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

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9
10 **Abstract**

11 *Purpose*

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

18 *Methods*

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

26 *Results and discussion*

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

35 *Conclusions*

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

41 **Keywords**

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

44 **1 Introduction**

45 In the challenging context of CO₂ emissions reduction targets coupled with more stringent vehicle driving test
46 cycles (ICCT 2014), the transportation sector is currently facing major issues in complying with upcoming
47 public policies. Electrification of the transportation sector generally appears to be a necessary evolution for
48 reaching the CO₂ targets planned during the 2015 United Nations Climate Change Conference (COP21) on the
49 Paris agreements. Indeed, in 2015, the transportation sector represented almost a quarter of Europe's greenhouse
50 gas (GHG) emissions (European Commission 2017) and road transportation is responsible for over 72% of these
51 emissions (European Environment Agency 2019). Passenger cars are responsible for approximately 12% of the
52 total European Union (EU) emissions of carbon dioxide (TNO 2016). In the new environmental context, the
53 transportation standards related to CO₂ emissions have been steadily increased, leading to a first step of setting
54 the European CO₂ emissions average fleet target to 130 grams of CO₂ per kilometer in 2015 (The European
55 Parliament and the Council 2009). At that time, it represented a reduction of approximately 18% from the 2007
56 fleet average of 158.7 grams of CO₂ per kilometer. By 2021, the reduction target for all new passenger cars will
57 be set at approximately 95 grams of CO₂ per kilometer (The European Parliament and the Council 2014). This
58 threshold will drop to 81 g/km (New European Driving Cycle (NEDC) reference (The Council of the European
59 Communities 1970)) in 2025, and finally, to 66 g/km in 2030. These increasingly strict thresholds will oblige
60 manufacturers to include more innovations in their vehicles and engines. In consideration of the increase in
61 population (United Nations 2017) and corresponding rise in mobility needs in terms of both traffic and vehicle
62 sizes (Scholl et al. 1996, WBCSD 2001), the passenger transport requirements, expressed in passenger-kilometer
63 (pkm), are constantly increasing (European Commission 2017). Thus, transportation is one sector in the EU
64 where GHG emissions requirements continue rising (Meyer et al. 2012), despite the deep technological
65 improvements and resultant fuel efficiency experienced in internal combustion engines (ICE) in recent years.
66 Meeting the EU targets will require a widespread deployment of low-carbon technologies that cannot be
67 achieved without considering vehicles' electrification options, such as battery electric vehicles (EVs) or plug-in-
68 hybrid vehicles (PHEVs).

69 As argued in Bauer et al. (2015), a massive development of transportation electrification could displace the
70 environmental impacts from GHG emissions to other environmental burdens, such as particulate matter (PM)
71 formation, acidification (Ac), or resource depletion (RD). Furthermore, passenger car electrification is often
72 considered as a zero CO₂ emission technology with regard to a tank-to-wheel (TTW) assessment, as defined by
73 the "activities and energy use and emissions associated with vehicle operation" (Brinkman et al. 2005).
74 However, these system boundaries exclude the "energy use and emissions associated with fuel production"
75 (Brinkman et al. 2005), defined as well-to-tank (WTT), as well as the vehicle's life cycle. Considering only the
76 TTW stage or even the complete fuel's life cycle (WTT and TTW, commonly named well-to-wheel (WTW)),
77 would lead to the potential transfer of impacts from life cycle stages to other areas. For example, any decrease in
78 CO₂ emissions during the usage stage would not avoid the consumption of resources required for battery
79 production. Therefore, only life cycle assessment (LCA) as defined by its inner definition (ISO 2006a, 2006b)
80 can address the entire system: WTT, TTW, and the vehicle's life cycle. LCA is also a multicriteria
81 environmental type of analysis that enables researchers to answer questions related to potential environmental
82 impacts that differ from the effects of global warming alone.

83 The evaluation of the environmental impacts induced by the electrification of the transportation sector is
84 becoming an urgent matter, as states, through public policies, are willing to increase the deployment of EV
85 technologies. Several incentives are being put in place at the consumer and state levels. For example, in France,
86 a subvention program (ecological bonus-malus¹) has been implemented since 2007 to promote the purchase of
87 electric cars. A conversion bonus has been also applied since 2015 for the scrapping of ICE vehicles registered
88 before January 1, 2006 with diesel engine, and January 1, 1997 for others (Ministry for Ecological and Solidarity
89 Transition 2009, 2017). The rationale of this policy is that electric powertrains do not produce any tailpipe
90 emissions (Sadek 2012) and thus are seen as drastically reducing GHG emissions (Nemry and Brons 2010).
91 However, in addition to several practical questions such as those regarding the deployment of charging stations
92 (and their costs), or the management of peak hours for supplying electricity², other environmental issues are
93 neglected. The first is the displacement of CO₂ emissions from TTW to WTT for EVs via energy production;
94 another is the increase of the contribution of the vehicle's production stage to the global life cycle (Tran et al.
95 2012). This leads to the main conclusion, i.e., that the impacts of the electrification of the transportation sector
96 have to be evaluated over the entire life cycle for both the energy carrier (WTT and TTW) and the vehicle. Yet
97 another issue is the displacement of the environmental impacts from the environmental LCA categories to other
98 entitles (Chan 2007). Indeed, while LCA applied to conventional vehicles mainly reveals the impacts regarding
99 global warming potential (GWP), Lombardi et al. (2017) showed that EVs give rise to increased human toxicity
100 and terrestrial acidification. As a consequence, a GWP indicator alone is insufficient for comparing different
101 types of vehicles (Nordelöf et al. 2014).

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

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

115 To assess the advantages and drawbacks of the electrification of the road passenger transportation sector, we
116 relied on the LCA methodology to provide robust and relevant environmental results. Following the European
117 recommendations (JRC - European Commission 2012), environmental impacts in categories other than GHG
118 emissions are considered. France is the study area, and French directives were followed. In the case that French
119 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 CO₂ eq./km. The amount of the aid is capped at 6,000 euros.

² This issue will not be studied in this article.

120 charging mix was performed, as electrification performances are geographically dependent (Lombardi et al.
 121 2017). The temporal horizon was the present time, and we focused on one class of vehicles: the C-segment,
 122 defined in Europe as midsize or medium cars (Commission of the European communities 1999), and equivalent
 123 to compact cars for the USA and UK. In addition, midsize cars are compared to buses, as buses must fulfill the
 124 same FU criteria for passenger transportation. Various levels of electrification options have been used for
 125 powertrains, based on the new homologated worldwide harmonized light vehicles test procedure (WLTP) for
 126 midsize cars (ICCT 2014). As a complement to the WLTP cycle, an "ARTEMIS" urban driving cycle (André
 127 2004) is assessed to compare passenger vehicles and buses.

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

130

131 **2. Material and method**

132 **2.1 Goal, scope, and products systems**

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

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

144

145 **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+)
<i>Powertrain</i>	<i>Fuel vector</i>							
Thermic	Gasoline	x		x	x	x		
	Diesel		x					
Electric	Electricity					x	x	x

146

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

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

157 The vehicles' specifications are based on the available manufacturers' data and French Institute of Petroleum
158 (IFPEN) research and development³ (R&D). This leads to the following breakdown for the vehicle's weight:
159 vehicle glider⁴ with options and gearbox, thermic engine, electric motor and electric generator, and battery. The
160 raw material components' splits of the vehicle's glider are based on the environmental improvement of products
161 (IMPRO) Car II report of the JRC scientific and technical reports (Nemry et al. 2009), in a percentage
162 corresponding to the medium gasoline car for the seven assessed cars. The buses' raw material components are
163 based on manufacturer data and IFPEN R&D. The materials choices and their operation are based on the
164 Ecoinvent process "glider, passenger car" for private cars and "bus, production RER (Europe)" for buses
165 (Spielmann et al. 2007). Extrapolations and assumptions have been made, according to experts. These are
166 described in Table 5.

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

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

179 We also followed European directives regarding outdated vehicles and batteries (The European Parliament and
180 the Council 2000). The end of life scenario for vehicles is thus modeled through a realistic recycling scenario for
181 out-of-date vehicles in France today, allowing us to reach the goals of the regulatory rates provided by the
182 European directives (The European Parliament and the Council 2005, 2006). This leads to rates per material,
183 which are divided into categories including recycling, energy recovery, and landfilling (Table 2). Further end of
184 life data have been added within the French context regarding average collection distances between sorting
185 centers and materials recovery infrastructures, but also in the context of energy consumption for material
186 recycling (ADEME 2018, 2008). A 2010 French collection rate for obsolete vehicles (69%) was also used, and
187 the distances from owner to wrecker and from wrecker to grinder (300 km in total) were considered within the
188 national context. French waste statistics have been modeled mostly for incineration (53 %) and landfilling (47
189 %) data when missing (Ministry for Ecological and Solidarity Transition 2014).

190

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.

191 **Table 2** Raw materials' end of life's scenario

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

192

193 Regarding energy carriers, the fossil fuels are modeled from Ecoinvent data (Frischknecht et al. 2005): the
 194 “Petrol, low-sulfur {Europe without Switzerland}| market for | Alloc Rec, U” and “Diesel, low-sulfur {Europe
 195 without Switzerland}| market for | Alloc Rec, U”. In the same way, the electricity mix is the French average mix
 196 from the Ecoinvent database “Electricity, medium voltage {FR}| market for | Alloc Rec, U”. This results in
 197 approximately 113 g CO₂ eq./kWh for the French electricity mix at the grid. However, France has a very low
 198 carbon electricity mix, owing to the main primary energy used (nuclear power). This means that the
 199 environmental performances of electrified vehicles are geographically dependent on the electricity mix. We
 200 performed a sensitivity analysis with an average European electricity mix, *ceteris paribus*. The Ecoinvent
 201 process used is “Electricity, medium voltage, production UCTE, at grid” and is representative of a European
 202 electricity mix of approximately 531 g CO₂ eq./kWh.

203 The fuel and electricity consumption for the seven passenger cars and the three buses were estimated using
 204 IFPEN vehicle simulators based on the Simcenter Amesim™ software. These conventional, hybrid, and EV
 205 simulators were developed and validated through component and vehicle tests (Badin et al. 2015, Badin et al.
 206 2013, Da Costa et al. 2012, Marc et al. 2010). The objective is to assess the energy carrier consumption in both
 207 the WLTP homologated driving cycle and the Artemis urban cycle (André 2004) for passenger cars and in an
 208 urban Paris-type driving cycle for buses. The WLTP cycle corresponds to an average speed of 46.6 km per hour
 209 over a distance of 23 km, representing a journey in real conditions. This cycle is based on real-driving data and is
 210 divided into four parts with different average speeds: low, medium, high, and extra high. Each part contains a
 211 variety of driving phases, stops, accelerations, and braking phases. The simulations were used to assess the
 212 hybrid consumptions, depending on the plug-in functionality: sustaining mode (same initial and final battery
 213 states of charge) for the HEV, depleting mode for the full-battery PHEV, and sustaining mode for the PHEV
 214 with an empty battery. Depleting mode is the optimal mode, as only the electric powertrain is used. We consider
 215 that passenger cars are mostly used for commuting between home and work and that the battery size of these
 216 PHEVs allows sufficient autonomy for the driver if the battery is loaded when needed (Loisel et al. 2014). The
 217 opposite case (sustaining mode with empty battery) assumes that the user does not charge his/her vehicle and
 218 instead uses liquid fossil fuels as the energy carrier. The PHEV behaves in a manner between that of an ICE
 219 gasoline vehicle and that of a degraded HEV. A hundred kilometer distance was simulated. The Artemis urban
 220 driving cycle is based on real-world driving patterns for Europe. The simulated urban cycle for buses was set to
 221 10.6 km/h.

222 The end of life was modeled according to an avoided burden allocation methodology (Nicholson et al. 2009,
 223 Allacker et al. 2017). A vehicle's end of life is based on manufacturer data as well as European directives such as
 224 The European Parliament and the Council. The end of life for wheels and tires is based on the ADEME report of
 225 2017. The end of life for batteries follows the European directive 2006/66/CE from The European Parliament
 226 and the Council and uses two different technologies from the Ecoinvent database in equal proportion:
 227 hydrometallurgical treatment, and pyrometallurgical treatment (Frischknecht et al. 2005).

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

241 To be consistent in the comparative assessment, an occupation rate has been applied for both passenger cars and
242 buses. The average occupation rate for a car is 1.3 persons and that for buses is 17.4 persons, according to the
243 General commissioner for sustainable development (2016) and the European Environment Agency (2008). The
244 occupation rate seems to be an influencing factor, as its range encompasses between 1 and 5 persons for C-
245 segment cars and between 1⁵ and 103 persons per bus in the average upper boundary for buses (OMNIL 2011).
246 A sensitivity analysis performed on the lower and upper boundaries of occupation rate for both transportation
247 modes showed that the three buses' architectures have the highest impacts for the lower boundary scenario. The
248 trade-off lies between 7 persons and 28 persons in the bus, to be competitive with the cars having the greatest
249 impact on climate change, e.g., PHEV gasoline (100 % thermic), and least impact, e.g., PHEV gasoline (100 %
250 elec.). For the opposite trend, the results are similar to those presented here for the average occupation rate,
251 except for the ICE diesel bus which ranks at fourth place.

252 Regarding the system boundary, the analysis addresses both energy vector life cycles, i.e., a WTW assessment
253 including the fuel/energy production (WTT) and the fuel/energy use (TTW); in that regard, the analysis
254 addresses the entire life cycle of the vehicles. The life cycle of liquid fossil fuels, e.g., gasoline and diesel,
255 includes crude oil extraction, transportation, refining, and distribution. For the electricity vector, we consider the
256 energy sources' supply, electricity production, and the transmission network, including losses. The vehicle's life
257 cycle encompasses vehicle production, powertrain (thermic and electric) production, tire production, battery
258 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.

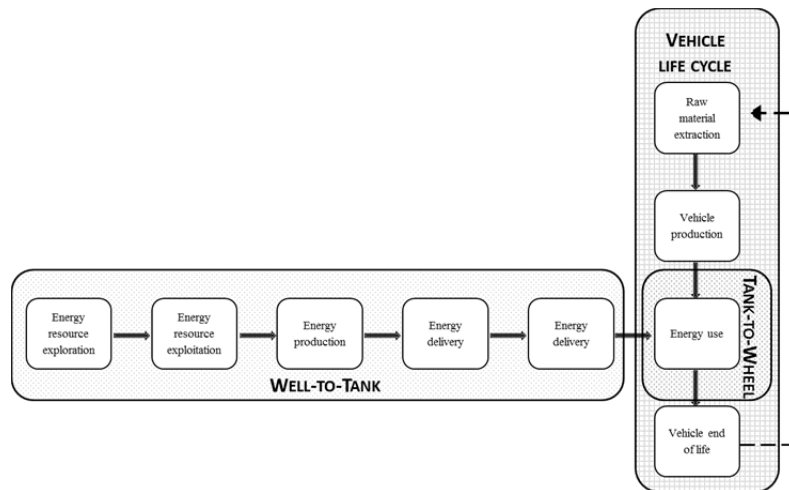


Fig. 1 Simplified life cycle stages considered for the study

259
260

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

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

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

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

273 The low heating value (LHV) values used for energy carriers are chosen in line with JRC data (JEC - Joint
274 Research Center-EUCAR-CONCAWE collaboration 2014), as well as the quantities of CO₂ emitted during fuel
275 combustion.

276

277 2.2 Life cycle inventory

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

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

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

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

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

299

300 **Table 3** Powertrain specifications

Type of vehicle	ICE gasoline	ICE diesel	MHEV 48V gasoline	HEV gasoline	PHEV gasoline	EV	EV +
<i>ICE engine</i>							
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		
<i>Electric motor</i>							
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
<i>Generator</i>							
Maximum power				30 kW	30 kW		
Maximum engine speed				9500 rpm	9500 rpm		
Maximum torque				163 Nm	163 Nm		

301

302 The batteries in this study have been modeled based on confidential data from ADEME, the French
 303 environmental management agency. They are based on lithium-ion nickel manganese cobalt (LiNMC)
 304 technology, and represent a homogeneous mix of two industrial technologies, with a 75 Wh/kg energy density.
 305 The battery pack has a 30-kWh energy capacity for the EV and 60 kWh for the EV+. The battery is downsized to
 306 8 kWh for the PHEV, 1.3 kWh for the HEV, and 1 kWh for the MHEV 48V. Details regarding the battery pack
 307 are listed in Table 4.

308 The GHG emissions related to battery production are approximately 127 kg CO₂ eq./kWh of the modeled
 309 battery, which is within the range of the data in the literature (Majeau-Bettez et al. 2011, Peters et al. 2017).

310

311 **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%

312

313 The main differences between the two technologies concern the metal used for the battery pack: metal, or metal
 314 alloy. The energy consumed per pack is also very different, e.g., one order of magnitude is equivalent to a factor
 315 of ten. At the battery module level, the quantity of plastic for housing the battery module also differs, on an order
 316 of magnitude. At the cell level, the macro data are similar in terms of cell weight, nominal power, and capacity,
 317 but differ in the energy used per cell. The anodes' materials are similar from one technology to another and only
 318 the contributions of the material weights are different; similar weights were ultimately found for both examined
 319 anode technologies. For cathodes, the total weight is approximately 15% different from similar raw material
 320 components. A comparison to existing data has been made thanks to other studies: Hao et al. (2017), Kim et al.
 321 (2016), and the literature review of Mia Romare and Lisbeth Dahllöf (2017).

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

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

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

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

336

337 **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

338

339 The TTW stage corresponds to the use phase, where the energy carrier is consumed to propel the vehicle. An in-
340 house vehicle simulator based on Simcenter AmesimTM software (Badin et al. 2015, Badin et al. 2013) is used to
341 assess the vehicle's fuel and electricity consumption, during both the WLTP and urban driving cycles, and for
342 passenger cars and buses. Pollutant emissions are recorded according to the Euro6b norms for CO, NO_x, PM,
343 and hydrocarbon compounds (HC) for gasoline. The Euro6b HC emissions norms for diesel vehicles were
344 extrapolated based on the Euro6c norm and future Euro7 norm (IFPEN experts) as only the total HC + NO_x was
345 provided in the standards. CO₂ correlates with fuel consumption, unlike other pollutant emissions. This leads to
346 the same values of pollutant emissions, regardless of the vehicle's liquid fuel's consumption.

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

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

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

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

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

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

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

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

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

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

388

389 **3 Results: life cycle impact assessment**

390 **3.1 Overview**

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

394 PHEV gasoline (100% elec.) refers to the depleting mode for the full battery, whereas PHEV gasoline
395 (100% thermic) refers to the mode for the empty battery.

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

400
401

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

402

			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

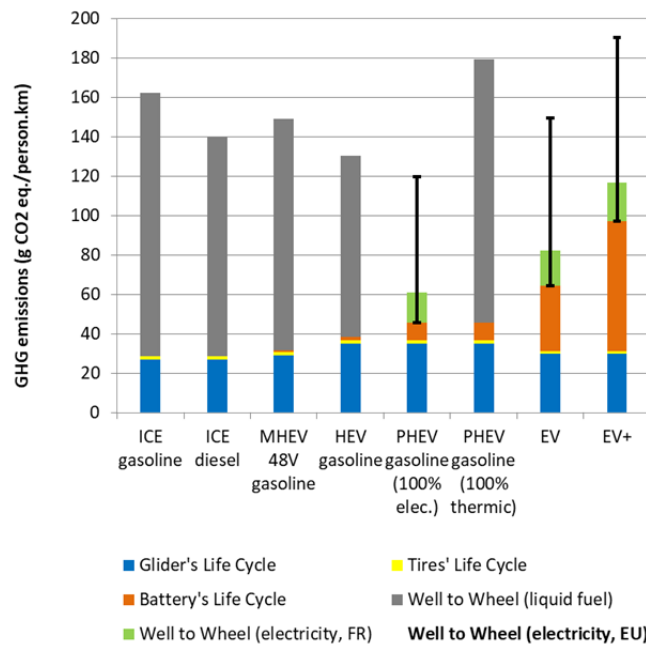


Fig. 2 Potential impacts on Climate Change of one person transportation over one km for worldwide harmonised light vehicles test procedure (WLTP) cycle for midsize cars, present time, French and European electricity mixes

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405 A focus on the electrified vehicles using electricity highlights that the PHEV, using 100% the
 406 energy carrier, has lower impacts than EVs for global warming potential, as well as for OD (Fig. 3), PM (Fig. 4),
 407 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
 408 energy carrier appears to have the same profile as a gasoline ICE for the WTW stage and a PHEV profile for the
 409 vehicle life cycle. In that regard, this leads to a somewhat nonsensical use of this powertrain and raises questions
 410 regarding consumer behavior.

411

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

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

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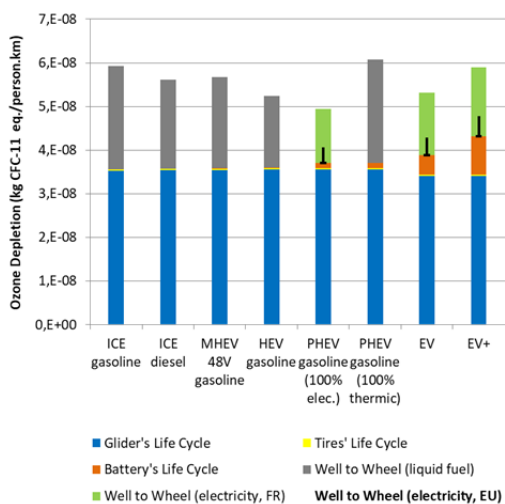
418 3.2 Passenger cars performing a worldwide harmonised light vehicles test procedure (WLTP) driving 419 cycle, French electricity charging mix

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

427

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

435
 436 The PM emissions indicator (Fig. 4) reports the negative effects on human health caused by primary particulate
 437 emissions and their precursors, but also gas-allowing particulate formations, i.e., so-called secondary
 438 particulates. It appears that battery life cycles contribute to this impact and that nickel is responsible for 25% of
 439 the impacts on the battery life cycle. The circuit boards contribute to approximately 13% of the impact. The
 440 emissions are related to metallurgy and nickel refining (which emits sulfur dioxide), accounting for this
 441 indicator. However these emissions are not occurring on-site, in regards to the vehicles' use.



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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

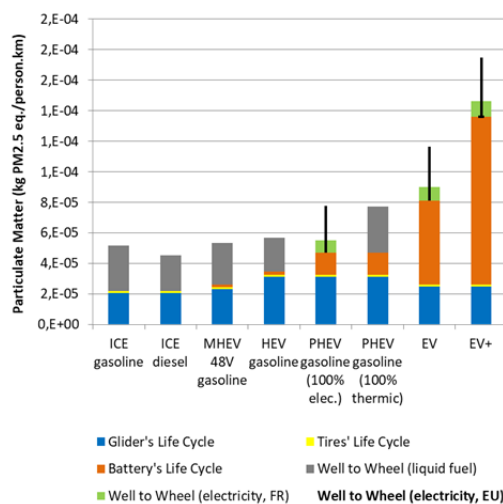
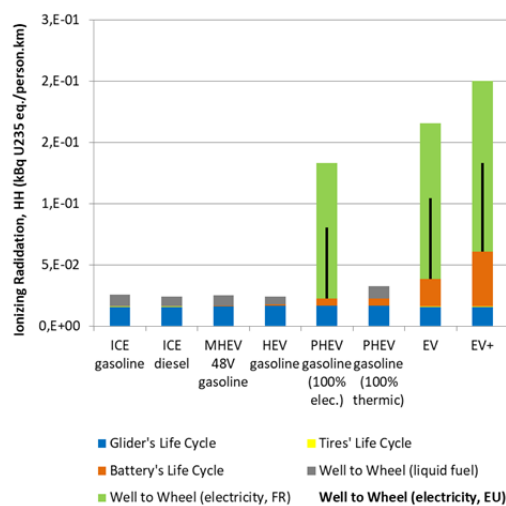


Fig. 4 Potential impacts on **particulate matter** emissions of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

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

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



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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

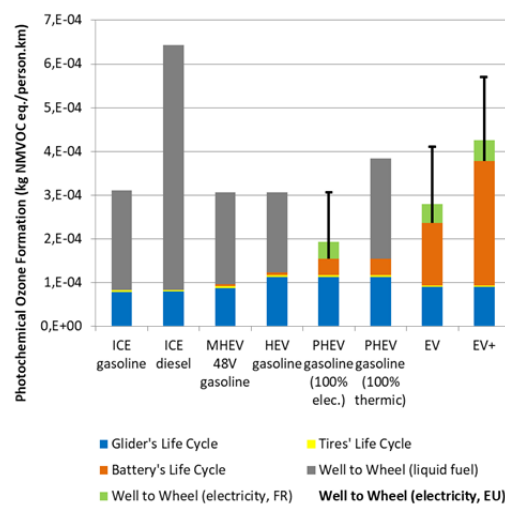


Fig. 6 Potential impacts on **photochemical ozone formation** of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

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

471
 472 Regarding Eu-terr. (Fig. 8), the PHEV (100% elec.) and EV have lower impacts than the other powertrains. ICE
 473 diesel has the highest impacts by far in comparison to the other vehicles. The PHEV (100% thermic) and EV+
 474 contribute more to Eu-terr. than ICE gasoline or low-hybrid powertrains.

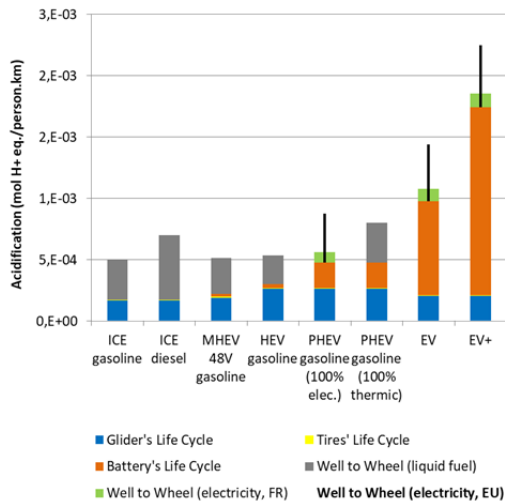


Fig. 7 Potential impacts on **acidification**. of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

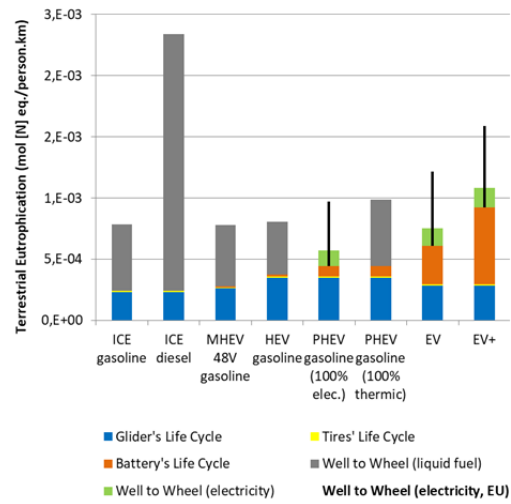


Fig. 8 Potential impacts on **terrestrial eutrophication**. of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

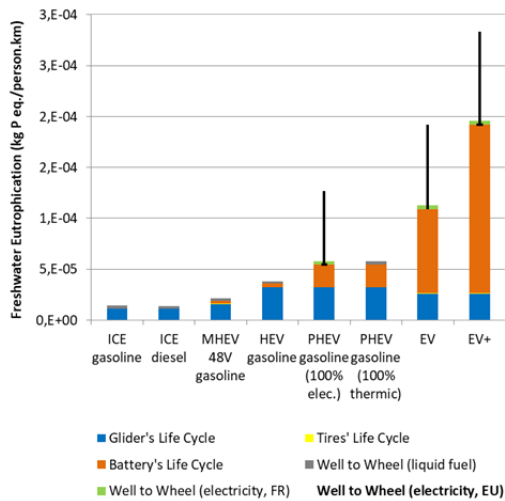


Fig. 9 Potential impacts on **aquatic eutrophication**. of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

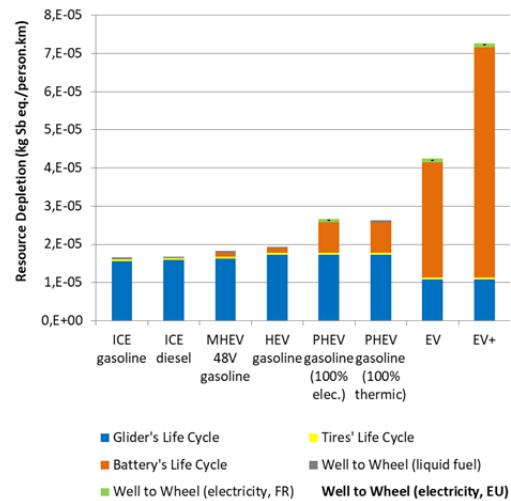


Fig. 10 Potential impacts on **resource depletion** (mineral, fossil, and renewables) of one person transportation over one km for WLTP cycle for midsize cars, present time, French and European electricity mixes

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476 3.3 Passenger cars performing a WLTP driving cycle, European electricity charging mix

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

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

490
 491 **3.4 Passenger cars and buses performing an urban driving cycle, French electricity charging mix**

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

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

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

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

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

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

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

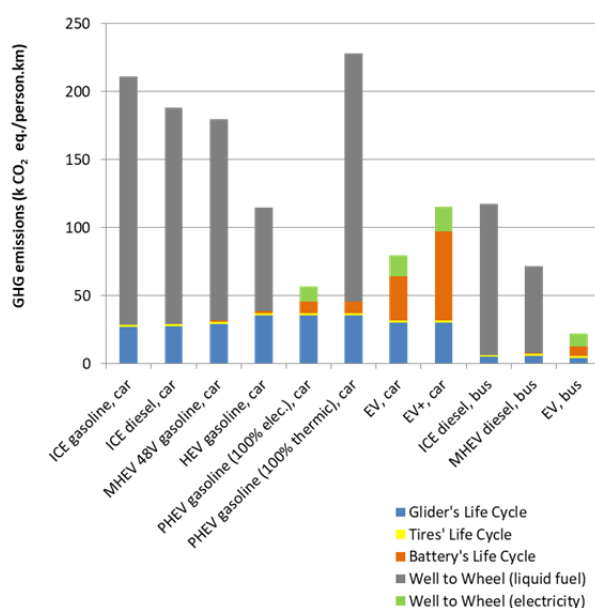


Fig. 11 Potential impacts on **climate change** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

513 **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
 514 electricity mix

Best case 2nd best case Worst case

515

		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

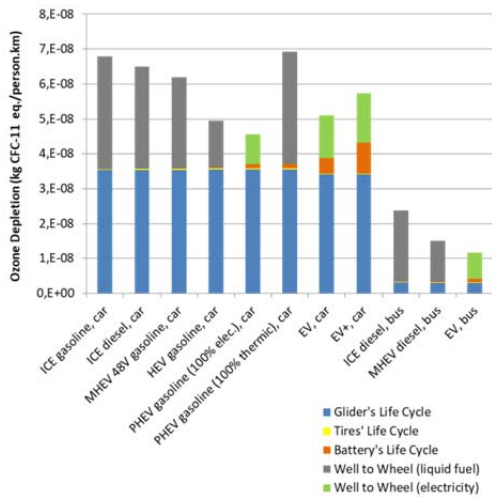


Fig. 12 Potential impacts on **ozone depletion potential** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

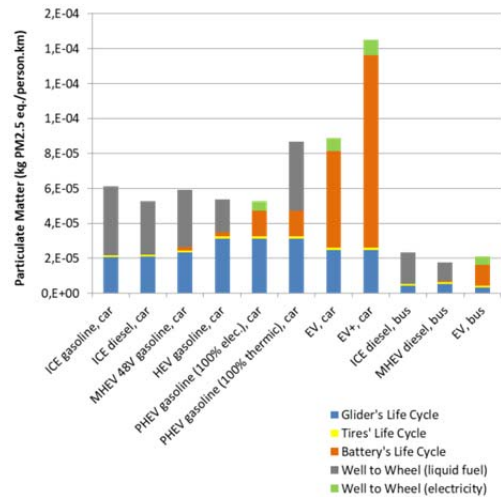


Fig. 13 Potential impacts on **particulate matter** emissions of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

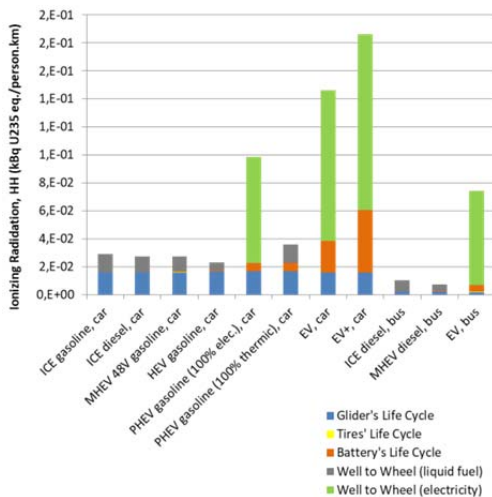


Fig. 14 Potential impacts on **human health** caused by **ionizing radiation** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

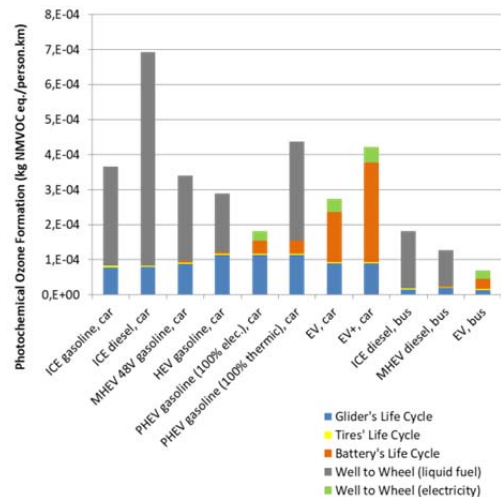


Fig. 15 Potential impacts on **photochemical ozone formation** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

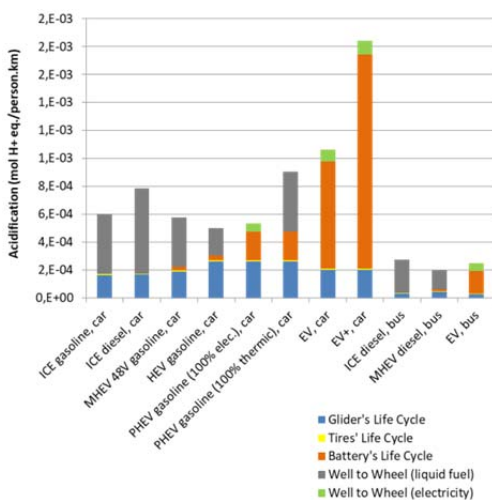


Fig. 16 Potential impacts on **acidification** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

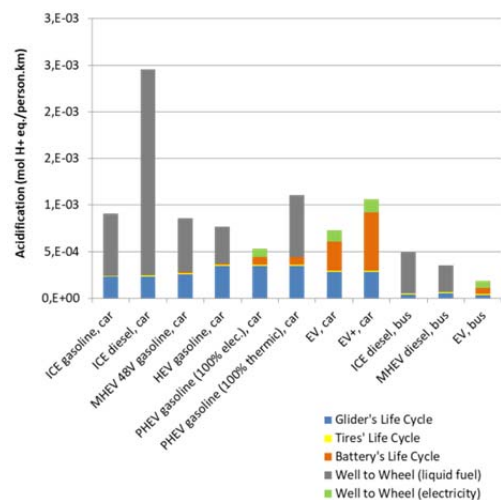


Fig. 17 Potential impacts on **terrestrial eutrophication** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

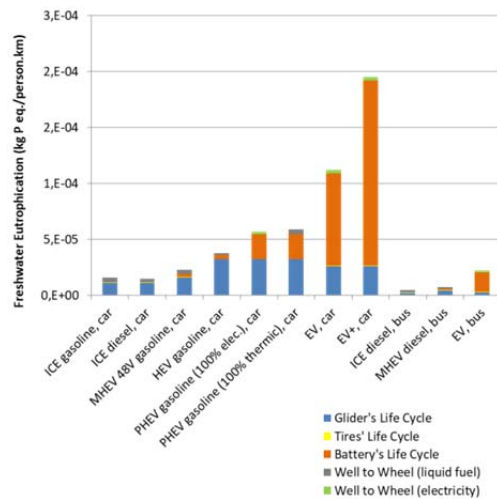


Fig. 18 Potential impacts on **aquatic eutrophication** of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

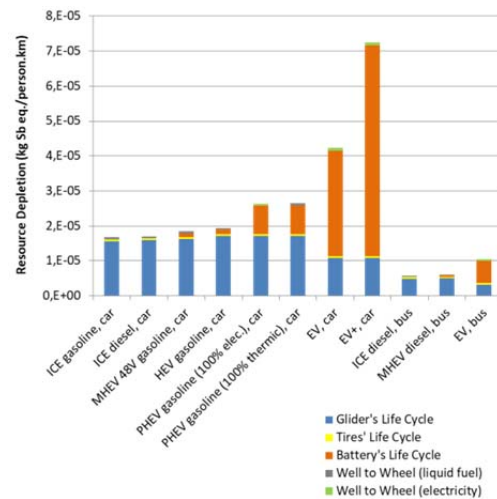


Fig. 19 Potential impacts on **resource depletion** (mineral, fossil, and renewables) of one person transportation over one km for urban cycle for midsize cars and bus, present time, French electricity mix

516

517 **4 Discussion**

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

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

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

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

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

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

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

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

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

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

590 Concerning the RD indicator, which is a very important issue when dealing with a battery, we believe that other
591 indicators assessing this depletion could be helpful for addressing it. Indeed, we are convinced that the question
592 of raw material criticality should be put in perspective for a large-scale deployment, in regards to both mass and
593 geographic level. The resources issue should not be treated based only on an environmental perspective, but
594 should be fully assessed based on economic, industrial, and geopolitical data, as addressed in Hache et al.
595 (2019). The issue of mineral resource location, the increasing dependency of the states, and the actor strategies
596 (states or companies) should be studied for the energy transition dynamic (World Bank Group 2017, OECD
597 2019, Bonnet et al. 2018, IRENA 2019). All of these factors are generally analyzed under a notion of criticality
598 that covers geopolitical risks (concentration of resources and or production, embargo, etc.) and economic risks
599 (market power, investment decisions, lack of financial contracts to hedge price volatility, under-investment, etc.).
600 The consideration of environmental or social aspects (emissions of pollutants during the production or trade
601 process, health consequences, landscape externalities, water needs etc.) has only recently been added to the
602 notion of criticality (Graedel et al. 2015). In addition to this, the notion of criticality is neither universal,
603 timeless, nor binary (Bonnet et al. 2018). Indeed, it actually varies according to the geographical scale being
604 considered (lithium does not appear in the European Commission's list of critical materials, but is viewed as
605 critical in the United States), the time scale (chromium, magnesite, and phosphate rock were critical in the
606 European Commission list in 2014, but not in 2017), and the consumer unit considered (country, sector,
607 company, or technology). Ultimately, it depends on the economic (commercial, financial), political (foreign
608 policy, national security), and industrial interests of a state. The need to consider all the criticality dimensions for
609 each of the strategic materials as essential for the energy transition requires the development of specific
610 quantification tools and appears to be fundamental for researchers, manufacturers, and policy-makers.

611

612 **5 Conclusion**

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

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

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

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

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

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

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

655

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663

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