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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

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

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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ACADEMIC YEAR: 2020-2021

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1. Introduction

The warming impact of greenhouse gas (GHG) emissions is continuously increasing globally, and the transportation sector is one of the significant drivers of GHG emissions. The transport sector accounts for 23% of the European Union's GHG emissions [1] and mainly relies on fossil fuels such as coal, oil, and gas that emit significant GHGs. Thus, continuing efforts are required to mitigate environmental impacts and reduce transportation's dependence on conventional fuels. Currently, electromobility might be a suitable option that generates lower air pollutant emissions than traditional vehicles in the transportation sector (Ellingsen et al. 2013 [2], Hawkins et al.2013 [3]). Although electric vehicles (EVs) provide significant benefits in terms of reduction of fossil energy consumption as well as pollutant emissions, it is unclear whether they have the potential to reduce life cycle emissions. Life cycle assessment (LCA), which consists of material production, vehicle and battery manufacturing, and recycling stages, has been introduced to assess various vehicles' energy and environmental impact. Nowadays, the reference model for calculating emissions related to vehicle production is the GREET model, which stands for greenhouse gases, Regulated Emissions, and Energy use in Transportation [4]. GREET model is an analytical tool that simulates the energy use and emission output of various powertrain and fuel combinations. However, it cannot assess the emissions produced during the use of the vehicle. For the calculation of driving emissions, the reference model at the European level is represented by the COPERT model (Computer Programme to calculate Emissions from Road Traffic). COPERT model is a traffic emission calculation program developed by the European Environment Agency (EEA) under the CORINAIR program [5]. It is a disaggregated top-down model that allows obtaining the emission values for each category of vehicles. The criticality of the model is given by its limited customization potential, so in this study the open-source python tool "VCAM" (Vehicle Consumption Assessment Model) has been used. VCAM is a lumped parameter model that assesses the fuel consumption of light-duty vehicles by implementing a physical model of the vehicle computing the energy required to perform a given driving cycle.

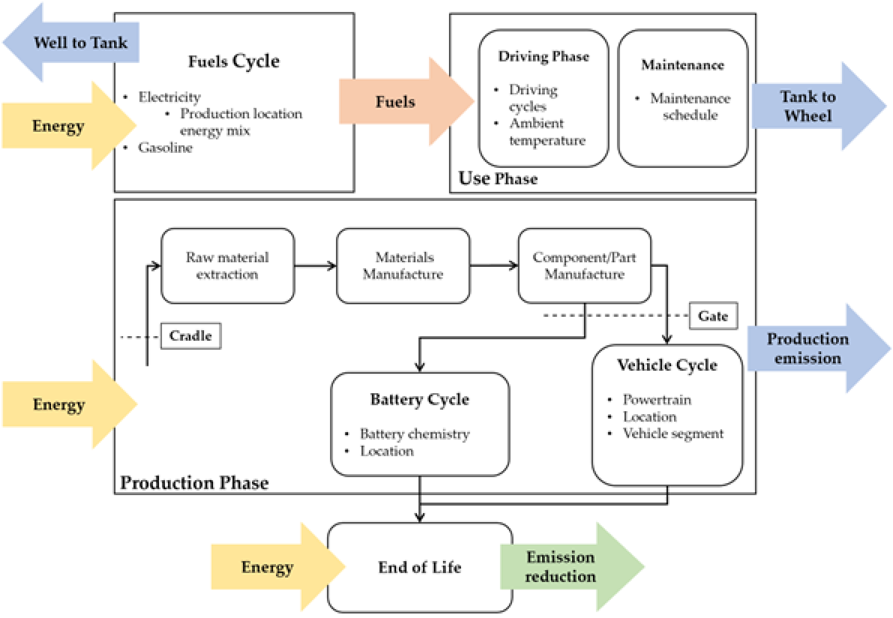

Figure 1 Vehicle's Life Cycle Assessment Flow Diagram

The life cycle assessment realized in this study highlights how electrical mix, battery chemistry, ambient temperature, and vehicle segment could remarkably affect the vehicle's life cycle emissions. Fig 1 shows the flow diagram of the study. Finally, this work aims to address the following research questions:

- 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?

2. Methodology

2.1 Vehicle production

Mathematical formulation

This section evaluates the environmental impact of all production processes, including extraction of raw materials, processing of materials, manufacturing of components and subcomponents, vehicle assembly, and painting. Although vehicles are 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 analyses their Cradle-to-Gate energy consumption and GHG emissions. The energy consumption and GHG emissions of all the different materials can be calculated through the following equation:

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

Where $EC_{j,m}$ is the energy consumption of process j related to 1 kg of processed material m. EC_m includes all emissions related to the extraction and processing of the materials from their raw states 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 refers to the CO_2 emissions to produce 1 kg of material m, f_s is the share of fuel per stage s and EF_f is the vector which contains the emission factors of different fuels (Oil, Diesel, Natural Gas, Coal, Electricity, Coke, Blast Furnace Gas, and Coke Oven Gas). 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:

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

$$GE[kgCO2] = \left(\sum_{\mathrm{m}} GE_{\mathrm{m}} \left[\frac{kgCO2}{kg_{Mat}}\right] * \%_{\mathrm{m}} \left[\frac{kg_{\mathrm{m}}}{kg_{Comp}}\right]\right) * comp\_weight\,[kg_{Comp}] + GE_{assembly}[kgCO2]$$

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, $comp\_weight$ is the weight of battery/vehicle.

Material production

This study defines steel production and transformation as iron ore extraction, ore processing, coke production, sintering, iron making, steel making, and steel transformation. According to the proportion, the Blast Furnace-Basic Oxygen Furnace (BF-BOF) technique and the Electric Arc Furnace (EAF) techniques are chosen as the ironmaking and steel-making methods. Subsequent steps such as casting, rolling, and cutting are also included, followed by transformation techniques including stamping and machining. The iron used in vehicles is mainly for the engine, indicating that the transformation process consists of iron casting, forging, and machining. The pre-treatment process of casting iron is like steel, including ore extraction and processing. The aluminum production processes include bauxite mining, anode and alumina production, smelting and lastly producing the ingots. The data relating to steel, iron, and aluminum production are imported from GREET model. Copper is used mainly for wire drawing in vehicles. In addition, compared to steel, aluminum and iron, the copper content is minor in the vehicles; therefore, this study only considers the specific energy consumption to produce copper. Since the Li-ion battery industry is still preliminary, detailed data is unavailable, a value for the energy consumption to produce the active material is used without considering all the different materials that make it. The total energy consumption to produce the active material is 263 MJ/t for the NMC111 battery, 288 MJ/t for NMC622, 319MJ/t for NMC811, 37.8 MJ/t for LFP, 38.6 for LMO, and 342 MJ/t for NCA [4]. Other materials refer to supplementary materials to support the battery operation, including graphite/carbon, binder, copper, aluminum, electrolyte, plastic, steel, coolant, thermal insulation, and electronic parts. Some of them, such as steel, aluminum, copper, and plastic, have been analyzed above.

Components assembly

The vehicle assembling process has been divided into six parts: paint production and painting, Heating, Ventilation and Air Conditioning (HVAC) and lighting, material handling, heating, air compressing, and welding]; the values of energy consumption and emission produced in these stages are taken from GREET. The battery assembly values are based on [2].

2.2 Fuels Production

This section calculates the emissions produced during the fuel production processes, named Well to Tank emissions (WTT).

Conventional fuels

In this study, reference was made to the values reported by the JEC Well-to-Tank report compiled by the Joint Research Centre[6], which estimates the gasoline WTT emission at a value of 17 g $CO_{2\text{-eq}}$ /MJ or 595 g $CO_{2\text{-eq}}$/L.

Electricity

Well-To-Tank emissions for electricity production are dependent on the grid emission factor (g CO_2/kWh) and are calculated with the following equation:

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

Where η_{charge} is the charge efficiency, EF is the grid emission factor, EC is the vehicle consumption, and lifetime is the total vehicle's mileage assumed to be 150000 km.

2.3 Use Phase

VCAM includes some standard reference driving cycles and the input files for modeling some customized specific driving sessions and simulating specific vehicles. The default driving cycles considered are:

- **UDDS**: simulates stop-and-go city driving. It is used to measure the fuel economy of the city.
- **HWY**: simulates highway driving at high speed by bringing the vehicle to maximum

speed, then fluctuating. This test measures fuel economy on the highway.

- **WLTP**: it provides a test of the vehicle's consumption with four different average speeds to obtain feedback as faithful as possible to reality.

After evaluating consumption, it is necessary to consider the exhaust emissions caused by the fuel combustion equal to 2.34 kg $CO_{2\text{-eq}}$/L. There is no tailpipe emission from BEVs. The emissions produced during the driving phase are called Tank to Wheel emissions (TTW). The model also includes the possibility of filling the vehicle maintenance schedule considering the replacement of tires, engine oil, and batteries and can estimate the emissions due to vehicle maintenance. The emissions related to maintenance are included in the "Vehicle Cycle emissions".

2.4 Battery End of Life

The calculation of the end of life and recycling process GHG emissions is highly dependent on the selected assumptions. Automotive batteries' second and third lives can be considered when used for battery storage applications. Moreover, recycling processes are still under development. In this study, the value proposed by Mia Romare et al. (2017)[7] through a review of available life cycle assessments on lithium-ion batteries of 3,5 kg CO_2/kg of battery is considered.

3. Results

Total life cycle emissions are obtained by summing the previously calculated emissions of all the LCA phases. All the results depend on the vehicle's characteristics so, to make the results as explanatory as possible, eight vehicle segments (A, B, C, D, E, F, J, S) are considered. In Table 1, the Life Cycle Assessment results are reported for different segments distinguishing between the various emission components assuming the EU grid emission factor for all the life cycle phases. Production emissions of the battery pack account for about 27% of BEVs' total life cycle emissions. For ICEVs, Tank-to-Wheel emissions account for most of the life-cycle emissions, about two-thirds, and Well to Tank fuel cycle emissions are the second largest contributor. Averaging over all segments considered, BEVs emit 58% less CO_2 than an equivalent segment ICEV over their lifetime (considering a lifetime mileage equal to 150000 km). In the case of BEV, production emissions represent on average 60% of the total life cycle emissions and they are about 77% higher than those of internal combustion vehicles, thus representing the real critical point of electric mobility. Some sensitivity analyses were then carried out on the parameters that most influence life cycle emissions.

3.1 Sensitivity analyses

Electricity mix

The carbon intensity of the electricity mix impacts both the production emissions and the Well-to-Tank emissions when BEVs are considered. Considering a C-segment BEV, production emissions related to the use of electricity amount to 49% of the overall equivalent carbon dioxide connected to vehicle production. Whereas for ICEVs, they count the 24%, assuming the European grid emission factor). Figure 2 shows the CO_2 production emission of ICEVs and BEVs (battery included) by varying the electricity mix. In the case of the considered BEV, the Volkswagen ID.3, the vehicle cycle emissions vary between 4500 kg $CO_{2\text{-eq}}$/vehicle with a full renewable electricity mix, and 8000 kg $CO_{2\text{-eq}}$/vehicle if production takes place in countries characterized by higher emission factors (EF). 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

Vehicle Segment	A		B		C		D		E		F		J		S	
Vehicle Type	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**
Vehicle Production	5222	3982	4516	4268	5580	4864	5490	5759	8387	8577	7204	7964	6150	7556	7912	8802
Battery Production	1700	0	2975	0	4391	0	5631	0	6728	0	7083	0	5241	0	6615	0
Well to Tank	5944	5241	6004	5373	6054	5801	6182	6213	8646	8822	7566	11308	6516	8732	7983	11436
Tank to Wheel	0	20701	0	21222	0	22912	0	24539	0	34843	0	44662	0	34489	0	45167
Vehicle Assembly	546	546	546	546	546	546	546	546	546	546	546	546	546	546	546	546
Battery Recycling	-177	0	-428	0	-502	0	-567	0	-624	0	-643	0	-547	0	-690	0
Life Cycle Emissions	13235	30471	13613	31409	16070	34123	17281	37057	23684	52789	21757	64480	17907	51323	22366	65951

Table 1 Life Cycle Emissions [$kgCO_{2\text{-eq}}$]

emissions, which depend 85% on electricity use (considering the NMC811 battery).

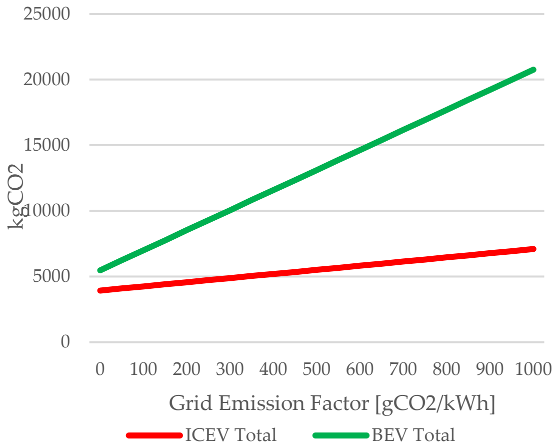

Figure 2 Battery and vehicles production emissions at different grid emission factor values

For example, the considered vehicle is equipped with a 62-kWh battery pack which production process emission range is in-between 1 $tonCO_{2\text{-}eq}$ (full renewable electricity mix) and 12 $tonCO_{2\text{-}eq}$ (EF: 1000$gCO_{2\text{-}eq}$/kWh).

Battery chemistry

So far, the results referring to batteries have been obtained with the hypothesis of energy density equal to 180 Wh/kg. The achievable energy density values are 100 Wh/kg and 120 Wh/kg, respectively, for LFP and LMO batteries, from 180 Wh/kg to 200 Wh/kg for NMC, while in the case of NCA batteries an energy density value of 260 Wh/kg is assumed, representing the best technology nowadays on the market.

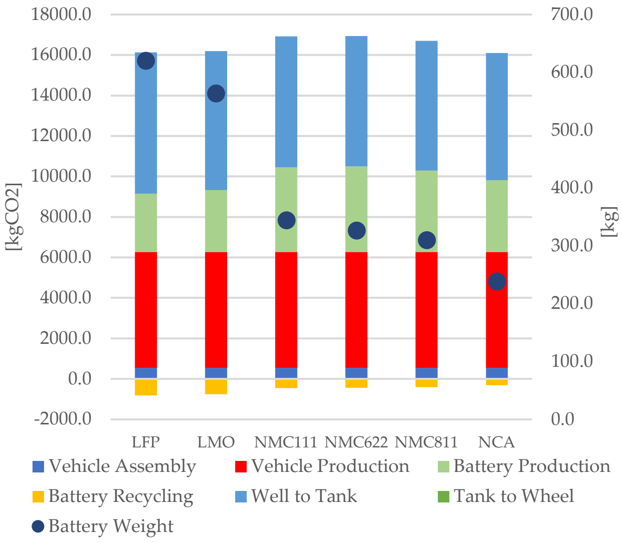

Figure 3 Life cycle emissions of C-segment electric vehicle with different battery chemistry

The results show that LFP and LMO are the less pollutant solutions (47 kg $CO_{2\text{-}eq}$/kWh and 49 kg $CO_{2\text{-}eq}$/kWh, respectively), followed by NCA (57 kg $CO_{2\text{-}eq}$/kWh) and NMC (67 kg $CO_{2\text{-}eq}$/kWh for NMC111, 68 kg $CO_{2\text{-}eq}$/kWh for NMC622 and 64 kg $CO_{2\text{-}eq}$/kWh for NMC811). All the results are obtained considering the European Emission Factor. Figure 3 shows the variability given by the different chemistry of the battery pack on life cycle emissions for the segments described above (with the European grid Emission Factor). 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.

Driving Cycles

In case of ICEVs, the HWY driving cycle is always the one with lowest consumption values because internal combustion engines consume less in steady-speed conditions, typical of motorway driving (about 4.5 L/100 km for a C-segment vehicle). Electric vehicles instead show their full potential in urban roads in which low segment vehicles consume about 10% less than highway driving due to regenerative braking potential. Consumption in city driving (UDDS cycle) considering F-segment BEV (Tesla Model S) is 30% higher than a C-segment BEV (VW iD3); considering ICEVs, the increase in consumption comparing the same categories is about 65%. In case of ICEVs, 50% of engine power variations increase life cycle emissions by 8%, while in case of BEVs, an increase of engine power does not affect the life cycle emissions.

Ambient temperature

The consumption can vary significantly as the ambient temperature changes. In table 2, the variations of a C-segment vehicle's Life Cycle emissions varying the ambient temperature are reported:

T [°C]	-30	-20	-10	0	10	20	30	40
BEVs	60%	45%	31%	15%	6%	0	1%	14%
ICEVs	3%	2%	0%	-1%	-2%	0	5%	21%

Table 2 Life Cycle Emission variation at different ambient temperature values

4. Fleet mix change scenario

The scenario is intended as a comparative analysis between the ICEV and BEV fleets to show what would be the environmental impact of a complete transition of the current ICE vehicle fleet in different countries. Some hypotheses have been made: the fleet of vehicles consists of three different categories (Small, Medium, Large), which represent the average characteristics of the segments A/B (small), C/D/J (medium), and E/F/S (large). First, production emissions of each vehicle category are obtained considering a grid emission factor equal to the global average (518g CO_{2-eq} /kWh). Then the current fleet mix of each country is assessed, and the CO_2 saving value per vehicle achievable replacing the current fleet of ICEVs with BEVs is calculated.

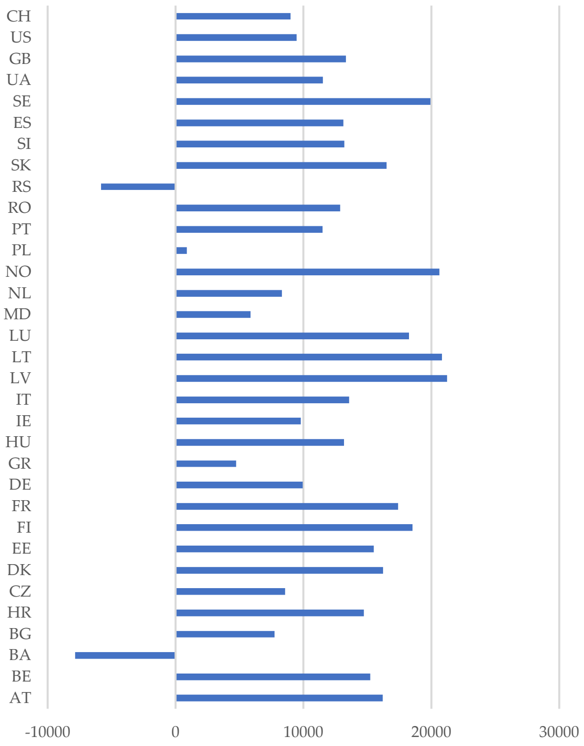

Figure 4 CO_2 saving per vehicle for different countries

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, have low Well to Tank emissions (200 $kgCO_{2-eq}$ per vehicle for Sweden and 370 kg CO_{2-eq} per vehicle 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, CO_2 saving is negative for some countries (Serbia and Bosnia and Herzegovina) indicating that substituting the current vehicles fleet with an electric counterpart would increase the overall fleet environmental impact. The results report the interval in which CO_2 savings range is - 7800 $kgCO_{2-eq}$/vehicle and +21200 $kgCO_{2-eq}$/vehicle with an average value of 12500 $kgCO_{2-eq}$/vehicle.

5. Future mobility scenario

The Life Cycle Assessment of electric vehicles has been evaluated using parameters and making assumptions based on the current state of the art. This scenario assesses how much future technological development can influence the results. Therefore, some assumptions have been made:

- The efficiency of vehicles is expected to improve, leading to a decrease in consumption of 20% in 2030 and 40% in 2050.
- A reduction in the carbon intensity of power generation of 55 % in 2030 is assumed following the Sustainable Development Scenario (SDS) and a grid emission factor equal to zero is assumed in 2050 according to the Net Zero-emission Scenario [8].
- An increase of the energy density (considering NMC and NCA batteries) to 300 Wh/ kg (for 2030) and up to 500 Wh/kg for 2050.

According to the assumptions, figure 5 shows the Life Cycle emissions of C-segment battery electric vehicles nowadays, in 2030 and 2050. Therefore, reducing the emission factor leads to a reduction of LCA emissions of BEV of 78% with respect to the ICEV. However, BEV production emissions are still higher (+22%) than ICEV ones. According to the assumptions, life cycle emissions will be reduced by 36% in 2030 and 63% in 2050. Battery production emissions are reduced by 58% in 2030 and 85% in 2050, while Well to Tank emissions reduction is directly proportional to the electricity emission factor.

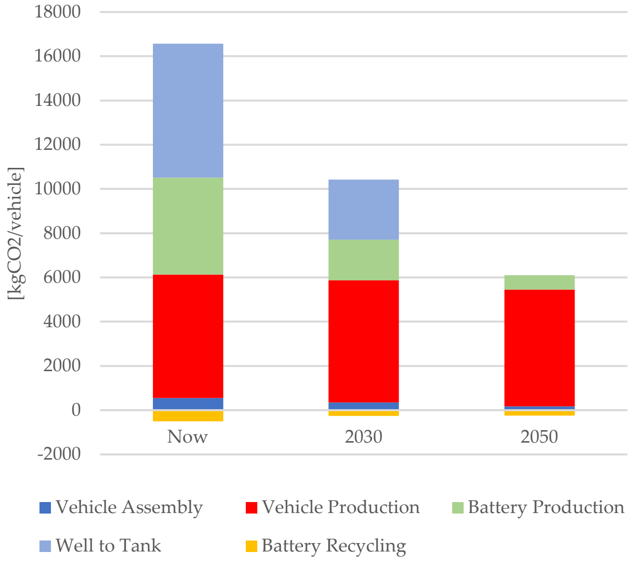

Figure 5 Life Cycle Emissions of segment C battery electric vehicles nowadays, in 2030 and 2050

The BEEP indicator is introduced and defined as the number of km at which the CO_2 savings are zero. In figure 6, the Break-Even Emission Points for each vehicle segment are reported (with the hypotheses of the scenario and WLTP driving cycle at ambient temperature).

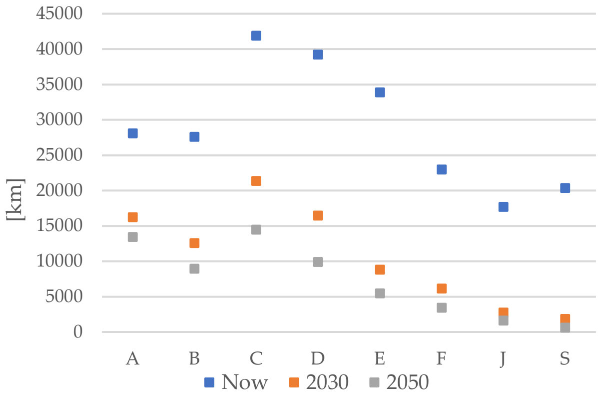

Figure 6 Break Even Emission Points for each vehicle segment nowadays, in 2030 and 2050

The critical issue nowadays mainly concerns low segment vehicles (A, B, C) that, to provide the same driving range as the ICEV counterpart, need batteries with high capacity, thus reducing possible CO_2 saving. However, the peak values of BEEPs are about 21000 km in 2030 and 14000 in 2050, so even increasing the capacities of the batteries, BEEPs values remain much lower than the current ones.

6. Conclusions

This study presented a comparative life cycle assessment of different vehicle technologies (BEVs and ICEVs), considering those parameters that influence the environmental impact of electric vehicles. The developed model allows total customization of all the vehicle 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. Regarding the use phase, through the VCAM tool, it is possible to modify the vehicle model specifications, the driving cycle, and the ambient temperature at which the vehicle is driven. The total GHG life cycle emissions for a C-segment vehicle are 34123 kg $CO_{2\text{-eq}}$ for an ICEV and 16069 kg $CO_{2\text{-eq}}$ for a BEV with an NMC battery. Comparatively, the values for an EV are about half that of an ICEV. Li-ion batteries incur nearly 25% of total GHG emissions of BEV production. Vehicle production accounts for 34% of BEVs' life cycle emissions and 14% for ICEVs (TTW accounts for 67% of total life cycle emissions).

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