POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Comparative assessment of life cycle GHG emissions of battery electric vehicles and internal combustion engine vehicles in different countries

MASTER OF SCIENCE THESIS IN

ENERGY ENGINEERING-INGEGNERIA ENERGETICA

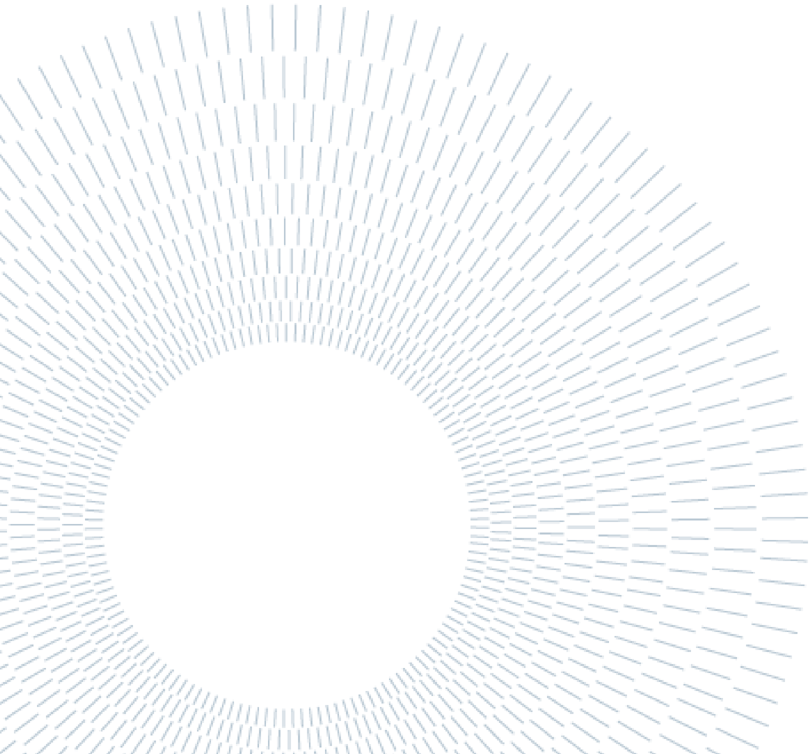
Author: **Stefano Stradiotti**

Student ID: 10499862

Advisor: Prof. Riccardo Mereu

Co-advisor: Ing. Francesco Davide Sanvito

Academic Year: 2020-2021



Abstract

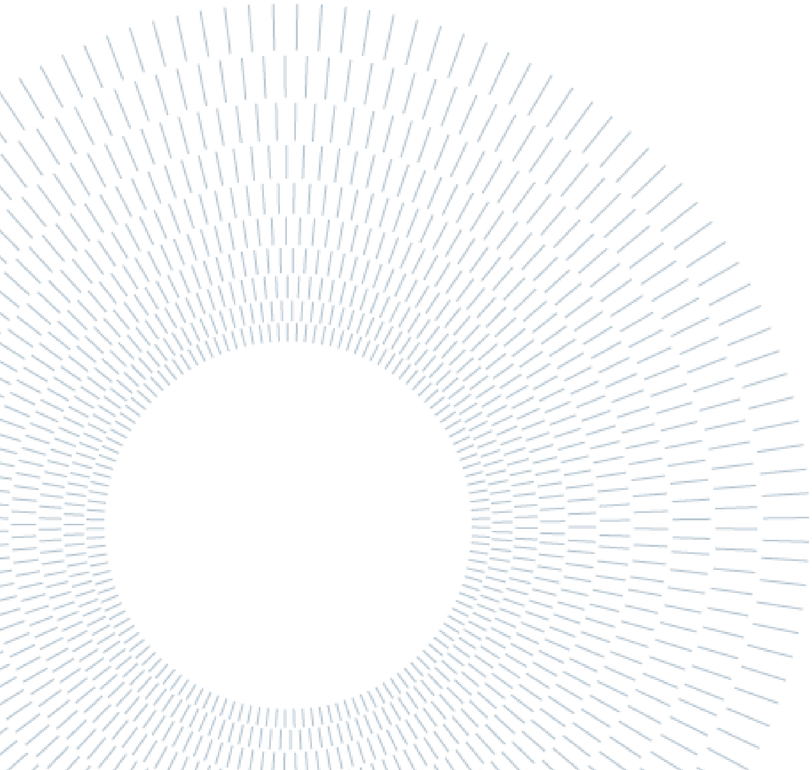
The increasing contribution of the transport sector, particularly lightweight vehicles, to global greenhouse gas GHG emissions over the past decades is posing a significant resistance toward the fulfillment of global net-zero emissions. One way forward for the sector's decarbonization is the adoption of battery electric vehicles (BEVs), which often generates a debate in public opinion about their actual environmental impact. Therefore, this work aims to highlight under which conditions the transition to BEVs is desirable and when it is not. All the steps that make up the life cycle emissions from the production phase to the use phase and the end of life of electric vehicles have been analyzed by comparing these values with ICE-powered vehicles. The model developed, which aims to calculate the production emissions of ICEV and BEV, has been integrated with the open-source python tool "Vehicle Consumption Assessment Model" (VCAM), developed by the SESAM group, which allows the calculation of CO2 emissions produced during the use phase of the vehicle. Furthermore, thanks to the great customization that the model allows, it was possible to identify the individual parameters that most influence the value of life cycle emissions and then study the effect of their variation. Looking at the results, it is clear the crucial role that the transition of the energy sector has. Decarbonization of the energy sector is directly reflected in reducing the grid emission factor, which influences the production emissions and the emissions related to the generation of electricity used for charging BEVs. In the end, two scenarios were developed. In the first scenario, the replacement of the current fleet of ICEVs with BEVs was simulated in a multi-country context. The second scenario showed how life cycle emissions could change substantially in the next future, thanks to the expected technological development (especially in terms of the energy density of batteries and electricity mix) according to the forecasts of the International Energy Agency (IEA).

Key-words: Electric Vehicles, Life Cycle Assessment, Vehicles GHG emissions

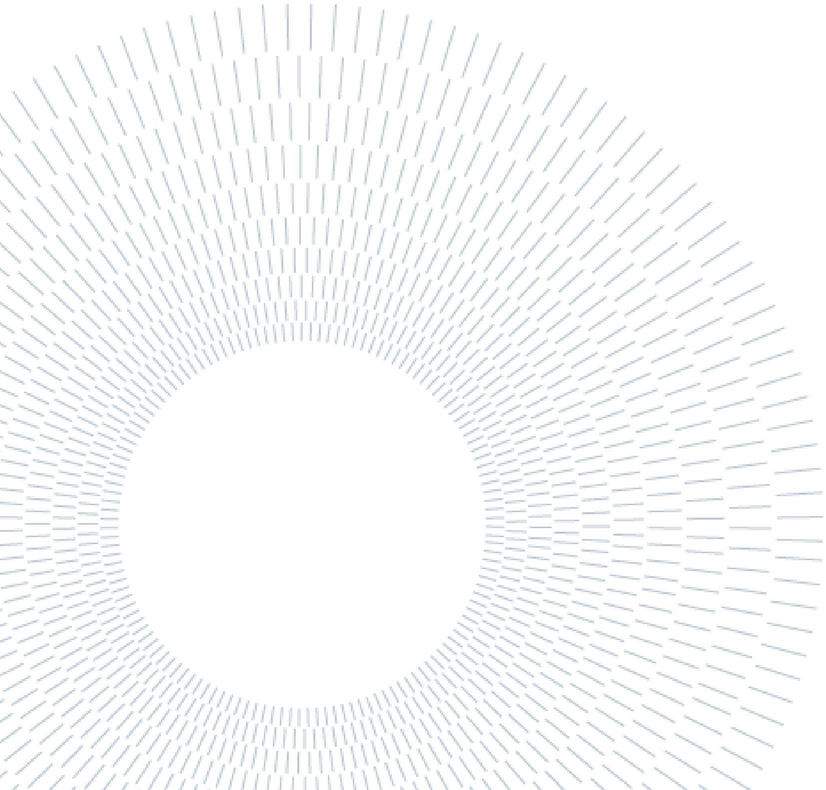
Abstract in Italiano

Il crescente contributo del settore dei trasporti, in particolare dei veicoli leggeri, alle emissioni globali di gas serra negli ultimi decenni sta ponendo una grande resistenza verso il raggiungimento delle emissioni nette globali zero. Un’alternativa per la decarbonizzazione del settore è rappresentata dall’utilizzo di veicoli elettrici a batteria (BEV) la cui adozione spesso generano un dibattito nell'opinione pubblica riguardo il loro effettivo impatto ambientale. Lo scopo di questo lavoro è, quindi, quello di evidenziare in quali condizioni il passaggio ai BEV sia auspicabile e quando no. Sono stati analizzati tutti gli step che compongono le emissioni del ciclo di vita, dalla fase di produzione alla fase di utilizzo e al fine vita dei veicoli elettrici, confrontando questi valori con i veicoli alimentati da motori a combustione interna. A tale scopo è stato sviluppato un modello in Python che mira a calcolare le emissioni di produzione di entrambi i powertrain considerati (ICEV e BEV) che successivamente è stato integrato con il modello Python open source Vehicle Consumption Assessment Model (VCAM), sviluppato dal gruppo SESAM, consentendo così il calcolo delle emissioni di CO2 prodotte durante la fase di utilizzo del veicolo. Grazie alla grande personalizzazione che il modello consente, è stato possibile individuare quali siano i singoli parametri che maggiormente influenzano il valore delle emissioni ciclo vita e quindi studiare l'effetto della loro variazione. Dai risultati, è chiaro il ruolo cruciale che ha la transizione del settore energetico, la cui decarbonizzazione si riflette direttamente nella riduzione del fattore di emissione della rete in quale influenza non solo le emissioni di produzione di entrambe le tipologie di veicolo, ma anche le emissioni legate alla generazione di energia elettrica utilizzata per la ricarica dei BEV. Alla fine, sono stati sviluppati due scenari, nel primo è stata simulata la sostituzione dell'attuale flotta di ICEV con equivalenti BEV in un contesto multi-paese, nel secondo è stato mostrato come le emissioni ciclo vita possano cambiare sostanzialmente nel prossimo futuro grazie allo sviluppo tecnologico (soprattutto in termini di densità energetica delle batterie e di mix elettrico) secondo le previsioni dell'Agenzia Internazionale dell'Energia (IEA).

Parole chiave: Veicoli elettrici, valutazione emissioni ciclo vita, emissioni gas serra dei veicoli



Contents



1 Introduction

1.1. GHG emissions in the transport sector

The transport sector is one of the leading sources of greenhouse gas (GHG) emissions around the globe and is currently responsible for almost 23% of the world's greenhouse gas emissions. For example, the EU’s transport emissions increased in 2019 by 0.8% and are expected to increase by 32% by 2030 compared to the 1990 levels[1]; focusing on passenger cars, they are responsible for about 12% of all GHG emissions in the European Union.

The transport sector mainly depends on fossil fuels such as coal, oil, and gas, which discharge enormous amounts of GHGs, the primary basis of climate change. Moreover, another relevant issue related to road transportation concerns the tailpipe emissions, such as COX, NOX, and Particulate Matter; these can directly affect human health and are one of the major causes of poor air quality in urban centers.

One promising way to reduce carbon dioxide (CO2) emissions from transport is to substitute internal combustion engine vehicles (ICEVs) with battery electric vehicles (BEVs), which have numerous advantages that are shown in the next paragraph.

BEVs produce zero GHG emissions in the operation phase; however, electricity supply, production of the power train, and EV batteries may still lead to significant GHG emissions and environmental impacts.

While the transition to electric mobility is still early in some of the largest car markets in some countries, the electric vehicle fleet is expanding quickly. In addition, the variety of models among which consumers can choose also continues to grow as manufacturers have launched new vehicles and announced the rollout of several new models soon. Figure 1.1 shows the top geographical areas for EV sales during the past decade.

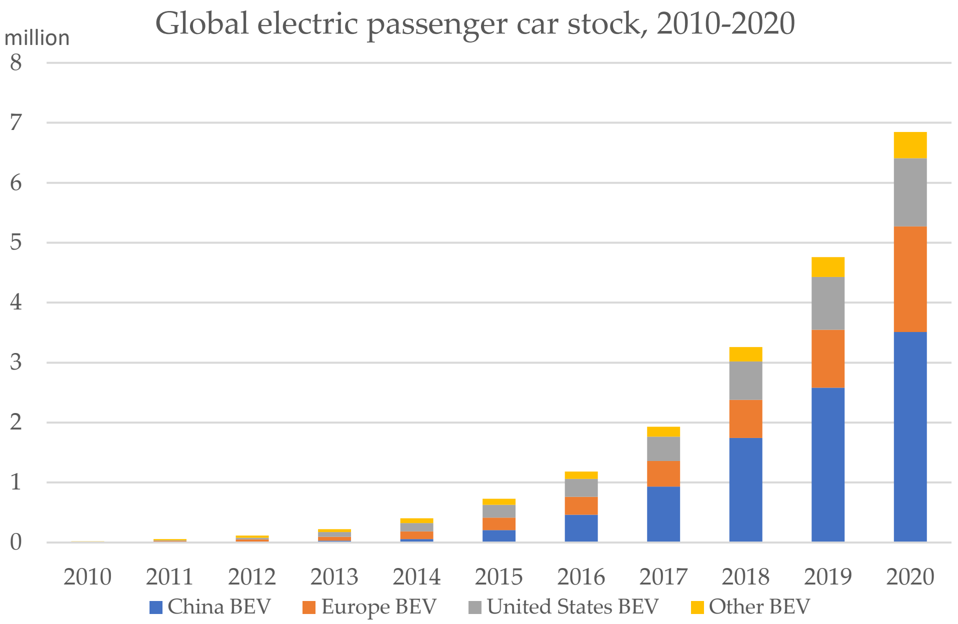


Figure 1-1: Global electric passenger car stock, 2010-2020 (IEA)[2]

Global EV sales reached 6.75 million units in 2020, 40 % more than 2019. This volume includes passenger vehicles, light trucks, and light commercial vehicles. The global share of EVs (BEV and PHEV) in global light vehicle sales was 8,3 % compared to 4,2 % in 2020. BEVs stood for 71 % of total EV sales, PHEVs for 29 %. Although the Global auto market improved by only 4,7 % over the crisis year of 2020, we have seen many electric car registrations in Europe because of two policy measures: first, 2020 was the target year for the European Union's CO2 emissions standards that limit the average CO2/km for new cars, second many European governments increased subsidy schemes for EVs to counter the effects of the pandemic.

Sales are increasing each year and are expected to rise by about 25 million in 2030[3]. Many countries are rapidly transferring their transport systems to future clean transport by adopting EVs to meet the CO2 reduction commitments of the Paris Agreement negotiated at the 2015 United Nations Climate Change Conference (COP21). Following the headwinds in 2019 and 2020, global EV sales were back on track in 2021. For this year, we expect EV sales to return to more normal growth and reach around 9,5 million units, higher if the remaining issues in supply and logistics are resolved.

1.2. Why electric vehicles?

Battery electric vehicles have been gaining traction thanks to their ability to deliver multiple advantages. These include:

- **Energy efficiency**: electric vehicles are three to five times more energy-efficient than internal combustion engine vehicles.

- **Energy security**: electric mobility boosts energy security as it transitions the road transport sector from its strong reliance on oil-based fuels reducing dependence on oil imports for any country. Electric mobility also incentivizes governments to equip themselves with an energy system based on renewable sources to generate electricity with zero CO2 emissions.

- **Air pollution**: thanks to zero tailpipe emissions, electric vehicles are very well suited for use in urban areas where many people are exposed to pollutants that are harmful to health.

- **Noise reduction**: electric vehicles are quieter than traditional vehicles, contributing to less noise pollution.

- **GHG reduction**: While it is recognized by all that the impact of electric vehicles is in reducing local pollutant emissions and improving air quality, mainly in urban centers, their overall impact on greenhouse gas emissions is a subject of debate.

Regardless of these advantages, some studies show that current EVs can lead to higher GHG emissions compared to ICEVs in some countries [4]. These studies can confuse the public and generate a debate. The use of fossil fuel energy for EV battery charging and inadequate operation and maintenance may be important factors leading to significant GHG emissions from EVs. There is still a lack of studies comprehensively assessing EV performance with various countries' current and future energy mixes. A few future-oriented studies have shown that the GHG emissions of EVs are lower than those of ICEVs, mainly due to engine hybridization and a higher proportion of renewable energy used for generating the electricity supply for battery charging.

The Life cycle assessment (LCA) is the most widely used environmental impact assessment method for vehicles; the details on its operation and how it is composted are presented later in chapter 1.5.

1.3. Research objective

This work aims to evaluate the convenience of adopting electric vehicles from a greenhouse gas emission point of view. All aspects that contribute to a vehicle's environmental impact will be considered, analyzing the product's life cycle, from the extraction and processing of the vehicle's materials to evaluating the tailpipe emission. The tool used for evaluating the production emissions by the scientific community and that will also be used in this work is the Life Cycle Assessment. This comprehensive and globally standardized structured method quantifies the emissions and resources consumed and the related environmental impact. This phase of the work was crucial to evaluate the emissions related to battery production, which is one of the major points against BEVs.

Subsequently, for the evaluation of the exhaust emission has been used a python opensource tool able to calculate the fuel consumption and the tailpipe CO2 emission of a vehicle having as input the vehicle characteristics, the ambient temperature, and the type of driving cycle.

Both evaluation of production emissions and those related to the use of the vehicle are parameterized on the location. In the first case, the electrical mix of the location considered directly influences those emissions related to industrial processes to produce the vehicle. In the second case, the electrical mix directly affects those emissions associated with the production of electricity used for charging the vehicle.

1.4. Research question

The critical issue of most of the available LCA (Life Cycle Assessment) in literature are mainly two:

- The emissions related to the production of the vehicle and the batteries are not always parameterized to the location. Usually, the studies evaluate the LCA emission considering only one specific location, not showing the variability of this aspect on the results.

- Use an average energy consumption value during the lifetime use of the vehicle without considering the impacts of ambient temperature and trip characteristics. Significant changes in energy consumption are linked to auxiliary energy demand and trip characteristics, especially under cold temperatures. At both cold and moderate temperature conditions, the EV presented lower energy consumption for urban driving than for rural and motorway operation, confirming its adequacy for application in metropolitan areas.

This thesis work aims to develop a model that provides a comparative life cycle assessment of different vehicle technologies and highlights the effect of electricity mix and battery chemistry on the LCA. The developed model has been integrated with a consumption simulation model that considers the trip characteristics and the variability of the ambient temperature.

- According to environmental parameters, what are the conditions in which electric vehicles and internal combustion engine vehicles are comparable?

- What are the fundamental steps to reduce BEVs' Life Cycle Emissions?

- Which are the impacts of technological developments (such as the increase of battery performance and the decarbonization of the energy sector) on the vehicle's life cycle emissions?

1.5. Vehicle Life Cycle Assessment

Life Cycle Assessment (LCA) is a structured, comprehensive, and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues associated with any goods or services. Life Cycle Assessment considers a product's entire life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste. Critically, LCA studies help avoid resolving one environmental problem while creating others. This unwanted "shifting of burdens" is where you reduce the environmental impact at one point in the life cycle, only to increase it at another point. Therefore, LCA helps to verify, in this case, that the additional environmental impact through the production of EVs concerning ICEVs is less than the reduction of emission that EVs lead to during the driving phase. Below is the flow diagram of the Life Cycle Assessment carried out in this study:

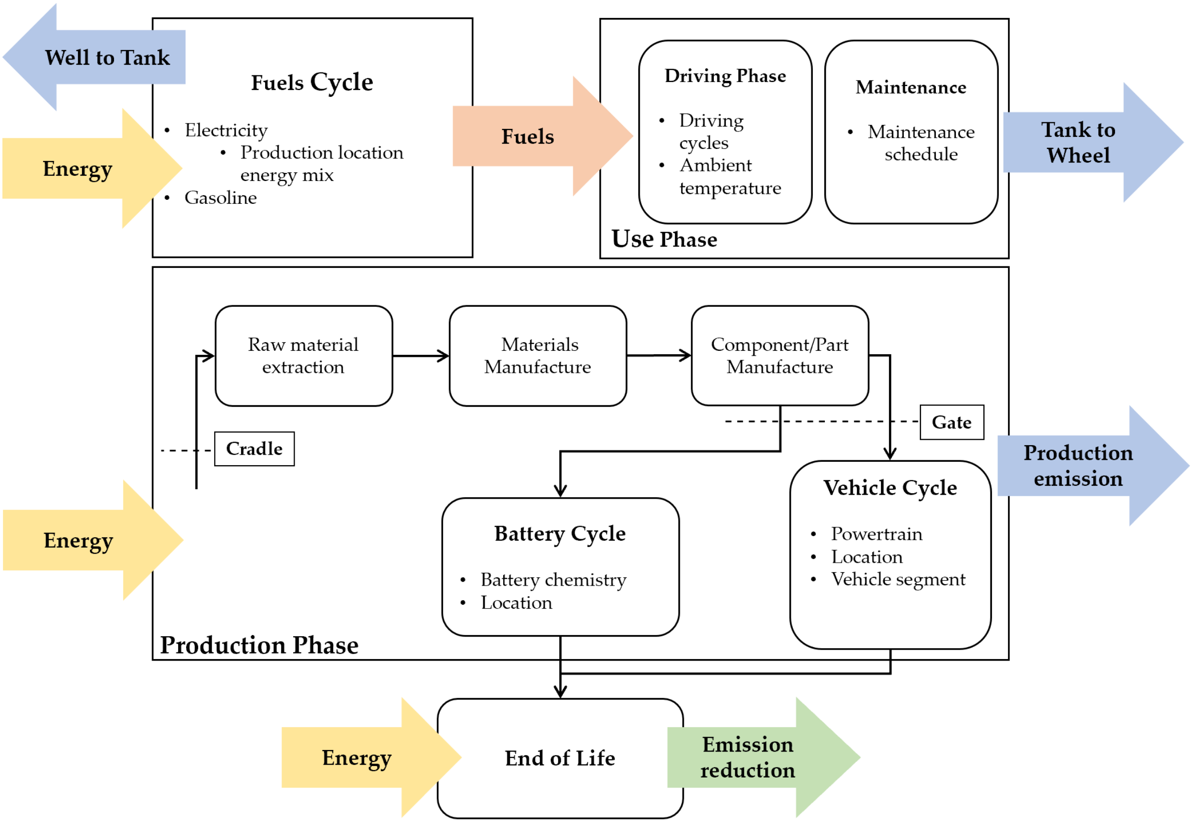


Figure 1-2 Life Cycle Assessment flow diagram

The study is divided into four fundamental parts:

- Production phase: it includes the vehicle and battery life cycle. The so-called Cradle to Gate emissions have been evaluated beforehand in this phase. That is the sum of emissions produced from the extraction of a single material to the production of the component/part that will then be assembled in the battery/vehicle. The term Cradle-to-Gate refers to the production emissions of all the materials that make up a given component: for example, with a battery cradle to gate emissions are intended for the production emissions of all the components of the battery disassembled.

- Fuels Cycle: The emissions produced during the fuel production processes are considered all the processes ranging from extraction to the finished product. In the case of electricity, a different grid emission factor is considered depending on the location. The emissions produced at this stage are called Well to Tank emissions.

- Use Phase: includes all emissions produced during the use of the vehicle, which is called Tank to Wheel emission. They are the sum of tailpipe emissions (in the case of ICEVs) and maintenance-related emissions.

- End of Life: in this phase, the recycling processes and possible emissions reduction that they can entail are evaluated. Each recycling process involves the additional emission of CO2 as it consumes energy. Still, the CO2 savings given by the possibility of reusing the materials makes the value of this component negative emissions.

Finally, the total life cycle emission of the vehicle is obtained as the sum of the four components; the results are in gCO2/vehicle or gCO2/km. A crucial assumption regards the lifetime mileage, which is assumed to be 150000 km, the value used in most studies.

2 Literature review

This section shows the now existing models that represent state of the art to carry out the Life Cycle Assessment of vehicles. Subsequently, a section is dedicated to reviewing the literature regarding the production emissions of the battery pack. It was decided to treat the battery production separately, being the most critical factor in assessing the convenience of electric vehicles to reduce greenhouse gas emissions. However, literature in this regard provides extremely different results, so it is essential to underline the motivations.

2.1. Greet Model (Production Phase)

Argonne's GREET model [5] is widely recognized as the "gold standard" for evaluating and comparing transportation fuels and vehicles' energy and environmental impacts. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model is an analytical tool that simulates the energy use and emissions output of various vehicle and fuel combinations. It is divided into two modules: Fuel Cycle Module and Vehicle Cycle Module.

2.1.1. Fuel Cycle Module (GREET 1)

The fuel cycle model evaluates the so-called Well-To-Tank emissions, i.e. the emissions produced during the various fuels' extraction, refining, and transport phases.

Developed in a spreadsheet format, the model estimates the full fuel-cycle emissions and energy use of various transportation fuels for road vehicles. The model calculates fuel-cycle emissions of five criteria pollutants (VOC, CO, NOx, PM10, and PM 2.5) and three greenhouse gases (CO, CH4, NOx).

Using various transportation fuels, the model also calculates fuel-cycle energy consumption, fossil fuel consumption, and petroleum consumption. The GREET model includes 17 fuel cycles: petroleum to conventional gasoline, reformulated gasoline, clean diesel, liquefied petroleum gas, and electricity via residual oil; natural gas to compressed natural gas, liquefied petroleum gas, methanol, hydrogen, and electricity; coal to electricity; uranium to electricity; renewable energy (hydrogen, solar energy, and wind) to electricity; corn, woody biomass, and herbaceous biomass to ethanol; and landfill gases to methanol.

A production pathway is defined for each fuel type, and for each step, energy consumption and associated emissions are evaluated. Then, the simplified path of petroleum fuels within the GREET model is reported as an example.

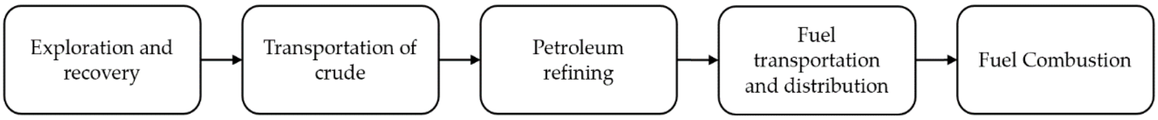


Figure 2-1 Petroleum fuels production pathway

2.1.2. Vehicle Cycle Module (GREET 2)

The vehicle-cycle model evaluates the energy and emission effects of vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling. GREET model provides a comprehensive, lifecycle-based approach to comparing the energy use and emissions of ICEV, BEV, PHEV, and FCEV. Each of them considers a conventional material and a lightweight material version. The model also calculates the energy use and emissions required for battery and fluid production.

The first step of the vehicle-cycle analysis is to estimate vehicle component weight. Then, the vehicle-cycle model considers its material composition (i.e., breakdowns of total component weight into each material).

The model then develops replacement schedules for components that are subject to replacement during a vehicle's lifetime (e.g., batteries, tires, and various vehicle fluids). Finally, the model considers the energy required and emissions generated during the recycling of scrap materials back into original materials for reuse, for disposal and recycling.

Finally, the estimates of energy used during the processes from raw material recovery to vehicle assembly are used for vehicle-cycle simulations. The fuel-cycle model is used in conjunction with the vehicle-cycle model to estimate total cycle results. Fig 2-2 shows how the two modules interact to estimate energy use and vehicle production emissions.

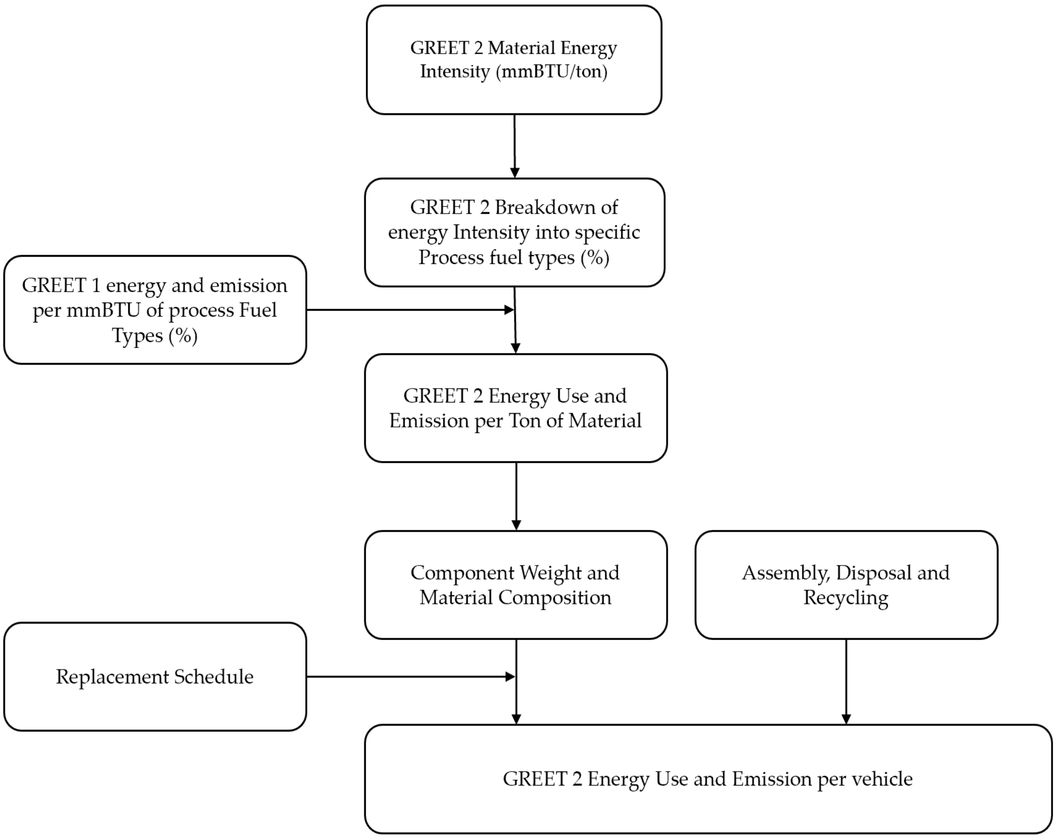


Figure 2-2 GREET model working scheme

The GREET model is, therefore, able to estimate the Life Cycle emissions of any vehicle configuration but has shortcomings:

- The results are only reliable if the life cycle assessment is conducted in the United States. Therefore, all simulation parameters are calibrated and designed to return reliable results exclusively in the United States (especially those of the fuel cycle). Wanting to make a life Cycle Assessment of a vehicle produced and used in Europe, some data are unreliable, such as the origin of raw materials and production emissions.

- The model cannot assess the consumption of vehicles during the use phase and therefore cannot evaluate the Tank-To-Wheel (ICEV) and Well-to-Tank (BEV) emissions associated with the use of the vehicle. In the case of ICEVs, Tank to Wheel emissions are the predominant emission component, and its assessment is crucial.

2.2. COPERT Model (Use Phase)

The evaluation of Tank to Wheel emissions cannot be separated from the evaluation of consumption and, therefore, from simulations that reproduce the vehicle's mode of use to estimate the emissions potentially producible during use. Therefore, a model running driving cycles as realistic as possible is needed to make this type of evaluation. The reference model at the European level is represented by the COPERT model [6] (Computer Programme to calculate Emissions from Road Traffic) is a traffic emissions calculation program developed by the European Environment Agency EEA under the CORINAIR program. It is a disaggregated top model that allows obtaining the emission values for each category of vehicles.

The model is based on three different methods for the assessment of exhaust emissions following the following scheme:

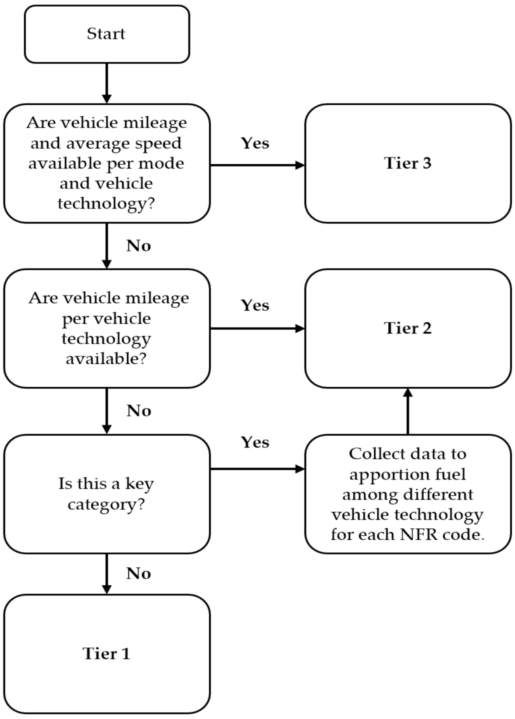


Figure 2-2 COPERT model decision tree

2.2.1. Tier 1

The Tier 1 approach for exhaust emissions uses the following general equation:

$$E_i = \sum_j (\sum_m (FC_{j,m} * EF_{i,j,m}))$$

Where:

E_i: emission of pollutant i [g]

$FC_{j,m}$: fuel consumption of vehicle category j using fuel m [kg]

$EF_{i,j,m}$: fuel consumption-specific emission factor of pollutant I for vehicle category j and fuel m [g/kg]

The vehicle categories to be considered are passenger cars, light commercial vehicles, heavy-duty vehicles, and L-category vehicles. The fuels to be considered include petrol, diesel, LPG, and natural gas. The equation requires the fuel consumption statistics to be split by vehicle category.

2.2.2. Tier 2

The Tier 2 approach considers the fuel used by different vehicle categories and their emission standards. Hence, the four broad vehicle categories used in the Tier 1 approach to describe the four NFR codes are sub-divided into different technologies k according to emission-control legislation. Therefore, the user needs to provide the number of vehicles and the annual mileage per technology. These vehicle-km data are multiplied by the Tier 2 emission factors.

Hence, the algorithm used is:

$$E_{i,j} = \sum_k (< M_{j,k} > * \ EF_{i,j,k}) \quad \text{or} \quad E_{i,j} = \sum_k (M_{j,k} * \ EF_{i,j,k} * N_{j,k})$$

where,

$< M_{j,k} >$: total annual distance is driven by all vehicles of category j and technology k [km/vehicle]

$EF_{i,j,k}$: technology-specific emission factor of pollutant i for vehicle category j and technology k

$M_{j,k}$: average annual distance drove per vehicle of category j and technology k [km/vehicle]

$N_{j,k}$: number of vehicles in nation's fleet f category j and technology k

2.2.3. Tier 3

In the Tier 3 approach, total exhaust emissions from road transport are calculated as the sum of hot emissions (when the engine is at its normal operating temperature) and emissions during transient thermal engine operation (cold-start emissions). The distinction between emissions during the 'hot' phase and the phase is necessary because of the substantial difference in vehicle emission performance during these two conditions. Concentrations of some pollutants during the warming-up period are many times higher than during hot operation, and a different methodological approach is required to estimate the additional emissions during this period. Total emissions can be calculated using the following equation:

$$E_{TOTAL} = E_{HOT} + E_{COLD}$$

where,

> E_{TOTAL} = total emissions (g) of any pollutant for the spatial and temporal resolution of the application,
>
> E_{HOT} = emissions [g] during stabilized hot engine operation,
>
> E_{COLD} = emissions [g] during transient thermal engine operation.

ICEVs emissions are heavily dependent on engine operating conditions. Different driving situations impose different engine operating conditions and therefore a distinct emission performance. In this respect, a distinction is made between urban, rural, and highway driving. Cold-start emissions are attributed mainly to urban driving, as it is expected that a limited number of trips start at highway conditions. Therefore, as far as driving conditions are concerned, total emissions can be calculated using the equation:

$$E_{TOTAL} = E_{URBAN} + E_{RURAL} + E_{HIGHWAY}$$

where

E_{URBAN}, $E_{RURAL}$and $E_{HIGHWAY}$ are the total emissions [g] of any pollutant for the respective driving situations. Finally, total emissions are calculated by combining activity data for each vehicle category with appropriate emission factors. The emission factors vary according to the input data (driving situations, climatic conditions).

The COPERT model is extremely detailed in evaluating the Tank to Wheel emission, but it is not very customizable. In this study, there is a need to evaluate Tank to Wheel emissions with customizable guide cycles and evaluate the dependence on ambient temperature. For this purpose, VCAM is used, an open-source python tool developed by the SESAM group that allows you to customize the simulation in more detail.

2.3. Battery Life Cycle studies review

As a first step toward understanding the emission implications of BEVs, a review of published studies of the cradle-to-gate GHG emissions for BEV traction batteries representing current technologies has been made. Table 1 provides a summary of data and results from previous studies.

Reference	Battery chemistry	Mass [kg]	Energy Density [kWh/kg]	CO2 emission			
				[kgCO2/kg]		kgCO2/kWh	
				Materials	Cell mfg	Materials	Cell mfg
Notter et al.(2010)[7]	LMO	300	0.114	5.8	0.16(2.4)	51	1.4
Dunn et al.(2014)[8]; GREET model [9]	LMO	210	0.13	4.9	0.27(3.9)	37	2.1
EPA (2013)[10]	LMO	na	0.08-0.1	6.2	0.18(2.9)	62	1.8
	NMC			8.7	3.4(62.1)	87	34
Majeau-Bettez et al. (2011)[11];	NMC	214	0.112	16		143	54

Hawkins et al.(2013)[12]					6.0(80-105) c		
Ellingsen et al. (2014)[13]	NMC	253	0.11	6.9	11.3(180) d	65	108
					18.5(300) e		176
					44.5(730) f		425
Kim et al.(2016)[14]	LMO NMC	303	0.08	6.1	5.2(120)	76	65
Mia Romare et al. (2017) [15]	na	-	-	-	-	60-70	70-110
Philippot et al.(2019)[16]	NCA	154	0.25	19.25	11.5	77	46
Kelly, Dai & Wang (2020) [17]	NMC	188	0.14	6.89	3.73	48	26
Kallitsis et al. (2020) [18]	NMC	253	0.11	17.32	11.55	157.45	104.96

Table 1 Battery Life Cycle studies review: *a) estimated based on materials breakdown; b) average value of the range in EPA (2013); c) estimated from the direct energy inputs in Ellingsen et al. (2014), 371-473 MJ/kWh, based on an electric and fossil energy share of 51.7% and 48.3% respectively and primary energy to an electricity conversion factor of 0.35 as in Majeau-Bettez et al. (2011); d) lower bound value; e) asymptotic value; f) average value of [Ellingsen])*

The inconsistencies across studies can be attributed to a variety of factors.

When there are no available primary data (collected directly from industrial operations) for emission and energy consumption, LCA studies use secondary data such as literature values and databases and often extrapolate or adjust them to approximate the actual operational data.

Notter et al. (2010) rely on expert estimates regarding energy consumption and the battery manufacturing phase while Majeau-Bettez et al. (2012) use literature value measured for stationary battery manufacturing. To estimate cell manufacturing energy, Dunn et al. (2012) estimated energy consumption in an R&D facility based on a climate control design and extrapolated to a large-scale production, of 6 million cells per year, in conjunction with direct measurement of the cell formation stage.

The study by EPA (2013) considers batteries with different chemistries and assigns higher GHG emissions to NMCs than to LMOs, this is because this study uses data from Notter et al. (2010) and Majeau-Bettez et al. (2012) for LMO and NMC batteries, respectively. In addition, the EPA study assigns zero GHG emission for cell manufacturing (considering the procedure as carried out manually) to NMC batteries. Instead, it assigns the largest value compared to all other studies regarding pack manufacturing.

Ellingsen et al. (2014) used real-world commercial production data for cell manufacturing and battery design and estimated GHG emissions of 172 kg CO2-eq/kWh battery for the representative case. The authors found that GHG emissions depend on production volume with emissions as high as 487 kgCO2-eq/kWh for low volume production.

The approaches taken by Majeau-Bettez et al. (2011) and Ellingsen et al. (2014) result in higher GHG emission estimates for cell and pack manufacturing than those found by Notter et al. (2010) and Dunn et al. (2012).

The production facilities' locations and the origins of the battery materials can also significantly affect the cradle-to-gate energy and environmental impacts of LIBs: manufacturing countries with carbon-intense grid mixes impact the CO2 emission and energy consumption of battery pack production directly.

Is evident that China continues to dominate the LIB supply chain[11], where its grid mix is high carbon intense because of high shares of black coal. Alternatively, countries with low carbon-intense grid mixes shift the environmental impact onto materials production instead [12]. Therefore, it is evident that the results vary significantly amongst different countries and regions due to the variable production techniques and specific manufacturing processes. In addition to varying grid mixes, regional industrial practices can also differ significantly [9].

Regarding the modeling of the End-of-Life phase, it was observed that pyrometallurgical or hydrometallurgical processes were assumed among the LCAs examined (Notter et al., 2010; U.S. EPA, 2013). Furthermore, several LCAs did not include the End-of-Life phase in the analysis because of the greater uncertainty (mainly due to lack of data) (Ellingsen et al. 2014; Kim et al., 2016; Majeau-Bettez et al., 2011).

One of the major discrepancies also concerns the estimation of energy consumption and CO2 production associated with the manufacturing/assembly phase which cannot be easily explained because information on facility design, production volume, and plant capacity is not public.

In some studies, module and pack assembly is assumed to be manual, and therefore not associated with any energy and environmental impacts, among other studies possible explanations for the different results are differences in production scales. It is also important to underline that the emission values estimated by the most recent studies are lower than the older studies, this is mainly due to different assumptions regarding the value of energy density of the batteries. The energy density determines the weight of the battery pack the lower is the mass of the battery pack the less the amount of material necessary for its production, and therefore the total Cradle to Gate emissions will be lower.

3 Methodology

The first part of the work focuses on evaluating energy consumption and the consequent emissions deriving from the production of the vehicle and, in the case of electric vehicles, also of the battery pack. To evaluate the emissions related to each processing/manufacturing process of the vehicle, it is necessary first to distinguish the energy sources used and then associate them with their emission factor.

As for the production phase for the batteries and the vehicle, the same basic methodology was used. The production cycle of each material that makes up the battery and the vehicle was analyzed, obtaining the emissions due to their production per unit mass [kgCO2/kg_material]. Finally, knowing the material composition of the single components and the energy consumption due to the assembly phase, it was possible to obtain the total emissions related to their production.

Subsequently, the emissions during the use of the vehicle will be calculated, which are composed of the exhaust emission, whose evaluation allows the prior evaluation of the consumption that is carried out through the VCAM tool [19], and the maintenance emissions.

The Well-To-Tank emissions of gasoline and electricity are then estimated by referring to the most recent literature. Finally, the recycling processes of batteries and their advantage in terms of CO2 savings are studied.

Two types of powertrains (BEV, ICEV) and 6 different Li-ion batteries chemistry (LFP, LMO, NMC111, NMC622, NMC811, NCA) will be analyzed through these phases.

3.1. Fuels Emission Factor

To evaluate the emissions related to producing a certain good, it is first necessary to evaluate the energy consumption of products whose environmental impact depends on the fuel used. The emission factor is a parameter that indicates the emissions of CO2 relative to the energy consumption of a certain fuel. In this work, different types of fuels have been considered, below are reported the fuels and the related emission factors [20]

Oil	Diesel	Natural Gas	Coal	Coke
77.7	74.4	56.2	120	107.5

Table 2 Fuels Emission Factor [gCO2/MJ]

The emission factor of the grid depends on the electricity mix considered. For this work, the electricity mix of European countries, the UK, the USA, and China were able to analyze the life cycle emissions parameterized based on the location making the analysis much more realistic and accurate, for example, it is possible to stimulate the production of individual materials in each country, and the assembly of the vehicle in another going to replicate what happens.

Below are the grid emission factors for all countries considered in gCO2/kWh obtained as a weighted average of the emission factors of the single power production methods for the electricity mix of a single country [21].

Country	EF	Country	EF	Country	EF	Country	EF
AT	147	LU	65.18	FI	82.79	RS	1076
BE	176	MD	568	FR	67.23	SK	107.31
BA	1164	NL	452.63	DE	418.82	SI	248.26
BG	486.21	NO	18.92	GR	657.31	ES	304.3
HR	187.95	PL	755.72	HU	252.96	SE	9.27
CZ	437.85	PT	349.78	IE	392.53	CH	712.2

DK	147.66	RO	262.52	IT	258.8	LT	63.69
EE	922.41	US	417	LV	49.16	GB	268.52

Table 3 Grid Emission Factor for different countries

It is important to note the huge difference in emission factors between countries, this calculates production emissions (but also those of use of the vehicle, see chapter 3.4) very dependent on the location considered.

The effect is even more evident for those processes that consume a lot of electricity. Subsequently, it will be shown how many processes of this type characterize the battery production chain, making the emissions related to the production of electric vehicles much more dependent on the location considered than ICEV vehicles are.

3.2. Mathematical formulation

The same approach was used for evaluating production emissions (both vehicle and battery), which is explained in this chapter. As a result, the energy consumption to produce 1 kg of each material can be calculated through the following equation:

$$EC_m = \sum_j EC_{j,m}$$

Where $EC_{j,m}$ in the energy consumption of process j related to the production of 1 kg of the material m e $m_m$is the mass of material used in process j. EC_m it is therefore inclusive of all emissions related to the extraction and processing of the material from its raw state to the final product. Emissions due to the industrial processes of the material can be calculated through the following equation:

$$GE_m = \sum_j \sum_{f=1}^{8} EC_{j,m} * f_s * EF_f$$

Where GE_m are the CO2 emissions to produce 1 kg of material m, f_s is the share of fuel per stage s and EF_f is the emission factor vector defined as:

$$EF = [EF_{oil} \mid EF_{diesel} \mid EF_{NG} \mid EF_{coal} \mid EF_{electricity} \mid EF_{coke} \mid EF_{bfg} \mid EF_{cog}]$$

Finally, it is thus possible to calculate the production emissions and energy consumption to produce the battery or the vehicle (from now on called components) such as:

$$EC[MJ] = \left(\sum_m EC_m \left[\frac{MJ}{kg_m}\right] * \%_m \left[\frac{kg_m}{kg_{Comp}}\right]\right) * comp\_weight[kg_{Comp}] + EC_{assembly}[MJ]$$

$$GE[kgCO2] = \left(\sum_m GE_m \left[\frac{kgCO2}{kg_{Mat}}\right] * \%_m \left[\frac{kg_m}{kg_{Comp}}\right]\right) * comp\_weight\ [kg_{Comp}] + GE_{assembly}[kgCO2]$$

Where, $\%_m$ is the weight percentage of a single material on component total weight, $EC_{assembly}$ and $GE_{assembly}$ are respectively the energy consumption and the emission associated with the assembly of the component.

The model, therefore, considers the energy consumption for each production process of each component, distinguishing the various energy sources and, through appropriate emission factors, can evaluate the production emissions of each component. This methodology has been applied to calculate the battery and vehicle production emissions.

The following paragraphs will analyze all the processes considered to produce individual materials and evaluate the percentage compositions of the single components of the vehicle and the battery.

3.3. Production Phase

This chapter covers the environmental impact of the whole production process, including extraction of raw materials, processing of materials, manufacturing of components and subcomponents, vehicle assembly, and painting. This study chooses only passenger cars with conventional materials as the reference vehicles to provide the most representative results. The vehicle Material Composition is imported from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) established by Argonne National Laboratory (ANL) [5].

	Steel	Iron	Aluminum	Copper	Glass	Plastic	Rubber	Others
ICEV	62.3%	10.9%	6.8%	1.9%	2.9%	11.1%	2.3%	1.8%
BEV	66.4%	2.0%	6.5%	4.7%	3.5%	12.1%	1.8%	3.0%

Table 4 Curb weight material composition

Although an ICEV or BEV (without batteries, tires, and fluids) is made up of various materials and several certain materials such as steel, iron, aluminum, copper, glass, rubber, and plastic account for over 97% of the weight of BEVs and over 98% for ICEVs. Therefore, this study focuses on these materials and analyzes their cradle-to-gate energy consumption and GHG emissions. The major differences in the material composition between the two are mainly related to the different types of engines and the greater quantity of electronic components present in BEVs.

3.3.1. Material’s Cradle to Gate emission

This section will analyze all the processes from extracting the raw material to producing the component / semi-finished product present in the vehicle/battery. For steel and aluminum, a more in-depth analysis will be made given the key role they play in the material composition of the vehicle and the battery, as well as being, as will be shown later, the two materials whose production and processing have a greater impact. For other materials, individual emission values per unit mass were used without distinguishing different types of the same material.

Steel

Two steel production methods are considered

1. **Integrated Mills**

These steel mills produce virgin steel products using mined iron ore. The steps in producing steel in an integrated mill are summarized below:

- Limestone extraction and processing: limestone is extracted and processed into lime
- Coke Production: coal is crushed and baked in ovens to remove impurities leaving a high carbon fuel for steel making.
- Ore Pelletizing: the rock is crushed into fine particles, and the iron ore within the rock is separated using magnets.
- Sintering is formed from steelmaking waste products such as iron ore powder, coke breeze, limestone, or other flux materials. These ingredients are fused with heat and then crushed into smaller pieces to be added to the blast furnace.
- Blast Furnace: iron ore pellets, sinter, and coke are added to the blast furnace. Limestone helps remove impurities, which float to the top of the furnace and are removed as slag. The coke combusts in the furnace and the resulting product is liquid pig iron.
- Basic O2 Processing: liquid iron is added to the basic oxygen furnace and oxygen to reduce the carbon content of the iron, thus converting it into steel.
- Hot/Cold Rolling: steel is cast into steel slabs and rolled through rollers into steel sheets. The rolling process begins with heated steel (hot-rolling), but further rolling is often done on cold sheet steel (cold rolling) depending on the type of steel you want to obtain
- Galvanizing: a thin zinc coating is sometimes applied to cold-rolled steel to prevent corrosion.

2. **Mini Mills**: in these mills, steel scrap is fed into a furnace and is melted using an electric arc from an electrode lowered into the furnace.

While both production approaches can be used to produce a variety of steel materials in this study only the integrated mill is considered to produce virgin steel and mini mils are considered only in the case of recycled steel. Three different steel types are used for vehicle manufacturing. Each material's relative contribution to the steel weight of the vehicle is presented in the following table:

Hot Rolled	Cold Rolled	Galvanized Rolled
21.1%	19.1%	59.8%

Table 5 Virgin steel types distribution on total steel weight of the vehicle

Each type of steel follows different production pathways, in the following table are shown what are the processes necessary to produce each type of steel.

Process	**Hot Rolled**	**Cold Rolled**	**Galvanized Rolled**	**Recycled**
Iron Ore Extraction and Processing	✓	✓	✓	
Coke Production	✓	✓	✓	
Sintering	✓	✓	✓	
Blast Furnace	✓	✓	✓	
Basic Oxygen Furnace	✓	✓	✓	
Hot Rolling	✓	✓	✓	
Skin Mill	✓			
Cold Rolling		✓	✓	
Galvanizing			✓	
Stamping	✓	✓	✓	✓
Electric Arc Furnace				✓
Rod and Bar Mill				✓
Machining	✓	✓	✓	✓

Table 6 Production Process for each steel type

Material flows were calculated from the reference plants from [5]. There is no mass preservation during the processing since there is waste. Given that energy consumption is provided per unit of mass it is necessary to consider the amount of material that flows within a process and not only the amount present upstream of the production chain. Table 8 summarizes the percentage loss of material through the production stages.

Hot Rolling	-3.07%
Skin Mill	-1.41%
Cold Rolling	-5.36%
Galvanizing	3.75%

Table 7 Mass Variation through the production process for each steel type

Aluminum

The Life cycle of aluminum products is depicted in Figure 4-1:

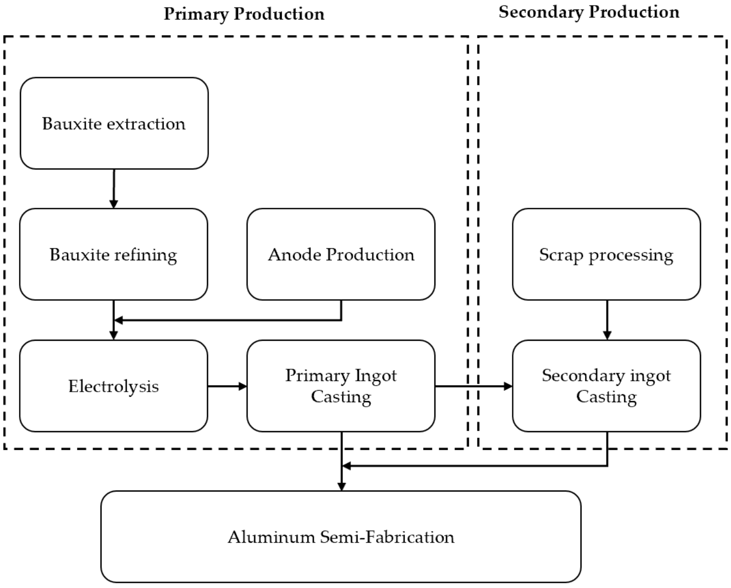


Figure 3-1 Aluminum parts production flow diagram

Primary aluminum is produced from bauxite, while secondary aluminum is recovered from aluminum scrap, including that recycled from spent aluminum products, collected from semi-fabricators including rolling mills, foundries, extrusion facilities, and manufacturers of aluminum products. Before the transformation, the process includes bauxite mining, anode, alumina production, smelting, and producing the ingots. First, the data relating to aluminum production is gathered from the GREET model. Subsequently, the material is subjected to hot / Cold rolling, extrusion, and stamping processes. Four types of processed products that make up the vehicle are considered: hot rolled aluminum., cold rolled aluminum and extruded aluminum. The following table shows which process each type of aluminum is subjected to.

Process	**Virgin Hot Rolled**	**Virgin Cold Rolled**	**Virgin Extruded**	**Recycled Hot Rolled**	**Recycled Cold Rolled**	**Recycled Extruded**
Bauxite Mining	✓	✓	✓			
Bauxite Refining:	✓	✓	✓			
Anode Production	✓	✓	✓			
Alumina Reduction: Hall-Heroult Process	✓	✓	✓			
Primary Ingot Casting	✓	✓	✓			
Scrap Preparation				✓	✓	✓
Secondary Ingot Casting				✓	✓	✓
Hot Rolling	✓	✓		✓	✓	
Cold Rolling		✓			✓	
Stamping	✓	✓		✓	✓	
Extrusion			✓			✓
Machining	✓	✓	✓	✓	✓	✓

Table 8 Production processes for each aluminum type

Plastic

A vehicle contains a wide variety of plastics inside; table 10 shows the percentage mass for each type of plastic compared to the total mass of plastic present in the vehicle (which accounts for about 11/12% of the total weight of the vehicle).

Type of Plastic	Share on total plastic weight in the vehicle	Energy consumption per production [MJ/kg]
ABS	7.6%	25.2
EPDM	7.1%	7.8
Liquid Epoxy	10.7%	61.9
GPPS	0.7%	24.0
HIPS	0.7%	23.7
HDPE	1.4%	11.8
LDPE	1.4%	15.4
LLDPE	1.4%	11.4
Nylon 6	1.1%	55.1
Nylon 66	7.0%	54.0
PC	3.5%	44.9
PET	1.7%	19.2
PP	18.1%	9.8
PUR Flexible Foam	12.2%	28.6
PUR Rigid Foam	11.6%	25.7
PVC	13.8%	19.4

Table 9 Mass percentage of each plastic-type on total plastic weight in vehicle and energy consumption for production.

Given the wide variety of plastics, it was decided to consider the entire plastic inside the vehicle as a material with the percentage composition shown in table 10. Then, knowing the energy consumption and the types of fuels necessary to produce each type of plastic, it was possible to calculate the energy consumption to produce the plastic mix.

Copper, iron, rubber, and glass

As far as iron, glass, rubber, and copper are concerned, different production processes have not been considered as the presence of only one type of each inside the vehicle has been considered: glass is present exclusively in the side windows, windshield, and rear window, copper is present mainly sub-element of wiring, rubber is present in tires and gaskets that hypothetically are considered as made of the same material, while iron when present is mainly in the form of cast iron. Therefore, the following table reports the energy consumption to produce the materials:

	Energy consumption [MJ/kg]	Source
Iron	9.297	[22]
Rubber	40.051	[22]
Glass	13	[5]
Copper	25.76	[5]

Table 10 Energy consumption of Iron Rubber Glass and Copper parts production

3.3.2. Vehicle Life Cycle

For the assessment of the production emissions of the vehicle, it is sufficient to use the material composition of each vehicle, presented in chapter 3.3, weigh those values for the cradle to gate emission of the individual materials, which are reported in the following table and then multiply for the vehicle weight:

Steel	Aluminum	Plastic	Iron	Rubber	Glass	Copper
45.2	103	27.1	9.297	40.051	13	25.76

Table 11 Vehicle's Material Cradle to Gate emissions [MJ/kg]

The values shown refer to the average value of cradle to gate emissions for each material. In addition, it is necessary to consider the environmental impact of vehicle assembly operations, whose estimation is problematic since multiple assembly pains and economies of scale depend on the size and location of the production plant come into play. This study has divided the assembling process into six parts: paint production and painting, Heating, Ventilation and Air Conditioning (HVAC) and lighting, material handling, heating, air compressing, and welding. Table 12 presents their detailed energy consumption. [5]

	Paint Production	**Painting**	**HVAC & Lighting**	**Heating**	**Material Handling**	**Welding**	**Compressed Air**
Natural gas	0	2427.69	0.00	3,146.2	0.00	0.00	0.00
Electricity	302.8	483.21	1,044.5	0.00	216.3	288.0	431.5
TOTAL	302.8	2,910.9	1,044.5	3,146.2	216.3	288.0	431.5

Table 12 Energy consumption for each Assembly Process

This way, assembly operations depended on the production location through the Grid Emission Factor.

3.3.3. Battery Life Cycle

The key components that contribute to the life cycle GHG emissions of a battery for an electric car include:

- Materials: Mining and refining processes, especially for aluminum, and synthesis of active materials such as nickel, cobalt, and graphite.

- Battery assembly: Climate control during cell assembly, which takes place in a “dry room” which maintains ultra-low humidity (<1% relative humidity) and other tightly controlled conditions to minimize contamination risks and ensure safety.

- End of life: battery recycling processes require energy and cause GHG emissions. These are partly compensated because recycling enables material recovery, thereby offsetting raw material mining and processing impacts.

Each life-cycle phase, including recycling, presents opportunities to further reduce the overall impact of BEVs compared to ICE vehicles by using low-carbon energy sources and achieving economies of scale. To get more accurate battery production values, we must get the upstream emissions for material collection and then sum the emissions due to the assembly phase. The electricity mix for materials and cell production can vary substantially across geographic regions.

Lithium-Ion Battery Design

A lithium-ion battery can be produced with several different lithium-based cathode and anode materials. Some electrode (anode and cathode) materials dominate electric vehicle battery production. Common is to use a mix of cobalt, nickel, and manganese oxides together with lithium as the cathode (NMC batteries), but it is also possible to use an iron phosphate (LFP). The cathode is coupled with an anode, most commonly graphite. The following table gives an overview of the most common cathode materials used in EVs today that are the subject of this study.

Cathode material	**Abbreviation**	**Advantages**	**Disadvantages**
Nickelate	NMC111	High energy density and operating voltage	High material cost per kWh
	NMC622		
	NMC811		
	NCA		
Phosphate	LFP	Long Cycle Life, low material cost, and better thermal stability	Lower cell potential can lead to larger systems and higher pack cost
Manganese Spinel	LMO		

Table 13 Li-ion batteries chemistry characteristics

A very important aspect concerns NMC batteries; the trend is to use more batteries with low cobalt content (NMC811) than those with higher content (NMC 622 and NMC111). This is because cobalt is a very expensive and carbon-intensive element as well as being extracted, often taking advantage of mistreated labor. There are fewer choices regarding the anode material. In this study, only graphite anode has been considered because it is the most common choice in EVs nowadays.

Battery materials

The relative weight of different pack components can help understand the importance of different parts. Additionally, it can help identify why the components contribute to a different extent to the life cycle. In table 14, the material composition of different batteries type is presented.[5]

	LFP	**LMO**	**NMC111**	**NMC622**	**NMC811**	**NCA**
Active Material	21.9%	43.5%	38.2%	36.1%	31.5%	34.6%
Graphite/Carbon	11.6%	15.6%	20.2%	22.1%	24.4%	23.4%
Binder	0.7%	1.2%	1.8%	1.2%	2.2%	1.2%
Copper	16.9%	8.2%	7.2%	7.1%	7.2%	6.8%
Aluminum	20.3%	16.8%	17.3%	17.8%	18.4%	18.0%
Steel	2.1%	0.6%	0.6%	0.6%	0.6%	0.6%
Electrolyte: $LiPF_6$	2.1%	1.4%	1.4%	1.4%	1.4%	1.4%
Electrolyte: Ethylene Carbonate	5.7%	3.9%	3.9%	3.8%	3.9%	3.8%
Electrolyte: Dimethyl Carbonate	5.7%	3.9%	3.9%	3.8%	3.9%	3.8%
Polypropylene	1.8%	0.8%	0.7%	0.6%	0.8%	0.6%
Polyethylene	0.4%	0.2%	0.2%	0.2%	0.2%	0.2%
Polyethylene Terephthalate	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Thermal Insulation	0.5%	0.3%	0.3%	0.4%	0.4%	0.4%
Coolant: Glycol	3.6%	2.1%	2.6%	2.9%	3.0%	3.2%
Electronic Parts	6.4%	1.4%	1.7%	1.8%	1.9%	1.9%

Table 14 Batteries material composition for each chemistry

For each material, its production cycle was analyzed, first determining the energy consumption for the production and then the associated CO2 emissions.

Some considerations have been made:

- Binder PVDF has been considered PVC. However, this simplification does not affect the results, given the small percentage of plastic mass present in the battery pack.
- Plastic was considered uniform and equal to the mix of plastics already considered in the vehicle production phase.
- There is no distinction between copper aluminum and steel previously considered and those present inside the battery pack.
- Thermal insulation is made of polypropylene.
- "Electronic parts" is comprehensive of 2 parts:
  - Each module has a state-of-charge regulator assembly that is composed of circuit boards with insulated wires running to each cell
  - BMS includes measurement devices and can control battery pack current and voltage, the balance of voltage among modules, and battery thermal management, among other parameters.

Below are reported the energy consumption to produce each material divided according to the fuel used.

Material/component	**Oil**	**Diesel**	**NG**	**Coal**	**Electricity**	**Source**
Active Material						
NMC111					263.1	[5]
NMC622					288.4	
NMC811					318.9	
NCA					342.3	
LMO					38.6	
LFP					37.8	
Graphite/Carbon	0.00	0.00	44.68	0.00	44.68	[8]
Binder PVDF	3.57	0.20	19.24	0.43	3.73	[8]
Copper	0.89	2.55	9.08	3.46	9.79	Previous calculation

Aluminum	7.51	2.12	32.50	2.68	57.18	Previous calculation
Steel	0.00	0.00	0.00	22.63	22.63	Previous calculation
Electrolyte: LiPF6	0.42	0.00	0.00	0.00	77.02	[8]
Electrolyte: Ethylene Carbonate	8.12	0.00	3.38	0.00	0.59	
Dimethyl Carbonate	0.00	0.00	1.34	0.00	0.09	
Polypropylene	2.83	0.20	20.74	0.35	3.24	Previous calculation
Polyethylene	2.83	0.20	20.74	0.35	3.24	
Polyethylene Terephthalate	2.83	0.20	20.74	0.35	3.24	
Thermal Insulation	2.83	0.20	20.74	0.35	3.24	[8]
Coolant: Glycol	15.24	0.00	15.24	0.00	0.81	
Electronic Parts	0.00	0.00	88.62	0.00	127.66	

Table 15 Production energy consumption per each battery material/component [MJ/kg]

The same approach used previously for the calculation of emissions to produce individual materials was used for the calculation of emissions.

By knowing the percentage composition on the mass of each battery material and the emissions associated with the production of each component, it is possible to determine the CO2 emissions per kg of battery considered.

However, measuring CO2 emissions relative to battery capacity would be more useful for comparing the different battery chemistry because different energy densities characterize each one. Below are reported the energy density values of commercial vehicles in recent years ([23],[24],[25]).

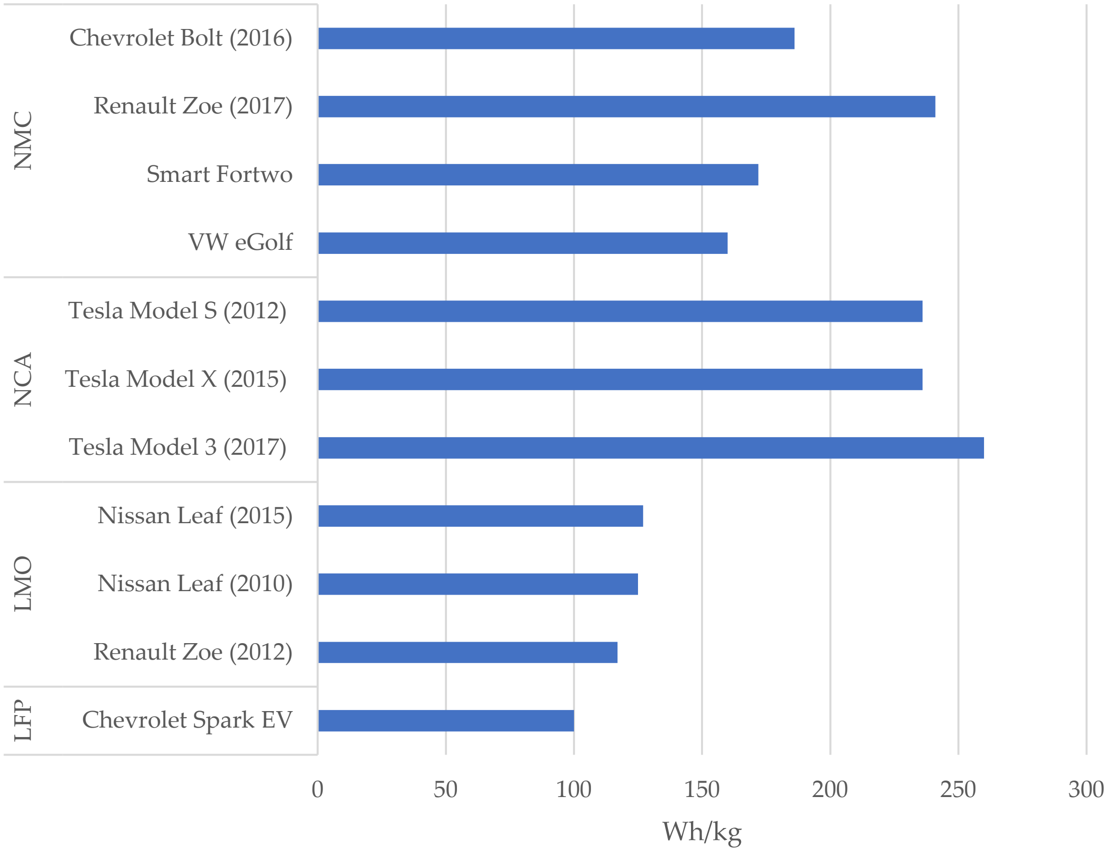


Figure 3-2 Energy Densities of different batteries in commercial vehicles

Subsequently, the current values for vehicles with registration after 2017 were considered to use values that can best reflect current and immediate future technology.

For NMC batteries, an energy density of 180 Wh/kg was considered, for LFP and LMO respectively 100 and 120 Wh/kg, finally for NCA the only value of 260 Wh/ kg was used because nowadays there is only one market player that uses this technology (Tesla, Inc.).

Manufacturing & Assembly

Three different approaches have been taken to estimate the energy required in battery assembly. Some studies use a bottom-up approach, in which the energy of individual steps in battery manufacturing is estimated and summed [[8],[23],[26]]. These studies generally assume assembly facilities operate at capacity. Only one of these considers the energy consumed by the dry room. Nonetheless, these studies estimate battery assembly to be between 1 and 5 MJ/kg.

Other studies use the top-down approach to apportion a fraction of total corporate energy consumption or a literature estimate for total primary fuel consumption for lithium-ion battery production from cradle to gate to battery assembly[13]. Top-down estimates of the energy intensity of battery assembly place it between 74 and 80 MJ/kg battery.

The third approach, using real-world energy consumption data, was taken by Ellingsen et al.[13], who were able to obtain energy consumption data for a battery cell manufacturer and a battery pack assembler. The latter plant, which employed mostly manual labor, had a very small energy consumption below 0.01 MJ/kg battery. However, the cell assembly plant exhibited a wide range of energy consumption between 100 and 400 MJ/kg battery.

In this study, the second type of approach was considered with a value of 77 MJ/kg_battery as it was more consistent with the methodology previously used for the evaluation of energy consumption, here the energy consumption in considered 80% from Natural Gas and 20% from electricity [5] considering an electrical mix dependent on the production place.

3.4. Use Phase

The emissions produced in this phase are called Tank-To-Wheel emissions. In the case of ICEVs, the exhaust emissions are due to the combustion of fuel. In the case of BEVs, there are no tailpipe emissions produced. To calculate the tailpipe emissions, it is necessary first to calculate the fuel consumption, that through an appropriate emission factor, it is possible to obtain the CO2 emission value. To the value of the Tank to Wheel, emission must then be added the emission value due to the maintenance phase of the vehicle.

3.4.1. Fuel consumption model (VCAM)

The open-source python tool "Vehicle Consumption Assessment Model (VCAM)"[19] is a lumped parameter model that assesses the fuel consumption of light-duty vehicles. The tool implements a physical vehicle model computing the energy required to perform a given driving cycle. The tool can simulate three different power trains, ICEV, BEV, and PHEV, and different types of vehicles can be modeled by inserting some key performance parameters. The model is split into vehicle longitudinal dynamics, power-train efficiency, and auxiliary systems. The first section is based on a power balance that computes the traction power required in each time-step summing up four different contributions: aerodynamic friction, rolling resistance, climbing resistance, and mass inertia. The auxiliary's consumption includes a constant value for electrical appliances and an electric consumption due to the HVAC system. The required thermal power is computed depending on the external temperature. The COP depends on the ambient temperature and the type of HVAC module of the vehicle. Two different configurations have been modeled: Air Conditioning and Positive Temperature Coefficient heater (AC+PTC), and Heat Pump with backup Positive Temperature Coefficient heater (HP+PTC). During the heating conditions, the thermal load for ICEV and PHEV is assumed to be satisfied with waste heat recovery from the engine, and a minor additional power is considered only to run fans. An additional power computed as a function of the external temperature and the reference driving cycles is included in the balance for BEVs due to the Battery Thermal Management System (BTMS) consumption. ICEV fuel consumption is computed considering an engine efficiency function of the load and a constant fuel loss for the time spent in idling mode. For BEVs, the electricity discharged from the battery is computed considering a constant discharge efficiency and including the regenerative breaking energy computed considering the maximum torque limitation and the upper limit to the SOC of the battery. Below are the flow diagrams for the calculation of ICEV and BEV consumption:

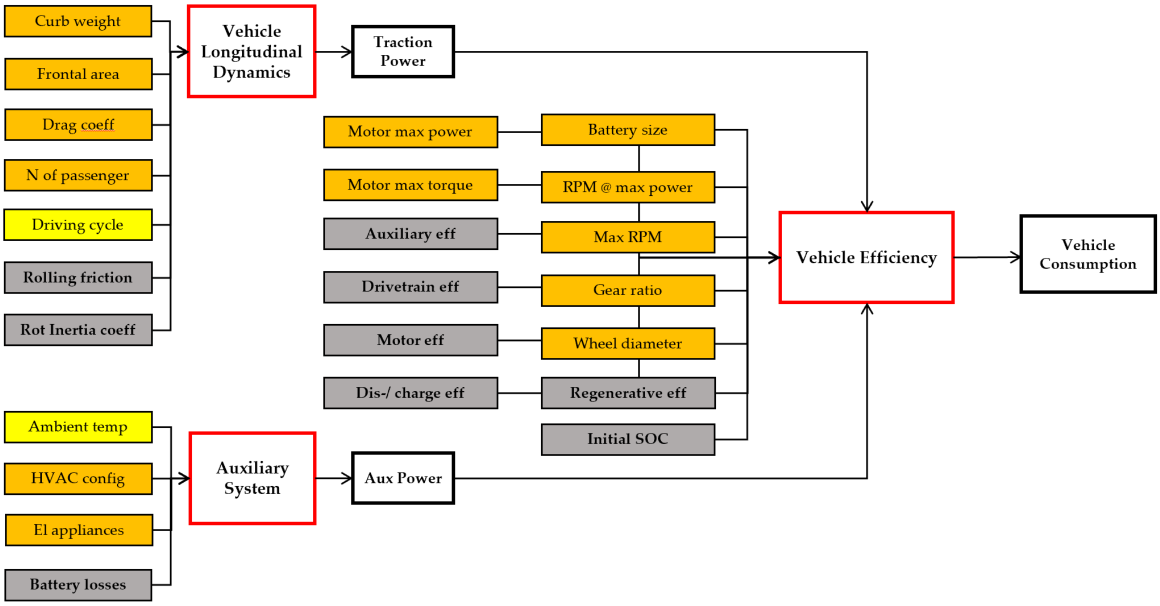


Figure 3-3 BEV powertrain modeling

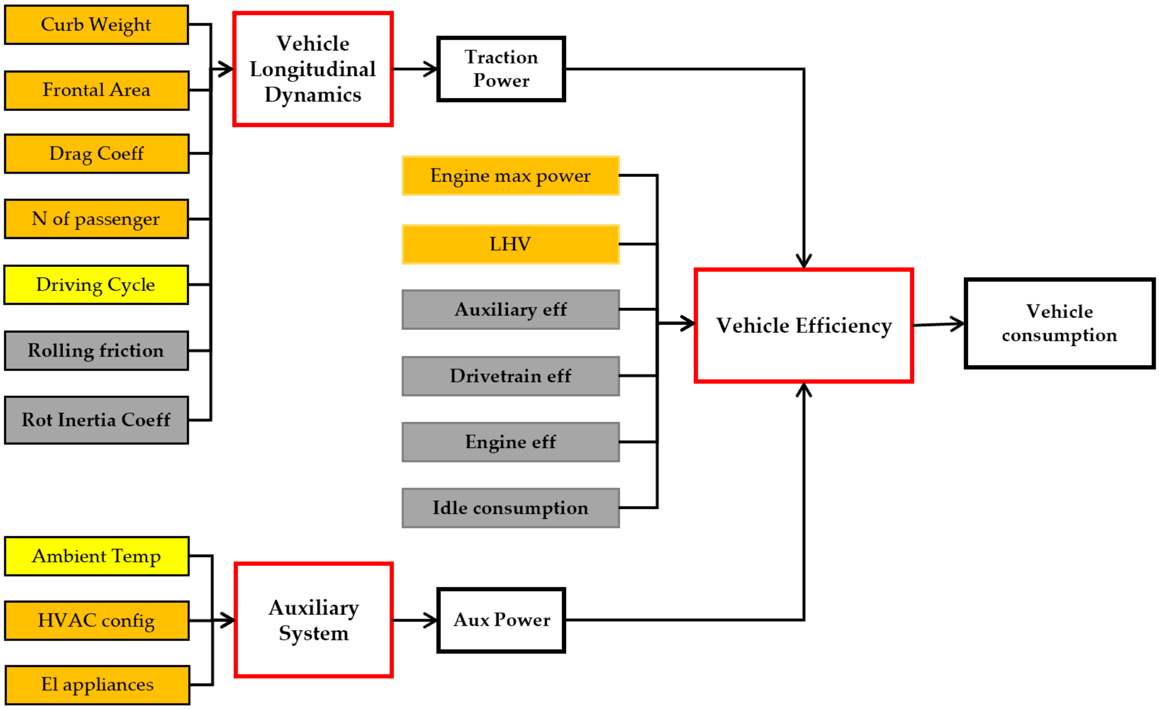


Figure 3-4 ICEV powertrain modeling

The model includes some standard reference driving cycles as well as the input files for modeling some specific vehicles. In this study, three guide cycles were considered:

- UDDS (Urban Dynamometer Driving Schedule): simulates stop-and-go city driving by bringing the test vehicle to speed and bringing it back to zero. It is used to measure the fuel economy of the city.

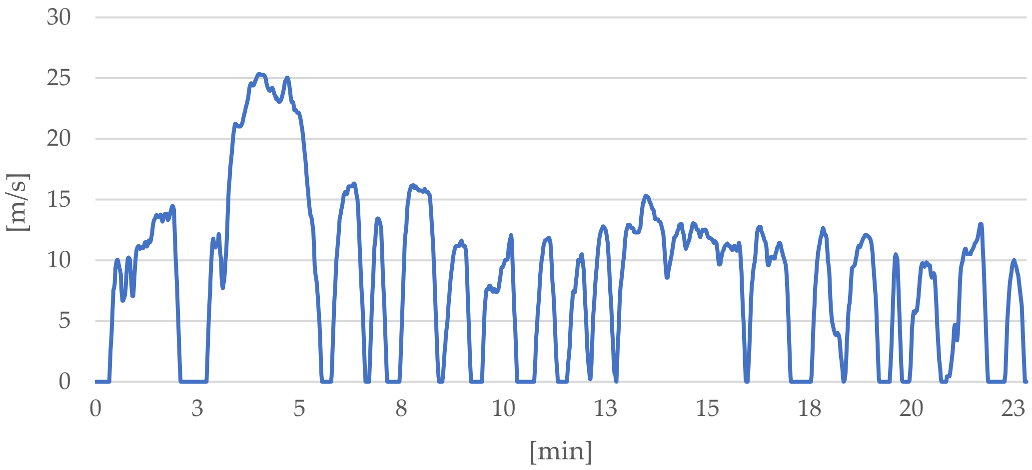


Figure 3-3-5 UDDS Driving Cycle

- HWY (Highway Fuel Economy Driving Schedule): simulates highway driving at high speed by bringing the vehicle to maximum speed, then making it fluctuate between various speeds in the range of 15-25 m/s throughout the test. This test measures fuel economy on the highway.

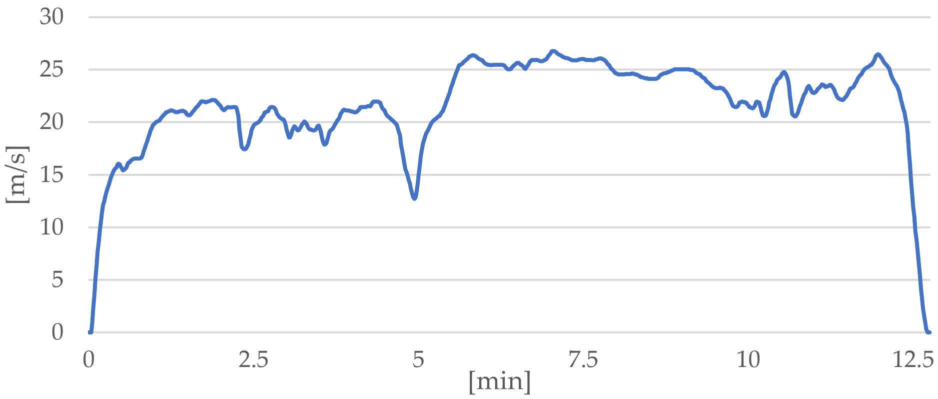


Figure 3-3-6 HWY Driving Cycle

- WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure): It replaces the NEDC driving cycle (New European Driving Cycle) and today represents the state of the art of driving cycles. It tests the vehicle's consumption with four different average speeds to obtain feedback as faithful as possible to reality based on the different driving styles adopted by motorists. The main differences between the NEDC cycle and the speed profile of the cycle are shown below.

	NEDC	WLTP
Cycle duration	20 min	30 min
Cycle distance	11 km	23,25 km
Driving stages	2 phases, 66% driving in an urban context and 34% driving outside the city	4 more dynamic phases, 52% driving in urban settings and 48% driving outside the city
Average/max speed	34/120 Km/h	46.5/131 Km/h
Test temperature	Measurements made between 20 and 30 °C	Test carried out at 23 °C

Table 16 NEDC and WLTP characteristics

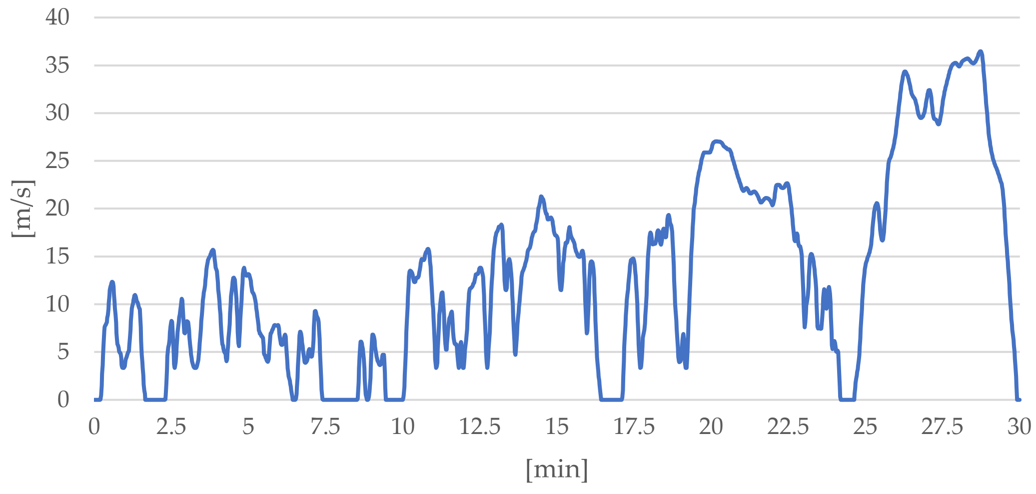


Figure 3-3-7 WLTP Driving Cycle

3.4.2. Tailpipe emission

The combustion process of the fuel causes the exhaust emissions (only those of CO2 are considered), then the chemical reaction that takes place inside an internal combustion engine is reported:

$$HC + O_2 + N_2 \xrightarrow{spark} CO_2 + H_2O\ +\ HC + CO + NO + heat$$

Whereby HC is gasoline. During the combustion process, 0.087 gCO2/ MJ_{HC} is produced, given the lower heating value (LHV) of HC of 34 MJ/kg and the HC density of 0.79 kg/L, an emission factor per liter of fuel consumed equal to 2.34 kgCO2/L is obtained.

3.4.3. Maintenance

This phase involves the emissions due to vehicle maintenance throughout the vehicle's life. In this phase, the main contributions to emissions are replacing tires and lead-acid batteries for all vehicles, engine oil and radiator coolant for conventional vehicles, and possible li-ion battery replacement in battery electric vehicles. The contributions of these factors are given in Table 18 [27].

	Maintenance Interval [km]	kgCO2/maintenance	Vehicle type
Tire	40000	108	BEV, ICEV
Lead-acid battery	50000	19.5	ICEV
Engine Oil	10000	3.22	ICEV
Radiator Coolant	27000	7.03	ICEV

Table 17 Maintenance emissions for vehicles

Overall manufacturing emissions for all segments of ICEVs and BEVs up to 150000 km are calculated obtaining 466 kgCO2/vehicle for ICEV and 380 kgCO2/vehicle for BEV. These values are included in the results under "Vehicle Production Emission".

3.5. Fuel Cycle

3.5.1. Gasoline

Well to Tank (WTT) analysis involves energy consumption and GHG emissions associated with the production and distribution of automotive fuels. The flow diagram of gasoline WTT is given.

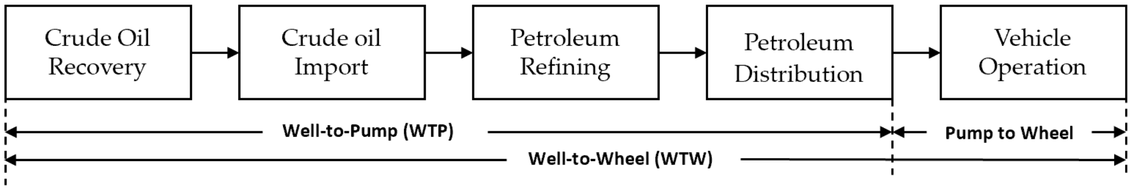


Figure 3-3-8 Gasoline Well to Tank calculation flow diagram

Estimating the carbon intensity of refinery products is difficult, given the complexity of the system and the iterations between the various energy and material flow. Due to the possibility of using different criteria to allocate emissions, there is no single LCA value for gasoline and diesel in the literature. Different allocation criteria can potentially be chosen to distribute emissions over different refinery streams leading to different results. In this study, reference was made to the values reported by the JEC Well-to-Tank report v5 [28] compiled by the Joint Research Centre [JRC], which estimates the gasoline WTT emission at a value of 17 gCO2eq/MJ. Considering a gasoline LHV of 34 MJ/L, WTT emissions are estimated at 595 gCO2eq/L.

3.5.2. Electricity

Well-To-Tank emissions for electricity production are expressed through the grid emission factor, in chapter 4.1 is already shown the great variability of that parameter, this influences in a directly proportional way the Well to Tank emissions that are calculated with the following equation:

$$Well\ to\ Tank\ [gCO2] = \eta_{charge} * \ EF\ [\frac{gCO2}{kWh}] * EC\ [\frac{Kwh}{km}] * lifetime\ [km]$$

It is therefore essential to consider for the assessment of life cycle emissions the place where the vehicle will then be used to evaluate WTT emissions

3.6. End of Life

3.6.1. Battery decommissioning

Developing an effective recycling industry is key to the sustainability of Li-ion batteries and by extension electric vehicles. A recycling system would reduce demand for raw materials, CO2 emissions, and negative local impacts from mining and refining by recovering critical materials. Furthermore, domestic recycling enables countries to reduce their reliance on imports for critical materials like rare earth. Before undergoing a recycling process, battery packs must first be discharged, then dismantled to at least the module level. Next, the modules are subjected to mechanical pre-treatment or a pyrometallurgical process, which a hydrometallurgical process must follow to recover critical materials in usable form.

- Mechanical pre-treatment primarily consists of shredding and sorting out plastic fluff, metal-enriched liquid, and metal solids. After sorting, most copper, aluminum, and steel casings are recovered. The remaining material resembles a black powder containing nickel, cobalt, lithium, and manganese [29].

- Pyrometallurgical recycling processes use high-temperature smelting (~1 500 degrees Celsius) to produce a concentrated alloy containing cobalt, nickel, and copper. These metals can then be extracted using a hydrometallurgical process. The lithium and manganese end up in a slag that can be processed further to recover lithium ([30],[31]).

- Hydrometallurgical recycling methods are based on leaching, removal of impurities, and separation. Leaching may be followed by solvent extraction and chemical precipitation to recover lithium, nickel, and cobalt.

Calculating the potential saving of CO2 obtained thanks to the recycling of batteries is extremely complex as today the technologies are still in the full development phase. However, this study has been considered the values proposed by Mia Romare et al. (2017) [15] which, through a review of available life cycle assessments on lithium-ion batteries for light-duty vehicles, estimate that hydrometallurgical and pyrometallurgical recycling would reduce the overall battery impact by 12 kgCO2/kWh and 15 kgCO2/kWh respectively or 3,5 kgCO2/kg of battery.

In this study, the proposed values per kg of battery are used to make it possible to differentiate the result according to the different chemicals through the different energy density values.

4 Scenario’s definition

4.1. Fleet mix change Scenario

This scenario aims to show what the environmental impact would be if we were to implement a complete transition of the vehicle fleet currently in different countries. The scenario is intended as a comparative analysis between the ICEV and BEV fleets to show the key differences between the two alternatives. Some hypotheses have been made:

- The fleet of vehicles consists of 3 different categories (Small, Medium, Large) characterized in the following way:

Category	**Vehicle segment**
Small	A B
Medium	C, D, J
Large	E, F, S

Table 18 Vehicle Segment categorization

- The driving cycle considered for the vehicle's entire lifetime is the WLTP cycle: this approximation slightly underestimates TTW emissions. However, the purpose of the scenario is to provide a comparative analysis between ICEV and BEV, making the error that is made on the absolute value of emission negligible.

- Countries' grid emission factors of 2020 (Table 3)

- Gasoline emission factor: 2,34 kgCO2/L

- Emissions from battery and vehicle production are obtained considering the global grid emission factor (518 gCO2/kWh)

- Lifetime is set to 150000 km

- NMC batteries for all the electric vehicles considered in this scenario

In this scenario, all the EU countries are considered with the addition of China, United States, and United Kingdom. The replacement of the current fleet of vehicles in each country with its electric equivalent is simulated. The current fleet mix of each country has been considered, and values are shown in table 19.

	S	**M**	**L**		**S**	**M**	**L**		**S**	**M**	**L**
AT	30.9%	56.1%	13.0%	*GR*	37.6%	54.8%	7.6%	*PL*	38.8%	53.0%	8.2%
BE	34.9%	54.9%	10.2%	*HU*	46.5%	45.1%	8.4%	*PT*	42.6%	47.5%	9.9%
BA	37.6%	54.8%	7.6%	*IE*	35.4%	58.5%	6.1%	*RO*	36.6%	56.1%	7.4%
BG	36.6%	56.1%	7.4%	*IT*	23.6%	69.6%	6.8%	*RS*	37.6%	54.8%	7.6%
HR	37.6%	54.8%	7.6%	*LV*	10.6%	59.8%	29.6%	*SK*	39.5%	51.3%	9.2%
CZ	39.5%	51.3%	9.2%	*LT*	10.6%	59.8%	29.6%	*SI*	35.7%	57.1%	7.2%
DK	36.6%	48.8%	14.5%	*LU*	36.6%	48.8%	14.5%	*ES*	28.2%	62.1%	9.7%
EE	14.7%	56.6%	28.7%	*MD*	36.6%	56.1%	7.4%	*SE*	35.7%	47.6%	16.7%
FI	23.7%	57.2%	19.1%	*NL*	51.9%	39.6%	8.4%	*UA*	38.8%	53.0%	8.2%
FR	32.8%	60.6%	6.6%	*NO*	18.3%	60.8%	21.0%	*GB*	35.8%	50.8%	13.1%
DE	36.6%	48.8%	14.5%	*CH*	37.6%	54.8%	7.6%	*US*	36.0%	51.0%	13.0%

Table 19 Fleet mix composition for different countries

Considering the fleet mix from a perspective of ecological transition of the vehicular transport sector is very important because depending on the area considered the needs and preferences of people regarding the type of vehicle change. Therefore, it is impossible to think that the transition to green mobility leads to a country where most people drive large vehicles (SUVs, Off-road vehicles, Sedans) to the large-scale adoption (at least in the short term) of small/city cars. With this perspective, the replacement of vehicles with their electric counterparts was simulated. The aim is to assess how much the type of fleet mix and the driving location affect LCA emissions. Break-Even Emission Point is a widely used parameter to compare the environmental impact di ICEVs e BEVs; it is defined as the number of km after which the CO2 savings values are defined as:

$$CO2_{Savings} = CO2_{ICEV\ FLEET} - CO2_{BEV\ FLEET}$$

is equal to zero.

When the vehicle is not yet used, its Life Cycle emissions are equal to the production emissions, which are higher in BEV vehicles due to the emissions related to the production of the battery pack so the $\mathrm{CO2_{Savings}}$ the value will be negative. To also characterize the effect of ambient temperature on consumption, for each country, the Tank-To-Wheel emissions have been evaluated at the average annual temperature (obtained by averaging the values of the last 40 years) of each country, whose values are shown in the following table:

Country	Temperature [°C]	Country	Temperature [°C]	Country	Temperature [°C]
AL	13,5	GR	16,7	PL	8,3
AT	8	HU	10,8	PT	16,2
BE	10,8	IE	9,8	RO	10,5
BA	10,1	IT	14,2	RS	11,6
BG	11,4	LV	5,2	SK	8,3
HR	12,4	LT	5,6	SI	9,4
CZ	8,2	LU	9,3	ES	15,7
DK	8,5	MK	10,4	SE	5,8
EE	4,8	MD	9,8	UA	8,3
FI	2,8	ME	9,6	GB	9,8
FR	11,5	NL	10,2	USA	10
DE	9,3	NO	3,9	CHINA	7,5

Table 20 Average annual temperature for each country

During the use phase, an ICEV vehicle emits an amount of CO2 equal to:

$$CO2_{ICEV\ FLEET}[\frac{gCO2}{km}] = \sum_{i}^{3} \%_i * \frac{EF_{gasoline}\left[\frac{gCO2}{L}\right]}{FC_i(T)[\frac{km}{L}]}$$

Where $\%_i$ is the mixed fleet percentage of the categories i and $FC_i(T)$ is the fuel consumption of category i (with i = small, medium, large) at temperature T. While a BEV vehicle produces a CO2 emission (produced upstream for the generation of electricity used for recharging) equal to:

$$CO2_{BEV\ FLEET}[\frac{gCO2}{km}] = \sum_{i}^{3} \%_i * EF_{grid}\left[\frac{gCO2}{kWh}\right] * EC(T)_i\left[\frac{kWh}{km}\right] * \eta_{charge}$$

Where EC_i is the electric consumption, η_{charge} is the charge efficiency, and EF_{grid} is the national grid emission factor.

Well to Tank emissions of BEV are always lower than the Tank to Wheel emissions of ICEV (depending on the electrical mix considered), and for this reason, as the kilometrage increases, the value of CO2 savings tends to increase until it reaches the BEEP. Each km traveled after the BEEP represents a saving in CO2 emissions obtained thanks to the adoption of the electric vehicle instead of the traditional vehicle with an internal combustion engine. Another factor to consider is the average annual mileage. If the distance is meager, it may take decades to reach the BEEP, significantly reducing the environmental benefit of BEVs.

4.2. Future Mobility scenario

So far, the Life Cycle Assessment of electric vehicles has been evaluated using values and making assumptions based on the current state of the art. However, it is appropriate to consider that we are only beginning the transition to sustainable mobility. Therefore, it is necessary to assess how much technological development in the future can influence the analyses conducted so far. So, it was decided to hypothesize a scenario that considers some future improvements:

- **Vehicle consumption**: efficiency of ICE vehicles is expected to improve. leading to decrease consumption by 20% for 2030 and 40% for 2050.

- **Energy mix**: a reduction in the carbon intensity of power generation of 55 % is assumed following the Sustainable Development Scenario (SDS) projections developed by the International Energy Agency (IEA) for 2030. By 2050 it is considered equal to zero, following the Net Zero-emission Scenario (IEA) assumptions.

- **Battery pack energy density and size**: in recent years the average size of the battery pack has continued to increase; this trend is set to continue, with BEVs reaching an average driving range of 350-400 km by 2030, which corresponds to the size of mid-range vehicle batteries of 70-80 kWh [32]. The increase in the size of the battery pack is accompanied by an increase in the average energy density (NMC / NCA batteries) up to average values of 300 Wh/ kg (for 2030) which is 15% more than the best value currently reached by Tesla Motors NCA batteries and up to a value of 500 Wh/kg for 2050.

- **Battery supply chain**: in the future, the relative impact of battery production on vehicle life cycle emissions is also set to increase as the electricity consumed in the use phase decarbonizes. Minimizing this impact will require reducing the carbon intensity of the energy mix used in battery production processes). Therefore, consumption in the assembly phase was assumed to be equal to 50 MJ/kWh (bottom-up approach).

5 Results

Total life cycle emissions are obtained by summing the previously calculated emissions of all the LCA phases. All the results depend on the characteristics of the vehicle considered. This study considers eight vehicles segments whose characteristics are shown in the following tables [33]:

Segment	**A**	**B**	**C**	**D**	**E**	**F**	**J**	**S**
Model	Fiat 500e	BMW i3	VW ID.3	Tesla Model 3	Audi e-Tron SB	Tesla Model S	Tesla Model Y	Porsche Taycan Turbo S
Max Power [kW]	83	135	107	211	265	568	377	560
Max Torque [Nm]	200	270	310	450	561	980	660	1050
Rpm Max	10235	13000	16000	13000	9000	18000	13000	16000
Curb Weight [kg]	1222	1057	1306	1284	1772	1544	1439	1581
Front Area [m^2]	2.1	2.3	2.4	2.3	2.7	2.4	2.4	2.3
Cx	0.31	0.3	0.27	0.23	0.28	0.24	0.23	0.25
Wheel diameter[inch]	15	20	18	19	20	19	19	20
Battery capacity[kWh]	24	42	62	80	95	100	74	93
P_elapp [W]	400	400	400	500	650	550	500	700
rpm max power	4600	4800	4600	4700	4660	5900	4700	6400
Gear ratio	9.6	9.7	10	9	9.2	9.7	9	11.6

Table 21 BEV segment characteristics

Segment	**A**	**B**	**C**	**D**	**E**	**F**	**J**	**S**
Model	Fiat 500	VW Polo	VW Golf	AUDI A4	Mercedes Benz E class	BMW Series 7	BMW X3	Porsche Panamera Turbo S
P max kW]	63	70	95	110	245	530	265	520
Curb Weight[kg]	975	1045	1191	1410	2100	1950	1850	2155
Frontal Area [m^2]	1.937	2.03	2.21	2.23	2.31	2.41	2.4	2.07
Cx	0.32	0.31	0.275	0.23	0.28	0.24	0.29	0.31
P_elapp W]	500	400	450	550	550	650	550	550

Table 22 ICEV segment characteristics

Is necessary to make some clarifications and hypotheses:

- The curb weight refers to the vehicle's weight without a battery pack, whose weight must be added in the following to evaluate Well to Tank emissions. For the results reported below, an NMC811 battery with an energy density of 180 Wh/kg was assumed for all vehicles presented.

- The emission factor of the European electric mix (294 gCO2/kWh) is used to evaluate both the vehicle and the battery's production emissions and the calculation of the Well to Tank emissions.

- A vehicle's lifetime mileage of 150000 km is considered.

- The WLTP guide cycle was used to assess WTT and TTW emissions.

- Use of the vehicle at room temperature (20°C).

Below are the results of the LCA for different segments distinguishing between the various emission components:

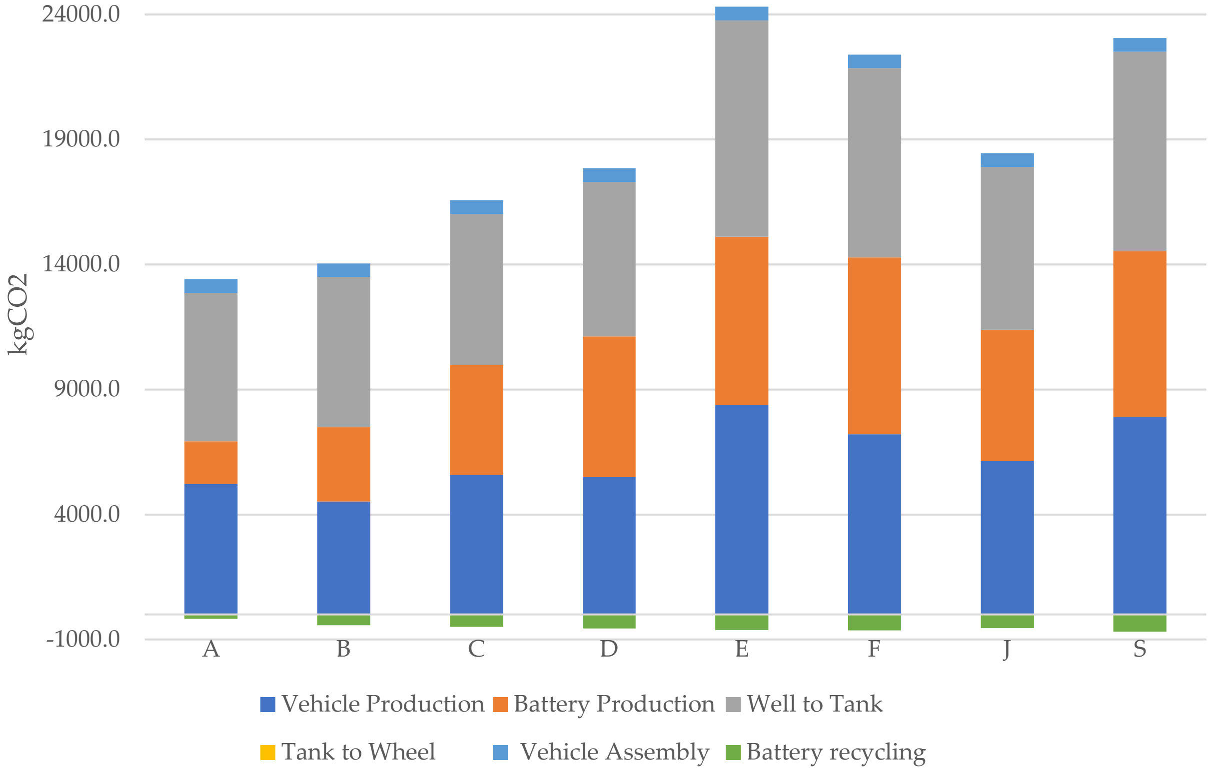


Figure 5-1 BEV Life Cycle Emissions

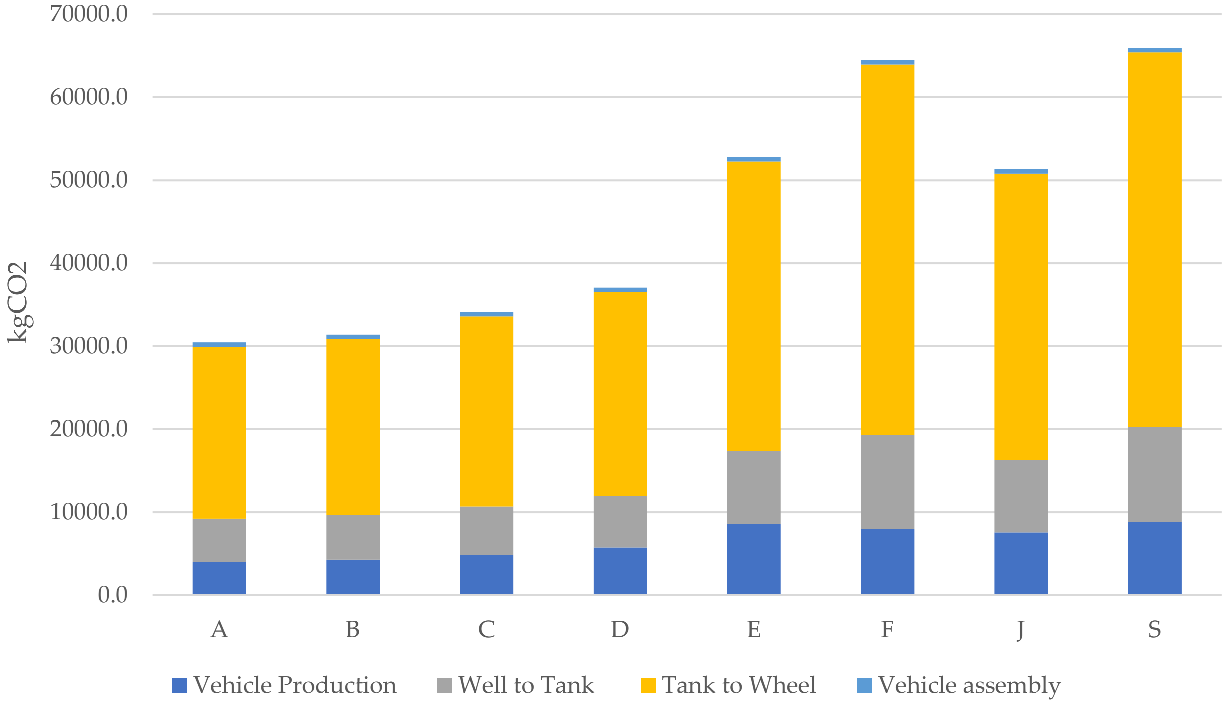


Figure 5-2 ICEV Life Cycle Emissions

In the case of BEV, production emissions represent on average 60% of the total life cycle emissions and are about 77% higher than those of internal combustion vehicles, thus representing the real critical point of electric mobility. The higher production emissions value is due to the battery pack's production emissions, about 27% of the total life cycle emissions. The second-largest contributor are WTT emissions which, considering the carbon intensity of the European electricity mix, account for 38% of life-cycle emissions.

The Tank-to-Wheel fuel phase accounts for most life-cycle emissions (about two-thirds). They can only be reduced by efficiency improvement measures such as carbon capture onboard or fuel switching that offsets CO2 emissions from tank to wheel (e.g. sustainable biofuels). An average consumption reduction of 69% is required to have life cycle emission values of ICEVs equal to those of BEVs.

A small BEV emits an average of 14.3 tonCO2 over its lifetime, 56% less than a similar size ICEV. As the size and power increase in the large BEVs segment, they save more GHG emissions concerning ICEVs because the increase in size and power between different categories is much more impactful in the case of ICE vehicles. The increase in weight and size of ICEVs is accompanied by more powerful engines that have a very impactful effect on Tank to Wheel emissions (this aspect will be deepened more in chapter 5.1.3).

In the case of ICEVs, the aspects that can be improved to reduce life cycle emissions are an efficiency improvement and a more eco-sustainable supply chain that uses, for example, recycled materials. On the other hand, more parameters can potentially lead to a variation of BEVs’ life cycle emissions.

Some sensitivity analyses were then carried out on the parameters that most influence the emission values of the life cycle. For these analyses, the C-segment vehicles (most representatives of the circulating fleet) are considered with the characteristics shown in table 21 and table 22.

5.1. Sensitivity analyses

5.1.1. Electricity Mix

The carbon intensity of the electric mix is a fundamental parameter that influences both production emissions by reducing the environmental impact of all industrial processes that use electricity as a source and the Well-To-Tank emissions of electric vehicles. The influence is even more significant in the case of electric vehicles, as can be seen from the graphs below, which show the percentage of energy consumption divided by energy source and the resulting emissions. (EU Grid EF).

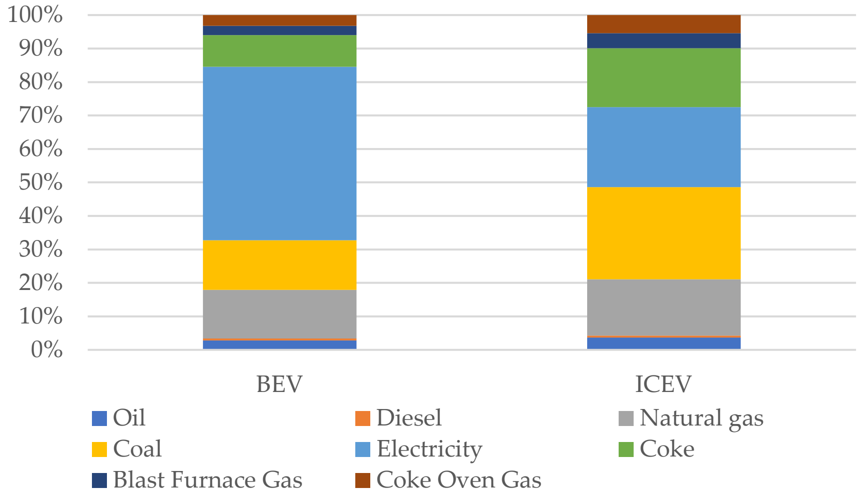


Figure 5-3 Production energy consumption divided per energy source

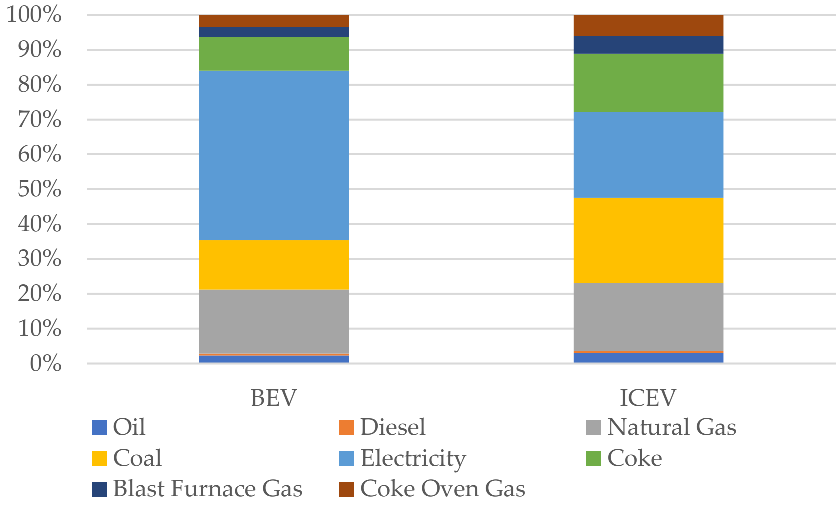


Figure 5-4 Production emission divided per pollutants

Considering the production of segment-C BEV, production emissions are due to 49% from the use of electricity as an energy source, in the case of ICEVs about 24%; this underline how a transition of energy production technologies must accompany the transition to electric mobility. Below are reported the Life Cycle CO2 emission of battery and vehicle production by varying the electrical production mix:

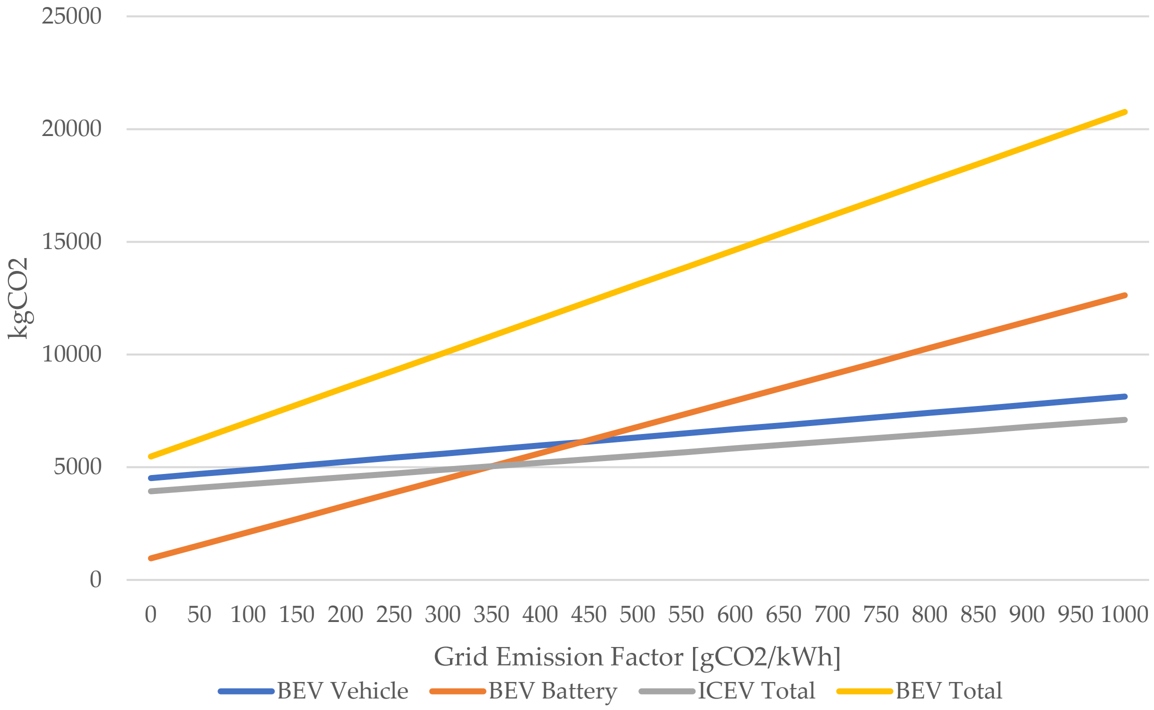


Figure 5-5 Battery and vehicles production emissions at different grid emission factor values

The production emissions of the battery increase linearly with the grid emission factor; this makes the environmental impact of the production of the batteries extremely dependent on the location considered. In the case of the BEV considered (Volkswagen ID3), vehicle cycle emission values vary between 4500 kgCO2/vehicle (full renewable electricity mix) exceeding 8000 kgCO2/vehicle if production is in countries with a very high carbon intensity. For example, the production of a C-segment vehicle in Europe (EF: 294 g $CO_{2\text{-eq}}$/kWh) is 38% less polluting than if the vehicle is produced in China (EF: over 700 g $CO_{2\text{-eq}}$/kWh). The effect is even more evident by evaluating the battery production emissions, which depend 85% on electricity use (considering the NMC811 battery). BEVs' production emissions (without battery) are slightly lower due to the higher presence of copper and aluminum, which are more carbon-intensive materials.

5.1.2. Battery energy density

So far, the results referring to batteries have been obtained with the hypothesis of energy density equal to 180 Wh/kg (medium-high value for current technology), but it is essential to highlight how much this parameter greatly influences the emissions associated with the production of the battery pack. Below is shown a graph that shows the various production emissions of the battery pack at different energy density values (with the hypothesis European electrical mix).

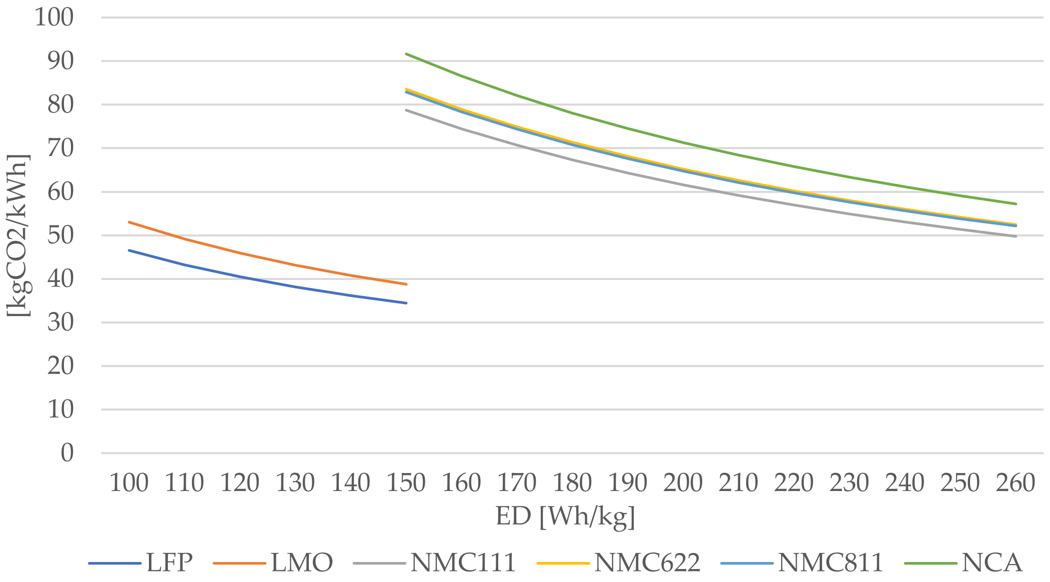


Figure 5-6 Battery production emission at different energy densities values

The results show that the most eco-sustainable solution is represented by LFP and LMO batteries, but we must consider their achievable energy density limit. The likely values of energy density are around 100/120 Wh/kg for LFP and LMO batteries, from 180 to 200 for NMC, while in the case of NCA batteries, an energy density value of 260 Wh/kg is assumed, which represents the best possible technology on the market. Below is the graph that shows the Life-Cycle emissions using energy density values appropriate to the current state of the art.

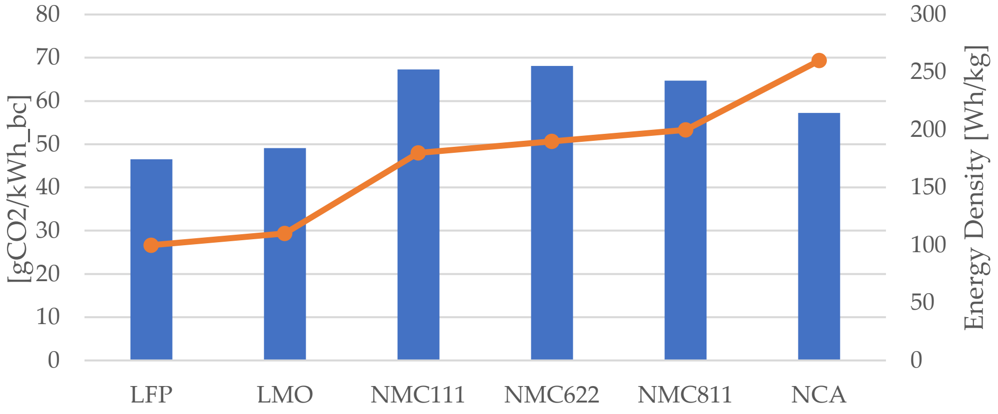


Figure 5-7 Production emission for 1 kWh of battery with different chemistries

The results show that LFP and LMO are the less pollutant solutions (47 kg CO_2/kWh and 49 kg CO_2/kWh, respectively), followed by NCA (57 kg CO_2/kWh) and NMC (67 kg CO_2/kWh for NMC111, 68 kg CO_2/kWh for NMC622 and 64 kg CO_2/kWh for NMC811). All the results are obtained considering the European Emission Factor. Figure 5-8 shows the variability given by the different chemistry of the battery pack on life cycle emissions for the segments described above. Despite the production emissions in the case of LFP and LMO batteries being lower than the other materials, the life cycle emissions are comparable with other chemistries due to the higher weight of the battery pack that causes an increase in vehicle consumption and so in Well to Tank emissions.

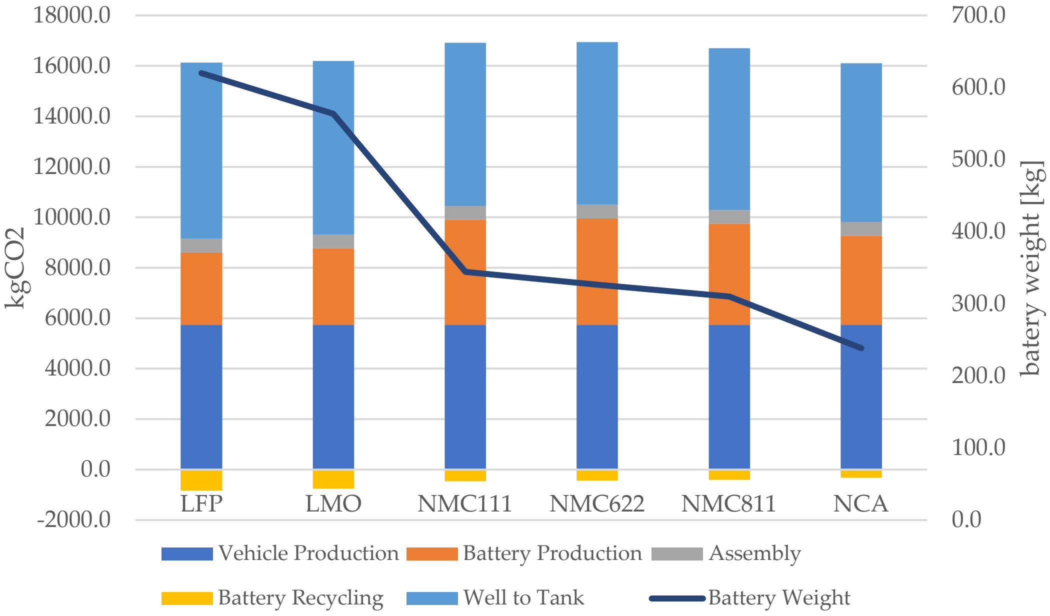


Figure 5-8 Life cycle emissions of C-segment electric vehicle with different battery chemistry

5.1.3. Driving Cycles

An essential component of Life Cycle emissions is represented by the vehicle's use phase and, therefore, by the Well-to-Tank and Tank to Wheel emissions (zero in the case of BEVs).

The emissions during use depend on the vehicle's characteristics (weight, power, battery capacity, aerodynamic coefficient, etc.) and how the vehicle is driven. The use of the vehicle is simulated through a driving cycle, i.e. a speed and acceleration profile that simulates a driving route, and it is possible to calculate the vehicle's consumption. VCAM can run different driving cycles also considering the effect of the ambient temperature, which is a parameter that significantly influences the consumption, especially of electric vehicles, as it directly affects the performance of the batteries. Below are reported two graphs showing the effect of the driving cycle on consumption.

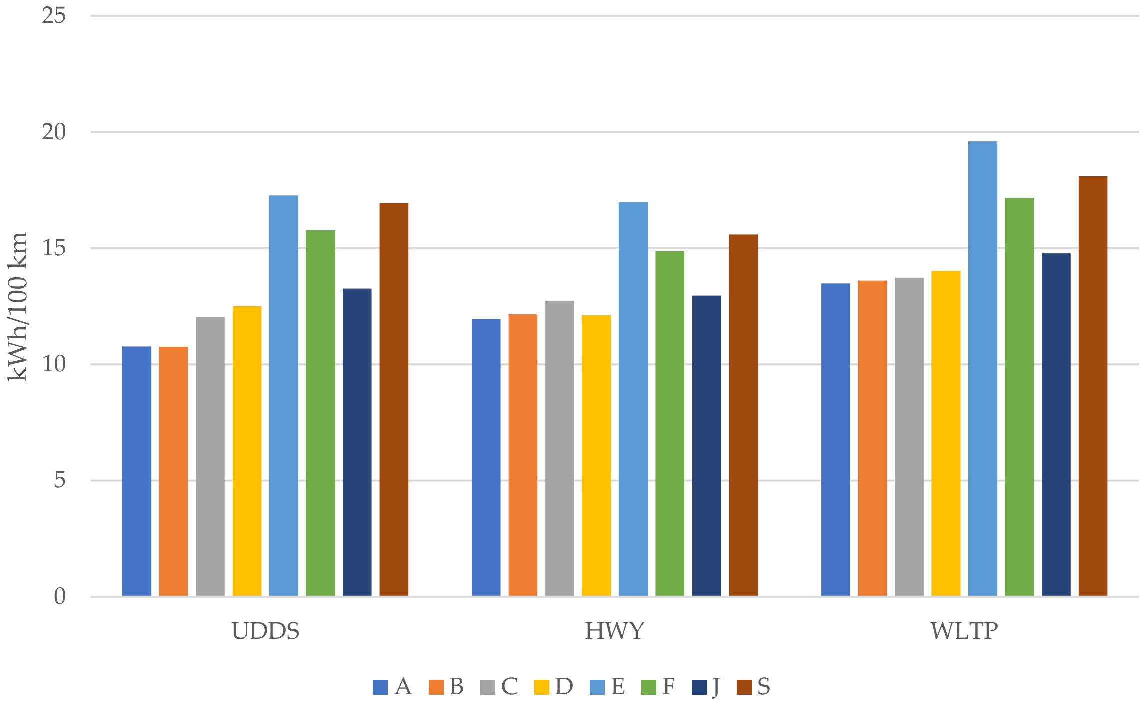


Figure 5-9 BEV Consumption for the different segments and driving cycles

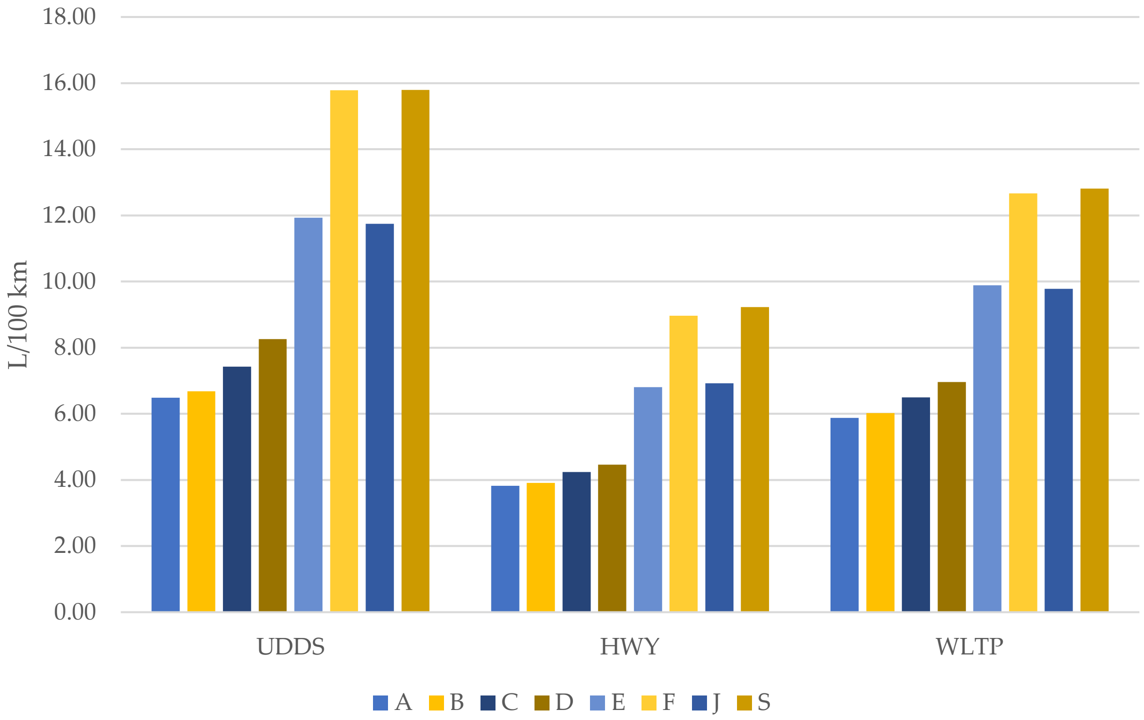


Figure 5-10 ICEV fuel consumption for the different segments and driving cycles

The behavior of the different powertrains is very different: in the case of ICEVs the HWY driving cycle is always the one with the lowest consumption, this is because internal combustion engines consume very little in steady-speed conditions typical of a motorway route, the same cannot be said for electric vehicles that instead show their full potential in urban routes in which they behave better than ICEVs from a consumption point of view (especially low segment vehicles). There is much less variability in consumption between different segments in BEVs than in ICEVs, where consumption can double depending on the segment considered. This is mainly because the increase in size between the different categories is much more impactful in the case of ICEVs for which the change of segment means an increase in weights and engine power that causes a big increase in consumption. In fig 5-2, a graph shows the percentage change in the emission life cycle of a C-segment vehicle by varying the engine power. In the case of electric vehicles, the fuel consumption values are more similar between different segments.

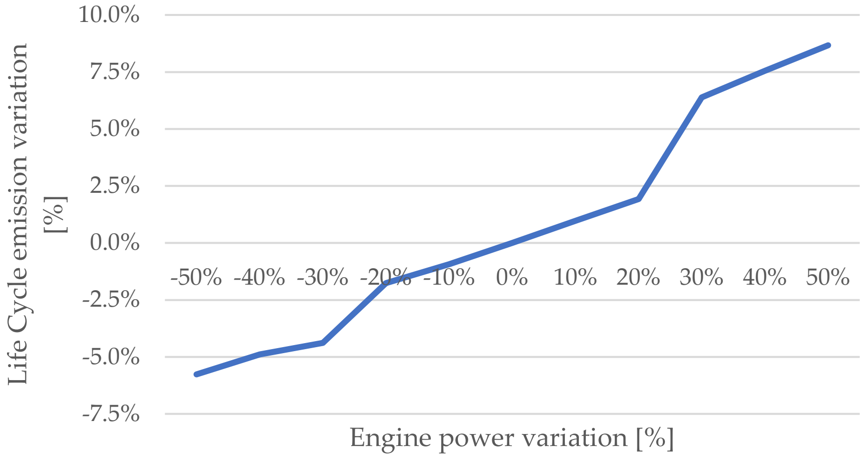


Figure 5-11 Segment C life cycle emission at different engine power increase/decrease

This increase in life cycle emissions is due to an equal increase in Well To Tank and Tank To Wheel emissions.

5.1.4. Driving Location

The driving location is essential for assessing emissions emitted during the vehicle's use phase. The driving country defines the Grid Emission Factor to be considered for charging the vehicle and consequently the value of the Well To Tank emissions. Below are reported the WTT emissions values for a C-segment vehicle with different values of Grid EF.

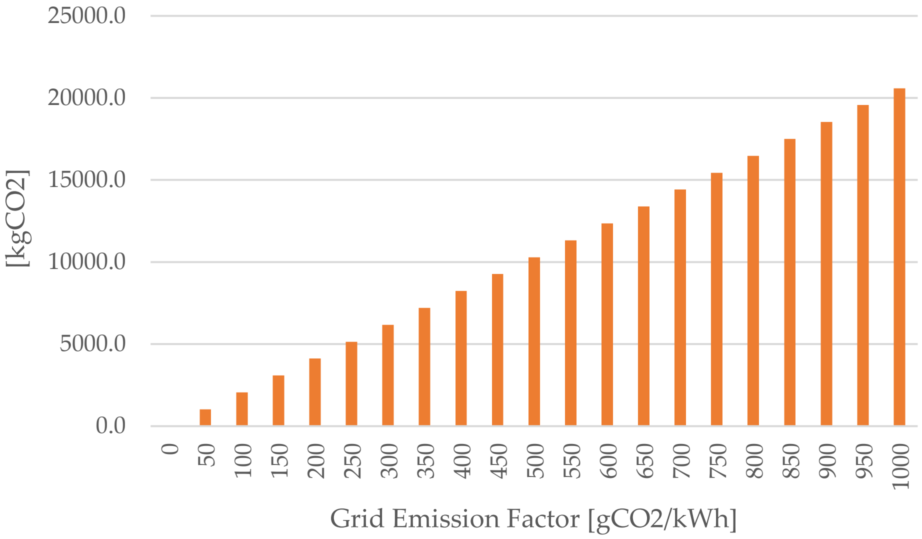


Figure 5-12 Well to Tank emissions at different Grid Emission Factor values

Another distinctive aspect of the driving location is the ambient temperature, so far considered equal to 20 ° C. However, consumption can vary significantly as the ambient temperature changes, producing different effects depending on the powertrain consideration. For example, below is the consumption of ICEV (VW GOLF) and BEV (VW ID.3) C-segment vehicles as the running WLTP driving cycle ambient temperature changes:

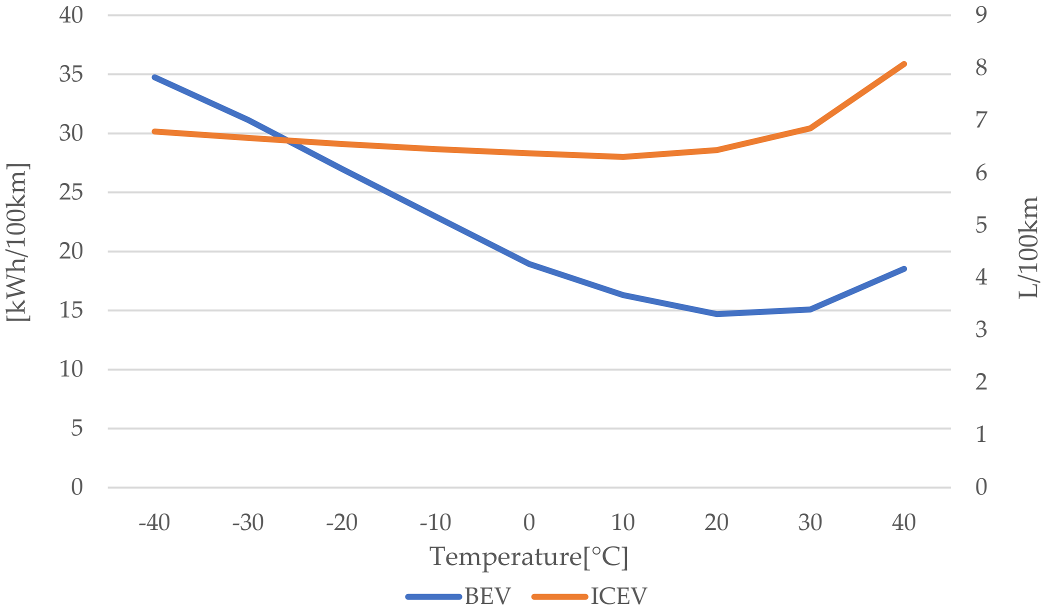


Figure 5-13 BEV and ICEV consumption at different ambient temperature values

In the case of electric vehicles, the temperature plays a fundamental role in evaluating consumption and, therefore, of Well-To-Tank emissions. Therefore, the consumption and emission values shown so far refer to the optimum temperature condition and are considered a minimum point; this makes it even more complicated to assess the environmental impact of electric vehicles. The table below reports the values of LCA emissions and the variability caused by the ambient temperature in the case of C-segment vehicles.

T [°C]	-40	-30	-20	-10	0	10	20	30	40
BEVs	73.1%	59.9%	44.8%	30.1%	15.4%	5.8%	0	1%	14%
ICEVs	5%	3%	2%	0%	-1%	-2%	0	5%	21%

Table 23 Life Cycle Emission variation for different ambient temperature values

The variability is very high: a C-segment BEV driven at average temperatures close to 0°C during its life cycle can have LCA emissions 15% higher than the same vehicle driven at an average temperature of 20°C. In the case of ICEVs, there is great variability in consumption at very high temperatures, for which consumption can increase by more than 20%.

5.1.5. Mileage

There is one last aspect to consider when assessing the impact of an electric vehicle compared to an internal combustion one: the mileage. As shown above, the production of electric vehicles is more polluting than that of traditional vehicles due to the battery pack production. If the vehicle is not used, electric vehicles have a clear disadvantage. The situation changes when the vehicle is used: if an average user travels the same roads in the same way with an electric vehicle and with an internal combustion vehicle, the emissions per unit of distance (gCO2/km) are much higher in the case of ICEVs given their high TTW emission values. After a certain mileage, the value of higher TTW emissions in the case of ICEVs compensates for the higher production emissions of the electric vehicle, thus making the latter the best solution from an environmental point of view. Therefore, when buying an electric vehicle, it is important to assess whether the BEEP will be exceeded using the same, otherwise, the environmental impact will be negative. Below are shown the BEEPs of the various segments previously described in the case of European Electricity Mix and different driving cycles at ambient temperature.

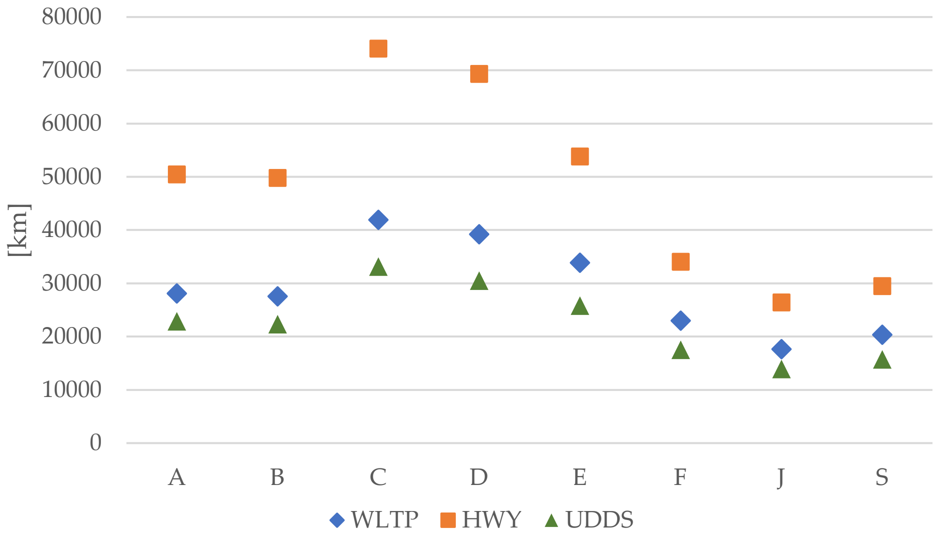


Figure 5-14 Break Even Emission Points for different vehicle segments and driving cycles

The lowest BEEP values are when the convenience of switching to electricity is higher in terms of environmental impact. For example, a C-segment electric vehicle used on the highway (HWY) instead of in the city (UDDS) has more than double BEEP.

Traditional ICE vehicles are more deficient (especially segments with low BEEP) in urban driving conditions characterized by the frequent start/stop and sudden accelerations, typical of the UDDS driving cycle.

Today, the biggest problem in the transition to electric vehicles is mainly low segment vehicles with higher BEEP values than vehicles in the upper segment. Although, this is mainly due to technical limitations, low-segment vehicles must be equipped with batteries even above 50/60 kWh to guarantee the same level of performance (especially in terms of autonomy) repeated to the ICEV equivalent. Therefore, it is necessary to have battery packs with higher energy densities to solve this problem and make even small vehicles competitive. To evaluate this aspect, the Future Mobility Scenario has been developed.

6 Scenario's evaluation

6.1. Fleet mix change Scenario Results

First, it was necessary to establish the production emissions of the fleet mix for each country. Production emissions was obtained as a weighted average of production emissions for each vehicle category (with an emission factor hypothesis of 518 gCO2/kWh equal to the global average) for the percentage of each category within the mix. The hypothesis on the production emission factor was made because of the difficulty of establishing where the circulating models are produced for each country: the same model in the United States can be produced in a different place from the same vehicle in Europe. The production emission values for both vehicle and battery pack, obtained as an average between the segment belonging to the different categories, are reported in the following table:

		Small	Medium	Large
Vehicle Production Emission	BEV	5596	8074	9080
	ICEV	5554	7770	10506
Battery Production Emission	BEV	3394	7385	9885

Table 24 Vehicle and battery production emission for each vehicle category

Three parameters characterized each country:

- Grid emission factor: The values are shown in table 3.
- Average annual ambient temperature: this influences consumption and, therefore, Well to Tank and Tank to Wheel emissions.
- Fleet mix: the values are shown in table 19.

In this way, life-cycle emission values are obtained for each fleet that effectively considers all the distinctive parameters between one country and another.

In Fig.6-1 the CO2 savings values are reported, defined as the difference in Life Cycle emissions between ICEVs fleet and BEVs fleet for each country(with the hypothesis lifetime mileage equal to 150000 km and WLTP driving cycle for the evaluation of consumption)

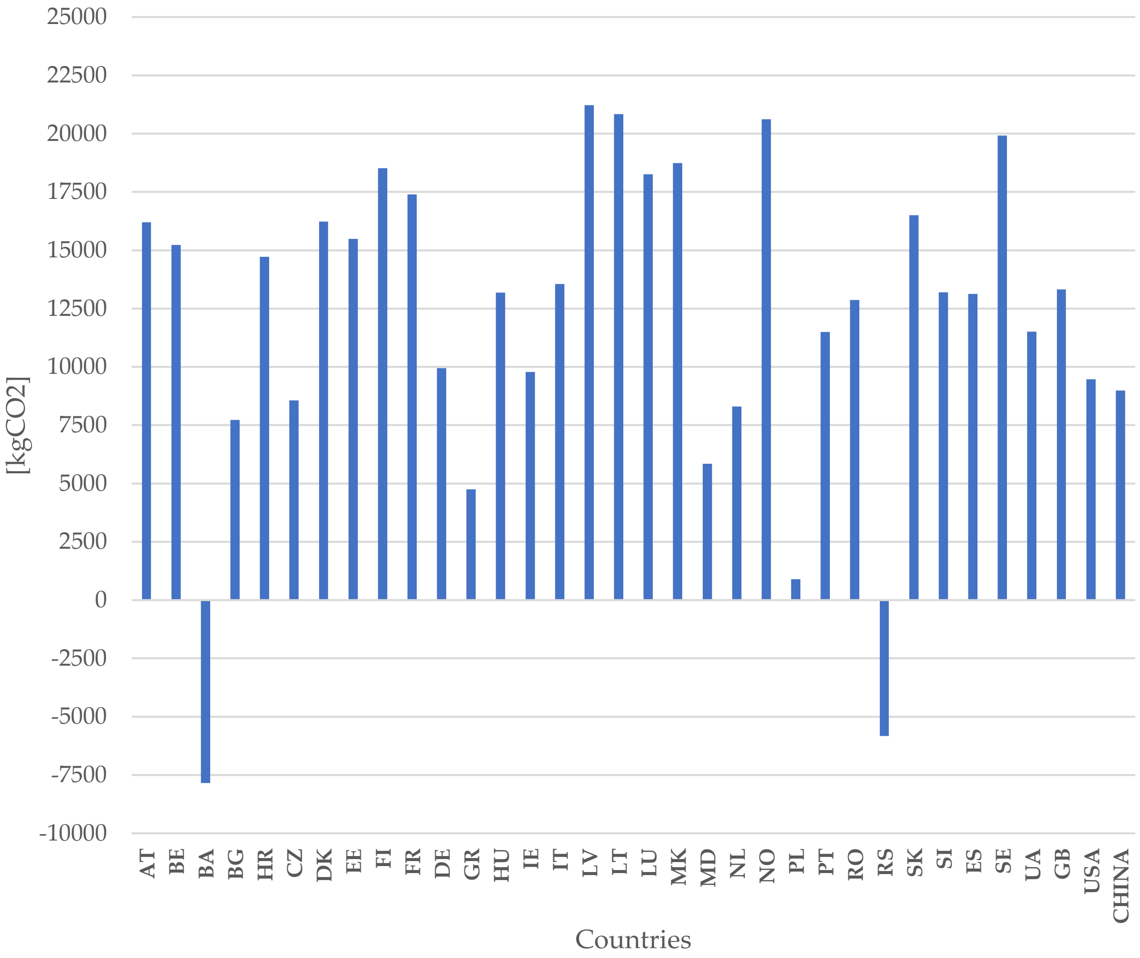


Figure 6-1 CO2 Saving per vehicle for different countries

In figure 4 the values of CO_2 savings for some of the countries analyzed are reported. The countries with higher CO_2 saving values are those whose change from ICEVs fleet to BEVs fleet would save more CO_2. For example, the Scandinavian countries, due to their high renewable penetration values allow low Well to Tank emissions (200 kgCO_2 for Sweden and 370 kg CO_2 for Norway, for example). The country with the highest CO_2 savings is Latvia, despite having a higher grid emission factor than some other countries. The highest CO_2 saving is due to Latvia's fleet mix, which currently adopts almost 30% of large vehicles whose replacement leads to higher CO_2 savings. On the other hand, the value of CO_2 saving is negative for some countries, indicating that substituting the current vehicles fleet with an electric counterpart would increase the overall fleet environmental impact. Considering all EU countries, an average value of CO_2 savings of 12500 kg CO_2/vehicle is obtained.

A very high CO2 savings value is not synonymous with low absolute emissions; going to see the LCA emission values of an average vehicle for each European country, you get the values shown in the graph below:

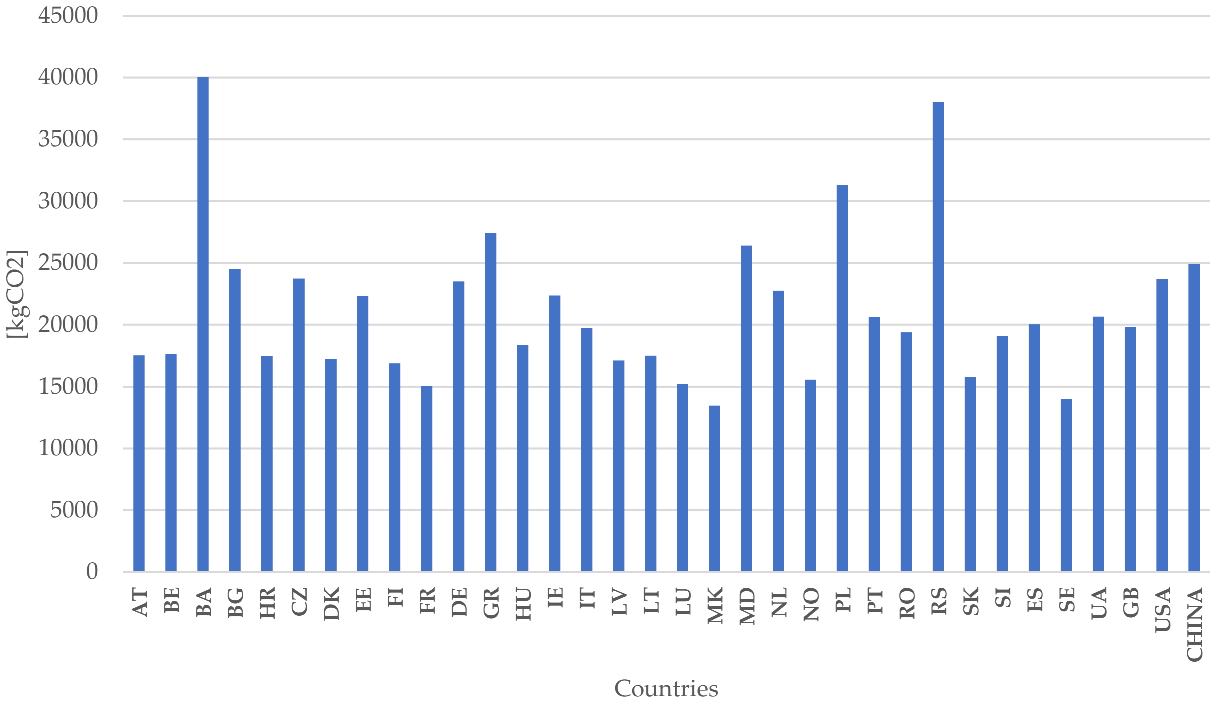


Figure 6-2 Life Cycle Emission for different countries’ fleet

It is noted that the higher values of CO2 savings do not always correspond to the lower values of Life Cycle emissions and vice versa. The absolute emission values depend mainly on the value of the emission factor, while the CO2 savings values are also significantly influenced by the fleet mix.

Below are the CO2 savings for each country, assuming a homogeneous fleet mix (33/33/33) and an emission factor value of 294gCO2/kWh (EU) to show the change in the average annual temperature.

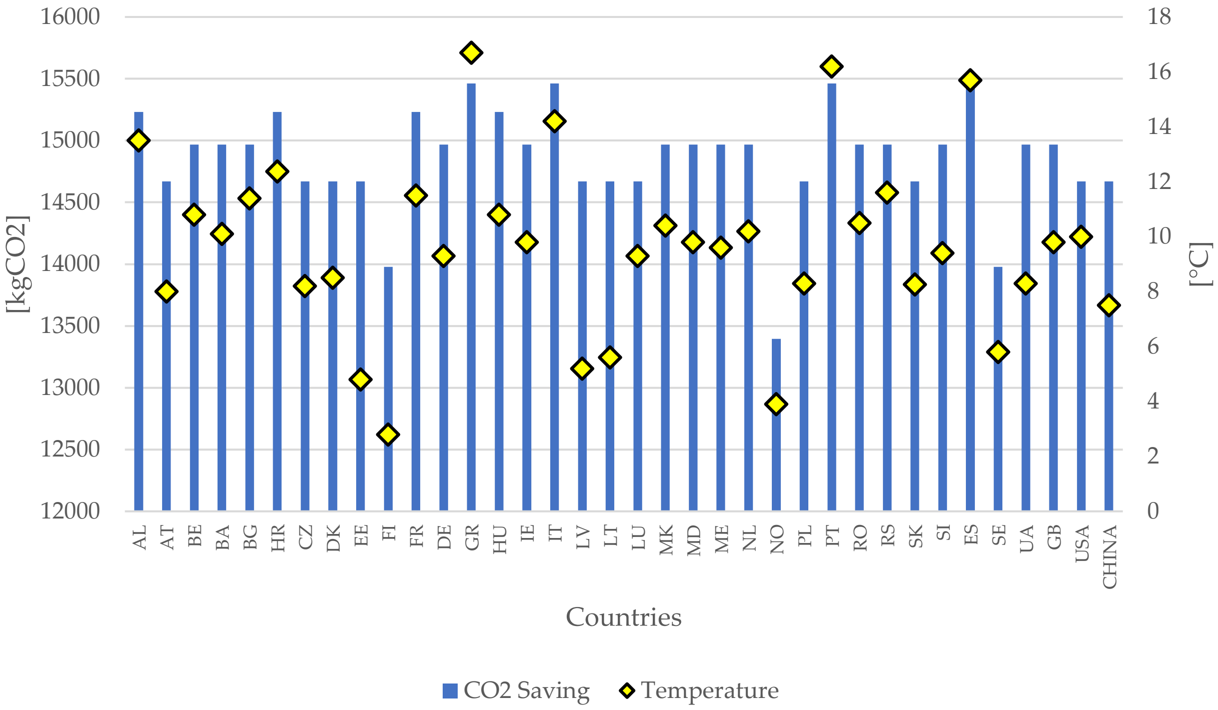


Figure 6-3 Effect of the ambient temperature on CO2 in different countries

Colder countries such as the Scandinavian ones have lower CO2 saving value with the same emission factor and Fleet mix and can be 15% lower than Mediterranean countries with milder climates; this is a penalizing aspect for battery electric vehicles as the ICEV life cycle emissions do not depend so much on the variation in ambient temperature.

6.2. Future Mobility Scenario Results

Below are reported the Life Cycle emissions of C Segment vehicles (whose characteristics are reported in table 21) nowadays, in 2030 and 2050, according to the assumptions presented in paragraph 4.2.

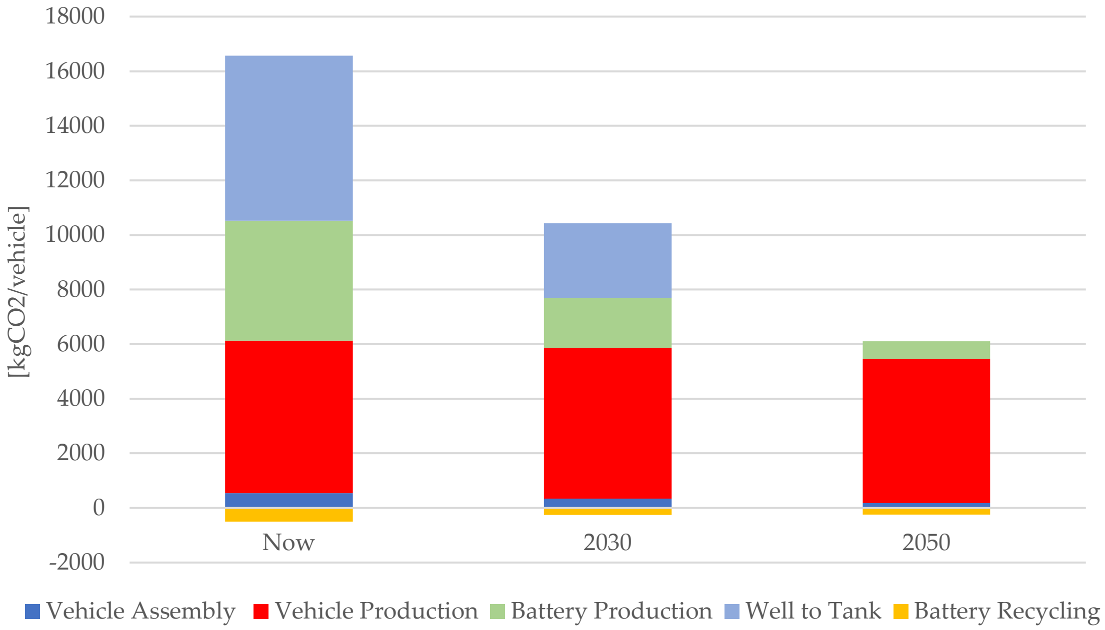


Figure 6-4 Life Cycle Emissions of segment C vehicles nowadays, in 2030 and 2050

The reduction of the emission factor leads to a reduction in emissions such that the entire life cycle of an electric vehicle in 2050 comes to have an environmental impact of 22% higher than the production of an ICEV of the same category and about 78% lower than the entire life cycle (also considering a reduction in ICEV consumption equal to 40%). Projecting the analysis into the future with even conservative hypotheses shows the lower environmental impact of electric vehicles from all points of view.

The critical issue that exists today mainly concerns low segment vehicles (A, B, C) that need batteries with such capacity that they end up for price and technical characteristics to belong to higher segments. This critical issue is destined to resolve over time and to show that it is essential to evaluate the values of Break-Even Emission Points: below are reported the BEEPs obtained with the hypotheses of the scenario and WLTP guide cycle at room temperature:

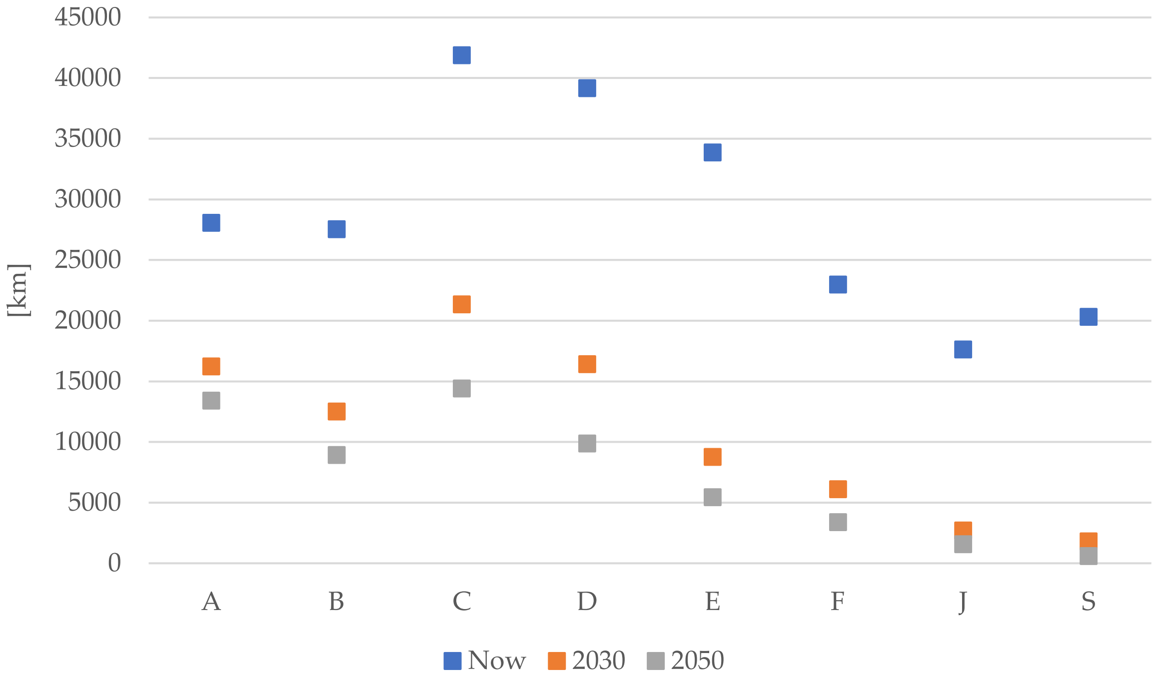


Figure 6-5 Break Even Emission Points for each vehicle segment nowadays, in 2030 and 2050

With the assumptions of this scenario, we have peak values of BEEPs equal to about 21000 km in 2030 and 14000 in 2050. Furthermore, it is noted that even increasing the capacities of the batteries the BEEP values remain much lower than the current ones. As a result, there is a lower variability of beeps between segments in 2030 and 2050, thus making all types of BEVs more convenient than the ICEV alternatives.

7 Conclusions and future work

7.1. Conclusions

This study presented a comprehensive and comparative life cycle assessment of different vehicle technologies (BEVs and ICEVs), analyzing those parameters that influence the environmental impact of electric vehicles. The developed model allows total customization of the simulation you want to carry out: all the vehicle characteristics can be modified in terms of powertrain and technical characteristics (power, weight, battery capacity, aerodynamic coefficient, material composition, etc..). In addition, all the production phases of the vehicle can be modified by choosing the location in which they are carried out and their environmental impact.

As for the use phase, through the VCAM tool, it is possible to modify the maintenance schedule data, the type of route (driving cycle), and the ambient temperature at which the vehicle is driven.

The results obtained were obtained by choosing simulation parameters consistent with the current technological development to show the difference in environmental impact between the two powertrains considered. Results show a general reduction in the environmental impact achievable thanks to electric vehicles, but the amount of emissions saved depends on numerous factors.

The most relevant are the Grid Emission Factor which influences both the production emissions and Well to Tank emissions of electric vehicles, the type of battery (understood as different chemistry and different energy density), and the mode of use of the vehicle.

Finally, two scenarios were developed with the intent to demonstrate the effect of replacing the current fleet of ICE-powered vehicles with the electric counterpart and to show projections on Life Cycle emissions considering the technological development expected for the coming years (2030 and 2050) in terms of battery energy density, energy mix, and powertrain efficiency. Through the fleet mix scenario, it is also shown that nowaday not all countries are ready for a transition to electric mobility due to electrical mix with very high carbon intensity.

In conclusion, electric vehicles are a possible solution against vehicular transport emissions and, as shown in the future mobility scenario, the development of more compact batteries and a less carbon-intensive electric mix will make BEVs even more ecological.

7.2. Future work

The subject matter is vast and there is ample room for improvement in assessing life-cycle emissions from vehicles. In the future, it would be desirable to conduct more detailed and in-depth studies on the evaluation of the battery pack's end of life, which today is a practice not widespread. Therefore, it isn't easy to estimate the actual reliable CO2 savings accurately. Another improvement would be a more in-depth analysis of vehicle production plants' supply chain, establishing where the various supplies come from, to estimate the Cradle to Gate emissions and the transport emissions of the individual components more accurately. This study has analyzed the effect of the variation of driving cycles on emissions, but it would be desirable to integrate a consumption and emissions simulator (such as VCAM) with a vehicular traffic model to overcome the problem of underestimation of consumption that often occurs with standardized driving cycles (WLTP, HWY, UDDS) that can never faithfully reproduce the real driving conditions. A further aspect that can be deepened concerns the grid emission factor, which is not constant over time. Depending on the electricity demand profiles in each country, variable mixes are used to meet it, so the WTT emissions of electric vehicles depend on the charging time of the vehicle.

Bibliography

[1] «Transport — European Environment Agency». https://www.eea.europa.eu/themes/transport

[2] «IEA – International Energy Agency». https://www.iea.org/

[3] «EV-Volumes - The Electric Vehicle World Sales Database». https://www.ev-volumes.com

[4] C. Buchal, H.-D. Karl, e H.-W. Sinn, «Kohlemotoren, Windmotoren und Dieselmotoren: Was zeigt die CO2-Bilanz?», *ifo Schnelldienst*, vol. 72, n. 08, pagg. 40–54, 2019.

[5] «Argonne GREET Model». https://greet.es.anl.gov/

[6] «COPERT | EMISIA SA». https://www.emisia.com/utilities/copert/

[7] D. A. Notter *et al.*, «Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles», *Environ. Sci. Technol.*, vol. 44, n. 17, pagg. 6550–6556, set. 2010, doi: 10.1021/es903729a.

[8] J. B. Dunn, L. Gaines, M. Barnes, M. Wang, e J. Sullivan, «Material and energy flows in the materials production, assembly, and end-of-life stages of the automotive lithium-ion battery life cycle», Argonne National Lab. (ANL), Argonne, IL (United States), ANL/ESD/12-3, giu. 2012. doi: 10.2172/1044525.

[9] «Argonne GREET Model».. available on: https://greet.es.anl.gov/

[10] «U.S. Environmental Protection Agency | US EPA». https://www.epa.gov/

[11] G. Majeau-Bettez, T. R. Hawkins, e A. H. Strømman, «Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles», *Environ Sci Technol*, vol. 45, n. 10, pagg. 4548–4554, mag. 2011, doi: 10.1021/es103607c.

[12] «Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles - Hawkins - 2013 - Journal of Industrial Ecology - Wiley Online Library». https://onlinelibrary.wiley.com/doi/full/10.1111/j.1530-9290.2012.00532.x

[13] L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, e A. H. Strømman, «Life cycle assessment of a lithium-ion battery vehicle pack», *Journal of Industrial Ecology*, vol. 18, n. 1, pagg. 113–124, 2014.

[14] H. C. Kim, T. J. Wallington, R. Arsenault, C. Bae, S. Ahn, e J. Lee, «Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis», *Environ. Sci. Technol.*, vol. 50, n. 14, pagg. 7715–7722, lug. 2016, doi: 10.1021/acs.est.6b00830.

[15] M. Romare e L. Dahllöf, «The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries», pag. 58.

[16] M. Philippot, G. Álvarez, E. Ayerbe, J. Van Mierlo, e M. Messagie, «Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs», *Batteries*, vol. 5, pag. 23, feb. 2019, doi: 10.3390/batteries5010023.

[17] J. Kelly, Q. Dai, e M. Wang, «Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries», *Mitigation and Adaptation Strategies for Global Change*, vol. 25, mar. 2020, doi: 10.1007/s11027-019-09869-2.

[18] E. Kallitsis, A. Korre, G. Kelsall, M. Kupfersberger, e Z. N. Nie, «Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries», *Journal of Cleaner Production*, vol. 254, pag. 120067, mag. 2020, doi: 10.1016/j.jclepro.2020.120067.

[19] F. Sanvito, M. Ferraro, R. Mereu, e E. Colombo, *Improving electric vehicle consumption representation in energy system modelling: the impact of temperature in all European countries*. 2020. doi: 10.13140/RG.2.2.26325.35046.

[20] «IPCC — Intergovernmental Panel on Climate Change». https://www.ipcc.ch/

[21] «IRENA – International Renewable Energy Agency». https://www.irena.org/

[22] Q. Qiao, F. Zhao, Z. Liu, S. Jiang, e H. Hao, «Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China», *Applied Energy*, vol. 204, pagg. 1399–1411, ott. 2017, doi: 10.1016/j.apenergy.2017.05.041.

[23] R. Schmuch, R. Wagner, G. Hörpel, T. Placke, e M. Winter, «Performance and cost of materials for lithium-based rechargeable automotive batteries», *Nature Energy*, vol. 3, pag. 267, apr. 2018, doi: 10.1038/s41560-018-0107-2.

[24] «A review on the key issues for lithium-ion battery management in electric vehicles - ScienceDirect». https://www.sciencedirect.com/science/article/pii/S0378775312016163

[25] G. E. Blomgren, «The Development and Future of Lithium Ion Batteries», *J. Electrochem. Soc.*, vol. 164, n. 1, pag. A5019, dic. 2016, doi: 10.1149/2.0251701jes.

[26] «China Dominates the Lithium-ion Battery Supply Chain, but Europe is on the Rise», *BloombergNEF*, 16 settembre 2020. https://about.bnef.com/blog/china-dominates-the-lithium-ion-battery-supply-chain-but-europe-is-on-the-rise/

[27] R. Kawamoto *et al.*, «Estimation of CO2 Emissions of Internal Combustion Engine Vehicle and Battery Electric Vehicle Using LCA», *Sustainability*, vol. 11, n. 9, Art. n. 9, gen. 2019, doi: 10.3390/su11092690.

[28] European Commission. Joint Research Centre., *JEC well-to-tank report V5: JEC well to wheels analysis : well to wheels analysis of future automotive fuels and powertrains in the European context.* LU: Publications Office, 2020. https://data.europa.eu/doi/10.2760/100379

[29] «Northvolt - the future of energy», https://northvolt.com/

[30] J. B. Dunn, L. Gaines, J. C. Kelly, C. James, e K. G. Gallagher, «The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction», *Energy Environ. Sci.*, vol. 8, n. 1, pagg. 158–168, dic. 2014, doi: 10.1039/C4EE03029J.

[31] «Our recycling process». https://csm.umicore.com/en/battery-recycling/our-recycling-process/

[32] «Prospects for electric vehicle deployment – Global EV Outlook 2021 – Analysis - IEA». https://www.iea.org/reports/global-ev-outlook-2021/prospects-for-electric-vehicle-deployment

[33] «EVSpecifications - Electric vehicle specifications, electric car news, EV comparisons», *EVSpecifications*. https://www.evspecifications.com

List of Figures

List of Tables