such materials must deal also with the largest reserves of Lithium and other rare metals to be in countries with strong resource nationalism and unstable governments. Another important aspect is that mining activities in such countries (mainly Asian) are performed with less stringent precautions than they are done in some other countries, as for example in European ones, and thus can have a deep impact on human health (EEA, 2018a). Mining of Neodymium is one of the process that produces a high quantity of dust which is mainly causing pulmonary embolisms and further health damages with a persistent exposure.

Lithium

Lithium is a soft, silvery-white alkali metal which is heavily used for battery manufacturing and the vast majority of BEVs are equipped nowadays with batteries having this chemical element. The main depots of Lithium are present in China and in countries of south America such as Argentina and Chile which was the leader in Lithium's production with a market share of 30% in 2010 (IEA, 2018b). Today, nearly half of world's proven reserves are in Bolivia. Studies on the actual availability of Lithium's reserves have demonstrated that this will not be a limiting factor for BEVs production, although an increase in the demand's level is expected for the next decade. After 2030, with the introduction of new technological developments it is reasonable to think of a reduction in the use of such material toward new ones that will allow batteries to be more efficient, lighter, smaller and cheaper.

Cobalt

Cobalt is a metal which is currently mostly mined as a by-product of Nickel and Copper because it occurs in the same ores. As for Lithium, it is used for battery manufacturing and at the same time it is more difficult to obtain. Big concerns are related to its price and availability, in the last 10 years the market price has increased more than 400% achieving values of $80.000\ USD/tonne$. A second major problem is related to the availability of this material; the Democratic Republic of Congo is holding more than 60% of Cobalt's world reserves (Conca, 2018). Moreover, the capacity to refine and process raw Cobalt is highly concentrated and the major player is China that has 90% of the refining capacity (IEA, 2018b).

REEs

Rare Earth Elements are key materials for the manufacturing of EVs components and for wind turbines. Especially 2 elements, Neodymium and Praseodymium, are critical due to their characteristics in making powerful magnets in electric motors and generators. Due to their variety and different usages, prices vary with significant fluctuations among countries. China is the country with the highest reserves for REEs with a 48% share (Silver, 2019) and in the last years has also dominated the production, with a provision of more than 95% of global supply. One aspect that must be taken into consideration is the REEs strong environmental impact. It is estimated that for the refining of $1\ ton$ of REEs are produced $75\ cubic\ meter$ of acidic wastes (Smith, 2015) and to avoid such critical environmental impact it will be fundamental to gradually substitute REEs with more eco-friendly materials in the long term.

2.3 Types of emissions

As already mentioned, one of the main advantages of electric mobility is its strong contribution to the decarbonization of transportation sector. The decarbonization process consists in the reduction of emissions released into Earth's atmosphere from various gases that contribute to the greenhouse effect. GHG emissions are increasing globally year by year to levels that were never reached before; in 2017 the total amount reached was about $58.710\ million\ tons\ of\ CO_2 - eq$ (Ambrosetti, 2018) and the transport sector accounted for 25% of the $CO_2 - eq$ emissions. Furthermore, it is increasing the percentage of people, worldwide and specifically in Asian and European countries, moving to cities and urban areas in which there is an higher concentration of pollutants above the air quality standards, to levels deemed as harmful for human health (EEA, 2018b).

The environmental footprint caused by the transport sector is mainly responsible for non-renewable resource consumption and emission of polluting substances leading to climate change effects, global warming, photochemical smog formation, ozone layer destruction, acid rain etc. When evaluating vehicle's life cycle for both ICEVs and EVs, it has been noted that generation of air pollution in form of GHGs come from vehicle's operation, fuel consumption and additional emissions are associated with refining processes and distribution of fuels (electricity for EVs) and to a lesser extent to manufacturing (lower for ICEVs compared to EVs) and disposal of vehicle.

Air pollution can also be split into 2 different categories, primary and secondary pollution. Primary pollution is emitted directly into the atmosphere while secondary air pollution is the result of chemical reactions between pollutants in the atmosphere.

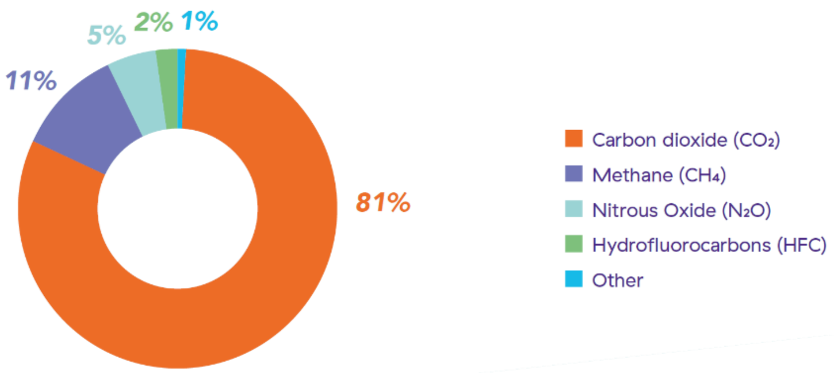


Fig. 10 Air emissions by atmospheric components at global level (% values)
[Source: Adapted from The European House – Ambrosetti elaboration on United]

The following gas and materials are the major pollutants from vehicle manufacturing and operation phases. The gases which are listed below are those that account for the GHG emissions coming specifically from the transportation sector.

- Particulate Matter (PM)

Particulate matter can be of several types and of many different substances. Those kinds of particulates originate from different sources but for what concerns the transport sector they are mainly originating from operations within combustion engines, from tires wear and from the braking system. One type of matter is the soot seen in vehicles exhaust gases and among them the most common are PM_{10} and $PM_{2.5}$ which are very fine particles that have a size of less than one-tenth of the diameter of a human air ($10\ \mu m$ and $2.5\ \mu m$). Those particulates pose serious problems for human health, due to their small size they can penetrate deep into lungs and cause infections and even death. Particulate matter can be also a primary or a secondary pollutant from Hydrocarbons, Nitrogen oxides and Sulphur dioxides.

From many studies conducted it has been possible to estimate also the amount of premature deaths registered in each country for the ambient particulate matter pollution for every million inhabitants (Ambrosetti, 2018).

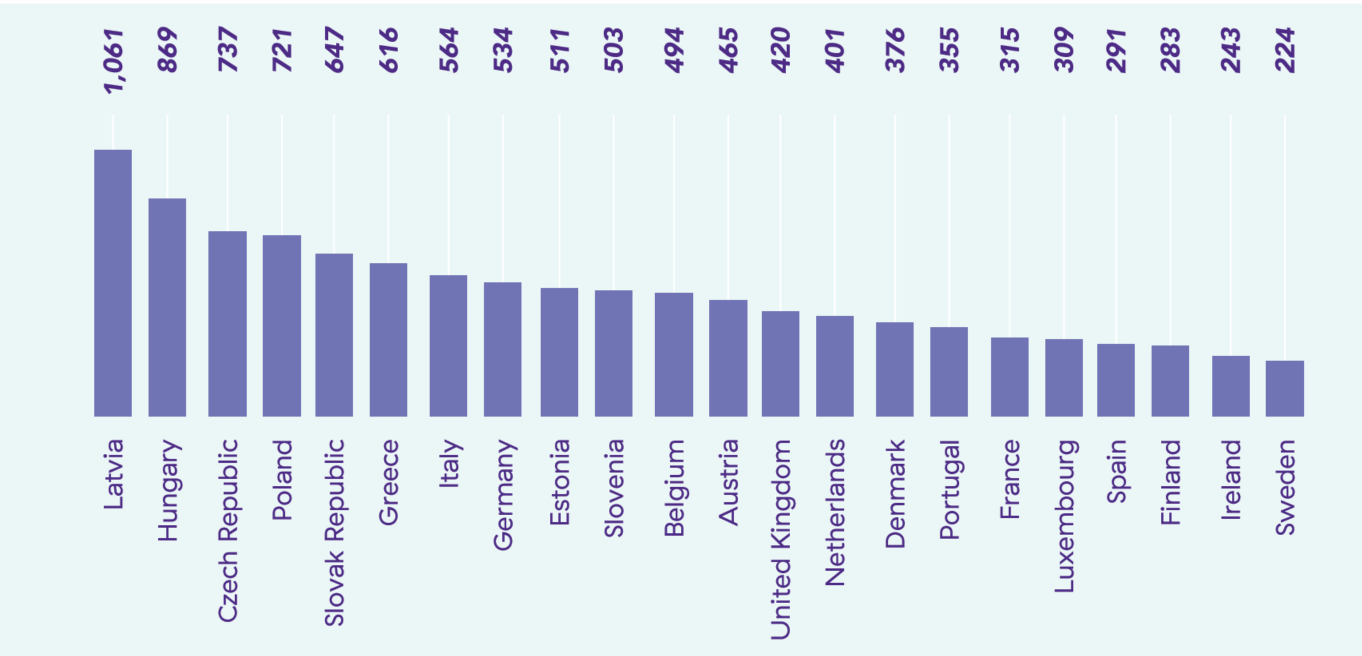


Fig. 11 Premature deaths from ambient particulate matter for every million inhabitants
[Source: Adapted from The European House – Ambrosetti elaboration on Global Burden of Disease (GBD]

- Volatile Organic Compound (VCO)

These pollutants are a class of organic chemicals which react with Nitrogen oxides in the presence of sunlight to form ground level ozone, a principal ingredient in smog. They are characterised by high vapor pressure at ordinary temperatures (between $15°C$ to $25°C$), that causes large number of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air and for this reason they have a good trait of volatility. Volatile Organic Compound are numerous and have different varieties, their effects on human health can be serious, irritating the respiratory system and being responsible for different types of cancer.

- Carbon Dioxide (CO_2)

Is the most emitted GHG into Earth's atmosphere by human activities and it is the main by-product of transportation sector. It is also the major contributor to global warming impact. CO_2 is produced when a combustion occurs (from fossil fuels or biological materials) and as the result of some chemical reactions. One of the main problems connected to such gas is the increasing amount registered in part per million (ppm) of cubic meter of atmosphere, which has seen an increase of those values constantly. During the industrial revolutions, starting from the mid-18th century values registered where in the order of $280\ ppm$ while in October 2016 a value of $402.31\ ppm$ was registered, demonstrating a 42% increase in the last $150\ years$, but mostly a growth of $2\ ppm/year$ in the last $10\ years$ (La Picirelli de Souza et al., 2018).

- Nitrogen Oxides (NO_X)

This class of pollutants form ground level ozone and additionally also particulate matter. They are being held responsible for air toxicity that causes irritation to the human respiratory system and can weaken body's defences against respiratory infections.

- Nitrous Oxide (N_2O)

This gas is one of the most common Nitrogen oxides, it is also known as "*laughing gas*" and it is also used in medical fields for its anaesthetic and pain reducing effects. It is produced during the combustion process within "*nitrous oxide engine*" (usually are racing cars) which is an ICE, that uses such gas to burn more fuel by providing more oxygen than air alone, resulting in a more powerful combustion. Compared to carbon dioxide it has an atmospheric lifetime higher and it is also responsible for ozone depletion. If a high concentration of Nitrous is inhaled without the presence of Oxygen, it can lead to serious health problems: loss of blood pressure, fainting and even heart attacks.

- Carbon Monoxide (CO)

This type of GHG is obtained from the incomplete fuel-combustion. This gas poses some serious problems to human's health since it leads to a decrease of Oxygen uptakes by lungs and can lead to a wide range of symptoms as the concentration increases. When inhaled, carbon monoxide blocks Oxygen from reaching vital organs such as brain and heart and can lead also to death. Road transportation and ICEs are the largest producer of such kind of emissions. Nowadays, values of such gas are slowing decreasing due to the introduction of new policies imposed by governments in many countries.

- Sulphur Dioxide (SO_2)

Sulphur Dioxide is mainly produced when fuel combustion occurs, the gas originates from the Sulphur contained in the fuel being burnt such as coal, oil and petroleum coke, which all have high Sulphur content. This type of gas can also react in the atmosphere to form fine particles and poses health problems, especially for those suffering of asthma.

- Methane (CH_4)

Is the second most important GHG which is emitted during the production and transport of coal, oil and natural gas. The effect of methane is higher than the one of carbon dioxide because the radiative forcing produced is higher, but the concentration of methane in the atmosphere is lower compared to CO_2. A second important characteristic of CH_4 is its considerably shorter residence time into the atmosphere compared to carbon dioxide (methane residence is around $10\ years$, compared with the $100\ years$ for CO_2).

In order to have a uniform way of measuring the impact of different GHGs it has been introduced the concept of $CO_2 - equivalent$, which allows to standardise any quantity and type of GHG in terms of CO_2 which would have the equivalent Global Warming Potential (GWP).

The Global Warming Potential can be defined as the ability of a GHG to trap extra heat in the atmosphere over time relative to carbon dioxide. GWP characterises and calculates the impact of GHGs on the extent to which they enhance radiative forcing. GWP is also dependent on the efficiency of the molecules as a GHG and its atmospheric lifetime. It is usually calculated over $100\ years$ and this measure is known as the "*100 years GWP*". Each GHG has a different GWP and it persists for a different time period in the atmosphere.

Species	Chemical formula	Lifetime [years]	Global Warming Potential (Time Horizon)		
			20 yrs	100 yrs	500 yrs
Carbon Dioxide	CO_2	30-95	1	1	1
Methane	CH_4	12	56	28	6,5
Nitrous Oxide	N_2O	120	280	310	170

Table 1 Global Warming Potential
[Source: Adapted from Greenhouse Gas Protocol, 2014]

A quantity of GHG can be expressed as $CO_2 - eq$ by multiplying the amount of the GHG by its 100 $years$ GWP values. If $1kg$ of methane is emitted, this can be expressed as $28\ kg\ of\ CO_2 - eq$:

$$1\ kg\ CH_4\ *\ 28\ =\ 28\ kg\ CO_2 - equivalent$$

2.4 CO_2 standards

In order to limit the amount of CO_2 emissions coming from vehicles, many governments have already started to introduce limitations and standards upon car manufacturers. These actions have the aim to push carmakers toward more efficient production of low and zero-emission vehicles.

The European Union already in 2009 and 2014 had posed some CO_2 limitations for new vehicles, cars and vans, sold in Europe. In 2009 were introduced respectively for 2015 and 2020, targets of $130g\ CO_2/km$ and $95g\ CO_2/km$ for new cars while $175g\ CO_2/km$ limit for 2017 and $147g\ CO_2/km$ for 2020, respectively for vans. In 2014, car's target for 2020 was moved to 2021. With this 2021's goal the values of carbon dioxide level will be reduced by a factor of 42% compared to 2005 levels'. In those years have also been set the objectives for 2025 and 2030, aiming to a further 15% and 30% CO_2 emission reduction (EU, 2017). Those bidding emissions targets for car manufacturers are set according to the average mass of their vehicle. If the target value in a given year is overcome by a car manufacturer, it is imposed to pay an excess-emission-premium for each car registered. On the other way, manufacturers are given incentives for introducing on the market low and zero-emission cars, if they succeed in putting on the market vehicles which are emitting less than $50g\ CO_2/km$ they are awarded with a "*super-credit*" system which has already been applied (EU, 2017). European average emission, registered in 2017 for new passenger car, was of $118.5\ gCO_2/km$ and below are reported values registered from some European countries.

Country	Italy	France	Germany	Netherlands	Norway	Sweden
Average new car's emissions [g CO2/km]	113.4	110.4	127.1	108.3	82.4	122.3

Table 2 Average New Car Emissions in the selected European Countries
[Source: Adapted from European Union, 2017]

As it is possible to see, only few countries have values which are close to the targets imposed for 2021. Norway is leading among all European countries due to its strong national policies that lead to high level of new EVs sold and at the same time the strong leverage on RES. Other countries still lag in order to achieve the imposed target of $95g\ CO_2/km$.

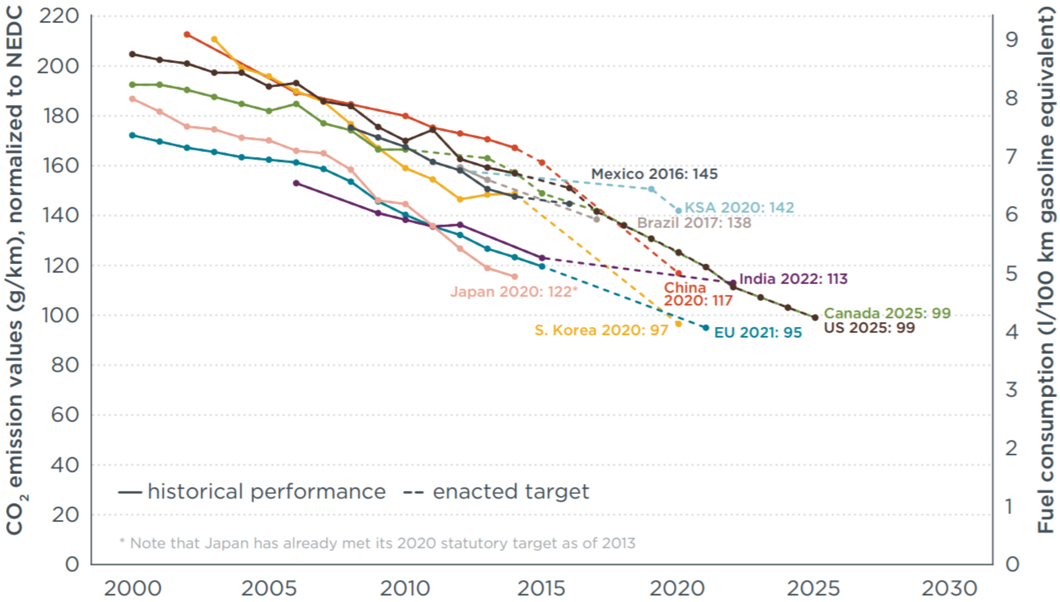


Fig. 12 Historical fleet CO_2 emissions performance and current standards (gCO_2/km normalized to NEDC) for passenger cars
[Source: Adapted from ICCT, 2017]

At global level, also many other countries have started the same introduction of targets to be achieved in the next years, but those imposed by EU are by far tougher compared to others. Today, 10 governments: Brazil, Canada, China, (EU), India, Japan, Mexico, Saudi Arabia, South Korea, and United States have established GHG emission standards for light duty vehicles, and other countries such as Australia, Thailand, and Vietnam are in the process of developing standards as well (ICCT, 2017).

3. Literature review on EV life cycle environmental impact

3.1 Introduction

The first aim of this chapter is to provide an overview of the literature review that has been conducted in order to evaluate all the scientific papers and documents on the EV life cycle environmental impact, adapting a cradle-to-grave perspective.

The analysis has been performed evaluating a total of 32 among documents, studies, scientific papers, industrial and car manufacturers reports which provided information on the EV life cycle phases and their relative emission values. Naturally, have been encountered a lot of variabilities associated to the different focus that each single study was tackling. The main differences are due to the different boundaries for the analysis to be conducted, to the several vehicle typologies considered, the countries evaluated for the analysis and all the different assumption that are essential in order to properly evaluate the EV life cycle emissions.

Among those 32 main documents analysed it is possible to distinguish:

- 16 LCAs studies; of such
  - 11 reported values for both BEVs and ICEVs and their emission values' comparison;
  - 12 reported values for some European countries;
  - Only 1 reported values for the use phase to be evaluated in Italy;
  - Only 4 reported values associated to the EoL phase.

- 4 "*Global Electric Vehicles Outlook*" (GEVO) reports (2016 – 2017 – 2018 – 2019).

- 12 scientific papers and reports; of such
  - 3 specifically evaluating the emissions arising from battery manufacturing;
  - 9 specifically evaluating the emissions coming from the use phase.

Most of the documents reviewed were selected among those, related to EVs, published in the last 5 years. The decision to evaluate most recent documents is because, as electric mobility is quite a new trend and the developments that are being introduced are fundamentally impacting on all the phases of the EV value chain and radically shaping their emissions; it is essential to review the most updated values.

The areas in which have been encountered the most important developments are those associated to the battery manufacturing and the use phase, this last is strongly affected by the energy mix of the selected country. In the last years, related to the battery pack it was possible to observe a considerable increase of the sizes (kWh), of the energy density (kWh/kg) and also an increase of the different chemistries being introduced on the market. As technological improvements are being introduced, new and more powerful battery solutions started to be presented on the market.

In this literature review are evaluated the different Lithium Ion battery chemistries and are specifically evaluated those mostly adopted on the market (NCM and LFP).

The second aim of such review is to provide information about all the elements that will be essential in order to properly define all the life cycle phases and variables associated to the emissions produced along the EV life cycle.

The emission-models that will be presented in the next chapters, are built according to the values found in such review and that is why is here fundamental to evaluate and quantify which is the environmental impact produced by electric vehicles. In order to define which is the environmental impact adapting an LCA-based perspective associated to EVs and ICEVs, are fundamentals the values and findings reported in such chapter.

The present chapter is structured to provide at first a definition of what is a Life Cycle Assessment (LCA) and then its application to the study of EVs. In the second part it is provided the literature overview of the LCA studies evaluated. In such section are illustrated the main findings related to each of the different LCA steps. In the last part are specifically evaluated the 3 main phases of the EV life cycle: manufacturing, use and End-of-Life. For each phase is provided a detailed description and analysis of the reviewed documents. To conclude this chapter, it is provided a detailed overview for all the LCA studies covered and the full document is available in *Annex 1*.

3.2 Life Cycle Assessment (LCA)

Among several methods that can be applied in order to evaluate and monitor the life cycle of a product, the Life Cycle Assessment (LCA) is a method which can be used in order to assess energy and raw material consumption, different types of emissions and other important factors related to a specific product. All those aspects are being measured, analysed and summoned over the entire product's life cycle from an environmental perspective, attempting to measure the cradle-to-grave impact on the ecosystem. The analysis embraces all those stages that from raw material extraction and processing, through manufacturing and assembling processes and finally use and end of life phases which overall constitute the entire product life cycle.

For its characteristics the LCA is one of the most comprehensive methods in assessing the environmental impact for its systematic approach in evaluating aspects and impacts of the product system analysed. The relative nature of an LCA is based on a functional unit which is a quantitative description of the service performance of the investigated product system. Once it has been defined, is kept as reference throw all the stages of the analysis. The depth of detail and time frame can vary significantly according to the boundaries and limitations posed by the analysis itself. It is straight forward that there is no single way of conducting an LCA study.

The best way for the application of this kind of analysis is to examine the product system as big as possible to have a clear picture of all components, relative flows (inputs, throughputs and outputs) and wastes/emissions. The main aim is to address the potential environmental impact of the product system studied and to identify hot spots in order to introduce improvements.

3.2.1 LCA steps

LCA analysis is performed following 4 main steps which are here described.

1. Goal definition

In the initial phase, it is defined the product system to be studied together with the basis and scope of the analysis. Particular attention needs to be dedicated to temporal (time scale), spatial (geographic) and system boundaries (identify and define the processes to be included in the product system), which may have relevant impacts in the development of the study. It is identified the functional unit that will serve as a reference unit within the overall analysis and are also posed some assumptions and limitations.

2. Inventory analysis

A process tree is created in order to map all flows from raw material extraction to waste treatment or recycling. Also, mass and energy balances are closed, and both emissions and consumption levels are accounted for. The aim of this part is to calculate the quantities of different resources required and the amount of emissions and waste generated per functional unit. For this part it is essential to have availability and consistency of data requirements.

3. Impact assessment

Emissions and consumptions are translated into environmental effects, which are then grouped and weighted. This phase provides indicators and the basis for analysing the potential contributions of the resource extractions and emissions in an inventory to several potential impacts. The results from the impact assessment are an evaluation of a product life cycle in terms of several impact categories (such as climate change, toxicological stress, noise, land use etc.), based on the functional unit.

In this phase it is possible to choose among 3 different methods:

- Eco-Points method

It consists in a directly way of measuring the environmental impact and there are no classification steps that occur. The evaluation principle is the distance to target principle, or the difference between the total impact in a specific area and the target value.

- Environmental Priority System

It is a system that attempts to translate the environmental impact into a sort of social expenditure, as the estimated financial consequences of any environmental problem caused by the activities investigated.

- Eco-Indicator 95 and 99

Eco-indicator 95 is a tool to simplify the analysis, standardising the most common approach. Using this indicator, once again, it is applied for the evaluation the distance to target principle; and targets are based on scientific data on environmental damage and not on policy statements. The 3 types of environmental damage for target values are: deterioration of the ecosystem, deterioration of human health and human deaths (1 fatality per million inhabitants per years). With eco-indicator 99 the distance to target approach is no longer included in the principle and there is a full development of the damage approach. The description and definition of damage models is performed with a deeper level of details and are considered a wider range of emissions and effects. As well as for the previous indicator, also here, are reported 3 damage categories and those are: human health, ecosystem quality and resources.

4. Improvement assessment

The final step in life cycle assessment is to identify areas, processes or flows which need improvements.

3.3 EV – Life Cycle Assessment

LCA studies on the automotive sector have been introduced for the first time in $1970s$ with the purpose of studying alternative ways for achieving a lower dependence on crude oil products (La Picirelli de Souza et al., 2018). Since then, new LCA studies have been performed over years with the aims of finding areas for technological improvement, trying to reduce the amount of emissions generated and for evaluating the environmental impact generated over the entire vehicle's life cycle. Generally, the total impact values are obtained as measures from the impact per kilometre multiplied by the kilometre range assumed to be driven over the entire vehicle's lifetime. With those studies being carried out, the LCA methodology became a validated approach that helped as a decision support tool in vehicle engineering. Moreover, LCA analysis allows vehicles' designers and manufacturers, fuel producers and distributors, as well as policy makers to make informed decisions regarding the environmental consequences on the entire vehicle's life cycle. The main reason justifying the suitability of such kind of assessment is due to the amount of emissions that are associated to the vehicle even before its use phase, and which are easily traced with this approach.

In the last 20 years, with the presence of EVs becoming a more and more consolidated solution on the market, there have been many LCA studies conducted on such class of vehicles in order to analyse and evaluate their environmental impacts and areas for improvements in their life cycle. Most of such analysis conducted by governments, institutions, manufacturing companies, researchers and universities were concentrated on the estimations of the performance of EVs, on energy consumptions, wastes and GHG emissions compared to traditional ICEVs.

Naturally, in more than 20 years literature, it is possible to find EV-LCA studies which differ from each other according to the different purposes of conducting the studies, to the product system analysed, to the boundaries and parameters studied. Most of the variations in terms of results are deeply influenced by the differences in the energy mix of countries in which manufacturing, and production occur, as well where the use of the vehicle occurs. It is as well important to highlight that among the studies there are significant differences in term of transparency with the data that they provide, assumptions to be made, system boundaries covered, if in the study are used ready-made data from earlier studies or if instead they relied on data that they were able to collect and measure. Another factor that has been given quite relevant importance is the age of the LCA analysis.

All EV-LCA studies are mainly based on the analysis of different cycles that are falling within the system boundaries of the product system evaluated. Those are:

- Vehicle cycle
- Fuel cycle
- Electricity production mix
- Battery cycle

3.4 EV – LCA Literature Overview

In this section it will be provided a literature overview of the different LCA studies analysed, with the aim of trying to map in a complete and comprehensive way the different studies and develop a clear picture of all the assumptions and limitations, emissions, wastes and GHG that are being measured and analysed when performing an EV – LCA. One of the characteristics evaluated in the analysis of these models is the strong correlation and high level of citation among the several LCA studies.

3.4.1 Goal and Scope

The general aims for conducting an EV – LCA are related to the comparison between ICEV, HV, PHEV and BEV in terms of environmental impacts, GHG emissions during vehicle's entire life cycle, the usage of critical materials in the manufacturing processes and the analysis of benefits arising from the adoption of one typology over the others. Among the several studies analysed there are differences with the focuses described in the previous paragraph; and according to the typologies of vehicles considered. Some studies include generally only ICEVs and BEVs while other consider also HV with different degrees of hybridization.

Most of the analysis are concentrated on countries in which there is an established presence of EVs and in other countries where electric mobility is starting to emerge as an alternative to traditional ICE powered vehicles. Studies are conducted by mapping the specific country situation performing accurate cradle-to-grave analysis or, on the other way, concentrating on some general and broad aspects, making a comparison among different countries. In this literature overview, specific cradle-to-grave studies analysed have been performed on Brazil (La Picirelli de Souza et al., 2018), Canada (Kukreja, 2018), China (Wu et al., 2018) and Europe (Tagliaferri et al., 2016) while others are mainly structured for making a comparison among the different scenarios in several countries, taking into consideration those previously mentioned and Australia, Czech Republic, France, Germany, Italy, Japan, Poland and United States.

In all studies there are some peculiarities regarding general definitions, settings, units of measure and ways of performing the analysis. Most of the analysis covered are performed according to the ISO 14040:2006 which is a technical standard for conducting performance on environmental management and LCA, setting principles and framework that must be followed.

It is possible to distinguish between 2 different methods of analysis; a first one conducted on general vehicles, whose values are obtained as average measures respectively of a country specific situation, while a second one referring to given models of both EVs and ICEVs, resulting in a more detailed approach due to the specific measures of autonomy, capacity, consumption, emissions, performances and weight of components. In both scenarios are considered compact passenger car which belong to the same vehicle's segment for EVs and ICEVs. Generally, the consumption is measured in l/km for ICEV and in kWh/km for BEV.

The functional unit is usually defined over the total number of driven km by a vehicle, values of distances can vary largely according to different vehicles, their usage and their life span. A general and broadly adopted measure, is to set the average life cycle km range as $150.000\ km$ to be covered (usually) in a period of time of 12 to $14\ years$ (La Picirelli de Souza et al., 2018), and so defining the functional unit as $1\ km$ driven, and relating to it all the measures related to emissions and other factors.

3.4.2 Assumptions and Limitations

Before starting the analysis, one of the most important part is related to the setting of assumptions and limitations which have the purpose of limiting the complexity of the product system analysed and to facilitate the study to be performed within system boundaries.

- Energy mix and fuel production

Normally, in all LCAs are taken as reference values of the national energy mix production without considering sub-national or regional specific production mix and it is also defined a general coefficient of energy loss during vehicle's charging that could be among $10 - 20\%$ of total energy drawn from the grid (EVE IWG, 2016; Peng et al., 2018). In the fuel cycle, it is also used to distinguish between the well-to-tank (WTT) and well-to-wheel (WTW) for differentiating the impacts occurring from different stages. The only fair way to compare the 2 vehicles typologies; BEVs and ICEVs, is by their WTW impacts. Among the general considerations, in the WTW analysis are never mentioned the amount of emissions generated for the construction of facilities, building, extraction plants etc (La Picirelli de Souza et al., 2018). Another important aspect to evaluate the environmental impact of transportation system is to consider the correct energy pathway.

- Vehicle's manufacturing

When evaluating the manufacturing of vehicle's components are generally included only the most relevant, for the emission's analysis, which for ICEVs and EVs are: powertrain, glider, engine and battery pack (Tagliaferri et al., 2016). In some of the analysis covered, it has been considered that EV and PHEV are being equipped with the same battery typology, although this is something not happening in reality but just for a matter of simplification and easier way of comparing results obtained (La Picirelli de Souza et al., 2018). In this broad literature review, it has been observed that some studies also reported values expressed in $MJ/kg\ of\ vehicle$ for vehicle's manufacturing area and that easily allowed to obtain the environmental impact coming from this segment of the EV and ICEV life cycle.

- Vehicle’s operating

For the normal functioning of EVs, it is assumed that they can be driven, taking into consideration average values of battery sizes and different types of vehicles, for a range of $160 \div 250\ km$ before being charged and that during their life time ($12\ to\ 14\ years$) there is no need to replace the battery (Wu et al., 2018). Charging efficiency for EV and PHEV is generally assumed to be at $90\% \div 96\%$ (Peng et al., 2018). For PHEV are generally considered 2 different modalities of operations: “*charge-depleting*” when the engine is off, and the vehicle is propelled by the electric motor with the energy stored in batteries and “*charge-sustaining*” mode that occurs when the battery reaches its minimum state of charge and the engine starts its operation. It is convenience to assume an electric autonomy of $60 \div 80\ km$ range for PHEV (La Picirelli de Souza et al., 2018).

In most of the studies were not deeply analysed the impacts of geographical parameters and those of the cooling system factors. Only one study, covered in literature overview, was very focused on those aspects considering impacts generated by the driving resistance (rolling, acceleration and aerodynamic resistance of vehicles), use of auxiliaries (heating, air conditioning and ventilation) and losses in converting the electric energy into mechanical energy due to inefficiencies of different components (Egede et al., 2015). Another important assumption is that all measures are based on lab driving conditions or those provided by car manufacturers rather than on real world driving conditions.

A further important factor that has been considered is the general occupation rate of vehicles which is assumed to be 1.6 people and it is affecting (even if minimally) vehicle’s weight and so consumption levels in kWh/km or l/km for EVs and ICEVs (La Picirelli de Souza et al., 2018).

3.4.3 Life Cycle Inventory

Life cycle inventory analysis is the second step in which all data, resources and inventory measures are being collected for the components, materials’ flows, emissions and energy consumptions levels. In this part, different methods or database have been considered in the different studies and the reasons are mainly related to the fact that most of those datasets are containing values and measures for specific countries and typology of vehicles. The most used datasets are:

- **GREET** (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) is a full life-cycle model sponsored by the U.S. Department of Energy. This tool includes 2 sub-models named Fuel-Cycle Model (*GREET 1*) which contains data of fuel cycles and vehicle operations, and a second one, Vehicle-Cycle Model (*GREET 2*) which evaluates the energy and emission effects associated with all phases of vehicle life-cycle (material recovery and production, vehicle’s manufacturing, assembly, disposal and recycling). GREET model includes in its database more than 100 fuel production pathways and more than 70 vehicle/fuel systems.

- **EcoInvent** is database software that was developed by the Swiss Centre for Life Cycle Inventories and in the last 20 years different versions have been released. It is the world's leading database for documented process data for thousands of products for different industrial sectors. It contains more than 14.700 Life Cycle Inventory datasets, a part of which are related to the energy supply and transport sector. The software is also giving the possibility to perform analysis on both fuel cycle and vehicle cycle.

- **Thinkstep – GaBi** is a software that allows to model every element of a product or system from a life cycle perspective**.** It relies on databases that detail energy and the environmental impact of sourcing and refining materials, production and manufacturing, disposal and recycling with more than 12.500 Life Cycle Inventory datasets.

Another possible way of performing this part of the analysis, is commonly referring to previous studies and leveraging on their data to further develop and performing the analysis. This approach has been used, in addition to databases, in all studies also for a matter of results comparison.

3.4.4 Cycles Overview

When performing the Life Cycle Inventory (LCI) phase it is important to have a clear picture of all the processes and flows to be mapped within the system boundaries. In order to do so, in all EV-LCAs are being evaluated 3 different cycles that compromise and impact on the entire EV life cycle.

- Vehicle

Vehicle's cycle is the core of the analysis for the comparison among the different typologies of vehicles being studied, mostly BEVs and ICEVs. Are covered generally, for both typologies, the stages of the life cycle trying to develop a comprehensive and clear picture. Some studies did not consider some stages in their analysis while some others, performing a cradle-to-grave analysis did a more detailed study including also transportation of components among stages and the relative importance of maintenance.

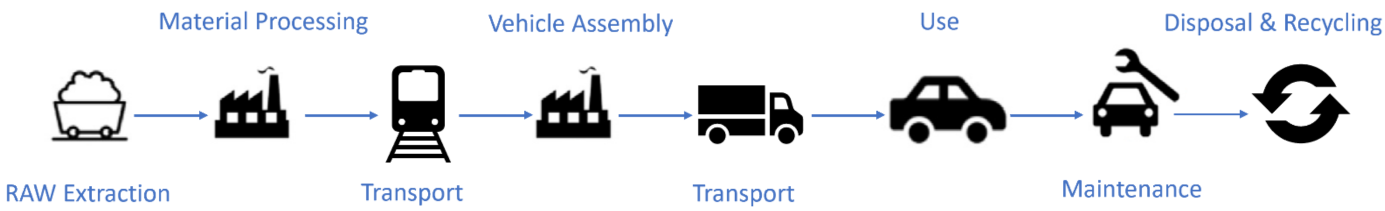


Fig. 13 Vehicle Life Cycle
[Source: Own production]

- Fuel

Fuel's cycle evaluated in the studies covered is generally standardised and all phases are covered in the LCA's overview. It is possible to distinguish within the overall cycle among the Well-to-Pump (WTP) and Pump-to-Wheel (PTW).

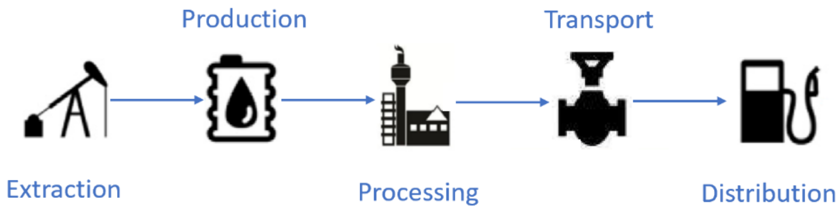


Fig. 14 Fuel Cycle
[Source: Own production]

- Electricity

Electricity production is a process that can be really different according to the geographical area or country considered, due to the differences in the energy mix production that takes into consideration all power sources: coal, natural gas, nuclear, oil, biomass, geothermal, hydro, solar, wind and CHP systems. Some countries are more relying on coal or natural gas to produce electricity and having low values of electricity being produced from RES e.g. China and the USA, which have values below 15% of total energy production mix; while other countries e.g. Brazil, Denmark, Canada, Colombia, Iceland and Norway have values higher than 65% of the total energy production mix from RES (Enerdata, 2018).

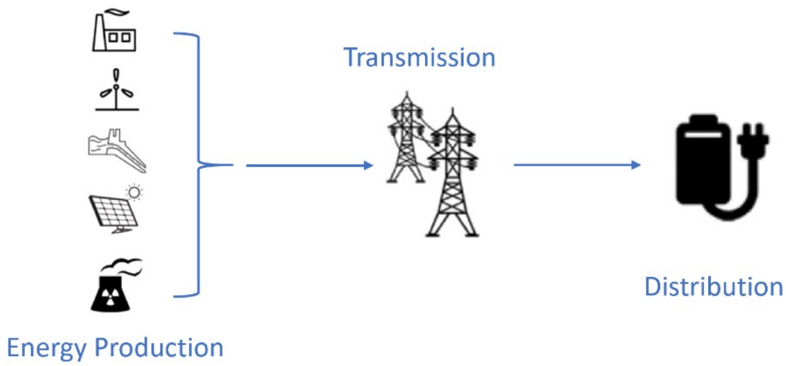


Fig. 15 Electricity Production
[Source: Own production]

3.4.5 Impact assessment

Once all the flows relative to materials, emissions, waste and energy consumptions have been measured and evaluated throughout the life cycle inventories of the product system to be studied, it is possible to evaluate the impact assessment. In most of the studies covered in the review, have been considered some of the most representative environmental impact categories by the automotive sector. Some studies focus on very few of them, those being performed with a general and broad approach, while others being carried out with a cradle-to-grave approach take into consideration a longer list of them. The most considered impact categories are:

- Acidification Potential (ACP)

This impact category derives from the acidifying pollutants such as NH_3, NO_2, NO_x and SO_x reaching the atmosphere and reacting with water vapor to form acids, which afterward fall on Earth and contaminate soils and waters. The measure to express ACP is given in $gSO_2 - eq/km$. The contribution of such pollutants arise from different phases considered in the vehicle life cycle such as manufacturing due to the large consumption of metals and plastic contained in the body shell and also to the combustion of fossil fuels for ICEVs and HVs (La Picirelli de Souza et al., 2018). For what concerns EVs and HVs, a consistent portion of such pollutants arise from battery manufacturing (Tagliaferri et al., 2016), while vehicle and battery recycling contributes to a reduction in terms of $gSO_2 - eq/km$ emissions. It is plausible to consider that the use stage impact of BEVs is generally similar to that of ICEVs, for terrestrial acidification (EEA, 2018a)

- Ozone Depletion Layer potential (ODP)

Ozone depletion refers to the destruction of the ozone's layer in the upper part of the atmosphere, resulting in an increased UV-radiation level on Earth's surface. This effect is mainly caused by Chlorofluorocarbons (CFCs) and that's why it is measured in $gCFC11 - eq/km$. High values for such impact category are due to vehicle and battery manufacturing phases, for their intense use of materials that are treated with these CFCs, specifically Aluminium and other metals. A minor contribution is also associated to the production of fuels as diesel and petrol. Recycling of vehicle's components and battery cells would allow to reduce the impact, coming from resource and energy savings.

- Human Toxicity Potential (HTP)

This indicator reflects the potential harm of chemical species released into the environment, based on the inherent toxicity of a compound and the potential human exposure. It covers the toxic emissions into atmosphere of Benzene equivalence (carcinogens) and Toluene equivalents (noncarcinogens) being measured in $gDB - eq/km$. According to most of the studies, the largest contribution for this indicator comes from EVs rather than ICEVs (Burchart-Korol et al., 2018; La

Picirelli de Souza et al., 2018; Tagliaferri et al., 2016), both in production and use phases. The reasons behind such higher values are to be attributed to the energy intensive processes that are required for manufacturing EV components such as battery, glider and powertrain. The battery production has the highest contribution in this impact category because of its high presence of toxic substances being released into the atmosphere, connected also to the different chemical treatments that batteries need to undergo. Additionally, during the mining and refining processes of metals, especially for Dysprosium and Neodymium, a large amount of toxic substances are being released into the environment, which represent a serious problem for human health (EEA, 2018a). A practical way in which it could be obtained a reduction of such impact category is with the development of RES for electricity production, contributing in the decarbonization process that will reduce the human toxicity impacts. In this sense, this index plays an important role for the decisions of using clean transportation vehicles.

- Eutrophication Potential (ETP)

Eutrophication is the effect that originates mainly from Nitrogen and Phosphorous in sewage outlets and fertilizers. Besides agricultural activities also wastewater discharges, with high concentration of mineral forms of these 2 substances, have deep impacts on both aquatic and terrestrial ecosystems. The main contributors can be defined as NH_3, HNO_3, NO and NO_2 to air while H_3PO_4, NO and NO_x to water, and this impact category is expressed in $gPO_4^{-3} - eq/km$. For these emissions the phases that provide consistent portions are vehicle's production and battery's production as well.

- Abiotic depletion potential (ADP)

Abiotic depletion refers to the potential negative impact on the diminishing amount of available resources, which aggregates metals and minerals. The measure for this category, taking as reference Antimony (Sb), is expressed in $gSb - eq/km$. The largest impacts for such category are due to vehicle's manufacturing and battery production which are together responsible for the 99% of the total environmental impacts of this category (La Picirelli de Souza et al., 2018). The possibility of recycling materials and components of both, batteries and vehicles, have the benefits to strongly reduce the environmental impacts of such category.

- Fossil fuels abiotic depletion potential (FDP)

The environmental impacts of this category refer to the depletion of non-renewable fuel resources such as coal, petrol and natural gas. The relative measure adopted for the evaluation of this category is expressed in $MJ - eq/km$. Naturally the worst values are associated to ICEVs and HVs which rely on fossil fuels, as energy sources for their operating, but it must be considered that also EVs can have consistent values for such environmental impact if the electricity that they are using for charging their batteries is not coming from RES.

- Global Warming Potential (GWP)

This impact category is the most used when evaluating the environmental impact on climate change and it is expressed in $gCO_2 - eq/km$. This measure helps in characterising the impact of different GHGs based on the extent to which they enhance radiative forcing. In all the studies covered, it has been possible to observe that the highest values for such impact category were always referred to ICEVs because GHG emissions are directly proportional to fossil fuel consumption. Even EVs have significant values for such environmental impact, due to the production and manufacturing of vehicle's components and batteries. A major factor that influences EV's emissions is the electricity mix that if not powered with RES leads EV to have significant values for the GHG emissions during their lifetime (Philippot et al., 2019).

For the different impact categories assessed, as it can be seen in *Fig. 16*, BEVs although being strongly contributing in lowering GHG emissions, resource consumptions and any kind of tailpipe emissions, on the other hand are not able to cope with the ICEV's values for some impact categories, mostly for human toxicity, freshwater ecotoxicity, terrestrial ecotoxicity and freshwater eutrophication (Burchart-Korol et al., 2018; EEA, 2018a). As already explained, such high values for impact categories arise from the manufacturing processes of both vehicle and battery.

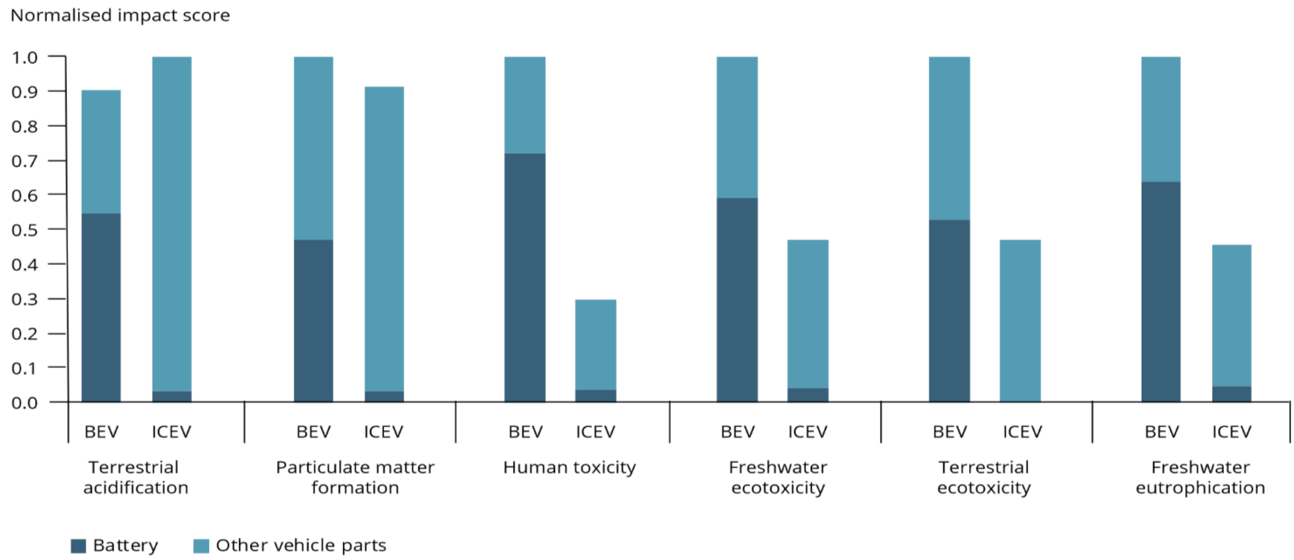


Fig. 16 Comparison of the impacts of production of ICEVs and BEVs across impact categories [Source: Adapted from EEA, 2018]

3.4.6 Improvement Assessment

The last phases covered in all EV-LCA are the sensitivity analyses and the improvement assessment. The sensitivity analyses conducted in the majority of studies, have the aim of making further considerations based on the assumptions of varying some parameters and to evaluate the uncertainties associated with the model by determining how an input parameter variation can be reflected on impact indicators. Generally, those changes can be considered on the life cycle km range and vehicles' lifetime (increasing the years of utilization); and the energy mix production trying to move it toward higher values of RES or as well varying the energy consumption required for the vehicle's use phase.

The areas mostly identified for improvements and for achieving lower environmental impacts are related to:

- evaluation for batteries' future use, once vehicle's lifetime has expired or battery efficiency achieved the 80% efficiency threshold;
- evaluation of alternative materials to be used for substituting REEs during manufacturing phase;
- evaluation of vehicle's production and manufacturing phases to be more relying on RES;
- evaluation of different charging system that would reduce the usage non-renewable resources, such as scheduled charging solution or V2X paradigms.

3.5 Phase I – Production

3.5.1 Battery manufacturing

At the beginning of 2017 the global installed capacity for Li – Ion battery manufacturing was $103.7\ GWh$ and it is estimated that by 2021 will be achieved a total capacity of $273\ GWh$ (Philippot et al., 2019). By the beginning of 2016 the main countries leading for Li – Ion battery manufacturing were Asian countries such as China, Japan, and Korea which hosted 88% of total global Li – Ion cell manufacturing capacity (Chung et al., 2016; Philippot et al., 2019), however there are other countries such as USA, Germany, Sweden, Poland and France which are strongly investing into this area.

Referred to battery manufacturing it is generally possible to distinguish among 3 different areas which contribute overall to such segment: mining and refining of materials, material processing and manufacturing/assembly stage. Usually the first area is sometime omitted in most studies and are just reported final values, although it is possible to observe significant differences among databases. Material extraction accounts for a minority portion on the entire vehicle life cycle GHG emissions but leveraging on secondary metal (rather than primary) it allows consistently to reduce the impact from such stage. Material processing involves a higher impact in terms of energy required for the treatment of materials and especially Aluminium is one of the materials which has high GHG emissions from its primary production, but very low for its second use. The last area usually accounts for more than half of the total GHG impact from all battery's production stages (Romare and Dahllöf, 2017), due to the consistent amount of energy required. Sometime in most studies, the line between the second and third stage is not a clear cut, and this makes it difficult to obtain clear values to be compared among studies.

The battery package is the core of the EV, and it is principally constituted by 4 main units: battery cells, cooling system, packaging and battery management system (BMS). For the evaluation of the environmental impacts of the battery production it has been performed a review of LCA studies on Lithium Ion batteries, that covered a period ranging from 1999 to 2017 and the evaluation of several additional studies which are considering battery manufacturing processes. The sources for inventories have been gathered from other studies that performed analyses on Lithium Ion batteries, previously published results and the battery database Batt-DB regarding the different Lithium Ion chemistries (Notter et al., 2010; Zackrisson et al., 2010). With such variety of Lithium Ion chemistries, it needs to be mentioned that while HEV batteries are mostly used as assistance during accelerations and thus require greater power density in order to shortly provide the energy that is required from the vehicle, BEVs and PHEVs use batteries as their primary energy sources and require, instead, optimal energy densities (Majeau-Bettez et al., 2011). With such clear distinction, it is than straightforward that HEVs rely on $LiFePO_4$ batteries while BEVs and PHEVs mostly on LiNCM batteries (Hawkins et al., 2013).

For the evaluation of their levels of energy consumption and environmental impacts are traditionally taken as functional unit different values among the analysed studies (MJ/km; battery kg; …), and the most adopted is a functional unit of 1 Wh of energy storage capacity produced.

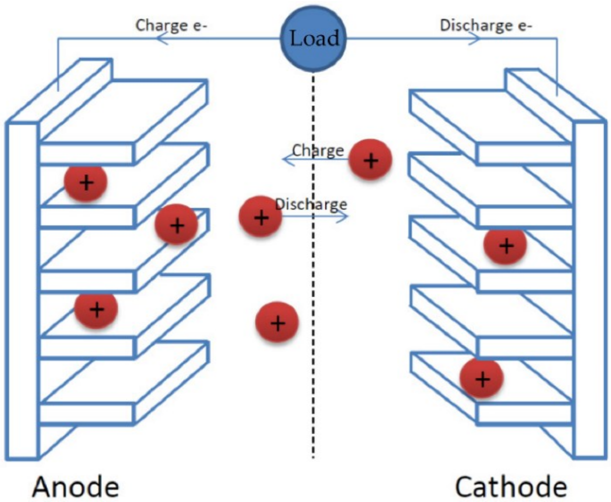


Fig. 17 Schematic illustration of a Lithium Ion cell
[Source: Adapted from Romare et al., 2017]

Fig.17 shows in a schematic illustration the role that the 2 electrodes, Anode and Cathode, have within the cell to "*store*" the Lithium ions depending on the state of charge (charge or discharge). The electrolyte is the substance that allows ions to flow among the 2 electrodes and that at the same time has to separate the 2 parts so that they cannot react with each other (Romare and Dahllöf, 2017). Of course, to ensure enough power and energy to be supplied to the vehicle more cells need to be aggregated into a battery back. For what concerns the weight of the battery, cells contribute to the largest portion to it and roughly 60% of the whole battery weight is due to the battery pack. In *Fig. 18* it is possible to observe the general contribution of each material to the whole amount of the battery weight.

Cell component	Wt% of total battery pack
The active material in the cathode	20%
The active material in the anode	10%
Separator	1-3%
Aluminium substrate (cathode)	2-3%
Copper substrate (anode)	8-13%
Electrolyte	9-12%
Battery management system	3%
Cooling	4%
Packaging	30%

Fig. 18 Components weight
[Source: Adapted from Romare et al. 2017]

Most of the environmental concern in terms of carbon emissions is related to battery production's processes which are strongly correlated to the electricity used in manufacturing (Hall and Lutsey, 2018). It is as well important to stress that raw material extraction and processing phases are providing a higher amount of GHG emission level for battery manufacturing rather than for the ICE equivalent, this is mainly related to the energy requirements in terms of processes to extract, refine and transform the mineral resources used in battery cell manufacturing (EEA, 2018a; Notter et al., 2010). These trends are showed in all the LCA studies analysed. A review found that all stages of battery production account for almost 33% up till 44% of total BEVs production emissions, of this total, cells' manufacturing and battery's assembly account for values that can even reach the 80% of total battery production emissions (Ellingsen and Hung, 2018), which are mainly caused by the production of the anode and cathode, plus required cables or the BMS (Notter et al., 2010).

Naturally, the studies covered are based on different assumptions and different levels of focus. Most of the differences can be related to the energy mix used, geographical plant's location and on 2 different approaches on which the analysis can be performed, top down or bottom up approach. Top down approach uses data from industry for a complete manufacturing plant and then divides the gross energy demand of this plant by the output of the plant, thus it tends to include more auxiliary energy uses and results in an higher values of GHG emissions and cumulative energy demand (Concawe, 2019). Bottom up approach, instead, uses data from industry and extrapolates the whole plant energy consumption on this basis.

A lithium Ion battery can be produced with several different combinations of Lithium based Cathode and Anode materials. The assessed Cathode chemistries in this review included Lithium Iron phosphate (LFP), Lithium Cobalt oxide (LCO), Manganese Spinel oxide (LMO), and composite oxides (LCN, NCM and NCA) (including Nickel (N), Cobalt (C), Aluminium (A) or Manganese (M)) (Peters et al., 2017; Romare and Dahllöf, 2017).

It is possible to summarize the results obtained and highlighting the average values for the cumulative energy demand (CED) and the main impact category, Global Warming Potential (GWP) (Peters et al., 2017) respectively in *Fig. 19* and *Fig.20*.

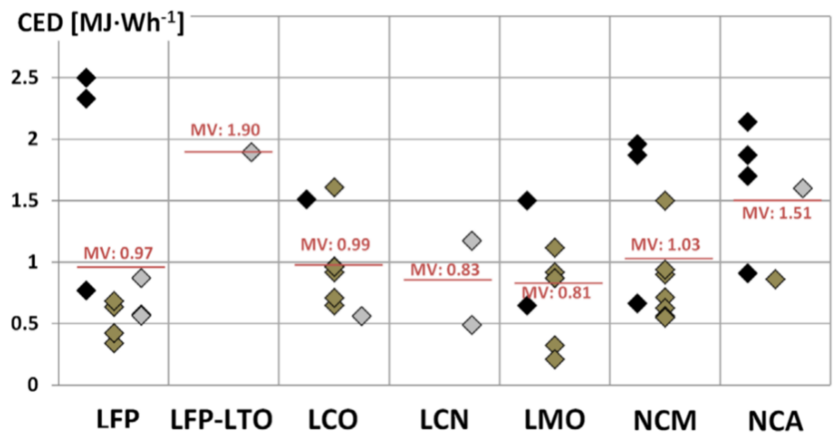


Fig. 19 CED results (battery pack) obtained for different battery chemistries [Source: Adapted from Peters et al., 2017]

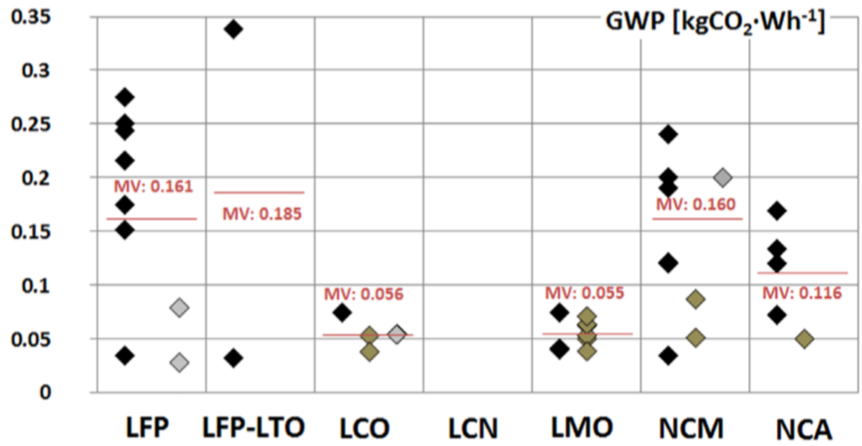


Fig. 20 GWP results (battery pack) obtained for different battery chemistries [Source: Adapted from Peters et al., 2017]

The mean values (MV in *Fig.19* and *Fig.20*) for the cumulative energy demand for the production of $1\ Wh$ of storage capacity is $1.182\ MJ/Wh$, while for the Global Warming Potential the mean value, from all existing studies, for the GHG emissions associated to the production of $1\ Wh$ of storage capacity is $110\ gCO_2 - eq/Wh$ value that is equivalent to $22\ gCO_2 - eq/km$ (Peters et al., 2017). It has been estimated that about half of total GWP values of BEV manufacturing are due to the manufacturing process related to the battery pack (EEA, 2018a).

It also possible to evaluate the broad literature overview conducted by Hall and Lutsey (Hall and Lutsey, 2018), covering more recent studies on battery production emissions and *Fig. 21* illustrates the results adapted from their study.

Authors	Year	Battery production emissions (kg CO_2e/kWh)	Additional notes
Messagie	2017	56	Assumes vehicle with 30 kWh battery constructed in the European Union, finding that BEVs will have lower life-cycle emissions than a comparable diesel vehicle when operated in any country in Europe.
Hao et al.	2017	96-127	Uses China grid for battery manufacturing. Finds substantial differences between battery chemistries. Batteries produced in U.S. create 65% less GHGs.
Romare & Dahllöf	2017	150-200	Reviews literature, concluding manufacturing energy contributes at least 50% of battery life-cycle emissions. Assumes battery manufacturing in Asia.
Wolfram & Wiedmann	2017	106	Models life-cycle emissions of various powertrains in Australia. Manufacturing inventories come primarily from ecoinvent database.
Ambrose & Kendal	2016	194-494	Uses top-down simulation to determine GHG emissions for electric vehicle manufacturing and use. Manufacturing process energy represents 80% of battery emissions. Assumes manufacturing grid representative of East Asia.
Dunn et al.	2016	30-50	Uses bottom-up methodology, with U.S. electricity used for manufacturing.
Ellingsen, Singh, & Strømman	2016	157	BEVs of all sizes are cleaner over a lifetime than conventional vehicles, although it may require up to 70,000 km to make up the manufacturing "debt."
Kim et al.	2016	140	Study based on a Ford Focus BEV using real factory data. Total manufacturing of BEV creates 39% more GHGs than a comparable ICE car.
Peters et al.	2016	110 (average)	Reveals significant variety in carbon intensities reported across literature based on methodology and chemistry.
Nealer, Reichmuth, & Anair	2015	73	Finds that BEVs create 50% less GHGs on a per-mile basis than comparable ICEs, and manufacturing (in U.S.) is 8%-12% of life-cycle emissions.
Majeau-Bettez, Hawkins, & Strömman	2011	200-250	Uses combined bottom-up and top-down approach. Different battery chemistries can have significantly different effects.

Fig. 21 Overview of battery production emissions
[Source: Adapted from Hall et Lutsey]

As it is possible to observe from above the values reported vary in a range between the $100 \div 200$ $kgCO_2 - eq/kWh$. Those variations are mainly due to the different geographical location considered for battery manufacturing and the energy mix used in that some country. In all Asian countries are reported values of emission which are higher while for European countries and the USA those are lower in relation to a lower usage of fossil fuels for the energy mix production. In this broad analysis have been taken into consideration that significant variations are also due to the performance of batteries such as cycle life, internal efficiency and energy density which in most cases are modelled in a very simplified way (Peters et al., 2017). Another possible way in which the same results for cell manufacturing can be obtained is by computing the amount of kWh of electricity required for each kg of battery for its manufacturing. Even on those values it is possible to observe that there is a significant variability among the studies and reports covered in this review with values ranging from less than 10 $kWh/kg\ of\ battery$ (Majeau-Bettez et al., 2011; Notter et al., 2010; Zackrisson et al., 2010), around 18 (Philippot et al., 2019) and 28 (Ellingsen et al., 2014). Considering a broader set of analysis and mostly considering different assumptions on the energy mix required for manufacturing, such values can even increase up till 50 $kWh/kg\ of\ battery$.

Some general considerations can be made relatively to all those studies analysed and mainly 2 aspects can be highlighted. The first one is that there is a near-linear relationship between emissions scale with battery weight and battery kWh capacity (Romare and Dahllöf, 2017), in support to this there are very little data available. The second consideration is about the possible future scenarios in which will be introduced improvements in battery manufacturing and relative lower amount of emissions will be produced.

As future EVs will be equipped with larger battery package this will allow to achieve a 50% increase in terms of battery size that at the same time will further contribute to an increase in the level of GHG emissions that could reach $+18\ gCO_2 - eq/km$ (Hall and Lutsey, 2018), the extra weight, as well, will also lead to higher in-use energy requirements per kilometre (EEA, 2018a). It is also expected that new batteries will be produced with cleaner electricity (higher penetration of RES), battery recycling options will tend to have more consolidated approaches, longer life cycle and as well as higher energy density that could reduce battery manufacturing emissions per kWh by more than a third, which is a value of approximately $47\ gCO_2 - eq/km$ (Hall and Lutsey, 2018), taking as reference the emissions of $130\ gCO_2 - eq/km$ for an BEV.

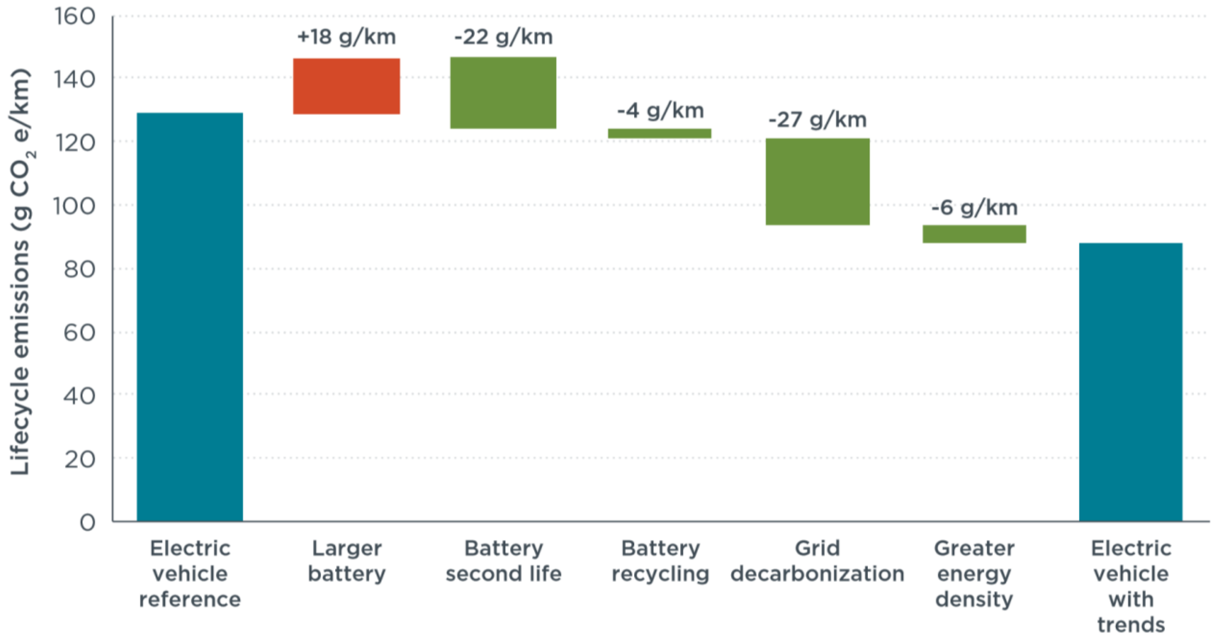


Fig. 22 Potential changes in battery manufacturing GHG emissions.
[Source: Adapted from Hall and Lutsey, 2018]

BEVs manufacturing components occur in different locations; focusing on battery manufacturing which is, as already explained, the most energy intensive process, it is highly concentrated in Asian countries (China, Japan and South Korea) where the energy mix is mainly relaying on non-renewable energy sources and so the carbon intensity for electricity production is higher compared to other countries (EEA, 2018a). One of the studies covered in such review, hypothesised that Lithium Ion battery production emissions could be reduced by almost 95% if the production would be shifted from Asian countries to Iceland that with its geothermal sources makes one of the greenest country for electricity production, obtaining an overall footprint of 18 to 23,5 $gCO_2 - eq/kWh$ which under standard assumptions could be translated into $4\ gCO_2 - eq/kWh$ (Saevarsdottir et al., 2014).

One final aspect that can be addressed in this phase, once battery manufacturing has terminated, is its transportation from the production plant to the point of assembly with the vehicle. This part was mostly excluded from the LCAs evaluated, but the GHG emissions from transportation depend on the carrying mode considered (which can be rail, road and sea transportation) and the distance travelled. Usually emissions values for freight forward transportation modes are expressed in $gCO_2/ton - km$.

3.5.2 Vehicle’s manufacturing

Each vehicle is composed by many units, which can be divided in sub-units up to single components. The main (and macro) units that have been usually considered are powertrain; electric motor and battery system for BEVs while the ICE for fuel-powered vehicles; and the glider. An important consideration is linked to the evaluation of materials, weights and quantities of components which consequently affect the production processes and also the environmental impacts produced (Tagliaferri et al., 2016). In all studies covered, the description of this part was done by taking into consideration specific vehicles for BEV and ICEV typologies, so the values tended to be accurately, and the 2 vehicles needed to belong to the same segment for favouring the comparison of results.

The functional unit is $1\ km$ driven and the average life cycle of both vehicles is expected to be $150.000\ km$, in this way all values of energy consumption and GHG emissions are expressed in MJ/km and $gCO_2 - eq/km$ respectively for ICEV and BEV. For the inventories, several options have been considered, as data coming from car manufacturers which provided info on the different manufacturing process, previous published studies and the Ecoinvent and GREET database.

The extraction of raw materials used for vehicle’s manufacturing has demonstrated to have a higher impact in terms of energy consumed and GHG emissions for BEV, due to the specific requirements for treating materials which are used in electric engines and their refining (Kukreja, 2018). Values for such processes are, as already mentioned, deeply influenced by the energy mix considered of the country in which such processes are occurring and that’s why there are values that present significative variations among the different scenarios analysed.

For the manufacturing phase, values of energy consumption are higher for BEVs compared to traditional ICEVs, as well as higher GWP values and these trends are demonstrated from all studies covered. This phase is the highest contributor for BEVs’ emissions during their lifecycle and it has, in many cases, also values that can be 40 to 70% higher compared to ICEV’s manufacturing (Hall and Lutsey, 2018; Hawkins et al., 2013).

It is possible to identify the average values associated to vehicle’s manufacturing for both BEV and ICEV in EU. The average emissions for the manufacturing phase are $47\ gCO_2 - eq/km$ for ICEVs and $83\ gCO_2 - eq/km$ for BEVs (taking into consideration both battery and vehicle’s manufacturing) (ICCT, 2018). The same analysis has been performed also in China, giving results of $49.5\ gCO_2 - eq/km$ for ICEVs and $75.5\ gCO_2 - eq/km$ for BEVs (taking into consideration both battery and vehicle’s manufacturing) (Peng et al., 2018). For computing the amount of emissions arising from such manufacturing stage is important to evaluate which is the amount of energy required, and by doing this it is possible to observe that most studies usually adopt a measure of $MJ/kg\ of\ vehicle$ and it is possible to observe that also here values are subject to variability among the different studies, but a general value can be set in a range between 25 to $40\ MJ$ of electricity for each kg of vehicle manufactured, with an average value in such literature overview to be set at $30\ MJ/kg\ of\ vehicle$ (Sullivan et al., 2010).

Another aspect that can be addressed in this phase, once vehicle manufacturing has terminated, is the transportation of the vehicle from the production plant to the point of use. This part was mostly excluded from the LCAs evaluated, but the GHG emissions from transportation depend on the carrying mode considered (which can be rail, road and sea transportation) and the distance travelled. Usually values for emissions for freight forward transportation modes are expressed in $gCO_2/ton - km$.

3.5.3 Electricity and fuel production

Electricity and fuel are the 2 power sources used for BEVs and ICEVs. As already illustrated in the above paragraphs, the role of these 2 power sources is fundamental for the analysis in terms of CO_2 emissions and environmental impact with the different impact categories. Moreover, the electricity mix production is not only directly affecting the use phase of BEVs, but it is sustaining the whole manufacturing processes over vehicle's lifetime, as well as for ICEVs.

The electricity mix production varies significantly from one country to another, the more it is relying on non-renewable resources as coal, natural gas, nuclear and oil the more it will be the amount of emissions generated. Countries that can rely on a consistent share of electricity being produced from RES, instead, will tend to have lower emission values and environmental impacts. As example, it has been measured that in countries, like China and the USA, with a high proportion of coal-based electricity generation, WTW NO_X, PM_{10} and SO_2 emissions of BEVs were up to 2, 3 to 4 and 4 times respectively those of ICEVs (Huo et al., 2015).

A relevant consideration must be made with respect to the "*20-20-20*" package; already introduced in *Chapter 1* highlighting here one of its objectives, which imposes for EU countries to reach a minimum of 10% of biofuels for transport energy consumption with respect to petrol and diesel.

All studies analysed in this review are based on some specific assumptions for the electricity production. In *Table 3* and *Table 4* are reported values for the electricity mix and transmission loss (% values); and the life cycle GHG factors for electricity generation ($gCO_2 - eq/MJ$), in the studied regions.

Data source	China	The U.S.	EU	Japan	Canada
Coal	65.21	30.40	21.60	33.52	9.86
Oil	0.07	0.59	1.80	11.19	1.22
Natural gas	3.14	34.16	18.60	40.44	9.35
Hydro	19.71	19.74	10.70	8.35	58.30
Nuclear	3.56	0.90	26.30	0.00	16.41
Solar	1.11	6.52	3.50	2.35	0.27
Wind	4.02	5.55	9.50	0.48	3.43
Biomass	1.08	1.53	5.80	2.78	0.78
Geothermal	0.00	0.43	0.20	0.25	0.00
Other	2.10	0.17	2.00	0.63	0.39
Transmission loss	6.47	6.50	7.00	4.56	10.63

Table 3 The electricity generation mix and transmission loss data

Sources adapted from: China (CEC, 2017), US (EIA, 2017), EU (Agora, 2017), Japan (IEA, 2016) and Canada (IEA, 2016).

Data source	China	The U.S.	EU	Japan	Canada
Coal electricity	274.41	271.90	215.56	270.80	277.20
Oil electricity	254.05	236.90	236.90	206.10	183.60
Natural gas electricity	150.20	128.30	103.60	156.50	131.20
Hydro power	2.81	7.20	3.40	3.10	6.10
Nuclear power	3.31	3.60	3.40	6.50	1.40
Solar electricity	15.69	14.70	14.80	14.70	14.70
Wind electricity	5.00	3.30	2.50	8.10	3.10
Biomass electricity	5.00	12.78	5.00	5.00	4.10
Geothermal electricity	10.00	11.70	7.90	4.20	7.90
Other types	5.00	5.00	5.00	5.00	5.00

Table 4 Life Cycle GHG factors for electricity generation [gCO_2-eq/MJ]

Sources adapted from: China (IEA, 2018b) , US (EIA, 2017) , EU (Buekers et al., 2014), Japan (Peng et al., 2018) and Canada (Mallia and Lewis, 2013).

3.6 Phase II – Use

In the use phase of both vehicles' typologies, this part was conducted leveraging on the same assumptions as already mentioned: average life cycle of $150.000\ km$, vehicle's lifetime of 12 to $14\ years$, fuel and energy consumption to be measured in $l/100\ km$ for ICEVs and $kWh/100\ km$ for BEVs and functional unit $1\ km\ driven.$ In most cases it was adopted the NEDC for vehicle's energy requirements during the use phase.

BEVs

In all the analysis that have been covered in this review, were done some assumptions for the charging efficiency which is some cases was set to be $90\ \div\ 96\%$ (Peng et al., 2018) or 85% with the GREET software. The consumption rate is varying among studies, according to vehicles' analysed and specific country roads and geographical conditions but generally it is possible to set a range between 15 to $25\ kWh$ over $100\ km\ driven$ (Huo et al., 2015) and a powertrain efficiency at 80% (Tagliaferri et al., 2016). The energy consumption is also affected by some specific vehicle's characteristics as size and weight. Heavier and larger EVs require more energy to accelerate and to go uphill, and they have greater rolling and air resistance than smaller and lighter EVs (Egede et al., 2015). Also auxiliaries can have a deep impact on vehicle consumption and they can range up till 50% due to weather conditions together with heating and ventilation systems (Notter et al., 2010). As it is possible to observe from all LCA studies reviewed, BEVs are generally heavier than comparable-sized ICEVs with factors ranging between 15% up till 30%.

It is demonstrated in all LCAs that EVs do not have any direct GHG emissions due to their operating (TTW stage), but the indirect emissions are directly proportional to electricity generation sources (WTW), that's why with a broad analysis on several countries are showed significantly different values for the emissions. Countries like China, Germany, Japan and Poland which have significant % values of energy produced from non-renewable sources, and especially from coal, present higher values for EV emissions during their use phase. Instead countries such as Brazil, Canada, Iceland and Norway which have more than 65% of their electricity mix coming from RES have consistently lower emission values. It is possible to assess that EVs are only as clean as their source of electricity. It is expected for the upcoming years, that as the RES will gain a higher share, the amount of GHG emissions savings of BEVs relative to ICEVs will increase. One of the problems that is present also for the EV configuration is the generation of particulate matter due to tyre wear, brakes and tire-road abrasion, as all motor vehicles do, and a second source of particulate matter is due to the electricity generation which is as well responsible for it. The emissions from brake pad abrasions are at the same time reduced, compared to ICEVs, thanks to the use of regenerative braking system.

ICEVs

Traditional petrol-powered vehicles analysed in this review, showed fuel consumption values that range from 5.5 to $9\ l/100\ km$ (Peng et al., 2018; Wu et al., 2018) for different vehicles and across different countries according to geographical conditions. The level of emissions is dependent on the fuel production and utilization within the combustion engine. Such use phase is the one which provides the highest contribution in terms of emissions from the entire ICEV's life cycle. During this phase it is also present the contribution of maintenance operations, which even if limited gives contribution to the amount of emissions produced in this phase, contrary to what happens for EVs which have to perform only minimal maintenance with battery checks.

Vehicle	China	The U.S.	EU	Japan	Canada
ICEV (L/100 km)	8.5	9.2	7.0	6.6	9.4
BEV (kWh/100 km)	21.5	23.4	17.8	16.8	23.9

Table 5 Vehicle fuel/energy consumption data

Sources adapted from: China (Huo et al., 2015); US (Huo et al., 2015); EU (Tagliaferri et al., 2016); Japan (Peng et al., 2018) and Canada (Requia et al., 2017).

3.7 Phase III – End of Life

The last phase of vehicle's life cycle is reached when the operating limit has been met or when the battery achieves the 80% efficiency threshold. Considered as a single phase, the End-of-Life represents the smallest impact in terms of total life cycle emissions and GHG (Tagliaferri et al., 2016).

Once this phase is entered there are several possibilities which could be undergone for both typologies of vehicles, dismantling and recycling or either disposal and reuse of vehicles' and batteries' components. This phase can lead to a reduction of emissions and providing energy savings, on the entire life cycle stages. As for example, increasing levels of recycling and reuse can reduce the high toxicological impact associated with the intensive use of metals extraction and processing for BEVs (Tagliaferri et al., 2016).

For BEVs, recycling of components is the possibility which gives the highest rate of benefits empowering circular economy's approaches. At European level there are some directives issued by the European Commission for what regards the End-of-Life phase of vehicles. The first one to be introduced was the "*ELV Directive – 2000/53/EC*" that aims, by extending producers responsibility on collecting materials used in their vehicles, to achieve 85% of materials to be recycled and making dismantling and recycling procedures more environmentally friendly (European Union, 2019). A second directive impacting on End-of-Life phase which is dedicated to the batteries and waste hazardous materials is the "*ELV Directive – 2006/66/EC*" that extends batteries producers responsibility, for their collection and recycling (European Union, 2019). The 3 main obligations to be fulfilled are:

1. Collection of 95% of the total number of batteries that have been put on the market.

2. Recycling the 50% of the total weight of the collected batteries.

3. To report to authorities on collected and recycled batteries.

Nowadays Lithium Ion batteries represent a validated solution over the different battery typologies on the market and for them there is a developed recycling industry (varying among countries) and the establishment by many car manufacturers of "closed loop" recycling systems. Recycling covers the possibility of reinjecting already used materials in the value chain, closing the loop and allowing for lower material extraction and energy required for its processing. In many countries there are already values for recycling Lithium Ion battery's components up till 95% such as in the USA and in Europe (Bobba et al., 2019). Components of the electric motor and its magnets are those mostly recycled, for their high presence of REEs, Cobalt, Nickel and Lithium which present the greatest incentive for recycling. One of the factors that must be achieved yet is the economy of scale, because still EVs do not have a long presence on the market and so recycling industries as well as recycling rates are still to be fully exploited, since BEVs have been sold mainly in the past 5 to $10\ years$. For recycling solution of Lithium Ion batteries, in the literature overview, it is possible to distinguish between 2 main techniques: Hydrometallurgic and Pyrometallurgic. The second one is the most diffused solution and widely adopted while the first one is still to be fully developed, but some pilots started to be carried out in European countries. The first one is also the most environmentally friendly solution allowing to considerably reduce the amount of emissions and at the same time reducing the amount of energy required for primary materials (Romare and Dahllöf, 2017). Pyrometallurgic solution instead is an energy intensive process characterised by its use of high temperatures in order to smelt battery's components; the reason way it is mostly adopted is for its ease of implementation.

The second alternative, once the End-of-Life phase is achieved, is the possibility of reusing the battery pack, extending its lifetime for stationary applications. When the battery efficiency achieves the 80% threshold it is no longer feasible for vehicle's use application, but it can be still largely employed in a variety of applications such as energy storage devices. It has been estimated that it is possible to extend battery life cycle (on average) for other $10\ years$ ($+72\%$ of its lifetime), until the battery reaches the 20% efficiency (Hall and Lutsey, 2018). Within this area there are many projects being developed in partnership with energy service companies and car manufacturers. Most of those, are dedicated to energy storage applications and stabilisation of energy fluctuations as production is coming from intermittent power sources (RES).

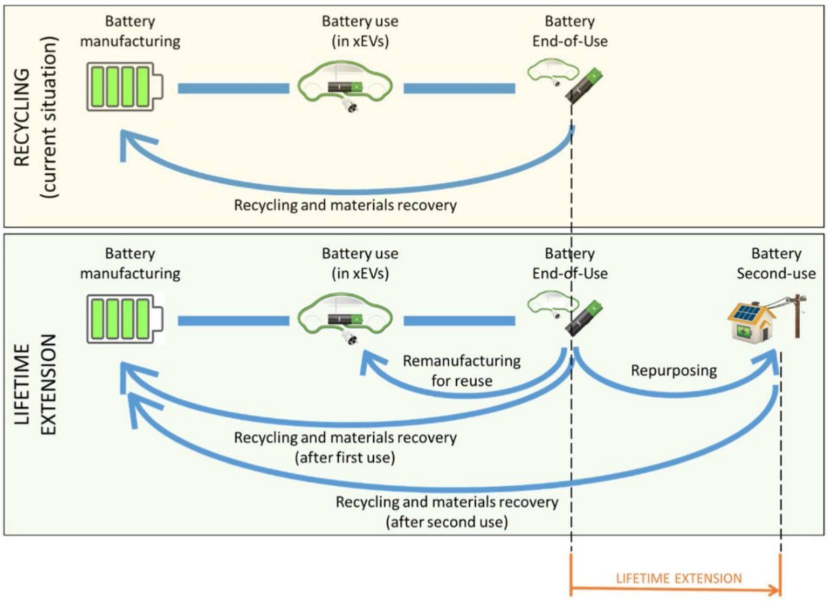


Fig. 23 Schematic End of Life patterns for Lithium Ion batteries
[Source: Adapted from Bobba et al., 2019]

Worldwide are many the players that are getting interested in those possibilities of combing vehicle's batteries and to promote also grid integration of RES. Such applications can provide significant savings in terms of GHG emissions, especially if batteries' reuse allow RES to displace energy from fossil fuels.

The only issue of this End-of-Life phase is that it is not yet a consolidated stage due to the limited number of years since EV have been considerably present on the market and the relatively low presence of established industries for recycling and due to the low volumes yet.

3.8 Literature overview

Here is reported a list of the main studies covered in the literature review, trying to highlight for each study the values that are reported for the electric vehicle life cycle emissions and some additional comments. The full document is attached in the Annexes (*Annex 1*).

Author(s)	Year	Typologies of vehicles	Lifetime km range	Countries	Life-cycle GHG emissions [gCO_2-eq/km]	Additional Notes
Burchart-Korol et al.	2018	BEVs & ICEVs	150.000	Poland	276,53	Cradle-to-grave approach with a particular focus on the electricity production and development of sensitivity analisis with different scenarios (2015 to 2050).
				Czech Republic	214	
Concawe review	2018	BEV (Nissan Leaf)	150.000	EU - average	116,66	Cradle-to-grave anaysis, considering different vehicles segments. Manufacturing of battery emissions are assessed to be equal in all countries of usage and regardless of the size (simplification of 150 kgCO2/kWh), same approach for vehicle manufacturing with 4,5 and 7 tons CO2/vehicle for segment B, C and D.
				Poland	174,66	
				Sweden	69,99	
		BEV (BWM i3)		EU - average	126	
				Poland	197,33	
				Sweden	67,33	
		BEV (Tesla model S)		EU - average	233,93	
				Poland	331,93	
				Sweden	158,6	
Hale et Lutsey	2018	BEV (Nissan Leaf)	150.000	EU - average	130,26	Assuming BEV consumption 20 kWh/100 km in all countries (simplification). Production of batteries is assumed to be in Japan and South Korea. General considerations made for energy savings from recycling, reusing and grid decarbonization.
				France	87,1	
				Germany	189,21	
				Netherlands	154,5	
				Norway	75	
				United Kingdom	128,4	
Kukreja	2018	BEV (Mitsubishi i-MiEV) ICEV (Ford Focus)	150.000	Canada	203	Cradle-to-grave approach and performed a sensitivity analisis on lifetime km range.
La Picirelli de Souza et al.	2018	BEVs, ICEVs & PHEVs (average vehicles)	150.000 150000	Brazil	15,76	Cradle-to-grave approach specific for Brazil.
Peng et al.	2018	BEVs, ICEVs & PHEVs (average vehicles)	-	China	170,15	Assumed real-world driving conditions considering a Well-to-Wheel (WTW) analysis. Did not consider the vehicle cycle and sub-national grid energy mix and the charging efficiency is set equal to 90%. Special focus on China.
				USA	130,88	
				Japan	55,51	
				Canada	125,28	
				EU	49,01	
Wu et al.	2018	BEVs (2010)	150.000	China	280,33	Evaluating 3 different scenarios for 2010, 2014, 2020 taking into consideration average vehicles. Focus more on vehicle cycle and fuel cycle rather than on battery manufacturing.
		BEVs (2014)			209,33	
		BEVs (2020)			177,33	
		ICEVs			-	
Asaithambi et al.	2017	BEVs & ICEVs (average vehicles)	250.000	China	-	Semplicistic analysis, consumption data set equal for all countries.
				USA	-	
				Germany	-	
				Japan	-	
Messagie	2017	BEVs (average vehicles)	150.000	Poland	159	Report to comper the values for EU countries, taking as reference a battery of 30 kWh and assuming 1,5 battery replacement over vehicle lifetime (battery manufactured outside EU).
				Germany	111	
				Netherlands	105	
				Italy	91	
				Spain	87	
				Belgium	69	
				France	37	
				Sweden	33	
				EU-28	89	
Ellingsen et al.	2016	BEVs (mini car)	180.000	EU - average	114,5	Cradle-to-grave analysis to investigate effects due to the increasing battery size and distance travelled.
		BEVs (medium car)			106,1	
		BEVs (large car)			162,8	
		BEVs (luxury car)			190,57	
Tagliaferri et al.	2016	BEV (Nissan Leaf)	150.000	EU - average	123,8	Cradle-to-grave approach; covering manufacturing, use and end-of-life phases. The study is based on values of the European energy mix and it is considering 2 different models of batteries for the BEV and models of HEV, PHEV and ICEV.
		BEV (Nissan Leaf)			118	
		HEV (Toyota Yaris Hybrid)			-	
		PHEV (Toyota Prius Plug-in)			-	
		ICEV (Toyota Yaris)			-	
Egede et al.	2015	BEVs (average vehicles)	150.000	-	-	Study focused on influencing factors and what are their impacts on vehicle operations. Development of 3 scenarios (100.000 km, 150.000 km and 200.000 km)
Ellingsen	2014	BEVs (average vehicles)	150.000	Norway	-	Cradle-to-gate analysis, considering battery production in Asia while assembly in Norway. Performed a sensitivity analisis on electricity mix.
Helmers et Marx	2012	BEV (Smart fortwo) ICEVs & PHEVs	100.000	Germany	140	2 models of BEV considered, a New Smart and a converted one from a petrol-powered configuration.
					108	
Majeau-Bettez et al.	2011	BEVs (only batteries)	-	EU - average	-	LCA on Li-Ion batteries, uses combined top-down and bottom-up approaches. Different battery chemistries have significant variations.
Notter et al.	2011	BEV (Volkswagen Golf) & ICEVs	150.000	EU - average	153,08	Analisis conducted with a bottom-up approach. It is assumed that battery production occurs in China. Conducted a sensitivity analisis on lifetime km range.

Table 6 LCA studies overview
[Source: Own production]

In *Table 6* is shown a brief overview of the literature review of the LCAs studies covered and those with a principal focus on some of the stages in the vehicle life cycle (such as battery manufacturing stage). For the whole literature review for the GHG emissions of BEVs, the analysis has been conducted on an overall 32 documents of which: conference articles, industry reports, scientific papers, university researches and other researches performed by institutions operating on the field of electric vehicles. Each of such documents is in somehow tackling the problem of emissions coming from BEVs and provided some interesting hints in order to deepen more in the analysis conducted. Among all documents, 16 performed a detailed LCA study on BEVs life cycle and among those 11 performed also a similar analysis for ICEVs and provided a general analysis in order to evaluate the differences of the 2 vehicle typologies to compare the obtained results. Only 1 study has provided values for the use phase of BEV in Italy (Messagie, 2017) and finally only 4 studies covered the EoL stage illustrating the possibilities associated to the scenarios of recycling and reusing.

Almost all documents reported in *Table 6* are based on assumptions of km range life cycle about $150.000\ km$ and a vehicle lifetime to be between 12 to 14 $years$.

It has been possible to evaluate that some studies performed the analysis on the same vehicle model e.g. Nissan Leaf which is also presented with different battery size ($24\ kWh$ and $30\ kWh$), or similarly the analysis is done on the same vehicle segment and also in such cases it was possible to compare the results among different studies. Comparing the results of the different studies it is easily possible to highlight the differences that are present considering the same segment or else exactly the same model, as previously mentioned. The reasons behind such differences are to be addressed to the different system boundaries and assumptions posed in order to cover the analysis. It is possible to identify 4 main elements that prove results to be so different from one study to another.

1. Battery and vehicle manufacturing location

The heterogeneity is inherently tight on the initial hypothesis of where the manufacturing as well as where the assembly is performed.

2. Vehicle consumption

Vehicle consumption values are influenced by many different factors such as driving behaviour, outside temperature, land morphology and road conditions. Some studies reported values that are provided by manufacturers while some other are providing their measures based on "*real-world*" driving consumptions. Most of the differences are to be explained also with the different energy mix of each country and that sometime, considering studies of different years but for the same country, can report different values for the energy mix due to improvements.

3. Use emissions

Such aspect is strongly related to the country of use and its energy mix that is used for charging the vehicle. The differences are due to the focus on the country analysed.

4. End-of-Life emissions

The emissions associated to the EoL phase are still subject to a lot of uncertainties mainly for 2 reasons. From one side there is not yet a consolidated recycling industry due to the relative short life of EVs since their introduction on the market; secondly due to the different techniques to be applied for the recycling of materials, which highlight uncertainties for the specific energy requirement.

4. Vehicle life cycle emission-model

4.1 Introduction

Starting from the literature review, which has been covered in the previous chapter, it was possible to gather information in order to develop an emission-model that is able to perform, in an easy way, an analysis on the environmental impact, in terms of CO_2 emissions generated from the whole vehicle life cycle. The present chapter is dedicated to the definition of the models, respectively for BEV and ICEV typologies, and it also provides which are the fundamentals and assumptions leveraged for the development of each model.

The primary objective of the CO_2 emission-model is to provide a simple tool, given some input variables for each specific phase of the vehicle life cycle; to track all the CO_2 emissions; to compare the results between the 2 vehicle typologies; to highlight differences and to easily provide the possibility to make general considerations on the values obtained.

The aim of this chapter is then to provide a description on the models that, grounded on the literature review, have been developed to analyse the life cycle impact in terms of CO_2 emissions arising from the whole vehicle life cycles for BEVs and ICEVs. A second aim is to highlight which are the results that are afterward being measured, covering all the phases of the BEV life cycle, and to compare the values obtained with those of the respective ICEV segment.

The model was developed following a comprehensive cradle-to-grave approach for measuring the carbon dioxide emissions which are expressed as $tonCO_2$ being released into the environment during all the phases, or else exactly provided as gCO_2/km as a function of the total km range covered, and then summoned upon all the phases. For such reason, firstly have been identified the phases that needs to be evaluated in the model, secondly the output parameters to be measured and lastly the input variables that are essential in order to properly structure the models.

The models have been implemented using Microsoft Excel and leveraging on several info gathered from databases, evaluated during the literature review such as the energy mix of different countries; fuels' emissions; emissions associated to different modes of freight forward transportation and values related to the EoL solutions.

The present chapter is structured in order to present at first a brief model overview with respect to both vehicle typologies analysed and evaluating which are the phases covered, the output parameters to be measured and the input variables that are shaping the structure of the model respectively for the 2 typologies. In the second part it is deeply analysed the BEV emission-model in all its phases, trying to map in an easy way the approach that has been followed for its construction. Each single phase is evaluated within the vehicle's life cycle and it is explained how its relative emissions are computed. To conclude this part is then presented a model wrap up section to evaluate the results obtained in their whole. The third part is dedicated (in a shorter way) to the definition and presentation of the ICEV emission-model, that based on some different considerations, is providing the possibility, as well, to measure the CO_2 emissions from the life cycle phases. In the last section of the present chapter are then analysed the computational examples provided for the 2 vehicle typologies and some comments are reported.

From the application of the emission-models it is then possible to make comparisons among the emissions occurring for the 2 vehicle typologies along their life cycles. Such results and comparisons will be further illustrated in *Chapter 5* together with 3 sensitivity analyses performed on different input parameters and showing how such changes are impacting on the overall life cycle's emissions.

4.2 Models overview

The models are based on the idea of performing a cradle-to-grave analysis on the entire vehicle life cycle and for doing this it has been required to evaluate which are the phases that needed to be covered. To evaluate properly which were the phases to be included in such analysis it was decided to follow the same structure of the majority of the LCA studies covered in the literature review with the possibility of integrating some phases that sometimes were not considered in all studies, e.g. transportation of battery and/or vehicle components among countries of production and use.

For each phase and its relative output emission value, it has been estimated a value for the CO_2 emissions which are expressed in terms of $tonCO_2$ as a total, or else exactly as gCO_2/km considering which is the contribution with respect to the total amount of km to be driven in the whole lifetime of the vehicle. Such value has been set equal to 150.000 km, as the most common value found in literature. In the sensitivity section, further analysis will be provided varying such parameter.

To compute the CO_2 emissions of each phase, firstly have been identified the output values that were required to be measured. Then, from the output values have been defined all the input variables that were impacting on them. Each single output value "i" is given as a function of different input variables that are particularly characterised for each phase addressed.

$$V_{Output\ i} = f(V_{input\ 1}, V_{input\ 2}, \dots, V_{input\ n})$$

Once the output values have been calculated for each phase, they have been aggregated for each phase to obtain the relative environmental impact, so then aggregating again the values of all the phases it was obtained the overall CO_2 emissions over the entire vehicle's life cycle.

$$CO_2\ emissions = \sum_i V_{output}$$

The analysis is based on a set of input variables that give the possibility to simulate all scenarios that embrace more than 180 countries for the manufacturing, assembly, use and EoL phases; possibility to choose which vehicle segment to be analysed from mini cars to large cars (making so varying both vehicle's weight as well as battery's weight, capacity and vehicle's consumption) and the possibility to choose also between the most preferred EoL solution to be performed on the vehicle and the battery (disposal, recycling or reusing). There are a lot of other variables which have an impact on the emissions produced and they will be clearly described in the following sections.

The distinction among the BEV emission-model and that of ICEV is due to the differences relative to the propulsion system implemented and so for its manufacturing and for the same reason for its use phase. In the first case a BEV is only relying on the electricity provided by the energy mix of the country of use while in the second case the model is calculating the emissions arising from fuel combustion. Most of the differences are also linked to the different weights among the same segment for BEVs and ICEVs and their effect with respect to other correlated variables such as vehicle's consumption, use of auxiliaries etc.

All the phases, output values and input variables addressed in the model will be further explained in detail in the next sections of this chapter. It will be firstly illustrated in $section$ 4.3 the BEV emission-model and following the ICEV emission-model in $section$ 4.4.

4.2.1 Life cycle phases & output values

The phases evaluated for the cradle-to-grave analysis are the same evaluated for most of the studies covered in the literature review, which reports those of the entire vehicle value chain.

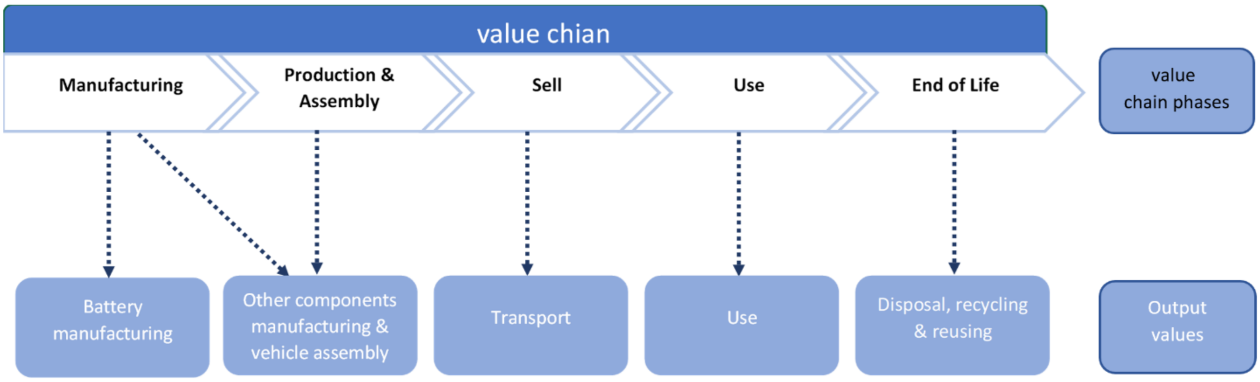


Fig. 24 Vehicle life cycle phases and output values
[Source: Own production]

As it is possible to observe from *Fig. 24,* 5 phases of the vehicle value chain are presented with their relative output values. The phases covered are manufacturing (battery and other components), production and assembly, sell, use and EoL. Each single phase is directly linked to one output value to be measured, only manufacturing phase is affecting 2 output values such as battery and vehicle manufacturing. The output values identified for the models are below illustrated.

- Battery manufacturing

It identifies all the emissions associated to the battery manufacturing process, which is something computed only for BEVs; for the ICEVs analysis this part is of course erased from the computation as they do not have any battery. Only Lithium Ion batteries are considered for the evaluation of the BEV emission-model.

- Other components manufacturing and vehicle assembly

It compromises all the emissions related to the manufacturing of other components, apart from the battery such as glider, powertrain and the vehicle itself and it compromises also the emissions for their final assembly for both BEV and ICEV. For ICEVs, this includes also the internal combustion engine manufacturing and its assembly with the vehicle.

Aggregating the values of these first 2 output values it is possible to estimate the amount of emissions produced from the manufacturing stage within the vehicle value chain.

- Transport

With this output value are reported the emissions associated to the freight forward modalities used to transport the battery and the vehicle from one country to another one. The emissions are calculated following respectively 2 different paths, a first one for the battery and a second one for the vehicle. With respect to the battery, are computed the emissions associated to the transport between the plant (country) of manufacturing to that of assembly and also from the plant (country) of assembly to the country of final use. For the vehicle instead are considered the emissions from the plant (country) of manufacturing and assembly to the country of final use. The analysis is considering 3 different scenarios for the transportation and those are rail, road or sea transport. The overall output CO_2 emission value is obtained as total amount of emissions coming from such 2 distinct paths.

- Use

This output value measures the amount of emissions associated to the use phase of the vehicle considered. For what concerns ICEVs those are related to the type of fuel used for powering the vehicle (diesel, methane or petrol) while for BEVs the emissions associated to the generation of electricity which varies from country to country according to the specific energy mix. All the studies analysed agree defining this phase as the most contributing to the CO_2 emissions from the whole vehicle's life cycle. It is important to highlight that when referring to BEVs use phase emissions need to be considered the WTW emissions produced for the electricity generation, as BEVs do not emit any tailpipe during their use phase (TTW). The same approach must be followed also for the fuels used to power an ICEV and so including also the WTT emissions generated during the exploration, exploitation, transportation, transmission, refining and distribution, so to have clearly defined which are the WTW CO_2 emissions from the usage of any fuel used to power the vehicle.

- Disposal, recycling and reusing

This output value aggregates the emissions relative to the EoL phase. There are several alternatives that can be undergone at this stage. It will be later discussed in the dedicated EoL section, which is the solution that has been implemented in the models. Commonly it is possible to distinguish among disposal of the battery and the vehicle, recycling of the battery and vehicle's components or even the reusing of the battery pack, which is the solution providing the highest material and energy savings due to the reduction of virgin material required for the manufacturing phases.

4.2.2 INPUT PARAMETERS

To each output emission value are associated one or more input variables. It is possible to distinguish the input variables among primary and secondary variables, where the first ones are independent and determined as input for the models while the latter are obtained because of the firsts and can deploy, as well, a relevant impact on the output value of each phase. Here below are briefly illustrated the input variables classified as primary and secondary, associated to each output value.

- Battery manufacturing

Primary: Country of production, vehicle's segment, specific energy required for battery manufacturing.

Secondary: Energy mix from country of production, battery's capacity and weight.

- Other components manufacturing and vehicle assembly

Primary: Country of manufacturing and assembly, vehicle's segment, specific energy required for vehicle manufacturing and assembly.

Secondary: Energy mix from country of manufacturing and assembly, vehicle's weight.

- Transport

Primary: Country of battery production, country of vehicle manufacturing and assembly, country of vehicle use, freight forward transport mode consumption, vehicle's segment.

Secondary: Vehicle's weight, battery "manufacturing to assembly" path, battery "assembly to final use" path, vehicle "assembly to final use" path.

- Use

Primary: Country of use, power source (fuel or electricity), vehicle's segment, vehicle's lifetime.

Secondary: Energy mix from country of use or fuel emission, vehicle's consumption.

- Disposal, recycling and reusing

Primary: EoL solution, vehicle's segment

Secondary: Specific energy required for EoL solution, vehicle's weight.

Adopting this perspective of illustration, it is possible to have the same way of reasoning for both typologies of vehicles analysed. All those primary and secondary variables will be examined in detail in the next sub-paragraphs where each single phase and relative output emission values will be illustrated together with a clarification of how the impact of each input variable is deploying an effect on the output variable.

4.3 BEV emission-model

As already mentioned in the previous section, the purpose of such model is to investigate the environmental impact of BEVs covering their whole life cycle. Such model assumes of analysing vehicles that are equipped with Lithium Ion batteries and that no battery change occurs during vehicle's lifetime. The vehicle km range is set equal to $150.000\ km$ and no particular indication is given for the number of years for the vehicle to operate, because the analysis is conducted on the parameter of the km driven. Usually it is possible to estimate a lifetime range of 10 up to 14 years to cover such distance, but it is not altering the way in which such model works. The number of years indicated as vehicle lifetime agrees with the values found during the literature review.

The model is built to work with general vehicle segment characteristics but changing such parameters in the input panel it is possible to introduce values for specific vehicle models and to perform the same simulation with a more accurate level of detail, which will be better illustrated in *Chapter 5*.

Contrary to the ICEV model, in the BEV model are counted the emissions coming from the battery manufacturing and its recycling. Another main difference is due to the values regarding the vehicle segment with respect to the weight, which in case of BEV are generally heavier compared to the respective ICEV's segment (mostly due to the contribution of the battery pack). One more difference is relative to the vehicle consumption which for BEVs is expressed in terms of $kWh/100\ km$ while for ICEV is computed as $L/100\ km$. For BEVs, vehicle's consumption is a function of the segment and other parameters that influence the driving behaviour. ICEVs consumption is differentiated according to the fuel considered as well as for the different segment evaluated or else exactly the vehicle's model analysed.

In *Table 7* are reported the characteristics for each vehicle segment identified and taken as reference for the BEV emission-model. Characteristic values for the vehicle segments have been set those of the most representative BEVs sold in Italy through 2018 (UNRAE, 2019). Such values have been also compared with average values found during the literature review and specifically from one study of Ellingsen (Ellingsen et al., 2014), demonstrating that values were similar for segments A and B. Moving toward heavier vehicle segments have been noticed differences, between the study of Ellingsen and the most sold vehicles in 2018, in term of battery capacity and this can be justified by the technological improvements that are being introduced for new battery packages, increasing as well capacity and energy density.

Vehicle SEGMENT	Battery capacity	Battery weight	Vehicle weight	Vehicle consumption	Vehicle Typology
-	[kWh]	[kg]	[kg]	[kWh/100km]	-
A	17,6	160	925	12,9	Mini car
B	41	305	1175	16,8	Small car
C	40	303	1277	13,1	Medium car
D	65	480	1367	18,3	Large car

Table 7 BEV segments' characteristics
[Source: Adapted from UNRAE, 2019]

Although more than 95% of Lithium Ion batteries are currently manufactured in Asian countries (Chung et al., 2016; Philippot et al., 2019), the emission-model is giving the possibility to set the country of manufacturing and production among all those provided in the database used for the model, which counts more than 180 countries from all over the world (*Annex 2*). The database used for the models is made of different databases that were gathered and by their combination it was possible to extend the amount of countries to be analysed.

In *Annex 2* is provided the full list of the gCO_2/kWh emission values for the countries' electricity production which will be referred as "*country energy mix*" when evaluating each single output value. Based on such list, as in *Annex 2*, it is possible to decide in which country or countries is going to be evaluated the analysis for the manufacturing, assembly, use and EoL phases of the BEV. In *Table 8* are only reported values of the emissions associated to the electricity production for the European countries.

Country	CO_2 emissions for electricity generation	Reference source	Year
-	[gCO_2/kWh]	-	-
Austria	134	IFI Database	2016
Belgium	143	IFI Database	2016
Croatia	258	IFI Database	2016
Czech Republic	425	IFI Database	2016
Denmark	149	IFI Database	2016
Estonia	685	IFI Database	2016
Europe	310	Enerdata	2017
Finland	180	IFI Database	2016
France	46	IFI Database	2016
Germany	403	IFI Database	2016
Greece	515	IFI Database	2016
Hungary	236	IFI Database	2016
Iceland	0	EnerData	2017
Ireland	389	IFI Database	2016
Italy	313	IFI Database	2016
Latvia	140	IFI Database	2016
Lithuania	230	IFI Database	2016
Luxemburg	284	IFI Database	2016
Malta	582	IFI Database	2016
Netherlands	391	IFI Database	2017
Poland	678	IFI Database	2016
Portugal	281	IFI Database	2016
Slovakia	147	IFI Database	2016
Slovenia	261	IFI Database	2016
Spain	241	IFI Database	2016
Sweden	37	EnerData	2017
Switzerland	37	EnerData	2017
Turkey	367	IFI Database	2016
United Kingdom	385	IFI Database	2016

Table 8 CO_2 emissions for electricity production from European countries

Such values have been gathered from: IEA (IEA, 2018a), IFI dataset of harmonised grid factors, NVE (NVE, 2018) and EnerData (EnerData, 2019).

In the following 5 sub-paragraphs will be provided a detailed overview of how values from each single output variable are computed and their contribution in terms of CO_2 emissions for each BEV value chain phase.

At the end of each sub-paragraph it is also provided a computational example based on a BEV belonging to the C segment, whose battery manufacturing is occurring in China, vehicle manufacturing and assembly are performed in China and use and EoL phases are exploited in Italy. The transportation among China and Italy is supposed to cover a distance of $10.000\ km$ and such is covered 30% by rail, 20% by road and the remaining 50% by sea transportation. The aim of such computations is just to illustrate how the model works on a practical example.

4.3.1 Battery manufacturing

Battery manufacturing CO_2 emissions represent the first output value to be measured. As it is possible to see in *Fig. 25* there are 3 primary variables which are impacting on the emissions generated from such first stage in the EV value chain and those are the country of battery production, the vehicle's segment and the specific energy required for battery manufacturing. The emissions associated to the battery manufacturing process are related to both the energy mix of the country of production and at the same time of the battery type, its capacity and weight, which are associated indirectly to the specific vehicle segment to which the vehicle belongs. For the battery type have been considered only Lithium Ion batteries, evaluating average values for the chemistries reviewed (mainly based on NCM and LFP).

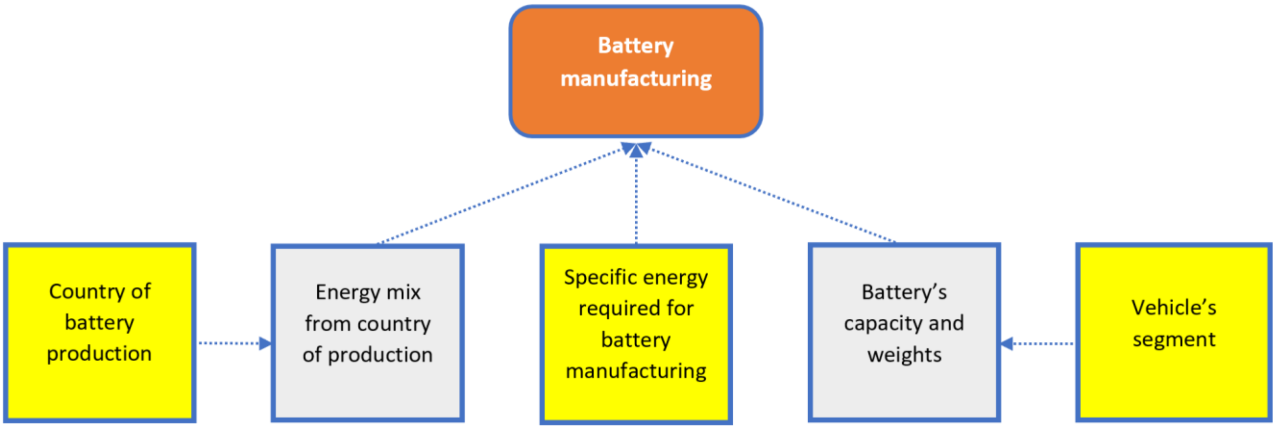


Fig. 25 Battery manufacturing input variables
[Source: Own production]

For the specific CO_2 emission values for the electricity produced in a given country it is possible to have a look at *Annex 2* while vehicle segments' characteristics are reported in *Table 7*.

During the literature review it has been observed that related to battery manufacturing, it is possible to distinguish among 2 main aspects of the battery pack manufacturing emissions. The first one is related to the cell material manufacturing and a second related to the cell manufacturing. Traditionally, are reported values to be equally divided among the two factors but according to the study of Ellingsen "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack" (Ellingsen et al., 2014), it has been decided to follow her suggested approach and adapt values of 38% for cell material manufacturing and 62% for cell manufacturing. Based on the same study it has been possible also to set the energy required for the battery pack manufacturing equal to $28\ kWh/kg\ of\ battery$, although in the literature review it was encountered a variability associated to the different studies (based on different assumption and also the different battery chemistries) this was recognized to be the most suitable value for the study of Lithium – Ion batteries with the studied chemistries.

For the computation of the energy required for the manufacturing process it has been set:

$$Energy\ required\ [kWh] = 28\ \left[\frac{kWh}{kg\ of\ battery}\right] * battery\ weight\ [kg\ of\ battery]$$

For the computation of the amount of CO_2 emissions from battery manufacturing it has been set:

$$Battery\ manufacturing\ \left[\frac{gCO_2}{km}\right] = \frac{\left(Energy\ mix\ \left[\frac{gCO_2}{kWh}\right] * Energy\ required\ [kWh]\right)}{150.000\ km}$$

This formula is expressing the whole energy required for the manufacturing of the battery pack, but it is important to remember that 38% of such overall value is dedicated to cell material manufacturing while the remaining 62% is for the cell manufacturing. This separation allows to introduce also the further variability associated to material manufacturing which can occur in a different country from that of battery manufacturing, which here instead are assumed to occur in the same plant (country).

The output emission value can be also computed as overall emissions coming from battery manufacturing, expressed in term of $tonCO_2$ by simply erasing from the previous formula the component of km range driven and reporting the energy mix in $tonCO_2/\ kWh$ rather than in $gCO_2/\ kWh$.

Computational example:

Battery manufacturing occurring in China for a vehicle of segment C.

$$Energy\ mix\ of\ China = 650\ \frac{gCO_2}{kWh}$$

$$Energy\ required = 28 *\ 303 = 8.484\ kWh$$

$$Battery\ manufacturing = \frac{650 * 8.484}{150.000} =\ 36,76\ \frac{gCO_2}{km}$$

$$Battery\ manufacturing = (650 * 10^{-6}) * 8.484 = 5,51\ tonCO_2$$

4.3.2 Other components manufacturing and vehicle assembly

The second output variable to be measured is relative to the emissions generated by other components manufacturing, such as electric engine, glider, powertrain, vehicle body and the final vehicle assembly process. Have been evaluated 3 primary variables which are the country of components manufacturing and vehicle assembly (assumed to occur in the same country), the vehicle's segment and the specific energy required for vehicle manufacturing and assembly. Secondary input variables are the energy mix of the country selected for the operations and the vehicle's segment, which is affected by the vehicle's weight.

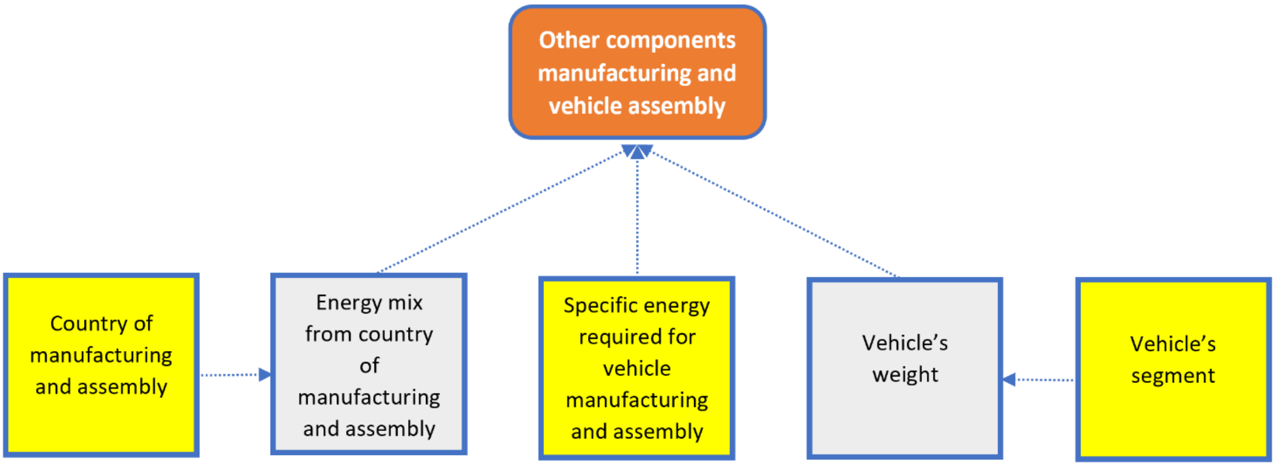


Fig. 26 Other components manufacturing and vehicle assembly input variables [Source: Own production]

In the literature review have been found many studies that reported how vehicle's manufacturing and its assembly (although this last being relatively low energy requiring) had emissions which were proportional to the vehicle's weight, due to a proportionality between the energy required for manufacturing and final assembly with the vehicle's weight. For the decision of the most suitable value it has been decided to select that of $30\ MJ/kg\ of\ vehicle$ (Sullivan et al., 2010). It is important to stress again that when evaluating the overall manufacturing and assembly process, that of higher environmental impact is represented by the manufacturing of the several components and of the vehicle itself while the assembly, being mostly a "manual" activity, requires a lower amount of energy and as a consequence has a lower impact in terms of CO_2 emissions.

The conversion from MJ to kWh is given by the relation:

$$1\ MJ = 0{,}2777\ kWh$$

For the computation of the amount of energy required for the manufacturing and assembly it has been set:

$$Energy\ required\ [MJ] = 30\ \left[\frac{MJ}{kg\ of\ vehicle}\right] * vehicle's\ weight\ [kg]$$

To change such value from MJ to kWh it is necessary to multiply the result by 0,2777.

To calculate the amount of emissions coming from such output variable is possible to set:

$$Vehicle\ manufacturing\ \left[\frac{gCO_2}{km}\right] = \frac{\left(Energy\ mix\ \left[\frac{gCO_2}{kWh}\right] * Energy\ required\ [kWh]\right)}{150.000\ km}$$

Such value can be also computed as overall emissions coming from vehicle manufacturing and assembly expressed in $tonCO_2$ by simply erasing from the previous formula the component of km range driven and expressing the energy mix in $tonCO_2/\ kWh$ rather than in $gCO_2/\ kWh$.

Computational example:

Vehicle manufacturing and assembly occurring in China for a vehicle of segment C.

$$Energy\ mix\ of\ China = 650\ \frac{gCO_2}{kWh}$$

$$Energy\ required = (30 *\ 1.277) * 0{,}2777 = 10.639\ kWh$$

$$Vehicle\ manufacturing\ and\ assembly = \frac{650 * 10.639}{150.000} = \ 46{,}10\ \frac{gCO_2}{km}$$

$$Vehicle\ manufacturing\ and\ assembly = (650 * 10^{-6}) * 10.639 = 6{,}90\ tonCO_2$$

4.3.3 Transport

Transportation emissions are evaluated and measured in the third output variable. Two different paths of analysis have been distinguished; transportation of the battery and that of the vehicle.

The battery is subject to transport from the plant (country) of manufacturing to the plant (country) of assembly with the vehicle and from that as well to the country of final use. Instead for the vehicle is considered that manufacturing and assembly are occurring in the same location and the only transport occurs from the plant (country) of manufacturing and assembly to the country of final use. From this stage, emissions are calculated separately for the battery and the vehicle and are then added to provide a unified emission value for all transportations.

As it is possible to see from *Fig. 27* there are many primary variables which are impacting on such output value. Countries of manufacturing, assembly and use allow to identify which are the steps in the route to be followed for the transportation. The vehicle segment is responsible for the definition of both battery's and vehicle's weight which pose the second big contribution to the computation of the emissions generated. The third main element is represented by the freight forward transportation mode which can be distinguished among rail, road and sea transport.

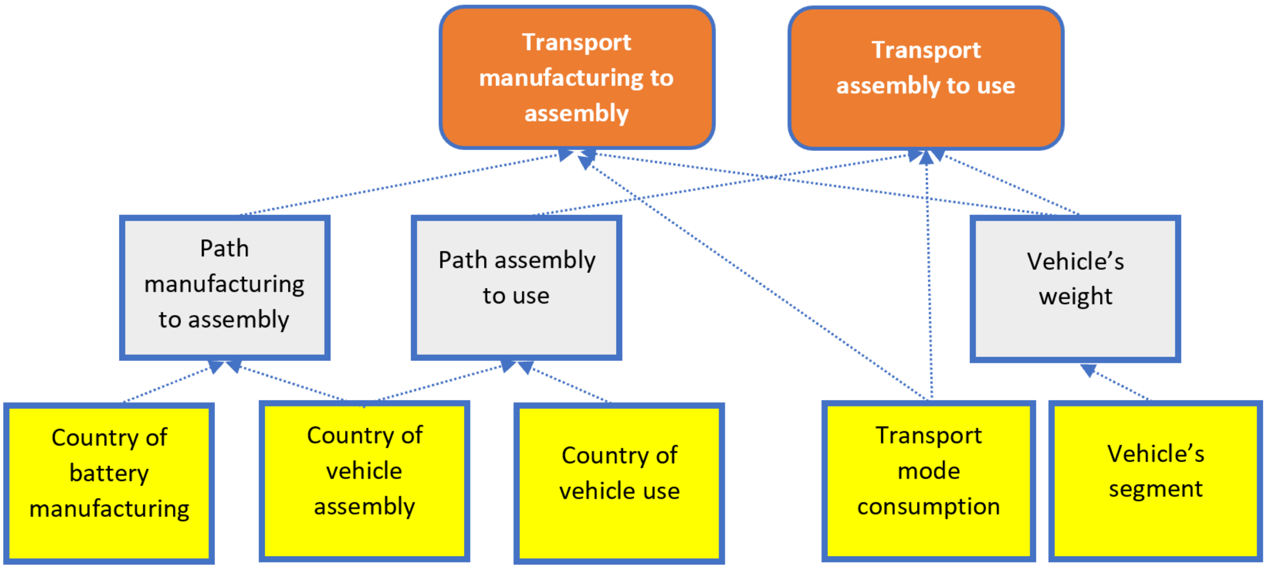


Fig. 27 Transport input variables
[Source: Own production]

The travel distance is computed as average value of the distance separating the countries of analysis and it has to be inserted manually in the model, as it was not possible to implement a clear function given all the different countries present in the database and also due to the variations of transport modes adapted from one configuration to another one. Else exactly the % allocation of how the travel is split among the 3 different freight forward transportation modes is manually inserted, and it is based on average values found in the literature review and industrial reports. Once again it is not possible to provide a function that allows to obtain values for all the different configurations that are provided by the model. A consideration is due to the fact that the distance covered by the battery may be different (and higher) compared to that one covered for the vehicle transportation in the case the battery is manufactured in a different country with respect to that of vehicle's manufacturing and assembly.

In the literature review have been identified 2 main ways of expressing the emissions associated to the transportation.

1. Expressing the amount of energy required for the transport of a ton per km, covered for the different freight forward transport modes, as $MJ/ton - km$.

2. Expressing the amount of emissions associated to the transport of a ton per km, covered for the different freight forward transport modes, as $gCO_2/ton - km$.

For a matter of simplicity and coherence with the parameters included in the analysis it has been decided to adapt the second option, although even the first one was able to provide the same results but with more passages.

Transport Mode	gCO_2/ton-km
Rail	16
Road	139
Sea	135

Table 9 Transport emission values for freight forward transport modes [Source: Adapted from IEA, 2015]

Values reported in *Table 9* have been gathered from the IEA as European values for the year 2015 (IEA, 2015). Although such values inserted in the model are specifically for the European scenario it has been possible to set them as reference due to the low variability encountered with other cases, but for a better level of analysis it is possible to change such values with more appropriate ones for other evaluations.

For the computation of the emissions associated to the battery's transport it has been set:

$$Battery\ transport\ \left[\frac{gCO_2}{km}\right] = \frac{(Distance\ * Battery\ weight) * ((\%rail\ *\ rail\ CO_2) + (\%road\ *\ road\ \ CO_2) + (\%sea * sea\ \ CO_2))}{150.000\ km}$$

Where % rail, % road and % sea refers to the % of distance covered with the specified modality.

For the computation of the emissions associated to the vehicle's transport it has been set:

$$Vehicle\ transport\ \left[\frac{gCO_2}{km}\right] = \frac{(Distance\ * Vehicle\ weight) * ((\%rail\ *\ rail\ CO_2) + (\%road\ *\ road\ \ CO_2) + (\%sea * sea\ \ CO_2))}{150.000\ km}$$

To measure the overall amount of emissions produced for the transportation it is possible to multiply the results of the previous formulas by the amount of km driven, which is equal to $150.000\ km$.

Generally, values obtained from such stage are the lowest among all the EV value chain phases and have a relative low impact on the entire EV life cycle.

Computational example:

Battery manufacturing is occurring in China, vehicle manufacturing and assembly occur in China and the use phase in Italy, for a BEV of segment C. Transportation is assumed to cover a distance of $10.000\ km$ for both battery and vehicle and the modes are divided as 30% by rail, 20% by road and the remaining 50% by sea transportation.

$$Battery\ transport = \frac{(10.000 * (303 * 10^{-3}) * ((30\% * 16) + (20\% * 139) + (50\% * 135)))}{150.000\ km} = 2{,}02\ gCO_2/km$$

$$Vehicle\ transport = \frac{(10.000 * (1.277 * 10^{-3}) * ((30\% * 16) + (20\% * 139) + (50\% * 135)))}{150.000\ km} = 8{,}52\ gCO_2/km$$

$$Total\ transport\ emissions = 2{,}02 + 8{,}52 = 10{,}54\ gCO_2/km$$

$$Total\ transport\ emissions = 10{,}54 * 150.000 = 1{,}58\ tonCO_2$$

4.3.4 Use

Emissions associated to the use phase represent the fourth output value which is also the most subject to variabilities according to the multitude of different possible scenarios. Such output value is also affected by many input variables which are divided among primary and secondary variables and contribute with deep impacts.

The first among the primary variables is the country of use, which is impacting on the energy mix that is required for the vehicle's charging. On top of all the possible scenarios, this input variable is demonstrated to be the one with the highest impact on such phase's emissions. Countries with high carbon emission from the electricity production have a greater environmental impact from the use phase with respect to those with a higher share of electricity being produced from clean energy sources. The impact of the energy mix can be very consistent on the entire vehicle life cycle and that's why usually this variable is the most important when evaluating the country of use of a BEV.

The second primary variable is represented by the vehicle's segment which is characterised by specific values of overall weight, battery capacity and vehicle's consumption. As it is possible to see in *Table 7* each vehicle's segment is characterised by a specific value of energy consumption for covering the distance of $100\ km$ and moving toward heavier vehicles it increases the energy consumption as well. Also, auxiliaries deploy an impact on vehicle's consumption, having the possibility of increasing it by the usage of heating, ventilation and air conditioning which are required according to the specific country of use and its relative temperatures along one year. Other aspects that are impacting on the consumption are given by the driving behaviour, the landscape of a country if it is mostly flat or with presence of hills and mountains, the average cruise speed and the urban or extra urban driving.

Power source is referred to the mean of propulsion which is representative of the different battery chemistry but that is also crucial in distinguishing among BEVs and ICEVs, because the first rely on a battery and an electric engine while the latter on an internal combustion engine.

Vehicle's lifetime is intended as the total km range to be driven. Such value is allowing to express which is the amount of total emissions produced during vehicle's life cycle as gCO_2/km.

For the computation of the emissions from the use phase, are also necessary to be included the values of charging efficiency (*CE*) and energy loss (*EL*). The first one refers to the amount of energy that is lost during the charging process and so between the charger and the battery, the second term instead refers to the amount of energy that is lost due to energy transportation and distribution from the generation plant to the point of distribution which is the charger itself. From the literature review it has been possible to observe that general values for charging efficiency range between 90% to 96%, according to the different vehicle considered, and for energy losses there is a range between 5% to 9%, according to the different country analysed. Have been taken as reference for the model the values of 96% charging efficiency and 7% for energy losses which is also the average value reported for European Union.

It is also important the contribution given by the auxiliaries as they can have a consistent impact on the energy consumption and so increasing vehicle's consumption. From the literature review it has been recognised that their impact is varying according to different parameters and it can reach values up to 10% or even 30% with adverse conditions. As suggested by the study "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles" (Notter et al., 2010) it is plausible to assign a value of 15% to evaluate average conditions for the usage of auxiliaries. In the sensitivity part covered in *Chapter 5* will be provided a dedicated analysis to the impact of auxiliaries on vehicle's consumption. Another important aspect that will be further investigated in the next chapter is the possibility of charging the vehicle using energy coming from RES and which is their impact in lowering the amount of CO_2 emissions produced during the use phase.

In *Fig.28* is presented a schematic view of the input variables affecting the use phase and the relative emissions.

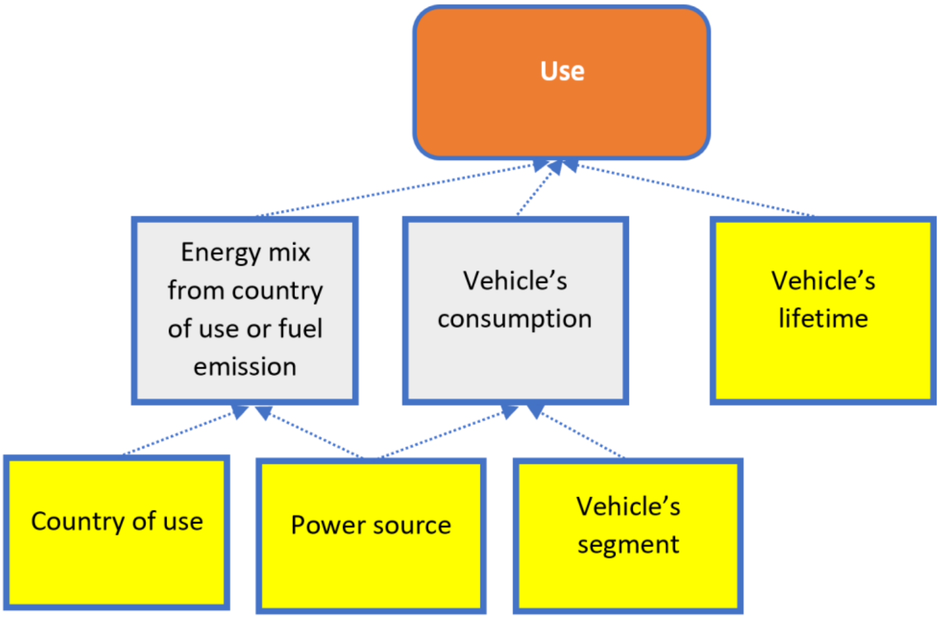


Fig. 28 Use input variables
[Source: Own production]

For the computation of the total vehicle's consumption it has been set:

$$Total\ consumption\ \left[\frac{kWh}{100\ km}\right] = vehicle's\ consumption\ by\ segment\ \left[\frac{kWh}{100\ km}\right] * auxiliaries$$

For the computation of the emissions of the use phase it has been set:

$$Use\left[\frac{gCO_2}{km}\right] = \left(Energy\ mix\left[\frac{gCO_2}{kWh}\right] * Total\ consumption\left[\frac{kWh}{km}\right] * (1 + (1 - CE)) * (1 + EL)\right)$$

Where *CE* stands for charging efficiency and *EL* for energy losses.

To measure the overall amount of emissions produced during the use phase it is possible to multiply the results of the previous formula by the amount of km driven, which has been set equal to $150.000\ km$.

Computational example:

Vehicle of segment C with use phase in Italy, auxiliaries set at 15%, charging efficiency set at 96% and energy losses equal to 7%.

$$Energy\ mix\ of\ Italy = 313\ \frac{gCO_2}{kWh}$$

$$Total\ consumption = 13{,}1 * 15\% = 15{,}06\ \frac{kWh}{100\ km}$$

$$Use = 313 * 15{,}06 * \left(1 + (1 - 96\%)\right) * (1 + 7\%) = 52{,}47\frac{gCO_2}{km}$$

$$Use = 52{,}47 * 150.000\ km = 7{,}87\ tonCO_2$$

4.3.5 Disposal, recycling and reusing

The EoL phase can have either positive or negative values for the contribution to the total amount of the CO_2 emissions generated and this is due to the different techniques to be used or at the same time due to the different choices between disposal, recycling or reusing of battery's and vehicle's components. In the model it has been set that the country where the EoL solution is applied is the same as the country of vehicle's use.

The disposal option is mostly adopted referring to vehicle's body and it consists in its shredding. Typically, this option can be adopted either for BEVs and ICEVs when no other possibilities are evaluated.

Reusing is suited for the battery pack whose lifetime can be extended with purposes of energy storage applications. This choice allows to reduce the amount of emissions that would be required for the production of a battery for other purposes and in this perspective, it contributes in a reduction of the emissions computed on the vehicle life cycle and such value is estimated as the same amount of emissions generated for its primary production.

Recycling is the option that is trying to be implemented and increased as much as possible with new regulations being introduced for automakers across all countries. This possibility allows to recover up till 95% of materials used in the battery pack, reducing the amount of virgin materials and energy required for manufacturing. As already mentioned in *section 3.6,* it is possible to distinguish among 2 different techniques which are the Hydrometallurgic recycling and the Pyrometallurgic ones.

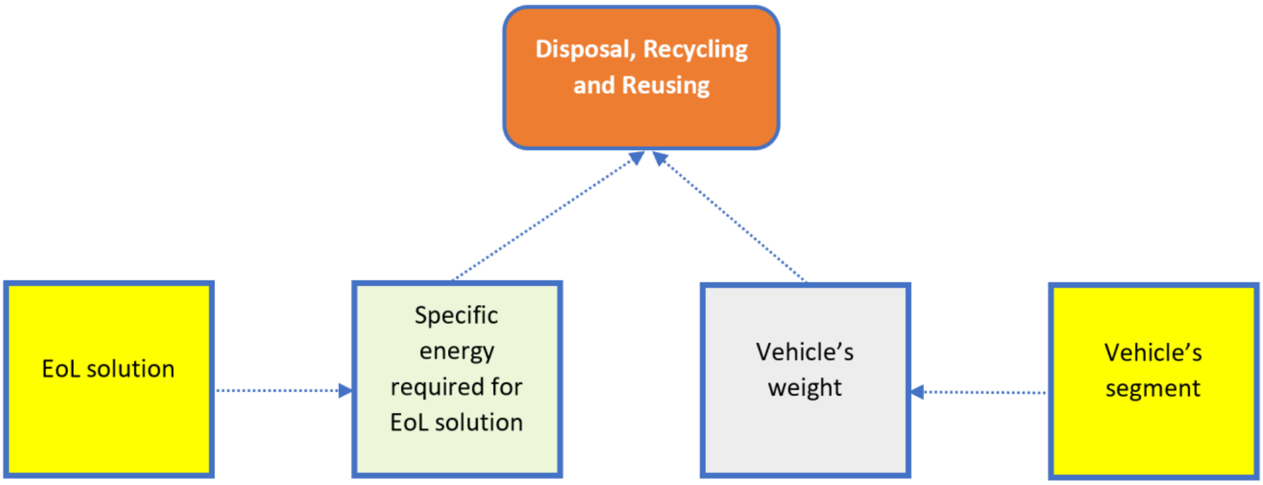


Fig. 29 EoL input variables
[Source: Own production]

As EoL solution it has been decided to set for the disposal of the vehicle's body, once the lifetime has expired, and for the recycling of the battery pack using the Pyrometallurgic technique. The literature review allowed to identify values for the energy required for disposal as $0{,}37 MJ/kg\ of\ vehicle$ (Kukreja, 2018) and for the energy required for the Pyrometallurgic technique as $2{,}88 MJ/kg\ of\ battery$ (Tagliaferri et al., 2016). The computation of the emissions for the 2 different paths is performed separately and then such values are aggregated in order to obtain a single output value from such stage.

The conversion from MJ to kWh is given by the relation:

$$1\ MJ = 0{,}2777\ kWh$$

For the computation of the emissions associated to the disposal of the vehicle it has been set:

$$Disposal \left[\frac{gCO_2}{km}\right] = \frac{\left(0{,}37 \left[\frac{MJ}{kg\ of\ vehicle}\right] * vehicle's\ weight\ [kg] * 0{,}2777\right) * Energy\ mix \left[\frac{gCO_2}{kWh}\right]}{150.000\ km}$$

For the evaluation of the emissions associated to the recycling of the battery with the Pyrometallurgic technique, it has been set:

$$Recycling \left[\frac{gCO_2}{km}\right] = \frac{\left(2{,}88 \left[\frac{MJ}{kg\ of\ vehicle}\right] * battery's\ weight\ [kg] * 0{,}2777\right) * Energy\ mix \left[\frac{gCO_2}{kWh}\right]}{150.000\ km}$$

Such values can be also computed as overall emissions coming from battery recycling and vehicle disposal in term of $tonCO_2$ by simply erasing from the previous formulas the component of km range driven and expressing the energy mix in $tonCO_2/\ kWh$ rather than in $gCO_2/\ kWh$.

Computational example:

Vehicle of segment C with EoL phase occurring in Italy.

$$Energy\ mix\ of\ Italy = 313\ \frac{gCO_2}{kWh}$$

$$Disposal = \frac{(0{,}37 * 1.277 * 0{,}277) * 313}{150.000\ km} = 0{,}27\ \frac{gCO_2}{km}$$

$$Recycling = \frac{(2{,}88 * 303 * 0{,}277) * 313}{150.000\ km} = 0{,}51\ \frac{gCO_2}{km}$$

$$Total\ EoL = 0{,}27 + 0{,}51 = 0{,}78\ \frac{gCO_2}{km}$$

$$Total\ EoL = 0{,}78 * 150.000 = 0{,}12\ tonCO_2$$

4.3.6 BEV model wrap up

The previous sub-paragraphs illustrated how the BEV CO_2 emission-model is built, and which are the input variables required to shape the output values.

It is, once again, important to highlight the flexibility of such model that can be used for working with general vehicles' values taken from each different segment or else exactly it is possible to work with more specific values which are inserted manually every time that required.

INPUT PARAMETERS BEV			
Fixed	km range	150000	km
	Lifetime	12	years
	Annual km range	12500	km/year
BATTERY	Cell material	38%	
	Cell manufacturing	62%	
	Country / Source for material processing	China	
	Energy mix country / source	650	gCO_2/kWh
	Country / Source for manufacturing	China	
	Energy mix country / source	650	gCO_2/kWh
	Energy required for manufacturing	28	kWh/kg battery
	Battery weight	303	kg
	Battery capacity	40	kWh
	Battery density	132,01	Wh/kg
VEHICLE	Country / Source for manufacturing	China	
	Energy mix country / source	650	gCO_2/kWh
	Energy required for manufacturing	30	MJ/kg vehicle
	Vehicle weight (without battery)	1277	kg
	Total vehicle weight	1580	kg
	Vehicle segment	C	Medium car
TRANSPORT	Battery's country of material processing	China	
	Battery's country of manufacture	China	
	Battery's country of use	Italy	
	Vehicle's country of production	China	
	Vehicle's country / source of use	Italy	
	Travelled distance Battery	10000	km
	Travelled distance Vehicle	10000	km
	Rail transport battery	30%	
	Rail transport vehicle	30%	
	Rail transport emissions	16	gCO_2/ton-km
	Road transport battery	20%	
	Road transport vehicle	20%	
	Road transport emissions	139	gCO_2/ton-km
	Sea transport battery	50%	
	Sea transport vehicle	50%	
	Sea transport emissions	135	gCO_2/ton-km
USE	Country of use	Italy	
	Energy mix country / source of use	313	gCO_2/kWh
	Vehicle consumption	13,1	kWh/100km
	Auxiliaries consumption	15%	
	Charging efficiency	96%	
	Energy Losses	7%	
	Total vehicle consumption	15,07	kWh/100km
EoL	Recycling: Pyrometallurgic	2,88	MJ/kg battery
	Country of recycling	Italy	
	Energy mix country	313	gCO_2/kWh
	Battery weight	303	kg
	Energy required for vehicle disposal	0,37	MJ/kg vehicle

Fig. 30 BEV input panel
[Source: BEV emission-model]

In *Fig. 30* it is possible to observe the BEV input panel, from the Microsoft Excel spreadsheet, that is used in order to define values for the input parameters, the values presented in the figure are those used for the computation example. Cells put in light green are those where it is possible to insert the desired values and so to set the input variables for the analysis to be performed. Having illustrated the vehicle's value chain phases and their relative output emissions values, it is now possible to make some general comments on them.

Battery manufacturing, assuming that it occurs in some Asian country as mentioned, is generally responsible for a portion ranging between 20% to 40% of the overall vehicle's life cycle emissions and that is very significant if almost one third of the whole emissions come from this stage, which still represents the main gap compared with the manufacturing of ICEVs.

Vehicle manufacturing and assembly emissions are demonstrated to be proportional with vehicle's weight and contribute for a portion that can, as well, range from the 20% to the 35% of the whole life cycle emissions.

Transportation of the battery and vehicle, although being based on realistic assumptions for the distance to be covered and the split among different freight forward transport modalities, is having a very limited impact in terms of emissions on the vehicle's life cycle, that's why in many studies analysed this has been considered as a negligible contribution.

The use phase is the most crucial, as highlighted by all studies and reports analysed, because it is subject to the highest variability due to the differences in the energy mix of the countries of use. Evaluating countries with high share of electricity production coming from RES there is a consistent reduction of emissions coming from the use phase, which is exactly the opposite for countries relying on fossil fuels for the electricity production. Together with such input variable it is also important to stress the relevance of all other variables and their effect on the overall emissions.

The EoL phase is also subject to variability but due to the different options that can be followed once the vehicle's lifetime has expired. Disposals of the vehicle and of the battery increase the amount of the CO_2 produced, the possibility of reusing the battery pack allows to extend its lifetime and so contributing in a reduction of the CO_2 emissions, that otherwise would be required in order to produce another battery. The possibility given by the recycling of components, as illustrated in *section 3.6,* must be distinguished among the Hydrometallurgic technique and the Pyrometallurgic one, the first is allowing to reduce the emissions associated to the life cycle due to a net savings of virgin material and energy required, while the second alternative requiring an higher energy content for the recycling of components cannot provide a net savings and instead increases the overall emissions for the vehicle's life cycle.

In *Fig.31* and *Fig.32* are reported the emission values respectively expressed in $tonCO_2$ and gCO_2/km, reported from the computational example. Each single output value is presented with its contribution to the total amount of emissions.

The CO_2 emissions distributed over the entire BEV's life cycle are presented in *Fig. 33*. At $0\ km$ are accounted the stages of manufacturing and transport, then until $150.000\ km$ the use phase and after that the contribution of the EoL solution applied.

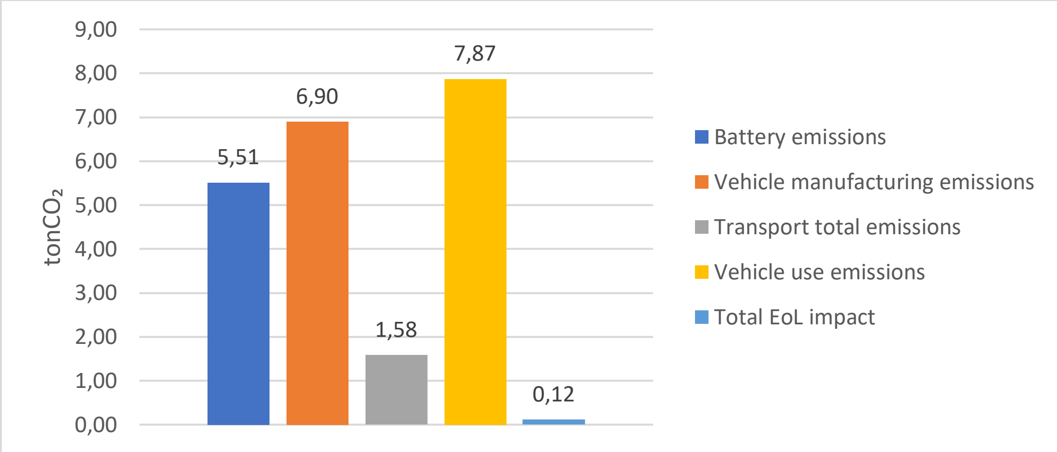


Fig. 31 BEV computational example emission values in tonCO2
[Source: Adapted from BEV emission model]

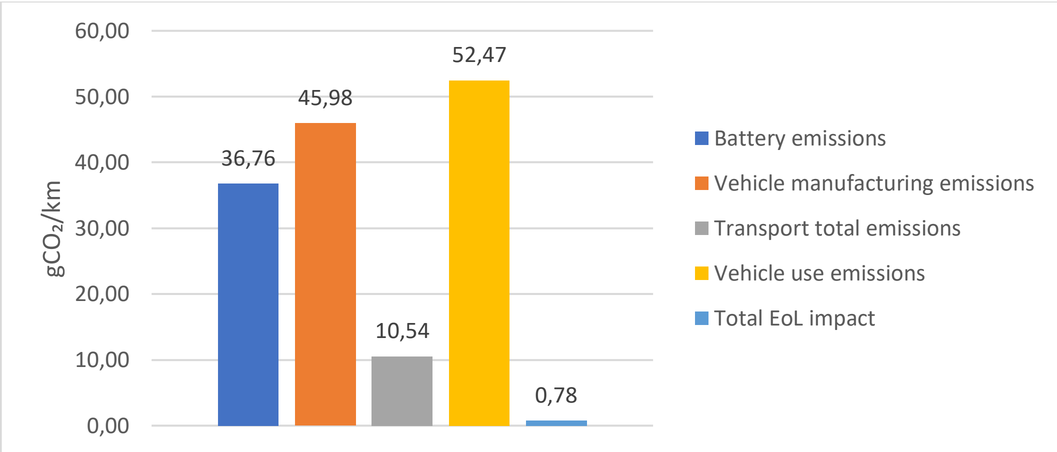


Fig. 32 BEV computational example emission values in gCO2
[Source: Adapted from BEV emission-model]

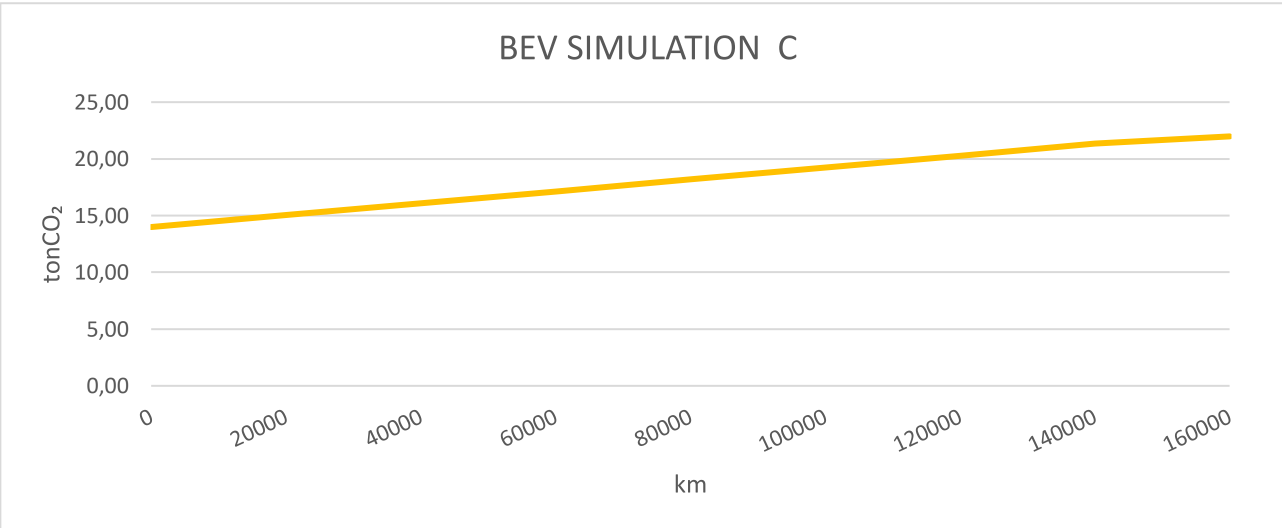


Fig. 33 BEV computational example LC emission values in tonCO2
[Source: adapted from BEV emission-model]

4.4 ICEV emission model

The ICEV CO_2 emission-model was developed to provide the possibility of measuring the environmental impact produced by traditional vehicles and by doing this also having the possibility to compare the results obtained from the BEV emission-model. The model is built with the same structure of the BEV one, making small and coherent adjustments where necessary. Also, in this model the characteristics set for the evaluations refer to general vehicle's segment values, but if a more specific and detailed analysis wants to be performed it is possible to adapt the values with those of a specific ICEV model. A more accurate analysis with specific vehicle's characteristics will be provided in *Chapter 5*.

As for the BEV model, the same value chain phases are considered, the only exception is battery manufacturing which of course is substituted by the presence of the internal combustion engine and so the output variable related to the amount of emissions associated to the battery manufacturing is erased from the computation. The other output values to be measured remain the same as for the BEV emission-model.

The ICEV emission-model is based on some more general assumptions which although being valid and proved to be coherent with real world data, are simplifying the analysis conducted. For such reason are aggregated the phases of manufacturing, production and assembly under a unified stage which provides as output value the overall CO_2 emissions for having a vehicle ready to be used (vehicle already equipped with the engine). Transportation of the vehicle, from the plant (country) of production to the country of use, is evaluated and are reported the relative emissions as output value. Then, the use phase is modelled according to the different fuel used for vehicle's sustaining during its operations and it has been decided to evaluate the scenarios of diesel, methane and petrol. In the last stage, EoL, is analysed the disposal of the vehicle in which are measured the emissions generated from the shredding of the vehicle.

The list of countries for the manufacturing, production and assembly as well as for the use and EoL phases, is the same as the one for the BEV emission-model, illustrated in *Annex 2*.

An important difference from the previous model is represented by the segment's characteristic values. ICEVs are less heavy compared to the corresponding BEV segments. Each single vehicle segment has been also evaluated with respect to the relative vehicle's consumption in the 3 different scenarios of diesel, methane and petrol, considering the average values found in the literature review. For some segments, where it was not possible to obtain directly such values, it has been performed a regression from other segments' values (specifically for segment B and E). All the information for the vehicle segments characteristics used for the model are provided in *Table 10*.

					Consumption [L/100km]	Consumption [L/100km]	Consumption [kg/100km]
ICEVs					Petrol	Diesel	Methane
Segment	A	951	kg	Mini car	4,5	3,1	2,9
Segment	B	1101	kg	Small car	5,1	3,6	3,2
Segment	C	1301	kg	Medium car	5,3	3,7	3,4
Segment	D	1551	kg	Large car	7	4,9	4,4
Segment	E	1701	kg	Executive car	7,4	5,2	4,7
Segment	F	1901	kg	Luxury car	9,1	6,3	5,8

Table 10 ICEVs segments' characteristics
[Source: Adapted from literature review]

Values from vehicle's weight and consumption have been gathered from studies and reports analysed in the literature review (Ellingsen et al., 2014; La Picirelli de Souza et al., 2018; Quattroruote, 2017). When performing an evaluation on a specific vehicle's model it is then possible to change such values and insert manually those for a more accurate analysis.

In the next sub-paragraphs will be illustrated the ICEVs life cycle phases, the relative output emission values to be measured and how they are obtained starting from the input variables.

At the end of each sub-paragraph it is also provided a computational example based on an ICEV petrol fuelled, belonging to the C segment, whose manufacturing, production and assembly are occurring in China while the use and EoL phases are exploited in Italy. The transportation among China and Italy is supposed to cover a distance of $10.000\ km$ and such is covered 30% by rail, 20% by road and the remaining 50% by sea transportation (same scenario evaluated as for the BEV computational example).

INPUT PARAMETERS ICEV			
Fixed	km range	150000	km
	Lifetime	12	years
	Annual km range	12500	km/year
	Conversion factors	1	MJ
		0,277	kWh
	Coefficient	100	
	Coefficient	1000	
VEHICLE	Country for manufacturing	China	
	Energy mix country	650,0	gCO_2/kWh
	Energy required for manufacturing	30	MJ/kg vehicle
	Vehicle weight	1301	kg
	Vehicle segment	C	Medium car
TRANSPORT	Vehicle's country of use	Italy	
	Travelled distance Vehicle	10000	km
	Rail transport vehicle	30%	
	Rail transport emissions	16	gCO_2/ton-km
	Road transport vehicle	20%	
	Road transport emissions	139	gCO_2/ton-km
	Sea transport vehicle	50%	
	Sea transport emissions	135	gCO_2/ton-km
USE	Country of use	Italy	
	Fuel used	Petrol	
	Fuel emissions	2380,0	L/100km
	Vehicle consumption	5,3	L/100km
EOL	Vehicle disposal	0,37	MJ/kg vehicle
	Country of disposal	Italy	
	Vehicle disposal	313	gCO_2/kWh

Fig. 34 ICEV input panel
[Source: Own production]

In *Fig. 34* it is possible to observe the input panel, from the Microsoft Excel spreadsheet, that is used in order to define values for the input parameters; the values present in the figure are those used for the computational example. Cells put in light red are those where it is possible to insert the desired values and so to set the input variables for the analysis to be performed.

4.4.1 Manufacturing, production and assembly

The first (aggregated) phase for the evaluation of the ICEV CO_2 emissions is represented by the manufacturing, production and assembly of the vehicle and its components such as glider, internal combustion engine, powertrain and vehicle's body. It is intended that as the output from such phase is possible to have a vehicle completely manufactured and ready to be used.

As for the BEV model, the input primary variables are the country for the operations to be performed and the vehicle's segment to be evaluated. The first variable is responsible for the energy mix of the country under analysis, while the second variable is affecting the vehicle's weight and so the amount of specific energy required for manufacturing.

As already illustrated in BEV emission-model, in the literature review many studies have been found that reported how vehicle's manufacturing and assembly had emissions which were proportional to the vehicle's weight. It is also here used the same coefficient for the energy required for vehicle manufacturing and assembly of 30 $MJ/kg\ of\ vehicle$ (Sullivan et al., 2010).

To calculate the amount of energy required for the manufacturing and assembly it is used the same formula identified in BEV model:

$$Energy\ required\ [MJ] = 30\ \left[\frac{MJ}{kg\ of\ vehicle}\right] * vehicle's\ weight\ [kg]$$

To change such value in kWh it is necessary to multiply the result for 0,2777.

To calculate the amount emissions coming from such output variable is possible to use the same formula identified in BEV model:

$$Vehicle\ manufacturing\ \left[\frac{gCO_2}{km}\right] = \frac{\left(Energy\ mix\ \left[\frac{gCO_2}{kWh}\right] * Energy\ required\ [kWh]\right)}{150.000\ km}$$

Such value can be also computed as overall emissions coming from vehicle manufacturing and assembly in $tonCO_2$ by simply erasing from the previous formula the component of km range driven and expressing the energy mix in $tonCO_2/\ kWh$ rather than in $gCO_2/\ kWh$.

Computational example:

Vehicle manufacturing and assembly occurring in China for a vehicle of segment C:

$$Energy\ mix\ of\ China = 650\ \frac{gCO_2}{kWh}$$

$$Energy\ required = (30 *\ 1.301) * 0{,}2777 = 10.811\ kWh$$

$$Vehicle\ manufacturing\ and\ assembly = \frac{650 * 10.811}{150.000} = \ 46{,}85\ \frac{gCO_2}{km}$$

$$Vehicle\ manufacturing\ and\ assembly = (650 * 10^{-6}) * 10.811 = 7{,}03\ tonCO_2$$

4.4.2 Transport

The emissions associated to the transport of the ICEV are computed exactly in the same way as it was done in the BEV emission-model, remaining valid all the assumptions previously introduced, and the description of the input variables required for the computation of the output values. The only thing that changes is vehicle's weight for a given segment and for the overall computation there is only the term associated to the vehicle's transport (being not applicable the battery transport).

For the computation of the emissions associated to the vehicle's transport it is used the same formula identified in BEV model:

$$Vehicle\ transport\ \left[\frac{gCO_2}{km}\right] = \frac{(Distance\ * Vehicle\ weight) * ((\%rail\ * \ rail\ CO_2) + (\%road\ * \ road\ \ CO_2) + (\%sea * sea\ \ CO_2))}{150.000\ km}$$

To measure the overall amount of emissions produced for the transportation it is possible to multiply the results of the previous formulas by the amount of km driven, which is equal to $150.000\ km$.

Computational example:

Vehicle manufacturing and assembly occur in China and the use phase in Italy, for a vehicle of segment C. Transportation is assumed to cover a distance of 10.000 km and the modes are divided as 30% by rail, 20% by road and the remaining 50% by sea transportation.

$$Vehicle\ transport = \frac{(10.000 * (1.301 * 10^{-3}) * (30\% * 16) + (20\% * 139) + (50\% * 135))}{150.000\ km} = 8{,}68\ gCO_2/km$$

$$Total\ transport\ emissions = 8{,}68 * 150.000 = \ 1{,}3\ tonCO_2$$

4.4.3 Use

The emissions associated to the use phase for ICEVs are the ones which account for the highest portion of the CO_2 produced along the entire ICEV's lifetime. As for the BEV, there are several input variables that are contributing in shaping the environmental impact produced. The 2 main input variables are given by the vehicle's segment and the fuel used for powering the engine. Choosing a vehicle's segment is directly determining vehicle's weight and its relative fuel consumption, as it is possible to observe from *Table 10*. Vehicle's consumption is also determined by the different fuel used and it is possible to distinguish among 3 fuels: diesel, methane and petrol. In *Table 11* are reported the values associated to the CO_2 produced during the use phase, from the combustion of 1 $liter$ of diesel or petrol or 1 kg of methane (Quattroruote, 2017).

Diesel	Methane	Petrol
gCO_2/L	gCO_2/kg	gCO_2/L
2650	2750	2380

Table 11 CO_2 emissions for different fuels
[Source: Adapted from Quattroruote, 2017]

The emission values presented in *Table 11* are only referring to the combustion of the given quantity of the respective fuel, which means that they only refer to the TTW stage. In order to obtain a complete WTW perspective it must be included also the portion of emissions coming from the WTT stage that compromises all the preliminary activities performed on the fuel. The chain of significant processes included in such stage encompasses exploration, exploitation, transportation, transmission, refining and distribution. In the literature review it was difficult to gather uniform data due to the high variability associated to: the type of fuel considered, the country of exploitation, the position of the well and the different processes that the fuel needed to undergo before reaching the country of use, the distance to be covered for its transport, the different values reported among studies across different years.

In order to gather information on such WTT stage have been analysed industrial reports and LCA studies on diesel and petrol, the main findings are reported in *Table 12* (Eriksson and Ahlgren, 2013; EU, 2015).

Reference	Fuel	Region	WTT [gCO2eq/MJ fuel]	TTW [gCO2eq/MJ fuel]	WTW [gCO2eq/MJ fuel]	% WTT/WTW
Gode et al. 2011	Petrol	Sweden	6,7	78,3	85	8%
Perimenis et al. 2010	Petrol EN 228	Europe	12,5	73	85,5	15%
Edwards et al. 2011	Petrol	Europe	14,2	73,3	87,5	16%
Keesom et al. 2012	Petrol	Europe	10 ÷ 27	75	85 ÷ 102	12% ÷ 27 %
Wang et al. 2004	Petrol	International	18,5			
JEC 2013	Petrol	Europe	13,8	73	86,8	16%
European Commission 2015	Petrol	Europe	18,97			
Gode et al. 2011	Diesel	Sweden	6,7	75,5	82,3	8%
Lopez et al. 2009	Diesel	Spain	12,4	73,4	85,8	14%
Keesom et al. 2012	Diesel	Europe	9 ÷ 24	75	84 ÷ 99	10% ÷ 24%
Perimenis et al. 2010	Diesel EN 590	Europe	14,2	74,8	89	16%
Edwards et al. 2011	Diesel	Europe	15,9	73,2	89,1	18%
Wang et al. 2004	Diesel	International	14 ÷ 17			
JEC 2013	Diesel	Europe	15,4	73	88,4	17%
European Commission 2015	Diesel	Europe	18,17			

Table 12 WTT emission values
[Sources: Adapted from EU, 2015 and Eriksson and Ahlgren, 2013]

As it is possible to observe from *Table 12* there is a consistent variability associated to the same fuel according to the different studies (for the reasons explained before). For such reason it has been decided to adapt a WTT % respectively for diesel and petrol equal to 15% and 14%, as WTT % computed across the whole WTW. So, considering those percentages it is possible to compute the CO_2 emission values associated to the WTT, taking as reference the TTW values from *Table 13* and obtaining the overall WTW CO_2 emission values.

	Diesel gCO_2/L	Petrol gCO_2/L
WTT	468	387
TTW	2650	2380
WTW	3118	2767

Table 13 WTT, TTW & WTW emission values
[Source: Values adapted from Table 11 and Table 12]

Once defined the fuel to be considered it is possible to evaluate which is the average consumption for covering a distance of $100\ km$ and estimate the overall CO_2 produced from the use phase.

For the computation of the emissions associated to the use phase it has been set:

$$Use \left[\frac{gCO_2}{km}\right] = Fuel\ emissions \left[\frac{gCO_2}{l}\right] * vehicle's\ consumption \left[\frac{l}{km}\right]$$

Such formula can be adapted for the computation associated to the use of diesel and petrol, while for methane it is required to change the formula as:

$$Use \left[\frac{gCO_2}{km}\right] = Fuel\ emissions \left[\frac{gCO_2}{kg}\right] * vehicle's\ consumption \left[\frac{kg}{km}\right]$$

For the total value of emissions generated during the use phase it is just required to multiply the value from the previous formula for the amount of km driven, which is equal to $150.000\ km$.

Computational example:

Vehicle of segment C using petrol to power the engine.

$$Use = 2.767 * (5{,}3 * 10^{-2}) = 146{,}65\ \frac{gCO_2}{km}$$

$$Total\ use\ emissions = 146{,}65 * 150.000 = 21{,}99\ tonCO_2$$

4.4.4 Disposal

The last phase to be addressed during the ICEV life cycle is represented by the EoL and in this case it has been set, according to the literature review, only the possibility of vehicle's disposal. The computation for the emissions associated to such output value is the same as reported for the BEV emission-model, evaluating only the shredding of the vehicle.

For the evaluation of the emissions associated to the disposal of the vehicle it is used the same formula identified in BEV emission-model:

$$Disposal\left[\frac{gCO_2}{km}\right] = \frac{\left(0{,}37\left[\frac{MJ}{kg\ of\ vehicle}\right] * vehicle's\ weight\ [kg] * 0{,}2777\right) * Energy\ mix\ \left[\frac{gCO_2}{kWh}\right]}{150.000\ km}$$

For the total value of emissions generated during the disposal phase it is just required to multiply the value from the previous formula for the amount of km driven, which is equal to $150.000\ km$.

Computational example:

Vehicle of segment C with disposal occurring in Italy.

$$Energy\ mix\ of\ Italy = 313\ \frac{gCO_2}{kWh}$$

$$Disposal = \frac{(0{,}37 * 1.301 * 0{,}277) * 313}{150.000\ km} = 0{,}28\ \frac{gCO_2}{km}$$

$$Total\ disposal\ emissions = 0{,}28\ * 150.000 = 0{,}042\ tonCO_2$$

4.4.5 ICEV model wrap up

The previous paragraphs illustrates how the ICEV emission-model is made and which are the input variables required to shape the output emission values. It is, once again, important to highlight the flexibility of such model that can be used working with general vehicle values taken from each different segment or else exactly it is possible to work with more specific values which are inserted manually every time that required.

In *Fig. 35* are provided the computational example emission values. It is important to highlight how the main contributions are given by the vehicle manufacturing which in this case evaluated (segment C) is responsible for the 25% of the CO_2 emissions and the use phase which is by far the most polluting phase, accounting roughly for the $70\ \%$ of the emissions produced along the vehicle life cycle. The contribution of the transport phase is not completely negligible but still it has a low impact, if considering a lower distance to be covered such value would be even more decreased. The disposal of the vehicle instead is possible to be considered as negligible due to the very limited amount of emissions provided.

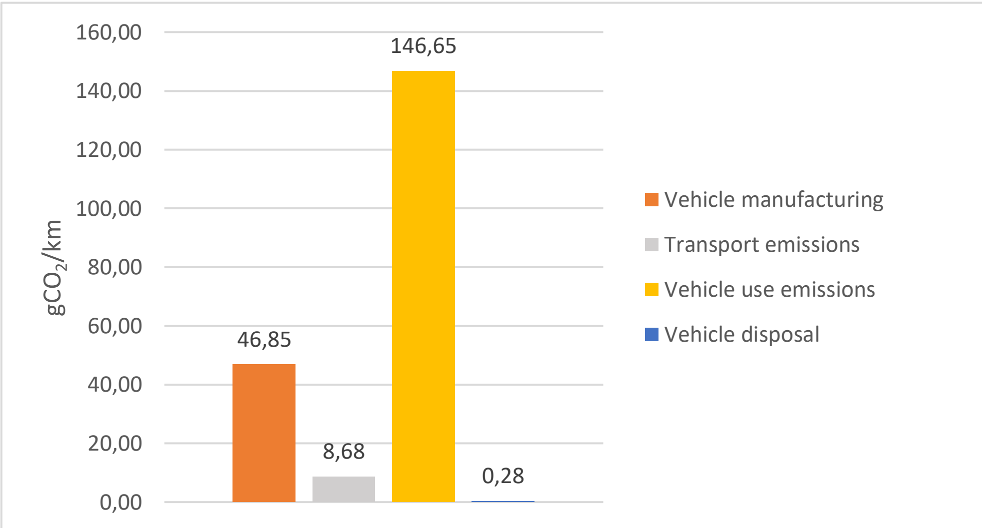


Fig. 35 ICEV computational example emission values in gCO_2
[Source: Adapted from ICEV emission-model]

In *Fig. 36* are presented the CO_2 emissions distributed over the entire ICEV life cycle. At $0\ km$ are accounted the stages of manufacturing and transport, then until $150.000\ km$ the use phase and after that the contribution of the EoL solution applied.

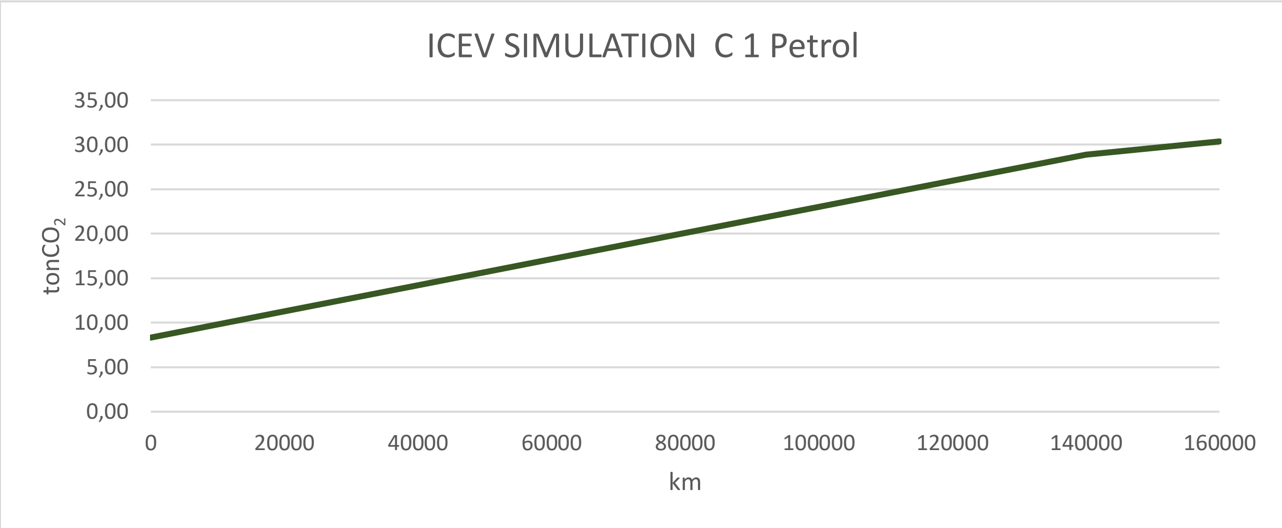


Fig. 36 ICEV computational example LC emission values in tonCO₂
[Source: adapted from ICEV emission-model]

4.5 Computational example BEV and ICEV comparison

Here are reported the emission values of the computational example for both BEV and ICEV, respectively in *Fig.37* and *Fig.38*. It is possible to highlight which is the weight that each single phase has over the entire vehicle life cycle emissions and how those change from one configuration to another. The emissions from the manufacturing stages for BEV (battery + vehicle) are almost double compared to the manufacturing stage for the ICEV (only vehicle). The transport is in both cases represented by very limited values and being the weights of the vehicles slightly different so are also the emission values associated to such stage, but still both values remain limited compared to other stages' values. What is important to notice is the difference in the use phase. The BEV configuration has a value of $52{,}47\ gCO2/km$ which accounts for the 36% of the entire BEV life cycle emissions while the ICEV configuration produces $146{,}65\ gCO2/km$ which is responsible for the 72% of ICEV life cycle emissions. The ICEV value is almost 3 times higher the BEV value and this is representative of which can be the impact of using a BEV instead of an ICEV.

Battery manufacturing	Vehicle manufacturing	Transport emissions	Vehicle use emissions	Battery recycling	Vehicle disposal	LC emissions
[gCO_2/km]	[gCO_2/km]	[gCO_2/km]	[gCO_2/km]	[gCO_2/km]	[gCO_2/km]	[gCO_2/km]
36,76	45,98	10,54	52,47	0,51	0,27	146,55
Battery manufacturing	Vehicle manufacturing	Transport emissions	Vehicle use emissions	Battery recycling	Vehicle disposal	LC emissions
[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]
5,51	6,90	1,58	7,87	0,08	0,04	21,98

% on LC CO_2 emissions					
25%	31%	7%	36%	0%	0%

Fig. 37 BEV computation example summary
[Source: Adapted from BEV emission-model]

Vehicle manufacturing	Transport emissions	Vehicle use emissions	Vehicle disposal	LC emissions
[gCO_2/km]	[gCO_2/km]	[gCO_2/km]	[gCO_2/km]	[gCO_2/km]
46,85	8,68	146,65	0,28	202,46
Vehicle manufacturing	Transport emissions	Vehicle use emissions	Vehicle disposal	LC emissions
[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]	[$tonCO_2$]
7,03	1,30	22,00	0,04	30,37

% LG CO_2 emissions			
23,1%	4,3%	72,4%	0,1%

Fig. 38 ICEV computation example summary
[Source: Adapted from ICEV emission-model]

In *Fig. 39* are represented the 2 curves of the emission values over the entire vehicles life cycles and their overlap gives the information of when the break-even point is achieved.

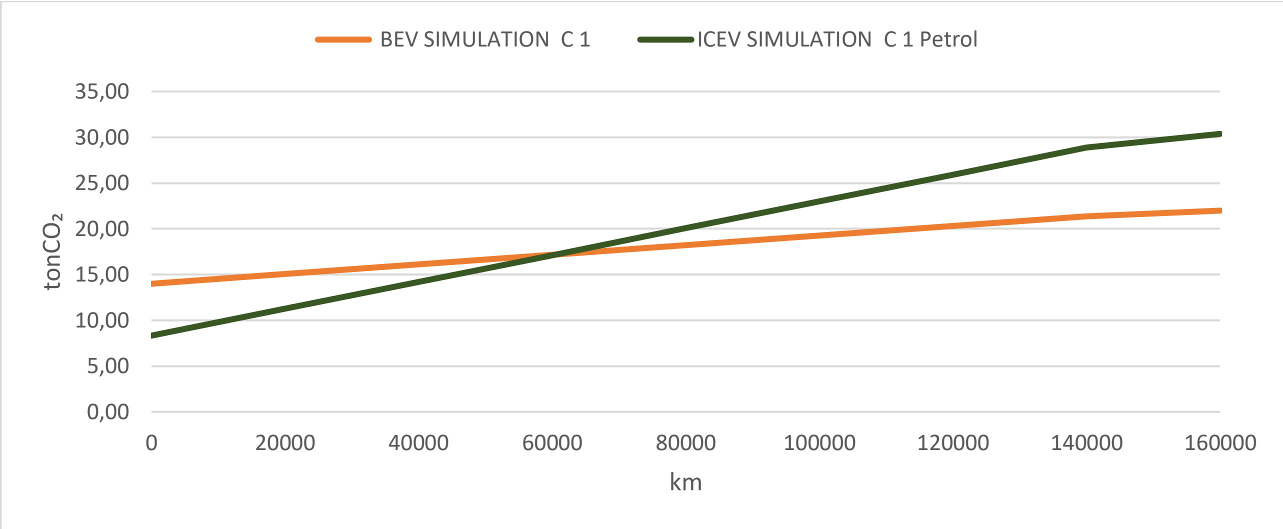


Fig. 39 BEV and ICEV LC computational example emission values
[Source: Adapted from emission-models]

The strong contribution given by the manufacturing of the battery and the vehicle itself, makes the BEV more polluting before the use phase begins. But the considerably lower amount of CO_2 produced during the use phase, allows the BEV to reduce the overall emission produced and to cross the ICEV emission's curve so to achieve the break-even point. In such computational example the break-even point is achieved when both vehicles have covered a distance of $60.362\ km$ and have been emitted $17{,}15\ tonCO_2$. Such point, considering the assumption that were previously made: covering a lifetime distance of $150.000\ km$ in $12\ \div\ 13\ years$ means that the BEV for more than the first $1/3$ of its lifetime is more polluting than the ICEV and only after $4{,}5\ years$ becomes more sustainable than an ICEV.

Such computational example had the aim of illustrating how the models works and which are the values that can be extracted from it and the relatively simplicity in comparing the values for the 2 vehicle typologies covered in the analysis. In the next chapter will be provided a more extensive analysis, evaluating different scenarios and vehicle segments, in order to show which are the differences among the different vehicle typologies and to go more in depth with the level of analysis.

5. Emission-model results and sensitivity analyses

5.1 Introduction

The following chapter is dedicated to the presentation of the results obtained from the application of the BEV and ICEV emission-models applied to different vehicle segments. The first aim of this chapter is to present the CO_2 emission values obtained for the 2 vehicle typologies over their entire life cycles and to compare those results. The second aim is to provide an overview of the sensitivity analyses conducted on the variations of some input parameters and evaluating how the CO_2 emission values change according to such variations.

The structure of the present chapter is divided into 2 main areas, the first one related to the presentation of the emission-models results with their comparisons for the 2 typologies, relative to the vehicle segments analysed; the second related to the different sensitivity analyses that have been conducted for BEVs.

For the development of the emission analysis, that will follow in the next sections, it has been decided to evaluate 16 different scenarios. Each single scenario is obtained from the combination of 4 vehicle segments respectively for BEVs and ICEVs; segments A, B, C and D which are adapted to 4 different countries of battery and vehicle manufacturing. For each scenario are also specifically evaluated use and EoL phases to be in Italy. The decision to adapt the last stages of BEVs' life cycle in Italy is to better analyse which is the actual situation in our country and which are the possible emission savings that could be achieved in the upcoming years, through the different scenarios evaluated. A better and deeper description of the scenarios and the methodology applied is provided in the following section.

The second part addressed in this chapter is dedicated to the sensitivity analyses that illustrate the variations of important parameters and variables which deploy a deep impact on the amount of CO_2 emissions produced along BEVs' life cycle with a special focus on the use phase.

The sensitivity analyses have been performed on different parameters such as the different energy mix to be used during the charge phase of a BEV; the specific BEV consumption and on different values of vehicle's lifetime (intended as km to be driven over vehicle's lifetime).

5.2 Scenario analysis

In this first section are illustrated the results of the analysis that has been conducted on 16 different scenarios for vehicle's CO_2 emission values for both BEVs and ICEVs. Due to the high variety of possible scenarios, given by the multitude of countries available to be selected for the analysis (as from *Annex 2*) it was decided to evaluate 16 scenarios that could be representative of real cases.

For the definition of a scenario were set 3 variables such as the vehicle's segment, the country of battery and vehicle manufacturing and the country of use for the vehicle (and the application of the EoL solution). The decision to set a single country for the complete manufacturing of the battery, the vehicle and their assembly, although being a simplistic assumption, it seemed plausible to be accounted as possible.

Variables	Values simulated
Vehicle's segment	•A •B •C •D
Country of battery and vehicle manufacturing	•China •USA •Germany •Italy
Country of vehicle use and EoL solution	•Italy (energy mix 2017)

Table 14 Scenarios variables
[Source: Own production]

As it is possible to observe from *Table 14*, have been selected 4 different vehicle segments respectively A, B, C and D, since these represents the vehicle typologies most adopted for both configurations as they are representative of mini, small, medium and large cars.

It must be highlighted that while for BEV segments have been considered values reported in *Table 7*; as obtained from the literature review and the most sold BEVs in Italy in 2018, for ICEV segments have been considered specific values of vehicles belonging to such segments. ICEV values selected are the ones representing characteristics of vehicles with the highest number of sales in Italy through 2018. In *Table 15* are reported segments' values respectively for BEVs and ICEVs.

Vehicle's segment	BEV			ICEV	
	BEV average consumption	Battery capacity	Weight	ICEV average consumption	Weight
	[kWh/100km]	[kWh]	[kg]	[L/100km]	[kg]
A	14,83	17,6	1.085	4,9 (petrol)	1.015
B	19,32	41	1.480	5,3 (petrol)	1.040
C	15,06	40	1.580	5,1 (diesel)	1.505
D	21,04	65	1.847	4,8 (diesel)	1.568

Table 15 Segments specific values [Source: Adapted from Quattroruote, 2019 and UNRAE, 2019]

BEVs average consumption values are computed already taking into consideration the usage of auxiliaries. For the ICEV segments it has been decided to evaluate segments A and B with vehicles being propelled with petrol while segments C and D instead with diesel. The reason for such distinction is because ICEVs powered with petrol were more adopted, in Italy through 2018, for segments A and B and for the same reason diesel with segment C and D, and so the analysis is also evaluating a closer-to-reality case.

The 4 countries evaluated for the analysis are selected for specific reasons:

- China

Is the global leader in the EV market on both sides, production and use. In 2018 were sold more than 1.2 million EV and it was achieved an overall threshold of more than 2.5 million EV circulating on Chinese streets. On the other side, it is the country that is producing more than 50% of the world stock of Lithium – Ion batteries and else exactly the 20% of EVs.

- USA

After all the main Asian countries (China, Japan and Korea), which hold the highest share of EV production, USA is the first country for Lithium – Ion battery production (around 10% to 15% of global market). Numbers related to the sales of EVs are also strongly increasing in the last years, with more than 350.000 units sold in 2018.

- Germany

Together with France it is the European country with the highest number of plants for batteries, vehicles and components production. Numbers related to the sales of EV are increasing in the last years and making Germany one among the first European countries for the adoption of non-traditional vehicles.

- Italy

Italy has been selected in order to evaluate which are the possibilities and the relative impacts arising from the application of an EV production “*100% made in Italy*”.

Coountry	Country energy mix [gCO_2/kWh]
China	650
USA	408
Germany	403
Italy	313

Table 16 Countries energy mix [Source: Adapted from Annex 2]

The reason to apply the use phase in Italy is because it was intended to study which is the impact of BEVs to be used in Italy and evaluating the differences in terms of CO_2 emissions when the vehicle follows different production paths before reaching such country. Secondly, to compare the results obtained for BEVs with respect to ICEVs, so to quantify the differences of CO_2 emission levels, looking at the Italian scenario.

All the simulations are conducted evaluating the output vales of the emission-models illustrated in the previous chapter. For BEVs are considered: battery manufacturing, vehicle manufacturing, transport, use and EoL. All the same output emission values are computed also for ICEVs, except only for battery manufacturing emissions, which naturally are not present.

5.2.1 Scenarios assumptions and variables

The evaluation of the different scenarios is carried out according to the emission-models structure already presented in *Chapter 4*. Here are reported the main assumptions, hypothesis and specific manufacturing energy requirements that were levered, in order to structure the models.

- The average vehicle lifetime has been set equal to $150.000\ km$, which is coherent with values obtained from the literature review. It can be also representative of a vehicle which has a lifetime of $12 \div 13\ years$ (covering around $12.000\ km$ per year). This unit of measure is very useful in order to express the amount of carbon dioxide produced per km.

- The specific energy required for battery manufacturing has been set equal to $28\ kWh/kg\ of\ battery$, as explained in C*hapter 4.3.1* (Ellingsen et al., 2014).

- The specific energy required for vehicle manufacturing and assembly has been set equal to $30\ MJ/kg\ of\ vehicle$, as explained in *Chapter 4.3.2* (Sullivan et al., 2010).

- The distances to be covered in order to move the battery and the vehicle from the country of manufacturing to the country of final use, are illustrated in *Table 17*. Such path distances are computed as mean values of distance separating the country of production to Italy. The % allocated to the different modes of freight forward transportation are hypothesized and adapted to values which better approximate real conditions. The emission factors associated to each freight forward transportation mode are those reported in *Table 9*.

Country of production	Distance to Italy [km]	Rail	Road	Sea
China	10.000	30%	20%	50%
USA	10.000	5%	5%	90%
Germany	1.500	75%	25%	0%
Italy	1.000	75%	25%	0%

Table 17 Transportation characteristics [Source: Own production]

- The use phase for both vehicle typologies is examined in Italy. BEV's charging is performed with an energy mix having a CO_2 emission value equal to $313 gCO_2/kWh$. For the ICEV typology are considered the WTW emission values associated to the production and combustion of the fuel used to propel the vehicle, values are reported in *Table 13*.

- For the EoL solution 2 different approaches have been considered. For BEVs have been set the battery recycling through the Pyrometallurgic technique and the vehicle's body disposal through shredding. For the ICEV configuration it has been considered only the disposal approach with the relative shredding of the vehicle. The Pyrometallurgic technique is performed with an energy request equal to $2{,}88 MJ/kg\ of\ battery$ (Tagliaferri et al., 2016), while for the disposal with shredding technique is requested a specific energy value of $0{,}37 MJ/kg\ of\ vehicle$ (Kukreja, 2018).

5.3 Scenarios results

In the following paragraphs will be illustrated the results obtained from the different scenarios simulations. The results are presented for each single vehicle segment.

5.3.1 Segment A

The first vehicle segment analysed is that of *"mini cars"*. Characteristics of the 2 vehicle typologies considered are listed in *Table 15*. In *Fig. 40* and *Fig. 41* are respectively reported values obtained for the BEV and ICEV CO_2 emission simulations.

- BEV emissions values

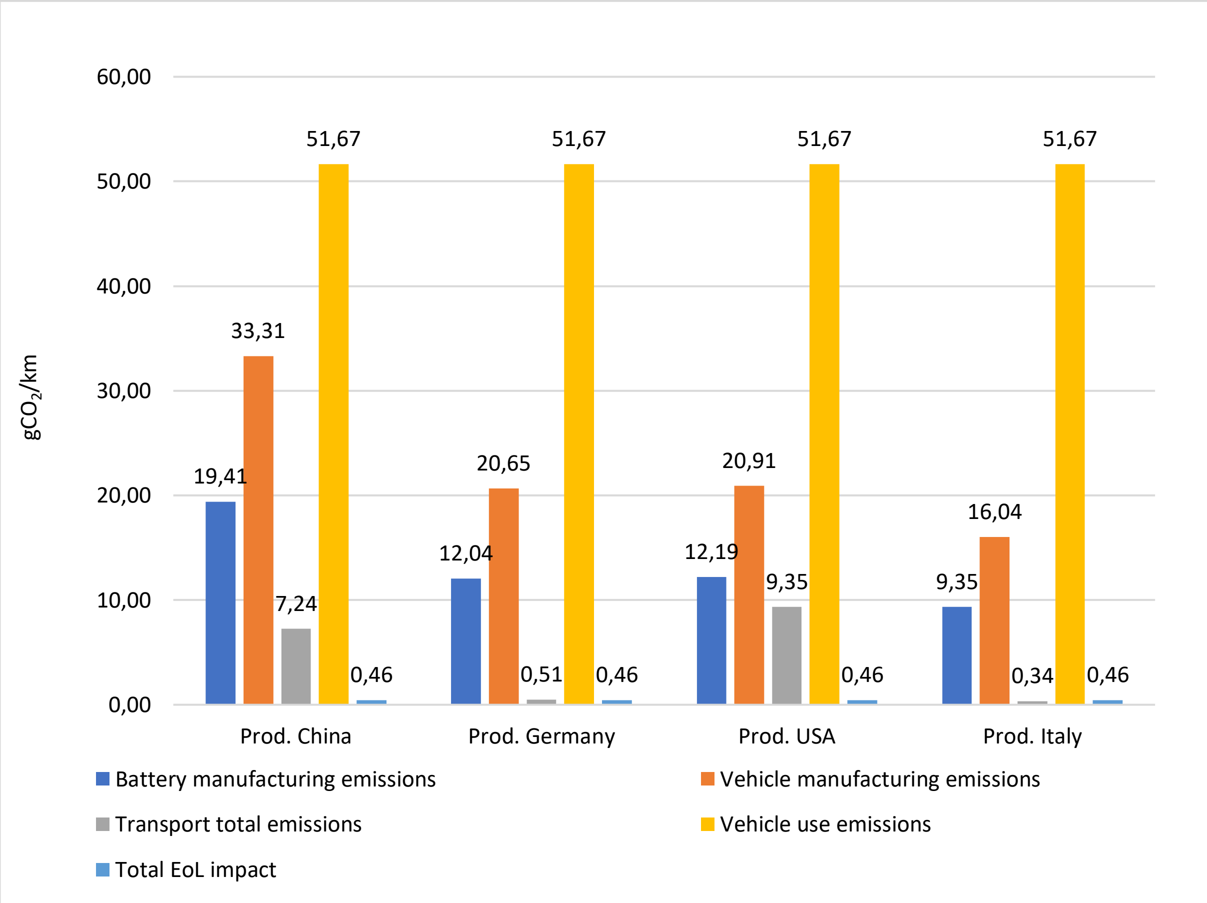


Fig. 40 BEV single phases results for Segment A [Source: Adapted from BEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	112,1	85,33	94,58	77,86

Table 18 BEV LC results for Segment A [Source: Adapted from: BEV emission-model]

- ICEV emissions values

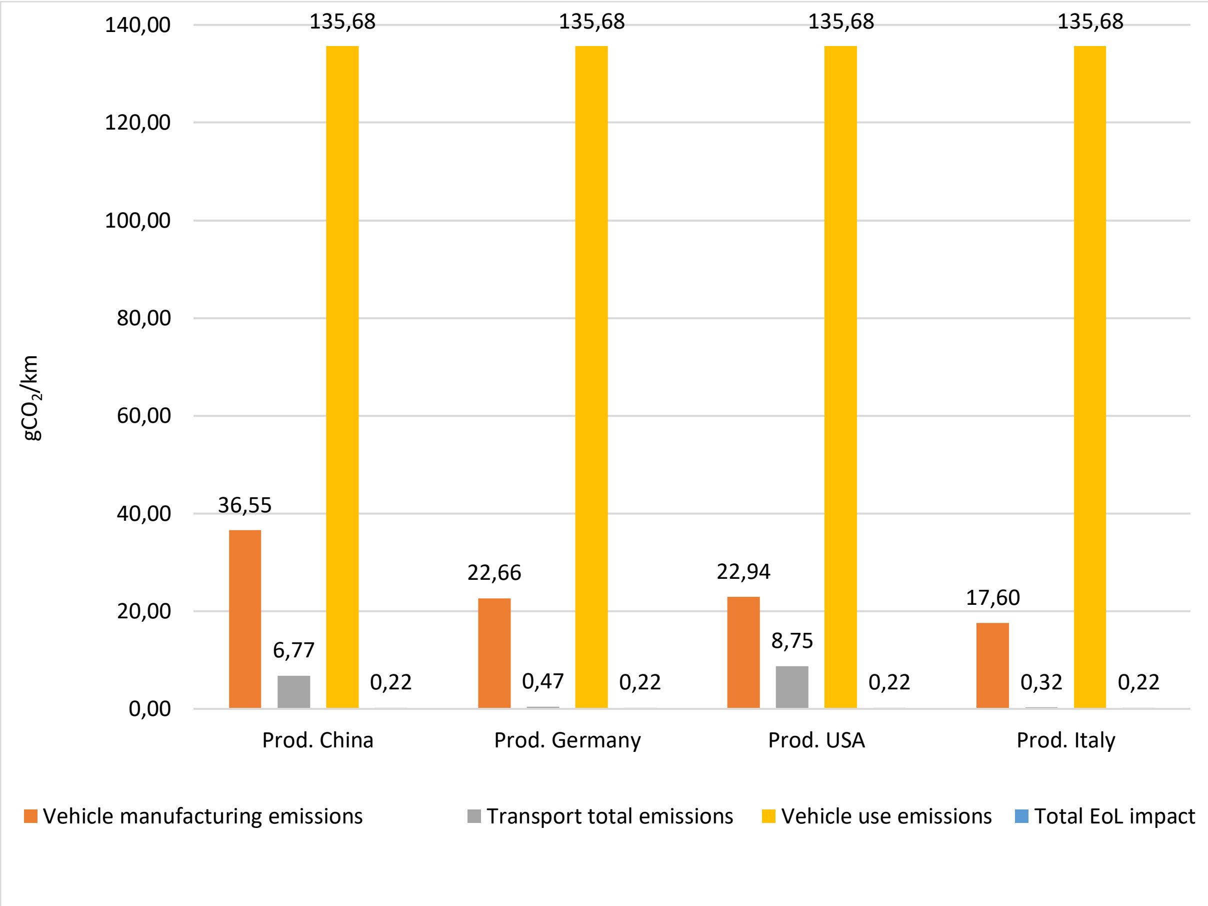


Fig. 41 ICEV single phases results for Segment A [Source: Adapted from ICEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	179,12	158,94	167,49	153,72

Table 19 ICEV LC results for Segment A [Source: Adapted from ICEV emission-model]

From the analysis conducted for segment A, it is possible to evaluate the BEPs that have been computed respectively for the "*best*" and "*worst*" case among BEVs and ICEVs. The "*best*" case is represented by production occurring in Italy while the "*worst*" with production occurring in China.

"*Best*" case BEP:

- $13.206\ km$
- $4{,}57\ tonCO_2$

"*Worst*" case BEP:

- $29.321\ km$
- $10{,}53\ tonCO_2$

5.3.2 Segment B

The second vehicle segment analysed is that of *"small cars"*. Characteristics of the 2 vehicle typologies considered are listed in *Table 15*. In *Fig. 42* and *Fig. 43* are respectively reported the values obtained for the BEV and ICEV CO_2 emission simulations.

- BEV emissions values

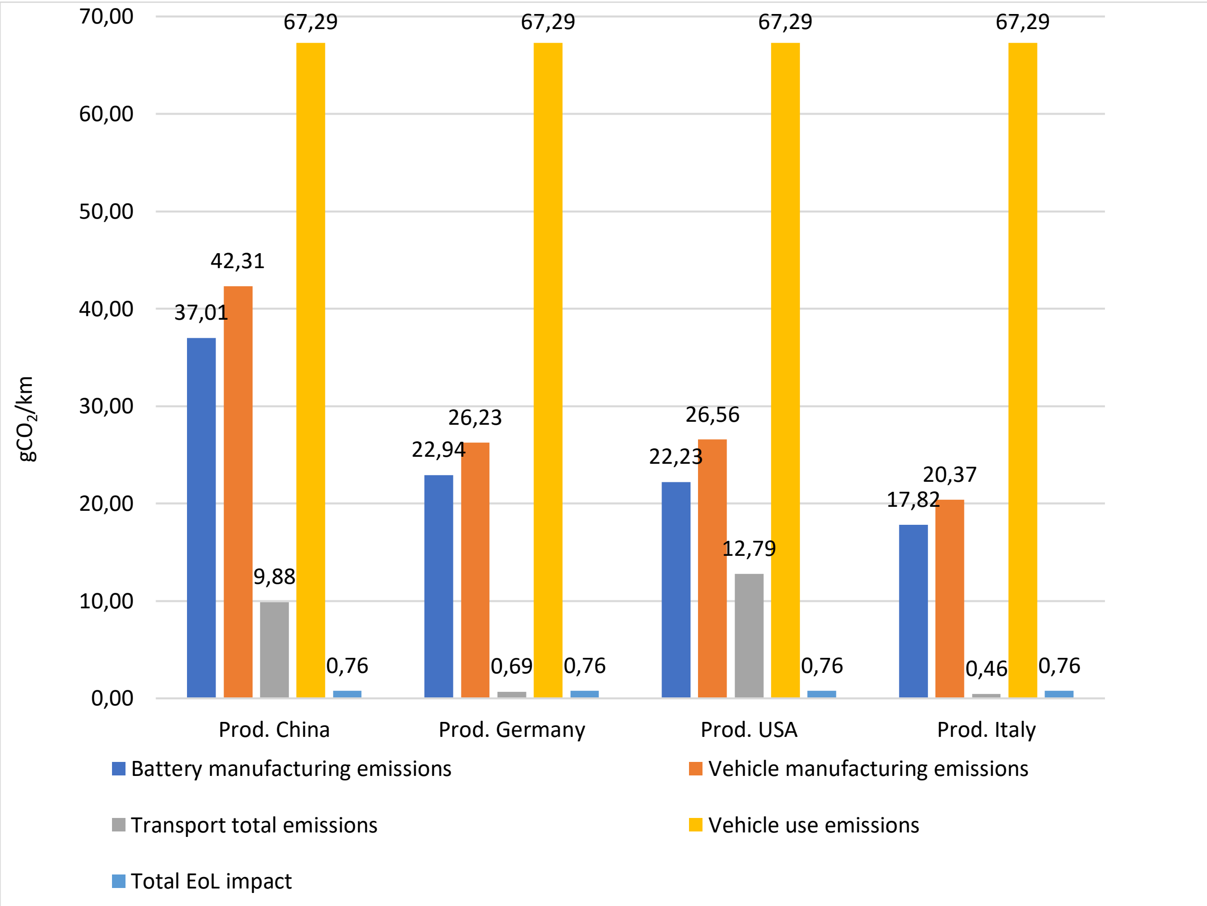


Fig. 42 BEV single phases results for Segment B [Source: Adapted from BEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	157,25	117,92	130,60	106,71

Table 20 BEV LC results for Segment B [Source: Adapted from BEV emission-model]

- ICEV emissions values

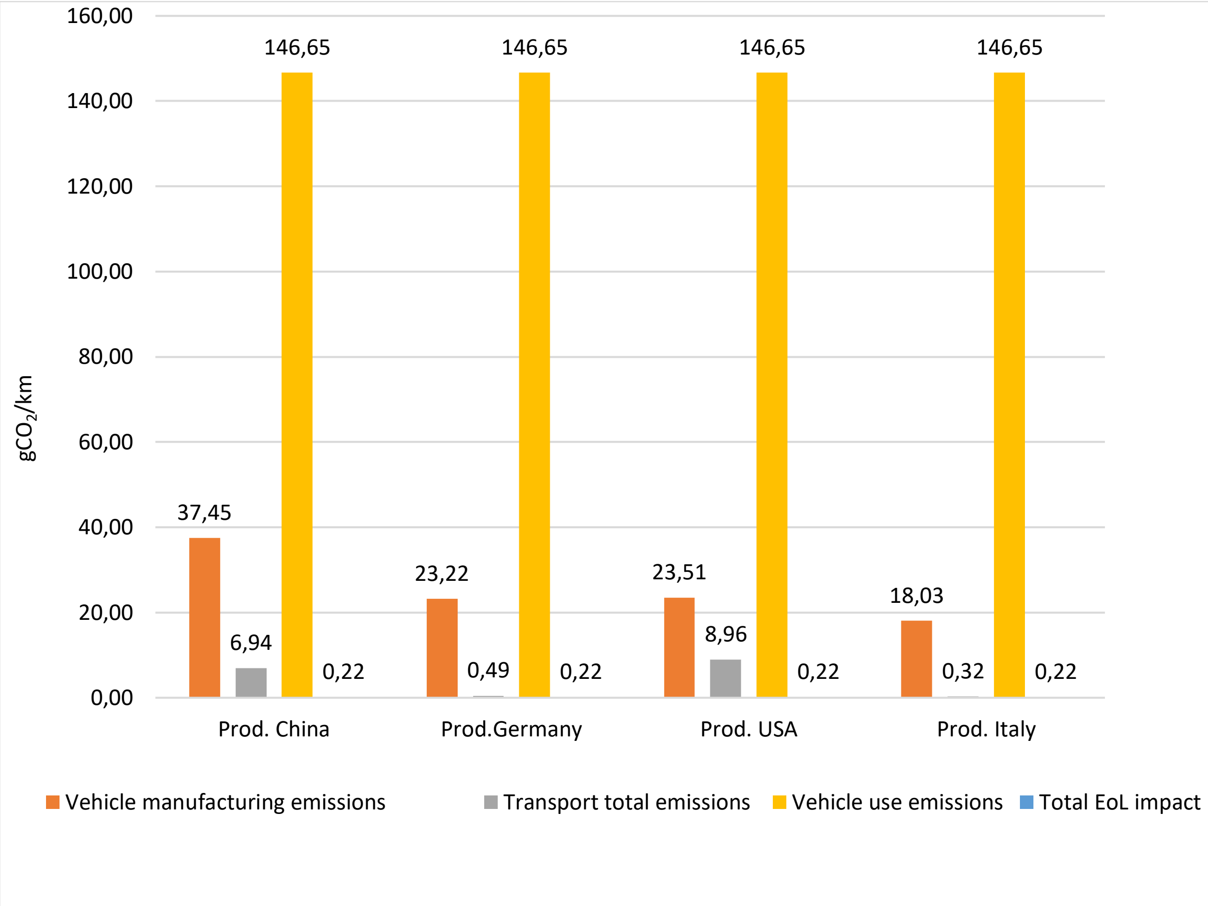


Fig. 43 ICEV single phases results for Segment B [Source: Adapted from ICEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	191,26	170,58	179,34	165,23

Table 21 ICEV LC results for Segment B [Source: Adapted from ICEV emission-model]

From the analysis conducted for segment B, it is possible to evaluate the BEPs that have been computed respectively for the "*best*" and "*worst*" case among BEVs and ICEVs. The "*best*" case is represented by production occurring in Italy while the "*worst*" with production occurring in China.

"*Best*" case BEP:

- $38.110\ km$
- $8{,}38\ tonCO_2$

"*Worst*" case BEP:

- $85.453\ km$
- $19{,}09\ tonCO_2$

5.3.3 Segment C

The third vehicle segment analysed is that of *"medium cars"*. Characteristics of the 2 vehicle typologies considered are listed in *Table 15*. In *Fig. 44* and *Fig. 45* are respectively reported the values obtained for the BEV and ICEV CO_2 emission simulations.

- BEV emissions values

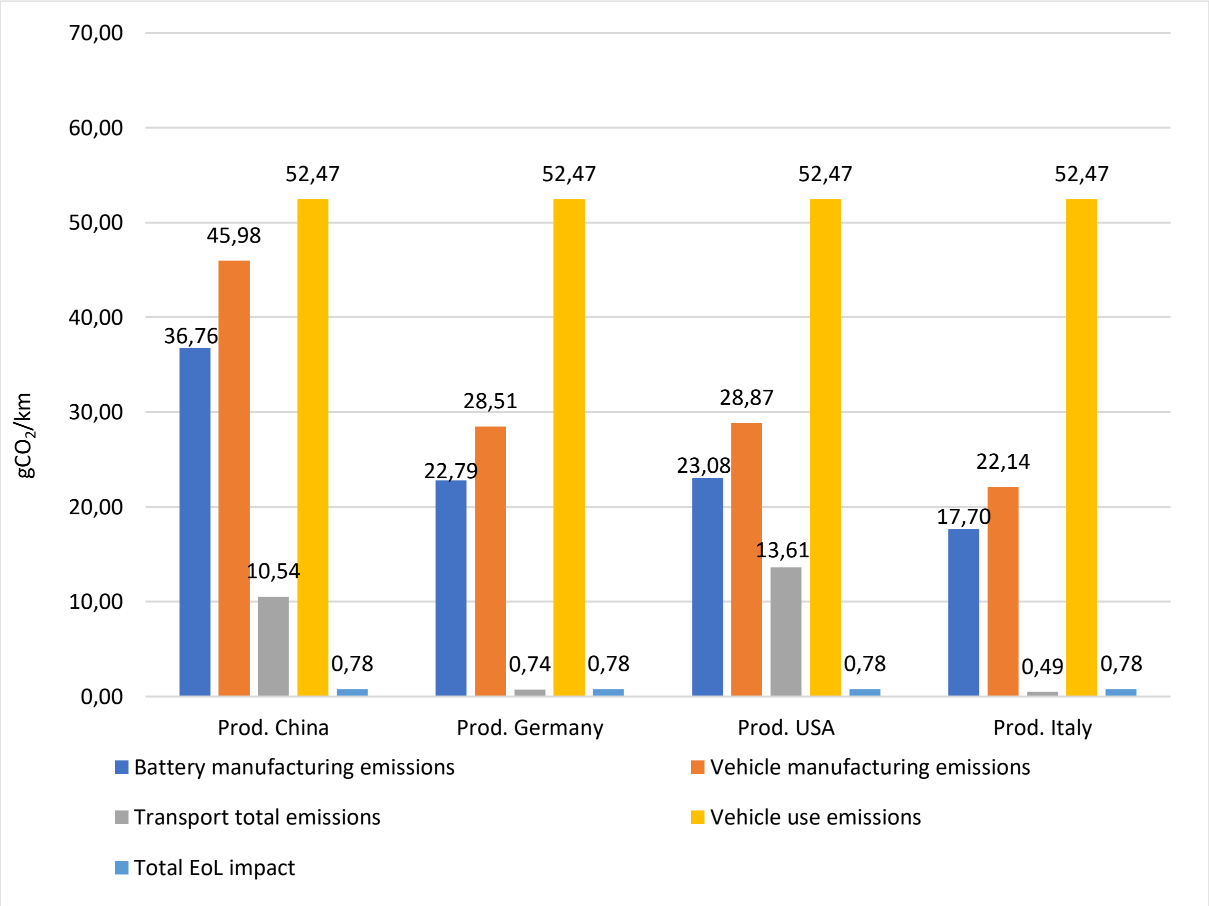


Fig. 44 BEV single phases results for Segment C [Source: Adapted from the BEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	146,54	105,29	118,81	93,59

Table 22 BEV LC results for Segment C [Source: Adapted from BEV emission-model]

- ICEV emissions values

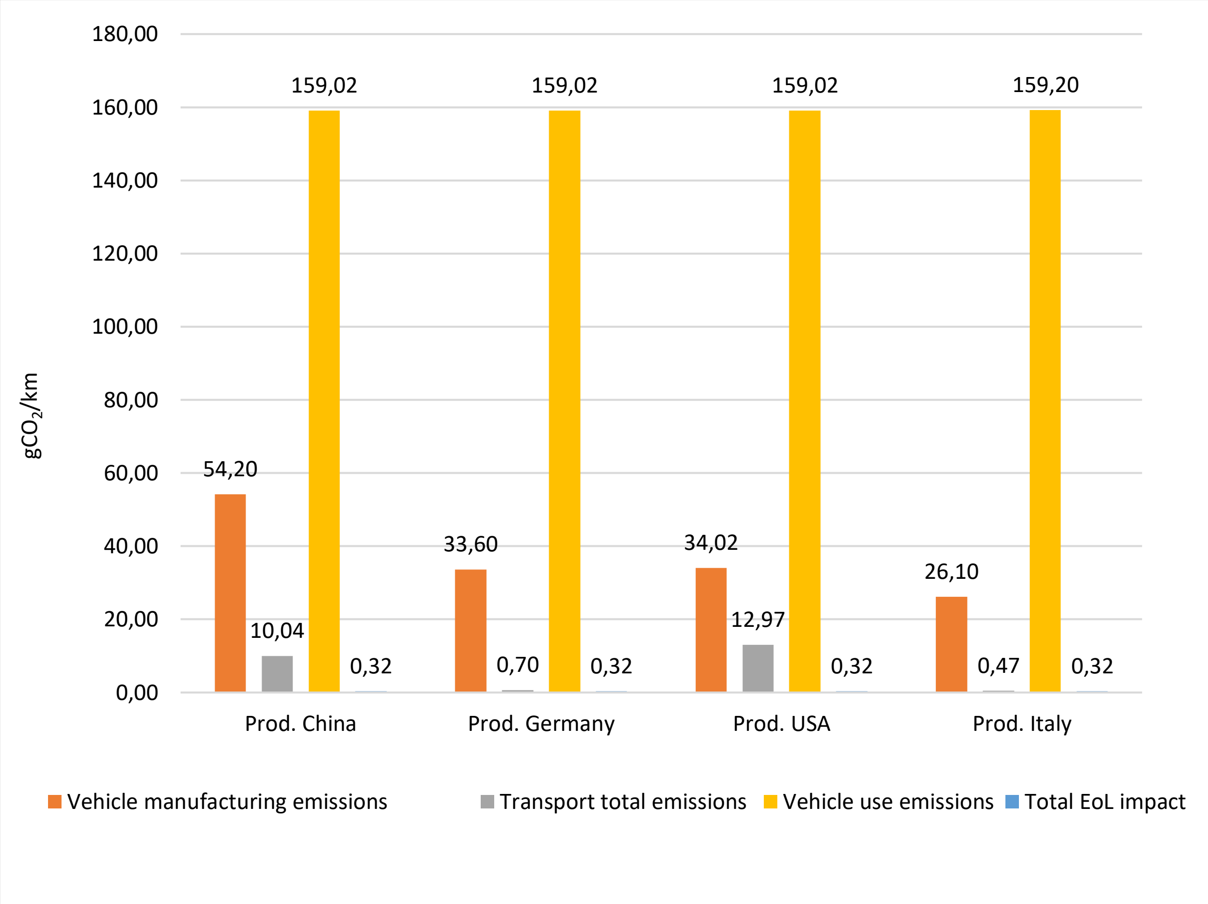


Fig. 45 ICEV single phases results for Segment C [Source: Adapted from ICEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	223,58	193,64	206,33	185,91

Table 23 ICEV LC results for Segment C [Source: Adapted from ICEV emission-model]

From the analysis conducted for segment C, it is possible to evaluate the BEPs that have been computed respectively for the "*best*" and "*worst*" case among BEVs and ICEVs. The "*best*" case is represented by production occurring in Italy while the "*worst*" with production occurring in China.

"*Best*" case BEP:

- $18.738\ km$
- $7{,}06\ tonCO_2$

"*Worst*" case BEP:

- $40.710\ km$
- $16{,}14\ tonCO_2$

5.3.4 Segment D

The fourth vehicle segment analysed is that of *"large cars"*. Characteristics of the 2 vehicle typologies considered are listed in *Table 15*. In *Fig. 46* and *Fig. 47* are respectively reported the values obtained for the BEV and ICEV CO_2 emission simulations.

- BEV emissions values

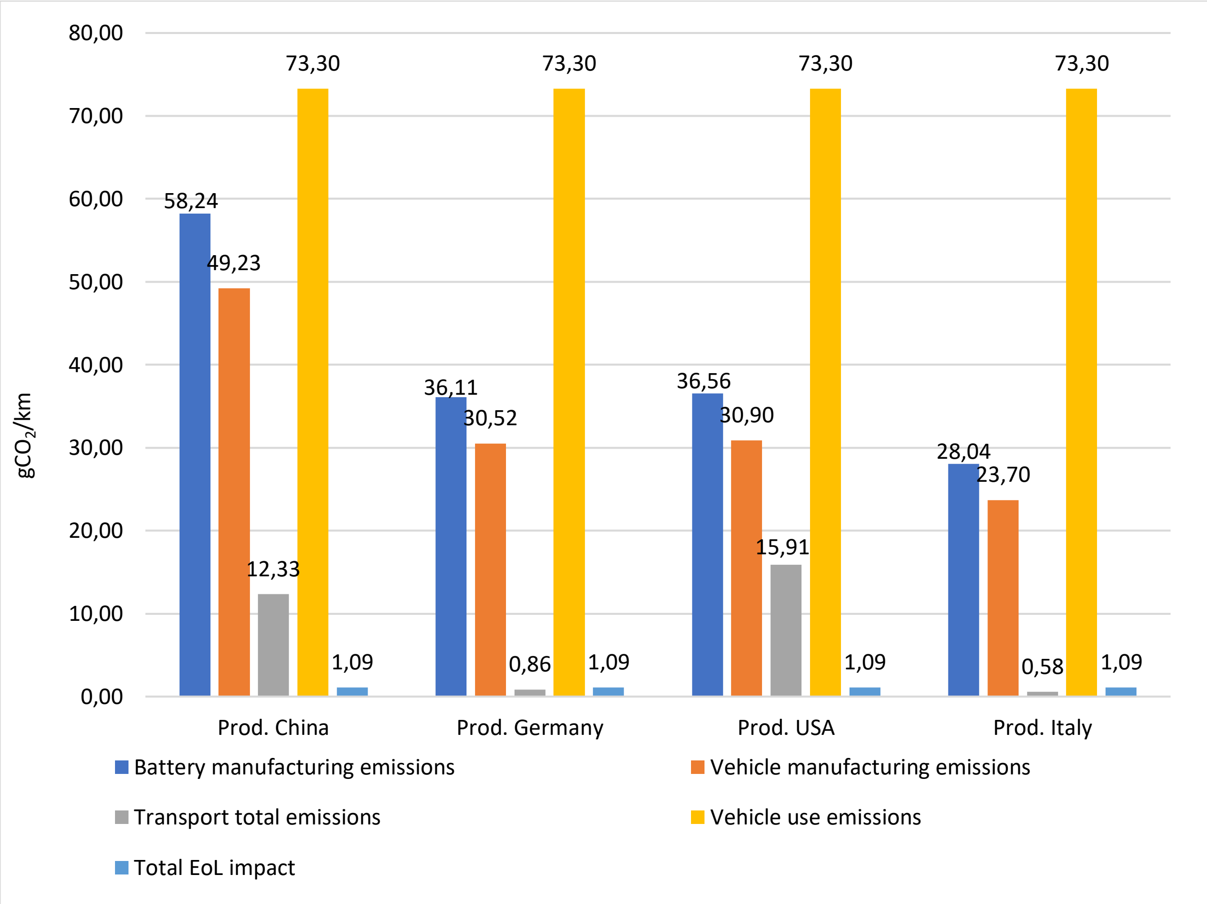


Fig. 46 BEV single phases results for Segment D [Source: Adapted from the BEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	194,18	141,88	157,77	126,72

Table 24 BEV LC results for Segment D [Source: Adapted from BEV emission-model]

- ICEV emissions values

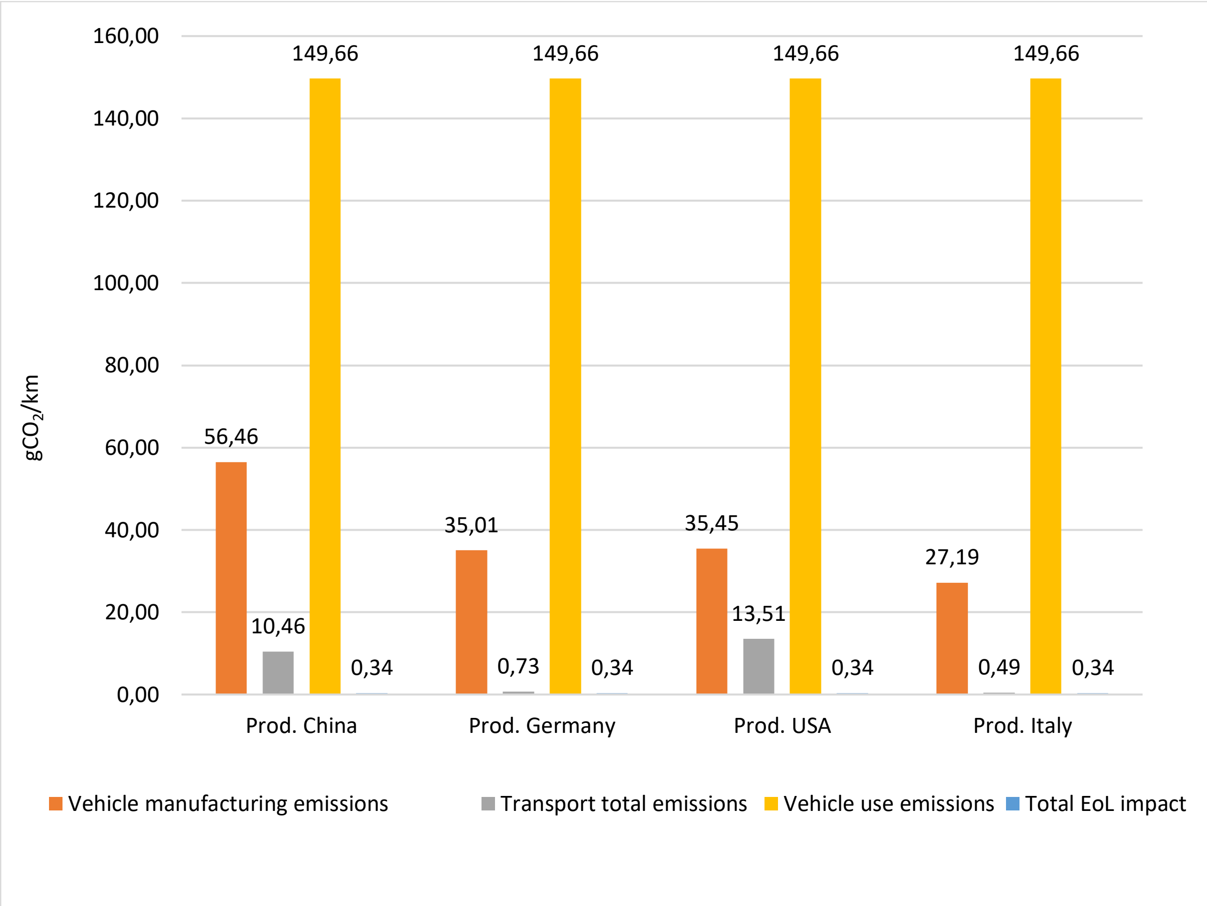


Fig. 47 ICEV single phases results for Segment D [Source: Adapted from ICEV emission-model]

	Prod. China	Prod. Germany	Prod. USA	Prod. Italy
LC emissions [gCO_2/km]	216,93	185,74	198,96	177,68

Table 25 ICEV LC results for Segment D [Source: Adapted from ICEV emission-model]

From the analysis conducted for segment B, it is possible to evaluate the BEPs that have been computed respectively for the "*best*" and "*worst*" case among BEVs and ICEVs. The "*best*" case is represented by production occurring in Italy while the "*worst*" with production occurring in China.

"*Best*" case BEP:

- $48.376\ km$
- $11{,}40\ tonCO_2$

"*Worst*" case BEP:

- $105.081\ km$
- $25{,}61\ tonCO_2$

5.3.5 Scenarios overview

In all the scenarios evaluated it was highlighted that the CO_2 emissions over the entire vehicle life cycles were lower for BEVs with respect to ICEVs, for all the 4 segments evaluated. In all the segments, the scenarios with the *"worst case"* was always that one for vehicle and battery manufacturing occurring in China. On the other side, the *"best case",* in all the segments covered is associated to the 100% Italian scenario. It is also possible to notice that the USA and Germany are always considered respectively the third and second best country in all segments for the emission values.

It is not surprising to observe that moving from segment A "mini cars" to segment D "large cars" there is an increasing trend in the emission values, as it is possible to observe from *Table 24*.

	Segment A	Segment B	Segment C	Segment D
China	*BEV: 112,1* *ICEV: 179,12*	*BEV: 157,25* *ICEV: 191,26*	*BEV: 146,54* *ICEV: 223,58*	*BEV: 194,18* *ICEV: 216,93*
Germany	*BEV: 85,33* *ICEV: 158,94*	*BEV: 117,92* *ICEV: 170,58*	*BEV: 105,29* *ICEV: 193,64*	*BEV: 141,88* *ICEV: 185,74*
USA	*BEV:94,58* *ICEV: 167,49*	*BEV: 130,60* *ICEV: 179,34*	*BEV: 118,81* *ICEV: 206,33*	*BEV: 157,77* *ICEV: 198,96*
Italy	*BEV:77,86* *ICEV: 153,72*	*BEV: 106,71* *ICEV: 165,23*	*BEV: 93,59* *ICEV: 185,91*	*BEV: 126,72* *ICEV: 177,68*

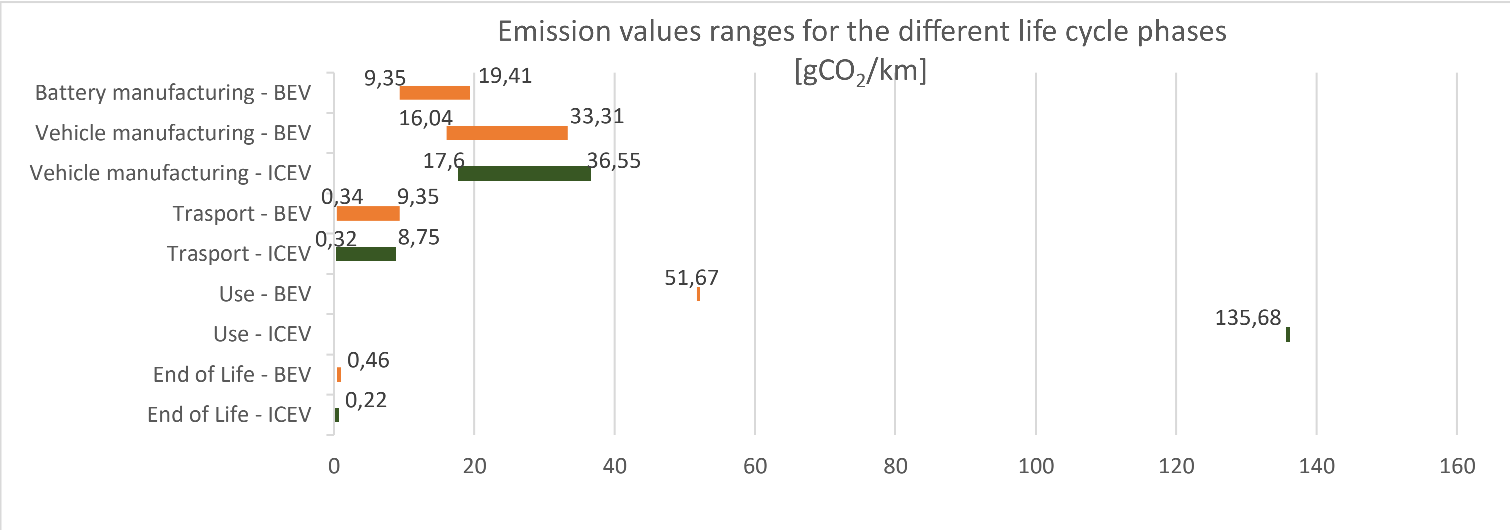
Table 26 Scenarios overview [Source: Adapted from BEV and ICEV emission-models]

It is important to notice that evaluating the results from segment A to segment D there is a consistent increase in the achievement of the BEP. This is demonstrated for both cases evaluated for each segment. For the "*best*" scenarios there is an increase (delta) from segment A to B of 24.904 km and 3,81 $tonCO_2$; from segment A to C there is an increase (delta) of 5.532 km and 2,49 $tonCO_2$, while from segment A to D there is an increase (delta) of 35.170 km and 6,83 $tonCO_2$.

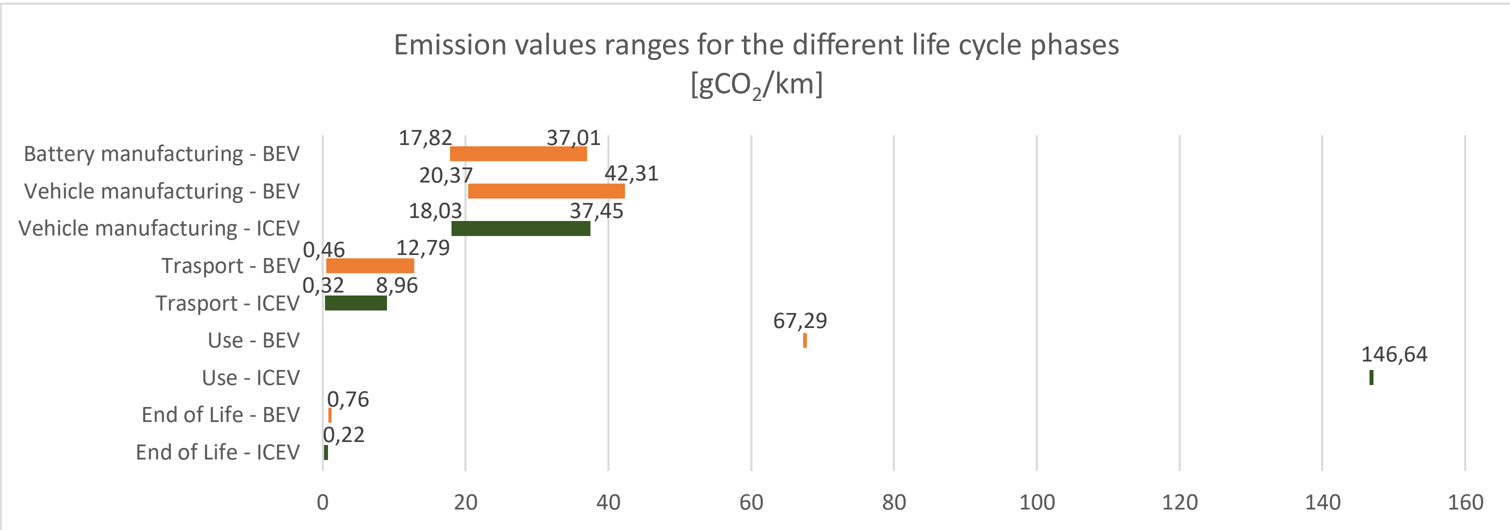
Respectively, for the "*worst*" cases there is an increase (delta) from segment A to B of 47.343 km and 8,56 $tonCO_2$; from segment A to C of 11.389 km and 5,61 $tonCO_2$ while from segment A to D an increase (delta) of 75.760 km and $15{,}08$ $tonCO_2$.

For each vehicle segment is also provided a comparison of the emission values among BEVs and ICEVs. Below are reported values for each single phase and are illustrated the ranges from the "*best*" to the "*worst*" scenario. In the use and EoL phases are reported only single values, as for each scenario the use and the EoL phases are considered to be exploited in Italy.

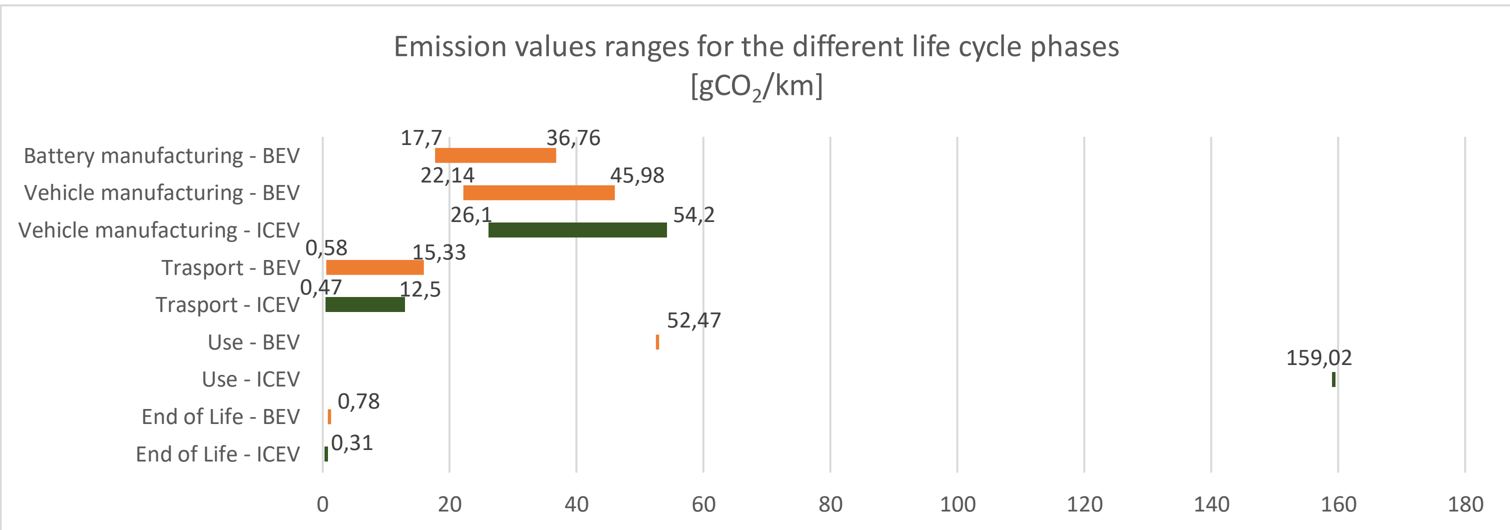
- Segment A



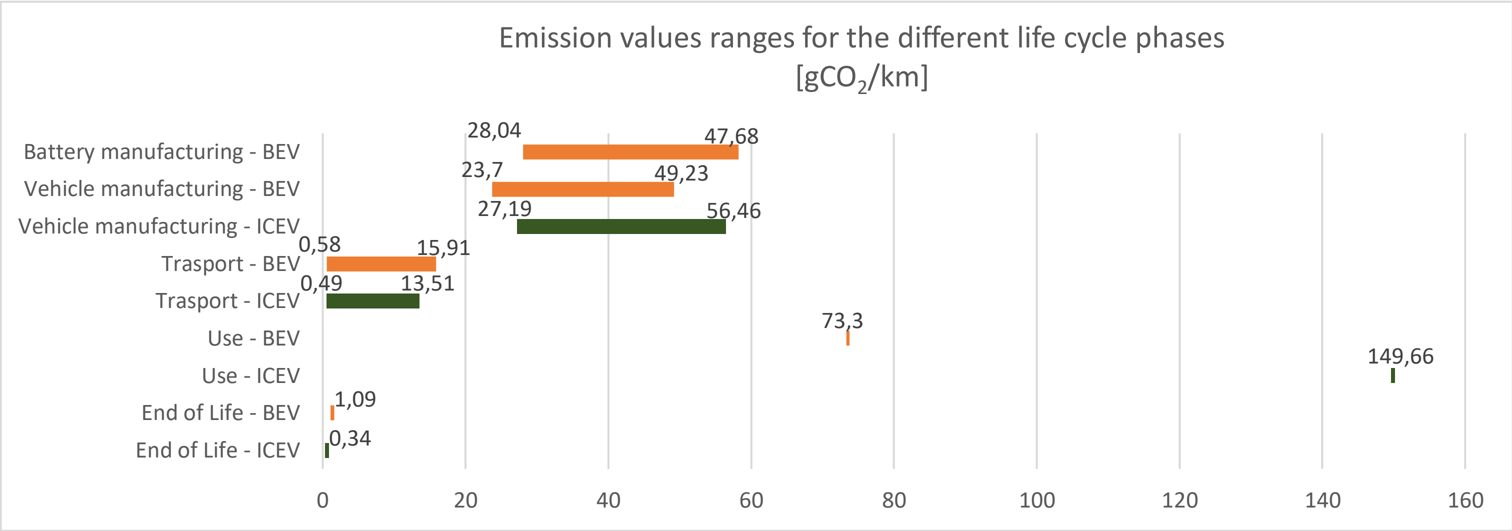
- Segment B



- Segment C



- Segment D



From the above representations of the ranges for the emission values from the different phases it is possible to notice that the spreads of the ranges associated to battery manufacturing, vehicle manufacturing and transport, increases moving from segment A toward segment D. It is also possible to observe that the highest transport emissions are not associated to the scenario that involves manufacturing stages in China, but it is relative to the scenario having the manufacturing occurring in the USA. The reason of such higher value is due to the high share of transport occurring with sea transportation which, in the present model, is adapted with high emission values.

5.4 Sensitivity analyses

In the following sections will be illustrated the sensitivity analyses that have been conducted on the variation of some input variables and other parameters, which have a fundamental impact on the overall quantity of the CO_2 emissions over the entire vehicle's life cycle. All the sensitivity analyses are conducted on the BEV typology and the aim is to investigate how changes in the normal conditions can provide an increase or vice versa a reduction of the overall emission quantity produced.

The 3 sensitivity analyses are developed to evaluate:

- Different energy mix used for charging the vehicle

The main focus of such analysis is to evaluate how the emissions associated only to the use phase are varying according to the different energy mix used for charging the vehicle. As the most contributing phase to the life cycle emissions is represented by the use phase, variations in such phase can deeply affect the overall life cycle emissions. The range for the variation of the energy mix has been set coherently with different RES quota penetration on the Italian energy mix.

- Different BEV's energy consumption

BEV's energy consumption is another key aspect when evaluating the use phase emissions and it poses also direct contribution to the overall amount of emissions produced during BEV's lifecycle. The range for the variation of BEV's consumption has been defined according to the different assumptions and hypothesis that were defined during the literature review and with carmakers declarations of different consumption levels according to different scenarios.

- Different km range

This analysis, contrary to the previous 2, is not evaluating the impact limited only to the use phase but to the entire vehicle's life cycle. When modifying the km range the emissions associated to the use phase get increased or reduced, as absolute value. All other phases' emissions, as they are divided for the (new) km range, are subject to a variation which generates either an increase or reduction for the quantity of gCO_2/km for each output value. Adopting different values of km range, which may be justified in reality with different combinations or even with accidents occurring, can have a negative or positive contribution in lowering or increasing the CO_2 emissions produced. The km range analysed has been defined according to values which are expected to be accounted as close-to-reality, coherently with the sensitivity analyses evaluated in the literature review.

All the sensitivity analyses are conducted on the 4 vehicle segments previously evaluated and have been taken has reference the "*best*" and "*worst*" scenarios. At the end of each sensitivity analysis is performed a $LC\ gCO_2/\ km$ emission evaluation in order to highlight the most significant variations and other important considerations.

In the first 2 sensitivity analyses is also present the ICEV scenario, as a benchmark among the 2 vehicle typologies.

5.4.1 Sensitivity analysis – Energy mix

As already evaluated in the previous sections of *Chapter 4* the use phase is providing the highest contribution of the CO_2 emissions over the entire vehicle's lifetime. The main contribution to such emissions is caused by the energy mix that is used for vehicle's charging. As already discussed in *Chapter 4.3.4,* countries with a high portion of energy being produced from RES have a lower environmental impact with respect to those having a stronger reliability on fossil fuels. The aim of such sensitivity analysis is to investigate how the CO_2 emission values vary during the use phase with variations associated to the different energy mix used for charging the vehicle.

As already introduced in the previous paragraph, have been fixed 2 reference scenarios that are respectively the *"best"* and *"worst"* scenarios evaluated. The first one is where all the manufacturing and assembly are occurring in China while the second is for the *"100% made in Italy"* scenario. Together with these scenarios are also reported, as a way of comparing the results, the respective ICEV emission values for the *"best"* and *"worst"* scenarios evaluated. The analysis is presented for all 4 vehicle segments covered.

In order to evaluate the different energy mixes to be accounted for the analysis, it has been decided to consider the use phase to be in Italy and to evaluate 3 different scenarios.

1. RES penetration equal to 50%

This value is representative of the estimate of a RES penetration that is expected to be reached in Italy by 2030. According to the data reported by TERNA the RES penetration in Italy covered the 43% of the gross electric production in 2014, while in the last years this trend lowered to 38% in 2017 (ISPRA, 2018).

2. RES penetration equal to 75%

This value is representative of a better estimate of a RES penetration that could be achieved in next years, it is not already possible to give a precise year data to such target, but for the present work it serves as a way of analysing possible future scenarios and as a benchmark.

3. RES penetration equal to 100%

This value is representative of an energy mix being produced 100% from clean energy sources. Although such value is still far to be thought as achievable for the Italian energy mix, it seems reasonable to think such scenario as the case where each single BEV owner has the possibility to charge his/her vehicle by the use of his/her RES plant, which can be for example a PV system or a mini wind system for residential application.

The evaluation of the Italian energy mix for the different RES scenarios is here computed considering the value provided by TERNA, taking as reference the year 2017 where is reported a value for the gross thermoelectric production (only fossil) of 512,9 gCO_2/kWh. The values for the different energy mixes are computed setting as reference the gross thermoelectric production for 2017 and so obtaining all other values multiplying such value for the RES quota evaluated.

The reason that lies behind the decision of choosing TERNA's value instead of the values provided in the EnerData database is that, TERNA is specifically evaluating the Italian situation and providing a more accurate level of details over the national energy production. Values reported in the EnerData database (*Annex 2*) are obtained from a coefficient regression taking as reference the projection values reported for Europe toward 2040 (*Annex 2*).

So, considering as reference TERNA's value and setting the base scenario where we have a RES quota penetration of 38% for the year 2017, this can be translated in an energy mix computed as:

$$Italian\ energy\ mix = (512{,}9\ gCO_2/kWh) * (1 - 0.38) \ = 318\ gCO_2/kWh$$

The main assumption that allows to apply such formula is that energy coming from RES is counted to have CO_2 emissions which are null (not considering the amount of emissions associated to the production of the RES plant).

In the same way, from the previous formula, it is possible to compute values for the different RES scenarios:

- RES penetration equal to 50% results as an energy mix of 256,45 gCO_2/kWh.
- RES penetration equal to 75% results as an energy mix of 128,23 gCO_2/kWh.
- RES penetration equal to 100% results as an energy mix of 0 gCO_2/kWh.

Below are reported all the results obtained for the BEV typology respectively for the "*best*" and "*worst*" cases. The analyses are divided for the different vehicle segments and are also reported, for a matter of comparison the relative ICEV values. Changes are evaluated only in the use phase, all other emission values remained unchanged.

5.4.1.1 Segment A

- "*Best*" case

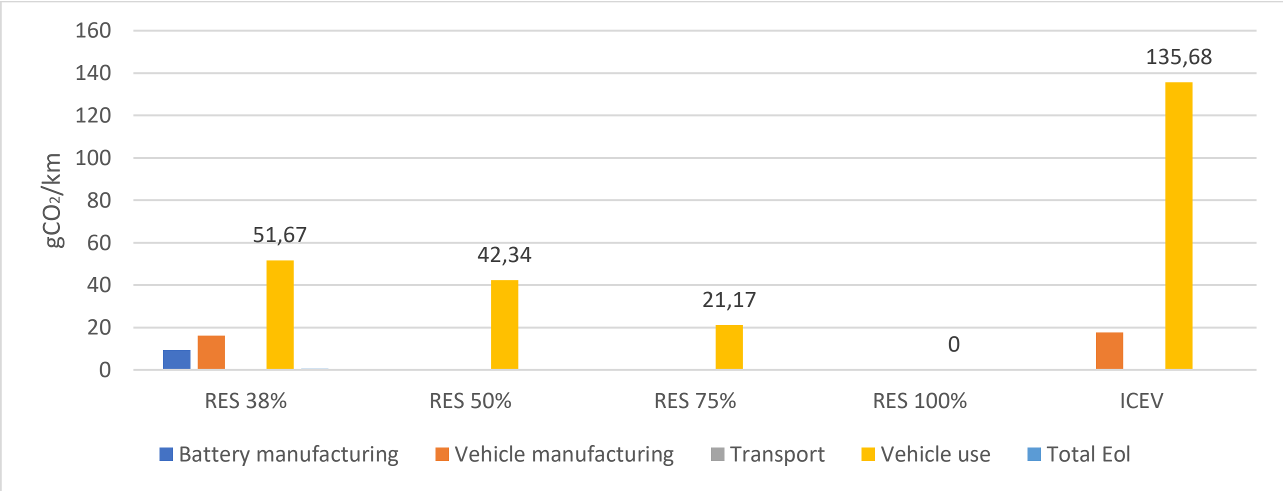


Fig. 48 Sensitivity analysis energy mix Segment A - best case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	77,86	68,53	47,36	26,19	153,82
% over RES 38%	100%	88%	61%	34%	-

Table 27 BEV LC results for Segment A - best case [Source: Adapted from BEV emission-model]

- "*Worst*" case

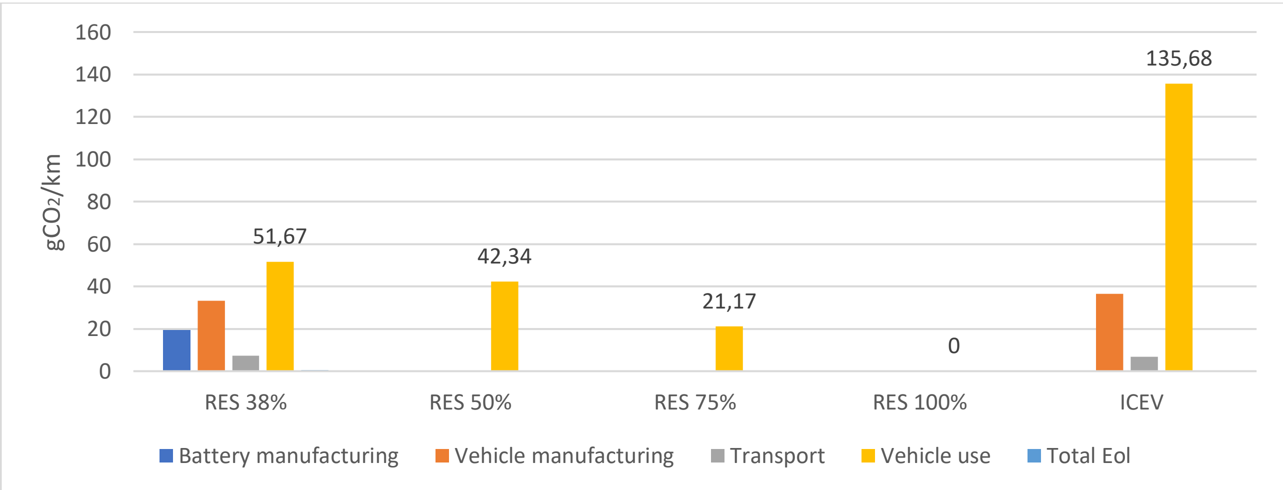


Fig. 49 Sensitivity analysis energy mix Segment A - worst case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	112,09	102,76	81,59	60,42	179,22
% over RES 38%	100%	92%	73%	54%	-

Table 28 BEV LC results for Segment A - worst case [Source: Adapted from BEV emission-model]

5.4.1.2 Segment B

- "*Best*" case

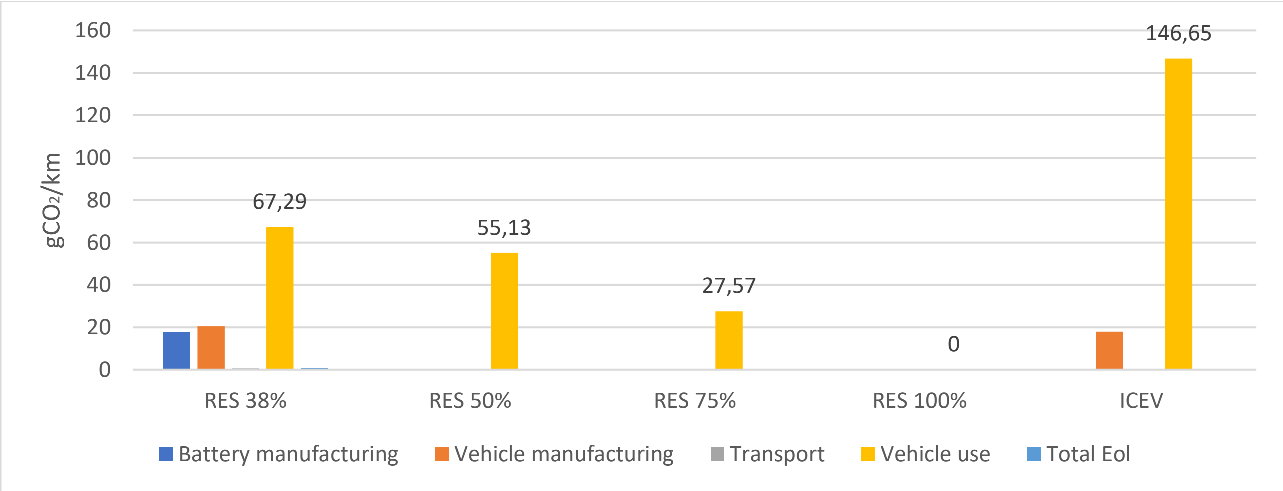


Fig. 50 Sensitivity analysis energy mix Segment B - best case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	106,7	94,54	66,98	39,41	165,22
% over RES 38%	100%	89%	63%	37%	-

Table 29 BEV LC results for Segment B - best case [Source: Adapted from BEV emission-model]

- *Worst*" case

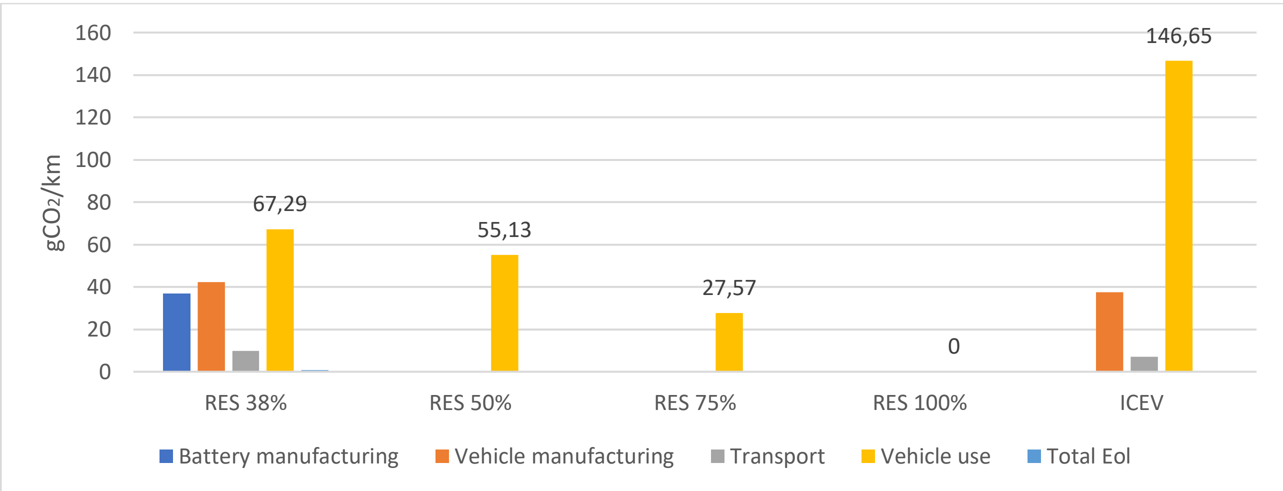


Fig. 51 Sensitivity analysis energy mix Segment B - worst case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	157,25	145,09	117,53	89,96	191,26
% over RES 38%	100%	92%	75%	57%	-

Table 30 BEV LC results for Segment B - worst case [Source: Adapted from BEV emission-model]

5.4.1.3 Segment C

- "*Best*" case

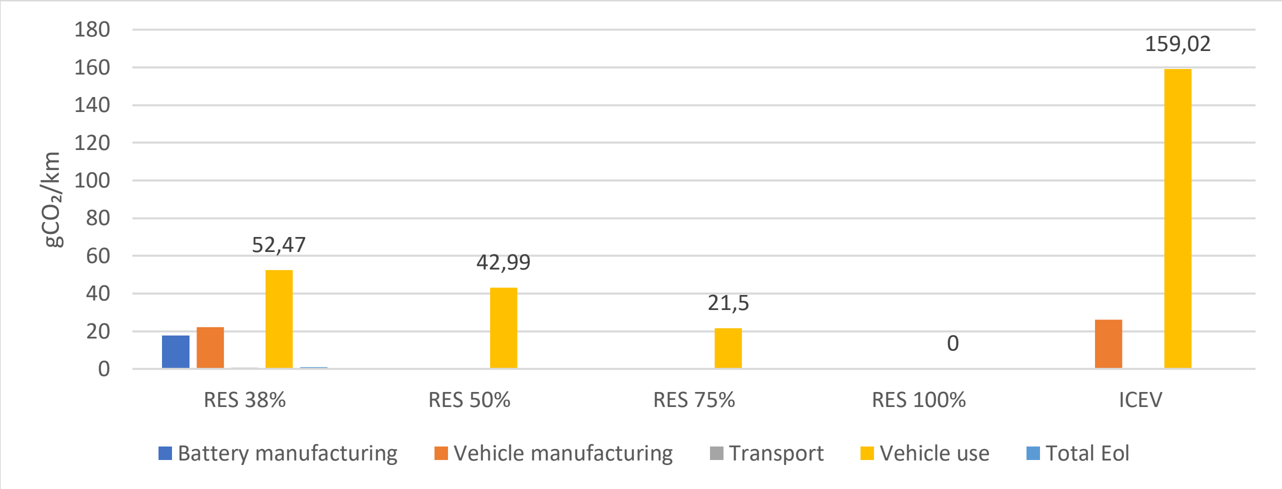


Fig. 52 Sensitivity analysis energy mix Segment C - best case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	93,58	84,1	62,61	41,11	185,91
% over RES 38%	100%	90%	67%	44%	-

Table 31 BEV LC results for Segment C - best case [Source: Adapted from BEV emission-model]

- *Worst*" case

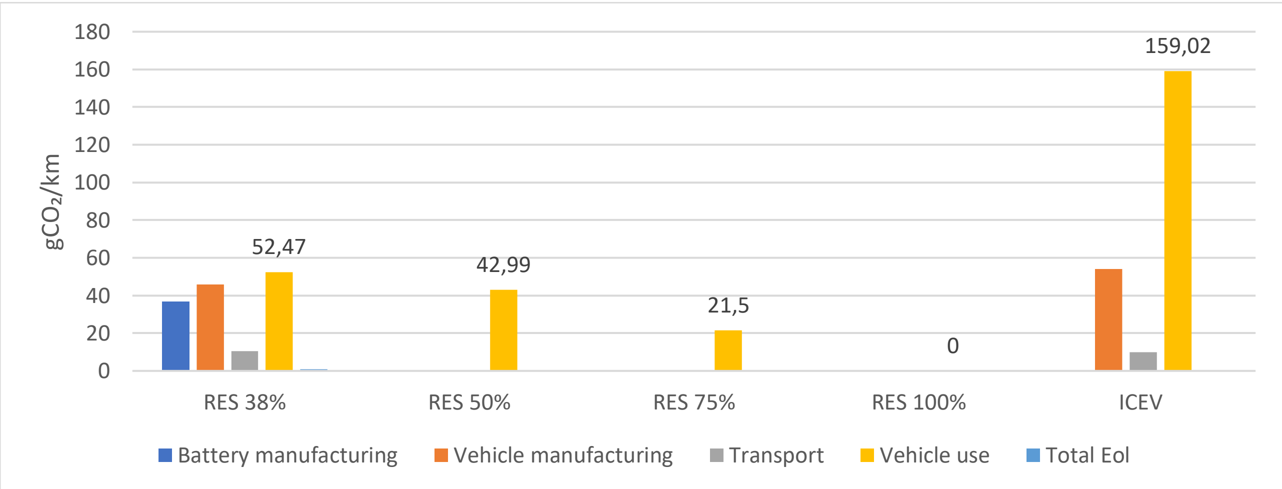


Fig. 53 Sensitivity analysis energy mix Segment C - worst case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	146,53	137,05	115,56	94,06	223,58
% over RES 38%	100%	94%	79%	64%	-

Table 32 BEV LC results for Segment C - worst case [Source: Adapted from BEV emission-model]

5.4.1.4 Segment D

- *"Best"* case

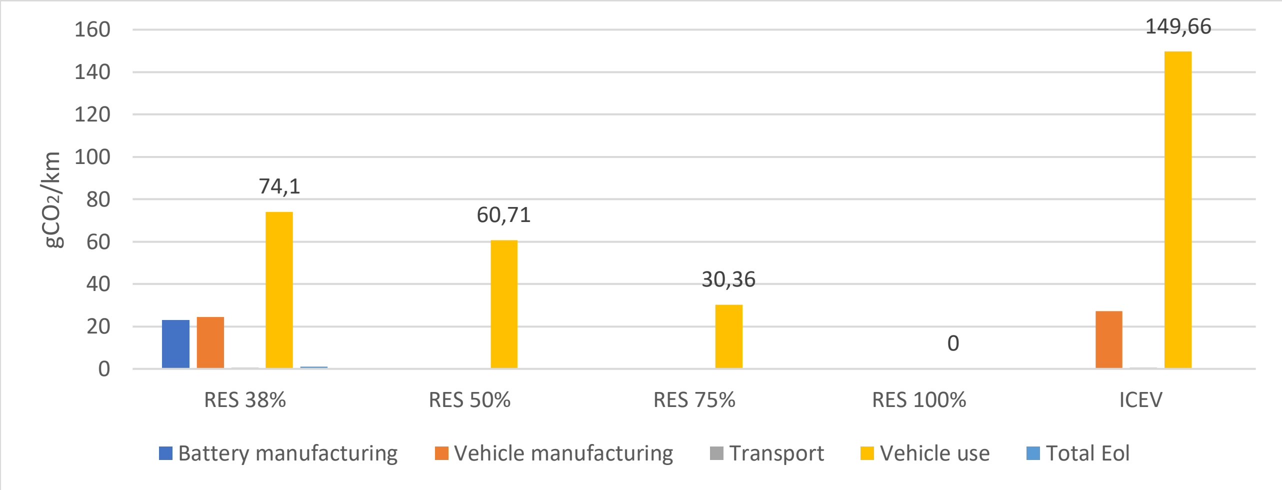


Fig. 54 Sensitivity analysis energy mix Segment D - best case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO2/km]	122,98	109,59	79,24	48,88	177,68
% over RES 38%	100%	89%	64%	40%	-

Table 33 BEV LC results for Segment D - best case [Source: Adapted from BEV emission-model]

- *Worst"* case

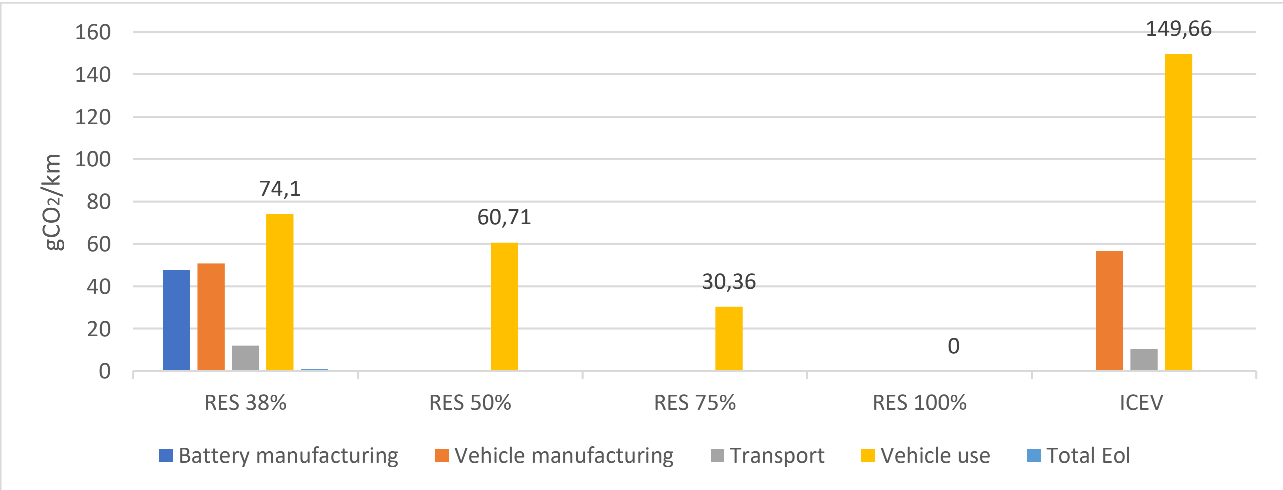


Fig. 55 Sensitivity analysis energy mix Segment D - worst case [Source: Adapted from BEV emission-model]

	RES 38%	RES 50%	RES 75%	RES 100%	ICEV
LC emissions [gCO_2/km]	185,42	172,03	141,68	111,32	216,92
% over RES 38%	100%	93%	76%	60%	-

Table 34 BEV LC results for Segment D - worst case [Source: Adapted from BEV emission-model]

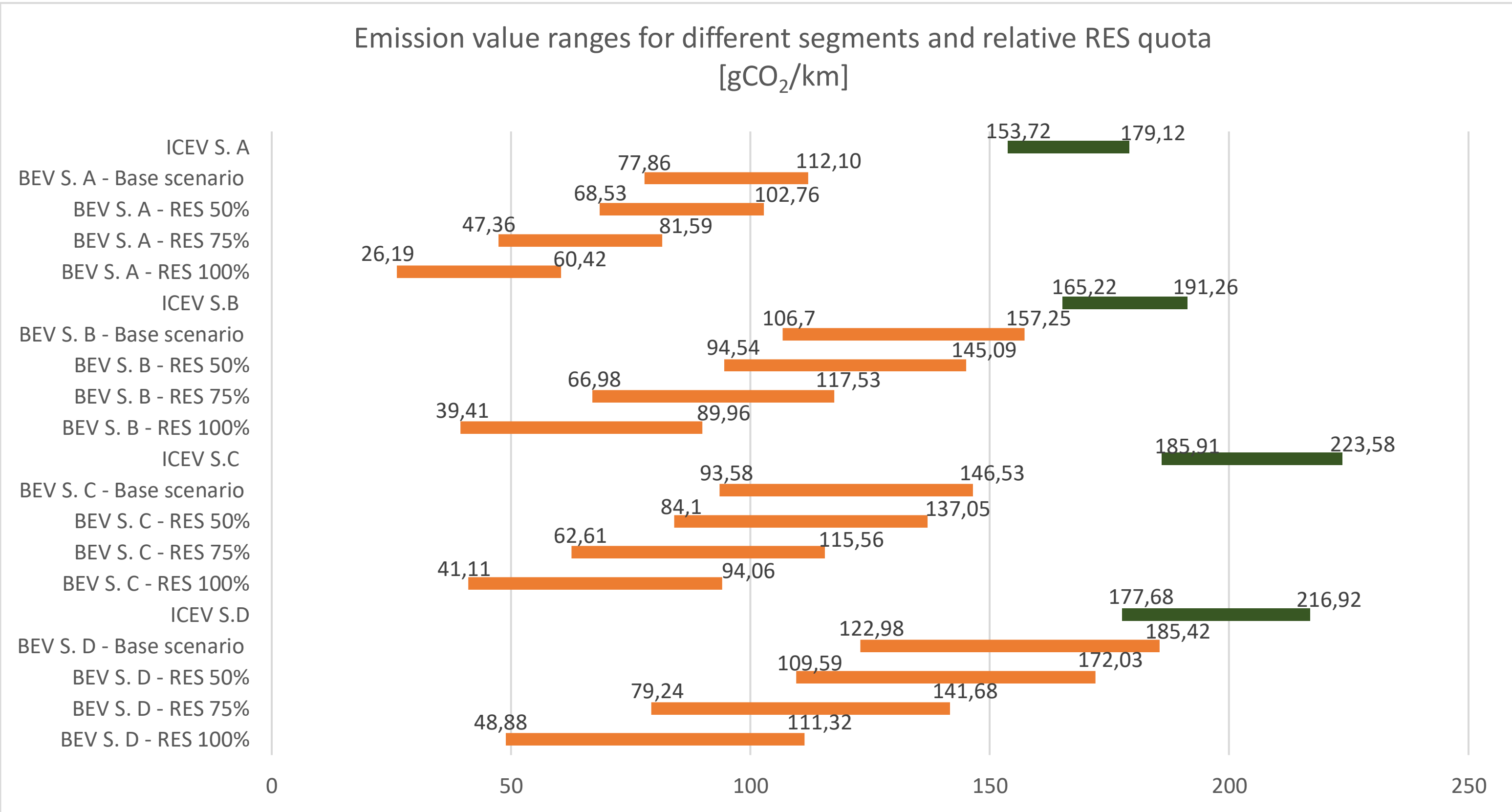
5.4.1.5 Scenarios overview

As it is possible to notice in all the scenarios and segments evaluated, when the energy mix gets cleaner or when RES penetration increases there is a consistent reduction of the CO_2 emissions associated to the use phase of the BEV. This decreasing emission trend is also posing a good contribution to the overall life cycle emissions. Increasing the RES penetration is becoming also more consistent the gap between BEV and ICEV as showed from *Table 27* to *Table 34.* It is easier to observe such trend in the emission ranges illustrated below, values are reported for "*best*" and "*worst*" cases.

vs	RES 50%	RES 75%	RES 100%
Segment A - best case	-12%	-39%	-66%
Segment A - worst case	-8%	-27%	-46%
Segment B - best case	-11%	-37%	-63%
Segment B - worst case	-8%	-25%	-43%
Segment C - best case	-10%	-33%	-56%
Segment C - worst case	-6%	-21%	-36%
Segment D - best case	-11%	-36%	-60%
Segment D - worst case	-7%	-24%	-40%

Table 35 LC CO_2 emission reduction for all scenarios [Source: Adapted from BEV emission-model]

It becomes clear that the possibility of relying on a private RES plant would allow EV owners to strongly reduce the amount of emissions associated to the use and to the relative life cycle of the vehicle.



5.4.2 Sensitivity analysis – Vehicle's consumption

In this section will be illustrated how changes in BEV's consumption may provide a strong impact on the overall use phase CO_2 emissions and on the entire vehicle's life cycle. In the literature review many studies have been evaluated that introduced the problem related to the consumption variations that a vehicle may incur when is evaluated the use phase. Generally, there is no clear evidence for a relationship among the vehicle's segment and weight with variations associated to vehicle's consumption. There are instead many other external factors which have an impact on such aspect. The most relevant to be addressed refers to:

- Use of auxiliaries (influenced by external temperatures)
- Driving behaviour (constant speed vs many accelerations)
- Charging behaviour
- Landscape morphology (mountain, hill or flat)
- Urban and extra-urban driving
- Battery efficiency (considering degradation effects or battery failures)

According to some studies evaluated (Egede et al., 2015; Kukreja, 2018; Notter et al., 2010), carmakers reports and documents consulted (Renault, 2019) it has been decided to study the variation on vehicle's consumption within a range of $\pm 20\%$. For the study of such variability are presented BEV's results for each segment, evaluating the different cases. The base scenario is given by the use phase evaluated in Italy (the value reported is the same for the *"best"* and *"worst"* scenarios, as the use phase emission values are the same) and results are compared with the respective of the ICEV segment.

- Segment A

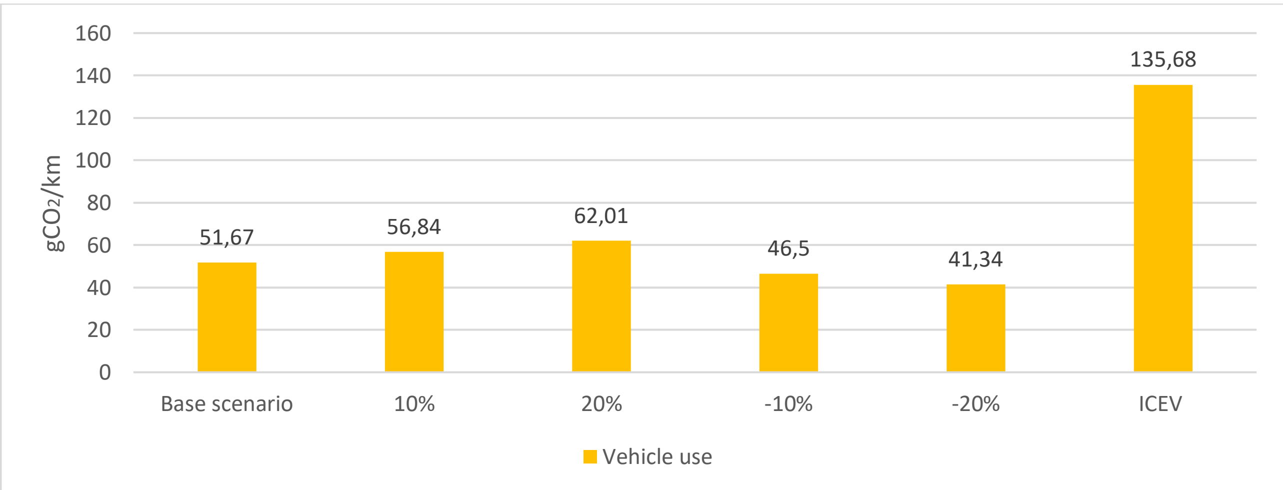


Fig. 56 Sensitivity analysis on vehicle's consumption Segment A [Source: Adapted from BEV emission-model]

	Base scenario	10%	20%	-10%	-20%	ICEV
LC emissions [gCO2/km]	77,86	83,03	88,2	72,69	67,53	153,82
% over base scenario	100%	107%	113%	93%	87%	-

Table 36 BEV LC results for Segment A [Source: Adapted from BEV emission-model]

- Segment B

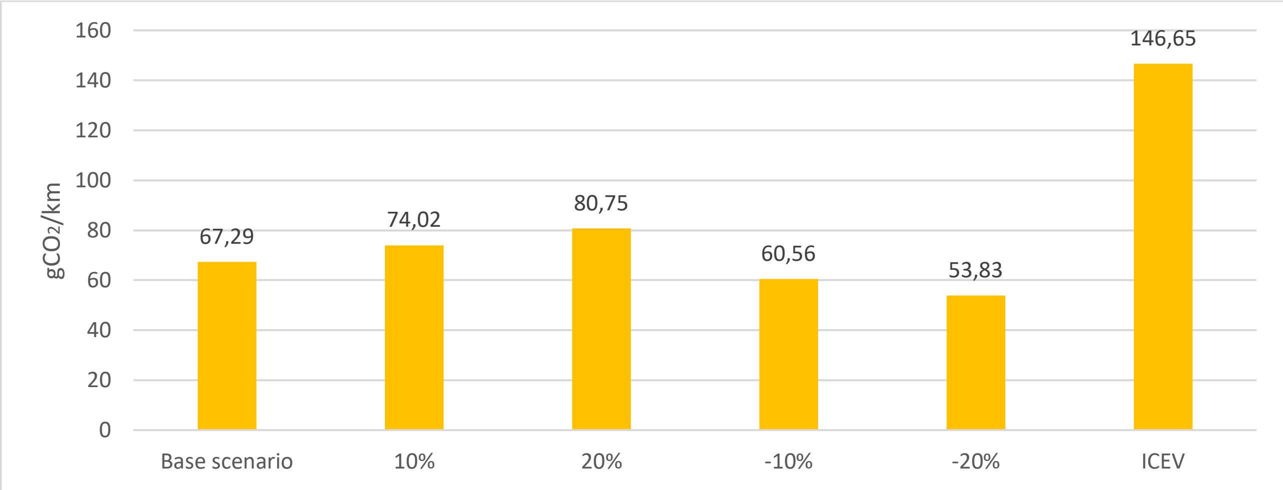


Fig. 57 Sensitivity analysis on vehicle's consumption Segment B [Source: Adapted from BEV emission-model]

	Base scenario	10%	20%	-10%	-20%	ICEV
LC emissions [gCO_2/km]	106,7	113,43	120,16	99,97	93,24	165,22
% over base scenario	100%	106%	113%	94%	87%	-

Table 37 BEV LC results for Segment B [Source: Adapted from BEV emission-model]

- Segment C

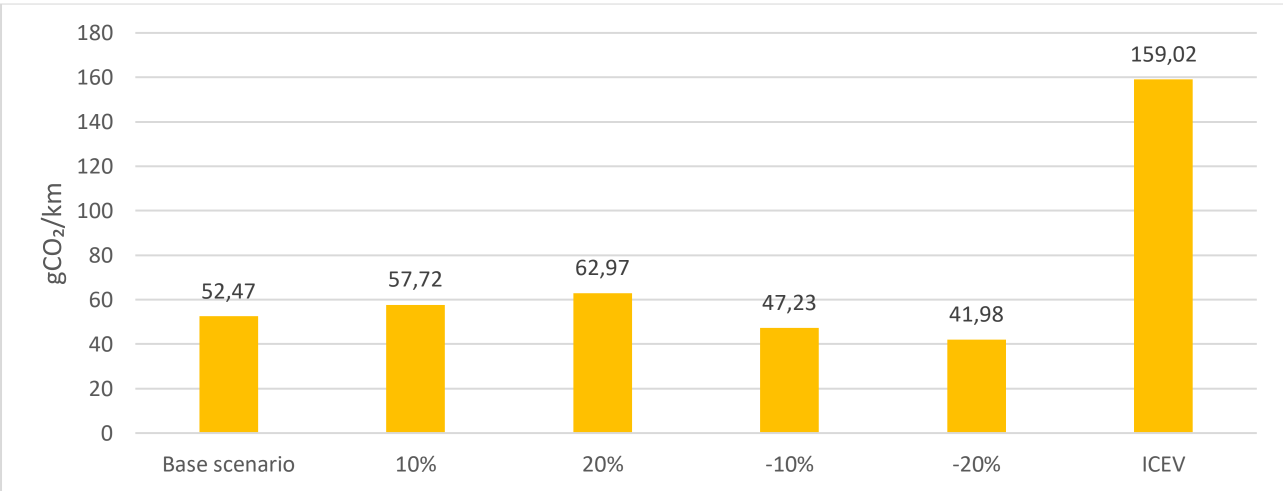


Fig. 58 Sensitivity analysis on vehicle's consumption Segment C [Source: Adapted from BEV emission-model]

	Base scenario	10%	20%	-10%	-20%	ICEV
LC emissions [gCO_2/km]	93,58	98,83	104,08	88,34	83,09	185,91
% over base scenario	100%	106%	111%	94%	89%	-

Table 38 BEV LC results for Segment C [Source: Adapted from BEV emission-model]

- Segment D

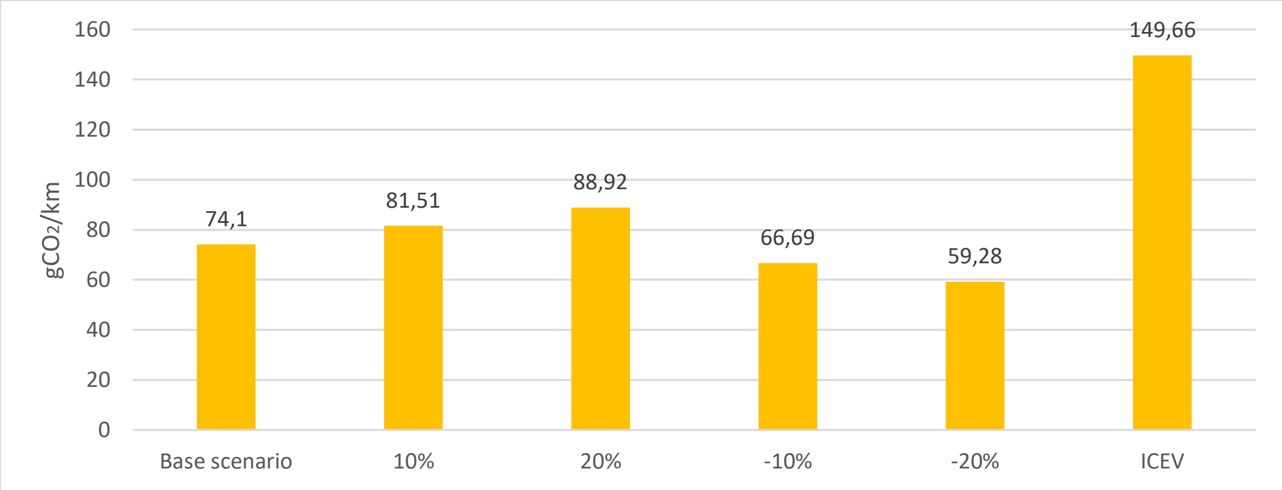


Fig. 59 Sensitivity analysis on vehicle's consumption Segment D [Source: Adapted from BEV emission-model]

	Base scenario	10%	20%	-10%	-20%	ICEV
LC emissions [gCO2/km]	122,98	130,39	137,8	115,57	108,16	177,34
% over base scenario	100%	106%	112%	94%	88%	-

Table 39 BEV LC results for Segment D [Source: Adapted from BEV emission-model]

It is possible to observe from *Table 40* the overview about the changes in $LC\ CO_2$ emissions for the vehicle segments previously evaluated.

vs	10%	20%	-10%	-20%
Segment A - base scenario	7%	13%	-7%	-13%
Segment B - base scenario	6%	13%	-6%	-13%
Segment C - base scenario	6%	11%	-6%	-11%
Segment D - base scenario	6%	12%	-6%	-12%

Table 40 LC CO_2 emission reduction for all segments [Source: Adapted from BEV emission-model]

It is important to mention that although in such analysis is considered a variation limited to $+20\%$, as upper bound, in some adverse and extreme cases could be even overcome such value.

5.4.3 Sensitivity analysis – lifetime km range

As already examined in *Chapter 4,* one of the most important input variables which impacts on the use phase and as well on the overall vehicle's life cycle is the km range to be driven. As illustrated in the previous chapter and in all the computational analyses that have been performed until this point, it has been worked with a fixed value of $150.000\ km$ which is in accordance with values found in the literature review. Such value is possible to be achieved during a lifetime of 12 to 14 years, with the hypothesis of covering a year distance of around $12.000\ km$. The aim of such sensitivity analysis is to evaluate the CO_2 emission impact when such value changes. The impact is naturally observed on the overall vehicle's life cycle phases.

Of course, the emissions produced during the use phase increase or decrease in absolute value but as the computation in gCO_2/km is obtained dividing the whole amount of CO_2 emissions by the km range; this value remains unchanged for all the different km range evaluated, as the proportion is kept constant.

In some LCA studies, covered in the literature review, many authors proposed such sensitivity analysis and adopted it to values that ranged from $100.000\ km$ to $300.000\ km$. The last value being exactly the double of the assumed vehicle's lifetime it seemed a bit too extreme to be accepted with creditability, mostly due to the problematics that can arise from battery's efficiency. For such reason it has been decided to evaluate such sensitivity analysis covering a km lifetime that ranged between values of $100.000\ km$ to $250.000\ km$.

In the next sub-paragraphs, the results are illustrated for all the vehicle segments and evaluated both the "*best*" and "*worst*" scenarios. The base scenario is set, as reference, with a vehicle's km lifetime at $150.000\ km$ and it is compared with all other cases. The other cases are evaluated, with the respective life cycle phases' emissions, ranging from $100.000\ km$ to $250.000\ km$ with steps of $25.000\ km$. It is assumed that no battery package substitution is occurring for the cases with a higher km range then the base scenario.

5.4.3.1 Segment A

- "*Best*" case or "*100% made in Italy*"

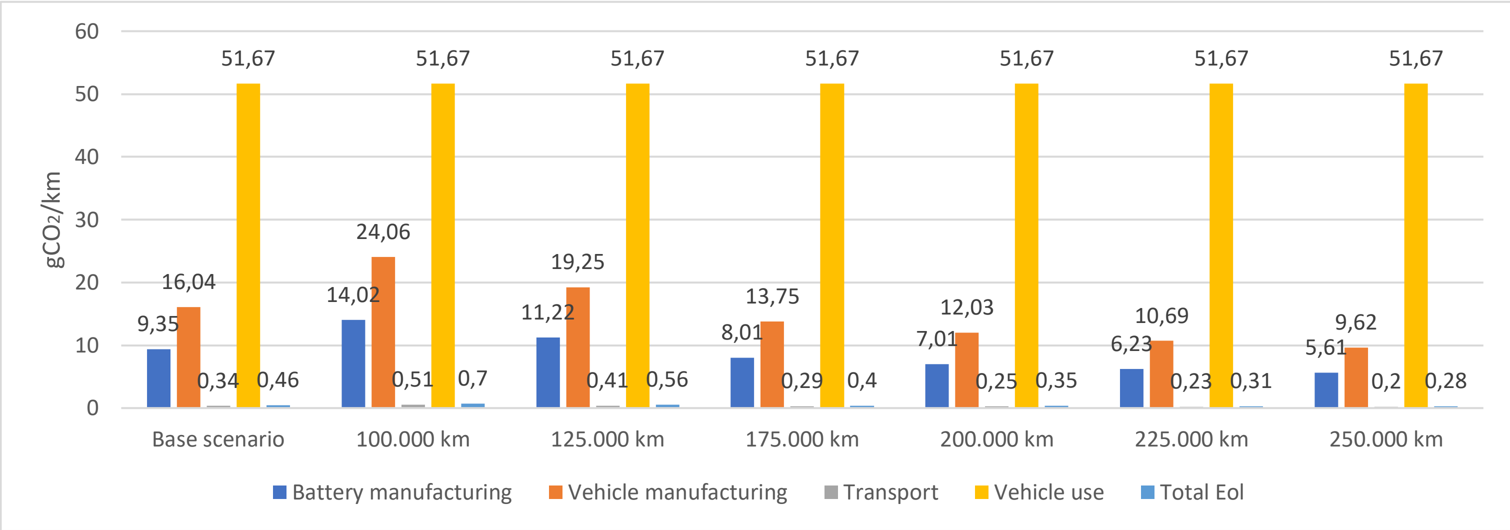


Fig. 60 Sensitivity analysis on vehicle's km range Segment A - best case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO_2/km]	77,86	90,96	83,11	74,12	71,31	69,13	67,38
% over base scenario	100%	117%	107%	95%	92%	89%	87%

Table 41 BEV LC results for Segment A - best case [Source: Adapted from BEV emission-model]

- "*Worst*" case

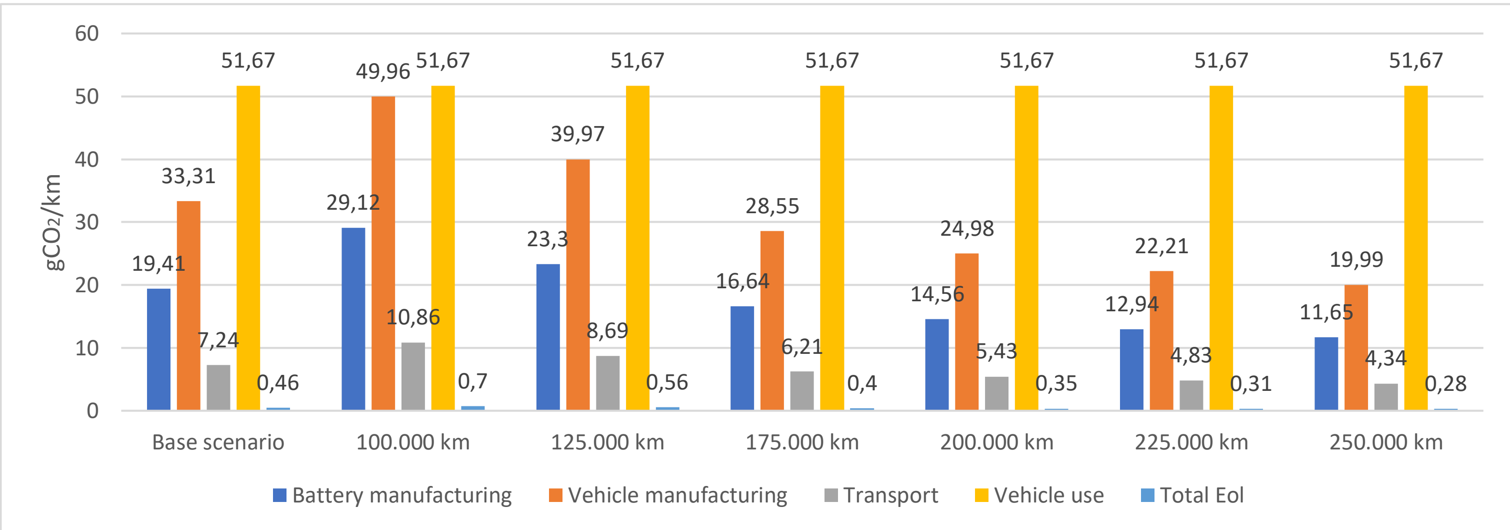


Fig. 61 Sensitivity analysis on vehicle's km range Segment A - worst case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO_2/km]	112,09	142,31	124,19	103,47	96,99	91,96	87,93
% over base scenario	100%	127%	111%	92%	87%	82%	78%

Table 42 BEV LC results for Segment A - worst case [Source: Adapted from BEV emission-model]

5.4.3.2 Segment B

- "*Best*" case or "*100% made in Italy*"

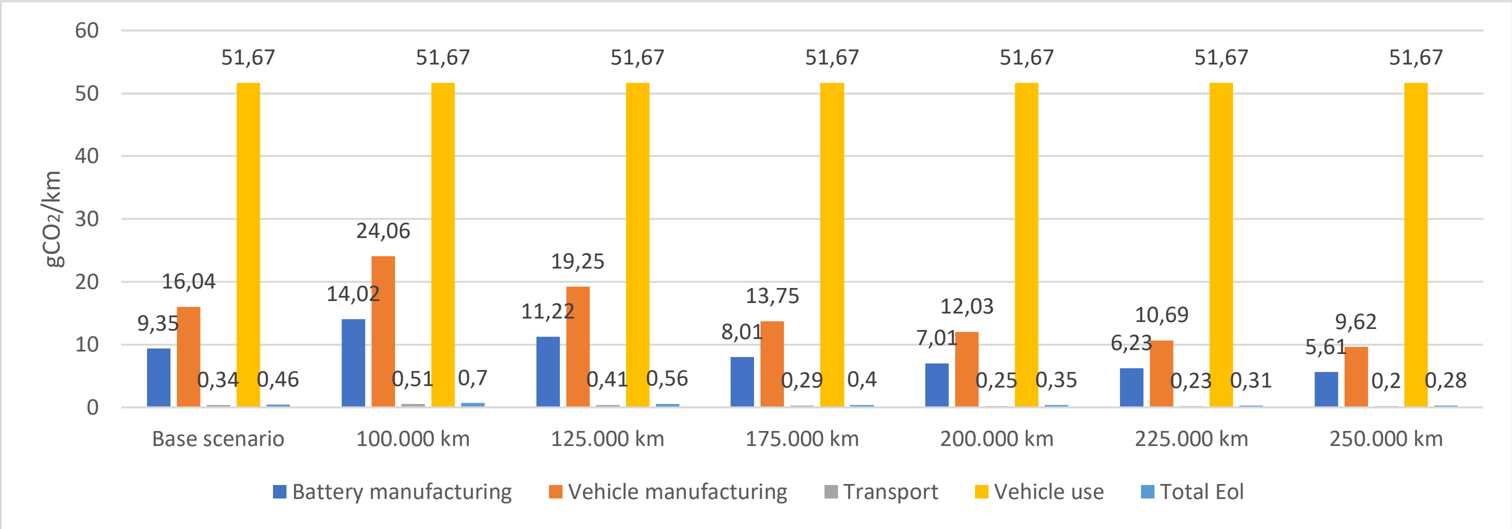


Fig. 62 Sensitivity analysis on vehicle's km range Segment B - best case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO2/km]	106,7	126,41	114,58	101,07	96,86	93,57	90,94
% over base scenario	100%	118%	107%	95%	91%	88%	85%

Table 43 BEV LC results for Segment B - best case [Source: Adapted from BEV emission-model]

- "*Worst*" case

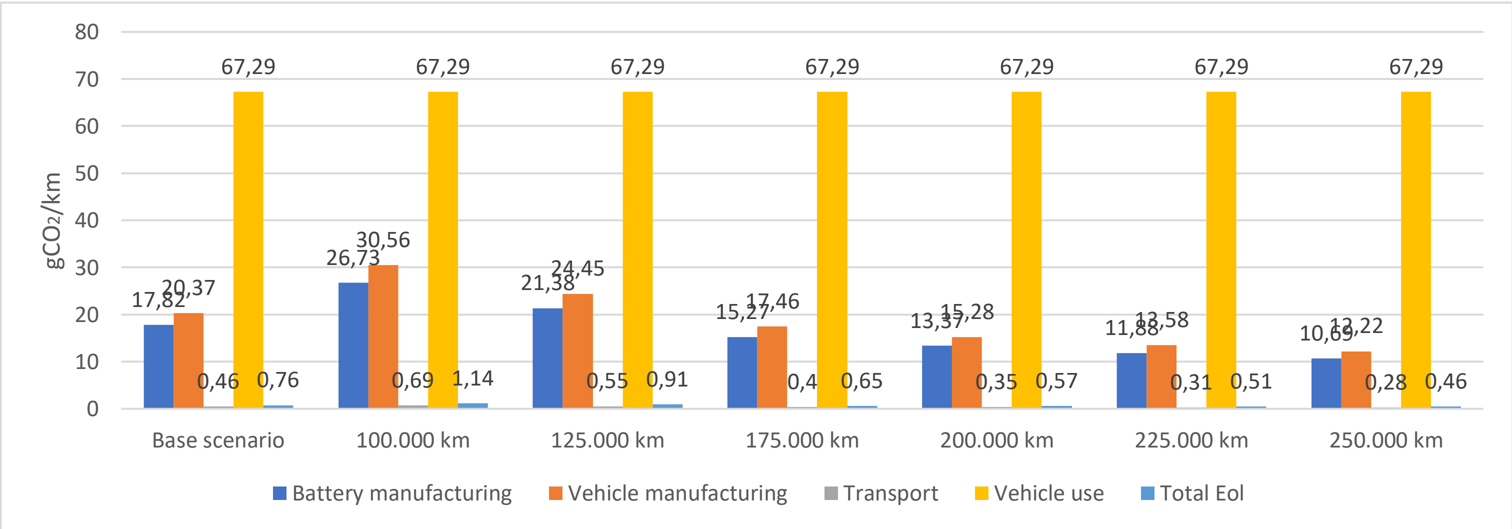


Fig. 63 Sensitivity analysis on vehicle's km range Segment B - worst case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO2/km]	157,25	202,22	175,23	144,4	134,76	127,26	121,27
% over base scenario	100%	129%	111%	92%	86%	81%	77%

Table 44 BEV LC results for Segment B - worst case [Source: Adapted from BEV emission-model]

5.4.3.3 Segment C

- "*Best*" case or "*100% made in Italy*"

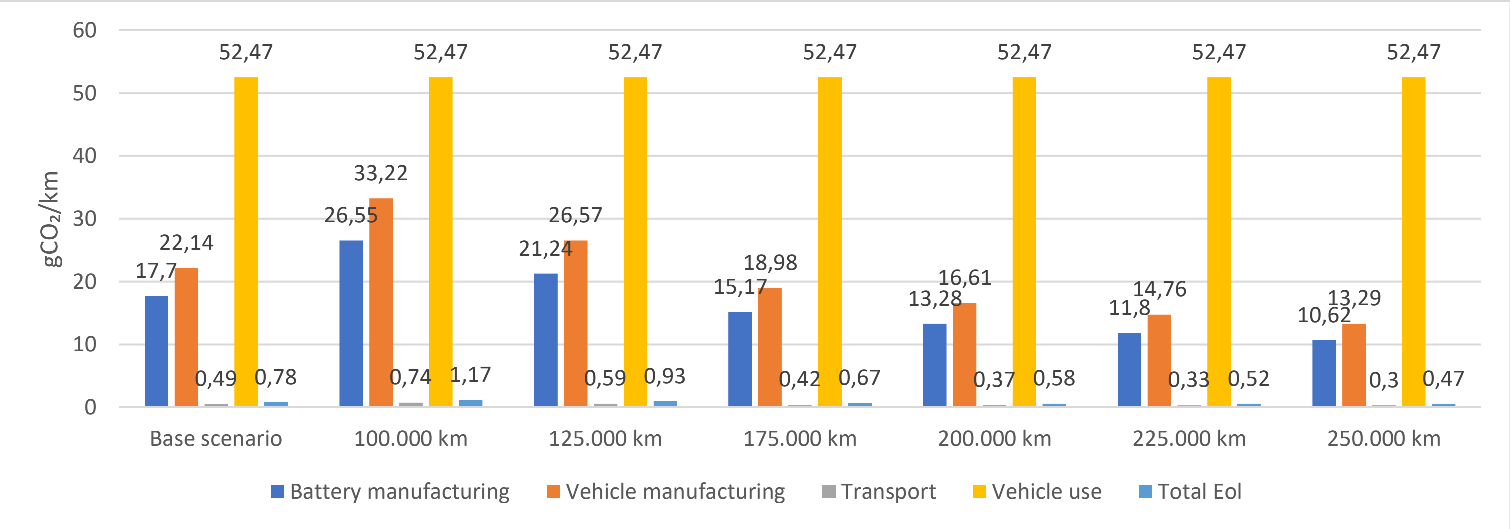


Fig. 64 Sensitivity analysis on vehicle's km range Segment C - best case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO2/km]	93,58	114,15	101,8	87,71	83,31	79,88	77,15
% over base scenario	100%	122%	109%	94%	89%	85%	82%

Table 45 BEV LC results for Segment C - best case [Source: Adapted from BEV emission-model]

- "*Worst*" case

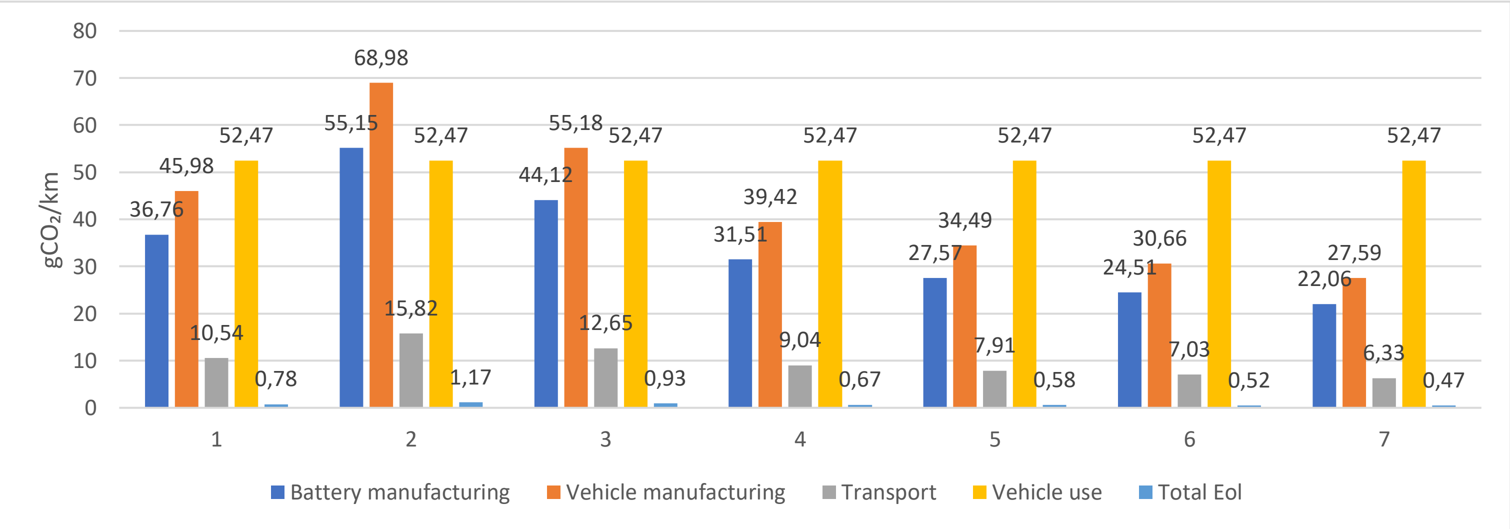


Fig. 65 Sensitivity analysis on vehicle's km range Segment C - worst case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO2/km]	146,53	193,59	165,35	133,11	123,02	115,19	108,92
% over base scenario	100%	132%	113%	91%	84%	79%	74%

Table 46 BEV LC results for Segment C - worst case [Source: Adapted from BEV emission-model]

5.4.3.4 Segment D

- *"Best"* case or *"100% made in Italy"*

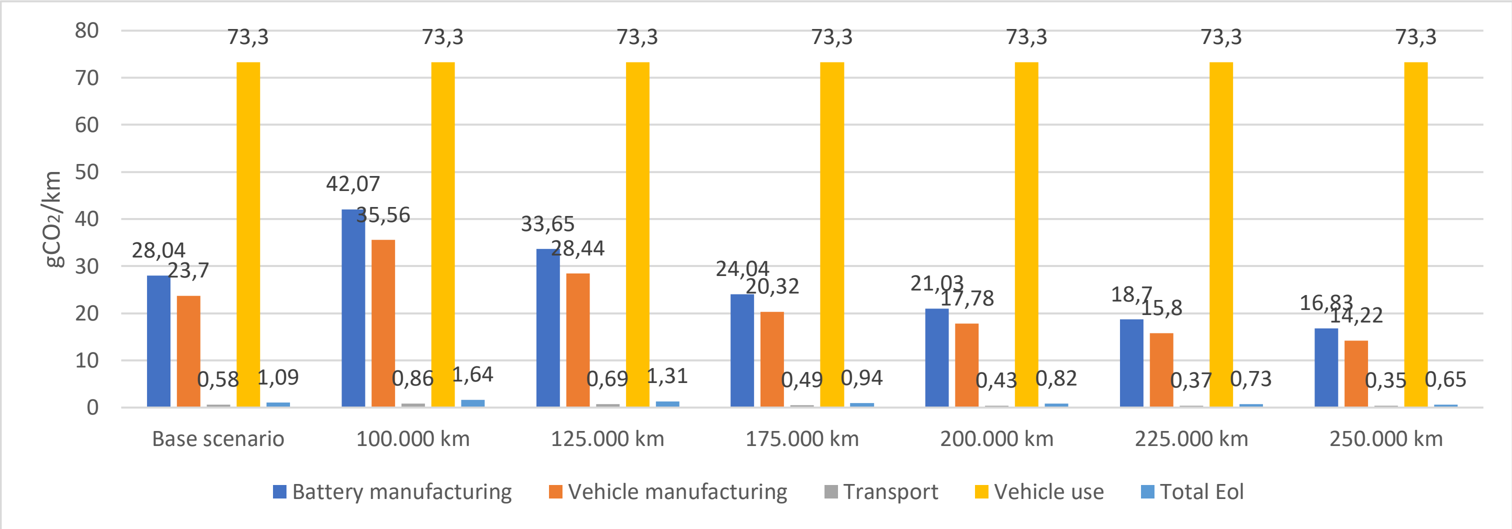


Fig. 66 Sensitivity analysis on vehicle's km range Segment D – best case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO_2/km]	126,71	153,43	137,39	119,09	113,36	108,9	105,35
% over base scenario	100%	121%	108%	94%	89%	86%	83%

Table 47 BEV LC results for Segment D - best case [Source: Adapted from BEV emission-model]

- *"Worst"* case

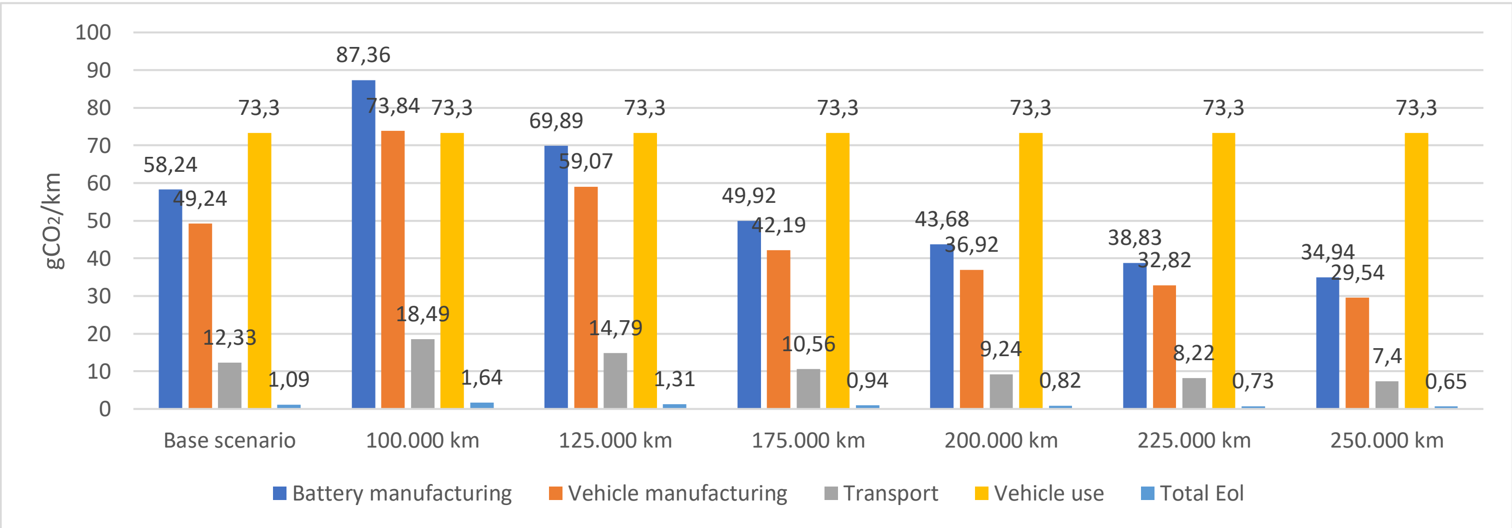


Fig. 67 Sensitivity analysis on vehicle's km range Segment D – worst case [Source: Adapted from BEV emission-model]

	Base scenario	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
LC emissions [gCO_2/km]	194,2	254,63	218,36	176,91	163,96	153,9	145,83
% over base scenario	100%	131%	112%	91%	84%	79%	75%

Table 48 BEV LC results for Segment D - worst case [Source: Adapted from BEV emission-model]

5.4.3.5 Segments overview

From the previous sections it is possible to notice how changes on vehicle's lifetime km can deploy fundamental impacts on the overall $LC\ CO_2$ emissions. Moving toward km values which are lower than the base scenario increase the amount of $LC\ gCO_2/km$ produced. This is due to the fact that the contribution of the stages of battery manufacturing, vehicle manufacturing, transport and EoL, have fixed values for their exploitation and decreasing the km range (which in the formulas used in *Chapter 4* is put at the denominator) increases as well the amount of CO_2 emission values coming from each of those stages in terms of gCO_2/km. It is the opposite case when the km range increases and so the overall emissions decrease. The only stage which remains unchanged is the use phase as the emissions are already computed for each km covered.

In *Table 49* are reported the changes in % for the overall $LC\ CO_2$ emissions for each case analysed according to the different segments. It is easy to notice that moving from the "*best"* to the "*worst*" case there is a consistent increase for the values below the threshold of $150.000\ km$ that can reach consistent shares of emissions. The opposite situation is verified when the km range exceeds the base scenario's value. It is also important to mention that sometime such high value of km range (more than $200.000\ km$) is possible to be achieved when considering also the change of the battery pack. This substitution allows to increase vehicle's lifetime and to reduce in such a way considerably the amount of emissions, but must be accounted also the emissions associated to the production of a new battery pack which would overcome the overall savings achieved with the km range extension.

vs	100.000 km	125.000 km	175.000 km	200.000 km	225.000 km	250.000 km
Segment A - best case	17%	7%	-5%	-8%	-11%	-13%
Segment A - worst case	27%	11%	-8%	-13%	-18%	-22%
Segment B - best case	18%	7%	-5%	-9%	-12%	-15%
Segment B - worst case	29%	11%	-8%	-14%	-19%	-23%
Segment C - best case	22%	9%	-6%	-11%	-15%	-18%
Segment C - worst case	32%	13%	-9%	-16%	-21%	-26%
Segment D - best case	21%	8%	-6%	-11%	-14%	-17%
Segment D - worst case	31%	12%	-9%	-16%	-21%	-25%

Table 49 LC CO_2 variations associated to different km range [Source: Adapted from BEV emission-model]

6. Conclusions

6.1 Model results

The models illustrated in the previous chapters gave important results for what concerns BEV's and ICEV's CO_2 emissions. Starting from the 16 different scenarios that have been studied, it is clear that the emissions associated to BEV's life cycle are lower compared to the respective ICEV segments. This first fundamental result is verified for all the cases analysed.

It is possible to notice that such result was obtained due to the fact that the analysis has been carried out for the use phase to be in Italy. If, different countries with a higher content of CO_2 emissions produced from the electricity generation would have been evaluated, then higher values for the overall amount of emissions generated along the entire BEV's life cycle would have been produced (specifically for the use phase).

Just as a matter of example it is possible to provide the case adapted to Poland, whose CO_2 emissions from the electricity production are about $678\ gCO_2/kWh$ (*Annex 2*), which is double more than the Italian emission value. Considering only the use phase to occur in Poland this would be translated, for a vehicle of segment A, considering the same characteristics as in *Table 15,* in $111{,}93\ gCO_2/km$ (computed over $150.000\ km$) which is almost the same value as for the respective ICEV of the same segment; emissions of the use phase for a petrol-powered vehicle belonging to segment A are equal to $135{,}68\ gCO_2/km$.

Evaluating the results from the 16 scenarios, it is clear that the highest contribution to the overall vehicle's life cycle emission comes from the use phase, both for BEVs and ICEVs. For BEVs the use phase accounted for a portion that ranged among the 38% (segment D – worst case) to almost 67% of the overall life cycle emissions (segment A – best case). The same evaluation can be made also for ICEVs whose use phase emissions ranged among 69% (segment D – worst case) to almost 89% (segment B – best case) of the overall life cycle emissions. As observed, the highest emissions during the use phase are produced from ICEVs.

For BEVs what plays the most important role to the contribution of the emissions coming from the use phase is the energy mix used for vehicle's charging. Although such emissions are not directly emitted at tailpipe, they are accounted from the electricity production.

For what concerns the emissions associated to the other phases it is easily noticed that BEVs have higher emissions coming from the manufacturing stage compared to ICEVs. They are additionally equipped with the battery pack and this provides a strong contribution to the amount of emissions produced. The emissions associated to battery manufacturing have been observed, in the scenarios analysed, to range among 12% (segment A – best case) to 30% (segment D – worst case) of BEV's overall life cycle emissions. If considering the overall manufacturing stage (battery + vehicle) values range among 32% (segment A – best case) to 55% (segment D – worst case). The contribution given by the battery pack increases the initial CO_2 emission gap that is present among BEVs and ICEVs. This is also the reason why if evaluated before the use phase, BEVs have higher values of emissions produced compared to traditional vehicles.

One important aspect associated to the emissions coming from the manufacturing stage has to deal with the location of the manufacturing plant. As highlighted for all the segments, the "*100% Italian* *scenario*" provides the best results for the CO_2 emissions produced from this stage. Such encouraging values are due to the values of the Italian energy mix, which is the cleanest among those of the countries analysed. Such good results were further analysed in the sensitivity analysis conducted on the different RES quota penetrations and allowed to evaluate how changes in the energy mix would further improve the CO_2 savings that could be achieved.

One important aspect that must be considered when comparing the results from the "*best*" and "*worst*" scenarios are the BEPs that have been computed. Considering the "*100% Italian scenarios*", values obtained from the different segments allowed to identify how such can provide a strong index for the achievement of a more sustainable mobility applied to our country. Although at the beginning there is a higher CO_2 emission production from BEVs manufacturing, evaluating the use phase in Italy there is the possibility to achieve the BEP respectively for segments A, B, C and D (considering an annual distance covered of around $12.000\ km$) after: 1.10 years, 3.17 years, 1.56 and 4.03 years. Considering BEV's lifetime to be around 12 to $14\ years$ this can be translated in the achievement of the BEP in a very short period of time, allowing all the years after the BEP to obtain net savings of CO_2 emissions compared to the respective ICEV.

Values from the BEV CO_2 emission-model were possible to be compared with those evaluated during the literature review. It is important to mention that most of the studies and LCAs reported information relative to general vehicles characteristics and did not provide all the information in order to properly classify vehicles as it is done in the presented emission-model. One of the main differences is that the developed emission-model tried to include all the variables that were impacting on BEV's life cycle emissions, contrary to some reviewed studies which performed, in some cases, analyses with a lower level of input variables or did not consider some.

As demonstrated by all reviewed studies, the stages contributing more to the CO_2 emission's production are represented by the manufacturing and the use phase, while transport and EoL provide a very limited emission contribution.

The reviewed studies and LCAs were mostly based on the assumption that the battery pack is manufactured in some Asian countries; mostly China, Japan and Korea (as it is in reality). Emission values reported in different studies based on such assumption (Ellingsen et al., 2016, 2014; Hall and Lutsey, 2018; Wu et al., 2018) were found to be in line with those obtained from the "*worst*" scenario for the different vehicle segments, as it is possible to compare values among those in *section 5.3* and from *Annex 1*. Although such values are reported gCO_2/km and in $gCO_2 - eq/km$ respectively from this emission-model and Annex values, it is possible to compare them and to notice a strong correlation.

Emission values associated the use phase, can be also easily compared among those obtained from the proposed emission model and those found during the literature review. Many studies adopted their analysis to European average values for the electricity mix (which can be set at $310\ gCO_2/kWh$ from *Annex 2*) which is very close to the Italian one ($313\ gCO_2/kWh$). Values can be easily compared among those of the literature review adapted to the European average with those provided from the emission-model adapted to the Italian scenario. Here again, values are reported gCO_2/km and in $gCO_2 - eq/km$ respectively from the emission-model and Annex values.

Studies focusing on the average European energy mix for the evaluation of the use phase (Concawe, 2019; Ellingsen et al., 2016, 2014; Hall and Lutsey, 2018; Messagie, 2017; Tagliaferri et al., 2016) provided values which are very close to those reported from the model and this is easily comparable looking at values reported in *section 5.3* and those in *Annex 1*.

Some of the small values' differences can be justified by the different assumptions on which such studies are built, just for example the different vehicle's consumption values, charging efficiency or the energy losses adapted for each specific vehicle and country.

With the proposed emission-model it is demonstrated to have obtained values which are coherent with those reviewed and so it is plausible to assume that values obtained from the BEV CO_2 emission-model are also representative of close-to-reality values.

6.2 Implications

6.2.1 Theoretical implications

The developed BEV and ICEV emission-models allow to evaluate which is the CO_2 environmental impact arising from the whole vehicle's life cycle. The models are structured in order to give the possibility to easily evaluate the CO_2 emissions by setting all the different input parameters as already described in *Chapter 4.* With all the data for the different energy mix of all the countries as provided in the database (*Annex 2*) it is theoretically possible to evaluate all the scenarios that want to be studied. With this model it is possible to set each single phase to occur in a different country and so to properly evaluate all the scenarios that can be thought.

Another of the main characteristics of such models is their versatility and application to the analysis of all the vehicles that want to be studied. By easily changing the values in the Microsoft Excel spreadsheet it is possible to simulate the analyses for all the vehicles, both electric and traditional.

One more aspect is related to the possibility of evaluating ICEVs which are using diesel or petrol to power the vehicle and to easily compere the results among the 2 vehicle typologies. The structure of the provided models allow also to easily perform the sensitivity analyses so to deepen in the evaluation of the emissions associated to BEV's life cycle.

6.2.2 Policy implications

The results obtained from the BEV emission-model illustrated which are the CO_2 savings that can be achieved with an electric vehicle compared to a traditional one. Applied to the Italian scenario, such encouraging and positive results, as showed in *Chapter 5,* give the possibility to evaluate some correlated topics associated to the development of electric mobility in Italy.

First of all, as highlighted with results obtained from the application of the "100% made in Italy" scenarios, it becomes relevant the contribution that would have the development of the manufacturing stage (battery and vehicle) to be performed in Italy. Compared to other countries the Italian energy mix, which is relying for a consistent share on RES, has a lower environmental impact in terms of gCO_2/kWh. The energy mix, which has been proved to be one of the most impacting factors on the life cycle emissions, is that one allowing Italy to be in a favourable condition for the evaluation of the establishment of the production and manufacturing stages. Compared to the 3 countries where manufacturing was performed, Italy was always the one having the best results as CO_2 emissions. The values obtained from the model application can serve, then, as stimulus for policy makers to favour the adoption and investments into electric mobility and to trigger the development of the so-called "*100% made in Italy*" scenario.

The possibility given by the presented emission-model is to provide also a tool that is able to quantify the overall CO_2 savings that can be achieved with electric vehicles and so deeply evaluate which will be the effects that electric mobility will have in the upcoming years. Positive values demonstrated by such work, together with all other studies and reports evaluated, allow to demonstrate how electric mobility will provide strong contributions in lowering the emissions coming from the transportation sector.

6.3 Model's limitations and future research

The models built in this thesis work had the aim of illustrating how CO_2 emissions can be calculated along vehicle's life cycle. The development of the models was strongly based on the literature review (as illustrated in *Chapter 3*) and all the correlated documents analysed.

One of the main problems that have been encountered during the development of such models was the possibility to obtain data for the electricity generation and all countries' energy mix. As showed, the energy mix is the most impacting factor when evaluating vehicle's life cycle emissions and the fact to do not have updated data till 2019 values and from a single dataset, in some way limits the results obtained from the application. As already discussed in *Chapter 4*, it was built a personal database from the combination of already existing database, found during the literature review.

The structure of the model anyway allows to introduce updated values (when available) so to better evaluate each single country condition and improve the accuracy of results. The same approach can be used also for vehicle's values and characteristics so to better tailor the level of analysis and obtain more accurate emission results.

It is expected that also values for the specific energy required for the manufacturing activities as well as for the different energy requirements for all the EoL solutions can be changed and updated in future, with new technologies and techniques being introduced. Just as example it is possible to mention the different EoL solutions as Hydrometallurgic and Pyrometallurgic. In the thesis work, it has not been considered the Hydrometallurgic solution due to the fact that it is still a technique not so diffused and also data reported for its specific energy requirements are not homogenous among the different sources analysed. It is anyway expected that in the upcoming years, with new developments and advancements on such field, this technique will be the most adopted, as it requires lower amount of energy and produces less environmental impact.

During the present thesis work have been addressed many topics related to the emissions produced during vehicle's life cycle. As the objective of the model was that of evaluating the CO_2 emissions it has been decided to follow a clear and straight line of proceeding in such analysis, but many correlated aspects can be considered for extending the present work and complementing it.

The first consideration which can be made is relative to the evaluation of the CO_2 emissions, which also for problems related to the access to more comprehensive database posed a limit to such analysis. In order to deepen more on such evaluation, it could be suggested to enlarge the analysis to the "$CO_2 - eq$" emissions and adapt a more comprehensive approach. It is important to consider how the split among the different greenhouse gases is contributing to the overall emission quantity and their effects on the environment, addressing the different impact categories as illustrated in *Chapter 3.3.5.*

Another aspect that could be further investigated is related to the PM emissions which are also strongly impacting on the environmental footprint generated by both electric and traditional vehicles. During the literature review have been covered some documents (Rangaraju et al., 2015; Timmers and Achten, 2016) which reported (very limited) values for the PM emissions for BEV, associated to the use phase. It could be interesting to extend the analysis to all BEV's life cycle phases and compare those results with those provided by traditional vehicles.

To investigate and compare the results for the CO_2 emissions, it can be suggested also to extend the analysis to different fuels considered for powering traditional vehicles. With new regulations and updated governments' policies, vehicles powered with biofuels and methane are becoming more diffused and adopted in the transportation sector. Such analysis' extension would provide a better overview of which is the actual scenario of the vehicles being used in the compact passenger car transportation sector.

As one of the objectives of the "20-20-20" package is to reach a minimum of 10% biofuels in the total consumption of diesel and petrol in the European Union, it becomes interesting to deeper the analysis on the evaluation of which could be the environmental impact produced by such biofuels and their relative CO_2 emission savings compared to traditional vehicles.

The sensitivity analyses performed in such thesis were chosen with the aim of analysing how changes on some parameters (related mostly to the use phase) would affect the overall vehicle's life cycle emissions. It is suggested that for a deeper and more accurate analysis to evaluate the different EoL solutions so to quantify better which is the emissions' savings that could be achieved with the different techniques. Another topic that could be addressed is related to the possible applications that the battery pack could fit, once has expired its vehicle's life. In this *section 6.4* are just mentioned some applications being implemented in those years but it is expected that within the next $5 - 10\ years$ there is the possibility to observe their mass adoption. This is mainly justified by the fact that nowadays it has not been reached the amount of years necessary to have the full capacity of batteries being reused, as electric vehicles have not yet been mass adopted on the market and at the same time have not expired their lifetime (as first generation vehicles).

The reusing solutions offered for the battery pack would allow to strongly reduce the amount of emissions associated to the production of storage devices and mostly contribute in reducing the amount of virgin materials and energy that would otherwise be used for their manufacturing.

6.4 E-mobility trends and future developments

Electric mobility development represents one of the main changes that the transportation sector together with that of the energy (production and distribution) are facing nowadays and that will deploy fundamental impacts in the upcoming years.

The analysis that has been conducted in this thesis work had also the aim of demonstrating how the projections of the CO_2 emission savings can be achieved with the development of such alternative form of mobility, and how it would be possible to reduce the environmental impact arising from the compact passenger vehicle transportation sector. Such encouraging results, demonstrated and provided also by many other reports, should serve as stimulus for a broader diffusion of electric vehicles.

It is important to stress that the development of electric mobility necessitates a strong support of a consistent net of charging infrastructures, without whom it is very difficult to achieve a large vehicles' adoption. A second fundamental key aspect is that the development of electric mobility must come together with the electric grid decarbonisation. Higher quotas of energy being produced from renewable energy sources represent the fulcrum for the abetment of the CO_2 emissions and to further lower the environmental impact of electric vehicles with respect to traditional ones. In the last years it has been observed a considerable increase of the amount of energy produced from renewable energy sources and a higher diffusion, at worldwide level, of plants producing electricity from renewable sources.

To boost the adoption of electric vehicles it is also necessary that national and local governments provide policy measures to incentivize the progressive shift from traditional vehicles. Many countries, as illustrated in *Chapter 1,* have started to introduce incentive measures and tax deductions to reduce also purchasing costs.

Electric mobility is also opening up the road to the possibility of developing many projects that properly fit with this new trend. Just to mention few, it is possible to evaluate the V2X paradigms which allow electric vehicles to be connected with buildings, chargers, electric grid, electric devices etc. Such connections are allowing a better level of data communication and also a smarter charging process. Another important area for projects to be evaluated is related to the second life of the battery pack, which once battery's efficiency lowers below the 80% threshold, can be further used and employed with several applications such as renewable energy grid storage, backup systems, small scale electricity production storage and many other. Such applications allow to extend battery's lifetime and at the same time to reduce the amount of emissions that would otherwise be generated for the manufacturing of other storage systems. In the last years numerous projects are being implemented at worldwide level by the main car manufacturer companies in partnership with start-ups and companies operating in such sectors.

It is plausible to assume that electric mobility will shape the future of the transportation and of the energy sector. It represents also a fundamental key for the transition toward a more sustainable mobility and for reducing the environmental impact provoked by the transportation sector.

Annex 1 – Literature review

	Author(s)	Year	Typologies of vehicles	Lifetime km range	Countries	Battery size & Technology
1	Burchart-Korol et al.	2018	BEVs & ICEVs	150.000	Poland Czech Republic	Li-Ion battery of 30 kWh energy density 114 Wh/kg 262 kg weight
2	Concawe review	2018	BEV (Nissan Leaf) BEV (BWM i3) BEV (Tesla model S)	150.000	EU - average Poland Sweden EU - average Poland Sweden EU - average Poland Sweden	Li-Ion battery of 30 kWh Li-Ion battery of 33 kWh Li-Ion battery of 100 kWh
3	Hale et Lutsey	2018	BEV (Nissan Leaf)	150.000	EU - average France Germany Netherlands Norway United Kingdom	Li-Ion battery of 30 kWh
4	Kukreja	2018	BEV (Mitsubishi i-MiEV) ICEV (Ford Focus)	150.000	Canada	Li-Ion battery of 16 kWh
5	La Picirelli de Souza et al.	2018	BEVs, ICEVs & PHEVs (average vehicles)	150.000	Brazil	Not specified
6	Peng et al.	2018	BEVs, ICEVs & PHEVs (average vehicles)	-	China USA Japan Canada EU	Not specified
7	Wu et al.	2018	BEVs (2010) BEVs (2014) BEVs (2020) ICEVs	150.000	China	Average Li-Ion battery 221 kg Average Li-Ion battery 221 kg Average Li-Ion battery 178 kg
8	Asaithambi et al.	2017	BEVs & ICEVs (average vehicles)	250.000	China USA Germany Japan	Not specified
9	Messagie	2017	BEVs (average vehicles)	150.000	Poland Germany Netherlands Italy Spain Belgium France Sweden EU-28	Li-Ion battery of 30 kWh
10	Ellingsen et al.	2016	BEVs (mini car) BEVs (medium car) BEVs (large car) BEVs (luxury car)	180.000	EU - average	Li-Ion battery of 17,7 kWh Li-Ion battery of 24,4 kWh Li-Ion battery of 42,1 kWh Li-Ion battery of 59,9 kWh
11	Tagliaferri et al.	2016	BEV (Nissan Leaf) BEV (Nissan Leaf) HEV (Toyota Yaris Hybrid) PHEV (Toyota Prius Plug-in) ICEV (Toyota Yaris)	150.000	EU - average	Li-Ion battery of 24 kWh, energy density 112 Wh/kg and 214 kg weight Li-Ion battery of 24 kWh, energy density 106 Wh/kg and 250 kg weight - - -
12	Egede et al.	2015	BEVs (average vehicles)	150.000	-	Not specified
13	Ellingsen	2014	BEVs (average vehicles)	150.000	Norway	Li-Ion battery of 26,6 kWh energy density 105 Wh/kg 253 kg weight
14	Helmers et Marx	2012	BEV (Smart fortwo) ICEVs & PHEVs	100.000	Germany	Li-Ion battery of 14 kWh energy density 87,5 Wh/kg 160 kg weight
15	Majeau-Bettez et al.	2011	BEVs (only batteries)	-	EU - average	Different Li-Ion typologies covered
16	Notter et al.	2011	BEV (Volkswagen Golf) & ICEVs	150.000	EU - average	Li-Ion battery of 34 kWh energy density 114 Wh/kg 300 kg weight

	Only for BEVs					
	Battery production GHG emissions [gCO_2-eq/km]	Vehicle production GHG emissions [gCO_2-eq/km]	Vehicle operation GHG emissions [gCO_2-eq/km]	Vehicle consumption data [kWh/100km]	Life-cycle GHG emissions [gCO_2-eq/km]	Additional Notes
1	18,2	56,6	201,73	19,9	276,53	Cradle-to-grave approach with a particular focus on the electricity production and development of sensitivity analisis with different scenarios (2015 to 2050).
	17,7	50,5	145,8	19,9	214	
2	30	35,33	51,33	15	116,66	Cradle-to-grave anaysis, considering different vehicles segments. Manufacturing of battery emissions are assessed to be equal in all countries of usage and regardless of the size (simplification of 150 kgCO2/kWh), same approach for vehicle manufacturing with 4,5 and 7 tons CO2/vehicle for segment B, C and D.
			109,33	15	174,66	
			4,66	15	69,99	
	33	27	66	16,1	126,00	
			137,33	16,1	197,33	
			7,33	16,1	67,33	
	100	46,6	87,33	18,1	233,93	
			185,33	18,1	331,93	
			12	18,1	158,60	
3	35	40	55,26	20	130,26	Assuming BEV consumption 20 kWh/100 km in all countries (simplification). Production of batteries is assumed to be in Japan and South Korea. General considerations made for energy savings from recycling, reusing and grid decarbonization.
	35	40	12,1	20	87,1	
	35	40	114,21	20	189,21	
	35	40	79,5	20	154,5	
	35	40	0	20	75	
	35	40	53,4	20	128,4	
4	198		2,2	21	203	Cradle-to-grave approach and performed a sensitivity analisis on lifetime km range.
5	2,27	6,35	7,14	17	15,76	Cradle-to-grave approach specific for Brazil.
6	75,5		94,65	21,5	170,15	Assumed real-world driving conditions considering a Well-to-Wheel (WTW) analysis. Did not consider the vehicle cycle and sub-national grid energy mix and the charging efficiency is set equal to 90%. Special focus on China.
	-	-	-	23,4	130,88	
	-	-	-	17,8	55,51	
	-	-	-	16,8	125,28	
	-	-	-	23,9	49,01	
7	18,08	42,20	220,05	19	280,33	Evaluating 3 different scenarios for 2010, 2014, 2020 taking into consideration average vehicles. Focus more on vehicle cycle and fuel cycle rather than on battery manufacturing.
	18,98	35,24	155,11	15,5	209,33	
	16,14	48,41	112,78	12,5	177,33	
	-	-	-	-	-	
8	-	-	142,8	20	-	Semplicistic analysis, consumption data set equal for all countries.
	-	-	220	20	-	
	-	-	130	20	-	
	-	-	80	20	-	
9	13	16	130	-	159	Report to comper the values for EU countries, taking as reference a battery of 30 kWh and assuming 1,5 battery replacement over vehicle lifetime (battery manufactured outside EU).
	13	16	82	-	111	
	13	16	76	-	105	
	13	16	62	-	91	
	13	16	58	-	87	
	13	16	40	-	69	
	13	16	8	-	37	
	13	16	4	-	33	
	13	16	60	-	89	
10	12,2	26,7	75,6	14,6	114,5	Cradle-to-grave analysis to investigate effects due to the increasing battery size and distance travelled.
	17,8		88,3	17	106,1	
	27,2	38,9	96,7	18,5	162,8	
	38,4	44,4	107,8	20,7	190,6	
11	53,8		70	17,3	123,8	Cradle-to-grave approach; covering manufacturing, use and end-of-life phases. The study is based on values of the European energy mix and it is considering 2 different models of batteries for the BEV and models of HEV, PHEV and ICEV.
	48		70	17,3	118	
	-	-	-	-	-	
	-	-	-	-	-	
	-	-	-	-	-	
12	-	-	-	-	-	Study focused on influencing factors and what are their impacts on vehicle operations. Development of 3 scenarios (100.000 km, 150.000 km and 200.000 km)
13	30,5	-	-	-	-	Cradle-to-gate analysis, considering battery production in Asia while assembly in Norway. Performed a sensitivity analisis on electricity mix.
14	10	47	83	14,5	140	2 models of BEV considered, a New Smart and a converted one from a petrol-powered configuration.
	-	-	-	14,5	108	
15	15 - 50	-	-	20	-	LCA on Li-Ion batteries, uses combined top-down and bottom-up approaches. Different battery chemistries have significant variations.
16	12,08	41	100	17	153,08	Analisis conducted with a bottom-up approach. It is assumed that battery production occurs in China. Conducted a sensitivity analisis on lifetime km range.

Annex 2 – Countries CO_2 emissions for electricity production

Country	CO_2 emissions for electricity generation	Source	Year
[-]	[gCO_2/kWh]	[-]	[-]
Abu Dhabi (ADWEC)	619,0	IFI Database	2016
Africa 2017	587,8	Enerdata	2017
Africa 2020	503	Enerdata	2017
Africa 2025	444	Enerdata	2017
Africa 2030	401	Enerdata	2017
Africa 2035	364	Enerdata	2017
Africa 2040	331	Enerdata	2017
Algeria	347,7	IFI Database	2016
Angola	170,4	IFI Database	2016
Argentina	425,0	IFI Database	2016
Armenia	416,0	IFI Database	2016
Asia-Pacific 2017	608,0	Enerdata	2017
Asia-Pacific 2020	554	Enerdata	2017
Asia-Pacific 2025	490	Enerdata	2017
Asia-Pacific 2030	449	Enerdata	2017
Asia-Pacific 2035	415	Enerdata	2017
Asia-Pacific 2040	379	Enerdata	2017
Australia	595,1	IFI Database	2016
Austria	134,3	IFI Database	2016
Azerbaijan	307,6	IFI Database	2016
Bahamas	1004,0	EnerData	2017
Bahrain	334,9	IFI Database	2016
Bangladesh	674,0	IFI Database	2016
Belarus	336,5	IFI Database	2016
Belgium	143,0	IFI Database	2016
Bolivia	229,6	IFI Database	2016
Bosnia and Herzegovina	508,5	IFI Database	2016
Brazil	104,4	EPE - IEA	2017
Brunei Darussalam	337,4	IFI Database	2016
Bulgaria	404,0	IFI Database	2016
Cambodia	688,0	IFI Database	2016
Cameroon	137,7	IFI Database	2016
Canada	123,4	IFI Database	2016
Chile	388,9	IFI Database	2016
China	650	? IEA	2017
Colombia	102,6	IFI Database	2016
Congo DR	0,9	EnerData	2017
Costa Rica	2,2	EnerData	2017
Côte d'Ivoire	257,8	IFI Database	2016
Croatia	258,0	IFI Database	2016
Cuba	536,7	IFI Database	2016
Curaçao	586,9	IFI Database	2016
Cyprus	554,0	IFI Database	2016
Czech Republic	425,0	IFI Database	2016
Denmark	149,2	IFI Database	2016
Dominican Republic	379,3	IFI Database	2016
Dubai (DEWA)	459,0	IFI Database	2016
Ecuador	248,0	IFI Database	2016
Egypt	338,6	IFI Database	2016
El Salvador	207,0	IFI Database	2016

Country	CO_2 emissions for electricity generation	Source	Year
[-]	[gCO_2/kWh]	[-]	[-]
Eritrea	586,9	IFI Database	2016
Estonia	685,0	IFI Database	2016
Ethiopia	0,2	EnerData	2017
Europe	310	Enerdata	2017
Europe 2020	281	Enerdata	2017
Europe 2025	245	Enerdata	2017
Europe 2030	213	Enerdata	2017
Europe 2035	191	Enerdata	2017
Europe 2040	174	Enerdata	2017
Fiji	770,0	IFI Database	2016
Finland	180,0	IFI Database	2016
France	46,0	IFI Database	2016
Georgia	73,5	IFI Database	2016
Germany	403,0	IFI Database	2016
Ghana	160,5	IFI Database	2016
Gibraltar	586,9	IFI Database	2016
Greece	515,0	IFI Database	2016
Guatemala	224,0	IFI Database	2016
Haiti	493,6	IFI Database	2016
Honduras	310,0	IFI Database	2016
Hong Kong	650,5	IFI Database	2016
Hungary	236,0	IFI Database	2016
Iceland	0,2	EnerData	2017
India	507,0	IFI Database	2016
Indonesia	547,9	IFI Database	2016
Iran (Islamic Republic)	382,7	IFI Database	2016
Iraq	105,0	EnerData	2017
Ireland	389,0	IFI Database	2016
Israel	612,5	IFI Database	2016
Italy 2017	313,0	IFI Database	2016
Italy 2020	283,8	EnerData	2017
Italy 2025	247,6	EnerData	2017
Italy 2030	214,7	EnerData	2017
Italy 2035	193,0	EnerData	2017
Italy 2040	175,7	EnerData	2017
Jamaica	528,6	IFI Database	2016
Japan	446,3	IFI Database	2016
Jordan	525,3	IFI Database	2016
Kazakhstan	652,8	IFI Database	2016
Kenya	173,9	IFI Database	2016
Korea (South)	433,5	IFI Database	2016
Korea, DRP (North)	228,5	IFI Database	2016
Kosovo	756,1	IFI Database	2016
Kuwait	493,7	IFI Database	2016
Kyrgyzstan	46,3	IFI Database	2016
Laos	560,0	IFI Database	2016
Latin America 2017	248,1	Enerdata	2017
Latin America 2020	223	Enerdata	2017
Latin America 2025	190	Enerdata	2017
Latin America 2030	170	Enerdata	2017

Country	CO_2 emissions for electricity generation	Source	Year
[-]	[gCO_2/kWh]	[-]	[-]
Latin America 2035	155	Enerdata	2017
Latin America 2040	145	Enerdata	2017
Latvia	140,0	IFI Database	2016
Lebanon	550,8	IFI Database	2016
Lithuania	230,0	IFI Database	2016
Luxemburg	284,0	IFI Database	2016
Madagascar	635,0	IFI Database	2016
Malaysia	498,3	IFI Database	2016
Maldives	2724,0	EnerData	2017
Malta	582,0	IFI Database	2016
Mauritania	989,0	EnerData	2017
Mauritius	813,0	IFI Database	2016
Mexico	366,4	IFI Database	2016
Middle-East 2017	658,1	Enerdata	2017
Middle-East 2020	579	Enerdata	2017
Middle-East 2025	508	Enerdata	2017
Middle-East 2030	457	Enerdata	2017
Middle-East 2035	409	Enerdata	2017
Middle-East 2040	350	Enerdata	2017
Moldova	316,5	IFI Database	2016
Mongolia	1056,0	IFI Database	2016
Montenegro	347,4	IFI Database	2016
Morocco	549,9	IFI Database	2016
Mozambique	933,1	IFI Database	2016
Myanmar	114,1	IFI Database	2016
Namibia	933,1	IFI Database	2016
Nepal	1,6	IFI Database	2016
Netherlands	391,0	IFI Database	2017
New Zealand	113,5	IFI Database	2016
Nicaragua	332,2	IFI Database	2016
Nigeria	268,2	IFI Database	2016
North America 2017	378,0	Enerdata	2017
North America 2020	377	Enerdata	2017
North America 2025	327	Enerdata	2017
North America 2030	284	Enerdata	2017
North America 2035	256	Enerdata	2017
North America 2040	233	Enerdata	2017
Norway	16,4	NVE	2017
Oceania	667	IEA	2017
OECD	392	IEA	2017
OECD Americas	400	IEA	2017
OECD Asia	556	IEA	2017
OECD Europe	291	IEA	2017
Oman	341,1	IFI Database	2016
Pakistan	305,4	IFI Database	2016
Panama	231,7	IFI Database	2016
Paraguay	0,1	EnerData	2017
Peru	408,0	IFI Database	2016
Philippines	674,0	IFI Database	2016
Poland	678,0	IFI Database	2016

Country	CO_2 emissions for electricity generation	Source	Year
[-]	[gCO_2/kWh]	[-]	[-]
Portugal	281,0	IFI Database	2016
Qatar	334,9	IFI Database	2016
Romania	334,0	IFI Database	2016
Russia	297,7	IFI Database	2016
Rwanda	401,0	IFI Database	2016
Saudi Arabia	335,0	IFI Database	2016
Senegal	503,0	IFI Database	2016
Serbia	574,1	IFI Database	2016
Seychelles	1331,0	EnerData	2017
Singapore	433,0	IFI Database	2016
Slovakia	147,0	IFI Database	2016
Slovenia	261,0	IFI Database	2016
Somalia	101,0	EnerData	2017
South Africa	933,1	IFI Database	2016
South Sudan	586,9	IFI Database	2016
Spain	241,0	IFI Database	2016
Sri Lanka	766,0	IFI Database	2016
Sudan	149,0	IFI Database	2016
Swaziland	933,1	IFI Database	2016
Sweden	37,4	EnerData	2017
Switzerland	36,9	EnerData	2017
Syrian Arab Republic	388,6	IFI Database	2016
Taipei (Chinese)	493,2	IFI Database	2016
Taiwan	595,2	EnerData	2017
Tajikistan	1,0	IFI Database	2016
Tanzania	259,5	IFI Database	2016
Thailand	423,0	IFI Database	2016
Togo	97,8	IFI Database	2016
Trinidad and Tobago	335,7	IFI Database	2016
Tunisia	325,7	IFI Database	2016
Turkey	366,9	IFI Database	2016
Turkmenistan	334,9	IFI Database	2016
Uganda	454,0	IFI Database	2016
Ukraine	338,9	IFI Database	2016
United Arab Emirates	338,3	IFI Database	2016
United Kingdom	385,0	IFI Database	2016
United States	408,0	IFI Database	2016
Uruguay	11,9	EnerData	2017
Uzbekistan	496,0	IFI Database	2016
Venezuela	143,4	IFI Database	2016
Vietnam	476,0	IFI Database	2016
World 2017	493,8	Enerdata	2017
World 2020	456	Enerdata	2017
World 2025	404	Enerdata	2017
World 2030	368	Enerdata	2017
World 2035	341	Enerdata	2017
World 2040	313	Enerdata	2017
Yemen	514,3	IFI Database	2016
Zambia	933,1	IFI Database	2016
Zimbabwe	933,1	IFI Database	2016

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