Life cycle assessment of hybrid passenger electric vehicle

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Daniele Candelaresi[a], *Antonio Valente*[b], *Eleonora Bargiacchi*[c], *and Giuseppe Spazzafumo*[a]
[a]DICeM, University of Cassino and Southern Lazio, Cassino, Italy, [b]ETH Zurich, Department of Chemistry and Applied Biosciences, Institute for Chemical and Bioengineering, Zurich, Switzerland, [c]Department of Energy, Systems, Territory and Construction Engineering (DESTeC), University of Pisa, Pisa, Italy

1 Challenges toward a sustainable transport sector

Tackling climate change is one of the most significant challenges of our times. Following the Paris Agreement ratification, the number of plans and policy actions to reach ambitious climate targets set by governance is growing worldwide. The 2030 Agenda on Sustainable Development, agreed by all the UN member States, defines the list of 17 Sustainable Development Goals (Fig. 1) for the wellbeing of an inclusive society [1] not only accounting for environmental-related actions but also targeting economic and social implications.

To underpin the implementation of this agenda and support the Paris Agreement, the European Union set an ambitious roadmap within the European Green Deal with the primary goal of reaching the carbon-neutrality by 2050 [2]. The roadmap toward this objective involves a plan of 50 actions to transition toward a clean energy system, sustainable industry and mobility, energy-efficient buildings, and strategies for the protection of biodiversity, restoration of ecosystems, reduction of air and water pollution, and circular economy. Besides this, to further emphasize the urgency of dealing with the climate crisis, the European Commission has recently set to raise the intermediate goal of greenhouse gas (GHG) emissions reduction for 2030 timeline [3], from 40% to 55% compared to the 1990 level that is estimated to be around 5.73 Gt CO_2 equivalents (CO_2 eq) [4]. As for actions planned outside of Europe, the major Asian economies recently announced targets for achieving net-zero emissions, particularly Japan and South Korea by 2050 and China by 2060 [5].

In 2016, the GHG emissions were estimated at around 50 billion tons of CO_2 eq. Fig. 2 shows the breakdown of the main contributions by the economic sector. The energy sector accounts for more than 73% of the total amount of GHG emissions, with the share for production of electricity, heat, and fuels for industry (iron and steel, chemicals, etc.) and buildings (residential and commercial purposes) around 42%.

Of the remaining 31% of the emissions allocated to energy, the transport sector accounts for around 16%. Other activities associated with the energy sector (fugitive emissions from energy productions, unallocated fuel combustion, energy to

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Fig. 1 The 17 UN SDGs.
Source: UN, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1), Arsenic Research and Global Sustainability—Proceedings of the 6th International Congress on Arsenic in the Environment, AS 2016. United Nations, New York. https://doi.org/10.1201/b20466-7.

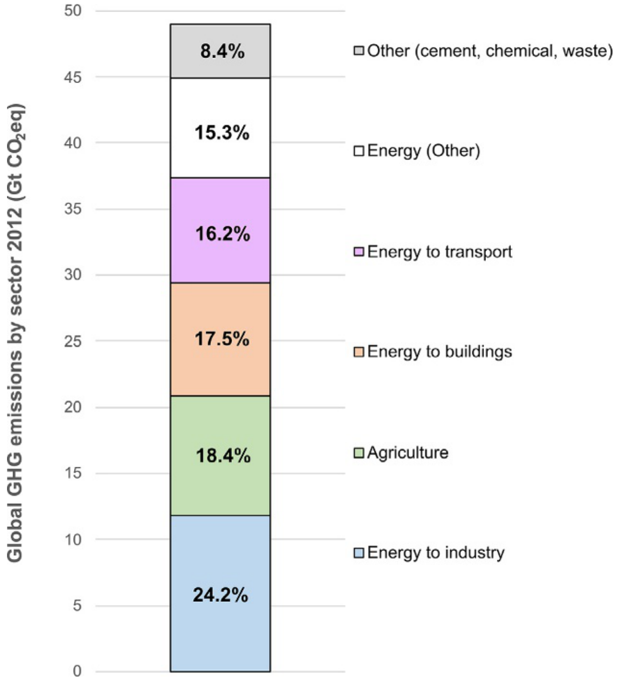

Fig. 2 Breakdown by sector of the global GHG emission.
Based on Our World in Data, 2020. Emissions by Sector [WWW Document]. URL: https://ourworldindata.org/emissions-by-sector (accessed 1.17.21).

agriculture and fishing) contribute approximately 15%. Focusing on the transport sector, the primary source of GHG emissions is associated with road transport; more specifically, the share of the global GHG emissions for rail, shipping, aviation, and road transport is estimated around 0.4%, 1.7%, 2%, and 12%, respectively. Besides this, the progressive growth in fuel consumption and the increase in the number of vehicles (especially in non-OECD countries) further emphasizes the urgency of finding sustainable transport options [6]. In this regard, the policy and decision-making in finding alternatives should not overlook the potential impacts of different points of the supply chain. In other words, environmental analyses should encompass the environmental burdens comprehensively, not limited to the sole production phase but including all related upstream processes (i.e., the procurement and distribution of raw materials) and downstream stages (i.e., the dismantling and the end of life). Furthermore, environmental assessments should identify burdens shifting from an impact category to another, from a point of the value chain to another, and from a sustainability dimension to another (e.g., from the environmental to the economic dimension).

2 Need for comprehensive sustainability checks

When evaluating different options, sustainability criteria are an essential part of governments and companies' strategies, and since each stage of a product value chain interacts with the society, the environment, and the economy, it is crucial to follow a life-cycle perspective. In this context, focusing on the environmental dimension, the standardized Life Cycle Assessment (LCA) methodology represents a central tool to evaluate the potential impacts of human activities from a life-cycle perspective [7, 8]. LCA studies provide crucial support to include a wide range of potential environmental impacts (not limited to carbon footprint) into decision-making processes following the so-called cradle-to-grave approach (i.e., from the procurement of raw materials up to the dismantling and final disposal/recycling). In assessing the economic performance, Life Cycle Costing (LCC) is well-established to calculate different economic life-cycle indicators (e.g., levelized cost, net present value, payback period, etc.) [9]. For evaluating the social dimension, Social Life Cycle Assessment (SLCA) is considered a pivotal methodology to implement social implications into decision-making processes [10, 11], though less mature than LCA and LCC. Despite LCC and SLCA are out of the scope of the present analysis, it is essential to remark that given the life-cycle approach and methodological similarities that the three approaches have in common, both LCC and SLCA could be depicted, mutatis mutandis, by the same methodological framework of standardized LCA (Fig. 3).

Given the relevance of the transport sector in the quest to achieve environmental targets, this chapter focuses on showing the role played by critical methodological and technical parameters on the environmental life-cycle performance of road vehicles. Among the wide range of new concepts and options foreseen for transport technologies [2], in line with the general scope of this book, the present chapter presents an illustrative LCA study applied to a hybrid electric passenger vehicle (HEV). In this

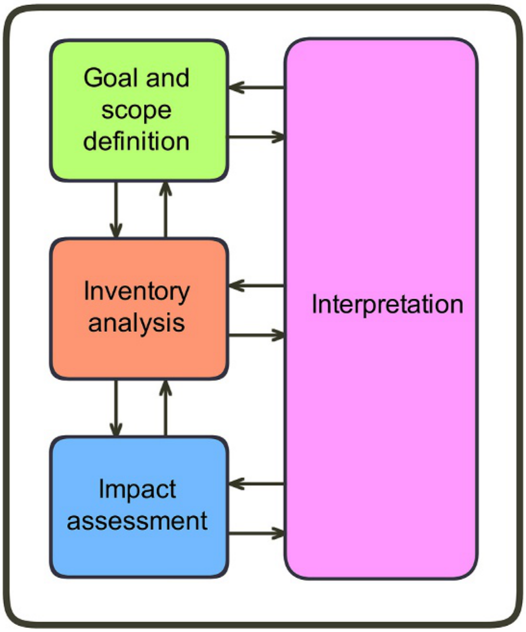

Fig. 3 The methodological framework of LCA.

regard, the emphasis is given to the relevance of selected key parameters (vehicle lifespan, weight, consumption, and occupancy rate) and their sensitivity to the characterization of the overall environmental performance.

3 The life cycle assessment methodology

The main goals of LCA are to compare the environmental profile of different options and to identify environmental hotspots along the supply chain of products and systems [12]. The framework for conducting a correct LCA is settled by the International Organization for Standardization, in particular by ISO 14040 and ISO 14044 [7, 8]. An LCA consists of four interconnected phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of results, as represented in Fig. 3. They will be described in the following paragraphs.

3.1 Goal and scope definition

The goal of an LCA must clearly state the reasons for which the study is carried out, their applications, and the intended audience. The scope of the LCA study comprises the definition of the methodological aspects such as:

- The definition of the system under analysis and its functions.
- Reporting the main assumption, limitation, geographical and time scope of the study.
- The definition of functional unit (i.e., the unit that quantitatively and qualitatively defines the main function of the system).
- The product system boundary (i.e., the main stages, processes considered within the system under analysis).
- Multifunctionality approach (i.e., for those systems performing more than one function, the procedure to allocate the impacts to the different products has to be described).
- The description of the environmental categories assessed in the analysis.

3.2 Inventory analysis

The LCA inventory analysis includes the data collection and calculation procedures to quantify input and output flows that are relevant to the investigated product system. The qualitative and quantitative information included in the inventory shall be collected unit process level, and the sources must be properly referenced when possible. In this stage, an important aspect to consider is the data quality specification (i.e., time-related coverage, geographical coverage, technology coverage, data precision, completeness, representativeness, and uncertainty). When collecting data, possible data classification can be subdividing them as energy, raw material, ancillary or other physical inputs; products, co-product, and waste; releases to air, water, soil; other environmental aspects.

The life cycle inventory (LCI) constitutes the input to the life cycle assessment associated with the provision of the functional unit. All calculations applied in the study to determine the elementary flows must be explicitly documented and reported in the study. Data must be properly validated, for instance, by checking the mass and energy balance law of conservation. As previously stated, and shown in Fig. 3, these phases are always coupled to the interpretation phase to spot potential inconsistencies and to improve data requirements.

In multifunctional systems, the inputs and outputs should be distributed between the different products or functions. In this situation, the standards [7, 8] recommend to use a multifunctionality procedure according to the following priority procedures:

- Dividing the unit processes into distinct sub-processes for which distinct and separate inputs and outputs can be collected (subdivision).
- Expanding the product system to include the different functions of the co-products (system expansion).
- When an allocation cannot be avoided, the physical allocation should be prioritized (i.e., distributing the inputs and outputs according to mass, volume, energy, mole basis).
- When a physical allocation is not viable, the allocation could be based on other relationships between such as the economic value.

3.3 Impact assessment

In the Life Cycle Impact Assessment phase (LCIA) the elementary inputs and outputs of the inventory level are translated into levels of impact category (selected in the goal and scope definition). The impact assessment procedure consists of two mandatory steps (classification and characterization) and two optional phases (normalization and weighting). These steps are specific to the applied LCIA method, which has to be clearly stated (e.g., ReCiPe, [13]):

- The classification assigns the elementary flows of the LCI results to the impact categories. In this phase, LCI elementary flows are attributed to one or more impact categories.
- The characterization phase consists in calculating the impact category results by multiplying the elementary flows for a characterization factor that represents the specific impact of the substance emission (or consumption) in the specific impact category.
- The normalization consists in relativizing the impact results to the reference value.
- The weighting assigns to each impact category a weight factor allowing the aggregation of different impact categories in a single score index.

3.4 Interpretation

This phase involves the interpretation of both LCI and LCIA data and results, iteratively and during all the LCA development (as shown in Fig. 3). In particular, the following checks are required: identification of issues based on the LCI and LCIA results; completeness, sensitivity and consistency checks; conclusions, limitations, and recommendations. A completeness check is needed to ensure that all the relevant data and information are included in the study. Sensitivity checks can be performed to assess the results fluctuations according to input changes. A consistency check is used to assess if the applied assumptions, methods, and data are consistent with the declared goal and scope.

Finally, the study must clearly state its limitations, conclusions based on data and make recommendations to the intended audience. Potential environmental bottlenecks and burden-shifting can be highlighted, as well as potential alternative can be proposed for technical aspects in specific life-cycle stages to improve the overall environmental performance.

4 Technical parameters and methodological aspects in LCAs of road vehicles

In any LCA, there are methodological aspects that can greatly influence the final result and the study interpretation. In the specific case of LCA of vehicles, methodological aspects linked to the section of the functional unit and the system boundaries worth further clarification (hereinafter referred).

Furthermore, it is also important to explore the sensitivity and the influence of specific technical parameters affected by uncertainty or variability, since their quantification can depend on several aspects such as the data source, the data provider, or the calculation procedure. In the specific case of passenger cars (objective of this chapter), the fuel consumption (typically expressed in kg/km), vehicle kerb weight (in kg), the useful vehicle life or lifespan (typically expressed in km traveled) and the occupancy rate (viz., the average number of passengers occupying the vehicle during its life) are relevant parameters that strongly affect the quantification of LCI flows, and, subsequently, the impact assessment. However, depending on the scope of the study, other technical parameters could be considered in addition to the aforementioned ones.

4.1 Functional unit in LCA of vehicles

The functional unit is defined as “the quantified performance of a product system for use as a reference unit in an LCA study” [7, 8], or, in other terms, a measure of the performance of the product system. The choice of the functional unit is crucial to ensure comparability among different LCA studies. Typical functional units for comparative studies in the field of transport can be referred to as distance traveled (e.g., 1 km traveled), typically applied when the vehicles under comparisons have the same characteristics in occupation rate or load capacity. When the comparisons are carried out between vehicles which function is to transport people (i.e., passenger cars, trains, buses, flights, etc.) with different occupation rates, the functional unit typically refers to the numbers of passengers that are transported over a unit distance (e.g., passenger* kilometer, pkm). Similarly, when the study goal is to compare vehicles to their freight load capacity (trucks, trains, flights, etc.), the functional unit should refer to a unit of weight transported over a unit of distance (e.g., tonne* kilometer, tkm).

4.2 System boundary definition in LCA of vehicles

The definition of the system boundaries consists of the selection of the stages included in the study. For instance, a “cradle-to-grave” study includes the activities from the

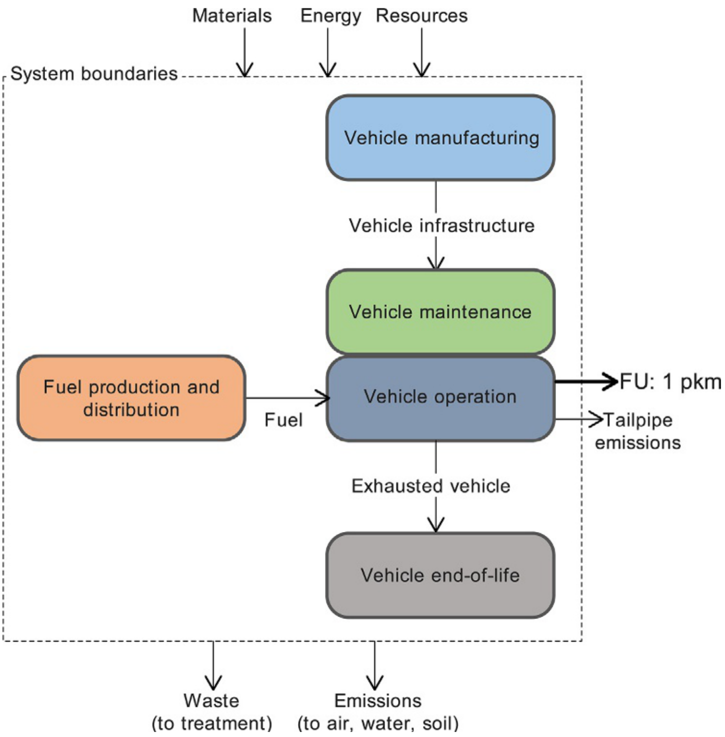

Fig. 4 System boundaries of a generic LCA for passenger road transportation.

extraction of raw materials until the recycling or disposal stage, including the intermediate stages such as processing, distribution, storage, and use. The system boundary of a study has to be defined according to the goal of the study. Defining the study boundaries means settling the boundaries between the technological system and nature, the geographical area, the time horizon, and the boundaries between the current life cycle and related life cycles.

In the specific case of LCAs of vehicles, the life cycle is typically divided into two distinct sub-life cycles, namely the vehicle life cycle and the fuel life cycle. Fig. 4 shows the system boundaries applied to a generic LCA of a vehicle together with the main life cycle stages. From top to bottom, Fig. 4 depicts the vehicle life cycle while from left to right the fuel life cycle, which has in common the stage of vehicle operation, i.e., when the vehicle tank is filled with the fuel.

More in detail, the vehicle life cycle typically includes the stages of:

- Vehicle manufacturing, from the extraction of raw materials through the various transformations that lead to the final product (passenger car or vehicle infrastructure).
- Vehicle operation, which refers to the period when the vehicle is performing its main function (passenger or load transportation). This phase involves the use of fuel(s).
- Vehicle maintenance, which occurs when there is a need to replace consumable components and materials such as tires or lubricating oil to ensure the vehicle's functionality during its operation over the useful life.

- Vehicle end of life, which refers to the phase in which the vehicle is transferred to the final disposal at the end of its useful life. It can include different disposal strategies such as recycling, reuse, and landfill disposal depending on several factors such as the considered materials, the recycling technologies as well as region-specific regulatory aspects in the matter of waste management.

The fuel life cycle includes the following phases:

- Fuel production.
- Fuel transport (e.g., by ship or oil pipeline).
- Conditioning and treatment (desulphurization, refining, etc.).
- Distribution (e.g., by road in tanker trucks, up to the refueling point for cars).
- Refueling station infrastructure.
- Fuel use, i.e., combustion in the vehicle engine when it is transformed into tailpipe emissions.

The various stages of the fuel life cycle, however, may differ depending on the fuel or the energy carrier considered.

Typically, in the automotive field, the so-called Well-to-Wheels (WTW) analyses are applied. WTW analyses consider the system boundaries from the *well* (for fuel extraction) to the *wheel* (of the running vehicle). Therefore, they cover the overall fuel life cycle, while only the vehicle operational phase is taken into account, i.e., excluding vehicle production and end of life. Optionally, the vehicle maintenance can be included in a WTW, merged with the vehicle operational stage. Moreover, WTW analyses include different subsets known as Well-to-Pump (WTP) and Pump-to-Wheels (PTW). In WTP, the system boundaries range from fuel production to the refueling stage; in PTW, the refueling to the vehicle operational stage are considered.

The main difference between a WTW and an LCA lies in the system boundaries. In particular, in addition to the fuel life cycle, LCAs include other vehicle life cycle stages such as vehicle manufacturing and vehicle end of life. Giving the lack of specific information related to end-of-life and final disposal of hybrid vehicles, the present work applies WTW boundary to the case study of an HEV including the burdens associated with the vehicle manufacturing stage.

4.3 Key technical parameters in LCA of passenger vehicles

Table 1 summarizes the key technical parameters that are taken into account for the LCA presented in this chapter and the values that are applied to the baseline case, which is assumed an HEV fuelled by gasoline taken from Candelaresi et al. [14].

Concerning the lifespan parameter, in the specific case of passenger cars, it can be expressed in years of useful life, hours of operation, or, in an equivalent way, in total distance traveled by the vehicle during its life (e.g., in km or mi). The conversion from operation hours to km can be easily obtained taking into account an average travel speed over the entire vehicle life expressed in km/h, while the conversion from years to km can be obtained taking into account the average annual distance traveled by the vehicle (e.g., km/year). A typical lifespan range for a conventional gasoline passenger car can be 15–20 years, 250,000–300,000 km (considering an average driving range of

Table 1 Main technical parameters to consider in LCA of passenger cars.

Parameter	Unit	Description	Value (HEV)
Lifespan	km	Total kilometers traveled during the useful life of the vehicle	300,000
Occupancy rate	Passengers	Average number of passengers occupying one vehicle	1.6
Consumption	kg/km	kg of gasoline consumed per kilometer traveled by the vehicle	0.025
Weight	kg	Vehicle kerb weight (does not include passengers and cargo)	1400

15,000 km/year for an average European passenger car) or 5000–6000 h (considering an average speed of 50 km/h) [15]. Usually, the lifespan affects the product's environmental impact, especially for the manufacturing stage the total product manufacturing impact is "spread" on the lifespan, so that with the same impact linked to production, a longer useful life usually brings beneficial effects in terms of impact per FU.

The average number of passengers occupying the vehicle during its life must be taken into account when addressing comparative LCA studies of passenger vehicles. This parameter (occupancy rate) is measured in the average number of passengers (p) carried by the vehicle. For a 5-seater car, the average occupancy rate for a generic European car is 1.6 p [16]. The higher the number of people occupying the vehicle for a single journey, the greater the environmental benefit since (neglecting increases in fuel consumption linked to the greater weight onboard) the impact linked to the traveled distance will always be the same, but the system will have better fulfilled its passenger transportation function. The product between lifespan in distance traveled (km) and occupancy rate in p gives the number of functional units provided by the vehicle (pkm) over its useful life.

Another parameter of acknowledged importance is fuel consumption. According to automotive practice, fuel consumption can be expressed in volume per distance traveled (e.g., L/km) for liquid fuels such as gasoline or diesel, in mass (e.g., kg/km) for gaseous fuels. Some authors express the fuel consumption in energy expenses per km (e.g., MJ/km) by multiplying the amount of fuel consumed per kilometer per its calorific value. In some cases, however, it is more convenient to consider the inverse of fuel consumption, namely the fuel economy, which represents the distance traveled by the vehicle per unit of mass, volume, or energy (e.g., km/kg, km/L or km/MJ). The fuel consumption of a vehicle is a highly uncertain parameter, as it depends on a considerable number of factors such as engine efficiency, the efficiency of the mechanical transmission from the engine to the wheels, vehicle kerb weight, additional weight due to the weight of passengers and goods, speed, driving style, route, traffic, vehicle aerodynamic drag coefficient, wind, tires and road condition and many more [17]. The fuel consumption is provided by manufacturers in vehicle technical datasheets, measured according to standard test-driving cycles defined by law, necessary for the vehicle approval and admission on the market. The data used in the present study refer to the New European Driving Cycle (NEDC) which provides three distinct consumption values based on the route: urban, extra-urban, mixed, or combined (urban + extra-urban). In particular, for this LCA, only the consumption values in the mixed driving cycle were considered for greater adherence to a real possible situation (some km traveled in urban mode and some km traveled in an extra-urban road). In Europe, the NEDC cycle has recently been replaced by the new Worldwide harmonized Light vehicles Test Cycle (WLTC) which provides four different classifications of consumption values based on cruising speed. In any case, given the transition phase from one test cycle to the other, it is still possible to find the consumption values expressed according to the NEDC. When compared to a conventional gasoline vehicle, a gasoline-fueled HEV usually shows a great advantage in terms of fuel consumption especially in urban routes since the electric motor is used instead of the internal combustion engine that would be throttled by traffic. The advantage of a reduced fuel consumption gradually decreases with the increase of cruising speed: in high-speed extra-urban routes such as highways, the HEV advantage linked to regenerative braking is no longer valid, while its consumption values become comparable to those of a gasoline vehicle. Nowadays, for an average European B-segment, a fairly efficient gasoline-powered 80 kW car can show an NEDC fuel consumption in mixed cycles of around 20 km/L, while a gasoline-fueled HEV (full-hybrid) shows a fuel consumption of 30–35 km/L in the mixed cycle and as much as 37–44 km/L in the urban cycle [18]. Finally, the vehicle kerb weight is also an important parameter to be considered because it affects not only the fuel consumption but also the particulate emissions that are not related to combustion, i.e., those due to wear of tires, brakes, and road.

5 Exploring the influence and sensitivity of key technological parameters: The case study of HEV vehicle

In the present work, an LCA is conducted to compare the environmental performance of an HEV with that of a conventional gasoline vehicle. Furthermore, a sensitivity analysis was conducted to explore the influence of the aforementioned main technological parameters on the total life-cycle environmental impact. Table 2 shows the main inventory data for the manufacturing of an 80 kW rated-power, full-hybrid HEV, with components and materials considered to produce one vehicle retrieved from Candelaresi et al. [14]. The impact categories explored in this study were global warming potential (GWP) characterized using the IPCC 2013 LCIA method [13], non-renewable cumulative energy demand (CED) characterized through the VDI LCIA method [19], and acidification potential (AP) characterized through the CML method [20]. For the characterization, the inventory was implemented in the software SimaPro [21] using the ecoinvent database for background processes [22].

Table 2 Main inventory data for vehicle manufacture (values per vehicle).

Components	**Materials**	**Unit**	**Value for HEV**
Body and chassis		p	1
Fluids		p	1
Internal combustion engine (ICE)		kW	58.4
	Steel, low-alloyed	kg	36.80
	Aluminum	kg	30.23
	Polyphenylene sulfide	kg	18.03
	Lubricating oil	kg	6.37
Fuel system		p	1
	Reinforcing steel	kg	1.45
Gasoline tank		p	1
	Polyethylene, HDPE	kg	17.5
	Injection molding	kg	17.5
Exhaust system		p	1
	Reinforcing steel	kg	34.9
	Synthetic rubber	kg	1.45
	Talc	kg	1.4
	Steel, low-alloyed	kg	25.2
	Platinum	g	1.6
	Palladium	g	0.6
	Rhodium	g	0.3
	Cerium concentrate, 60% cerium oxide	kg	0.04
	Zirconium oxide	kg	0.14
	Aluminum oxide	kg	0.02
	Polyphenylene sulfide	kg	0.1
Li-ion battery		kWh	1.8
Electric motor		kW	48.6
Power control unit		kg	33.3
Gearbox		kg	80
Starting system		p	1
Cooling system ICE		kg	29.1
Electronics for control units		kg	1.3
Tires		p	4
Energy			
Natural gas		MJ	1933
Electricity		kWh	691

Further details can be found in Candelaresi et al. [14].

5.1 Data collection and inventory data

For comparative purposes, the life-cycle performance of the HEV is compared with the one of a conventional gasoline vehicle (Operation, passenger car/RER) retrieved from ecoinvent database. The data regarding fuel consumption and emissions declared from manufacturers for each type of vehicle are collected from technical datasheets from various manufacturers (Ecoscore database, https://ecoscore.be/en/home). Table 3 shows the fuel economy and tailpipe emissions for both the HEV and the gasoline vehicle. The main exhaust emissions, expressed in g/km and released by the manufacturers, include carbon dioxide, carbon monoxide, unburned hydrocarbons (HC), and nitrogen oxides (NO_x).

Manufacturers usually express fuel consumption in terms of fuel economy rather than its inverse (fuel consumption). To have a term of comparison, it should be considered that 40.404 and 26.667 km/kg correspond, respectively, to 30.3 and 20 km/L of gasoline, assuming a gasoline density of 0.75 kg/L. It should also be noted that due to the lower fuel consumption and the partial distance traveled in electric mode, the HEV vehicle shows lower CO_2 emissions than the traditional vehicle. From Table 3 data, it was possible to calculate the vehicle life-cycle consumption and emissions and to build the inventory data for the vehicle operational stage, shown in Table 4. Values are referred to the whole vehicle's useful life, i.e., per total kilometers traveled. Alongside the tailpipe emissions presented in Table 3, there are particulate emissions associated with tyre, brake, and road wear, which can affect air quality in an urban environment. Data for maintenance inputs were taken from the GREET model [23] and include the replacement of tires, lubricating oil, and antifreeze fluid. One battery replacement was considered necessary during the HEV useful life.

5.2 LCA results: Comparison of HEV vs conventional gasoline vehicle

Fig. 5 shows the results of the comparative analysis between the HEV and the gasoline vehicle, with the total life-cycle impact expressed per pkm, for three different impact categories: GWP, CED, and AP.

Overall, under all three different indicators, the HEV vehicle exhibits a better environmental performance than the conventional gasoline vehicle. This advantage is more pronounced for the carbon and energy footprint, and in this case, it was mainly associated with the reduction in fuel consumption and consequently in CO_2 tailpipe

Table 3 Fuel economy and tailpipe emissions for the vehicles under study [14].

Vehicle	Fuel economy (km/kg)	CO_2 (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)
HEV	40.404	75	0.196	0.0282	0.0060
Gasoline	26.667	105.4	0.29254	0.0412	0.0205

Table 4 Main inventory data for vehicle operation and maintenance (values per useful life).

Item	Unit	HEV	Gasoline
Operational inputs			
Gasoline (unleaded)	t	7.5	11.2
Maintenance inputs			
Lubricating oil	kg	34.6	34.6
Ethylene glycol	kg	12.9	12.9
Decarbonized water	kg	8.6	8.6
Tires	p	12	12
Li-ion battery	kWh	1.8	–
Emissions			
Carbon dioxide	t	22.7	31.6
Carbon monoxide	kg	59.4	87.8
Hydrocarbons, unspecified	kg	8.54	12.4
Nitrogen oxides	kg	1.82	6.2
Brake wear emissions	g	374	334
Road wear emissions	kg	4.1	3.7
Tire wear emissions	kg	24.1	21.5

emissions. Also, concerning acidification footprint, the HEV performs better than the gasoline vehicle for a reduction in consumption, but this advantage is less marked because the vehicle's electrical components are built with materials that increase the impact of acidification compared to a conventional vehicle manufacturing.

To highlight the hotspots of the environmental performance, Fig. 6 shows the impact breakdown for the two options under the three considered impact indicators. It can be observed that in both cases, GWP is mainly influenced by tailpipe emissions (black bar), especially by CO_2 emissions, which are indirectly linked to fuel consumption. The carbon footprint linked to the vehicle infrastructure (blue bar in GWP, 6a)

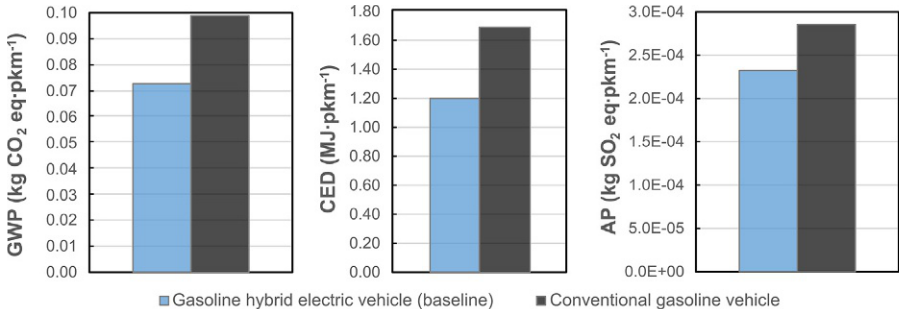

Fig. 5 Impacts per pkm in GWP, CED, and AP for the gasoline HEV compared to a conventional gasoline vehicle.

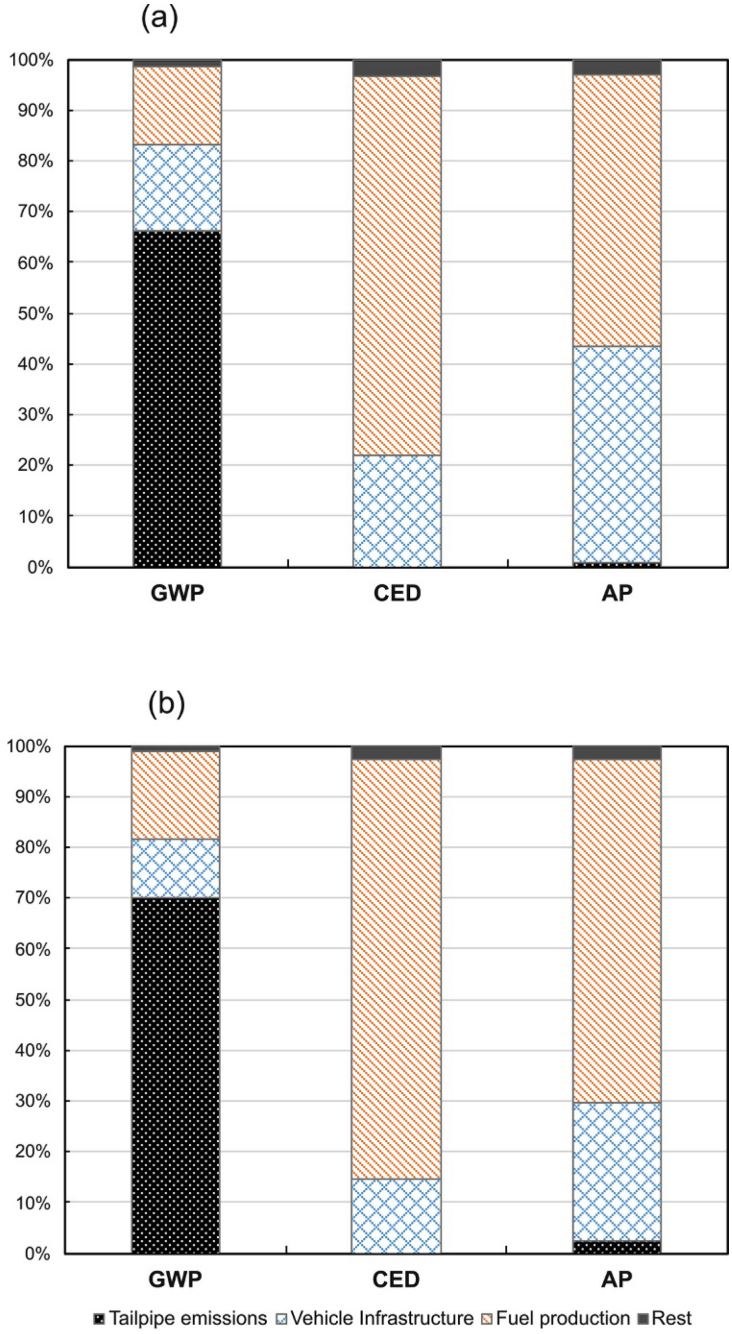

Fig. 6 Impact breakdown of (A) gasoline HEV and (B) conventional gasoline vehicle.

has a slightly higher incidence on the total in the case of the HEV than in the case of the gasoline vehicle (6b), due to the greater vehicle complexity, but this increase is balanced by a reduction in tailpipe emissions (g/km). Fuel production shows a marginal but not negligible incidence on the carbon footprint in both cases.

The impact in CED is mostly associated with fuel production and distribution, therefore, a fuel-saving in the vehicle operational phase leads to a significant reduction in the absolute energy footprint shown in Fig. 5. In the case of the HEV, since the CED absolute value has decreased, the vehicle infrastructure assumes a slightly higher percentage of the total but still less important than fuel production. Regarding acidification footprint, an important share of the impact is linked, in both cases, to gasoline production, which shows a rather high incidence on the total since it contains sulfur and other substances. Also for this case, the reduction in fuel consumption rewards the HEV, which shows a lower incidence of fuel production.

Alongside this reduction, however, there is a considerable increase in the AP impact associated with the vehicle infrastructure due to materials used for the manufacturing of the Li-ion battery, the electric motor, and other electrical/electronic components, which is not counterbalanced by the fact that the HEV is equipped with a smaller ICE than the traditional vehicle. Tailpipe emissions have minor importance in the acidification footprint and are mainly linked to nitrogen oxides emissions (NO_x). In the case of the HEV, however, the mixed electric/thermal travel mode allows to considerably reduce NO_x tailpipe emissions, which therefore become negligible to the incidence on the total acidification impact. Finally, other contributions, which for example include the maintenance phase and particulate emissions due to tire wear, assume a negligible role for all impact categories under evaluation.

5.3 Sensitivity of key technical parameters

After assessing the baseline case, Table 5 shows the variation range and variation step assumed for the sensitivity analysis of HEV total impact under the three considered impact indicators as the technical parameters change.

Figs. 7–9 show the results of the sensitivity analysis for the GWP, CED, and AP, respectively. The x-axis shows the percentage variation of the technical parameter with respect to the baseline case, while the y axis shows the relative variation of the total impact with respect to the base case for each impact category. It is possible to observe that for all three impact indicators, the total impact follows a hyperbolic

Table 5 Variation ranges of main technical parameters considered for sensitivity analysis.

Parameter	Unit	Range for HEV	Variation step
Lifespan	km	200,000–400,000	25,000
Occupancy rate	Passenger	1.2–2	0.1
Consumption	kg/km	0.02–0.03	0.005
Weight	kg	1100–1700	300

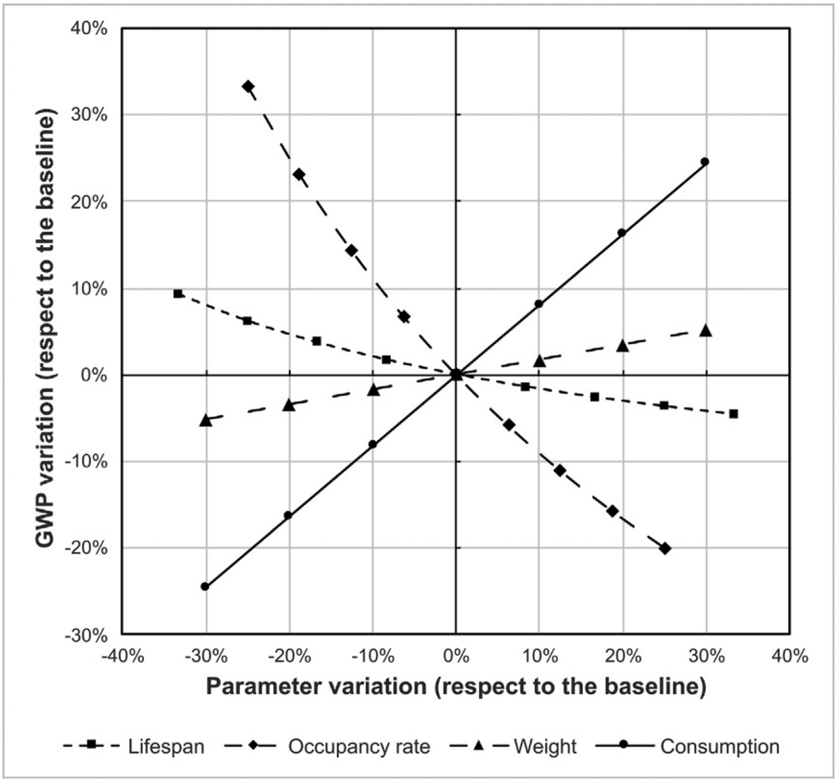

Fig. 7 Influence of vehicle technical parameters on GWP impact.

trend as the lifespan and occupancy rate parameters vary, while it follows a linear trend as consumption and weight vary. In particular, lifespan and occupancy rate generate descending hyperboles, so as these parameters increase, the total impact decreases, while consumption and vehicle kerb weight generate ascending lines, increasing the total impact as their parametric value increases.

It can also be observed that the hyperbola linked to the occupancy rate is always more pending than the hyperbola of the lifespan, just as the consumption line is always more pending than that of weight. A small variation in the occupancy rate or fuel consumption parameters can therefore induce a large variation in the total impact value of a vehicle LCA. Furthermore, by comparing the different slopes between the various figures, it can be concluded that the hyperbola linked to the occupancy rate always shows the same slope, so this parameter has the same incidence for all the impact categories analyzed, while the lifespan has a much more marked incidence on AP, intermediate on CED and lower on GWP since its slope varies between the three figures and is greater in AP. For the same reason regarding the slope of the curve between the various figures, consumption shows a greater influence on GWP, intermediate on CED, and lower on AP, while weight shows a greater influence on AP and lower

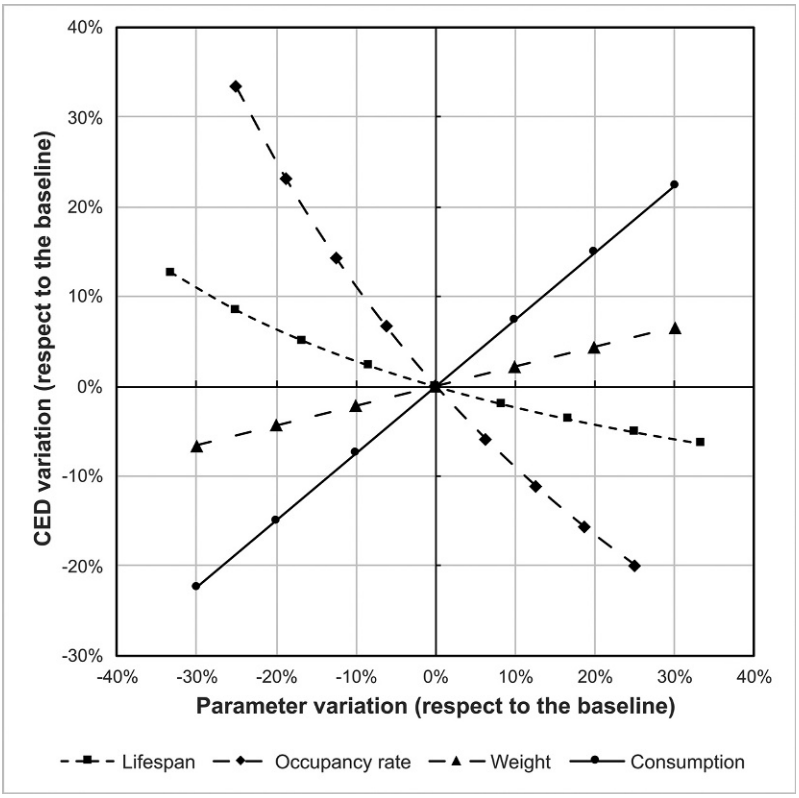

Fig. 8 Influence of vehicle technical parameters on CED impact.

on GWP. Overall, among the four explored technical parameters, fuel consumption, and occupancy rate are found to be the most accentuate drivers to the environmental performance of vehicles. In this sense, potential actions to improve the environmental performance of vehicles could prioritize the improvement of these aspects. It should be noted that these actions not necessarily must be of technical or engineering nature, potential actions could involve for instance informative campaigns targeted to end-users promoting an increase of the average occupancy rates or by promoting the advantages of more efficient drive styles.

6 Conclusions

The present chapter showed the usefulness of the LCA methodology in analyzing the environmental performance of road vehicles comprehensively. In particular, the methodology was applied to compare the performance of an HEV against

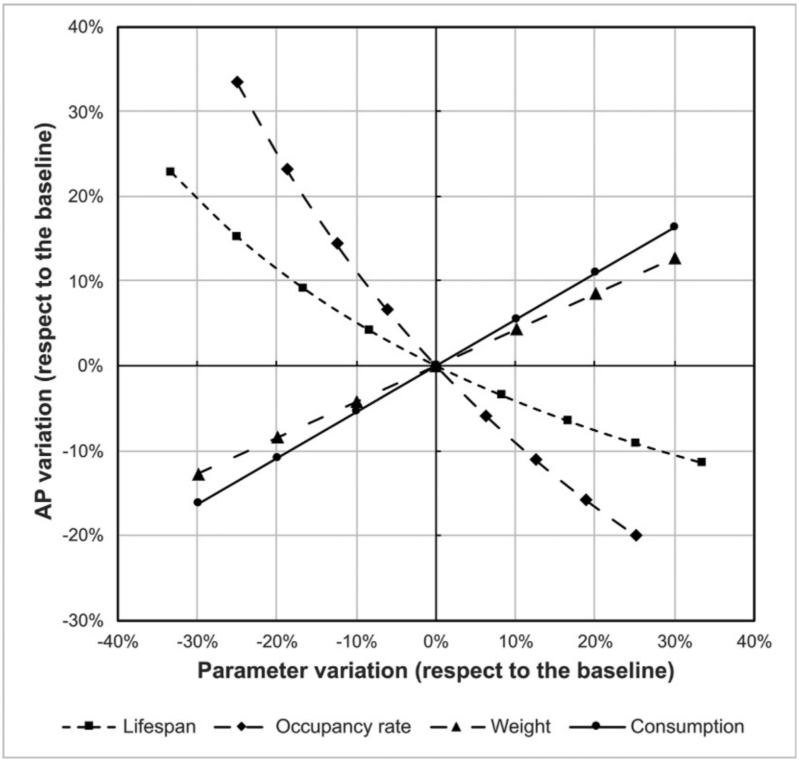

Fig. 9 Influence of vehicle technical parameters on AP impact.

the one of a conventional gasoline vehicle. Besides, the sensitivity analysis of selected technical parameters on the carbon, energy, and acidification footprint was performed.

Under the selected impact categories, the obtained results highlighted a general superior environmental performance of an HEV fuelled with gasoline the one of its corresponding conventional gasoline. In both options, tailpipes emissions are found to dominate the carbon footprint. Fuel consumption arises major concerns in acidification and energy footprint, the vehicle infrastructure played a relatively less relevant role in carbon and energy footprint, while it is found to be significant in the acidification category.

Concerning the sensitivity of technical parameters presented in this work, all of them are found to have a significant influence on the environmental life-cycle performance, with a particular criticality found for occupancy rate and fuel consumption.

Finally, it is important to specify that the average superior environmental performance of the hybrid solution is closely linked to the driving style and the traveled route (urban/extra-urban) combined with some HEV specific technical features such as lower emissions/consumption in transient mode (e.g., acceleration, regenerative braking, etc.) and a downsized internal combustion engine.

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