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Comparative environmental life cycle assessment of several powertrain types for cars and buses in France for two driving cycles: "Worldwide Harmonised Light Vehicle Test Procedure" cycle and urban cycle.

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Abstract

Purpose

Environmental assessments in the transportation sector are often lacking in transparency and completeness. In this article, the environmental trade-offs in road passenger transportation between conventional vehicles and electrified vehicles are compared, using life cycle assessment (LCA) methodology. Hence, the relevance of a massive electrification approach can be questioned. Assessing a set of current midsize passenger cars and buses allows for investigation of potential environmental issues. This is the first detailed LCA concerning several hybridization levels for cars and buses, and it is based on real consumption data for two traffic conditions.

Methods

We focused on the ISO standards (ISO 2006a, 2006b) and analyzed the energy carriers' life cycle and the vehicle's life cycle. The functional unit is clearly defined as the transportation of one passenger over one kilometer in specific driving conditions from a point A to a point B, without prejudice toward the path taken. Vehicle specifications were derived based on the available manufacturers' data, literature, and French Institute of Petroleum (IFPEN) experts. For the use stage, two driving cycles were assessed: the "Worldwide Harmonised Light Vehicles Test Procedure" (WLTP) cycle and an urban cycle. France was selected as the study area, and a sensitivity analysis was performed based on a European electricity charging mix for electrified vehicles.

Results and discussion

Battery electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) exhibit the highest climate change (CC) mitigation potential, provided that the electricity mix has low carbon and that the PHEV is used with a fully-charged battery. With these conditions, PHEVs can perform even better than EVs. In that regard, PHEVs using only a thermic engine perform the worst in regards to CC indicator. It is also worth mentioning that electric buses are the best solution in urban traffic conditions for decreasing greenhouse gas emissions. Among powertrains, the electrified powertrains are even more important when performing in urban cycles. For other environmental indicators, such as particulate matter emissions, EVs perform worse than conventional thermic vehicles.

Conclusions

The results underline the importance of considering vehicles' life cycles for LCA in the transportation sector and the need for multicriteria environmental analysis. Therefore, electrification of the transportation sector should not be driven by a single CC indicator, as this may generate potential environmental drawbacks. It is also crucial to adapt public policies to the local context because the results are highly sensitive to the electricity charging mix.

Keywords

Life cycle assessment, road transportation, passenger car, energy mix, buses, electrified vehicles, driving conditions.

1 Introduction

In the challenging context of CO_2 emissions reduction targets coupled with more stringent vehicle driving test cycles (ICCT 2014), the transportation sector is currently facing major issues in complying with upcoming public policies. Electrification of the transportation sector generally appears to be a necessary evolution for reaching the CO_2 targets planned during the 2015 United Nations Climate Change Conference (COP21) on the Paris agreements. Indeed, in 2015, the transportation sector represented almost a quarter of Europe's greenhouse gas (GHG) emissions (European Commission 2017) and road transportation is responsible for over 72% of these emissions (European Environment Agency 2019). Passenger cars are responsible for approximately 12% of the total European Union (EU) emissions of carbon dioxide (TNO 2016). In the new environmental context, the transportation standards related to CO_2 emissions have been steadily increased, leading to a first step of setting the European CO_2 emissions average fleet target to 130 grams of CO_2 per kilometer in 2015 (The European Parliament and the Council 2009). At that time, it represented a reduction of approximately 18% from the 2007 fleet average of 158.7 grams of CO_2 per kilometer. By 2021, the reduction target for all new passenger cars will be set at approximately 95 grams of CO_2 per kilometer (The European Parliament and the Council 2014). This threshold will drop to 81 g/km (New European Driving Cycle (NEDC) reference (The Council of the European Communities 1970)) in 2025, and finally, to 66 g/km in 2030. These increasingly strict thresholds will oblige manufacturers to include more innovations in their vehicles and engines. In consideration of the increase in population (United Nations 2017) and corresponding rise in mobility needs in terms of both traffic and vehicle sizes (Scholl et al. 1996, WBCSD 2001), the passenger transport requirements, expressed in passenger-kilometer (pkm), are constantly increasing (European Commission 2017). Thus, transportation is one sector in the EU where GHG emissions requirements continue rising (Meyer et al. 2012), despite the deep technological improvements and resultant fuel efficiency experienced in internal combustion engines (ICE) in recent years. Meeting the EU targets will require a widespread deployment of low-carbon technologies that cannot be achieved without considering vehicles' electrification options, such as battery electric vehicles (EVs) or plug-in-hybrid vehicles (PHEVs).

As argued in Bauer et al. (2015), a massive development of transportation electrification could displace the environmental impacts from GHG emissions to other environmental burdens, such as particulate matter (PM) formation, acidification (Ac), or resource depletion (RD). Furthermore, passenger car electrification is often considered as a zero CO_2 emission technology with regard to a tank-to-wheel (TTW) assessment, as defined by the "activities and energy use and emissions associated with vehicle operation" (Brinkman et al. 2005). However, these system boundaries exclude the "energy use and emissions associated with fuel production" (Brinkman et al. 2005), defined as well-to-tank (WTT), as well as the vehicle's life cycle. Considering only the TTW stage or even the complete fuel's life cycle (WTT and TTW, commonly named well-to-wheel (WTW)), would lead to the potential transfer of impacts from life cycle stages to other areas. For example, any decrease in CO_2 emissions during the usage stage would not avoid the consumption of resources required for battery production. Therefore, only life cycle assessment (LCA) as defined by its inner definition (ISO 2006a, 2006b) can address the entire system: WTT, TTW, and the vehicle's life cycle. LCA is also a multicriteria environmental type of analysis that enables researchers to answer questions related to potential environmental impacts that differ from the effects of global warming alone.

The evaluation of the environmental impacts induced by the electrification of the transportation sector is becoming an urgent matter, as states, through public policies, are willing to increase the deployment of EV technologies. Several incentives are being put in place at the consumer and state levels. For example, in France, a subvention program (ecological bonus-malus[1]) has been implemented since 2007 to promote the purchase of electric cars. A conversion bonus has been also applied since 2015 for the scrapping of ICE vehicles registered before January 1, 2006 with diesel engine, and January 1, 1997 for others (Ministry for Ecological and Solidarity Transition 2009, 2017). The rationale of this policy is that electric powertrains do not produce any tailpipe emissions (Sadek 2012) and thus are seen as drastically reducing GHG emissions (Nemry and Brons 2010). However, in addition to several practical questions such as those regarding the deployment of charging stations (and their costs), or the management of peak hours for supplying electricity[2], other environmental issues are neglected. The first is the displacement of CO_2 emissions from TTW to WTT for EVs via energy production; another is the increase of the contribution of the vehicle's production stage to the global life cycle (Tran et al. 2012). This leads to the main conclusion, i.e., that the impacts of the electrification of the transportation sector have to be evaluated over the entire life cycle for both the energy carrier (WTT and TTW) and the vehicle. Yet another issue is the displacement of the environmental impacts from the environmental LCA categories to other entitles (Chan 2007). Indeed, while LCA applied to conventional vehicles mainly reveals the impacts regarding global warming potential (GWP), Lombardi et al. (2017) showed that EVs give rise to increased human toxicity and terrestrial acidification. As a consequence, a GWP indicator alone is insufficient for comparing different types of vehicles (Nordelöf et al. 2014).

The objective for the passenger transportation sector is to enable the mobility of citizens and connect people to each other and to the goods and services of the economy (Scholl et al. 1996). To do so, the LCA must integrate this objective within its own functional unit (FU), whose definition, according to the ISO standards (ISO 2006a) for LCA studies, is the quantified performance of a product, system, or service. However, environmental studies addressing transport do not quantify the performance offered by a product or service, but rather focus on the product or service itself (Nordelöf et al. 2014). For this reason, the current study introduces an appropriate FU that accounts for performance through the vehicle occupation rate and in the context of use via a driving cycle from a point A to a point B.

This article aims at assessing several powertrains for cars and buses from an environmental perspective, to determine if a suggested option can mitigate the impacts of the transportation sector. This objective is consistent with the public policies designed to promote electrified vehicles. However, geographical context and driving conditions could have a major role to play in a more ecologically-friendly choice of transportation. Indeed, the electricity source is a key parameter and is very sensitive to the country being studied (Hawkins et al. 2013).

To assess the advantages and drawbacks of the electrification of the road passenger transportation sector, we relied on the LCA methodology to provide robust and relevant environmental results. Following the European recommendations (JRC - European Commission 2012), environmental impacts in categories other than GHG emissions are considered. France is the study area, and French directives were followed. In the case that French directives were not available, European directives were used. A sensitivity analysis with a European electricity

[1] The vehicle must fulfill several conditions of which a maximum emission rate of 20 g CO_2 eq./km. The amount of the aid is capped at 6,000 euros.

[2] This issue will not be studied in this article.

charging mix was performed, as electrification performances are geographically dependent (Lombardi et al. 2017). The temporal horizon was the present time, and we focused on one class of vehicles: the C-segment, defined in Europe as midsize or medium cars (Commission of the European communities 1999), and equivalent to compact cars for the USA and UK. In addition, midsize cars are compared to buses, as buses must fulfill the same FU criteria for passenger transportation. Various levels of electrification options have been used for powertrains, based on the new homologated worldwide harmonized light vehicles test procedure (WLTP) for midsize cars (ICCT 2014). As a complement to the WLTP cycle, an "ARTEMIS" urban driving cycle (André 2004) is assessed to compare passenger vehicles and buses.

The rest of the paper is organized as follows. Section 2 discusses the materials and methodology. Section 3 presents our main findings, and these findings are discussed in Section 4. Section 5 concludes the paper.

2. Material and method

2.1 Goal, scope, and products systems

The goal and scope definition is the first step of the LCA, according to the ISO standards. This step clearly identifies the objectives of the evaluation.

The purpose of our study is to highlight the trade-offs between several levels of electrification based on the LCA methodology, in regards to the environmental performances in the passenger transportation sector. To achieve this goal, seven midsize architectures were assessed over the WLTP cycle. In addition, French and European electricity charging mixes were studied to address the electrification issue. The seven selected midsize vehicles are representative of the market and are described in Table 1: an ICE gasoline vehicle, an ICE diesel vehicle, a mild hybrid electric vehicle (MHEV) based on a 48V battery pack network associated with a gasoline engine, a full hybrid electric vehicle (HEV) with a high-voltage network (gasoline engine and power split architecture), a plug-in hybrid electric vehicle (PHEV) with a gasoline engine, an EV, and an EV with an extended battery capacity (EV+).

Table 1 Characteristics of the seven studied passenger cars

		Internal combustion engine - gasoline (ICEg)	ICE-diesel (ICEd)	Mild hybrid electric vehicle (MHEV)	Full hybrid electric vehicle (HEV)	Plug-in hybrid electric vehicle (PHEV)	Battery electric vehicle (EV)	EV with extended capacity (EV+)
Powertrain	*Fuel vector*							
Thermic	Gasoline	x		x	x	x		
	Diesel		x					
Electric	Electricity					x	x	x

As the study focuses on passenger cars, we also included buses in the second part of the study. To be consistent from an LCA perspective, we assessed the performance of the same seven passenger cars described above in an urban driving cycle. This allowed us to compare not only two driving cycles for the same vehicle but also to compare a passenger car solution with a bus solution, given the geographical offerings of the bus transportation sector in France for the Parisian sector. We based the comparisons on the hypothesis that the traveled path is the same for passenger cars and buses. This could be adapted and/or discussed, according to the city context (Huang and Levinson 2015).

We considered existing vehicles rather than theoretical ones because the final goal of this analysis is to show that there are optimal solutions (or efficient choices) for both consumers and policy makers from an environmental perspective when, e.g., choosing a passenger transportation solution or launching public policies.

The vehicles' specifications are based on the available manufacturers' data and French Institute of Petroleum (IFPEN) research and development[3] (R&D). This leads to the following breakdown for the vehicle's weight: vehicle glider[4] with options and gearbox, thermic engine, electric motor and electric generator, and battery. The raw material components' splits of the vehicle's glider are based on the environmental improvement of products (IMPRO) Car II report of the JRC scientific and technical reports (Nemry et al. 2009), in a percentage corresponding to the medium gasoline car for the seven assessed cars. The buses' raw material components are based on manufacturer data and IFPEN R&D. The materials choices and their operation are based on the Ecoinvent process "glider, passenger car" for private cars and "bus, production RER (Europe)" for buses (Spielmann et al. 2007). Extrapolations and assumptions have been made, according to experts. These are described in Table 5.

The energy consumption values for electricity or natural gas in vehicle production are based on the IMPRO Car I report of the JRC scientific and technical reports (Nemry et al. 2008) for midsize car and on the Ecoinvent process for buses.

Special attention has been paid to each vehicle's end of life, as it is an important stage (Kanari et al. 2003). This is even more true for those with lithium-ion batteries, which are massively used by car manufacturers (Majeau-Bettez et al. 2011), and for which the environmental burdens can be important. Complicating things further, industries have little experience in managing the end of life of a battery. In addition, this subject is complex (Schmidt et al. 2004), as it integrates issues related to the dispersive use of metals, their weak availability, and the existing regulations. Moreover, the potential metals of interest might only be available in small quantities, unless special recycling is performed (Gerrard and Kandlikar 2007). As car manufacturers made agreements on this subject for a French project (PE International AG and Gingko 21 2013), we founded our assumptions on this report, and we built a realistic scenario for France that satisfies the regulatory objectives.

We also followed European directives regarding outdated vehicles and batteries (The European Parliament and the Council 2000). The end of life scenario for vehicles is thus modeled through a realistic recycling scenario for out-of-date vehicles in France today, allowing us to reach the goals of the regulatory rates provided by the European directives (The European Parliament and the Council 2005, 2006). This leads to rates per material, which are divided into categories including recycling, energy recovery, and landfilling (Table 2). Further end of life data have been added within the French context regarding average collection distances between sorting centers and materials recovery infrastructures, but also in the context of energy consumption for material recycling (ADEME 2018, 2008). A 2010 French collection rate for obsolete vehicles (69%) was also used, and the distances from owner to wrecker and from wrecker to grinder (300 km in total) were considered within the national context. French waste statistics have been modeled mostly for incineration (53 %) and landfilling (47 %) data when missing (Ministry for Ecological and Solidarity Transition 2014).

[3] IFPEN technological offer regarding sustainable mobility is structured around hybrid and electric powertrains, IC powertrains, and connected vehicles.

[4] Vehicle's glider encompasses vehicle body and wheels.

Table 2 Raw materials' end of life's scenario

	Recycling	*Energetic recovery*	*Landfilling*
Ferrous and non-ferrous material	95%	5%	
Plastics, rubber, fibers	50%	30%	20%
Glass	90%		10%
Fluids	50%	50%	
Paints and others		40%	60%

Regarding energy carriers, the fossil fuels are modeled from Ecoinvent data (Frischknecht et al. 2005): the "Petrol, low-sulfur {Europe without Switzerland}| market for | Alloc Rec, U" and "Diesel, low-sulfur {Europe without Switzerland}| market for | Alloc Rec, U". In the same way, the electricity mix is the French average mix from the Ecoinvent database "Electricity, medium voltage {FR}| market for | Alloc Rec, U". This results in approximately 113 g CO_2 eq./kWh for the French electricity mix at the grid. However, France has a very low carbon electricity mix, owing to the main primary energy used (nuclear power). This means that the environmental performances of electrified vehicles are geographically dependent on the electricity mix. We performed a sensitivity analysis with an average European electricity mix, *ceteris paribus*. The Ecoinvent process used is "Electricity, medium voltage, production UCTE, at grid" and is representative of a European electricity mix of approximately 531 g CO_2 eq./kWh.

The fuel and electricity consumption for the seven passenger cars and the three buses were estimated using IFPEN vehicle simulators based on the Simcenter Amesim™ software. These conventional, hybrid, and EV simulators were developed and validated through component and vehicle tests (Badin et al. 2015, Badin et al. 2013, Da Costa et al. 2012, Marc et al. 2010). The objective is to assess the energy carrier consumption in both the WLTP homologated driving cycle and the Artemis urban cycle (André 2004) for passenger cars and in an urban Paris-type driving cycle for buses. The WLTP cycle corresponds to an average speed of 46.6 km per hour over a distance of 23 km, representing a journey in real conditions. This cycle is based on real-driving data and is divided into four parts with different average speeds: low, medium, high, and extra high. Each part contains a variety of driving phases, stops, accelerations, and braking phases. The simulations were used to assess the hybrid consumptions, depending on the plug-in functionality: sustaining mode (same initial and final battery states of charge) for the HEV, depleting mode for the full-battery PHEV, and sustaining mode for the PHEV with an empty battery. Depleting mode is the optimal mode, as only the electric powertrain is used. We consider that passenger cars are mostly used for commuting between home and work and that the battery size of these PHEVs allows sufficient autonomy for the driver if the battery is loaded when needed (Loisel et al. 2014). The opposite case (sustaining mode with empty battery) assumes that the user does not charge his/her vehicle and instead uses liquid fossil fuels as the energy carrier. The PHEV behaves in a manner between that of an ICE gasoline vehicle and that of a degraded HEV. A hundred kilometer distance was simulated. The Artemis urban driving cycle is based on real-world driving patterns for Europe. The simulated urban cycle for buses was set to 10.6 km/h.

The end of life was modeled according to an avoided burden allocation methodology (Nicholson et al. 2009, Allacker et al. 2017). A vehicle's end of life is based on manufacturer data as well as European directives such as The European Parliament and the Council. The end of life for wheels and tires is based on the ADEME report of 2017. The end of life for batteries follows the European directive 2006/66/CE from The European Parliament and the Council and uses two different technologies from the Ecoinvent database in equal proportion: hydrometallurgical treatment, and pyrometallurgical treatment (Frischknecht et al. 2005).

According to ISO standards, the definition of an FU relies on the quantified performances of a system of products, with the intention of finding the reference unit of the LCA (ISO 2006a, 2006b). The reference unit or reference flow is defined as the measurement of the process outputs necessary to fulfill the function as expressed by the FU. The function of our system is the transportation of people from one point to another in certain traffic conditions. Accordingly, the FU chosen for this study is the transportation of one person for one km in similar driving conditions, expressed as passenger per kilometer (p/km). We assumed that the lifetime of the passenger vehicles was 150,000 km, as in Hawkins et al. (2013), Notter et al. (2010), Szczechowicz et al. (2012), and Sharma et al. (2013), considering a lifetime for the vehicles of 10 years and 15,000 km/year of driving. Buses are assessed over 12 years and 40,000 km/year of driving, leading to 480,000 kilometers according to IFPEN experts. We supposed that the battery will last eight years for passenger cars and six years for buses, based on commercial manufacturer guarantees as few in-the-field feedbacks exist as the BEV market is quite recent. The driving conditions are the WLTP for the comparative passenger cars LCA and the urban cycle for the comparison of passenger cars with buses.

To be consistent in the comparative assessment, an occupation rate has been applied for both passenger cars and buses. The average occupation rate for a car is 1.3 persons and that for buses is 17.4 persons, according to the General commissioner for sustainable development (2016) and the European Environment Agency (2008). The occupation rate seems to be an influencing factor, as its range encompasses between 1 and 5 persons for C-segment cars and between 1[5] and 103 persons per bus in the average upper boundary for buses (OMNIL 2011). A sensitivity analysis performed on the lower and upper boundaries of occupation rate for both transportation modes showed that the three buses' architectures have the highest impacts for the lower boundary scenario. The trade-off lies between 7 persons and 28 persons in the bus, to be competitive with the cars having the greatest impact on climate change, e.g., PHEV gasoline (100 % thermic), and least impact, e.g., PHEV gasoline (100 % elec.). For the opposite trend, the results are similar to those presented here for the average occupation rate, except for the ICE diesel bus which ranks at fourth place.

Regarding the system boundary, the analysis addresses both energy vector life cycles, i.e., a WTW assessment including the fuel/energy production (WTT) and the fuel/energy use (TTW); in that regard, the analysis addresses the entire life cycle of the vehicles. The life cycle of liquid fossil fuels, e.g., gasoline and diesel, includes crude oil extraction, transportation, refining, and distribution. For the electricity vector, we consider the energy sources' supply, electricity production, and the transmission network, including losses. The vehicle's life cycle encompasses vehicle production, powertrain (thermic and electric) production, tire production, battery production, maintenance, and the end of life, as shown in Fig. 1.

[5] We choose not to include cases in which no passengers were in the bus.

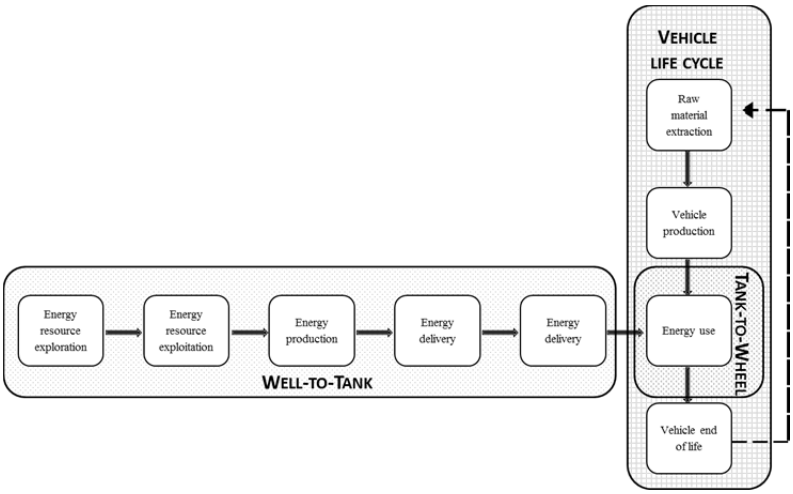

Fig. 1 Simplified life cycle stages considered for the study

It is worth mentioning that the infrastructures, roads, and charging stations are not part of our analysis. These elements should be included for a large-scale deployment study. The auxiliaries' consumptions and the emissions from tire wear and braking have also been excluded, based on the reproducibility of these emissions within the cases. These should be included to obtain a net value.

The perimeter of the study is France, as the locations for assembly and usage of the vehicles are in France.

The LCA is conducted with regards to ISO standards and is modeled with SimaPro 8.0.4.30® software. The main database used is Ecoinvent version 3.1, with the system models "allocation, recycled content".

The emissions of pollutants during the use phase are based on worldwide emissions standards for passenger cars, i.e., Euro6b (2008) and the assessed consumption provided by the IFPEN simulator. We also added a multiplication factor of seven for NOx emissions for diesel passenger cars, in accordance with several test results regarding real driving emissions (RDE) (European Commission 2018). This "seven times coefficient" has been approved by the French, German, Netherlands, and UK governments.

The low heating value (LHV) values used for energy carriers are chosen in line with JRC data (JEC - Joint Research Center-EUCAR-CONCAWE collaboration 2014), as well as the quantities of CO_2 emitted during fuel combustion.

2.2 Life cycle inventory

The goals and scope description of our study described above allowed us to perform a quantitative analysis of all flows, material, and energy, in and out, in the described process. The main assumptions and detailed data are presented in this section.

The WTT stage focuses on the production of the energy carrier, from its source through its delivery to the vehicle. The Ecoinvent database version 3.1. was used (Frischknecht et al. 2005). We used the processes "Petrol, low-sulfur {Europe without Switzerland}| market for | Alloc Rec, U" and "Diesel, low-sulfur {Europe without Switzerland}| market for | Alloc Rec, U". They are not representative of the current fuel delivered at filling stations, as we did not include the 5% ethanol or 7% biodiesel, but we decided not to implement added biases in the analysis with biofuel compositions in the fuels at the pump. This will be addressed in another ongoing study.

The WTT stage for PHEVs and EVs implies an electricity supply. The French average mix from the Ecoinvent database has been used, i.e., "Electricity, medium voltage {FR}| market for | Alloc Rec, U", in the same way.

Our objective does not consider consumers' habits and thus does not presume the charging profile of the electricity.

Table 4, Table 5, and Table 5, present the characteristics of the studied vehicles. The vehicles are modeled based on data relative to an ICE gasoline vehicle, which were collected by IFPEN experts on a wide range of information. Other studied vehicles have been duplicated from this ICE gasoline vehicle and have been customized based on models and expert opinion. This leads to fictitious vehicles: not commercial vehicles *per se*, but representative of their category, i.e., an average powertrain for existing vehicles on the market. For example, the PHEV gasoline vehicle is derived from the ICE gasoline vehicle glider with a Prius-type powertrain. The detailed characteristics for each powertrain are listed in Table 3. This table excludes battery characteristics, which are detailed in Table 4.

Table 3 Powertrain specifications

Type of vehicle	ICE gasoline	ICE diesel	MHEV 48V gasoline	HEV gasoline	PHEV gasoline	EV	EV +
ICE engine							
Maximum power	96 kW	88 kW	96 kW	72 kW	72 kW		
Maximum engine speed	6250 rpm	4750 rpm	6250 rpm	5215 rpm	5215 rpm		
Maximum torque	229.2 Nm	285.5 Nm	229.2 Nm	142 Nm	142 Nm		
Piston displacement	1.198 L	1.6 L	1.198 L	1.798 L	1.798 L		
Electric motor							
Maximum power			12 kW	70 kW	70 kW	80 kW	80 kW
Maximum engine speed			7000 rpm	18000 rpm	18000 rpm	8000 rpm	8000 rpm
Maximum torque			57 Nm	163 Nm	163 Nm	260 Nm	260 Nm
Generator							
Maximum power				30 kW	30 kW		
Maximum engine speed				9500 rpm	9500 rpm		
Maximum torque				163 Nm	163 Nm		

The batteries in this study have been modeled based on confidential data from ADEME, the French environmental management agency. They are based on lithium-ion nickel manganese cobalt (LiNMC) technology, and represent a homogeneous mix of two industrial technologies, with a 75 Wh/kg energy density. The battery pack has a 30-kWh energy capacity for the EV and 60 kWh for the EV+. The battery is downsized to 8 kWh for the PHEV, 1.3 kWh for the HEV, and 1 kWh for the MHEV 48V. Details regarding the battery pack are listed in Table 4.

The GHG emissions related to battery production are approximately 127 kg CO_2 eq./kWh of the modeled battery, which is within the range of the data in the literature (Majeau-Bettez et al. 2011, Peters et al. 2017).

Table 4 Batteries' specifications

Type of vehicle	MHEV 48 V gasoline	HEV gasoline	PHEV gasoline	EV	EV+
Energy capacity	1 kWh	1.3 kWh	8 kWh	30 kWh	60 kWh
State of charge operating window	70%	60%	60%	85%	85%

The main differences between the two technologies concern the metal used for the battery pack: metal, or metal alloy. The energy consumed per pack is also very different, e.g., one order of magnitude is equivalent to a factor of ten. At the battery module level, the quantity of plastic for housing the battery module also differs, on an order of magnitude. At the cell level, the macro data are similar in terms of cell weight, nominal power, and capacity, but differ in the energy used per cell. The anodes' materials are similar from one technology to another and only the contributions of the material weights are different; similar weights were ultimately found for both examined anode technologies. For cathodes, the total weight is approximately 15% different from similar raw material components. A comparison to existing data has been made thanks to other studies: Hao et al. (2017), Kim et al. (2016), and the literature review of Mia Romare and Lisbeth Dahllöf (2017).

The wheels and tires for passenger cars have been modeled based on JRC scientific and technical reports (Nemry et al. 2008), for both weights and components. Their lifespan is assumed to be equal to 40,000 kilometers, regardless of vehicle. A passenger car is modeled with four wheels and four tires. As for buses, the wheel and tire weights are based on manufacturer data, but the raw materials composition is the same as that for passenger cars. The lifespan is also considered to be 40,000 kilometers, and the buses are modeled with six wheels and six tires.

For the raw material composition of the glider for passenger vehicles, the data are modeled based on the medium gasoline car assessed in the IMPRO CAR II report (Nemry et al. 2009). Starting from this breakdown, some adjustments are carried out with the help of automotive experts.

The bus composition is modeled using the Ecoinvent v3.1. database, and confidential French manufacturer data. This leads to the following glider composition for the bus, as presented in Table 5.

The energy consumption for passenger vehicle production, in natural gas and electricity, is based on the IMPRO CAR I report (Nemry et al. 2008) for a midsize car. The quantity of energy for the production of buses is based on a related Ecoinvent process (Spielmann et al. 2007).

Table 5 Raw material composition (%) for gliders, passenger vehicles, and buses

Materials	Proxy Ecoinvent process	Composition (%) of the glider (passenger car)	Composition (%) of the glider (bus)
Iron	Cast iron	9.5	9.6
Pig iron	Pig iron		4.7
Steel	Steel, low alloyed Steel, chromium steel 18/8, hot rolled	40.9	0.21 6.43
High-strength steels	Reinforcing steel	9.8	42.32
Copper	Copper	0.9	1.02
Zinc	Zinc	0.2	-
Lead	Lead	0.7	0.8
Aluminum	Aluminum, cast alloy	9.0	15.57
Magnesium	Magnesium	0.2	-
Other metals	Steel, chromium steel 18/8, hot rolled	0.4	-
PP	Polypropylene, granulate	9.0	-
PE	Polyethylene, high density, granulate	2.4	-
PA	Glass fiber reinforced plastic, polyamide, injection molded	0.4	-
ABS	Acrylonitrile-butadiene-styrene copolymer	0.8	-
PUR	Polyurethane, flexible foam	2.3	-

PET	Polyethylene terephthalate, granulate, amorphous	0.1	-
Other plastics	Polypropylene, granulate	2.0	-
Rubber/ Elastomer	Synthetic rubber	2.1	-
Oil	Lubricating oil	0.6	0.7
Refrigerant	Refrigerant R134a	0.05	0.02
Other fluids	Propylene glycol, liquid	2.6	0.2
Glass	Flat glass, uncoated	2.4	4.57
Textile	Polyethylene terephthalate, granulate, amorphous	1.0	
Other	Alkyd paint, white, without water, in 60% solution state	3.0	0.3
Rubber/ Elastomer	Synthetic rubber	-	3.8
Sulfuric acid	Sulfuric acid	-	0.32
Rock wool	Stone wool, packed	-	3.7
Brass	Brass	-	0.03
Pitch	Pitch	-	0.5
PEHD	Polyethylene, high density, granulate	-	5.16

The TTW stage corresponds to the use phase, where the energy carrier is consumed to propel the vehicle. An in-house vehicle simulator based on Simcenter Amesim^{TM} software (Badin et al. 2015, Badin et al. 2013) is used to assess the vehicle's fuel and electricity consumption, during both the WLTP and urban driving cycles, and for passenger cars and buses. Pollutant emissions are recorded according to the Euro6b norms for CO, NOx, PM, and hydrocarbon compounds (HC) for gasoline. The Euro6b HC emissions norms for diesel vehicles were extrapolated based on the Euro6c norm and future Euro7 norm (IFPEN experts) as only the total HC + NOx was provided in the standards. CO_2 correlates with fuel consumption, unlike other pollutant emissions. This leads to the same values of pollutant emissions, regardless of the vehicle's liquid fuel's consumption.

An additional emission coefficient for NOx for diesel passenger cars has been added based on the requirements of several European member states, to thereby properly assess real driving emissions.

In regards to bus pollutant emissions, the Euro6 diesel heavy trucks norm has been followed, considering the bus driving cycle and the use of the crankshaft per kilometer. These simulations result in fuel and electricity consumptions that are linked with pollutant emissions.

From the simulations, it is observed that the batteries of the EVs – 30 kWh and 60 kWh for passenger cars – guarantee a daily home-work trip without the need to charge the battery during the day. For buses, the 170kWh capacity of the battery requires a midday charging.

Two simulation models were used to estimate the hybrid consumptions, depending on the plug-in functionality: sustaining mode (same initial and final battery state of charge) for the HEV and depleting mode for the full-battery PHEV. As we do not assume consumer behaviors for the charging PHEVs, we perform a sensitivity analysis for a PHEV with an empty battery. These are the two extreme profiles for PHEVs, i.e., full battery and empty battery, and are used to cover every possible consumer's behavior.

For the maintenance stage, within the FU of 150,000 km for a passenger car and 480,000 km for a bus, the tires were supposed to be replaced 4 times for cars, and 12 times for buses.

The battery pack is considered to be replaced for both passenger cars and buses according to lifetime assumptions, in different proportions owing to different lifetimes: eight years over ten years for passenger cars resulting in 1.25 battery ; and six years over twelve years for buses, resulting in two batteries.

The end of life stage has been modeled according to the avoided impacts methodology (Allacker et al. 2017), considering the environmental impacts related to upgrade processes and the avoided impacts of recovery materials.

The end of life for a passenger car has been accounted for in accordance with French directives (The European Parliament and the Council 2000), car manufacturers' experiences, and present technologies. This leads to a specific end of life per material after having considered collection, transportation to the upgrading sites, and application rates at each step.

For batteries, a 50/50 hypothesis for end of life treatment is applied for the hydrometallurgical Ecoinvent process and pyrometallurgical Ecoinvent process. A minimal collection rate of 45% has been considered, as specified by the The European Parliament and the Council (2006).

We choose to quantify the potential environmental impacts using the recommended methodology of the European Commission, i.e., the so-called International Reference Life Cycle Data System (ILCD) midpoint 2011 methodology (JRC - European Commission 2012). The chosen impact categories correspond to classification I: "recommended and satisfactory", or II: "recommended but in need of some improvements", as established by the European Commission. Indeed, we believe that classification III: "recommended, but to be applied with caution" is no longer mature enough to draw conclusions. Thus, we only present the following recommended midpoints for the classification I: climate change (**CC**) (IPCC 2007), ozone depletion potential (**ODP**) (World Meteorological Organization 1999), and PM/respiratory inorganics (**PM**) (Rabl and Spadaro 2004). For classification II, we included ionizing radiation, human health oriented (**IR-HH**) (Frischknecht et al. 2000), photochemical ozone formation (**POF**) as applied in ReCiPe (van Zelm et al. 2008), **Ac** (Seppälä et al. 2006, Posch et al. 2008), terrestrial eutrophication (**Eu terr.**) (Seppälä et al. 2006, Posch et al. 2008), aquatic eutrophication (**Eu-aq.**) as implemented in ReCiPe (Mark Goedkoop et al. 2008), and **RD** (mineral and fossil), based on the Centre for Environmental Studies (CML) 2002 methodology (Guinée 2002).

3 Results: life cycle impact assessment

3.1 Overview

The results for passenger midsize cars performing the WLTP cycle are presented in Fig. 2 to Fig. 10, and details concerning the contributions of each stage are available in Table 6. The figures present the results for both the French electricity mix and the European mix, which are only used as energy carriers during the TTW stage.

PHEV gasoline (100% elec.) refers to the depleting mode for the full battery, whereas PHEV gasoline (100% thermic) refers to the mode for the empty battery.

If we consider the overall performances of electrified vehicles as compared to thermic ones, it is not evident, based on the selected environmental indicators, that all electrified vehicles show better performances than thermic vehicles. Indeed, electrified vehicles have advantages regarding CC (Fig. 2) in most powertrain configurations, but for other environmental indicators, the success highly depends on the level of electrification.

Table 6 Total potential environmental impacts for the selected indicators for the transportation of one person over one km for worldwide harmonized light vehicles test procedure (WLTP) cycle for midsize cars, present time, French electricity mix, and European electricity mix as energy carrier

Best case	2nd best case	Worst case

			ICE gasoline	ICE diesel	MHEV 48 V gasoline	HEV gasoline	PHEV gasoline (100% elec.)	PHEV gasoline (100% thermic)	EV	EV+
Climate Change (CC)	kg CO2 eq	FR	1,62E-01	1,40E-01	1,49E-01	1,31E-01	6,13E-02	1,80E-01	8,23E-02	1,17E-01
		EU					1,19E-01		1,49E-01	1,90E-01
Ozone Depletion (OD)	kg CFC-11 eq	FR	5,93E-08	5,62E-08	5,67E-08	5,24E-08	4,95E-08	6,07E-08	5,31E-08	5,89E-08
		EU					4,06E-08		4,29E-08	4,77E-08
Particulate Matter (PM)	kg PM2.5 eq	FR	5,18E-05	4,54E-05	5,32E-05	5,68E-05	5,50E-05	7,73E-05	9,01E-05	1,46E-04
		EU					7,79E-05		1,16E-04	1,75E-04
Ionizing Radiation HH (IR-HH)	kBq U235 eq	FR	2,57E-02	2,41E-02	2,54E-02	2,44E-02	1,33E-01	3,24E-02	1,66E-01	2,00E-01
		EU					8,04E-02		1,05E-01	1,34E-01
Photochemical Ozone Formation (POF)	kg NMVOC eq	FR	3,11E-04	6,43E-04	3,07E-04	3,06E-04	1,92E-04	3,84E-04	2,79E-04	4,26E-04
		EU					3,06E-04		4,10E-04	5,70E-04
Acidification (Ac)	molc H+ eq	FR	4,96E-04	6,98E-04	5,11E-04	5,37E-04	5,62E-04	8,00E-04	1,08E-03	1,86E-03
		EU					8,74E-04		1,44E-03	2,25E-03
Terrestrial Eutrophication (Eu-terr.)	molc N eq	FR	7,82E-04	2,34E-03	7,81E-04	8,08E-04	5,71E-04	9,86E-04	7,55E-04	1,08E-03
		EU					9,71E-04		1,22E-03	1,59E-03
Freshwater Eutrophication (Eu-aq.)	kg P eq	FR	1,44E-05	1,35E-05	2,16E-05	3,81E-05	5,75E-05	5,77E-05	1,12E-04	1,96E-04
		EU					1,27E-04		1,92E-04	2,83E-04
Mineral, fossil & ren resource depletion (RD)	kg Sb eq	FR	1,66E-05	1,68E-05	1,83E-05	1,94E-05	2,66E-05	2,63E-05	4,24E-05	7,27E-05
		EU					2,61E-05		4,19E-05	7,21E-05

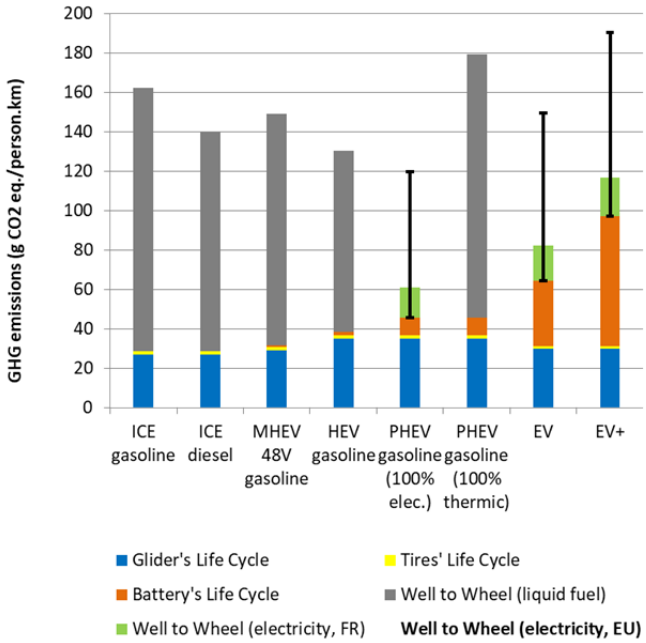

Fig. 2 Potential impacts on Climate Change of one person transportation over one km for worldwide harmonised light vehicles test procedure (WLTP) cycle for midsize cars, present time, French and European electricity mixes

A focus on the electrified vehicles using electricity highlights that the PHEV, using 100% electricity as the energy carrier, has lower impacts than EVs for global warming potential, as well as for OD (Fig. 3), PM (Fig. 4), IR-HH (Fig. 5), Ac (Fig. 7), Eu-aq (Fig. 9), and RD (Fig. 10). The PHEV using 100% of liquid fossil fuel as the energy carrier appears to have the same profile as a gasoline ICE for the WTW stage and a PHEV profile for the vehicle life cycle. In that regard, this leads to a somewhat nonsensical use of this powertrain and raises questions regarding consumer behavior.

For some indicators, thermic vehicles perform better than or equivalent to electrified ones, as is the case for the impacts on IR HH (Fig. 5), Ac (Fig. 7), Eu-aq (Fig. 9), or RD (Fig. 10).

It is important to note that environmental performances are not always linked to the level of electrification, as might have been expected. Indeed, the results show that it is not evident that the more the vehicles are electrified, the more environmentally-friendly they are.

3.2 Passenger cars performing a worldwide harmonised light vehicles test procedure (WLTP) driving cycle, French electricity charging mix

The results for CC (Fig. 2) vary among the different powertrains using electricity as the energy carrier, with lower impacts than those using liquid fossil fuels. This is mostly owing to the very low carbon content of French electricity production. The gliders have quite similar impacts between the different vehicles studied regarding the CC indicator, except for the HEV and PHEV, which have higher contributions owing to the two internal motors (thermic and electric). The production stage for both glider and battery accounts for between 65% and 79% of the global impact. Regarding the WTW stage, its contribution is more significant for thermic vehicles and low-electrified vehicles, e.g., MHEV and HEV, accounting for between 67% and 86% of the total impact.

For ODP (Fig. 3), PHEV (100% elec.) seems to be the best candidate, whereas EV+ vehicles have quite the same impacts as ICE gasoline vehicles. The vehicles' production stages contribute significantly to the ODP indicator, mostly owing to refrigerant fluids. For thermic vehicles, the WTT stage impacts are non-negligible, because of oil drilling. In regards to electrified vehicles, the French electricity mix also has a contribution to this indicator related to uranium production, which is a major component of nuclear electricity production. Regarding the total impacts for the ODP indicator, the results are not so different from one powertrain to another, with a slight advantage for electrified powertrains.

The PM emissions indicator (Fig. 4) reports the negative effects on human health caused by primary particulate emissions and their precursors, but also gas-allowing particulate formations, i.e., so-called secondary particulates. It appears that battery life cycles contribute to this impact and that nickel is responsible for 25% of the impacts on the battery life cycle. The circuit boards contribute to approximately 13% of the impact. The emissions are related to metallurgy and nickel refining (which emits sulfur dioxide), accounting for this indicator. However these emissions are not occurring on-site, in regards to the vehicles' use.

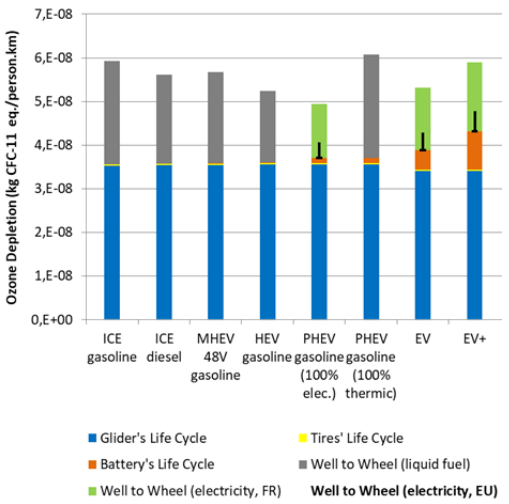

Fig. 3 Potential impacts on **ozone depletion potential** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

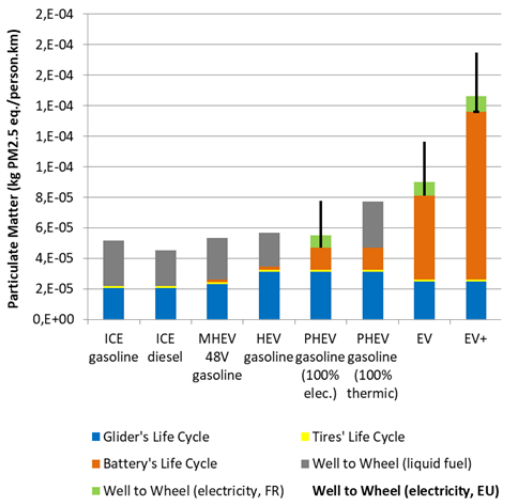

Fig. 4 Potential impacts on **particulate matter** emissions of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

Regarding IR-HH (Fig. 5), it is highly understandable that vehicles propelled by electricity vectors have higher impacts related to electricity consumption. Indeed, the IR indicator assesses the emissions of ionizing substances, which for French electricity are contributed through its production, which is mostly based on nuclear energy (and thus on uranium). The treatment of the residues produced by uranium ore treatment is the main contributor to the impacts. The locations of uranium mines are concentrated in the USA, Australia, Canada, Namibia, and Nigeria. Emissions linked to uranium are thus concentrated in these areas, leading to the question of global and local impacts, as was the case for the POF indicator. Indeed, environmental indicators as IR, PM formation, Ac, Eu-terr. and Eu-aq., or RD indicators can be analyzed as local indicators, as contrasted with global warming potential or ozone depletion indicators, which are global.

The results for POF (Fig. 6) vary significantly according to the various powertrains. The PHEV (100% elec.) performs much better than all other powertrains, but the EV also has lower impacts than all thermic powertrains. Indeed, liquid fossil fuels contain high quantities of volatile organic compounds, whose combustion generates NOx. ICE diesel is the worst candidate for this indicator, mostly owing to the TTW stage, which for diesel engines, emits NOx in higher quantities than for gasoline engines. This is related to the RDE coefficient applied to the diesel engine, which will be removed for future diesel engines. Notably, battery life cycle has an important contribution to this indicator: a significant proportion of the total impact of the EV+ for POF is generated by the battery life cycle. It appears that the metals used for battery production, such as lithium, nickel, cobalt, and copper, contribute to approximately 45% of the batteries' impact.

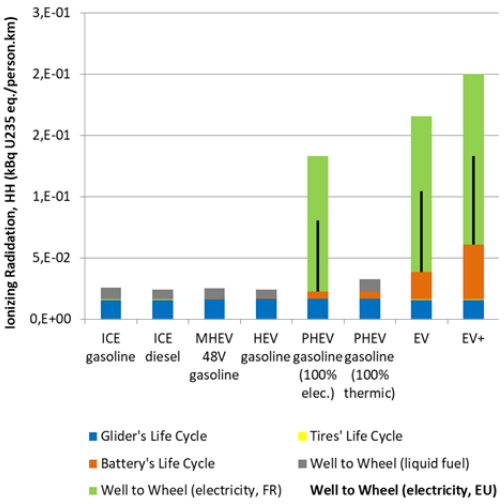

Fig. 5 Potential impacts on **human health** caused by **ionizing radiation,** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

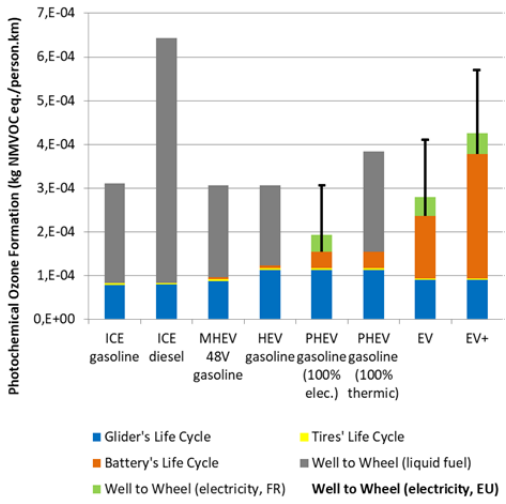

Fig. 6 Potential impacts on **photochemical ozone formation** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

Batteries contribute significantly to the Ac potential indicator (Fig. 7), leading to significant impacts for the EV and EV+ that are linked to the battery size. Nickel is mostly responsible for the Ac impacts, i.e., 55% of the battery life cycle, followed by copper (15%) and lithium (6%). These are chemical products used to extract metals from ore, thereby emitting sulfur dioxide into the air. The same trend is observed for the Eu-aq. potential through old sulfur compound treatments. The RD indicator follows the same ranking, with significant impacts for vehicle and battery life cycles. For the vehicle life cycle, it is mainly zinc, lead, aluminum, and the electric motor when present, that contribute to the impacts. Regarding the battery life cycle, the circuit board has major contribution to the impacts, and more precisely, the tantalum contained in the capacitor.

Regarding Eu-terr. (Fig. 8), the PHEV (100% elec.) and EV have lower impacts than the other powertrains. ICE diesel has the highest impacts by far in comparison to the other vehicles. The PHEV (100% thermic) and EV+ contribute more to Eu-terr. than ICE gasoline or low-hybrid powertrains.

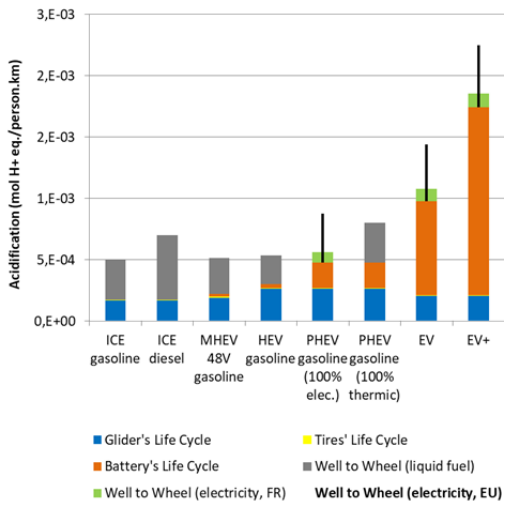

Fig. 7 Potential impacts on **acidification.** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

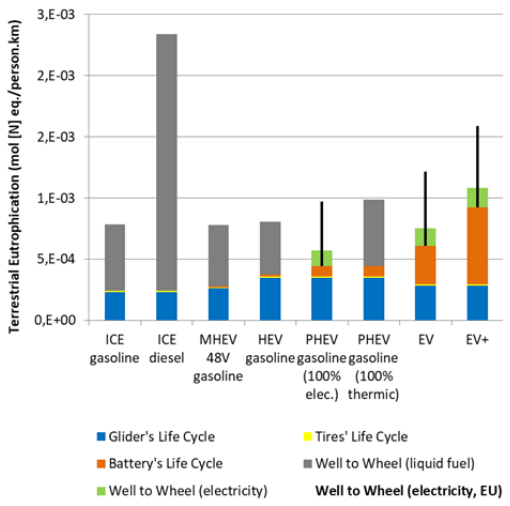

Fig. 8 Potential impacts on **terrestrial eutrophication.** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

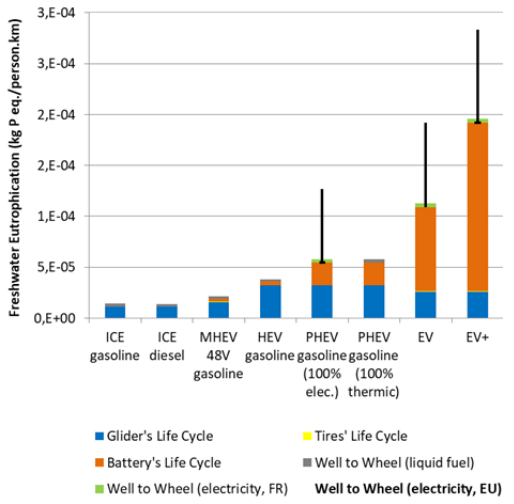

Fig. 9 Potential impacts on **aquatic eutrophication.** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

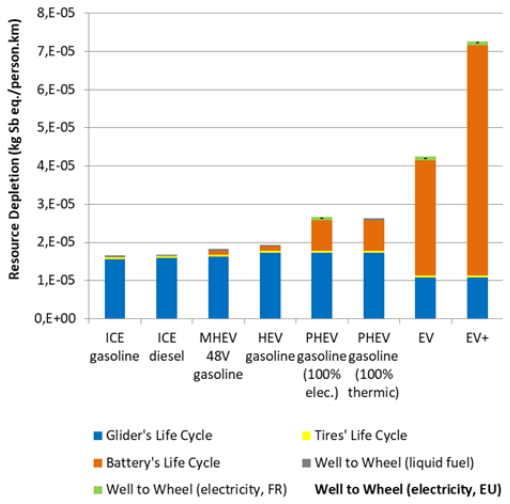

Fig. 10 Potential impacts on **resource depletion** (mineral, fossil, and renewables) of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

3.3 Passenger cars performing a WLTP driving cycle, European electricity charging mix

A cautionary point regarding the electricity mix should be raised. Indeed, France is a particular case, given its electricity mix composition. Nuclear energy is the major component of the French electricity mix and in its generation. This leads to very low GHG emissions for the electricity sector in France. However, the European mix is much more carbonated, and the question regarding the inversion of trends related to electrification is relevant. In particular, depending on the electricity production means, i.e., nuclear, coal, renewables, and others, the environmental impacts generated by this energy vector could be equal to or higher than those generated by more commonly-used energy pathways for vehicles, i.e., fossil liquid fuels. The following part presents a sensitivity analysis with European electricity mix, which increases the impacts of EVs on average by 30% and those of EV+ by 20%. Notably, for the CC (Fig. 2) and POF (Fig. 6) indicators, the European electricity mix reverses the previous trends with the French mix. The potential impacts on ODP (Fig. 3) are the only indicator

for which the European mix decreases the impacts. The use of the European mix instead of the French mix has no effects on the RD indicator (Fig. 10). In that regard, the interest in EVs depends significantly on the electricity supply mix.

3.4 Passenger cars and buses performing an urban driving cycle, French electricity charging mix

As we studied passenger transportation via passenger cars, we also consider passenger transportation via buses. The detailed results are available in Table 7, and in Fig. 11 to Fig. 19.

To facilitate a comparison of passenger cars and buses, we analyzed an urban driving cycle. Indeed, the perimeter of the study is France, and bus network is mainly located in the urban area. Thus, we analyze the ARTEMIS urban driving cycle (André 2004) for passenger cars, and a ADEME-Autonomous Parisian Transportation Administration (RATP) cycle representative of an urban Parisian driving cycle for buses (Coroller, P. and Plassat, G. 2003).

Given the high mileage traveled by the buses (40,000 km per year over 12 years), the glider's life cycle contribution to the total impacts is proportionally lower than that for cars. This is also true for the battery's life cycle (Fig. 11). WTW emissions are thus preponderant, and this again increases the differences between the buses' powertrains. In comparison with cars, this leads to lower impacts for equivalent powertrains. The buses' hybridization represents a gain in comparison to ICE bus for the indicators for which the use stage is preponderant: not Eu-aq., nor RD.

Depending on the indicator, a bus is not always the most appropriate solution. Indeed, it appears that for the CC indicator (Fig. 11), it is worth taking a PHEV car, rather than an ICE bus. However, it is always better to take an electric bus than a passenger car.

If we compare the three studied buses, the electric bus performs better for the CC (Fig. 11), ODP (Fig. 12), POF (Fig. 15), and Eu-terr. (Fig. 17) indicators.

The results for PM emissions (Fig. 13) and Ac (Fig. 16) are quite similar throughout the three buses' powertrains.

Electric buses are worse for IR-HH (Fig. 14), Eu-aq. (Fig. 18), and RD (Fig. 19).

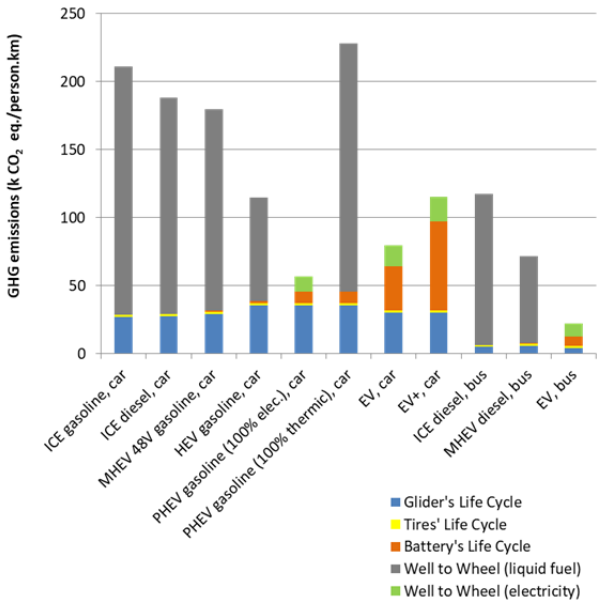

Fig. 11 Potential impacts on **climate change** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

Table 7 Total potential environmental impacts for the selected indicators for the transportation of one person over one km for urban cycles for midsize cars and bus, present time, French electricity mix

Best case	2nd best case	Worst case

		Passenger car								Bus		
		ICE gasoline	ICE diesel	MHEV 48 V gasoline	HEV gasoline	PHEV gasoline (100% elec.)	PHEV gasoline (100% thermic)	EV	EV+	ICE diesel	Hybrid	Electric
Climate Change (CC)	kg CO_2 eq	2,11E-01	1,88E-01	1,79E-01	1,14E-01	5,64E-02	2,28E-01	7,96E-02	1,15E-01	1,18E-01	7,18E-02	2,19E-02
Ozone Depletion (OD)	kg CFC-11 eq	6,78E-08	6,51E-08	6,20E-08	4,95E-08	4,56E-08	6,93E-08	5,09E-08	5,73E-08	2,38E-08	1,51E-08	1,17E-08
Particulate Matter (PM)	kg PM2.5 eq	6,13E-05	5,27E-05	5,90E-05	5,36E-05	5,25E-05	8,67E-05	8,87E-05	1,45E-04	2,34E-05	1,75E-05	2,08E-05
Ionizing Radiation HH (IR-HH)	kBq U235 eq	2,92E-02	2,76E-02	2,76E-02	2,32E-02	9,87E-02	3,60E-02	1,46E-01	1,86E-01	1,05E-02	7,31E-03	7,41E-02
Photochemical Ozone Formation (POF)	kg NMVOC eq	3,65E-04	6,92E-04	3,40E-04	2,88E-04	1,81E-04	4,38E-04	2,73E-04	4,21E-04	1,82E-04	1,26E-04	6,84E-05
Acidification (Ac)	molc H+ eq	6,02E-04	7,88E-04	5,76E-04	5,02E-04	5,34E-04	9,05E-04	1,06E-03	1,84E-03	2,76E-04	2,02E-04	2,47E-04
Terrestrial Eutrophication (Eu-terr.)	molc N eq	9,07E-04	2,45E-03	8,58E-04	7,67E-04	5,32E-04	1,11E-03	7,33E-04	1,07E-03	5,00E-04	3,55E-04	1,89E-04
Freshwater Eutrophication (Eu-aq.)	kg P eq	1,56E-05	1,44E-05	2,23E-05	3,77E-05	5,66E-05	5,89E-05	1,12E-04	1,95E-04	4,32E-06	6,96E-06	2,20E-05
Mineral, fossil & ren resource depletion (RD)	kg Sb eq	1,68E-05	1,69E-05	1,84E-05	1,93E-05	2,63E-05	2,65E-05	4,23E-05	7,26E-05	5,71E-06	6,09E-06	1,04E-05

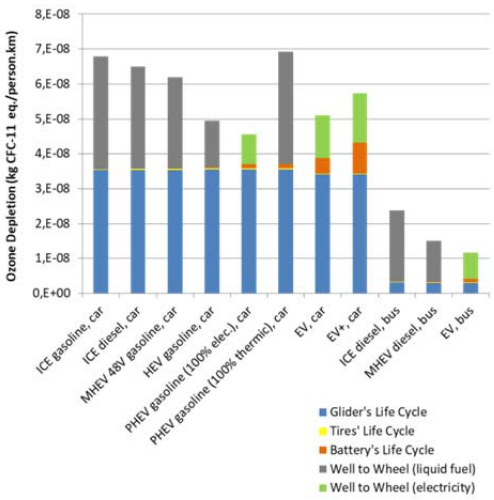

Fig. 12 Potential impacts on **ozone depletion potential** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

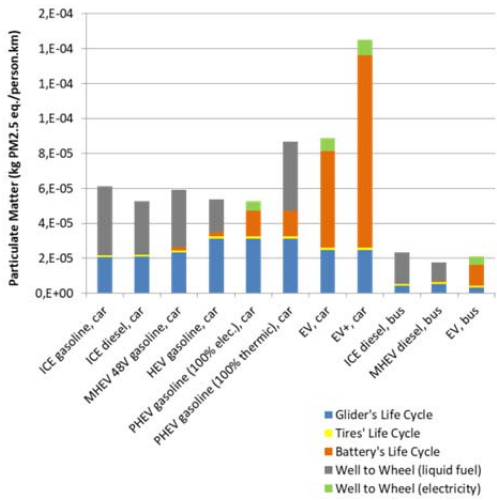

Fig. 13 Potential impacts on **particulate matter** emissions of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

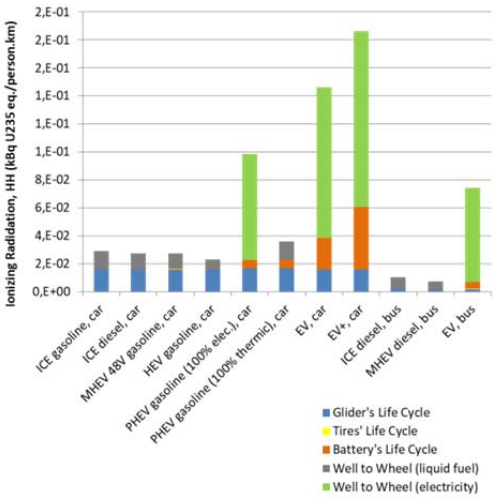

Fig. 14 Potential impacts on **human health** caused by **ionizing radiation** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

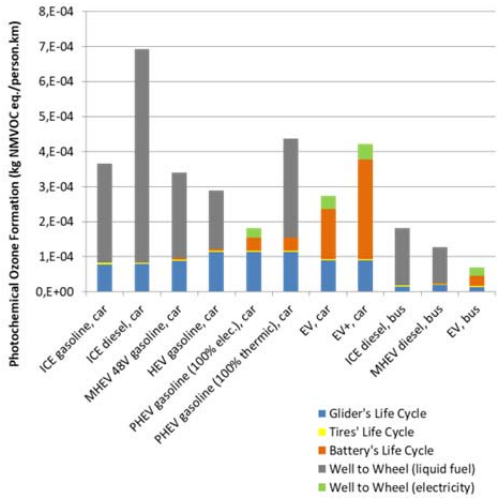

Fig. 15 Potential impacts on **photochemical ozone formation** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

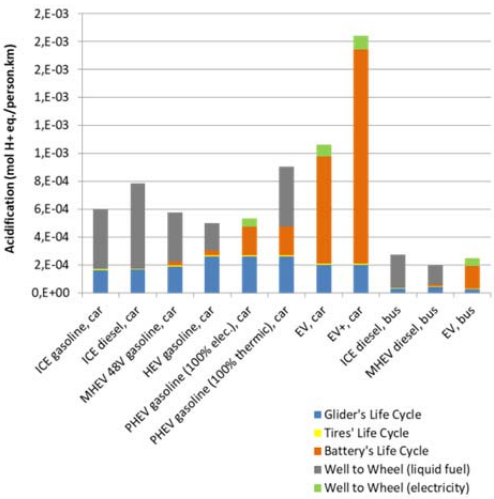

Fig. 16 Potential impacts on **acidification** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

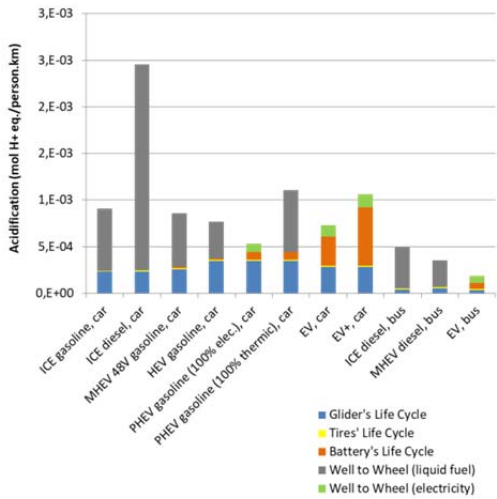

Fig. 17 Potential impacts on **terrestrial eutrophication** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

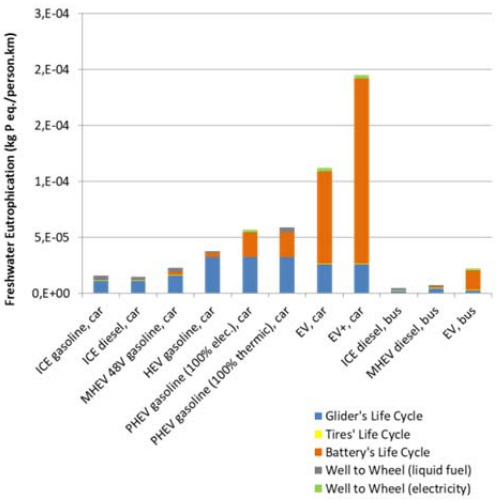

Fig. 18 Potential impacts on **aquatic eutrophication** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

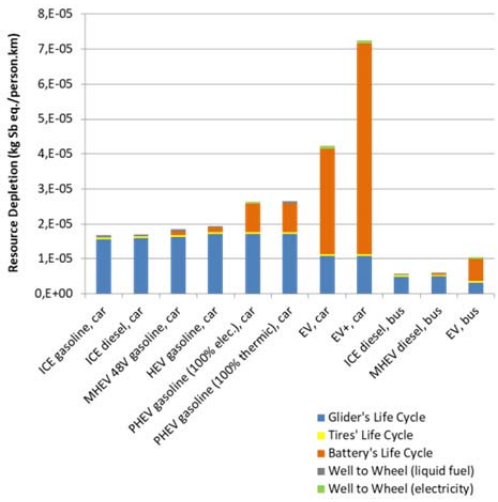

Fig. 19 Potential impacts on **resource depletion** (mineral, fossil, and renewables) of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

4 Discussion

In the context of growing electrification, this paper presents an objective overview, based on LCA methodology, (ISO 2006a, 2006b) for seven current vehicles and three buses. As shown in the previous sections, the determination of the best environmental solution for the personal transportation sector is not trivial. Indeed, our results show that the answer can differ according to several parameters such as powertrains, driving conditions, occupation rate, considered midpoints, and location.

GHG emissions are often spotlighted for electrified vehicles - PHEV, EV – and the advantages of these powertrains are clearly demonstrated based on this indicator, in a French context. However, our study highlights that other important environmental indicators such as PM emission, Ac, Eu-Ac, and RD could be lower for non-electrified vehicles. As noted throughout the paper, the indicators depend on the above-quoted parameters: powertrains, driving conditions, and location, but also on methodological aspects in the context of global and local indicators and consumer behavior. Thus, among powertrains, the results can depend significantly on the consumers. For example, if a PHEV is used with an empty battery, it is entirely uncompetitive in terms of environmental impacts. Indeed, a PHEV would have impacts from an electrified powertrain with an equivalent of a conventional gasoline vehicle consumption. This was the case in Netherlands, where financial incentives for PHEVs were highly significant, until Dutch authorities measured the real emissions of the Dutch PHEV fleet. The clear conclusion was that in many cases, the thermic use led to significantly higher emissions than officially announced, leading to the removal of tax rebates (TNO 2016). This raises concerns regarding the smart use of PHEVs and social behavior.

Driving conditions are also identified as a key parameter throughout our results. Indeed, electrified vehicles - PHEV, EV, and EV+ - are less sensitive to traffic than thermic vehicles - ICE, MEHV, and HEV - which are less competitive in urban conditions, except for HEV. Indeed, the gaps between electrified and ICE powertrains are higher in urban conditions. Thus, it is tempting to enhance the use of electrified vehicles for urban or congested areas, and it may be wise to adapt cars offered to the consumer and their use. It is also important to notice that the pollutant emissions during vehicle's operation are based on EURO norms calculated from the WLTP cycle. These emissions might be underestimated for some pollutants in urban traffic conditions and could be compared

with other models such as those developed by COPERT (European Environment Agency) or the Handbook of Emission Factors for Road Transport (INFRAS 2019).

The location context is also highly important, as it strongly affects the environmental performances of electrified vehicles. Our research shows that depending on a French location or European location, the conclusions regarding electrification deployment could differ. This raises a cautionary point regarding massive and general electrification deployment, as the electricity charging mix represents an important parameter to consider.

With regards to methodological aspects, the environmental performances per powertrain can vary from one midpoint to another and the conclusions as well. For example, the rankings of the studied powertrains are not comparable for global warming potential and PM emissions. This raises two questions: the first regards endpoints and the second regards weighting in general. Even if midpoint indicators have less uncertainties than those at the endpoint level, midpoints analysis could be difficult and could lead to divergent conclusions which would not be helpful for policy makers and/or consumers (Bare et al. 2000).

The second question concerns the midpoint indicators, and the non-differentiation between global and local indicators. This is a very important matter, as we saw that results can highly differ from one indicator to another and can lead to inverse trends per environmental indicator. Thus, this question also depends on the problem raised and the pursued goal of the LCA. If the goal of electrification is to mitigate the effects of the transport on human health, it would be wise to either regionalize impacts, or at least to differentiate the impacts occurring on the use site with others. This allowed us to see the electrification potential, even for the PM indicator, and if the emissions occur in a context where there is no human exposure. Indeed, the only emissions occurring on the use site are the TTW emissions and thus, the French electricity mix generates very little PM during the combustion stage. PM formation occurring during the battery life cycle stage would not have an impact on the use site. However, batteries' life cycles will still have impacts on PM formation, but mostly in regards to the metallurgical factory. This leads to questions regarding the selected indicators, and in a wider way, to the definition of the LCA indicator. Indeed, the midpoint indicator for PM formation is defined to assess impacts on human health. However, and especially for PM formation, the exposure context and the population exposed are crucial (Humbert et al. 2011). It could then be discussed whether to focus on this indicator within a given geographical context.

Electric buses seem to be a very good alternative for urban travels, whereas ICE buses are not always competitive (compared to a PHEV car, for example). However, the direct comparison between buses and passenger cars shall be taken carefully as buses are a common travel solution and do not optimize the travelling of one passenger where a passenger car would. Thus buses' impacts could be considered lower if all the transported persons were traveling the same route. Furthermore, this study does not consider the improvements in human well-being from the decreased traffic when using public transport rather than passenger vehicles. Indeed, beyond the fact that having an occupation rate below two for individual cars for commuting, and thus having environmental issues as described in this article seems very counterintuitive, the car ownership itself also raises questions. Besides its cost from the consumer side (Paulley et al. 2006), it generates also noise, visual pollution, accident risks, and many other drawbacks. It seems also that e-mobility concepts as car sharing, between individuals or throughout industrial initiatives, tends to increase (Bardhi and Eckhardt 2012) and could represent a trend to the car ownership's decrease. Thus, car sharing may be a solution to increase car's

occupancy which might lower the associated burdens of travelling by passenger cars. Public policy could then consider ways to encourage this mode and allow the achievement of ambitious sustainable goals.

Although not studied in this work, it seems that electric buses, owing to battery weight, might not be able to contain as many people as thermic buses. However, and as a first approach, we believe that it is important to compare the several alternatives without intentionally adding too many different parameters, so as to be able to identify the improvement possibilities. Thus, biofuels were not integrated into the fossil fuels in this study, whereas current fuels delivered at the pump contain a proportion of biofuel. These refinements will be studied in an ongoing future work.

Concerning the RD indicator, which is a very important issue when dealing with a battery, we believe that other indicators assessing this depletion could be helpful for addressing it. Indeed, we are convinced that the question of raw material criticality should be put in perspective for a large-scale deployment, in regards to both mass and geographic level. The resources issue should not be treated based only on an environmental perspective, but should be fully assessed based on economic, industrial, and geopolitical data, as addressed in Hache et al. (2019). The issue of mineral resource location, the increasing dependency of the states, and the actor strategies (states or companies) should be studied for the energy transition dynamic (World Bank Group 2017, OECD 2019, Bonnet et al. 2018, IRENA 2019). All of these factors are generally analyzed under a notion of criticality that covers geopolitical risks (concentration of resources and or production, embargo, etc.) and economic risks (market power, investment decisions, lack of financial contracts to hedge price volatility, under-investment, etc.). The consideration of environmental or social aspects (emissions of pollutants during the production or trade process, health consequences, landscape externalities, water needs etc.) has only recently been added to the notion of criticality (Graedel et al. 2015). In addition to this, the notion of criticality is neither universal, timeless, nor binary (Bonnet et al. 2018). Indeed, it actually varies according to the geographical scale being considered (lithium does not appear in the European Commission's list of critical materials, but is viewed as critical in the United States), the time scale (chromium, magnesite, and phosphate rock were critical in the European Commission list in 2014, but not in 2017), and the consumer unit considered (country, sector, company, or technology). Ultimately, it depends on the economic (commercial, financial), political (foreign policy, national security), and industrial interests of a state. The need to consider all the criticality dimensions for each of the strategic materials as essential for the energy transition requires the development of specific quantification tools and appears to be fundamental for researchers, manufacturers, and policy-makers.

5 Conclusion

Using LCA methodology, we assess the different environmental performances of seven types of passenger cars: ICE gasoline, ICE diesel, MHEV 48V gasoline, HEV gasoline, PHEV gasoline, EV, and EV+. These vehicles were studied on a WLTP cycle, with two simulations for PHEV (empty battery and full battery). The first interest of our LCA approach is to demonstrate that among all of these powertrain configurations, the EV and PHEV, with a fully-charged battery, are competitive for several indicators in a French context of use: global warming potential, ODP, POF, and Eu-terr. The best results are obtained for PHEV, for which the battery is smaller.

The driving conditions interact directly with our results, as we observe that the same passenger vehicles have different impacts according to the WLTP cycle or urban driving cycle. Indeed, vehicles using electricity as the energy carrier emit less during urban driving cycles than those propelled with liquid fossil fuels.

A sensitivity analysis for the electricity charging mix for vehicles using electricity as the energetic vector showed a strong influence on this parameter. Indeed, it seems very important to perform specific assessments for a given country or a given mix compositions, as we saw that they significantly influence the results. In France, the electricity mix is very low carbonated and EVs' use has all legitimacy. However attention should be paid to the capacity to deliver low carbon electricity and if the actual production could answer a future increasing energy demand. Another specific attention concerns when the EV's charging occurs considering that electricity mix varies across the day and the season.

This article also puts buses in perspective as compared to urban driving cycle for passenger cars, as it appears to suggest a possible evolution of the mobility sector in a more sustainable way. Electric buses seem to be the best solution for passenger transportation. However, this result does not consider the charging points' development, the potential increase of the fleet to be able to answer the needs during the charging times and all logistical issues related to such a deployment.

The present study confirms the strong dependence of electro-mobility deployment on the battery market and technologies. The results for EV+ have significant impacts owing to battery size, even for the previously-quoted indicators where EVs are competitive. In contrast, a PHEV used as an ICE vehicle has no benefit from an environmental perspective for those indicators and is worse than its thermic counterpart. This highlights the problematic issues of consumer behavior for a PHEV given this charging aspect, and the need to integrate social sciences when launching public policy to promote new technologies.

This study highlights the value of the multi-criteria evaluation provided by the LCA method in enriching the debate on the future of vehicle engines, by studying the complete life cycle for both vehicle and fuel use with simulated consumptions for all of the existing powertrains. A reduction in the impacts on CC through the use of plug-in-hybrid vehicles with lighter batteries than EVs, even if well-managed, has impacts on PM formation, IR, eutrophication, non-renewable RD, etc. All these environmental criteria constitute many possible subjects for further study in our research. Vehicle electrification will not be the only solution to the decarbonization of light vehicle transport. Other energy pathways should be considered.

The deployment of new mobility forms (urban car-sharing or self-service transport), intermodal approaches, and new services (dynamic travel information, etc.) should constitute a turning point in the future and should greatly impact the vehicle technologies used. Analyzing this complete reshaping of the mobility and the uncertainties regarding the adoption of these new mobility forms should constitute the next step of our research. By linking an LCA approach and a dynamic fleet model including a heterogeneous consumer base, we can thus contribute to improving our understanding of possible mobility futures, by considering environmental externalities in a forward-looking perspective.

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