The transport of goods in the urban environment: a comparative Life Cycle Assessment of Electric, Compressed Natural Gas and Diesel light-duty vehicles

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Abstract

A comparative environmental assessment of electric and traditional light-duty vehicles has been performed in the present study. The analysis has focused on an aspect that has often been overlooked in electric mobility Life Cycle Assessments: the transport of goods in urban environments. The analysis has been performed using primary data from the manufacturer for the production of light-duty vehicles and an ad hoc kinematic model for the use phase.

This study has ironed out most of the comparison inequalities that arise in a comparative Life Cycle Assessments of vehicles, comparing three light-duty vehicles, which only differ as far as the powertrain configuration is

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concerned, during a specific function (the delivery of goods in urban environments), where they have resulted to be mutually interchangeable.

The electric motor presents advantages in urban environments, because of the numerous stops and regenerative braking that take place during urban deliveries. Its good performance emerges as the load of the vehicle is increased, thus making the comparison with Internal Combustion Engine Vehicles particularly favorable for Electric Vehicles when it comes to the delivery of goods.

During the life cycle of the vehicle, these aspects compensate for the higher impacts of Cumulative Energy Demand, Global Warming, Abiotic Depletion - fossil fuels and Photochemical Oxidation that arise from the production of the electric vehicle.

These advantages remain negligible in impact categories driven by resource consumption and manufacturing activities, such as abiotic depletion, acidification and eutrophication. Electric mobility is still hindered in these categories by the cumbersome role of batteries.

Key Words: Light-duty vehicle, comparative LCA, electric vehicles, delivery services, use phase, urban logistics.

1 Introduction

The transport sector in the EU is responsible for approximately 30% of the total energy consumption and 27 % of the total greenhouse gas (GHG) emissions. A large share of these emissions is imputable to road traffic, which is the dominant mode of freight movement, and it accounts for the largest share of freight-related emissions within countries [1]. In 2012, road transport in Europe accounted for 75.1% of the total inland freight transport (% of the total inland tkm). This percentage will surely increase, as motorization rates are increasing worldwide. Apart from their contribution to energy consumption and greenhouse gas emissions (GHG), internal combustion engine vehicles (ICEV) also contribute substantially to air pollution. They in fact remain one of the major sources of NOx, PM10 and non-methane volatile organic compound (NMVOC) emissions; in 2009, they were responsible for 42%, 14% and 17% of the NOx, PM10 and NMVOCs in Europe, respectively [2]. The effects of car emissions are significant in urban areas where traffic is often highly congested and the dispersion of pollutants may be limited [3]. Several legislations have attempted to control these emissions by setting benchmarks and targets, such as the +2° target, to which the EU has committed to reduce CO_2 emissions [4], and the 7th Environment Action Program objectives of " levels of air quality that do not give rise to significant negative impacts on, and risks to human health and the environment" [5].

In this context, electric vehicles are gaining momentum since they remove emissions directly from urban areas and rely on an energy vector -electricity- which can help decouple transportation from oil consumption.

1.1 State-of-the-art

In the attempt to evaluate whether EVs represent a suitable option, many studies have tried to compare their environmental performances with those of internal-combustion-engine vehicles (ICEVs).

On the basis of the assumption that the main source of impact in the life of a vehicle is the operation phase, many studies have compared ICEVs and EVs by means of well-to-wheel analyses (WTW) [6], i.e. considering only the direct impacts of the operation phase and of the production of fuels and electricity.

However, the architecture and technology of vehicles are becoming more and more complex, mainly in order to achieve better efficiency and higher environmental standards [6]. The role of the production phase is thus becoming more relevant for both the reduction of use phase emissions and fuel consumption and because of the greater complexity and sophistication of the production stages.

This is why the comparison of vehicles is moving through "complete Life Cycle Assessments" [7], which compare different vehicles over their entire life cycle, considering their production, use, maintenance and end-of-life (EoL). In a recent study it was proposed to include also the infrastructure and the entangled effects transportation – infrastructure in the complete life cycle [8].

It is evident, from literature, that the production of batteries is somehow challenging the benefits of EV mobility, as highlighted in the work by Gaines et al. [9] and the study by Majeau-Bettez et al. [10]. It has been confirmed in more recent studies by Sanfélix et al. in 2015 [11] and 2016 [12]. Some studies have accounted for the impacts of the production of the batteries and have asked whether they compensate for the benefits obtained in the use phase [13].

The important role of batteries in electric mobility has encouraged many authors to evaluate their environmental impacts. Most of them have focused on Lithium-Ion batteries for traction applications, due to their prominence in this field, and in particular on lithium manganese oxide ($LiMn_2O_4$) and lithium ion phosphate ($LiFePO_4$) batteries [14]. Only a few of them have analyzed different types of batteries for electric vehicle applications. This is the case of the study by Hammond et al. [15], where the authors compared the technical and environmental performance of Lithium-Ion batteries (LIB), Li-Ion Polymer (LIP) and Sodium Nickel Chloride (NaNiCl) batteries, and the study by Gerssen-Gondelach and Faaij [16]. Ellingsen et al. [17] and Phillipot et al. [18] studied the key parameters that determine the impact of batteries, while Ellingsen [19] identified the potential for reducing the impact of battery production with a cleaner energy mix. The use of batteries in stationary applications at the end of their lifetime [20] in the traction sector has been proposed as a promising way of reducing their impacts. It has been analyzed in the recent studies by Cusenza et al. [21] and Ioakimidis et al. [22].

Since an electric vehicle is more than just an ICEV with a couple of batteries, the mobility system should be studied in a holistic way, that is, by assessing how all the components interact with each other and influence the overall impact of the vehicle [23].

For example, if the mass of alternative vehicle components is different, then each extra kilogram is accompanied by an increase in the power requirements (engine size, fuel consumption, etc.), all of which affect the performance and both the initial and operational costs of the vehicle [24].

As different studies have attempted to compare EVs and ICEVs, problems have arisen. The choice of comparable vehicles is difficult, because a vehicle has many different functions and performances to fulfil.

A general comparison between an average ICEV and an average EV could be considered unfair, as EVs are generally smaller and more compact than ICEVs [25]. Therefore, many studies have tried to compare vehicles that are at least of the same size. Hawkins et al. [6], for example, compared vehicles that, apart from their size and mass, had similar driving performances.

Recent studies have tried to compare vehicles from the same segment: small passenger cars [26], mid-size vehicles [27], and compact 5-seaters [28]. Tagliaferri et al. [29] selected a Nissan Leaf, a Toyota Yaris, a Toyota Prius, a Yaris Hybrid and a Toyota Prius Plug-In as reference vehicles to represent BEV, ICVE and PHEVs, respectively. The model for the glider for both ICEV and BEV was based on Ecoinvent 2.1, while other components were derived from literature data. Similarly, Tamayao et al.[30] and Yuksel et al. [31] selected a Chevrolet Volt (PHEV), a Nissan Leaf (BEV) and a Toyota Prius (HEV).

A theoretical vehicle structure has been considered in many studies and existing databases have been adapted to suit the vehicle that was being analyzed. The Life Cycle Inventory of a Golf A4 [32] has been the basis for many LCA studies, from the one by Notter et al. [33] at the beginning of the decade, to the very recent ones [34]. In the study by de Souza [34], it was used to represent conventional vehicles, and it was the basis for PHEV and BEV, which were assumed to have the same chassis, with the only difference being related to the powertrain and power supply (battery). Rangaraju et al. [35], who compared compact BEV and compact traditional vehicles, considered a Peugeot iOn to characterize the BEV, and a Polo1.2 TSI and a Polo 1.4TDI to characterize the petrol and diesel versions, respectively. In order to model the latter vehicles, the life cycle inventory of the Golf was rescaled to their needs.

Some other studies, in an attempt to solve comparison inequalities, have compared a conventional vehicle with its repowered version. This is the case of the study by Helmers et al. [36], where a conventional Smart was compared with its electrified version, and the study by Lombardi et al. [37] which solved the problem of comparison inequalities by comparing a conventional midsize car (GM Chevrolet Malibu) with its repowered BEV, HEV and Fuel Cell versions.

However, the path is still long and tortuous, because different vehicles are usually used for different purposes.

A novel type of study has focused on a fleet scale rather than on a vehicle level. This is the case of the studies by Garcia et al. [38] and Bohnes et al. [39].

1.2 Contribution of the present study

In this study, we have circumscribed the comparison as much as possible: we have compared three light-duty vehicles, which only differ as far as their power trains are concerned, and which are used for a specific function: urban delivery services.

The European commission defines the term “urban freight transport” (UFT) as "the movement of freight vehicles whose primary purpose is to carry goods into, out of and within urban areas”. The sector is dominated by private sector organizations, and it is highly responsive to market stimulations. It is a continuously evolving and growing market, especially thanks to e-commerce.

The sector has its own particular features, depending on the market segment, but it is moving toward Just-in-Time (JIT) deliveries, both when it comes to business-to-business and business-to-consumer [40].

Time pressure causes a fragmentation of loads and increase the number of deliveries, and this in turn leads to a higher inefficiency than before the advent of e-commerce and JIT deliveries; this is what has been called the 'last mile issue' [41].

UFT is causing a number of negative effects in cities since it is increasing road congestion, which in turn affects air quality and causes noise pollution. Moreover, it is perceived as intimidating by pedestrians and cyclists [42]. However, road UFT will remain the main transportation means for the “last mile”, due to its inherent flexibility.

The aim of this study is to evaluate the benefits that can be derived from the operation phase of an electric light-duty vehicle and to establish whether these benefits are compensated for by higher impacts in other life cycle stages –with particular focus on production.

Unlike many other studies in which a theoretical vehicle structure has been modeled or existing databases have been adapted to suit the vehicle that is being analyzed, in the present paper, the production relies on primary data provided by the manufacturer.

Moreover, the literature on electric vehicles has mainly been focused on passenger cars and has overlooked other means of transport [7]. In their review on the LCA of electric vehicles, Marmiroli et al. highlighted this discrepancy: among 44 revised studies, only 3 analyzed vehicle types other than passenger cars [43]. The present work is one of the few studies to have considered a different type of vehicle from a passenger car, i.e. a light duty vehicle, and to have considered the transportation of goods rather than of passengers. Giordano et al. [44] and Bartolozzi et al. [45] evaluated light-duty vehicles used for the delivery of goods, while Lee et al., in their parametric LCA, compared medium-duty electric trucks with nine non-electric technologies [46]. The work by Bi et al. [47] in which wireless and plug-in charging in urban and suburban trips in Michigan were compared, is an interesting study on bus electrification [48].

Urban freight transport is taking on an ever-increasing role in urban mobility strategies, thanks to the explosion of the e-commerce sector over the last decade [49]. The use of electric vehicles for the delivery of goods in urban areas could be of interest for the development of a new mobility paradigm.

Moreover, this study is the only one that has compared three identical vehicles, in which only the powertrain and the related auxiliaries are different, thereby avoiding, or at least reducing comparison inequalities as much as possible.

The comparison has involved the evaluation of a considerable number of impact categories, along with the well investigated Global Warming and energy consumption ones.

The transportation of goods in urban areas has here been represented by a standard delivery service of a light-duty vehicle from the warehouse to the place of delivery and its re-entry to the warehouse.

The use phase is usually described in literature using an average consumption and relying on generic databases. In this article, the use phase has been modeled using a kinematic model, developed in the MatLab environment, that relies on specific efficiency maps for the vehicle under study.

In order to describe a reliable urban delivery scenario, the kinematic model has been run under different loading conditions and using a mix of different driving cycles to consider the different characteristics of an urban driving situation.

2 Materials and Methods

The Life Cycle Assessment (LCA) method was chosen to compare the environmental performances of EVs with traditional vehicles. The LCA is a suitable tool to evaluate whether the acclaimed benefits of the adoption of a technology are hiding burden shifting. Burden shifting can in fact be caused by moving the burden to another phase/ activity or to another environmental compartment.

The study has adopted a process-based LCA, using the attributional approach. LCA is structured in four phases: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. The four phases are related to each other and the process is iterative. Thus, the obtained preliminary results influence the scope of the analysis and the consequent request for and analysis of the data.

2.1 Goal and Scope

The goal of the assessment presented hereafter was to compare the performance of an electric light-duty vehicle with two ICE light-duty vehicles (Diesel and Compressed Natural Gas) involved in the delivery of goods in an urban environment, in order to evaluate the benefit of electric mobility for this specific application.

The scope defines the main characteristics of an intended LCA study, and covers such issues as temporal, geographical and technological coverage, the employed mode of analysis and the overall level of sophistication of the study [50]. The subparts of the goal and scope are reported hereafter.

2.1.1 Functional unit and reference flow

The pivot of a life cycle analysis is the functional unit, which describes the primary function fulfilled by a product system and enables different systems to be treated as functionally equivalent [50].

The choice of the functional unit is not always straightforward [51]. It is important to define an appropriate functional unit, since different functional units convey different results [52]. This choice can influence the results of a comparative LCA to a great extent.

In this study, the three light-duty vehicles were supposed to be used in an urban logistic scenario. The functional unit was the delivery service, and the reference flow was one km of a delivery mission. The delivery service included a trip from a warehouse to the distribution locations and back to the warehouse.

This choice of functional unit was motivated by the evidence that the three vehicles performed differently under different load conditions, as will be shown clearly in section 2.2.2. For this reason, a combination of representative load conditions of a standard delivery mission was preferred to the more common ton*km unit, which would erroneously convey the idea of a linear relationship between load and consumption.

In comparative studies of high life time products, a length of use time must be included in the description function [24]. In the case of vehicles, the life time is usually expressed in mileage. The life span considered for the preliminary analysis was the mileage proposed by the manufacturer (240.000 km).

The particular feature of the system under study is that it analyzes the same vehicle type, that is, a light-duty vehicle, but which is equipped with three different power trains: Electric, Diesel and Compressed Natural Gas (CNG).

These power trains were produced in the same plant, thus the comparison did not suffer from endogeneity related to the plant environment or site-specific circumstances.

Moreover, the three light-duty vehicles were considered interchangeable in the urban logistic scenario defined for the analysis, since they have the same performances and geometry, different maximum loads but the same load volume, which is the limiting aspect in an urban delivery service. Moreover, the limiting factor in delivery services is the time, rather than the mileage: the range provided by the batteries is enough for the electric version to fulfil the number of daily missions, return to the depot and recharge at night [49].

The aforementioned characteristics of the three configurations are reported in detail in Table 1.

Table 1: Characteristics of the vehicles

Characteristic	*u.m.*	*Diesel LDV*	*CNG LDV*	*Electric LDV*
Gross Vehicle Weight	kg	5200	5200	5200
Load volume	m^3	18	18	18
Max load	kg	2495	2115	2064
Maximum Power	kW	107	100	80
Nominal Power	kW	-	-	40
Maximum torque	Nm	350	350	300
Euro class	-	Euro 6	Euro 6	Euro 6
Kerb weight	kg	2577	2960	3039
Battery capacity	kWh	-	-	64

The way in which the mission is driven affects the results of the analysis to a great extent. Thus, a sensitivity analysis was conducted on different driving cycles considered suitable for the delivery services, that is, NEDC, WLTP2, WLTP3 and CADC-U, and an ad hoc driving cycle developed by the manufacturer to represent an urban delivery environment.

2.1.2 System boundary and data quality

The system under study ranges from component production to the use phase of the vehicle, and passes through the assembly at the main plant. The End of Life phase of the vehicles was disregarded because no primary data were available on this phase. The authors preferred to make a reliable comparison between all the other phases of the life cycle instead of relying on data from literature, as those available are somewhat variable and uncertain.

The inventory of the components used to assemble the vehicles was provided by the manufacturer. The primary data also included the consumption of electricity and natural gas from the grid, and the wastes produced by the plant.

The use phase was evaluated using an ad hoc developed kinematic model for the vehicles under study, considering efficiency maps provided by the manufacturer. Different load conditions and driving cycles can be examined with this model to investigate a wide range of situations considered likely to happen in the urban environment.

Secondary data, which were taken from the EcoInvent 3.3 database, were used for the background processes: the production of the materials for the components, the production of energy and heat and their distribution through the national grids, and the vehicle transportation emissions during transport, by means of car transporters, from the plant to the matriculation countries.

The producers of the components assembled in the plants are mainly located in Europe. The material composition of their components were available on the IMDS, but the energy and auxiliary flows were not available as primary data, therefore data from the EcoInvent 3.3 database were used. When available, representative data of the European industrial sector were chosen.

The environmental burdens resulting from the operation of BEV mainly depend on the electricity mix [33]. The influence of the electricity mix was tested by replacing the Italian-mix with the Norwegian one.

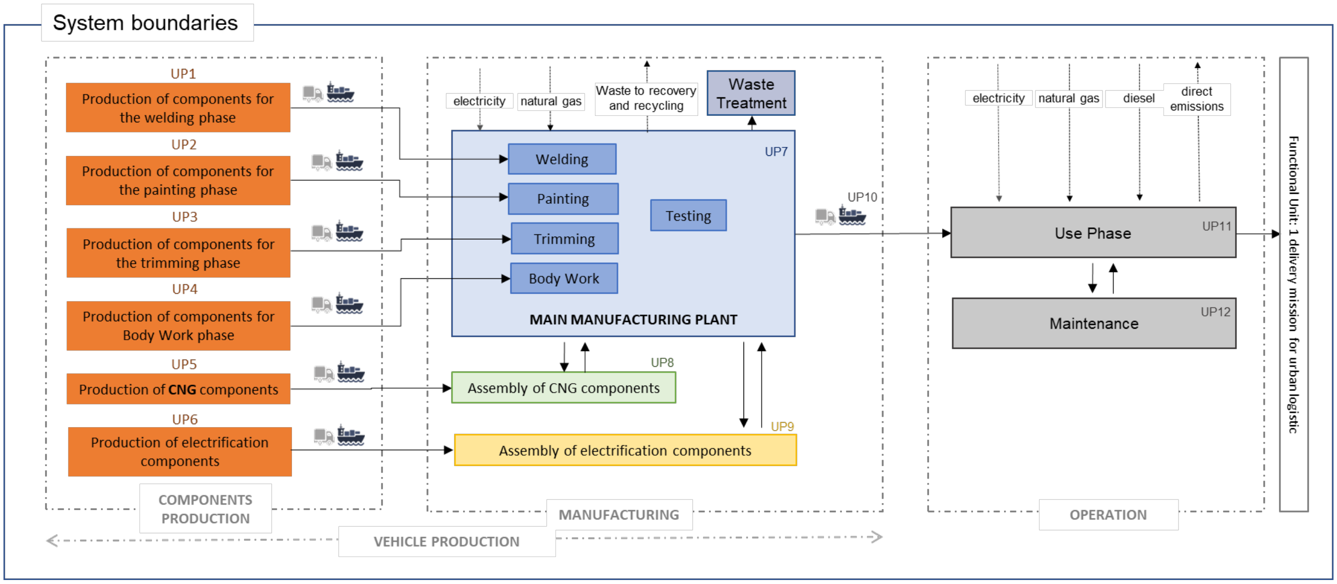


Figure 1: System boundary

A synoptic view of the system is presented in Figure 1: the upstream processes include the production of the components of the vehicles (UP from 1 to 6), sorted according to the steps in the plant chain they are entering. The core processes include the manufacturing of the vehicles. The three vehicles were assembled in the same plant (UP 7). The production stages involved: 1. welding and painting, which were exactly the same for the three vehicles; 2. Trimming, whereby the interior and exterior parts were assembled; 3. Bodyworks, whereby the chassis and the remaining components were assembled. During the bodywork phase, the CNG vehicle was transferred to plant 2 (UP 8), where the CNG tanks were installed. The electric vehicle was transferred to plant 3 (UP 9), where the components related to the electrification of the vehicle were installed. Both vehicles were then returned to plant 1 for the final test. The powertrain components for the diesel vehicle were assembled at the main plant (UP7).

Finally, the three vehicles were assumed to be distributed on the European market (UP 10). The vehicle use phase was included in the study. The use phase was simulated though a kinematic vehicle model, developed in the Matlab environment in order to assess the impact of the use phase of each vehicle. Data provided by the manufacturer were used to build and validate the model.

2.1.3 Allocation and multifunctionality

The multifunctionalities were solved – when allocation was unavoidable – by means of the allocation of the Cut-Off System Model. The philosophy that underlies this approach is that the primary production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. In the same way, the producers of waste do not receive any credit for recycling or re-using products resulting from any waste treatment [53]. This is why the wastes produced at the plant are split into two flows: the one that goes to a landfill and the one that goes to a recycling plant. As far as the latter is concerned, only the transportation to the platform was included in the analysis and no benefits were credited for the recycled materials.

As far as the eventual secondary life of the components is concerned, when the vehicle was considered to have reached its end of life, allocation was chosen in such a way as to result in the highest possible environmental burdens for the vehicles. All the burdens from battery production were allocated to its first life, even though it might have been reused (e.g., batteries that are no longer suitable for vehicle traction might be used in stationary applications) [33].

2.1.4 Impact assessment

Electric vehicles are currently in the spotlight because of health and environmental concerns and for political and energy security reasons. Their effectiveness should be validated considering impact categories that account for these issues. Therefore, such well-known categories as global warming (GW) and cumulative energy demand (CED) were considered in this study. These two categories have already been widely investigated in other LCA studies, especially in well-to-wheel analyses.

The "Abiotic depletion-fossil fuels" helps demonstrate how effective EVs are in decoupling the transport sector from its reliance on fossil fuels, and therefore on fuel producing countries.

Another benefit of the use of EVs, related to the WTW analysis, is a reduction in air pollutants in urban areas. For this reason, some studies have included VOC, NO_X, SO_2 and PM10 emissions in their LCI [54]. For example, [36] included the particulate matter formation category (PMF) in their analysis, while [6] also included photochemical ozone formation in their study, in order to assess the role of such traditional pollutants as VOC, NO_x etc… in the formation of photochemical pollution in urban areas.

Local impacts, such as air pollution, are highly dependent on site-specific characteristics, and the ability of LCA to model local impact categories is still a matter of debate, since it is not a site-specific tool. However, it can be adopted to account for local conditions, using such archetypes as highly populated or lowly populated areas where the emissions occur [55].

Impact categories concerning resource consumption (ADP, ADP – fossil fuels) [56] and ecotoxicity have been investigated [13] when the impacts of the production phase gained attention.

All the above impact categories have been considered in the present study: CED was accounted for by referring to the CED method, while the other categories were assessed using the April 2013 updated version (v. 4.2) of the CML baseline method [50].

2.2 Life cycle inventory

2.2.1 Vehicle production

The life cycle inventory was prepared by considering the large number of data provided by the manufacturer, on the basis of the structure of the plant, which is described in detail hereafter.

The core processes include all the assembling phases. The assembly mainly takes place in Plant 1 (UP 7), and partially in Plant 2 (UP 8) and Plant 3 (UP 9).

The production in Plant 1 (UP 7) begins in the Welding Shop, where the body is assembled. The components are metal sheets. In the first phase, lateral panels and floors are welded together, and then the cubing welding phase takes place in which the doors and hood are welded to form the body of the vehicle. The loading, handling and welding phases are all mechanized and performed by robots. After the quality controls, the body enters the Painting Shop, but if the body fails the controls it is sent to the recovery section.

In the Painting Shop, the body is washed and then undergoes a cataphoresis treatment. This process involves the electro-deposition of paint by means of immersion under a continuous electrical current. The deposited film is acrylic or epossidic resin, and it confers an elevated anticorrosive property to the body. This process ends with the drying of the body at a high temperature (150 °C – 180 °C). The body is then sealed with polyurethane sealants and painted by robots.

The next phases consist of the assembly of the components. Such components as the dashboard, seats, etc…are installed on the body of the vehicle during the trimming phase.

The Body Work phase, in which the chassis, powertrain, driveline and after-treatment system are assembled and then combined with the body from the trimming phase, takes place at the same time. (the Body Work phase also includes the windshield, mirrors, headlights, etc.).

After all these operations, the vehicle is complete and is sent to the testing area, where the alignment and the hydraulic tests are performed. Tests on the bench are also performed in this area. After the tests, the vehicle is finished and is transferred to the commercial park, where it is ready to be placed on the market.

During the bodywork phase, the CNG vehicle and the BEV are transferred to plant 2 (UP 8) and plant 3 (UP9), respectively. The CNG tanks and pipes are installed on the vehicle at plant 2 (UP8). The total capacity of the tanks is 246 lt. The vehicle is then returned to Plant 1, where the assembly process continues. The electrification process of the BEV takes place at plant 3 (UP9). This process consists of the assembly of all the components related to the electric powertrain system: the on-board battery chargers (the vehicle is equipped with a 3.5 kW charger, which is used as standard charger, and 22 kW charger, which is included as an option for fast charging), the batteries, the supercapacitor, the traction inverter and the driveline RG 40-80 kW. The supercapacitor is an electric storage devices that can store a large amount of power and release it quickly; it is used as an ancillary device to recover energy from braking and to provide the necessary boost during quick accelerations [57]. This process also involves the assembly of the auxiliaries: the cooling system (pipes, fans, dual stage pump 205 CV), the high voltage heater (HVH), the Electric Hydraulic Power Steering (EHPS) and the DC/DC converters. After the electrification stage, the BEV is returned to Plant 1 for final assembly and tests. The diesel vehicle is assembled entirely at Plant 1.

The authors were provided with the bill of materials (BOM) from the manufacturer for the production phase. However, full details of the BOM are not reported for confidentiality reasons. Nevertheless, the way the data were processed is explained in detail hereafter.

First, the components were sorted according to the stage in the assembly line they entered. Then composition of the components was taken from the International Material Data System (IMDS). The components were then divided again into large and relevant components and simpler, smaller components. The data on the production of the relevant large components was acquired directly from the suppliers, when available, otherwise by referring to the Environmental Product Declaration (EPD), gray literature or datasheets from EcoInvent. The smaller parts made of the same material and by means of similar manufacturing technologies were summarized and modeled as a single datasheet using EcoInvent datasets that were representative of the average European manufacturing processes. More detailed information on how the material composition was modeled in our study is available in the supplementary material section.

The production of the components included the extraction of raw materials, the transportation of raw materials to a European plant and the manufacturing of the components, assuming average European working conditions.

The energy and gas consumptions were taken from the gas meter and electricity meter at the plant. The consumptions of the last three years were reported on a daily basis. The wastes produced yearly at the plant were listed and reported along with their masses, the European Waste Codes (EWC), the final destinations; the amount of wastewater and their treatment were also given.

As mentioned in section 2.1.3, the disposal of wastes in landfills and through incineration was modeled using EcoInvent datasets, whereas only transportation to the platform was considered for wastes sent for recycling.

The main production of the plant is the light-duty vehicle analyzed in this study. As a secondary activity, the manufacturer also produces spare parts for other vehicle types of the same company.

The production time of each version was supplied by the manufacturer: it was slightly less for the diesel version than for the CNG and Electric version. All the flows that affect the plant were allocated to the three type of vehicles, according to the number of produced vehicles of each version and to its production time.

2.2.1.1 Distribution

Once the vehicles are finished, they are distributed to the European retailers (UP 10). No primary data were available on sales distribution. For this reason, the same distribution of newly registered LDV cars in Europe for the year 2015 [58] has been hypothesized for the sales of our vehicles; all the produced vehicles were considered sold.

The produced vehicles were transported by means of car transporters, for overland transport, and by means of ships, for maritime transport, and these modes were modeled using the EcoInvent “Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Rec, U” and “Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Rec, U” datasets, respectively.

2.2.2 Operation

2.2.2.1 Use phase

As far as the use phase is concerned, most LCAs rely on the average kilometric consumption to compare different powertrains. The most common databases present emissions and consumptions divided according to the class of vehicles (Euro 3,4,5...) and to the vehicle typology (passenger car, truck, ...). However, the emissions and consumptions of vehicles are characteristics that depend to a great extent on the vehicle typology and, for the same vehicle category, the driving style can significantly affect the performances. For this reason, a kinematic model, in which the operating conditions of the vehicle were derived from efficiency maps provided by the manufacturer, has been developed in this study. The emissions and consumptions were tailored to the vehicle under study. In order to investigate a wide range of conditions, the performances of the vehicles were analyzed under different driving cycles and considering different load percentages.

2.2.2.1.1 Driving missions

Some reference urban driving cycles (Artemis, NEDC, WLTP…) and a real-world driving cycle were selected from among the driving cycles.

Table 2 reports the main specifications of the driving mission sets per each vehicle class (Diesel, CNG and Electric): the duration (s), the length (km), the specific energy consumption (at the wheel level) in traction (SEC-tract) and braking (SEC-brake) stages (kWh/km), the average vehicle speed in traction (km/h), the maximum vehicle speed (km/h) and the average vehicle power demand in traction (kW).

Table 2: Main specifications of the two driving missions.

Name	*Time [s]*	*Length [km]*	*SEC-tract [kWh/km]*	*SEC-brake [kWh/km]*	*V-tract [km/h]*	*V-max [km/h]*	*P-tract [kW]*
NEDC	1180.00	10.34	0.36	-0.34	44.70	80.00	15.98
AUDC	993.00	4.83	0.56	-0.47	25.48	57.70	14.15
URBAN	2583.00	13.48	0.47	-0.42	29.86	75.29	14.07
WLTP-2	1477.00	14.64	0.35	-0.21	44.64	80.00	15.60
WLTP-3	1800.00	20.81	0.40	-0.35	52.01	80.00	20.59

Figure 2 depicts the frequency distribution of the power demand of the Diesel vehicle with maximum load over the five driving missions. The AUDC pattern shows a high frequency for low power (close to 0kW) and for high power (40kW for 0% load, 60kW for 100% load). The NEDC distribution instead occurs over the 10-30 kW range.

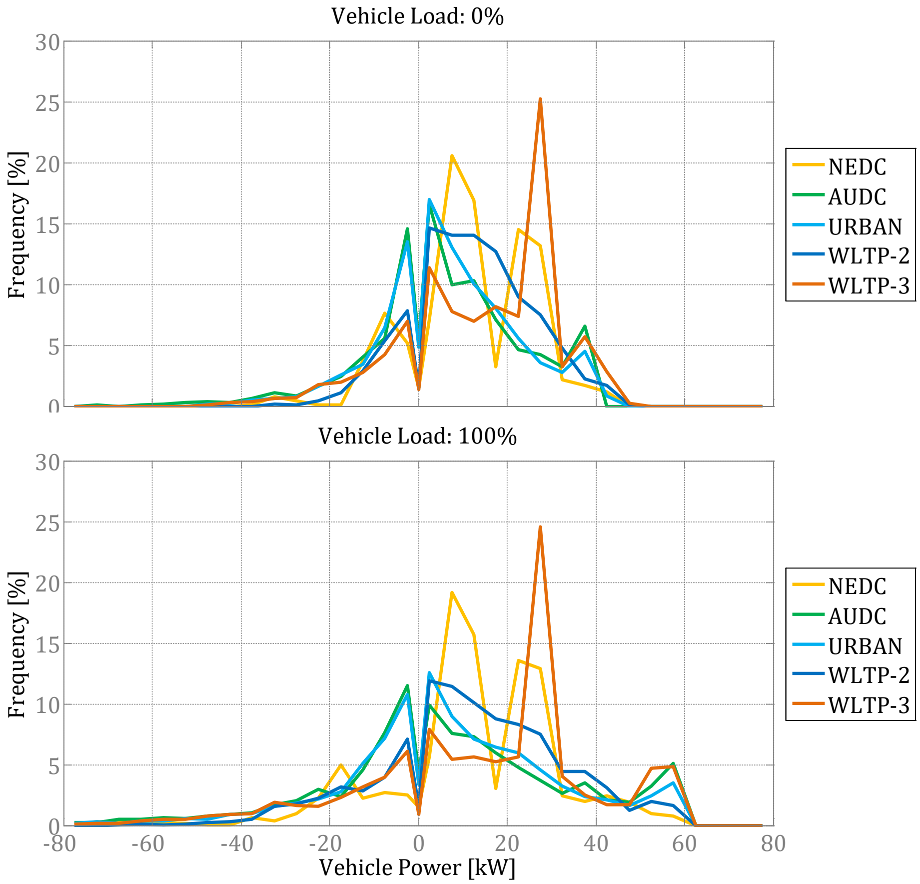


Figure 2: Vehicle power frequency distribution for the two driving missions.

2.2.2.1.2 Energy and CO_2 emission model

The energy model uses a kinematic vehicle approach, where the operating conditions of the system and the control variables are obtained directly with respect to the kinematic state of the system itself. This approach was implemented in the Matlab environment. This methodology was considered to be consistent with the purpose of this investigation, where different vehicle typologies, equipped with several powertrains, were compared in terms of energy consumption and CO_2 emissions.

Two different vehicle models were developed, that is, one for the conventional vehicles (Diesel and CNG) and the other for the electric vehicle (BEV).

The power demand for the powertrain was calculated from the vehicle velocity patterns, which were considered as input for the kinematic model, by considering the driveline efficiency chain and the efficiency of each machine (engine, e-machine and battery) as a function of the operating points.

The total power required at the powertrain level, which is the engine for the conventional vehicles and the e-machine for the electric vehicles, is the sum of several components: rolling resistance, grade resistance and drag resistance. If the road is flat, the equation of the power demand is reduced to the following structure:

$$P_v = \left(m_v \cdot g \cdot r_v + \frac{1}{2}(\rho_{air} \cdot c_x \cdot A_v) \cdot {v_v}^2 + \left(m_v \cdot \frac{N_{wh} \cdot I_{wh}}{R_{wh}}\right) \cdot \dot{v}_v\right) \cdot v_v$$

where m_v is the vehicle mass, g is the gravitational acceleration, r_v is the rolling resistance coefficient of the vehicle (0.008), ρ_{air} is the air density (1.22 kg/m^3), c_x is the aerodynamic drag coefficient (0.58), A_v is the frontal area of the vehicle (3.8 m^2), v_v is the vehicle velocity, I_{wh} is the single wheel inertia (1.56 km m^2), N_{wh} is the number of wheels (4), R_{wh} is the dynamic wheel radius (0.35 m) and $\dot{v}_v$ is the vehicle acceleration.

The power at the final-drive level, P_{fd}, is obtained as follows:

$$P_{fd} = \begin{cases} P_v & \boldsymbol{traction} \\ \gamma_{br} \cdot \gamma_{fr} \cdot P_v & \boldsymbol{braking} \end{cases}$$

where the factor γ_{fr} represents the power split between the two axles of the vehicle and γ_{br} represents the power share managed by the mechanical frictional brakes during braking. The two values were kept constant for all the simulations. The former, γ_{fr}, was set equal to 0 (i.e. the rear axle fully manages the braking) to maximize the energy recovery for the BEV, while the latter, γ_{br}, was set equal to 0.8 and to 1 for the BEVs and any conventional vehicle, respectively, since the vehicle was tested for standard driving conditions in which the deceleration maneuvers are not extreme and vehicle stability should not be compromised.

The required power at the powertrain level, P_{pt}, was calculated from P_{fd} and the driveline as follows:

$$P_{pt} = \left(P_{fd} \cdot \varepsilon_{fd}^{k} + I_{tr} \cdot \omega_{tr} \cdot \dot{\omega}_{tr}\right) \cdot \varepsilon_{tr}^{k} + I_{ice} \cdot \omega_{ice} \cdot \dot{\omega}_{ice} + I_{em} \cdot \omega_{em} \cdot \dot{\omega}_{em}$$

where I_{tr} is the transmission inertia, ε_{fd} and ε_{tr} are the efficiency of the final-drive and the transmission, respectively, I_{ice} and I_{em} are the inertia of the internal combustion engine and of the electric machine, respectively, and k is equal to 1 if the vehicle is braking and to -1 otherwise. The inertial term of the engine I_{ice} was set at 0 for the BEVs, and I_{em} was set at 0 for any conventional powertrain.

Figure 3 shows the scheme of the kinematic approach used to estimate the energy consumption and CO_2 emissions of the vehicles (WTT and TTW). The scheme for Normal Production (NP), regarding Diesel and CNG, is highlighted in yellow. The scheme for the electric version is shown in blue.

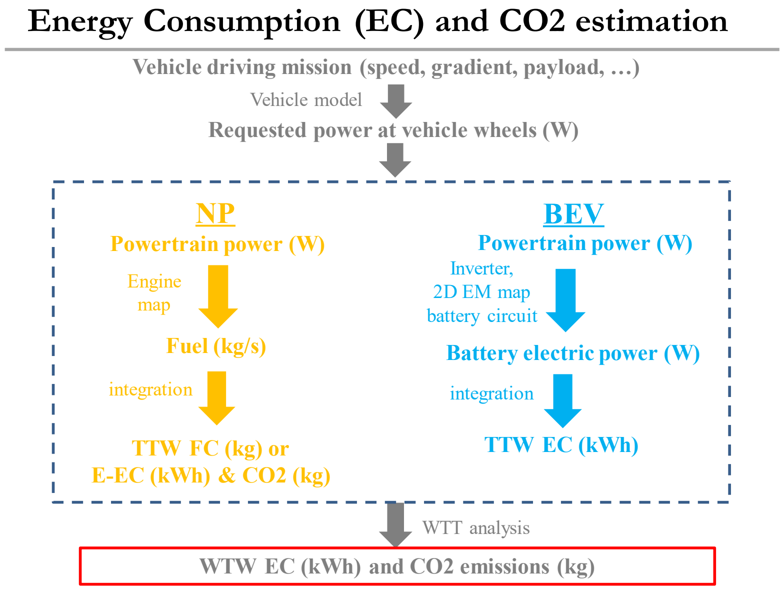


Figure 3. Scheme of the kinematic approach used to estimate energy consumption and CO2 emissions (WTT and TTW).

2.2.2.1.2.1 Conventional powertrain

The engine speed, ω_{ice}, is a function of the vehicle velocity v_v and the transmission speed ratio τ_{tr}, as follows:

$$\omega_{ice} = \tau_{tr} \cdot \tau_{fd} \cdot \frac{v_v}{R_{wh}}$$

where τ_{fd} is the speed ratio of the final drive and R_{wh} is the dynamic radius of the wheel.

The power of the engine, P_{ice}, is obtained from P_{pt}, where the inertia of the e-machine I_{em} is set to zero:

$$P_{ice} = P_{pt} = \left(P_{fd} \cdot \varepsilon_{fd}^{k} + I_{tr} \cdot \omega_{tr} \cdot \dot{\omega}_{tr}\right) \cdot \varepsilon_{tr}^{k} + I_{ice} \cdot \omega_{ice} \cdot \dot{\omega}_{ice}$$

The vehicle model checks that the operating point of the engine, defined as a (ω_{ice}, P_{ice}), is within the engine boundaries, so as to guarantee the correct functioning of the vehicle.

The engine performance was estimated in terms of fuel consumption. The model employs experimentally-derived quasi-static 2D maps as a function of the engine speed and torque, and the mass flow rate of fuel was evaluated by interpolating the 2D map (FCM). Figure 4 shows the efficiency map of the Diesel engine as a function of torque and speed. High efficiency values are indicated with hotter colors (see the color-bar for further details). The fuel consumption, FC (kg), was then determined by integrating over the driving mission time horizon, as follows:

$$FC = \int_{0}^{T} FCM(\omega_{ice}, P_{ice}) \cdot dt$$

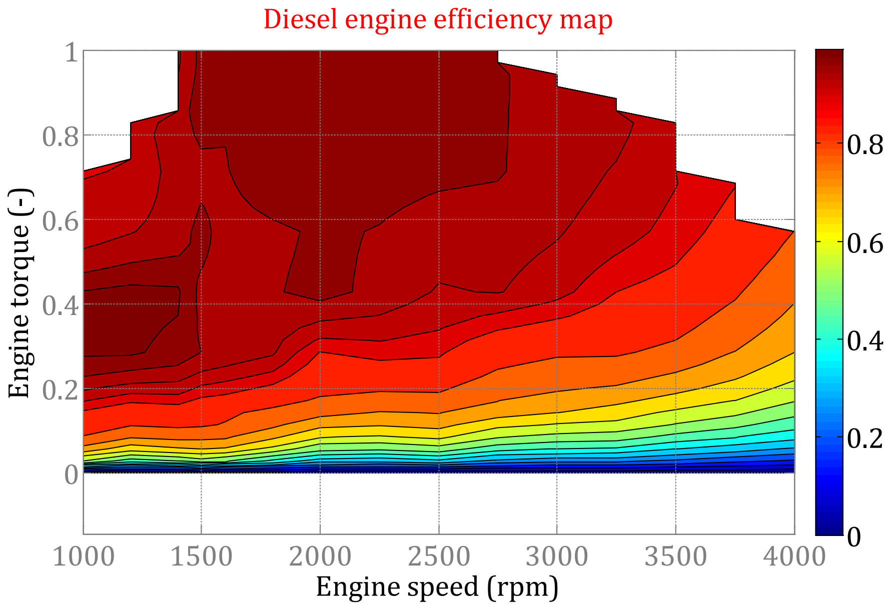


Figure 4: Diesel engine efficiency map as a function of the engine torque and speed.

The corresponding tank-to-wheel (TTW) CO_2 emissions were instead determined linearly as follows:

$$CO_{2,ttw} = k_{co2,ttw} \cdot FC$$

The $k_{co2,ttw}$ factor was obtained considering a combustion reaction of fuel with air and considering an average fuel composition taken from literature data. Table 3 reports the value for each fuel type in two different units.

Table 3: TTW CO_2 conversion factor for different fuels.

Parameter k	Unit	Diesel	CNG
TTW CO_2	[pound CO_2 / BTU Fuel]	161.3	117
TTW CO_2	[kg CO_2 /kg Fuel]	3.006	2.42
LHV	kWh/kg	12.05	13.42

The corresponding TTW energy consumption was determined as follows:

$$EC_{ttw} = LHV \cdot FC$$

where LHV represents the lower heating value of the fuel. (See Table 3 for more details.)

2.2.2.1.2.2 Electric powertrain

The electric machine speed, ω_{em}, is a function of the vehicle velocity v_v and the transmission speed ratio τ_{tr}, as follows:

$$\omega_{em} = \tau_{tr} \cdot \tau_{fd} \cdot \frac{v_v}{R_{wh}}$$

where τ_{fd} is the speed ratio of the final drive and R_{wh} is the dynamic radius of the wheel.

The power of the e-machine, P_{em}, is obtained from P_{pt}, where the inertia of the engine is set to zero, as follows:

$$P_{em} = P_{pt} = \left(P_{fd} \cdot \varepsilon_{fd}^{k} + I_{tr} \cdot \omega_{tr} \cdot \dot{\omega}_{tr}\right) \cdot \varepsilon_{tr}^{k} + I_{em} \cdot \omega_{em} \cdot \dot{\omega}_{em}$$

The vehicle model checks that the operating point of the e-machine, defined as a (ω_{em}, P_{em}), is within the e-machine boundaries, in order to guarantee the correct functioning of the vehicle.

The electric machine model simulates the power conversion from the mechanical to the electric form, considering the energy losses by means of efficiency maps, which are functions of the machine torque and speed. Figure 5 shows the efficiency map of the e-machine as a function of torque and speed. High efficiency values are indicated with hotter colors (see the color-bar for further details). The electric machine efficiency was therefore estimated by interpolating the 2D efficiency map of the e-machine (EEM), as a function of the e-machine mechanical power and speed, as follows:

$$\varepsilon_{em} = EEM(\omega_{em}, P_{em})$$

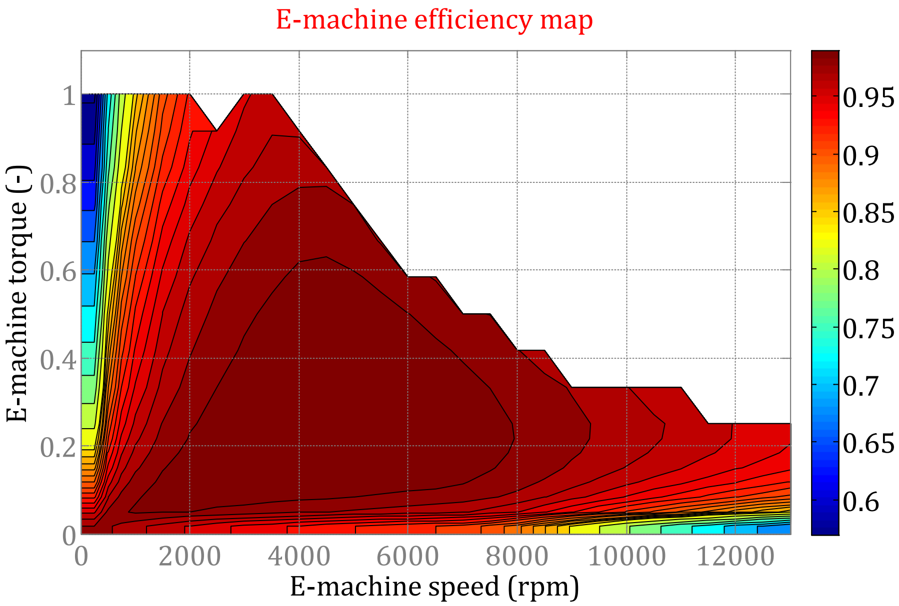


Figure 5: E-machine efficiency map as a function of torque and speed.

The electric power demand of the battery, $P_{bat,el}$, is determined as follows:

$$P_{bat,el} = P_{em} \cdot \varepsilon_{em}^{k} \cdot \varepsilon_{inv}^{k}$$

where ε_{inv} is the inverter efficiency and k is equal to 1, if the vehicle is braking, and is equal to -1 otherwise.

If the powertrain has to provide tractive power, the model checks that P'_{dem} does not exceed the maximum power that the battery can handle. The actual battery power demand is then saturated according to the minimum, $P_{bat,min}$, and maximum, $P_{bat,max}$, battery power, as follows:

$$P_{bat,dem} = \max\left(\min\left(P'_{dem}, P_{bat,max}\right), P_{bat,min}\right)$$

The battery power losses were modeled using an equivalent resistance circuit, in which the resistance and the open-circuit voltage of the battery were State of Charge-dependent. This allowed a lumped representation of more complex chemical processes to be realized. The equilibrium power equation states:

$$P_{bat,chem} = V_{bat} \cdot I_{bat} = P_{bat,dem} + R_{bat} \cdot I_{bat}^{2}$$

where V_{bat}, I_{bat}, R_{bat} are the voltage, the current and the total resistance of the battery, respectively, and $P_{bat,chem}$ is the chemical battery power demand.

The flowing current was determined by solving the above second-order polynomial:

$$I_{bat} = \frac{V_{bat} - \sqrt{V_{bat}^2 - 4 \cdot R_{bat} \cdot P_{bat,dem}}}{2 \cdot R_{bat}}$$

The battery temperature was assumed to be constant and the temperature effect was therefore disregarded. The State of Charge (SOC) represents the electrical status of the battery and depends on the equivalent battery capacity and on the flowing current.

$$SOC = SOC_0 - \int \frac{I_{bat}}{C_{bat}} \cdot dt$$

where SOC_0 is the initial SOC of the battery and C_{bat} is the battery capacity (Ah).

FIAMM SONICK batteries require an internal temperature of 270 °C to 350 °C for correct operation. This introduces a constant thermal flow through the battery, due to a temperature gradient with the external environment.

When the battery is not working, the system is partially discharged to power the DC heater in order to keep the average internal temperature equal to the minimum operating temperature. This energetic loss is reduced with an efficient insulation system, with a thermal conductivity of 0.006W/mK. It has been estimated on average to be as much as 130 W (whether the vehicle is operating or not, or whether it is connected to the grid or not). This consumption was converted into a specific energy consumption of 0.053 kWh/km for a 28-kWh battery.

The battery energy consumption, BEC (kWh), was determined from the sum of the integral of the battery chemical power $P_{bat,chem}$ over the driving mission time horizon, and the thermal management term as follows:

$$BEC = \frac{1}{3.6e6} \int_0^T P_{bat,chem} \cdot dt + \frac{0.053}{28} \cdot E_{bat} \cdot D_{mis}$$

where E_{bat} is the battery energy content (kWh) and D_{mis} is the driving mission distance (km).

The TTW energy consumption also accounts for the charger and battery losses, when the battery is charged at the end of the trip ($\varepsilon_{bat,RC}$ is the battery efficiency for the given re-charging power), as follows:

$$\mathrm{EC}_{ttw} = \frac{BEC}{\varepsilon_{chrg} \cdot \varepsilon_{bat,RC}}$$

2.2.2.1.2.3 Tank to Wheel analysis

Figure 6 shows the trend of the TTW CO_2 emissions for the two different vehicles (Diesel and CNG) for five driving conditions (colored bars) and three loads (0%, 50% and 100% of the carrying load in the left, middle and right charts, respectively). The CO_2 average and standard deviation of each group are reported in red at the top and in blue at the bottom, respectively.

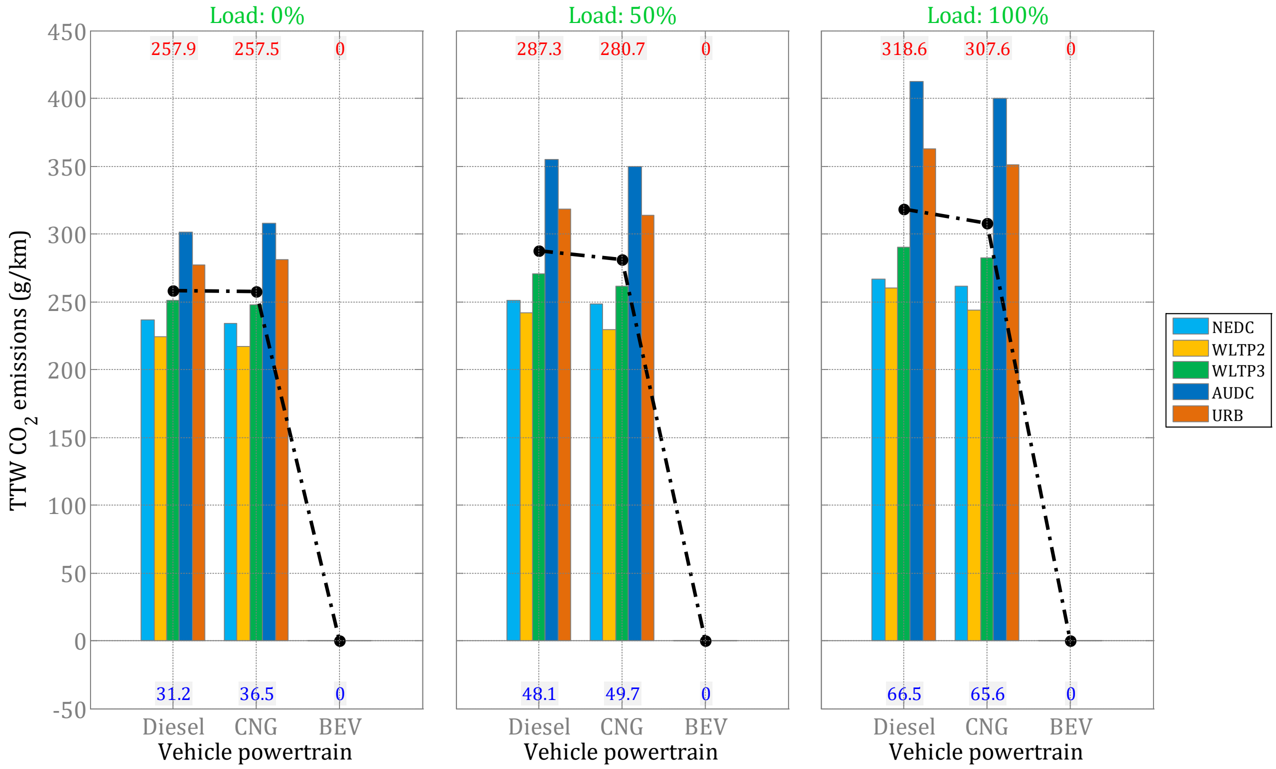


Figure 6: TTW CO_2 emissions for three different vehicles for several driving conditions and loads.

Figure 7 shows the trend of the TTW energy consumption for the three different vehicles (Diesel, CNG and BEV) for five driving conditions (colored bars) and three loads (0%, 50% and 100% of the carrying load in the left, middle and right charts, respectively). It can be observed that the electric vehicle is the best solution, in terms of energy consumption, which is reduced by 50-55% with respect to the diesel vehicle, where higher benefits are obtained for higher loads. It is also less invariant to the driving conditions, since its EC deviation ranges from 20 to 30 Wh/km, against higher values (130-270 Wh/km) of its diesel counterpart.

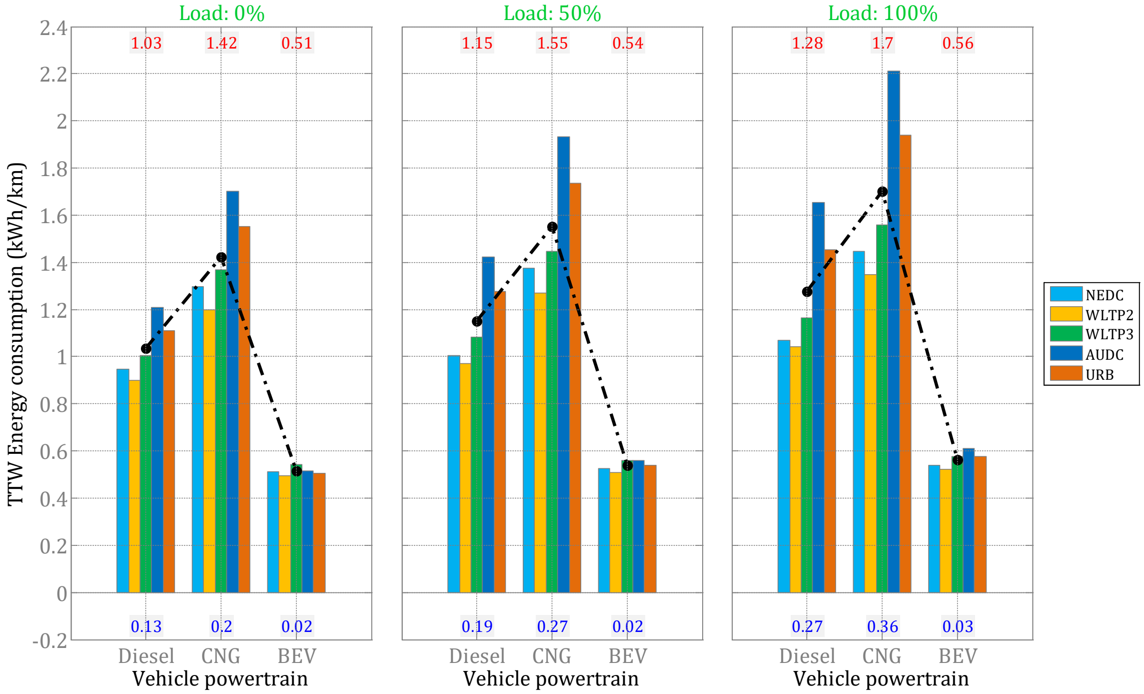


Figure 7: TTW energy consumption for three different vehicles for several driving conditions and loads.

Table 4 reports the efficiency chain comparison between Diesel and BEV over the AUDC with 0% load. The BEV regenerative share was set to 80% for this analysis. The efficiency was calculated as the ratio of the EC at the previous component level to the EC of the current one. For instance, the efficiency at the wheel level of the BEV (80.5%) is the ratio of the vehicle EC (231 Wh/km) to the wheel EC (287 Wh/km).

The efficiency of the diesel at the wheel level is much lower than that of the BEV, due to the complete loss of the braking energy, 80% of which is instead recovered by the electric vehicle. However, this huge advantage can be halved if the WTT chain is inefficient, as is currently the case in several countries. The Diesel configuration is far better than the CNG counterpart (33-37%), and this aspect has so far determined its extensive adoption.

Table 4: Efficiency chain comparison between Diesel and BEV over the AUDC with 0% load.

	Energy Consumption (Wh/km)		**Efficiency (-)**	
	Diesel	BEV	Diesel	BEV
Vehicle	229	231		
Wheel	378	287	0.606	0.805
Engine/motor	433	298	0.873	0.963
Tank/battery	1207	344	0.359	0.866
BMS	-	366	1.000	0.940
Plug	-	472	1.000	0.775
Charger	-	533	1.000	0.886
Total	1207	533		

Table 5 lists the TTW CO_2 emissions and TTW energy consumption of each vehicle for two different delivery missions (M1 and M2). A delivery mission is a sequence of different driving cycles, each with a different vehicle load. Mission M1 represents an urban scenario, where frequent delivery trips are required at part-load. Mission M2 simulates a complete delivery trip, where the weight of the vehicle gradually reduces, due to a series of intermediate delivery stops within the city, and the vehicle returns to the central station by highway with no cargo. The last row of each mission group reports the average of each quantity for a specific vehicle. The electric vehicle reduces TTW energy consumption by 57%. The overall effect of a different mission has been identified to be around 5%, due to the high consumption impact of full load driving conditions. This analysis has highlighted two points of strength of the BEV configuration: 1) different driving missions and vehicle loads affect its performance to a lesser extent than its conventional counterpart; 2) the greatest improvements are achieved under full-load urban driving conditions. However, this vehicle shows the least benefit for non-cargo highway conditions.

Table 5: TTW CO_2 emissions and TTW energy consumption for each vehicle for two different delivery missions (M1 and M2).

			CO_2-ttw (g/km)			EC-ttw (Wh/km)		
Mission	Cycle	Load	DIE	CNG	BEV	DIE	CNG	BEV
M1	AUDC	50	355.2	349.8	0	1424.5	1934.4	561.1
	AUDC	0	301.1	307.6	0	1207.7	1700.8	515.6
	URB	50	318.1	313.8	0	1275.9	1735.1	540.0
	URB	0	277.2	280.9	0	1111.6	1553.2	506.0
			312.9	313.0	0	1255.0	1730.9	530.7
M2	AUDC	100	412.7	399.8	0	1655.2	2210.4	609.4
	URB	100	335.2	327.6	0	1344.6	1811.3	554.1
	AUDC	50	355.2	349.8	0	1424.5	1934.4	561.1
	URB	50	318.1	313.8	0	1275.9	1735.1	540.0
	WLTP	0	224.2	217.0	0	899.3	1199.6	494.5
			329.1	321.6	0	1319.9	1778.2	551.8

Figure 8 shows the trend of the TTW energy consumption of the BEV configuration for different regenerative braking factors (0, 40, 60 and 80%), driving conditions (one bar color for each cycle) and vehicle loads (one chart for each load). The default value of the recovery factor is 80%. The total consumption increases by 14% when regenerative braking is completely disabled for an empty vehicle. This increment is even greater for heavier vehicle loads, that is, 20% and 25% for half and full load, respectively. These results prove that braking energy recovery is a key factor for the success of BEVs. To this end, the thermal management of the battery and e-machine and vehicle dynamics to maintain stability during heavy braking when the contribution of the mechanical brakes is minimal will need further development and enhancement to maximize the amount of energy recovery.

The relative impact of regenerative braking at the brake level was compared with that at the TTW level. On average, it drops by about 50%, due to additional losses that reduce its relative importance. For instance, the relative increment of energy consumption of the no-recuperation case, with respect to the 80%-case, is 87% at the brake level for a full-load driving over the AUDC, but it drops to 43% at the TTW level.

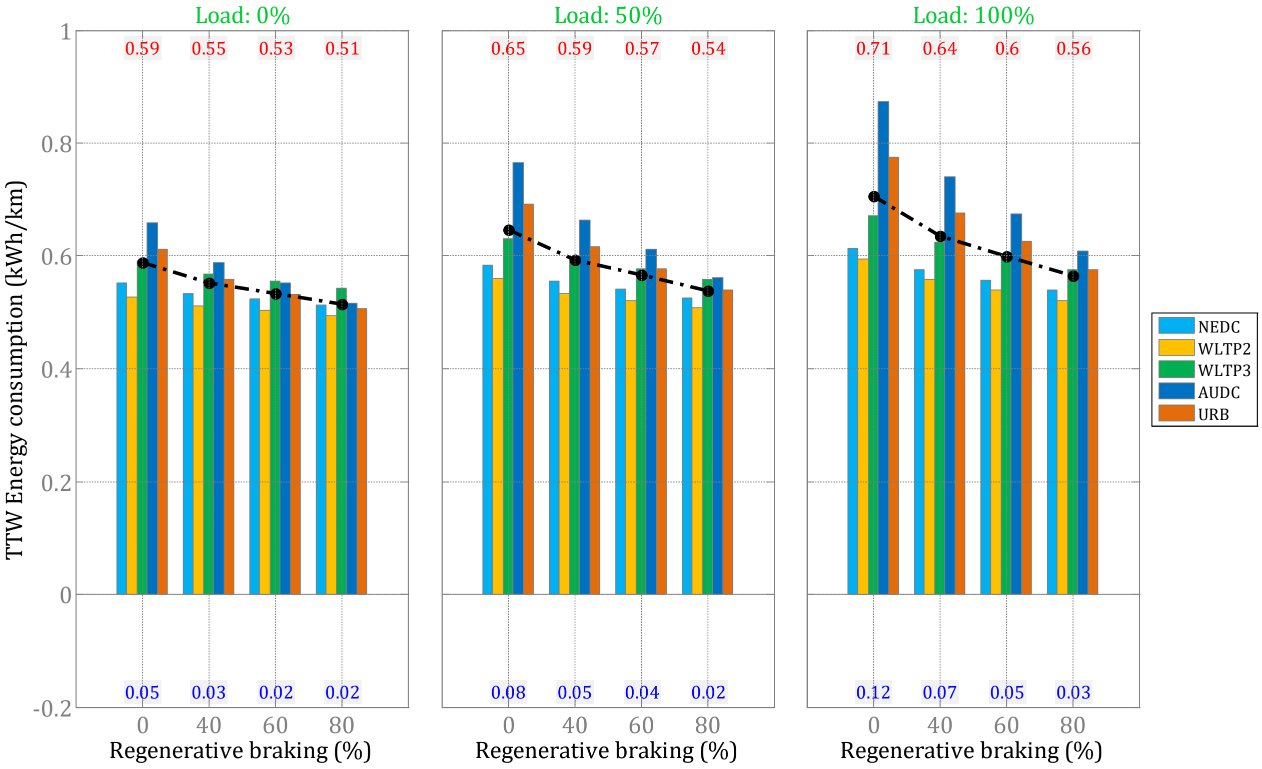


Figure 8: TTW energy consumption of the BEV configuration for different regenerative braking factors, driving conditions and loads.

2.2.2.1.3 Other use phase emissions

The model was not used to calculate any other relevant direct emissions (CO, NOx, PM, etc.), apart from CO_2, because the emission maps contain sensitive data for the manufacturers. However, the manufacturer provided emission data for the vehicle pertaining to the WHTC (*World Harmonized Transient Cycle*), so we extended this information to the other cycles. This implies certain limitations, because emissions are highly dependent on the driving cycle, and because WHTC is an engine test-bed. The data are reported in Table 6.

Table 6: Emissions from the WHTC for Diesel and CNG

Emission	*Unit*	*Diesel*	*CNG*
CO	*mg/kWh*	*58*	*488,7*
NOx	*mg/kWh*	*395*	*120*
PM	*mg/kWh*	*4,9*	*0,3*
HC	*mg/kWh*	*98*	*-*
CH_4	*mg/kWh*	*-*	*223,7*
NMVOC	*mg/kWh*	*-*	*2,7*
Energy consumption (50% load)	*kWh/km*	*1.29*	*1.77*

The upstream emissions from electricity production and fuel production were modeled using the EcoInvent database: "Diesel {RER}| market group for | Alloc Rec, U" for diesel; "Natural gas, high pressure {Europe without Switzerland}| market group for | Alloc Rec, U" for natural Gas and "Electricity, low voltage {IT}| market for | Alloc Rec, U" for electricity produced in Italy.

2.2.2.1.4 Non-exhaust emissions

Non-exhaust emissions include particulate matter from tire wear and brake wear and from abrasion of the road surface. These emissions can be significant in an impact assessment because the PM emissions from tires and brakes largely consist of metals, including significant proportions of heavy metals [59]. In EcoInvent 3, emissions are expressed in terms of kg tire, brake or road abrasion. Non-exhaust emissions per km could thus be scaled directly to the vehicle weight, which means that the emissions had to be defined in terms of kg/kg vehicle and for 1 km (kg/(kg×km)). In this study, we have used the values of kg of abrasion /kg vehicle* km from [59] for ICEV vehicles (see the values in Table 7) and multiplied them by the average Gross Vehicle Weight (GVW) of the different analyzed missions (GVW was hypothesized to vary during the delivery mission, because the goods were delivered along the route).

Table 7: Non-exhaust emissions for LDVs

kg of abraded material/(kg vehicle km)*	*Diesel*	*CNG*	*Electric*
Tires	5.73E-08	5.73E-08	5.73E-08
Brakes	4.45E-09	4.45E-09	8.9E-10
Road	9.79E-09	9.79E-09	9.79E-09

The road wear and tire wear were considered to be the same for ICEV and BEV, while the brake emissions of the BEV were considered to be 20% of those of the ICEV since, due to regenerative braking, mechanical brakes are used considerably less [60].

In order to take into consideration that these emissions occurred in cities, the EcoInvent datasets was modified and the subcompartments were specified: a highly populated area was chosen for the emissions to the air, while an urban area was chosen for the emissions to the soil.

2.2.2.2 Maintenance and component replacement

As a result of the limited relevance of maintenance, as established from literature in [61] and [25], this stage has been disregarded in many LCA studies. Moreover, maintenance is unpredictable, as it depends on the individual user's behavior and on environmental conditions, and it can change considerably from case to case. Some of the few authors who have accounted for it used generic data as scaling factors [61], or average data taken from literature [6].

However, since the complexity of vehicles is expected to grow, the impact associated with maintenance is also expected to grow. The maintenance of EVs is expected to be lower than that of ICEVs [62]. It has been hypothesized that BEVs will cause less wear of the brake pads and disks, and all the typical replacements of ICEVs, such as that of the oil, oil filters, spark plugs, timing belts and fuel filters, will be avoided. All the repairs needed for the exhaust system will also become unnecessary.

In this study, the data on maintenance and component replacement have been provided by the manufacturer for the diesel version, and the CNG has been assumed to be the same as that of a diesel vehicle.

Maintenance was modeled considering: 1. the frequency of the replacements of the components and parts provided by the manufacturer; 2. the production of the replacement parts as being the same as the production of the originals; 3. the consumptions and emissions due to replacement operations could be disregarded.

Table 8: maintenance operations and their frequency

Maintenance Operation	*Diesel*	*CNG*	*Electric*
Oil change	Every 40.000 km	Every 40.000 km	-
Oil filter change	Every 40.000 km	Every 40.000 km	-
Timing belt change	Every 60.000 km	Every 60.000 km	-
Alternator belt	Every 60.000 km	Every 60.000 km	-
Fuel filter change	Every 40.000 km	Every 40.000 km	-
Brake fluid change	Every 60.000 km	Every 60.000 km	Every 60.000 km
Air filter change	Every 40.000 km	Every 40.000 km	-
Cooling fluid change	Every 120.000 km	Every 120.000 km	-
Lead Battery change	Once	Once	-
Tire substitution	Three times	Three times	Three times
NaNiCl Battery	-	-	-

The brake fluid change and tire substitution for the electric version were assumed to have the same frequency as the ICEV versions. As a first assumption, the battery lifetime was considered to be the same as the vehicle lifetime.

3 Results and discussion

3.1 Impact assessment

The Cumulative Energy Demand was calculated using the CED method; the abiotic depletion, abiotic depletion-fossil fuels, global warming (100a), ozone layer depletion, photochemical oxidation, acidification and eutrophication were assessed using the April 2013 updated version (v. 4.2) of the CML baseline method [50]. The results are presented hereafter divided per production, operation and complete LCA.

3.1.1 Vehicle Production (UP1-UP10)

The results pertaining to component production and vehicle manufacturing have been grouped under the label "vehicle production" and are discussed and presented in this section.

Figure 9 compares the production of the three versions of the vehicle. The impacts were normalized to the highest score in each category. The production includes all the processes, that is, from component production to distribution on the market; the numeric values are available in the supplementary material section.

The production of the electric vehicle shows the highest impact in each category. This is not surprising, since the electric version is heavier and the production of batteries has been shown to have a relevant impact.

This excess is particularly noticeable for abiotic depletion, photochemical oxidation, acidification and eutrophication. In order to understand the origin of these gaps, the total contribution was divided by the unit processes.

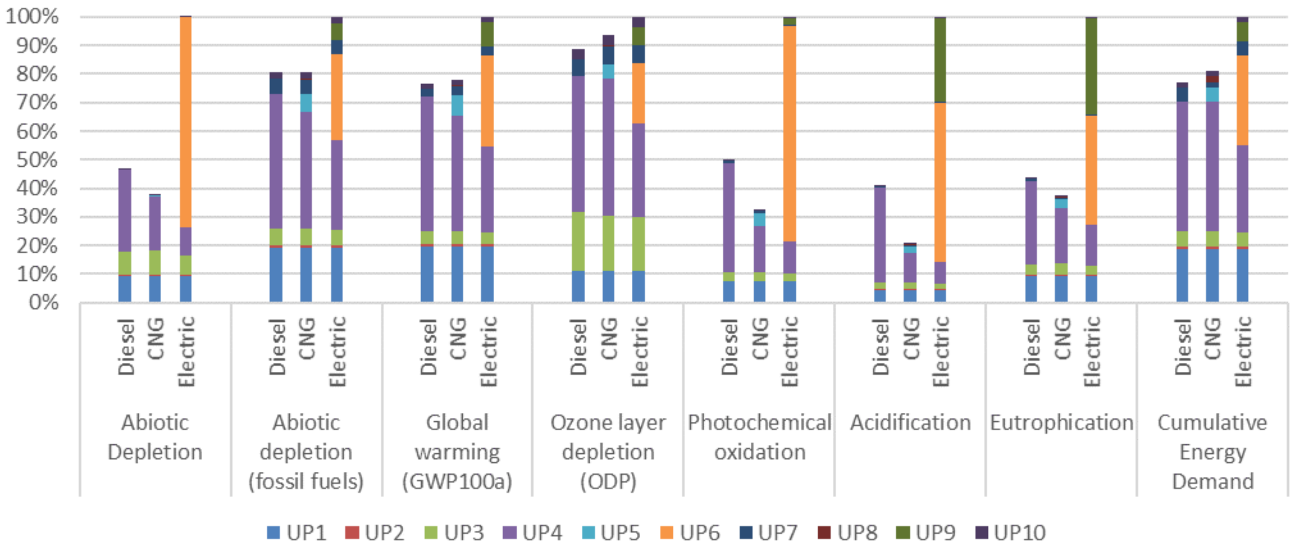
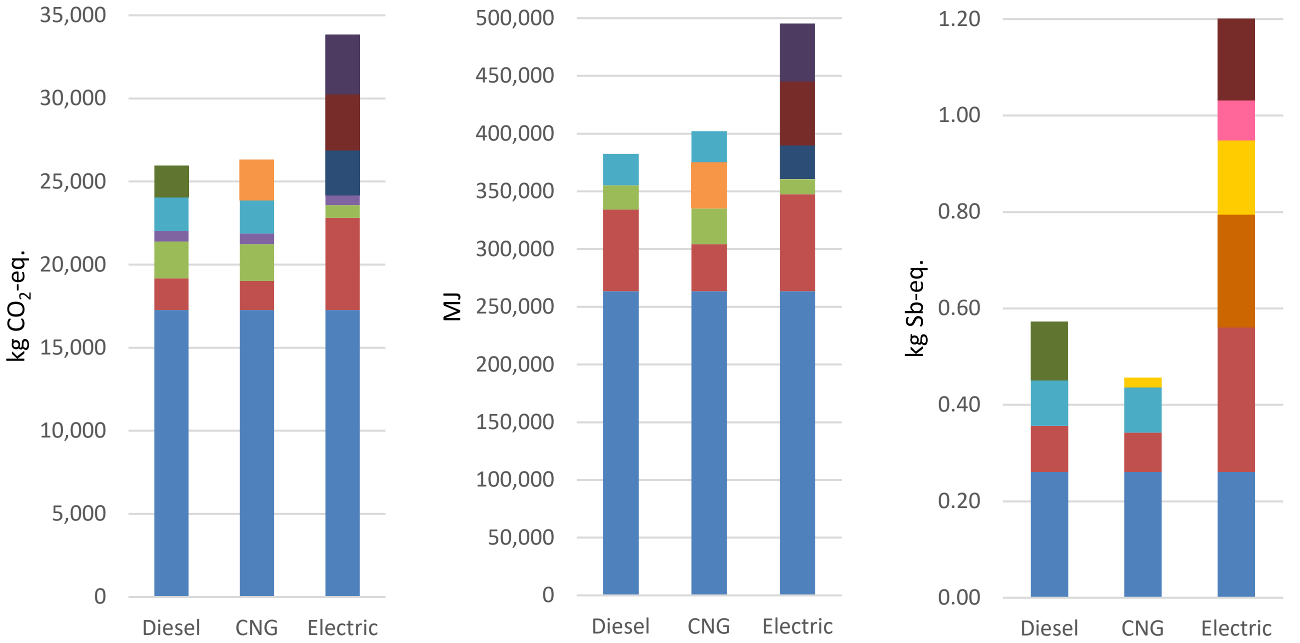


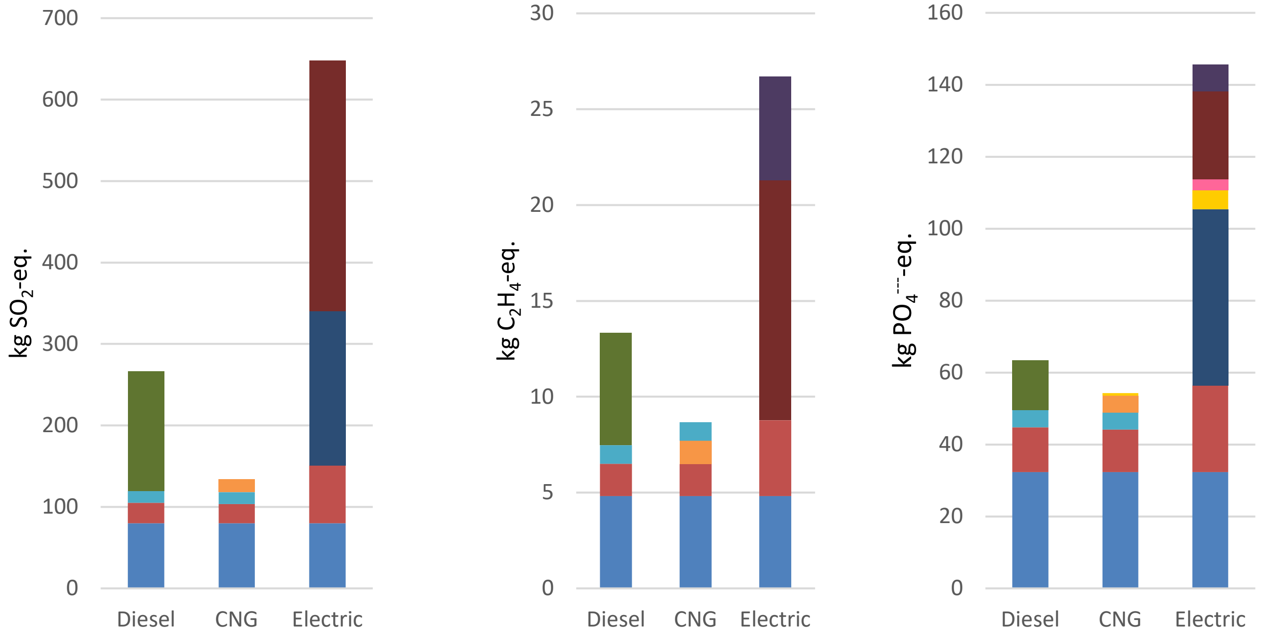
Figure 9: Comparison of the impacts of vehicle production (UP1-UP10) - Process contribution

Since the three configurations present the same glider and interiors, there is no difference in the impacts for welding, painting and trimming (UP1-UP3). Differences instead arise when it comes to the bodyworks (UP 4) and subsequent processes: the electric version presents a lower impact for the bodyworks, but this is compensated for by the electrification components (UP6) and manufacturing at the plant where the electrification of the glider takes place (UP9).

In order to better understand these differences, we grouped together the components and the processes common to all three vehicles in Figure 10. In this way, it was possible to compare only the parts that differ from one configuration to another and to highlight the components that caused most of these deviations. The classical impact categories (Global Warming, CED) and those where the difference between the powertrains emerged the most, according to Figure 9, namely abiotic depletion, photochemical oxidation, acidification and eutrophication (for the numeric values, see the supplementary material section) are analyzed in Figure 10. All the common processes and components in Figure 10 are grouped together under the label “common components and processes”, and the components with the greatest impact in each impact category are highlighted. The remaining components are grouped together under the label ‘others’.



(a) Global warming **(b) Cumulative Energy Demand** **(c) Abiotic Depletion**



(d) Acidification **(e) Photochemical Oxidation** **(f) Eutrophication**

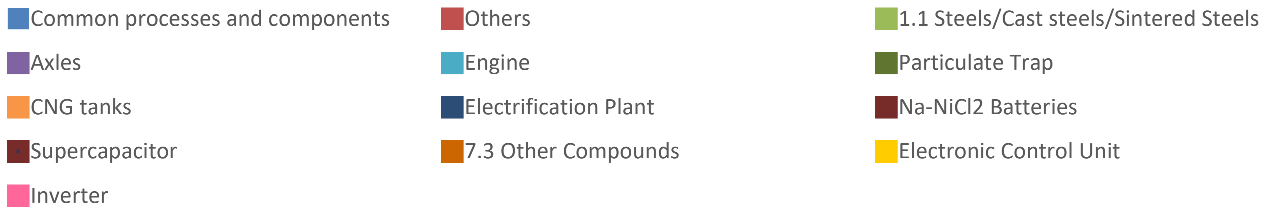


Figure 10: Contribution of the components to the impacts of the vehicle production

It emerges, from Figure 11, that more than 70% of the gap in each category is caused by a set of components related to the powertrain: as far as Global Warming is concerned, the main difference between the three powertrains is due to the engine and the particulate trap for the Diesel vehicle (which represent 22% and 23%, respectively, of the specific components of the diesel version that are not shared with the other vehicle configurations), the engine (22%) and CNG tanks (27%) for the CNG vehicle and the supercapacitors (20%), Na-NiCl batteries (22%) and operation at the electrification plant (UP9) (16%) for the electric configuration. Na-NiCl batteries also play a significant role in acidification and photochemical oxidation, and represent more than 50% (52% and 57%, respectively) of the electric-specific components.

3.1.2 Use phase

The emissions and energy consumption of the use phase have been dealt with in detail in the life cycle inventory section (2.2.2.1). The results of only one mission are reported hereafter, in particular to show the effects of the direct emissions, including the pollutants that are not calculated by the model (CO, NOx, PM, HC, CH_4, NMVOC), and the relative importance of non-exhaust emissions.

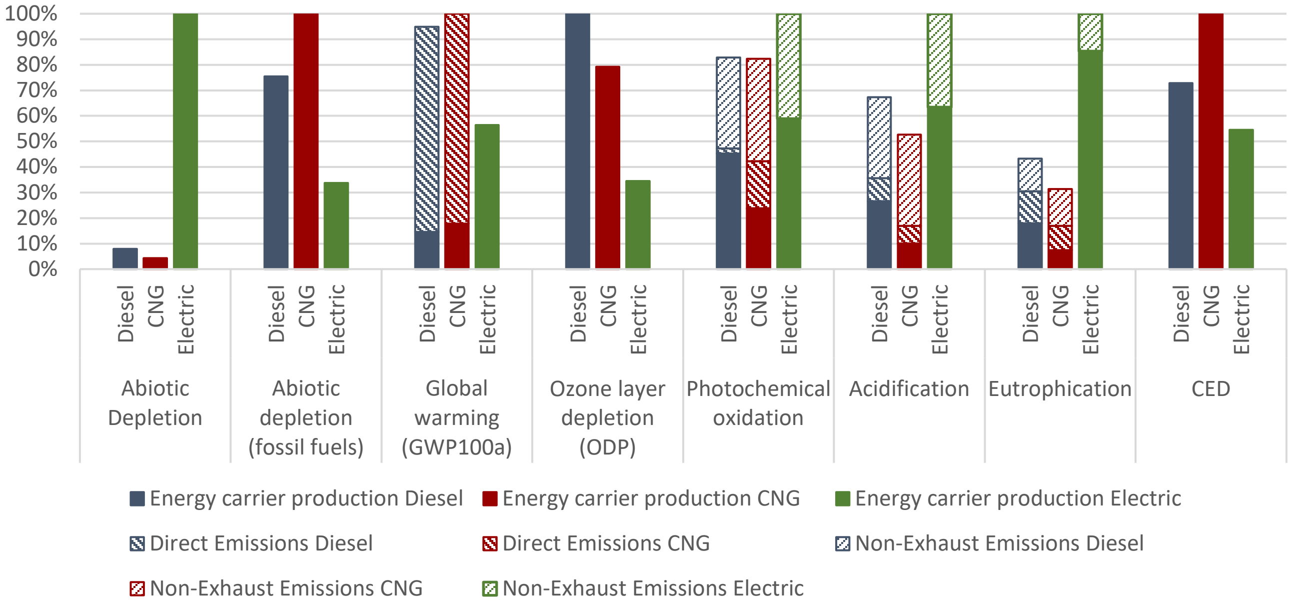


Figure 11: Impacts of the Use phase – 1 km driven in delivery mission M1.

During delivery mission M1 (see the description in section 2.2.2.1), the average kWh/km required by the three vehicles is 1.25 kWh/km for Diesel, 1.73 kWh/km for CNG and 0.53 kWh/km for the electric version.

The higher efficiency of the electric version shows a direct benefit pertaining to the consumption of fossil fuels (Impact category - Abiotic Depletion (fossil fuels)) and in CED. However, in CED, which takes into account the efficiency of electricity production and its distribution, this gap is almost halved, due to a high primary Energy factor and losses during distribution.

The depletion of abiotic resources in the electric version is driven by the copper required to distribute the electricity at a low voltage throughout the country and the silver used in the production of the photovoltaic panels that produce part of the national supply of electricity. Copper depletion represents 32% of the total impact (1.3E-07 kg Sb-eq), and this is followed by gold and silver at 18% and 17%, respectively; instead, the first voice for the diesel version is cadmium (28%; 9.6 E-09 kg Sb-eq), which is depleted in zinc-lead mining operations.

In the global warming impact category, 87% and 83% of the impacts are due to direct CO_2 emissions for Diesel and CNG, respectively, while the release of unburned CH_4 is responsible for 1.4% of the total impacts for CNG. The contribution to the use phase for CNG and diesel is mainly due to direct CO_2 emissions: the higher GW of the CNG version directly reflects the lower efficiency of this powertrain and the subsequent higher consumption of fuel.

The Abiotic depletion – fossil fuel category reflects what has already been expressed by CED: all the impacts are due to the production of the energy carriers in this category and are related to the efficiency of the three powertrains; however, compared to CED, the electric version here benefits from the RES used to produce part of the Italian electricity supply.

Ozone layer depletion is mainly due to the release of refrigerants from the cooling compressors used in the transportation process of natural gas through pipelines. As a result of the high reliance of the Italian electricity mix on natural gas, these effects are also visible for the electric version. The predominance of diesel production is due to the release of refrigerants from the on-shore extraction of oil and gas. This release is not observed in the EcoInvent dataset for offshore plants, which are the main sources of the natural gas consumed in Europe.

Non-exhaust emissions play a role in photochemical oxidation, acidification and eutrophication. They present almost the same impact for all three vehicle versions: the lower brake wear of the electric LDV is offset by a higher Gross Vehicle Weight, which is the direct scaling factor of non-exhaust emissions. What drives the impacts in these categories is once again the energy carrier production, which means that the contribution of coal to electricity generation plays a significant role in all these categories. The first contributor to photochemical oxidation and acidification is SO_2 emissions, which are mainly released at coal power plants (75%) and during mining operations (25%). This is followed by VOC emissions during the transportation of natural gas.

The same is true for acidification, where 50% of the SO_2 emissions is released directly at the hard coal power plants. As far as eutrophication is concerned, 60% of the impacts is due to phosphate emissions to water as a result of spoil and sulfidic tailing disposal in hard coal mining operations [63].

It is worth noticing that none of these impacts takes into account the avoided EV emissions at the place of use, even though some spatial considerations are included in the classification of emissions into archetypal conditions, for example high vs low population density areas.

3.1.2.1 Maintenance

As far as maintenance operations are concerned, the electric version benefits from the simpler configuration and thus from a reduced number of component replacements (Figure 12). However, this phase is negligible over the overall life cycle, since it represents less than 1% in each category, except for abiotic depletion, where it represents 5% of the overall impacts for the Diesel and CNG versions (see the supplementary material for the numeric values).

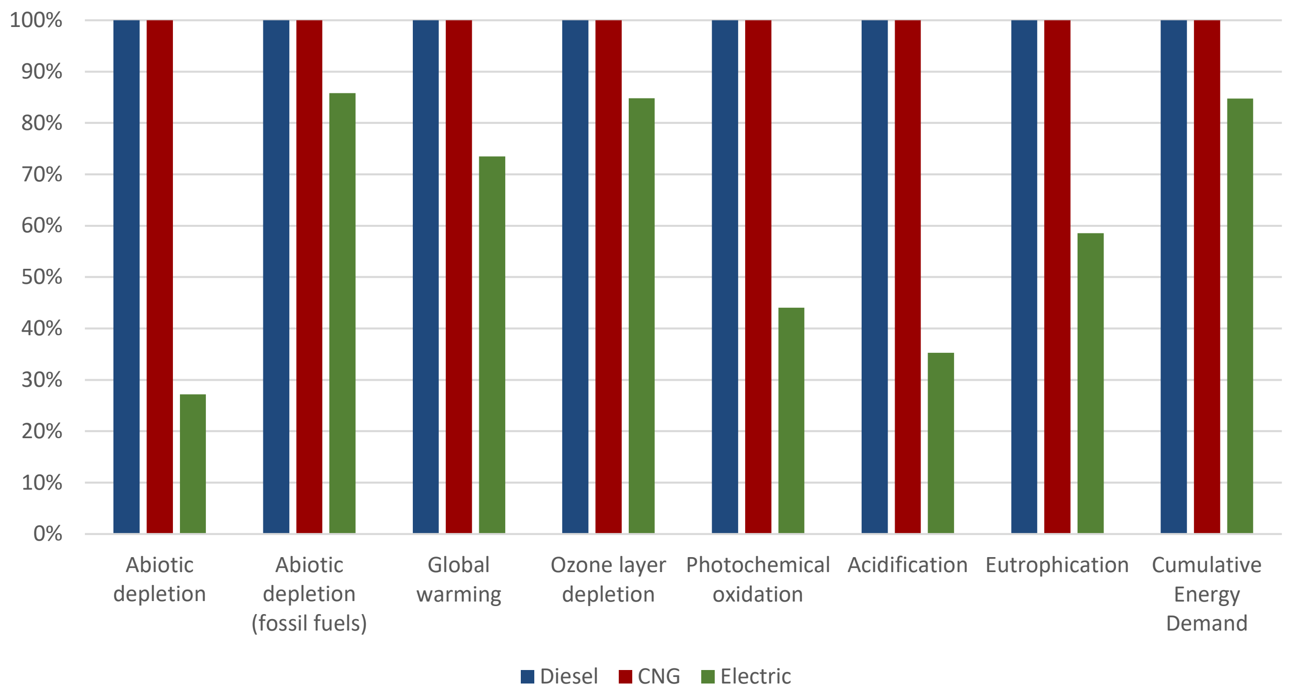


Figure 12: Maintenance operation

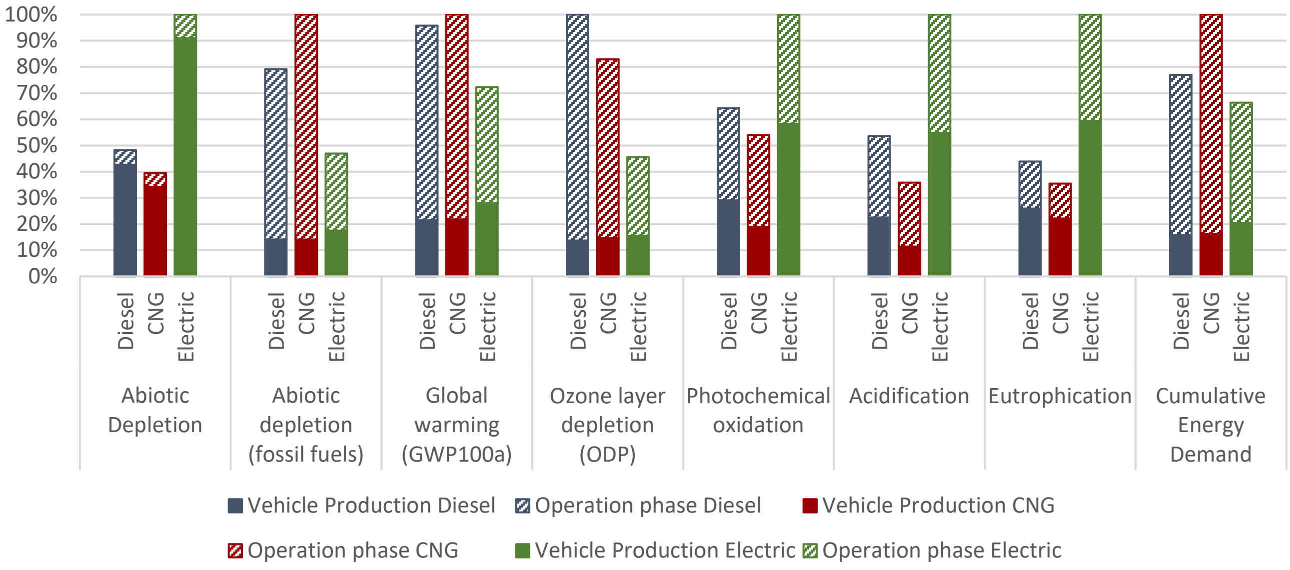
It is difficult to compare the results with the literature because the few studies that have included this topic did not present a disaggregated value of the maintenance impact. However, the aforementioned negligibility has been confirmed.

3.1.3 Complete Life cycle

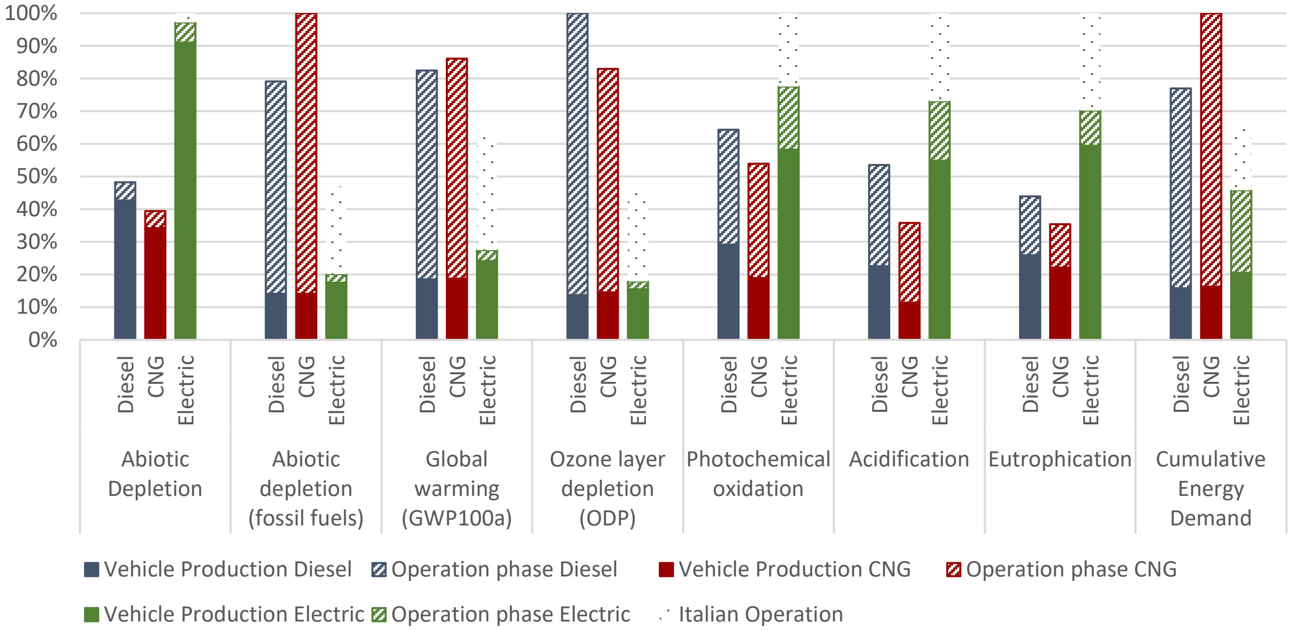
Fifteen driving patterns were investigated for each vehicle:

- Five vehicle speed profiles, based on 4 driving cycles used for vehicle certification and on 1 ad hoc driving cycle developed by the vehicle manufacturer for delivery missions in urban environments.
- Three loading cases: kerb weight, full load and 50% load.

Thus, 45 different results were obtained, but only a meaningful combination of these parameters has been considered hereafter. According to what was expressed in section 2.2.2.1, a meaningful load and speed combination was used to build a realistic urban delivery mission (M1), which in turn was used to analyze the complete life cycle. Figure 13 shows the complete LCA of the three vehicles, driven according to delivery mission M1 (for the description see section 2.2.2.1 and for the numeric values see the supplementary material section). A second delivery mission (M2), obtained considering a different load and speed combination, was considered, but for the sake of concision, all the details and the results on mission M2 are listed in the Supporting Information.



(a)



(b)

Figure 13: (a) Complete life cycle impacts per travelled km (vehicle lifetime of 240.000 km and use phase M1) using the Italian electricity mix (b) Complete life cycle impacts per travelled km (vehicle lifetime of 240.000 km and use phase M1) using the Norwegian electricity mix

It is evident from Figure 13(a) that the use phase is still a dominant stage in the Life Cycle of the three vehicles. The impacts of the internal combustion engine vehicles (Diesel and CNG) are always dominated by the use phase. The only exceptions are Abiotic depletion and Eutrophication. The former is not a surprise, since it is closely related to the raw material use (excluding fossil fuels).

The electric version provides savings for all the categories related to fossil fuels and their combustion (abiotic depletion – fossil fuels, Global Warming, CED), even in a country that is still dominated by fossil sources for electricity production, such as Italy.

It presents higher impacts than diesel and CNG in four impact categories out of eight: Abiotic depletion, photochemical oxidation, eutrophication and acidification. The impacts in all these categories are dominated by the production phase.

In order to have a better understanding of the results pertaining to the complete life cycle, they have been converted into a synoptic format in Figure 14.

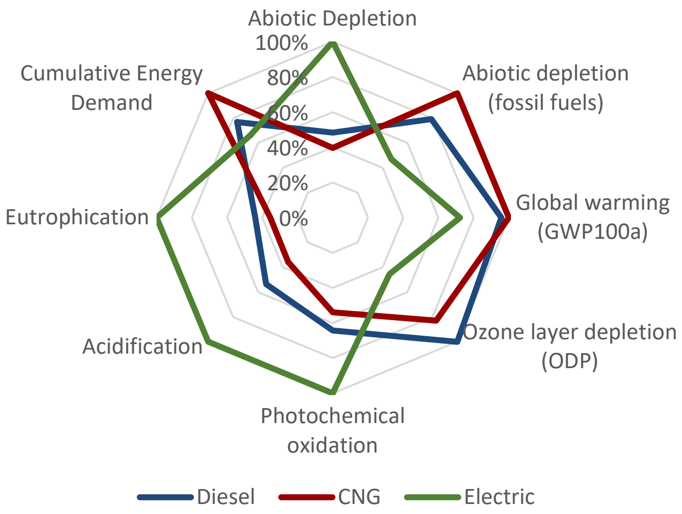


Figure 14: Complete life cycle, impact per travelled km (vehicle lifetime of 240.000 km and use phase M1) using the Italian electricity mix

Looking at the electric vehicle, operation is still a relevant phase, but the reliance on electricity makes it possible to decouple transportation from fuel consumption and Global Warming. To do so, we investigated what occurred when an electricity mix mainly based on renewables was used: the Norwegian case (see Figure 13(b)). Using such a mix also allowed the beneficial energy balance to be expressed (see the CED category). The electric version shows a very efficient use of energy (less than half of the energy required at the wheel), but most of the obtained benefit is lost upstream for the production of electricity from fossil fuels (the Cumulative Energy Demand to produce 1 kWh of electricity at a hydropower plant is 1.07 kWh, while it is 3 kWh to produce the same amount of electricity in a hard coal plant in the EcoInvent dataset).

Figure 13(b) shows the reduction in impact that could be obtained by recharging the vehicle with a low carbon energy mix, such as the Norwegian one, compared to the Italian situation. The dotted areas in green highlight the potential benefit that may be achieved from the use of the Norwegian electricity mix, compared to the Italian situation. Significant advantages are obtained in all the impact categories. However, the reduction in the use phase impacts does not change the hierarchy in those categories where the electric vehicle performs worse than Diesel and CNG in the Italian case, i.e. the categories dominated by the production phase.

Even in a country with a high RES penetration (such as Norway, where more than 96% of the electricity production comes from hydroelectric sources [64]), the Electric version performs worse than the diesel and CNG ones in four impact categories out of eight. The case of Norway points out the issue of the production phase for electric vehicles. As shown in section 3.1.1, the gap between conventional vehicles and EVs can be ascribed to a handful of components; among them, the battery emerges.

The analyzed electric vehicle is equipped with sodium nickel chloride batteries (NaNiCl, also known as ZEBRA batteries); in order to reduce the burden of this component, the choice of more eco-friendly batteries could help reduce the production hotspot. To date, there are only a few studies that have compared NaNiCl batteries with other typologies for traction applications. The study by Hammond et al. [15] seems to suggest an environmental benefit for LIB production compared to NaNiCl batteries, without any effect on the performance: according to that study, the CO_2 emissions for the production of a Lithium-ion battery are 5.4 kg CO_2/kWh, compared to 32.4

kg CO_2/kWh for ZEBRA batteries, while SO_2 emissions are 1.5 kg SO_2/kWh for Lithium-ion batteries and 4.0 kg SO_2/kWh for ZEBRA batteries. However, no other impact categories were analyzed.

4 Conclusion and future work

The advantages of electric mobility are still under debate, because of the offset between higher production impacts and a more efficient use phase, and because of the role played by the electricity mix used to recharge the vehicle.

While this debate has so far mainly been focused on passenger vehicles, the present study has focused on a less investigated field: the delivery of goods in urban environments.

The particular feature of the present study is that three light commercial vehicles produced by the same manufacturer with three different powertrains (Diesel, Compressed Natural Gas and Electric) have been compared. They only differ as far as the powertrain and the related components are concerned, and they have been assembled in the same plant. This allows the comparison to be freed from most of the inequalities that affect comparative Life Cycle Assessments of powertrain alternatives.

The function selected for the comparison is the delivery of goods in an urban environment, and the functional unit is a standard delivery mission. The analysis is based on primary data on the production phase provided by the manufacturer. An ad-hoc kinematic model, developed in the Matlab environment, was implemented for the use phase to obtain the emissions and consumption in this phase, while the non-exhaust emissions were based on literature data; the maintenance phase was based on the displacement rate of the main components, which was provided by the manufacturer. The delivery mission was defined using a meaningful load and speed combination that was able to describe a standard delivery mission.

The detailed analysis of the production phase showed that the electric version has a greater impact than the internal combustion engine versions in all the considered impact categories. The gaps are driven in particular by a handful of components: the batteries, supercapacitor, inverter and electronic control units.

The results from the kinematic model have shown that the electric motor presents advantages in urban environments, because of the numerous stops and regenerative braking that are typical of urban deliveries. Its good performance emerges as the load of the vehicle is increased, thus making the comparison with ICEV particularly favorable for electric vehicles when it comes to the delivery of goods.

By considering the complete life cycle, it emerges that the electric vehicle performs better than the Internal Combustion Engine versions (Diesel and Compressed Natural Gas) in four out of eight of the analyzed impact categories – namely Abiotic Depletion-fossil fuels, Global Warming, Cumulative Energy Demand and Ozone Layer Depletion – even in a country (Italy) where electricity production is still dominated by fossil fuels. The impact categories where the electric version performs worse – Abiotic Depletion, Photochemical Oxidation, Acidification and Eutrophication – are dominated by the production phase.

A comparison with a near zero carbon electricity mix was performed, assuming that the use phase occurs in Norway. The effect of such an artifice showed that adopting a Renewable Energy Source-based electricity mix enhances the benefits in the categories where EVs already performed better in the Italian situation, i.e. all the categories related to fossil fuels and their combustion (abiotic depletion – fossil fuels, Global Warming, Cumulative Energy Demand). However, it does not upset the order of the results in the other categories, and this highlights that the production phase remains an issue for electric vehicles.

Electric light duty vehicles represent a promising means for the delivery of goods in urban environments, and their implementation should be accompanied with a Renewable Energy Source based electricity mix. However future work should be directed toward improving production technologies and materials in order to make electric vehicles competitive in all of the considered impact categories.

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Author contributions: E.S., G.D., M.V and B.M. conceived the paper. M.V. developed the kinematic model and tested it. He wrote the related section in the paper. B.M. collected and processed production data, performed the Life Cycle Assessment and wrote the paper. E.S and G.D. revised the paper.

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