

Impact on the environment and on human health of internal combustion, hybrid and battery electric powered vehicles in a life cycle perspective

Francesco Di Maria^{1,*}, Daniela Cesari², and Federico Sisani¹

¹DI Dipartimento di Ingegneria, University of Perugia, via G. Duranti 93, 06125 Perugia, Italy

²ISAC CNR, Istituto di Scienze dell'Atmosfera e del Clima CNR UOS di Lecce, S.P. Lecce – Monteroni km 1.2, 73100 Lecce, Italy

Abstract. Different power trained passenger cars were compared in a life cycle perspective (LCA) considering the Italian context for the year 2019. Main findings shows that battery electric vehicles, based on the current Italian energy mix, have the lower global warming emissions about 0.1 kgCO_{2eq}/km. Lower particulate emissions of about 5x10⁻⁴ kgPM_{2,5eq}/km and impact on human health about 7x10⁻⁷/km DALY were detected for petrol hybrid electric vehicles. Lower photochemical emissions of about 5x10⁻⁴ kgNMVOC_{eq}/km were found for gasoline internal combustion engines vehicles.

1 Introduction

Road transport still remain one of the most critical source of airborne emissions affecting the quality of urban environments and human health. According to [1] this sector contributes to about 39% to 80% for NO_x and about 11% for PM emissions. Further restrictions to be implemented by upcoming Euro 7 standard is currently driving the automotive industry to replace the fossil and/or renewable fueled vehicles with hybrid and battery electric powered ones.

This transition will affect several aspects and in particular the environmental one, posing a strong debate about the effective sustainability of this transition [2-4].

Life cycle assessment approach (LCA) results largely adopted in literature for investigating the environmental and human health consequences due to different scenarios and system. In previous LCA studies [5] investigated the different impacts due to diesel fueled and battery electric vehicles (BEV) in Italy reporting that BEV had lower impacts concerning the amount of kgCO_{2eq} and kgSO_{2eq} emitted but higher impacts concerning the emissions of kgPO_{4eq} and g 1,4-DCB_{eq}. Similar findings were also reported by [6]. [7] reported that BEV had lower emission of kgCO_{2eq} and kgCFC11_{eq} compared fossil fuelled ones. Higher greenhouses emissions related to the primary energy demand (MJ), for different powered cars, were detected by [8] concerning BEV. For the impact on human health, nowadays there is a growing interest toward new indicators aimed to quantify the potential effects induced by air pollutants. Particular focus was PM emissions and the related effects on human health. Although the toxic effects of PM were already correlated with some chemical and physical properties [9-10], the toxicity mechanisms are not yet fully known. Some studies [11-13] suggested that several adverse health effects could be associated to the oxidative potential (OP) of PM, which leads to high concentrations of reactive oxygen species (ROS), chemical species capable of causing damage at the cellular

* Corresponding author: francesco.dimaria@unipg.it

level. For this reason, the OP of atmospheric particulate has started to be considered as a general indicator of risks for human health associated to PM.

Based on this evidence the present study aims to compare in a LCA perspective the environmental impact of different power trained cars (*e.g.* gasoline, diesel, hybrid and BEV) related to the Italian context. Furthermore, a literature review was also carried out about the latest studies reporting about the evidence of the correlations detected between OP and PMs generated by traffic.

2 Material and methods

The present study was conducted with particular reference to the Italian context considering cars homologate according to standard \geq Euro 6. For this reason, data used in the study were retrieved from literature, official reports and other technical documents concerning the specific area and/or areas with equivalent legal regulation and technological implementation in terms of cars emission and environmental legislation (*i.e.* EU27 and North America).

2.1 The Euro 6 Italian passenger car fleet

Table 1 reports the consistency of the Italian Euro 6 passenger cars. Table 2 reports the geometric mean (μg) and the variance (σ^2) related to the amount (kg) of regulated pollutants emitted in exhaust per km driven by the different car sizes and powertrains. Table 3 report the non-exhaust PM emissions due to break and tyre abrasion [14-19]. The reduction of emissions due to regenerative break systems for BEV, PHEV and Petrol-HEV were also considered [20]. The amount of fuel consumed ranges from about 0.027 kg/km for small size PHEV to 0.092 kg/km for large size ICEVg whereas the electrical energy consumed ranged from about 0.04 kWh/km for small size PHEV to about 0.175 kWh/km for large size BEV. The yearly mileage ranges from about 1.1E+4 to about 2.0E+4 for all the different sizes and powertrains and the larger share, from about 48% up to 68% resulted driven in rural areas. The share of mileage driven in urban area and highway ranged from about 15% to about 30% and from about 8% to about 32%, respectively.

Table 1. Number of different powertrain and size Italian passenger cars homologate according to Euro 6 standard.

Powertrain	Size	Average weight (kg)	Euro 6 IT fleet	References
BEV	Small	1200		[21-25]
	Medium	1600	22,627 ^(a)	
	Large	1800		
PHEV	Small	1500	275	
	Medium	1700	4,956	
	Large	2300	8,536	
Petrol-HEV	Small	1100	23,626	
	Medium	1400	196,738	
	Large	1700	32,461	
Diesel-HEV ^(b)	Medium	-	5,932	
	Large	-	5,927	
ICEVg	Small	1200	298,1750	
	Medium	1600	33,0127	
	Large	2000	38881	

ICEVd	Small	1200	464978
	Medium	1600	3671357
	Large	2000	373631

Legend: a=global;

Table 2. Geometric mean (m_g) and variance (σ^2) of the emissions measured from Euro 6 passenger cars.

Powertrain	Size	Regulated pollutants (kg/km)					References
		CO ($\mu g/\sigma^2$)	NOx ($\mu g/\sigma^2$)	PM ($\mu g/\sigma^2$)	THC ($\mu g/\sigma^2$)	PN ($\mu g/\sigma^2$)	
PHEV	Small	3.80e-4/7.32	1.17e-5/10.7	6.71e-7/4.99	2.97e-5/6.51	1.50e12/4.54	[26-30]
	Medium	1.76e-3/1.94	2.00e-5/3.66	6.12e-7/3.93	1.69e-5/2.10	1.50e12/2.60	
	Large	3.03e-5/51.7	5.82e-5/3.21	7.51e-7/71.5	1.30e-6/94.5	2.30e12/10.2	
Petrol-HEV	Small	4.62e-4/7.08	9.67e-6/5.08	1.48e-6/1.03	4.18e-5/8.70	2.57e12/1.46	[26,28;31-34]
	Medium	8.25e-5/7.18	1.00e-5/17.1	3.30e-7/3.65	9.49e-6/19.3	2.00e11/7.25	
	Large	1.67e-4/4.43	1.40e-5/8.63	1.18e-6/5.76	1.00e-6/30.1	2.30e12/4.78	
ICEVg	Small	5.33e-4/15.3	1.70e-5/28.3	6.00e-7/9.16	5.00e-6/36.5	1.63e11/27.4	[26,32;34-9]
	Medium	1.55e-4/11.5	8.70e-6/6.50	5.00e-7/74.7	1.69e-5/87.4	2.16e11/81.1	
	Large	2.23e-4/4.50	1.42e-5/8.34	6.75e-7/5.15	1.35e-6/116	1.06e12/4.74	
ICEVd	Small	3.00e-5/18.3	1.19e-4/15.5	6.00e-7/787	4.00e-6/20.6	3.50e10/138	[30,32,35,38,40,41]
	Medium	3.10e-5/23.8	3.16e-4/13.4	2.00e-7/67.5	1.25e-5/5.91	4.90e9/70.0	
	Large	1.56e-4/21.6	3.11e-4/8.96E4	4.42e-7/11.1	3.95e-5/8.81	1.28e11/22.6	

Table 3. Geometric mean (μ_g) and variance (σ^2) of kg of different classes of PM emitted per km driven from brake and tyre abrasion for different car sizes and power trains.

Powertrain	Size	Brake non-exhaust ($\mu g/\sigma^2$)			Tyre non-exhaust ($\mu g/\sigma^2$)		
		(kg/km)			(kg/km)		
		PM<2.5	2.5<PM<10	PM>10	PM<2.5	2.5<PM<10	PM>10
BEV	Small	4.17E-7/1.52	6.30E-7/1.52	2.14E-1/1.52	3.44E-1/1.52	1.47E-6/1.52	3.26E-6/1.52
	Medium	5.55E-7/1.52	8.40E-7/1.52	2.85E-1/1.52	4.58E-1/1.52	1.96E-6/1.52	4.35E-6/1.52
	Large	6.25E-7/1.52	9.45E-7/1.52	3.20E-1/1.52	5.16E-1/1.52	2.21E-6/1.52	4.89E-6/1.52
PHEV	Small	5.21E-7/1.55	7.88E-7/1.55	2.67E-1/1.55	4.30E-1/1.55	1.84E-6/1.55	4.07E-6/1.55
	Medium	5.90E-7/1.55	8.93E-7/1.55	3.03E-1/1.55	4.87E-1/1.55	2.08E-6/1.55	4.62E-6/1.55

	Large	7.98E- ⁷ /1.55	1.21E- ⁶ /1.55	4.09E- ⁷ /1.55	6.59E- ⁷ /1.55	2.82E- ⁶ /1.55	6.25E- ⁶ /1.55
Petrol-HEV	Small	3.82E- ⁷ /1.55	5.78E- ⁷ /1.52	1.96E- ⁷ /1.55	3.15E- ⁷ /1.55	1.35E- ⁶ /1.55	2.99E- ⁶ /1.55
	Medium	4.86E- ⁷ /1.55	7.35E- ⁷ /1.55	2.49E- ⁷ /1.55	4.01E- ⁷ /1.55	1.72E- ⁶ /1.55	3.80E- ⁶ /1.55
	Large	5.90E- ⁷ /1.52	8.93E- ⁷ /1.55	3.03E- ⁷ /1.55	4.87E- ⁷ /1.55	2.08E- ⁶ /1.55	4.62E- ⁶ /1.55
ICEVg	Small	1.97E- ⁶ /1.63	3.40E- ⁶ /1.63	1.28E- ⁶ /1.63	3.71E- ⁶ /1.61	1.59E- ⁶ /1.61	3.91E- ⁶ /1.61
	Medium	2.58E- ⁶ /1.63	4.45E- ⁶ /1.63	1.68E- ⁶ /1.63	4.86E- ⁶ /1.61	2.08E- ⁶ /1.61	5.12E- ⁶ /1.61
	Large	3.20E- ⁶ /1.63	5.52E- ⁶ /1.52	2.08E- ⁶ /1.63	5.98E- ⁶ /1.61	2.56E- ⁶ /1.61	6.30E- ⁶ /1.61
ICEVd	Small	1.97E- ⁶ /1.63	3.40E- ⁶ /1.63	1.28E- ⁶ /1.63	3.71E- ⁶ /1.61	1.59E- ⁶ /1.61	3.91E- ⁶ /1.61
	Medium	2.58E- ⁶ /1.63	4.45E- ⁶ /1.63	1.68E- ⁶ /1.63	4.86E- ⁶ /1.61	2.08E- ⁶ /1.61	5.12E- ⁶ /1.61
	Large	3.20E- ⁶ /1.63	5.52E- ⁶ /1.52	2.08E- ⁶ /1.63	5.98E- ⁶ /1.61	2.56E- ⁶ /1.61	6.30E- ⁶ /1.61

2.2 The Life Cycle Assessment

2.1 Goal, scope and functional unit

The LCA was developed according to the ISO [42-44]. Calculations were performed by SimaPro 8.5.2.

The goal was to assess environmental and human health impacts associated to direct and indirect emissions from Italian passenger cars in the year 2019 respecting standard not lower than Euro 6 one [32,45]. Powertrains considered were: plug-in hybrid electrical vehicles (PHEV); petrol hybrid vehicles (petrol-HEV); gasoline internal combustion engines (ICEVg); petrol internal combustion engines (ICEVp); BEV. Three main size groups, depending on their average weight (*i.e.* small, medium, large) were identified (Table 1).

Powertrain fueled by compressed/liquid natural gas and liquefied petroleum gas were not included in the study. Main backgrounds were represented by fuel, energy, materials and chemicals necessary for the construction, use and maintenance of the vehicles (Fig. 1). Main foregrounds were represented by emissions due to tyre and brake abrasion and by exhaust emission for those vehicles powered by internal combustion engines. The end of life of the vehicles and of their components were assumed to be practically the same for all the different power train systems considered and for this reason not included in the present study. The functional unit chosen was the distance of 1 km driven that was also assumed as reference unit.

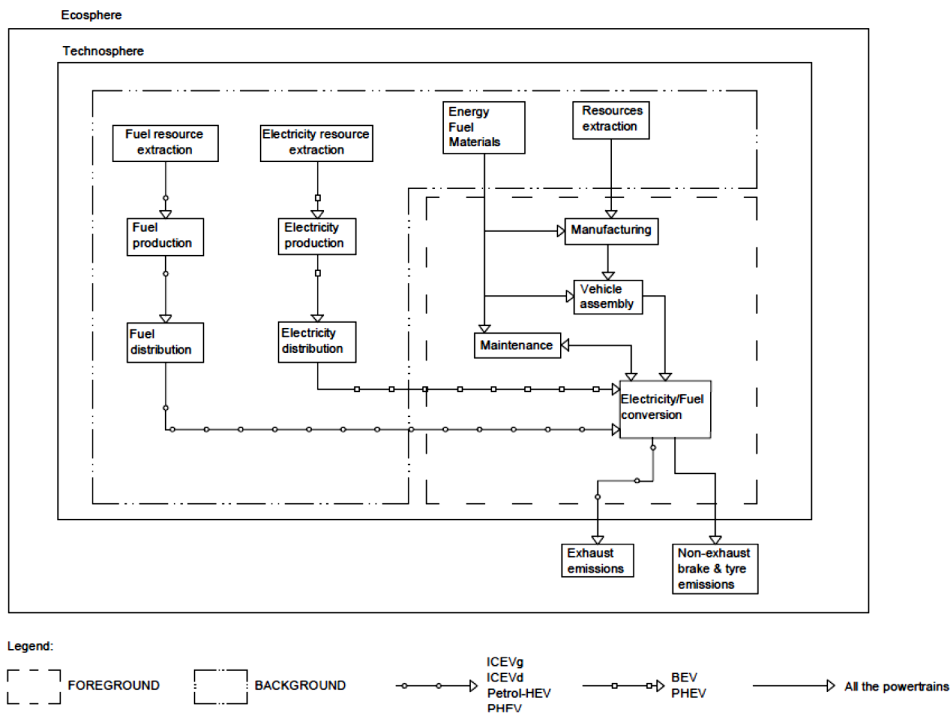


Fig. 1. Systems boundaries for (a) battery electric vehicles (BEV), (b) plug-in hybrid electric vehicle (PHEV), (c) petrol and diesel hybrid vehicles (petrol-HEV; diesel-HEV), (d) petrol and diesel internal combustion engines (ICEVg; ICEVp).

Table 4. Midpoint and Endpoint impact indicators.

Impact category	Unit
<i>Environmental Midpoint ILCD 2011+</i>	
Global warming potential – GWP	kg CO ₂ eq
Photochemical Ozone Formation - POF	kg NMVOC _{eq}
Particulate matter – PM	kg PM _{2.5} eq
Resource Depletion – RD	kg Sbeq
<i>Human health Endpoint IMPACT 2000+</i>	
Human health – HH	DALY

2.2 Impact indicators and assessment method

Environmental and health consequences were assessed by using both mid and end point impact indicators (Table 4). Midpoint indicators used for the assessment of the environmental consequences were: global warming (GWP) (kgCO₂eq); particulate matter (PM) (kgPM_{2.5}eq); photochemical ozone formation (POF) (kgNMVOC_{eq}); resource depletion (RD) (kgSb_{eq}). For the assessment of the consequences on human health the end point human health (HH) (DALY) was adopted.

Midpoint indicators were quantified by the ILCD 2011+ assessment method [46] whereas the endpoint indicator HH was quantified by the IMPACT 2000+ assessment method [47].

2.3 Oxidative Potential and cars PM emission

The OP of fine aerosol (PM_{2.5}) has been widely applied to evaluate both its oxidation ability and its impact on health [48] and can be quantified by measuring the dithiothreitol (DTT) consumption rate (nmol/min*m³) of particulate matter, with DTT serving as a substitute for cellular reductants [49]. Since the DTT consumption rate is considered to be influenced by the chemical composition of PM_{2.5} (e.g. organics, metals, inorganics, carbonaceous, elemental and metallic species) several studies investigate the correlation between the DTT consumption rate and PM_{2.5} chemical compounds.

Various studies have reported the significant correlation between DTT and different chemical components of particulate matter in the atmosphere, including humic-like substances, water soluble organic compounds (WSOC) and water soluble transition metals (WSTM) [50-52]. However, it is worth to highlight that the contributions of respective PM sources to its oxidative potential remain largely unresolved because of the complex interactions among chemicals that are DTT-active.

Considering traffic emissions, the DTT activity could be related to many pollutants produced by this source. We must say that “traffic” is a source category influenced by different kinds of emissions deriving from many different vehicle types and related processes [53]. In addition to the primary PM emissions from exhaust and the emissions of organic and inorganic gaseous PM precursors from the combustion of fuel and lubricant, vehicles emit significant amounts of particles through the wear of brake linings, clutch, and tyres. These are deposited onto the road and subsequently re-suspended by vehicle traffic together with crustal/mineral dust particles and road wear material. Source apportionment studies reported in literature showed traffic source profiles containing elemental carbon (EC), Fe, Ba, Zn, Cu and Pb (Viana et al., 2008b) with hopanes and steranes, that can be used in receptor models (RMs) for distinguishing exhaust from gasoline and diesel powered engines, together with the certain OC fractions [54]. Metals such as Cu, Zn, Mn, Sb, Sn, Mo, Ba, and Fe are markers of brake wear and can serve as indicators of traffic re-suspension [55, 56]. Some of these cited chemical species are well correlated with DTT activity. For example, in [50] and [51] and in [52] strong positive correlations between DTT activity and OC, EC, and water-soluble transition metals were showed. Further, in table 5 some studies on oxidative potential of PM are reported as example, where DTT values (normalized per volume, nm/min*m³) and the PM component potentially inducing PM oxidative potential are indicated.

A recent study [57] reported that, for PM_{2.5} fraction, carbonaceous species, *i.e.* organic carbon (OC), elemental carbon (EC), WSOC, secondary organic carbon (SOC), and some of the measured metal elements such as Cu, Fe, Mn, Sr, Mg, Al, Ti, V well correlate with the DTT activity. The source apportionment study present in this study showed that the mixed sources of traffic and road dust resuspension and coal combustion were the major sources of the oxidative potential of PM_{2.5} while the direct vehicle emission contributed the least to DTT activity.

In [51] it has been showed that the major drivers of DTT activity of fine PM are biomass burning and secondary aerosols, with their respective annual contributions of 35 and 31 %. This is followed by vehicle emissions contributing 16 % annually, while road dust contributes minimally (9 %) to the DTT activity of PM_{2.5}. Considering OP studies reported in literature, it is reasonable asserting that a transition from gasoline/diesel powered engines vehicle to electric engines could have an impact to exhaust emissions and on OP activity of urban aerosol according to the reduction of carbonaceous species emissions; otherwise, OP activity due to metals associated to not exhaust emissions (detectable in brake wear and road dust) should not change. Obviously, this assertion should be confirmed by dedicated sampling campaign to be performed in urban areas. Furthermore, the expected increase in

electrical energy consumption due to the larger diffusion of BEV could lead to an increase of both gaseous emissions, including PM_{2.5}, and fossil fuels consumption for power plants currently supplying > 65% of the whole Italian electricity needs.

Table 5. DTT (nmol/min·m³) and the PM components potentially inducing PM oxidative potential. This kind of information has been obtained in all studies for whom the squared Pearson correlation coefficients (R²) between measured chemical species and the DTT assay response was ≥ 0.5.

PM components	DTTv (nmol/min·m ³)	Reference
WSOC, BrC, SO ₄ ²⁻ , NH ₄ ⁺ , EC, OC, K, Ca, Mn, Fe, Cu, Zn	0.1 – 1.5	[51]
OC, EC, NO ₃ ⁻ , Ca ²⁺	0.19 (± 0.10)	[58]
black carbon, NO ₃ ⁻ , NH ₄ ⁺	0.33 (± 0.20)	[59]
OC, Polycyclic Aromatic Hydrocarbons	0.23 (0.11 – 0.34)	[60]
Cu, Zn, Cr, Fe, Mn	0.3 – 1.7	[61]
NO ₃ ⁻ , SO ₄ ²⁻ , NH ₄ ⁺ , WSOC, Mg, Al, K, Ti, Fe, PAHs	0.62 (± 0.21)	[62]

3 Results and discussion

Direct emissions from fuel combustion represents the main contribution to GWP (kgCO₂eq) for ICEVd, ICEVg, petrol.HEV and PHEV (Fig. 2) whereas contributions to construction and fuel supply resulted significantly lower. Those associated to maintenance were practically marginal. BEV showed kgCO₂eq/km halved compared to previous cars with a large contribution to GWP of the electricity (kWh/km) consumed.

Large and medium ICEVg and both PHEB and BEV cars showed higher POF (kgNMVOCeq/km) emission.

For ICEVg the larger contributions to POF were represented by exhaust emissions and to fuel supply. Also in this case maintenance resulted negligible.

For both PHEV and BEV emissions of kgNMVOCeq/km were largely influenced by the maintenance.

Lower average emissions of PM (kgPM_{2.5}eq/km) were detected for patrol-HEV and for medium and small ICEVd even if the higher standard deviation was detected for the PHEV Large and ICEVg Medium cars, respectively. In this case the larger average contributions to PM emissions were represented by fuel supply, by the non-exhaust (*i.e.* tyre and brake abrasion) and by the construction phase. BEV showed the higher average values of kgPM_{2.5}eq/km. In this case the most relevant contributions were, in order of importance: the electricity production; the construction; and the tyre non-exhaust. The incidence of brake non-exhaust resulted practically negligible due to the effect of the regenerative braking system (Table 3). Both PHEV and BEV showed the higher average FWE emissions (kgPeq/km) mainly due to the contribution of the electricity production whereas both large ICEVg and ICEVd showed the higher values for A (molCH₄eq/km). In this last case the main contribution was due to the fuel supply. BEV were charged by the higher average (CTUe/km) and RD (kgSbeq/km) emissions. Of particular interest appears the results that in a life cycle perspective the impact on human health (DALY) of BEV is practically

similar to the one of ICEVg and that best performances (i.e. lower impact) were achieved by petrol-HEV and small size ICEVd.

The amount of kgCO₂eq emitted from BEV, ICEVd and ICEVg reported in the study of [5] were in line with those reported in the present study. The same study reported also the kmPM_{2,5} emitted from these vehicles were practically the same whereas the emissions of kgNMVOC resulted lower for BEV and higher for ICEVg.

In another study [63] BEV resulted charged by the higher emission of kgPM_{2,5}eq and mol H₂eq compared to ICEVd and ICEVg.

In comparing ICEVg, HEV, PHEV and BEV [8] found higher GWP for the first power trained cars.

Even if the expected increase in electrical energy consumption due to the larger diffusion of BEV will probably increase of gaseous emissions and PM_s from power plants, [58] found that high PM levels are not necessarily correlated to high OP activity since the influence of chemical composition. Figure 3 reports some correlations found in literature between DTT (nmol/min*m) and some different chemical compounds detected in PM.

This is another aspect worthy to be investigated for having a global picture of the impact on the environment and on human health related to the new private mobility paradigm.

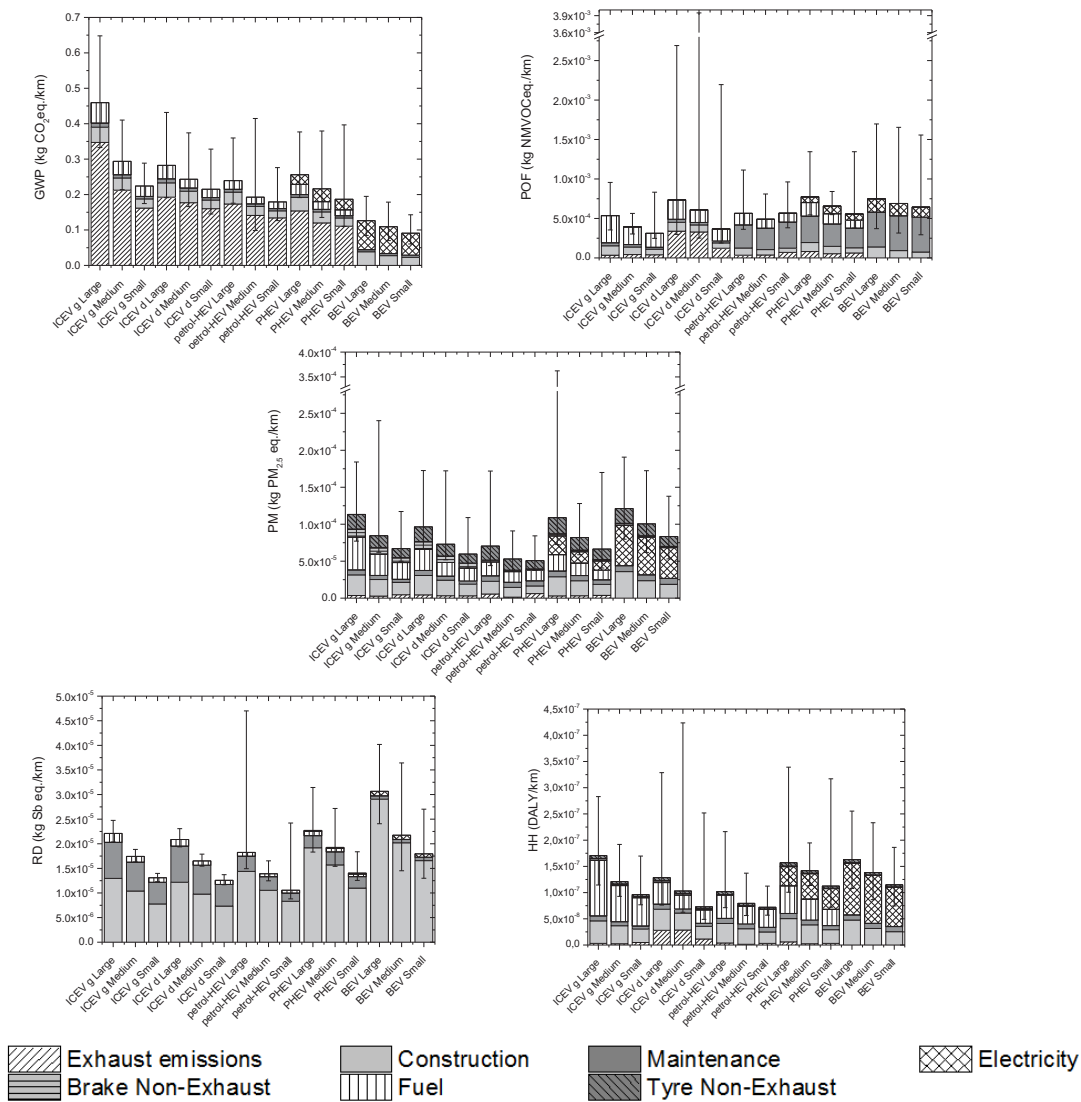


Fig. 2. Geometric mean and standard deviation of the characterization of the midpoint environmental impact indicators.

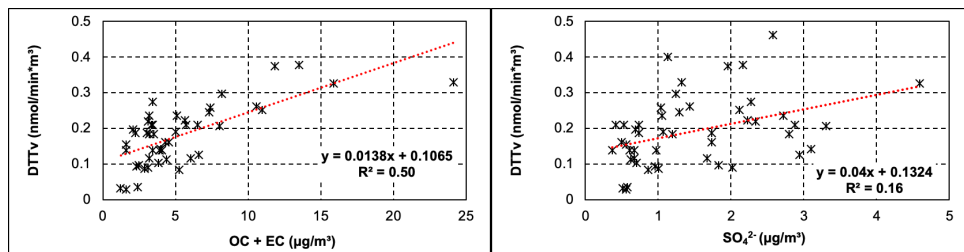


Fig. 3. Example of correlations between DTTv (nmol/min·m³) and different chemical species (i.e. carbonaceous species and sulphate, µg/m³) [58].

4 Conclusions

Based on the current Italian electricity mix, battery electric vehicles resulted credited by the lower greenhouses emission compared to both fossil fuelled and hybrid ones. Quite similar or in any case comparable emissions levels were found concerning particulate matter and resource depletion. The same results were also achieved concerning the consequence on human health for which petrol hybrid vehicles were credited by the lower impacts. What affects the current emission levels in particular of battery electric vehicles is represented by the ones associated to the construction phase, by particulate emissions due to tyres abrasion and by the electricity consumption. A particular care has to be pointed on this last aspect. In fact, since the larger diffusion of battery electric vehicles this could lead to an overall increase of the Italian electrical energy demand causing an increase of the amount of fossil fuel to be exploited in thermal power plants with possible increase of the overall impacts. Finally more research activity resulted necessary for a better understanding of the correlation between particulate emissions from the different activities considered and oxidative potential.

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