Comparing the life-cycle CO_2 emissions of the best-selling electric and internal combustion engine cars in Italy

Romeo Danielis*[1], Marco Giansoldati*, Mariangela Scorrano*

[*] *Dipartimento di Scienze Economiche, Aziendali, Matematiche e Statistiche "Bruno de Finetti"*
Università degli Studi di Trieste, Via dell'Università, 1 – 34123 Trieste, Italy.

Abstract

Introduction. The question of whether battery electric vehicles (BEVs) emit more or less CO_2 than Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs) along the entire life cycle is still a debated topic in the scientific literature and in the popular press. This paper contributes to the debate by providing an estimate for the best-selling cars in Italy.

The methodology. On the basis of the VCA database reporting the CO_2 emissions of most of the cars on sale in Italy in 2016, we perform a life-cycle analysis including fuel and electricity production, car\battery manufacturing and disposal, and direct and indirect emissions during the car use.

Results. Currently, the BEVs emit 24% less CO_2 than gasoline ICEVs, 26% less than diesel ICEVs, and 12% less than HEVs. In 2026 the savings could further increase to 38%, 40% and 24%, respectively, assuming the past trends towards a cleaner electricity mix and no improvement in the conventional and HEVs technologies

Conclusion. BEVs should be promoted as an alternative to the ICEVs not only because they reduce air and noise pollution in urban areas but also because they contribute to decrease global CO_2 emissions.

Keywords: battery electric vehicles (BEVs), Internal Combustion Engine Vehicles (ICEVs), Hybrid Electric Vehicles (HEVs), CO_2 emissions, life cycle assessment

1. Introduction

The scientific and industrial progress in battery production together with the manufacturing effort of some large Asian companies (such as the Japanese Panasonic and the Koreans LG and Samsung) lead to the development and production of better electric batteries in terms of performances (kWh for unit of weight, mass, volume, numbers of charging cycles, and charging times) and costs, not only for the electronic industry but also for the car industry. This allowed some new car manufacturers (Tesla Motors) or established ones (initially, Nissan and Renault, and BMW, Chevrolet plus others later) to develop purely electric vehicles, i.e. equipped only with an electric engine (henceforth BEV, *Battery Electric Vehicle*) as an alternative to the traditional cars with internal combustion engine (henceforth ICEV, *Internal Combustion Engine Vehicle*).

The comparison between BEVs and ICEVs can be made considering many features including performances (acceleration, speed, road holding, driving comfort), autonomy, batteries charging times, energy and fuel efficiency and, of course, purchase, use and maintenance cost. In this paper we focus on CO_2 emissions, neglecting emissions of local pollutants (PM, CO, NOx, SO_2, O_3, VOC) and noise pollution. Furthermore, we do not discuss the consumption of rare materials, acidification (Messagie *et al.* (2014) or aspects of geopolitical strategy linked to the independence from oil producing countries.

[1] Corresponding author: Romeo Danielis (romeo.danielis@deams.units.it). Tel.: +39 040 5587076; fax: +39 040 567543

Our interest for the problem of CO_2 emissions stems from the fact that transportation is responsible for the main part of CO_2 emitted in Italy. In 2014 the contribution of land transportation (goods and passengers) was 29.4%, compared to the 28.2% of the energy sector, the 14.4% of the manufacturing industry, and the 12% of the housing sector. The potential reduction in CO_2 emissions in passenger transport deriving from the substitution of ICEVs with BEVs is thus a very important environmental issue.

The advantage in terms of local pollutants is also obvious: BEVs have zero emission during their use, thus being particularly appealing for the urban use. However, the production of electricity requires in many cases the use of fossil fuels (coal, oil, natural gas or biomasses). It is thus correct to admit that BEVs determine a geographic transfer of emissions of local pollutants: from the cities to the places where the plants for the production of electricity are located. When these are located in low densely populated areas, with no wind spreading pollutants in residential areas, the damage deriving from local pollutants is probably limited. This is different from the case of CO_2 emissions since the place of emission is not relevant, but it is instead important whether the overall amount of emissions stemming from the use of BEVs is greater or not than that deriving from the ICEVs. The aim of this paper is limited to this topic. Such a topic has been debated - with reference to the American and, less frequently, to the European case – in several scientific and non-scientific contributions, with no clear-cut conclusion, as reported in the next Section. This paper is focused on Italy. We want to find out how the country specificities in terms of the car models more frequently bought and of the electricity mix affect the overall result. As it will be documented in the next Sections, the Italian fleet comprises mostly small to medium size cars, hence less polluting than the larger cars, but the electricity mix is rather clean, since the coal share has been largely substituted over the years by natural gas.

Before entering into the details of the analysis, it is important to point out that the comparison between BEVs and ICEVs is usually made between pure electric cars, on the one hand, and gasoline or diesel cars, on the other hand. Yet, the spectrum of vehicles is more complex, as there are also alternative fuel vehicles such as natural gas cars, liquid propane gas cars, hybrid cars (such as the Toyota Prius or the Toyota Auris) and, more recently, plug-in hybrid cars, known also as PHEVs (the most popular model in Europe is the Mithsubishi Outlander; while in the United States the Chevrolet Volt). In this paper, HEVs, which reached in 2016 a market share of 2.1% in Italy, will be compared to the diesel or gasoline ICEVs, whereas PHEV will not be considered since their presence in Italy is still very limited.

The main contribution of this paper is to provide a life-cycle comparison of the CO_2 emissions of the different car technologies (BEV, diesel ICEV, gasoline ICEV, HEV) based on the most frequently sold cars in Italy relative to the year 2016. To our knowledge, no similar estimate has been yet published. Apart from the focus on Italy, a specific feature of this paper is to compare the most popular models and not a generic or representative car models. Hence, the result account for the specific consumer's preferences.

We anticipate that the main result is that, on the basis of the 2016 electricity mix, the BEVs generate a lower amount of CO_2 emissions than ICEVs: 24% less than gasoline ICEVs, 26% less than diesel ICEVs and 12% less than HEVs. If the electricity mix continues to improve as in the last 27 years while no improvement takes place for the ICEVs, the advantage of the BEVs over to the other technologies will increase in the year 2026 to 38%, 40% and 24%, respectively. Obviously, these results depend on available data and on various assumption that are illustrated in detail in the paper.

The article is structured as follows: Section 2 reviews the literature, Section 3 illustrates the methodology, Section 4 describes the data on direct and indirect CO_2 emissions in the car use phase, Section 5 illustrates how the total life-cycle estimates have been made. Section 6 draws the main conclusions and highlights the main caveats.

2. Literature review

There is a large number of papers comparing the energy and environmental performance of vehicles powered by different fuels. Hawkins et al. (2012, 2013a) review 55 studies from peer-reviewed and grey literature, providing environmental, energy or material assessments. Rusich and Danielis (2013, Table 1, p. 4) summarize the results presented in 35 recent papers comparing different vehicle technologies regarding the environmental impact only. They find that BEVs generally emit lower CO_2 emissions than the conventional internal combustion engine vehicles ICEVs. The result is, however, strongly dependent on how electricity is produced and distributed. If carbon intensive sources are used, CO_2 emissions produced by BEVs are comparable or, in some cases, even higher than some advanced ICEVs[2]. Abdul-Manan (2015) deals with the uncertainty in estimating the potential reduction of Greenhouse Gas (GHG) emissions. He performs an international analysis by examining the average carbon intensity for grid electricity from over 200 countries, by considering all vehicles models on sale in the USA. The overall conclusion is that in many instances BEVs emit less GHG emissions than ICEVs but more than HEVs. The Union of Concerned Scientists' report (UCS, 2015) focuses on global warming emissions in the USA. By recognizing the need to perform a spatially disaggregated analysis, they divide the US into 26 "grid regions". The emissions connected with battery production and disposal are included in the analysis, although a high level of technological uncertainty is recognized. The emissions from extraction and transportation of fuels used in electricity production, the emissions from extraction, refining, and the transportation of the fuels to filling gasoline stations are also included. The analysis is limited to two BEVs (the Nissan LEAF and Tesla Model S) and two comparable ICEVs (a midsize car with a fuel economy of 29 MPG and a vehicle weight of 3,000 lbs). The main finding is that over its lifetime — from manufacturing to operation to disposal — a BEV generates about 50% fewer GHG emissions than a comparable gasoline car. Holland et al. (2015) perform a very complex and detailed analysis, combining a theoretical discrete-choice model of vehicle purchases, an econometric analysis of electricity emissions, and the AP2 air pollution model to estimate the geographic variation in the environmental benefit from driving electric vehicles. They include both global and local air pollutants (from driving and electricity production, inclusive of the diffusion models), measured at county level and estimate the marginal emissions factors for each pollutant at each of the 1,486 power plants considered due to an increase in regional electricity load. A set of BEVs and equivalent gasoline vehicles are compared in terms of damages and environmental benefits. A scenario analysis is also performed. They find that: a) the second-best BEV purchase subsidy ranges from \$3,025 in California to -\$4,773 in North Dakota, with a mean of -\$742; and b) that 90% of local environmental externalities from driving BEVs in one state are exported to others, implying they may be subsidized locally, even when the environmental benefits are negative overall. Messagie et al. (2014) analyze the European countries. They report the results of a full LCA of petrol, diesel, fuel cell electric, compressed natural gas, liquefied petroleum gas, hybrid electric, electric battery, bio-diesel and bio-ethanol vehicles. They consider all the family cars registered in Europe in 2011, together with their raw material production, transport, manufacturing, use, maintenance and end-of-life. As far as CO_2 emissions are concerned, they find that conventional vehicles using fossil fuels have the largest impact on climate change. Hybridization has a positive effect on climate change. Except for the bioethanol vehicle using fuel produced from sugar cane, BEVs are found to have the lowest impact on climate change. Yet, the energy source used to generate the electricity is of crucial importance. In this respect, mineral resource depletion, fuel cell electric, HEVs and BEVs have the highest impact due to the use of specific materials in the fuel cell, i.e. the NiMH and the lithium battery. However, the authors argue that recycling such components might reduce significantly this impact. The selection of the vehicle

[2] By making use of a meta-analysis to estimate the demand for electric vehicles, Giansoldati et al. (2017) consider, among other attributes, also the level of global and local emissions. They notice that in most of the contributions they analyzed the measurement of pollutants released in the atmosphere by a selected vehicle is not reported in absolute terms, but often in comparison with those of an alternative powertrain technology.

segment has an influence on the environmental impact: segments dominated by larger, heavier vehicles have a larger impact. More recently, Messagie (2017) compiled a study for Transport&Environment concluding that environmental performance of EVs is today already better than the one of conventionally fueled vehicles. The life cycle analysis shows that even when powered by the most GHG intensive electricity in Europe, the carbon footprint of EVs is lower.

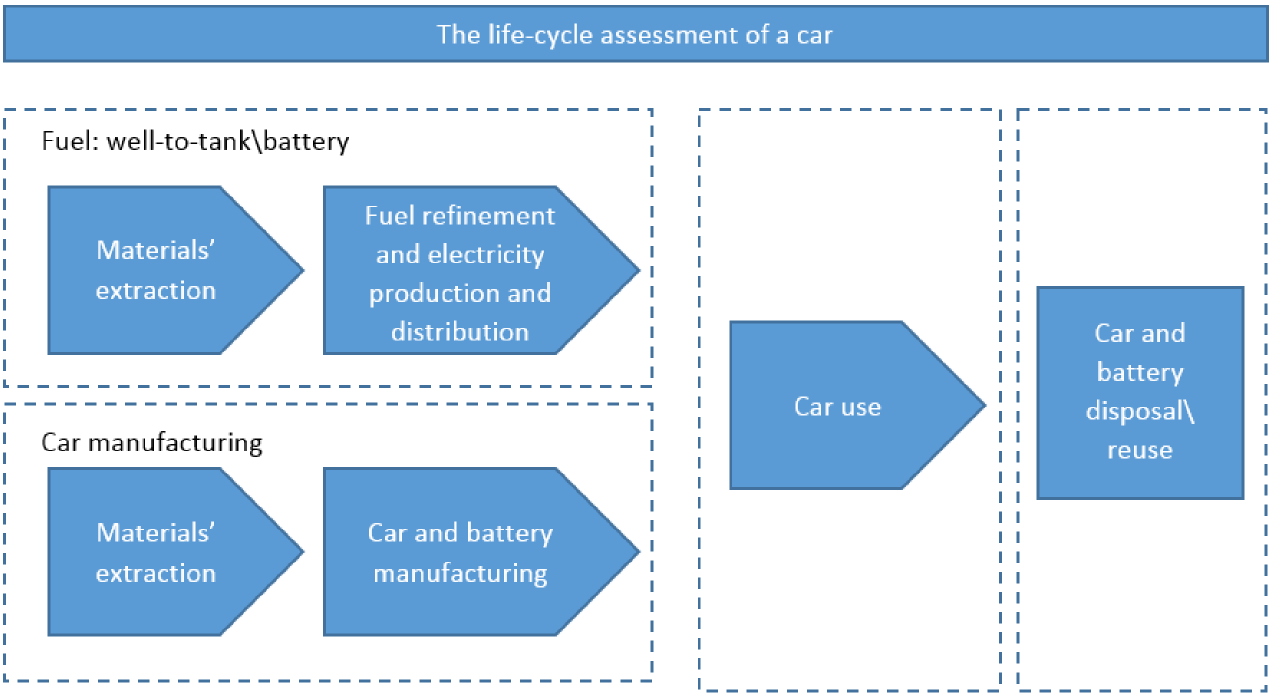
3. The methodology

CO_2 emissions depend on a number of factors. A comprehensive analysis which aims to be as complete as possible has to take into account the entire life cycle of both car and the fuel. It requires an accurate knowledge of materials and technologies used in the production processes, as well as the availability of data not always easy to obtain, either because confidential or covered by industrial secrecy. In addition, some of the parameters to be applied might not be stable over time due to technological progress, industrial choices, market trends or the regulatory framework. Nonetheless, there is a sufficient consensus that an analysis on the entire car life cycle has to take into account the emitted CO_2:

- in the phases of extraction, refinement, and distribution of the fuel needed to operate the ICEVs or to produce electricity;
- in the production and transmission of electricity;
- in the production of car components, including the battery, their assembly, disposal or reuse;
- during the car use phase.

Graphically, the car life cycle phases may be depicted as in Figure 1.

Figure 1- Schematic representation of the life-cycle analysis of a car



To estimate the model, the following data are required:

- CO_2 emissions to extract and refine the raw materials needed to produce fuels, electricity, cars and batteries.
- CO_2 emissions to produce and distribute fuels and electricity;
- CO_2 emissions to produce and dispose of the car;
- CO_2 emissions to manufacture and dispose of the batteries;

- CO_2 emission per km travelled by ICEVs (gasoline, diesel, hybrid);
- electricity consumption per km travelled by BEVs;

4. Data and direct and indirect CO_2 emissions during the car use phase

In this section we will illustrate: a) the data used to estimate the direct CO_2 emissions of ICEVs and HEVs caused by fuel combustion; b) the indirect emissions of BEVs due to electricity production and distribution; and c) summarize the results on the use phase of the car.

4.1 Data on direct CO_2 emissions of ICEVs and HEVs caused by fuel combustion

The cars sold in the European market can be differentiated by brand, model and type. The best known database containing the most relevant information on cars is managed by the U.S. Environmental Protection Agency (EPA, 2016). Yet, since this database does not include some of the cars sold in the Italian market, we make use of the database maintained on behalf of the British Government by the Vehicle Certification Agency (VCA) (http://www.dft.gov.uk/vca/). The VCA database we downloaded in August 2016 contains information on 4,511 car models on sale in the United Kingdom, including data on fuel consumption during urban, extra-urban and combined trips and CO_2 emissions per km travelled. VCA does not conduct its own tests. It states to have obtained the data from official documents, alerting the users that differences in consumption between data reported in the database and those obtained in real traffic may occur. The reported fuel consumption and CO_2 emission levels most likely corresponds to the New European Driving Cycle (NEDC), defined in accordance with European directives. These data, as largely recently debated in the press due to the "dieselgate", are probably more "generous" than those obtained by the EPA cycle test.

Considering all models inserted in the VCA database and categorized by type (as proposed by the VCA), the average values of CO_2 emitted in the use phase is reported in Table *1*. The values refer to the combined cycle, which is the average of the values recorded in the urban and extra-urban cycle.

Table 1 – Average values of CO_2 emissions for cars in the database distinguished by type of supply

Type	N° of cars in the database	Average CO_2 emissions (g/km)	Minimum CO_2 emissions (g/km)	Maximum CO_2 emissions (g/km)
Gasoline Electric	8	158	139	199
Gasoline	2095	151	84	380
Diesel	2275	124	79	261
Diesel Electric	11	110	94	164
Gasoline Hybrid	71	107	70	168
Electricity/Diesel	4	48	48	48
Electricity/Gasoline	27	51	13	84
Electricity	19	0	0	0
Total	4510			

Source: Our elaboration from VCA (2016) data

Most cars are either fueled by diesel or gasoline. The cars classified as "Gasoline electric" have the largest average emissions, equal to 158 CO_2 g\km. This category comprises 8 hybrid cars including some luxury cars manufactured by BWM and Lexus.[3] Their emissions vary from a minimum of 139 CO_2 g\km to a maximum values of 199 CO_2 g\km. The cars classified as "Gasoline" emit on average 151 CO_2 g\km, with a minimum of 84 CO_2 g /km and maximum of 380 CO_2 g\km. A lower average value is recorded in the diesel category 124 CO_2 g\km (min 79 and max 261). The average emissions of "Gasoline hybrid" is equal to 107 CO_2 g\km. HEVs have much lower average emission levels. Of course, pure electric cars have zero emissions during use.

From the database we search data for the 10 top selling models in Italy during the year 2016 (Table 7, Table 8, Table 9 in the Appendix). The information on the top selling models comes from UNRAE (2016). More recent data show the most sold models comprise almost the same models. Since some models were not included in the database (e.g. Lancia Ypsilon) and since for hybrid technology fewer than 10 model were available, our selection does not include exactly 10 cars for every fuel type. We believe that this number asymmetry does not have a large impact on our results. The average values of CO_2 emissions of the cars we selected are reported in Table 2.

Table 2 – CO_2 Emissions by propulsion system in the best-selling Italian cars

Type of propulsion system	Average CO_2 emissions (g/km)	Minimum CO_2 emissions (g/km)	Maximum CO_2 emissions (g/km)
Gasoline ICEVs	111	95	125
Diesel ICEVs	108	92	129
HEVs	92	48	121
BEVs	0	0	0

Source: our elaboration on VCA (2016) data

It can be observed that, on average, the best selling cars in Italy have lower CO_2 emission than the cars listed in the VCA database (Table *1*). Gasoline ICEVs emit on average 111 g CO_2/km whereas gasoline cars in the VCA database emit on average 151 g CO_2/km. Similarly lower average emissions are found for the diesel ICEVs (108 versus 124) and for the HEVs (92 versus 107). It is a clear indication that Italian buyers purchase cars with smaller engines. These data are in line with the values reported on the UNRAE website which reports for the year 2016 an estimate of the average CO_2 emissions of 112,7 (g/km) for the cars sold in Italy.

As already mentioned, both our estimates based on the VCA database, and those provided by the UNRAE database derive from the documents supplied by car manufacturers and resulting from the application of the NEDC test which are notably lower in terms of fuel consumption than those reported by the EPA database. For the subset of the cars for which we had information from both sources (15 out of 30 cars) we have compared the two databases. It results that the EPA estimates of the cars' CO_2 emissions in the combined cycle are 76% higher than those reported in the VCA database. Since the EPA database does not include all the models on sale in Italy, we opted for using the VCA data. A potential underestimation is of the "real world" CO_2 emissions, however, to be acknowledged.

4.2 Data and estimates of indirect emissions of BEVs due to electricity production and distribution

The estimation of indirect emissions of electric vehicles requires information on the average consumption of electricity per km travelled and on CO_2 emissions generated to produce and distribute electricity.

[3] The eight cars in the sample are the BMW 3 Series Saloon F30, from February 2012, BMW 3 Series Saloon F30, from February 2012, BMW 5 Series F10/F11, from March 2010, BMW 5 Series F10/F11, from March 2010, BMW 5 Series F10/F11, from March 2010, LEXUS LS, MERCEDES-BENZ S-Class Limousine, Model Year 2016, MERCEDES-BENZ S-Class Limousine, Model Year 2016.

The former is retrieved data from the VCA database for 12 BEVs (Table 10 in the Appendix). Since the BEV market still in its initial phase and their market share is still highly unstable, we decided to keep al 13 cars. On average, the BEVs consume 145 kWh of electricity per km travelled. It can be noticed that their energy efficiency is quite heterogeneous and affected, although not exclusively, by their size. The BEVs are on sale in Italy, are sufficiently comparable (exception made for Tesla Model S) to the selected best-selling ICEVs and HEVs. Also for BEVs we compared the data on energy consumption reported by the VCA database with those published by the EPA. EPA estimates are on average 32% higher.

The information on CO_2 emissions generated to produce and distribute electricity is supplied by ISPRA (Table 3), an agency of the Italian government. It refers to the CO_2 quantity per kWh consumed and includes the energy losses deriving from the electricity transmission.

Table 3 – Factor emission per kWh of electricity at the counter [g CO_2/kWh]

Year	1990	2000	2005	2010	2011	2012	2013	2014	2015	2016
g CO_2/kWh	577	498.3	464	388	377.6	372.6	327.3	309.4	315	330.6*

Source: ISPRA (2017, p. 28), *estimated

The 2016 value is equal to 330.6 g. CO_2/kWh. If we multiply this value by 0.145 KWh on average needed to cover one km with an electric car, we have an estimate an estimate of the CO_2 emitted on average per km travelled with a BEV. The estimate is equal to 51 grams of CO_2.

It can be observed that there has been a very large improvement in factor emission in the last decades due to the substitution of oil with natural gas, and to the gradual increase of solar and wind energy.[4] By regressing the time series of the factor emissions over time, it results a yearly decrease of 9.5 points (the R-squared of the regression is equal to 0.9 and the standard error of the coefficient is – 15). Extrapolating this trend to 2026, one gets a value of 241, which represents a time-series estimate of the CO_2 factor emission of electricity consumption if the past trend of improvement would continue with the same pace as in the past 26 years. The assumption makes sense but it is rather optimistic since: (a) much of the substitution of coal with natural gas has already taken place, and (b) the increase of renewables sources has benefitted in the past of large subsidies that have been reduced in the recent years due to public budget constraints. Obtaining an emission factor equal to 241 in 2026 might prove, consequently, a quite challenging policy goal.

.

4.3 Summary of the results concerning the use phase of the car

Direct and indirect CO_2 emissions during the use phases of car use of the four propulsion systems analyzed are summarized in Table 4.

Table 4 – Average CO_2 emissions for type of supply in the selected sample for Italy

	Average CO_2 emissions (g/km)
ICEV – Gasoline*	111
ICEV – Diesel*	108
HEV – Hybrid*	92
BEV**	51

[4] In 1990 the electricity mix was 41% oil, 20% natural gas, 12% coal, 20 renewables (mostly water) and 1% others. In 2015 the electricity mix was 2% oil, 38% natural gas, 15% coal, 39% renewables (15% water, 5% wind, 9% sun, 2% geothermic and 7% biomass and others) and 5% others.

* Directly emitted in the use of car due to fuel combustion
** Indirectly emitted to produce electricity

It results that ICEVs emit more than twice the CO_2 than BEVs, whereas HEVs emit 80% more CO_2 than BEVs[5].

5. Total life-cycle emissions

5.1 The emissions deriving from car manufacturing

In order to a full life-cycle assessment, one needs to add the emissions generated during the manufacturing of the car and batteries and their end of life treatment. Since the BEVs are relatively new and the battery technology, especially regarding the end of life treatment, is rapidly evolving, the estimates presented in the literature are still controversial. We refer to the contributions by Daimler AG (2012), Hawkins et al. (2012, 2013), and Automotive Science Group (2014).

Table 5 – Hawkins et al. (2013) estimates of CO_2 emissions in grams of g CO_2 equivalent per km.

	BEV – European mix, Li-NCM battery*	ICEV - diesel	ICEV - gasoline
Base car	34,0	34,0	34,0
Engine	2,7	4,0	4,0
Other components	4,8	5,5	5,5
Battery	31,0	0,6	0,6
Phase of use, not connected to the fuel	7,2	8,9	8,9
Fuel\electricity	97,0	170,0	200,0
Disposal\reuse	4,7	3,4	3,4
Total	181,4	226,4	256,4

*Li-NCM: nickel-cobalt lithium ion
Source: Hawkins et al. (2013)

Table 5 reproduces part of the wider and largely-cited scholarly article by Hawkins et al. (2013). Their analysis concerns nine types of impact beyond the greenhouse effect. [6] The reference BEV is the 24 kWh battery Nissan Leaf and the reference ICEV is Mercedes Model A. Results are reported in terms of CO_2 grams equivalent, a unit of measurement that allows to take into account greenhouse gas with different climate-change effects.[7] It can be observed that:

- BEVs with a European electricity mix, overall produce less emissions than ICEVs: 29% less than gasoline ICEVs and 20% less than diesel ICEV.[8]
- Exception made for the significant difference linked to fuel\electricity (with ICEVs emitting more than twice the BEVs, similarly to what we estimated for Italy), the main difference between ICEVs and BEVs is related to the battery: BEVs' batteries generate more than 30g of CO_2 equivalent than the ICEVs.

---

[5] For a comparison between this result and those obtained for other European countries, see Cavallaro et al. (2018).

[6] Global warming (GWP100), terrestrial acidification (TAP100), particulate matter formation (PMFP), photochemical oxidation formation (POFP), human toxicity (HTPinf), freshwater eco-toxicity (FETPinf), terrestrial eco-toxicity (TETPinf), freshwater eutrophication (FEP), mineral resource depletion (MDP), and fossil resource depletion (FDP).

[7] For example, a ton of methan that has a climate-change potential 21 times higher than CO_2, is accounted as 21 tons of CO_2 equivalent. In this manner it is thus possible to compare different types of gases in terms of their contribution to the greenhouse effect. The higher is the global warming potential the larger is the contribution to the greenhouse effect.

[8] Hawkins et al. (2013) update their previous contribution and state: "We find that EVs powered by the European electricity mix reduce GWP by 26% to 30% relative to gasoline (originally 20% to 24%) and 17% to 21% relative to diesel (originally 10% to 14%)."

As a result, electricity consumption accounts for 53% of total emissions for BEVs, whereas the production and end-of-use treatment of the battery account for 17% of total emissions. As far as ICEVs are concerned, fuel combustion account for 75-78% of total emissions.

5.2 An estimate of the life-cycle emissions in Italy of the different car technologies

The estimates made by Hawkins et al. (2013), reported in Table 5, are fully accepted by us a base for our estimates, but for the row fuel\electricity (in bold) which is substituted by our estimate on the direct and indirect CO_2 emissions in the use phase based on the Italian electricity mix and on the best-selling car in the Italian market. For the HEVs, not considered by Hawkins et al. (2013), we use the same estimates of gasoline ICEVs since many HEV are fueled by gasoline. The results are illustrated in Table 6.

Table 6 – A first estimate for Italy: Average CO_2 emissions (g/km)

	BEV	ICEV - diesel	ICEV – gasoline	HEV
Base car	34,0	34,0	34,0	34,0
Engine	2,7	4,0	4,0	4,0
Other components	4,8	5,5	5,5	5,5
Battery	31,0	0,6	0,6	0,6
Phase of use, not connected to the fuel	7,2	8,9	8,9	8,9
Fuel\electricity	**48,0**	**108**	**111**	**92**
Disposal\reuse	4,7	3,4	3,4	3,4
Total	135,4	164,4	167,4	148,4

Source: Based on Hawkins et al. (2013) with our estimates on Fuel\electricity.

The main result is that BEVs produce a lower amount of CO_2 emissions than ICEVs: 24% less than gasoline ICEVs, 26% less than diesel ICEVs and 12% less than HEVs. These results are based on the 2016 electricity mix. If the electricity mix continues to improve as in the last 27 years (as estimated in Scorrano and Danielis, 2018), reducing the emission factor from 330.6 to 241, the savings of the BEVs relative to the other propulsion systems would further increase: 38% less relative to gasoline ICEVs, 40% less relative to diesel ICEVs and 24% less relative to HEVs. Of course, these estimates assume no improvement in the conventional and hybrid engines.

5.3 CO_2 emitted to product ion lithium batteries: an in-depth analysis

The battery, its production and disposal or use; is a very important component of the BEVs, which is able to make a difference with the ICEVs in terms of CO_2 emitted. Hawkins et al. (2013) base their estimate of 31 g of CO_2 equivalent for BEVs battery on the assumption that the nickel-cobalt lithium ion battery (LiNCM) lasts for 150.000 km. They acknowledge this hypothesis is crucial for the estimation, despite it is not accepted by all members of the scientific community. The life of the battery mostly depends on its degree of deterioration, the number of charging cycles performed, the type of charging and the climate. However, the knowledge of how these aspects impact battery life is still at early stages. On the one hand, the real battery life surprised many commentators lasting much longer than predicted; on the other hand, there is a growing diffusion in the BEVs market of batteries with much larger capacity (up to 100 kWh to improve cars range, and up to 400 kW charging technology to reduce charging time).

A recent contribution by Dunn et al. (2015) shows, for example, that CO_2 emissions connected to the production of batteries are not that large. They argue a) that CO_2 emissions connected to lithium-ion batteries depend from the scale of production: the larger the scale the lower the emissions; and b) that in some cases the battery recycle allows to drastically reduce the emissions that their manufacturing generate. These assumptions lead them to conclude that larger CO_2 emissions by BEVs with respect to ICEVs deriving from the battery production are completely compensated after only 25 thousand mm of travel.

5.4 Production and distribution of oil fossil fuels

The refinement and transportation of oil fossil fuels leads to the production of large amounts of CO_2 emissions that should be included in the ICEVs life cycle assessment. In a similar fashion, the emissions released in the extraction of energy sources required to produce electricity, such as coal and natural gas, should be incorporated in the BEVs life cycle assessment. However, the evaluation of these emissions is affected by a substantial lack of reliable information. Given these uncertainties and difficulties, such emissions are often neglected or are taken into account in a not very transparent manner. In order to avoid the insertion of further elements of uncertainty, we thus decided not to include the abovementioned emissions in our estimates. Nevertheless, we refer the interested reader to Edwards et al. (2013) for an in-depth analysis.

6. Conclusion and caveats

The question of whether BEVs emit more or less CO_2 than ICEVs along the entire life cycle, i.e. including the extraction of raw materials, production of cars and fuels, and use of automobiles, is still debated in the scientific literature and in the media. To the best of our knowledge, there are no estimates that considered the Italian case.

This article aims to fill this gap providing a comparative estimation through the following strategy. First, we relied on the VCA database which includes information on energy consumption and CO_2 emissions for more than 45 thousand cars on sale in the United Kingdom (and most of them also in Italy). Second, we focused only on the top selling cars in Italy in 2016. Third, we took into account CO_2 emissions during the production of electricity as estimated by ISPRA (2017) for the year 2016 and we provided a forecasts for the year 2026. Fourth, we incorporated our estimates with the one made by Hawkins et al. (2013) for the manufacturing and disposal of cars and batteries.

The main result is that BEVs overall emit lower CO_2 than ICEVs and, more precisely, 24% less than gasoline ICEVs, 26% less than diesel ICEVs, and 12% less than HEVs. If the electricity mix continues to improve in Italy with the same pace shown in the last 27 years, the savings of the BEVs relative to the other engines could further increase and lead to emission that will be 38% less than gasoline ICEVs, 40% less than diesel ICEVs and 24% less than HEVs, assuming no improvement in the conventional and hybrid propulsion systems.

Three main caveats apply.

1. There are several areas of uncertainty, in particular with reference to the emissions deriving from the production and disposal of batteries for electric cars, but also with respect to the emissions released for the extraction, transportation and refinement of gasoline and diesel, as well as for the extraction and transportation of coal and natural gas.
2. BEVs and ICEVs are highly segmented by size and weight, therefore a more homogeneous comparison could be performed focusing on specific segments. In particular, BEVs are differentiated (and will probably be even more in the future) on the basis of the battery size and range. PHEVs were not considered due to their limited diffusion in Italy.
3. A widely recognized key factor to undertake the comparison is the electricity mix. In the recent years, the share of renewable sources has increased in Italy (and worldwide) helping to make BEVs more environmentally efficient. This trend derives from technological innovation, choices of economic agents (families, firms, energy producers) and from public policies, all factors that influence the parameters employed in this study. As long as the share of renewable sources will

continue to grow, the advantage of BEVs in terms of CO_2 emissions relative to ICEVs will further increase.

References

Abdul-Manan AFN (2015) Uncertainty and differences in GHG emissions between electric and conventional gasoline vehicles with implications for transport policy making. Energy Policy 87: 1–7.

Automotive Science Group (ASG) (2014-02-04). "Life-cycle Assessment of 1,300 Models Reveals Best of 2014". ASG Press Room. Retrieved 2014-02-22.

Cavallaro, F, Danielis, R, Nocera, S, & Rotaris, L (2018). Should BEVs be subsidized or taxed? A European perspective based on the economic value of CO2 emissions. Transportation Research Part D: Transport and Environment, 64, 70-89. Daimler AG. (2012). Environmental brochure: Smart fortwo electric drive. Daimler AG, Mercedes-Benz Technology Center, Stuttgart, Germany.

Dunn JB, Gaines L, Kelly JC, James C, Gallagher KG (2015) The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy & Environmental Science, 8(1), 158-168.

Edwards R, Larivé JF, Rickeard D, Weindorf W (2013) WELL-TO-TANK Appendix 4 - Version 4.0. Description, results and input data per pathway. Publications Office of the European Union, Luxembourg.

Giansoldati, M., Rotaris, L., Danielis, R., & Scorrano, M. (2017). La stima della domanda di auto elettriche basata sulla metanalisi. Rivista di Economia e Politica dei Trasporti, n. 2, art. 5.

Hawkins T, Gausen O, Stromman A (2012) Environmental impacts of hybrid and electric vehicles—a review. International Journal of Life Cycle Assessment 17(8): 997–1014

Hawkins TR, Singh B, Bhawna B, Majeau-Bettez G, Strømman AH (2013a) Corrigendum to: Comparative environmental life cycle assessment of conventional and electric vehicles Journal of Industrial Ecology. Journal of Industrial Ecology, 17(1), 158-160.

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013b) Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of Industrial Ecology, 17(1):53–64.

Holland SP, Mansur ET, Muller NZ, Yates AJ (2015) Are there environmental benefits from driving electric vehicles? The importance of local factors, American Economic Review106(2):3700−3729

ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale (2017) Fattori di emissione atmosferica di CO_2 e altri gas a effetto serra nel settore elettrico, Rapporto 257, Rome.

Messagie M, Boureima FS, Coosemans T, Macharis C, Mierlo JV (2014) A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. Energies 7(3): 1467-1482.

Rusich A, Danielis R (2015) Total cost of ownership, social lifecycle cost and energy consumption of various automotive technologies in Italy. Research in Transportation Economics 50, 3-16.

Scorrano M, Danielis (2018) Scenari futuri del mix elettrico in Europa e in Italia: un'applicazione del modello ARIMA per l'analisi delle serie storiche, in: Giorgio Osti, Luigi Pellizzoni (a cura di), Energia e innovazione tra flussi globali e circuiti locali, Trieste, EUT Edizioni Università di Trieste, 2018, pp. 103-120.

U.S. Environmental Protection Agency (October 2014). "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014" (PDF). EPA. Retrieved 2014-10-11. See Table 7.2 – MY 2014 Alternative Fuel Vehicle Powertrain and Range; p. 98; Table 7.3 for overall fuel economy (mpg-e), p. 100; Table 7.4 for tailpipe CO_2 emissions, p. 102; and Table 7.5 for upstream CO_2 emission, p. 105.

UCS - Union of Concerned Scientists (2015). Cleaner cars from cradle to grave. How electric cars beat gasoline cars on lifetime global warming emissions. http://www.ucsusa.org/EVlifecycle. Accessed 1 October 2016

UNRAE (2016), Unione Nazionale Rappresentanti Autoveicoli Esteri, Top 10 per alimentazione - Settembre 2016, , sito visitato il 3 gennaio 2016, http://www.unrae.it/

VCA - Vehicle Certification Agency (2016) Car and Van Fuel Consumption / CO_2 Databases, http://www.dft.gov.uk/vca/index.asp. Accessed 3 January 2017.

Appendix

Table 7 – Diesel cars

Car manufacturer	*Model*	*Description*	*CO_2 g/km*
CHRYSLER JEEP	Jeep Renegade, MY2015	1.6 120bhp 4x2	115
DACIA	Duster Euro6, 2015	dCi 110 4X2	115
FIAT	500 X, 2015 onwards	1.3 MultiJet 95 bhp	107
FIAT	500L MPW, August 2013 onwards	1.3 16v MultiJet 95 bhp - Dualogic - Euro 6	104
FIAT	Panda, From February 2012 onwards	1.3 16v MultiJet 95 bhp - Cross	119
HYUNDAI	Tucson	1.7l CRDi Blue Drive 2WD, 104kW	129
NISSAN	Qashqai Euro6, 2015	dCi 110 16/17 inch wheel	99
RENAULT	Captur Euro6, 2015	dCi 90 EDC	99
RENAULT	Clio Euro6, 2015	dCi 90 EDC	92
VOLKSWAGEN	Golf	1.6 TDI 110PS 7speed DSG GT Edition	104

Source: VCA (2016)

Table 8 – Gasoline cars

Car manufacturer	*Model*	*Description*	*CO_2 g/km*
CITROEN	C3	PureTech 68 VT	102
FIAT	500 & 500C, September 2015 onwards	0.9 TwinAir Turbo 105 bhp	99
FIAT	Panda, From February 2012 onwards	0.9 Twin Air Turbo 90 bhp - Cross	114
FIAT	Punto, 2012 onwards	1.2 8v 69 bhp	124
MERCEDES-BENZ	A-Class, Model Year 2016	A180 with 16" rear wheels	119
PEUGEOT	208	1.6 THP 208 S&S (GTi 30th)	125
TOYOTA	Aygo, MY2015	1.0 VVT-i 5-speed Manual	95
TOYOTA	Yaris, 2016	1.33 VVT-i 6-speed M-drive S - 15" alloys	114
VOLKSWAGEN	Polo	1.0 60PS Stop-Start Match	106

Source: VCA (2016)

Table 9 – Hybrid cars

Manufacturer	*Model*	*Description*	*CO_2 g/km*
LEXUS	CT, MY2015	Advance Plus	94
LEXUS	NX, MY2015	300h SE	121
LEXUS	RX, MY2015	RX450h SE	120
TOYOTA	Auris, MY2015	Hybrid Active 1.8 VVT-i E-CVT	79
TOYOTA	Prius, 2016	Active 1.8 15" wheels	70
TOYOTA	RAV4, MY2016	Hybrid AWD 2.5 VVT-i Auto	118
TOYOTA	Yaris, 2016	1.5 VVT-i Auto - 16 " alloys	82
VOLVO	V60 MY17	D5 AWD Plug in Hybrid	48

Source: VCA (2016)

Table 10 – Pure electric cars

Manufacturer	*Model*	*Description*	*Wh/km*
BMW	i Series, From November 2013	i3	129
CITROEN	C-Zero	C-Zero	126
KIA	Soul	EV	147
MERCEDES-BENZ	B-Class, Model Year 2016	B250 e with 16" rear wheels	176
MITSUBISHI	i-MiEV	i-MiEV	135
NISSAN	Leaf	Leaf	173
NISSAN	Leaf, 2016	Leaf 30kWh	150
PEUGEOT	iOn	iOn	126
RENAULT	Zoe	Zoe	146
TESLA	Model S	70	185
VOLKSWAGEN	Golf	eGolf	127
VOLKSWAGEN	UP	e-UP	117
Average value			145

Source: VCA (2016)