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Electric Cars vs Diesel and Gasoline: A Comparative LCA Ranging from Micro-Car to Family Car

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Abstract: The purpose of this paper is to compare the environmental performances of electric vehicles and homologous gasoline and diesel vehicles, taking into account the overall life cycle potential impacts of the analyzed vehicles, in a Life Cycle Assessment (LCA) perspective. To this aim, a wide range of vehicles were taken into account: Smart Fortwo, Chevrolet Spark, Fiat 500, Volkswagen Golf, Ford Focus and Kia Soul. Considering different vehicle models - from the small city car to the family car — highlighted that advantages and disadvantages of the electric vehicle do not depend on the category to which the vehicle belongs.

The analysis shows that electric vehicles perform better than traditional ones, in terms of greenhouse gases emissions, depletion of non-renewable resources and emissions of atmospheric pollutants affecting urban areas. Nonetheless, electric vehicles prove to be non-competitive for Life Cycle Impact categories like water eutrophication and human toxicity, for which the environmental impacts due to the battery life cycle play a decisive role.

Key words: LCA, electric vehicle, internal combustion engine vehicle, LCIA regionalization, geographical distribution of pollutants

1. Introduction

It is widely spread the idea, among the general public, that electric vehicles in general — and electric vehicles for private transport in particular — can play an important role in a sustainable road transport system, being able to reduce emissions of both greenhouse gases and atmospheric pollutants.

The growing awareness towards these themes involves both press and government bodies. In fact, if numerous general press releases have been published on this subject, a growing interest of the government authorities towards these themes is also to be registered. Moreover, there is a general consensus within the scientific community about Life Cycle Assessment (LCA) being the more suitable methodology to be adopted to investigate the potential improvements due to the substitution of traditional vehicles (both gasoline and diesel fuelled) with electric ones [1, 2]. In fact, a wide number of LCA studies have been developed on this theme. T. Hawkins et al. [1] and later A. Nordelöf et al. [2] made a review of about 50 and 70 studies respectively and found out that none of them were to be considered satisfying. The main critical aspects were due on one hand to the limited number of potential impacts considered in the assessment phase and on the other hand to an inadequate characterization of the electrical charging mix, i.e. the mix of energy sources and conversion technologies used to produce the recharging mix.

Although recent studies developed in the framework of the Research Fund for the Italian Electrical System [5] have been recognised to bridge these gaps [6], it is clear that some issues may need to be further addressed. Regular updating is of capital importance in LCA of electric automobile sector,

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characterised by rapidly changing developments and innovations.

As already highlighted in the past [7], in a Life Cycle perspective, the environmental performances of electric and conventional vehicles are influenced by a number of parameters, among which the most relevant are fuel and energy consumptions and power mix. Recently, an interesting review [8] identifies other important factors such as climatic conditions, the capillarity of the charging infrastructures, the driving conditions, the mobility policies and the vehicles typologies.

Starting from this last consideration, the present paper deals with two aspects still little investigated. First, , the study doesn't consider generic and ideal electric and internal combustion engine vehicles, but real vehicles, already present on the 2015 Italian market in the three motorisations: electric diesel and gasoline. For these vehicles, real characteristics (weight, fuel and energy consumptions, range, expected lifetime, etc.) were considered. The wide range of vehicles involved in the analysis, ranging from micro cars to family cars, allowed to investigate if there were a particular vehicle size for which the transition towards electric vehicles were to be considered more (or less) favourable. Last, the performance of the vehicles are compared on the basis of energy consumptions and emission factors of a urban driving cycle as urban areas are the place of choice for the use of electric vehicles (thanks to the absence of tailpipe emissions and because of their limited range).

2. Material and Methods

The following paragraphs describe the assumptions and results of the LCA study in accordance with the ISO 14040 [3]: goal and scope definition, inventory analysis, impact assessment and interpretation of the results.

2.1 Goal and Scope Definition

The aim of the study is to compare the environmental performances of electric vehicles with homologous gasoline and diesel fuelled vehicles, taking into account commercial models for which the three motorisations are available. The vehicles under analysis are representative of different sizes, ranging from micro cars to family cars, and cover the main market segments related to the private passenger transport in urban area. The selected car types are: Smart For Two, Chevrolet Spark, Fiat 500, Volkswagen Golf, Ford Focus and Kia Soul. All the electric vehicles considered are equipped with Li-ion batteries and all the internal combustion engine vehicles considered belong to the Euro 6 category, with the exception of the Fiat 500 Diesel (Euro 5), because at the time of preparation of the study, official data concerning the real pollutant emissions per kilometer were not available.

2.1.1 Functional Unit

The functional unit represents the unit of measurement of the service provided by the analysed system. The service provided by a private vehicle is the passenger transport. Accordingly, the functional unit of the study is based on the kilometers travelled by the vehicles, that is 1 km*passenger, considering an average vehicle load factor of 1.62 passenger/vehicle. The load factor doesn't have a direct effect on the vehicles comparison, as it doesn't vary from one type of vehicle to another. Nonetheless, it helps in comparing different transport modes (bicycle, motorcycle, public transport, etc.). Moreover, the load factor affects the pollutants emissions in the use phase of the vehicles [10], both directly (for what concerns brake, tyre and road wear) and indirectly (as it determines fuel/energy consumptions). The load factor used in this study is consistent with the assumptions made by the Environmental Protection Agency (EPA www.fueleconomy.gov) for the estimation of fuel consumptions and with the main new type-approval test cycles. The functional unit is the unit of scale on which all the inputs and outputs in the Life Cycle

Inventory phase and all the potential impacts in the Life Cycle Impact Assessment phase are expressed. This means that, in this article, all the impacts, for all the life cycle phases, are referred to 1 km travelled.

2.1.2 Choice of the Impact Categories

The impact categories considered in this study address issues such as greenhouse gas emissions and atmospheric pollutants emissions (especially in urban areas), as these aspects represent the main drivers for the transition towards electric mobility. With regard to this last aspect, the study evaluates the potential impacts related to air acidification, photochemical ozone formation potential and particulate matter formation potential. Other aspects such as water and soil eutrophication and human toxicity (both cancer and non-cancer effects) are analysed in the study because they are identified as a weakness in the electric vehicles performances [11]. These Life Cycle Impact Assessment indicators are quantified in accordance with the methods suggested by the Joint Research Centre [12], in the framework of the *European Platform on Life Cycle Assessment*.

2.1.3 System Boundary

The approach chosen to describe and analyse the system is a cradle to grave approach and it considers: vehicles production and dismantling; battery production and dismantling (calculated separately only for the electric vehicles); complete energy carrier supply chains (including primary energy sources production); vehicles use phase; vehicles maintenance phase and road maintenance.

2.2 Inventory

As regard background processes, most of the secondary data used in this study derives from Ecoinvent database, v3 [13], the most used database for LCA applications. Assumptions and primary data used to represent the main phases are described in the following paragraphs.

2.2.1 Vehicles Production (and Dismantling)

To better represent the characteristics of the analysed vehicles, the production (and dismantling) of the vehicles is distinguished between powertrain (i.e., all the components which are required for generating and transmitting the propulsive energy for the vehicle) and glider (i.e., all the remaining components of the vehicle which are not strictly related to the propulsion technology).

Moving from one type of vehicle to another, the relative weight of the powertrain compared to the glider varies. In Ecoinvent v3 database, being 100 the vehicle weights, the allocation between glider and powertrain is 91% glider and 9% powertrain for electric vehicles, 74% glider and 26% powertrain for gasoline fuelled vehicles and 70% glider and 30% powertrain for diesel fuelled vehicles. In this study, only for electric vehicles, the proportion between glider and powertrain has been changed, assuming that the powertrain weight is proportional to the engine power. Moreover, Ecoinvent provide data related to the production of average vehicles representative of an average world market. Vice versa, in this study, for each type of vehicle, a country of production for the electric version is identified and, for the analysis, the gasoline and diesel version of the vehicle are supposed to be produced in the same place as the electric version. To this aim, the average world data were adapted to represent the specific country of production, at least for what concerns the power mix used during the vehicles assembly phase. This assumption assured that homologous vehicles were compared on the basis of the same production (and dismantling) conditions and, at the same time, it allowed to differentiate impacts for vehicles coming from different geographical areas.

Table 1 shows, for each type of vehicle, the country where the production process takes place.

A relevant aspect to consider, when carrying out this kind of analysis, is represented by the vehicle lifetime. Efforts have been made to obtain vehicles more and more energy-efficient, with low environmental impacts.

Table 1 Country where the vehicles are produced.

Vehicle	Country
Smart Fortwo	France
Kia Soul	South Korea
Chevrolet Spark	South Korea
Ford Focus	USA - Michigan
Volkswagen Golf	Germany
Fiat 500	Mexico

Accordingly, the impacts due to the vehicles construction phase play increasingly significant roles, both in absolute terms and as a percentage of the overall life cycle impacts. Of course, the more the vehicle lifetime is short, the heavier the effect of these impacts is and underestimations of the real vehicle lifetime bring to overestimations of the impacts generated from vehicles characterised by greater production impacts (i.e., electric vehicles). Conversely, assuming excessively long vehicles lifetimes could bring to an underestimation of the impacts. The vehicles lifetime assumed in Ecoinvent v3 is of 150000 km, regardless the vehicle segment or the fuel used. In this study, the vehicle lifetime is reasonably assumed to be dependent both on the vehicle segment and on the type of fuel used, according to the more recent studies [14, 15] on this subject. The following table shows the vehicles lifetimes assumed in the present paper as a function of vehicle size and motorisation

Table 2 Average lifetime (km) assumed in this study, as a function of vehicles size and motorization.

Size	Gasoline [km]	Diesel [km]	Electric [km]	Vehicles considered in this study
micro	150000	200000	175000	Smart Fortwo
mini	180000	210000	200000	Chevrolet Spark, Fiat 500
medium	210000	240000	230000	VW Golf, Ford Focus
big	210000	240000	230000	Kia Soul

2.2.2 Battery Production (and Dismantling)

Ecoinvent v3 considers, for a vehicle lifetime of 150000 km, a battery lifetime of 100000 km [16]. In literature, many different assumptions are used on the subject [17], in relation to the battery lifetime and to the option of substituting the battery during the vehicle lifetime. Nevertheless, when drawing up this paper, no scientific evidence has been found about the battery lifetime being 100000 or 150000 km. Studies of ageing of Li-ion batteries seem to indicate that, at present, the electric vehicles end-of-life (i.e. when they have lost 20% of their capacity) could be reasonably set to 200000 km [18]. Besides, a behavioral study [19] shows that batteries continue to meet daily travel needs of drivers well beyond a capacity fade of 80% and that most of drivers would not perceive a service loss when the battery capacity fade is 80, 70 or 60% of the original energy capacity. As a consequence, drivers would continue to use the vehicle even if the battery has conventionally reached its end-of-life.

The discussion forum Electrek [1] has recently published an analysis developed on around 350 Tesla Model S and X that highlights that, for this car, the battery end-of-life could be of over 300000 km. **Fig. 1** shows the battery decay of Testa Model S and Model X as a result of the distance travelled.

Therefore, it would appear appropriate, according to the authors' opinion, to consider the useful battery lifetime as long as the vehicle lifetime. This assumption has been adopted for this study.

2.2.3 Vehicles Use Phase

As regard the vehicles use phase, vehicles fuel consumptions are derived from measures published by the Environmental Protection Agency (EPA)[2], because in this database, consumptions are calculated using a common methodology for all vehicles. Moreover, EPA database offers the possibility to compare the vehicles performances on the basis of a urban driving cycle. As regard Internal Combustion Engine Vehicles (ICEV)

[1] https://electrek.co/2018/04/14/tesla-battery-degradation-data/.
[2] http://www.fueleconomy.gov.

the main emission factors are derived from the application of COPERT Model [20] for the elaboration of the Italian National Emissions Inventory [21]. The non-exhaust emissions (i.e., tyre, brake and road wear emissions due to the movement of the vehicle) are calculated as a function of the gross vehicle weight [10]. Results are in accordance with the National Emissions Inventory data [21].

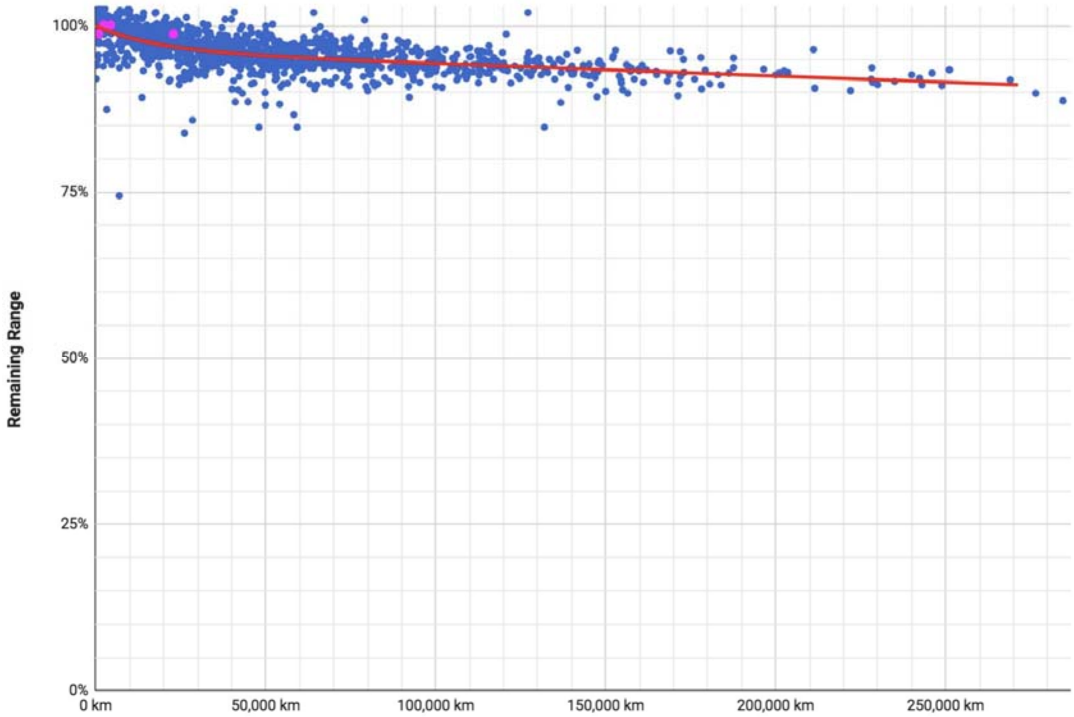

Fig. 1 Battery decay for Tesla S and X Models as a result of the distance travelled.

2.2.4 Energy Carrier Supply Chain

As regard internal combustion engine vehicles, given the relevance of potential impacts due to the fossil fuels (gasoline and diesel oil) supply chains and given the excessive approximations in the Ecoinvent v3 crude oil dataset, a crude oil production mix referred to Italy was created, according to the official data published by the Ministry of Economic Development [22, 23]. For what concerns electric vehicles, the recharging mix was built as marginal mix, according to the data related to the Index of Marginal Technology published by GME (Gestore dei Mercati Energetici) for the year 2014 [24], as suggested in a recent research [5]. In other words, rather than considering an average power mix, this study takes into account a mix composed by the combination of energy sources and technologies that have been marginal during the charging time, in accordance with the hourly charging profile shown in Fig. 2.

Thus, the recharging mix is the power mix that would meet the demand of additional energy during the hours in which the recharging process takes place. This mix is characterised by a percentage of renewable energy sources far below the national average mix and it constitutes a high conservative assumption [5]).

The marginal technologies efficiency derive from national official data [4] while emission factors for the regulated pollutants emissions (CO_2, NO_x, SO_x, Particulate) of the thermal power plants are derived from the annual declaration of the Italian EMAS registered power plants [26]. Finally, the mix of natural gas import has been corrected to reflect the Italian mix of import, according to ENI declarations for year 2013 [27].

3. Results and Discussion: Life Cycle Impact Assessment

Under the assumptions described above, that represent as good as possible the Italian context, the study highlights that electric vehicles perform better than traditional vehicles for what concerns greenhouse gas emissions, as they are able to reduce by about half these emissions if compared with homologous gasoline vehicles (Fig. 4).

As regard particulate matter formation (Fig. 5 electric vehicles still perform better than both gasoline and diesel ones. Exceptions are represented by Fiat 500 and Ford Focus. The Fiat 500 0.9 TwinAir (gasoline fuelled) presents performances that are similar to the electric model thanks to the high level of efficiency of the gasoline model and because of the unusual (for its segment) heavy weight of the electric version. As regard Ford Focus, the electric model (2015 model) is again really heavy for its category and this seriously penalize the performances of the electric model if compared to the internal combustion engine models.

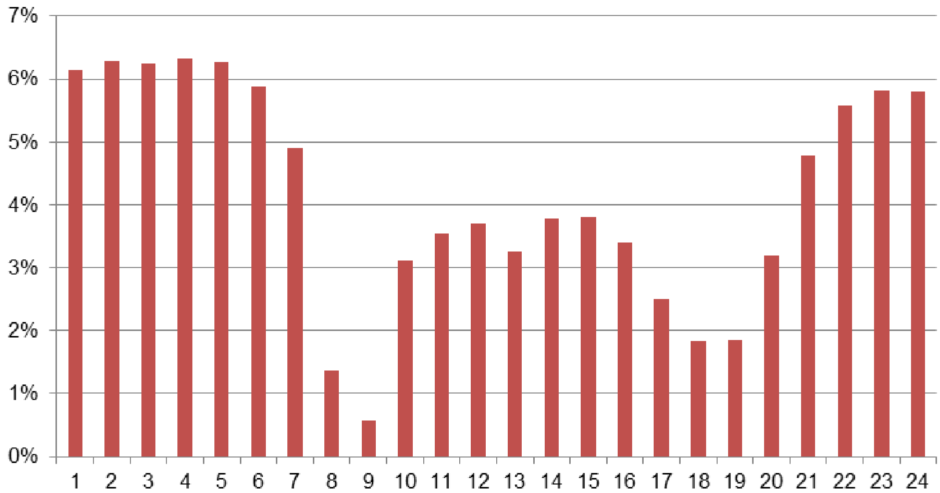

Fig. 2 Hourly charging profile (as percentage of energy recharged) used for the electric vehicle.

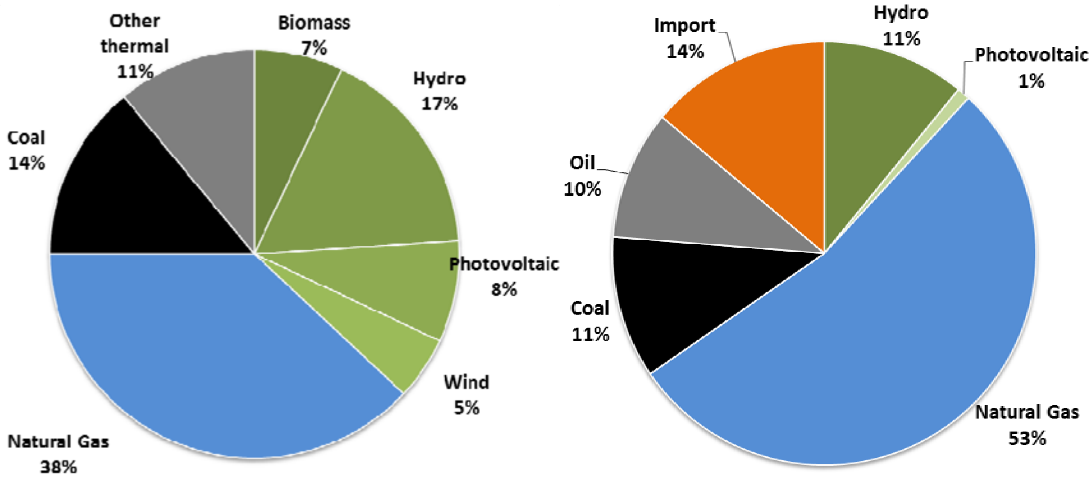

Fig. 3 Mix 2014 considered in this study (on the right).

As regard photochemical ozone formation (Fig. 6), electric vehicles clearly perform better than internal combustion engine vehicles in all the analysed cases. However, electric vehicles are not currently competitive for indicators like freshwater eutrophication or human toxicity, for which the impacts due to the battery production and dismantling play a decisive role.

Other impacts categories have been considered in the study, in addition to the ones reported above, such as marine and terrestrial eutrophication, human toxicity (cancer and non-cancer effects) and non-renewable resources depletion. Although in general electric vehicles show advantages as compared to homologous internal combustion engine vehicles, for what concerns freshwater eutrophication and human toxicity (i.e., emissions of toxic substances due to row materials extraction and processing) electric vehicles perform worse than traditional ones.

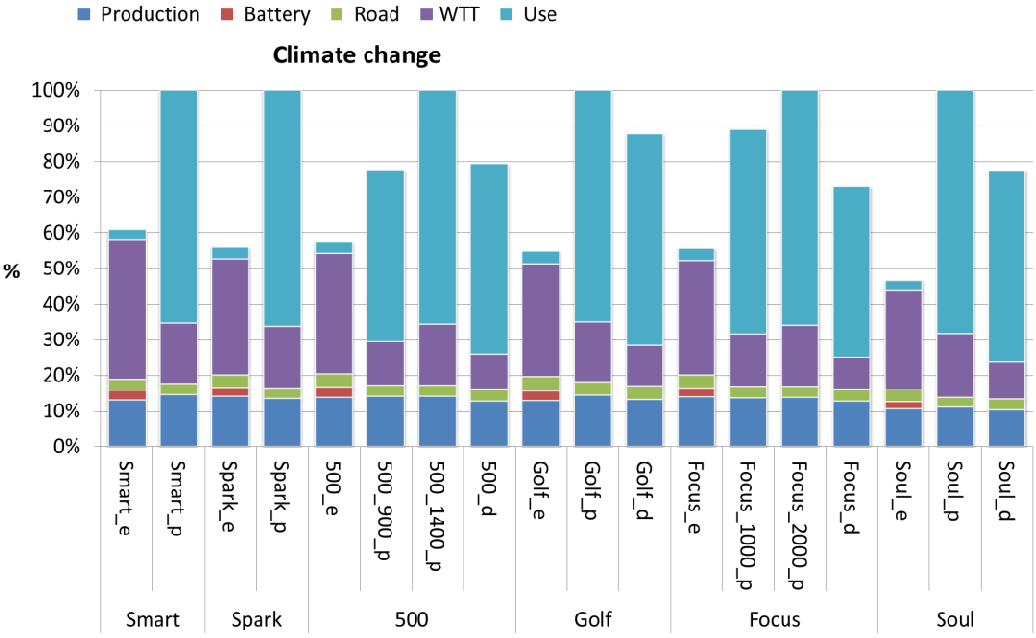

Fig. 4 Comparison in terms of greenhouse gas emissions over the entire life cycle of electric (_e), gasoline (_p) and diesel (_d) homologous vehicles.

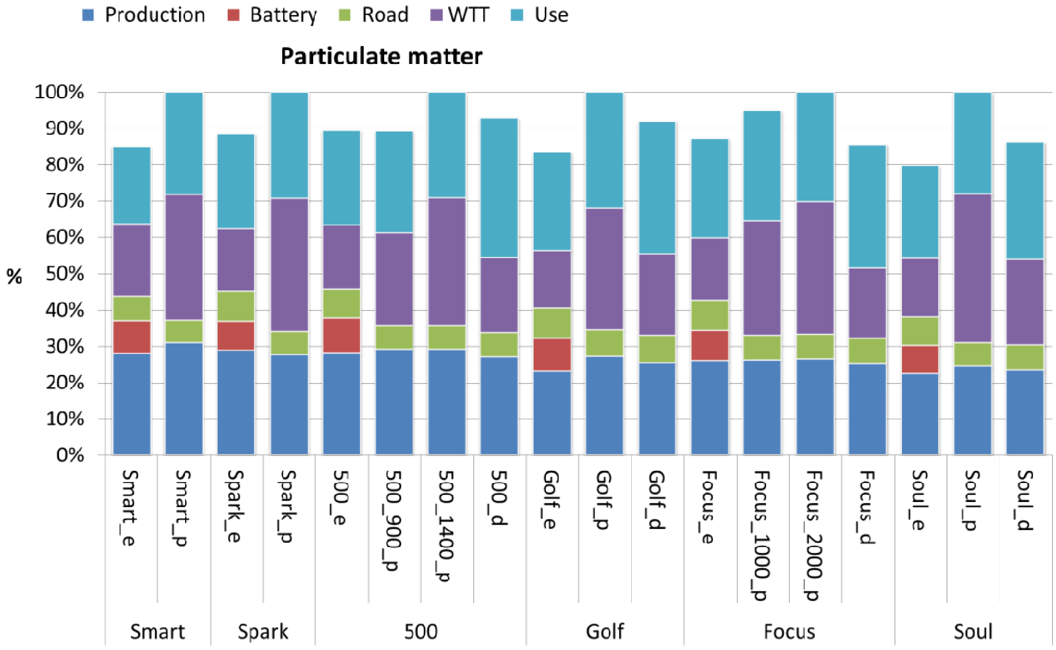

Fig. 5 Comparison in terms of particulate matter formation over the entire life cycle of electric (_e), gasoline (_p) and diesel (_d) homologous vehicles.

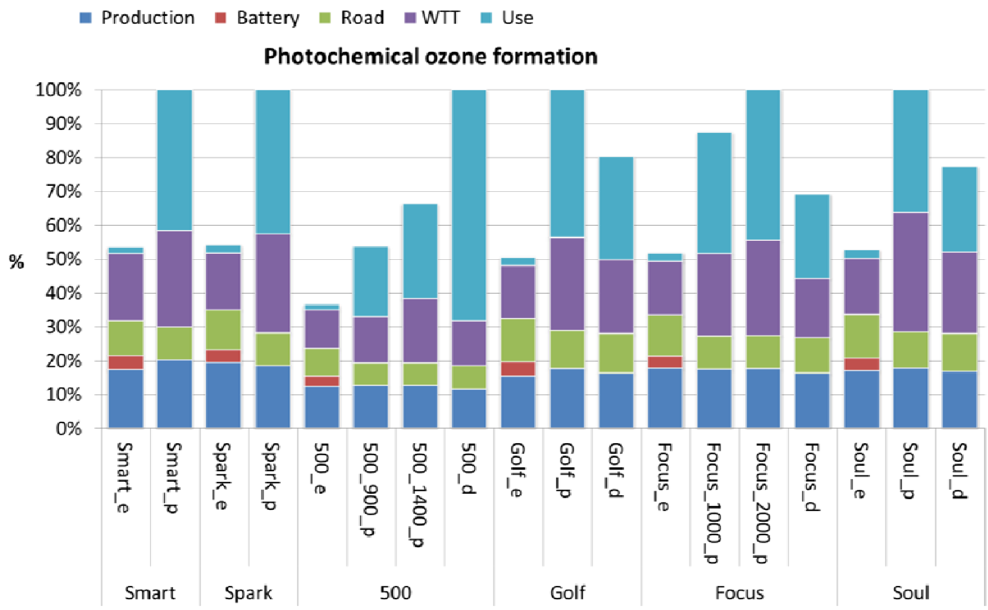

Fig. 6 Comparison in terms of Photochemical ozone formation over the entire life cycle of electric (_e), gasoline (_p) and diesel (_d) homologous vehicles.

It would be interesting, from a policy-maker point of view, to compare technologies in terms not only of per-phase contributions, but also of geographical distribution of the impacts. This analysis has been developed for the VW Golf models, considered as representative of the most widely used middle size vehicle on the market.

To this aim, the impacts have been allocated to four areas:

- Italy, where the use phase of the vehicles takes place, as well as the maintenance and end-of-life of vehicles and Li-ion battery. Besides, also the fossil fuels refining and distribution processes take place in Italy;
- Germany, where VW Golf vehicles are produced and the eGolf battery is actually assembled;
- European Union, where most of the semi-finished products (steel, glass, plastics, etc.) are produced;
- Extra EU, where most of row materials and fossil fuels come from and where the Li-ion battery cells are produced (more specifically in South Korea).

Fig. 7, Fig. 8 and Fig. 9, show the geographical distribution of respectively CO_2eq emissions, particulate matter formation and photochemical ozone formation. The figures indicate that, considering the only impacts that take place in Italy leaves the ranking among the vehicles performances unchanged. Moreover, the “environmental” gap between the electric vehicle and the traditional ones is even greater.

3.1 Sensitivity Analysis

The robustness of the results of the study has been evaluated through a sensitivity analysis, as suggested by the ISO 14040 for comparative LCAs. The sensitivity analysis investigated the effect of parameters that can heavily influence the environmental performance of vehicles. The first scenario considers that the electric vehicle is recharged by photovoltaic production during the day (36% of the total energy used in average by the electric vehicle) and by the marginal power mix during the night. The second scenario assumes a battery lifetime of 150000 km (regardless of the vehicles lifetime). Finally, the third and fourth scenarios consider that the electric vehicles lifetime are equal to the homologous gasoline and diesel vehicles lifetime respectively.

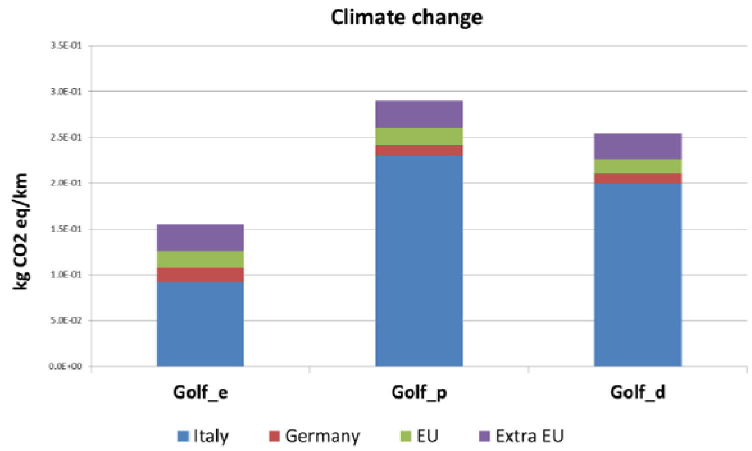

Fig. 7 Geographical distribution of pollutant emissions that contribute to climate change.

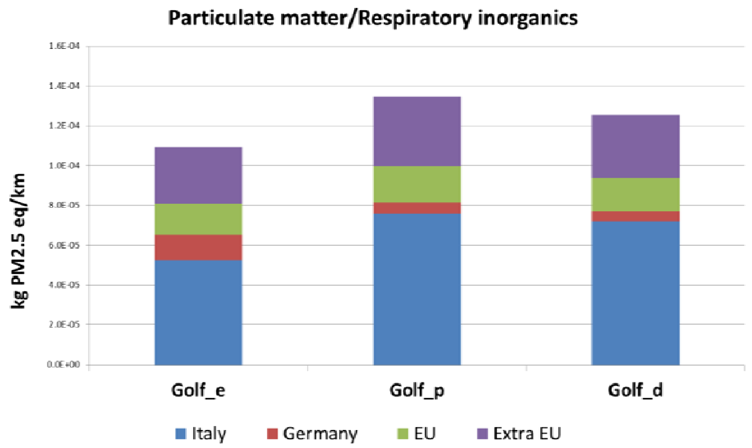

Fig. 8 Geographical distribution of pollutant emissions that contribute to the particulate matter formation (PM2.5).

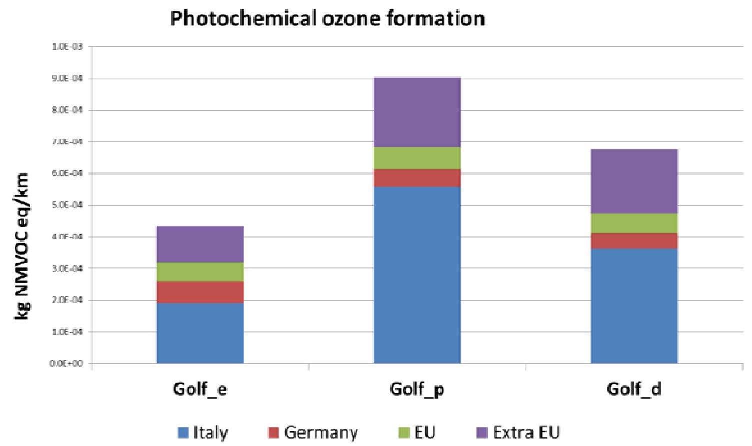

Fig. 9 Geographical distribution of pollutant emissions that contribute to the photochemical ozone formation (tropospheric ozone).

In all the analyzed scenarios, the ranking among the vehicles performances remain unchanged. In other words, even considering conditions adverse to electric vehicles, internal combustion engine vehicles show higher environmental impacts than electric ones, in terms of both climate change and atmospheric pollutants (i.e., particulate matter and tropospheric ozone).

Particular attention has been paid, lately, to the CO_2eq emissions due to the battery life cycle, even by general press An illustrative example is represented by: https://www.focus.it/tecnologia/motori/quanto-inquina-davvero-l-auto-elettrica.

Most of these communications refer to a recent study [28] that identifies a very wide range of variation for emissions of CO_2eq due to the battery production. Under the assumptions discussed above and with reference to the data published by Ecoinvent v3, we estimated for the production and dismantling processes of the eGolf 2016 a CO_2eq emission of about 2 t (1972 kg). It should be noted that the allocation system used for this study is the one called Ecoinvent default (APOS, at the point of substitution) and provides that about the 25% of the material constituting the battery can be recovered and reused for the production of new batteries. This battery is characterised by a capacity of 24.2 kWh and a weight of 312 kg. This means that the specific emissions of CO_2eq is equal to about 81.5 kg CO_2eq/kWh of capacity or 6.3 CO_2eq/kg of battery. According to our hypotheses and assuming that the average distance travelled could be reasonably set to 15000 km, the pay-back time for the surplus of CO_2eq emissions due to the battery lifecycle could be set in about one year of vehicle use (seeFig. 10).

The above-mentioned study [28] indicates 115-200 kg CO_2eq/kWh as a more realistic range of values. The latter value is almost three times higher than the one used in the present study (81.5 kg CO_2eq/kWh). The reasons for this difference could be various, but it should be surely noted that [5] considers technologies available in a period from 2011 to 2016 and that more recent studies considered in their review show lower values. Anyway, in a sensitivity analysis perspective, even considering a value of 200 kg CO_2eq/kWh (see “battery max” in Fig. 11) it can be seen that the CO_2eq emissions due to the battery life cycle do not compromise the advantages of the electric vehicle use.

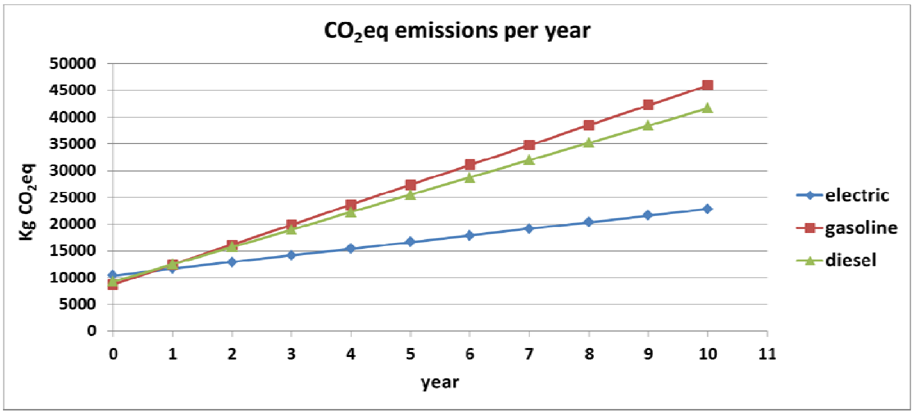

Fig. 10 Pay-back time for the surplus of CO_2eq emissions per life cycle phases due to the battery lifecycle. Assuming that the average distance travelled is 15000 km, the pay-back time is equal to about 1 year.

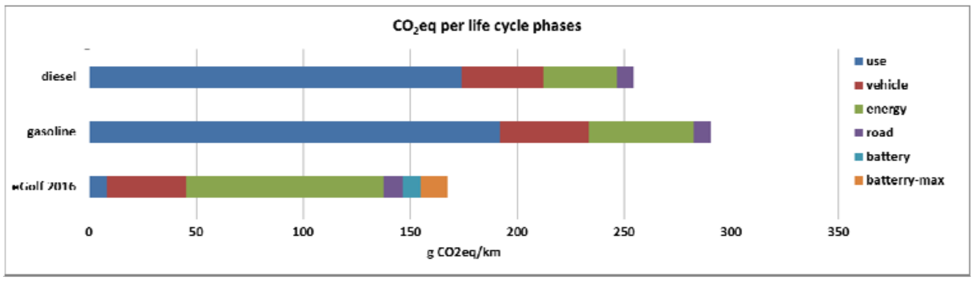

Fig. 11 CO_2eq emissions due to the battery lifecycle. The value associated to “battery” is referred to a battery with specific emissions of 81.5 kg CO_2eq/kWh capacity, while “battery-max” + “battery” is referred to a battery with specific emissions of 200 kg CO_2eq/kWh capacity.

Besides, it should be noted that, in order to assess future scenarios, it may not be entirely justifiable to extrapolate emissions data referred to the kWh of the battery capacity.

If this kind of analysis is appropriate for the evaluation of technological alternatives *ceteris paribus*, this is not true if the aim of the analysis is to determine future emissions of greater batteries (from 50 or 100 kWh). Indeed, emissions due to the battery life cycle strongly depend more on materials used to produce the battery itself (and thus on the battery weight) rather than on the energy density of the battery. In other words, for a given weight, the more the energy density of the battery grows, the more the battery capacity grows. As a consequence, CO_2eq emissions due to battery production and dismantling are likely to remain almost unchanged or at least to have a less than linear growth with capacity. A concrete example is represented by the 2016 eGolf (considered in this study) that is equipped with a battery of 24.2 kWh capacity, with a weight of 312 kg. The 2017 version of the vehicle is equipped with a battery of 35.8 kWh capacity (almost 50% more than 2016), with a weight of 318 kg. Moreover, Kreisel Electric[3] claims to be able to produce a battery of 55.7 kWh capacity, with a weight of 330 kg and a lifetime of more than 400000 km.

4. Conclusion

The analysis carried out confirms that, for all the considered sizes – from micro cars to family cars, passing through small and compact, electric vehicles present environmental impacts lower than the homologous internal combustion engine vehicles. This is particularly true if we consider Climate Change and pollutants emissions that contribute to impact categories such as Particulate Matter formation, Air Acidification or Photochemical Ozone formation. Moreover, regardless of the size, electric vehicles are not able to prevail, at present, for aspects that concern Freshwater Eutrophication or Human Toxicity for which an important role is played by the impacts due to the battery life cycle. In general, the environmental impacts of the electric vehicles are dependent on the vehicle weight (that influences both consumptions and vehicles production). In that regard, it should be pointed out that this study considers electric vehicles that are derived from the homologous internal combustion engine versions rather than specifically designed.. The choice of the vehicles has been driven by the goal of comparing electric vehicles with homologous diesel and gasoline vehicles that were present on the market, i.e. offering, as far as possible, the same service to users. One interesting point for future studies should be to investigate the environmental performances of vehicles designed *ex novo*, examining in depth aspects concerning vehicle design and materials used, especially in the production phase of the vehicle. Nevertheless, this consideration opens the issue of how to consider cross technological improvements, namely those improvements (i.e., low rolling resistance tyres, body in carbon fibre) that could be applied also to internal combustion engine vehicles, being independent from the propulsion system.

Acknowledgments

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