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The environmental impact of electric vehicles: A novel life cycle-based evaluation framework and its applications to multi-country scenarios

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ABSTRACT

Electric mobility is being studied as a possible solution for reducing the environmental impact associated to the transportation sector. However, there is a huge ongoing debate among scholars and practitioners on the extent to which Electric Vehicles perform better in terms of greenhouse gases emissions against Internal Combustion Engine Vehicles, and especially on the variables that affect such performance. To the best of our knowledge, most of the studies addressing the topic mainly focus only on some specific phases of a vehicle's life cycle, such as vehicle manufacturing and use, while comprehensive evaluations of the greenhouse gases emissions during a vehicle's life cycle are quite rare. Therefore, the paper aims to develop a comprehensive evaluation framework in order to estimate the environmental impact associated to Electric Vehicles and Internal Combustion Engine Vehicles, by adopting a Life Cycle Assessment approach. The evaluation framework is then adopted to estimate the environmental impact associated to Electric Vehicles and Internal Combustion Engine Vehicles in four different scenarios, each one assuming different countries in which the phases of a vehicle's life cycle take place. Results show that CO_2 emissions over the Electric Vehicle's life cycle are lower than the ones associated to a comparable Internal Combustion Engine Vehicle in all the scenarios analysed. Moreover, the analysis highlights: (i) the huge impact on a vehicle's CO_2 emissions associated to the geographical location in which the upstream phases of the vehicle supply chain take place (mainly for Electric Vehicles); (ii) the primary impact played by the use phase on the Electric Vehicles CO_2 emissions, followed by the vehicle and battery manufacturing ones. Both evidences reinforce the impact of the energy mix on the environmental performance of Electric Vehicles, as further confirmed by the sensitivity analysis. The paper contributes to the extant literature by reaffirming the better environmental performance of Electric Vehicles compared to Internal Combustion Engine Vehicles in terms of CO_2 emissions over the whole life cycle, also providing policymakers with useful suggestions for the promotion of Electric Vehicles as a means to tackle environmental issues.

1. Introduction

The transportation sector is at the core of national and supranational decarbonization policies (European Commission, 2018; Lah, 2017), as it accounts for around one fourth of greenhouse gases (GHG) emissions worldwide (International Energy Agency, 2018a), most of them related to road transport (Transport and Environment, 2018). Moreover, in recent years the increase of the GHG emissions in many countries due to the transportation sector has been higher than the one caused by other sectors (International Energy Agency, 2018b).

In this scenario, electric mobility is being studied as a possible solution for achieving a more sustainable mobility and reducing environmental impact associated to the transportation sector (Ellingsen et al., 2014; Knobloch et al., 2020; Van der Zwaan et al., 2013). Electrification represents one of the most relevant emerging trends in the transportation sector (McKinsey, 2017), as more than 2 million electric vehicles (EVs) were sold in 2018, with an expected dramatic increase in the next years (Bloomberg NEF, 2019). Several EV typologies may be identified, such as Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEV), which can be distinguished based on different features as powertrain, full electric or hybrid configuration and battery size (ENEL e Ambrosetti, 2017; International Energy Agency, 2019). Among them, market forecasts are pretty aligned in considering BEVs as the reference EV typology, both today and for the future (EV-volumes, 2019; International Energy Agency, 2019). However, there is a huge ongoing debate among scholars and practitioners on the extent to which EVs diffusion would determine

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Nomenclature

AUX_i	Specific vehicle consumption increase due to auxiliaries in country i
BC_j	Battery capacity related to segment j
BEV	Battery Electric Vehicle
BME_{ij}	Battery Manufacturing Emissions related to country i and vehicle segment j
BTE_{ji1i2}	Battery Transportation Emission related to segment j, from country i1 to country i2
BW_j	Battery weight related to segment j
B2U	Battery Second Use
CE	Circular Economy
CO_2	Carbon dioxide
D_{i1i2}	Distance from country i1 to country i2
EL	Energy loss due to energy transportation and distribution
EoL	End of Life
EV	Electric Vehicle
GHG	Greenhouse Gases
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LFP	Lithium Iron Phosphate
LiB	Lithium Ion Battery
NCM	Nickel Cobalt Manganese
$OCMVAE_{ij}$	Other Components Manufacturing and Vehicle Assembly Emission related to country i and vehicle segment j
PHEV	Plug-in Hybrid Electric Vehicle
RES	Renewable Energy Source
SCO2Ei	Specific CO_2 emission levels associated to energy related to country i
SCO2F	Specific CO_2 emission levels associated to fuel
$SCO2T_{rail}$	Specific CO_2 emissions due to rail transportation
$SCO2T_{road}$	Specific CO_2 emissions due to road transportation
$SCO2T_{sea}$	Specific CO_2 emissions due to sea transportation
SER_{BM}	Specific energy requirements for battery manufacturing
SER_{BR}	Specific energy requirements for battery recycling
SER_{OCMVAE}	Specific energy requirements for Other Components Manufacturing and Vehicle Assembly
SER_{VD}	Specific energy requirements for vehicle disposal
SVC_EV_j	Specific Vehicle consumption for an EV related to vehicle segment j
SVC_ICEV_j	Specific Vehicle consumption for an ICEV related to vehicle segment j
TSO	Transmission System Operators
TTW	Tank-to-Wheel
UE_{ji}	Use Emissions related to segment j in country i
VTE_{ji1i2}	Vehicle Transportation Emission related to segment j, from country i1 to country i2
VW_j	Vehicle weight (battery excluded) related to segment j
WTW	Well-to-Wheel
η_{charge}	Charging efficiency
$\%_{rail}$	Share of the transportation distance covered by rail transportation
$\%_{road}$	Share of the transportation distance covered by road transportation
$\%_{sea}$	Share of the transportation distance covered by sea transportation

a GHG emissions reduction compared to Internal Combustion Engine Vehicles (ICEVs) (Le Petit, 2017; European Environment Agency, 2018; Mock, 2018; Peng et al., 2017; Tagliaferri et al., 2016), and especially on the variables that affect such performance.

Starting from these premises, the paper aims to develop a comprehensive evaluation framework to estimate the environmental impact associated to EV and ICEV, by adopting a Life Cycle Assessment (LCA) approach. LCA is one of the most comprehensive methods to assess the environmental impact of a product, which embraces all the phases along the entire product's life cycle, from raw material extraction and processing, to manufacturing and assembling processes, to use and end-of-life (EoL) (ISO, 2006).

With reference to the automotive sector, LCA-based studies have been introduced since the 1970s to identify new ways for achieving a lower dependence on crude oil-based products (de Souza et al., 2018). Following the increasing interest towards e-mobility, many LCA studies have been conducted in the last 20 years to evaluate the environmental impact of such vehicles (Hawkins et al., 2013; Wu et al., 2018). Despite the fact that EVs, with particular reference to BEVs, do not have any direct GHG emissions due to their use (the so-called Tank-to-Wheel - TTW - phase) (Del Pero et al., 2018; Tagliaferri et al., 2016), indirect emissions during this phase are related to electricity generation (the so-called Well-to-Wheel – WTW - phase). As a consequence, EVs emissions related to their use in countries which have a significant share of energy produced by non-renewable energy sources and especially by coal - such as China and Poland (Enerdata, 2019) - are higher compared to countries with a higher Renewable Energy Sources (RES) penetration (European Environment Agency, 2018). Furthermore, an exhaustive analysis of a vehicle's GHG emissions should adopt a cradle-to-grave approach, i.e., including all the phases during its life cycle (Kukreja, 2018; Petrauskienė et al., 2020; Velandia et al., 2019). However, to the best of our knowledge, most of the studies currently available mainly focus only on some specific phases, such as vehicle manufacturing and use.

Following the development of the comparative LCA-based evaluation framework, the paper presents its application to four scenarios, each one assuming different countries in which the phases of a vehicle's life cycle take place. The four scenarios differ in terms of the country in which the upstream phases of a vehicle's life cycle take place (i.e., battery manufacturing, other components manufacturing and vehicle assembly and transportation), to estimate the differences in terms of CO_2 emissions due to the geographical locations in which such phases take place. Italy was chosen as the country in which the vehicle use and EoL phases take place in all the four scenarios. Italy is one of the major automotive markets worldwide (ACEA, 2019). Despite a very low level of penetration of EVs compared to other European countries, it is expected to show a dramatic increase of EV penetration in the next years (Energy and Strategy, 2019). Moreover, the environmental impact associated to EV diffusion in Italy is worth evaluating in the light of the high level of RES penetration in the Italian energy mix (Ministero dello Sviluppo Economico, 2019). Finally, a sensitivity analysis is carried out with reference to the most impactful phases during an EV's life cycle, i.e., battery manufacturing and use phases.

The remainder of the paper is structured as follows. Section 2 illustrates the literature background. In Section 3, the LCA-based comparative evaluation framework is introduced and described, along with the methodological aspects and their limitations. Section 4 presents the results of the applications of the evaluation framework to the four scenarios, also including a sensitivity analysis. Finally, Section 5 provides concluding remarks, as well as limitations and avenues for future research.

2. Literature background

A literature review was carried out to obtain a deep understanding of the extant knowledge base on the topic and to identify the research gaps to be addressed (Saunders et al., 2009). Table 1 shows the 33 contributions identified on the frameworks evaluating the environmental impact of EVs and ICEVs, covering a period from 2010 to 2020.

2.1. Analysis of the literature

The identified contributions are first classified based on their scope, i.e., distinguishing between theoretical and empirical contributions. The former aim at creating new frameworks to evaluate the vehicles environmental impacts, while the latter aim at applying existing frameworks to specific contexts. The majority of contributions (23 out of 33) are empirical ones, while nine contributions address both theoretical and empirical developments. Finally, only one contribution exclusively focuses on the theoretical development.

More than half of the contributions (18 out of 33) are dedicated to a BEV-ICEV comparison, while others include further vehicle typologies, such as Fuel Cell Electric Vehicles (FCEVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs), or just focus on EVs.

As far as the phases of a vehicle's life cycle are concerned, five phases can be identified: material extraction, manufacturing, transport, use and EoL. The contributions mainly focus on the use phase, followed by the manufacturing phase. Material extraction, transportation and EoL phases are definitely less investigated. In the following subsections, each phase is described, with particular reference to the typical GHG emissions values and their determinants.

2.1.1. Material extraction

This phase includes the set of processes to obtain materials required for battery and vehicle manufacturing, such as ore mining, extraction, separation and material processing (European Environment Agency, 2018; Qiao et al., 2019).

The extraction of raw materials required for EVs manufacturing has a higher impact in terms of energy required and GHG emissions compared to ICEVs, due to the specific requirements for treating materials that are used in electric engines and especially batteries (Kukreja, 2018). Most of the studies on GHG emissions associated to raw material extraction focus on batteries, whose GHG emissions are typically estimated as a percentage of GHG emissions associated to battery manufacturing, with a typical value of around 20% (European Environment Agency, 2018). GHG emissions related to raw material extraction for other vehicle's components manufacturing are mostly embedded in the manufacturing phase emissions (European Environment Agency, 2018). In general, material extraction accounts for a minor portion of the GHG emissions during a vehicle's life cycle (European Environment Agency, 2018), and related emissions are influenced by the energy mix of the countries in which such processes take place (Concawe, 2019). Moreover, the use of secondary metals (rather than primary) may allow reducing the environmental impact associated to such phase.

2.1.2. Manufacturing

This phase includes the production and assembly of components that constitute a vehicle (Mock, 2018). The ones that are usually considered in the analysed studies are powertrain, electric motor and the battery system for EVs, engine and glider for ICEVs (Concawe, 2019; Mock, 2018).

GHG emissions related to this phase are affected by the type of materials used, amount and weight of components, which in turn affect the amount of energy required during the manufacturing processes (Tagliaferri et al., 2016). It typically ranges between 25 and 40 MJ per kg of vehicle manufactured (Sullivan et al., 2010).

In general, this phase shows one of the major contributions on the overall GHG emissions of an EV during its life cycle, with absolute values that can be up to 40–70% higher compared to ICEVs (Hall and Lutsey, 2018; Hawkins et al., 2013; Romare and Dahllöf, 2017). This is mainly due to the battery manufacturing process, with particular reference to cells manufacturing and battery assembly processes. GHG emissions for battery manufacturing range between 100 and 200 $kgCO_2$-eq/kWh (Hall and Lutsey, 2018). Such variation is mainly due to the different geographical locations considered for battery manufacturing and the related energy mix, in addition to the amount of energy required during the manufacturing process (Mock, 2018; Peng et al., 2017). The latter is strongly influenced by the estimation procedure, such as top down and bottom up approaches (Concawe, 2019). Furthermore, a significant variability emerges even among studies adopting the same procedure, with average values ranging from less than 10 kWh/kg of battery to 28 kWh/kg (Majeau-Bettez et al., 2011; Notter et al., 2010; Zackrisson et al., 2010; Ellingsen et al., 2014; Philippot et al., 2019).

2.1.3. Transport

This phase includes the transport of components and materials between countries in which the extraction and manufacturing phases are performed and the subsequent transport of a vehicle from the country in which the manufacturing phase takes place to the country in which the vehicle is used (Kukreja, 2018).

GHG emissions are influenced by the distance covered from one location to another and the transportation modes adopted, such as by rail, road, and sea. One of the main parameters affecting such emissions refers to components or vehicle weight (Kukreja, 2018). Given its minor contribution to a vehicle's GHG emissions during its life cycle, such phase is considered outside the system boundaries in most of the analysed studies.

2.1.4. Use

This phase covers the use of a vehicle (European Environment Agency, 2018), whose GHG emissions typically represent the biggest share of the total vehicle's life cycle emissions, especially for ICEVs. They considerably vary across studies, due to many factors such as vehicle characteristics, specific energy and fuel consumptions, use of auxiliaries, driving behaviour, land morphology and weather conditions.

Regarding specific energy consumption for EVs, it ranges between 15 and 25 kWh over 100 km driven (Huo et al., 2015). The most relevant factors affecting it are related to vehicle and battery characteristics, such as size and weight (Egede et al., 2015), auxiliaries such as heating and air conditioning system, which can increase the specific energy consumption by up to 50% depending on weather conditions (Notter et al., 2010), and charging efficiency, which takes into account energy loss during the charging phases, which is typically set around 4 ÷ 10% (Peng et al., 2017).

Specific fuel consumption for ICEVs ranges between 5.5 and 9 L/100 km (Peng et al., 2017; Wu et al., 2018). Variations are mainly due to differences in vehicle types, land morphology and weather conditions.

GHG emissions are highly dependent on the fuel production and use. The most investigated fuels are diesel and petrol, followed by biofuels. Many papers adopt a TTW approach, while only a few adopt a WTW approach. Regarding the latter, typical emission values range between 2,500 and 2,850 gCO_2-eq/L for petrol and between 2,750 and 3,200 gCO_2-eq/L for diesel (Asaithambi et al., 2019; Concawe, 2019; Eriksson and Ahlgren, 2013; European Commission, 2015; Mock, 2018; Peng et al., 2017; Wu et al., 2018). Variations depend on several factors, such as country of exploitation, position of the well, industrial processes required and distance to be covered for fuel transportation (European Commission, 2015).

2.1.5. End-of-life

This phase comprises all the possibilities that are available once a vehicle reaches its operating limit, which is typically equal to

Table 1
Overview of the analysed contributions.

Author(s) & Year	Source	Vehicle type	Geographical area (use phase)	Theoretical development	Empirical development	Phases of the vehicle's life cycle covered				
						Material extraction	Manufacturing	Transport	Use	EoL
Gómez Vilchez and Jochem, 2020	Transportation Research Part D: Transport and Environment	BEV, FCEV, HEV, ICEV, PHEV	China, France, Germany, India, Japan, US	✓	✓		✓		✓	✓
Petrauskienė et al. (2020)	Journal of Cleaner Production	BEV, ICEV	Lithuania		✓	✓	✓		✓	✓
Concawe (2019)	Concawe review	BEV, ICEV	Europe, Poland, Sweden		✓		✓		✓	
International Energy Agency (2019))	IEA Report	BEV, FCEV, HEV, ICEV, PHEV	World		✓	✓	✓		✓	✓
Bekel and Pauliuk (2019)	The International Journal of Life Cycle Assessment	BEV, FCEV, ICEV	Germany		✓		✓		✓	✓
Velandia et al., 2019	The International Journal of Life Cycle Assessment	BEV, ICEV	Brazil		✓		✓	✓	✓	✓
Li et al. (2019)	Energies	BEV, ICEV	China	✓	✓		✓		✓	✓
Onat et al. (2019)	Applied Energy	BEV, HEV, ICEV, PHEV	Qatar		✓				✓	
Ajanovic and Haas (2019)	Journal of Sustainable Development of Energy, Water and Environment Systems	BEV, HEV, ICEV, PHEV	China, Europe, Norway, US		✓		✓		✓	✓
Qiao et al. (2019)	Energy	BEV, ICEV	China	✓	✓	✓	✓	✓	✓	✓
Wu et al. (2018)	Journal of Cleaner Production	BEV, ICEV	China		✓		✓		✓	✓
Kukreja (2018)	Greenest City Action Plan	BEV, ICEV	Canada		✓	✓	✓	✓	✓	✓
Burchart-Korol et al.,2018	Journal of Cleaner Production	BEV, ICEV	Czech Republic, Poland		✓		✓		✓	
de Souza et al. (2018)	Journal of Cleaner Production	BEV, ICEV, PHEV	Brazil		✓	✓	✓	✓	✓	✓
European Environment Agency, 2018	European Environment Agency report	BEV, HEV, ICEV, PHEV	Europe		✓	✓	✓	✓	✓	✓
Hall and Lutsey (2018)	ICCT	BEV, ICEV	Europe, France, Germany, Norway, The Netherlands, United Kingdom		✓		✓		✓	
International Energy Agency (2018b)	IEA Report	BEV, ICEV, PHEV	World		✓	✓	✓		✓	
Mock (2018)	ICCT	BEV, ICEV	Europe, France, Germany, Norway, The Netherlands, United Kingdom		✓		✓		✓	
Del Pero et al. (2018)	Procedia Structural Integrity	BEV, ICEV	Europe, Norway, Poland		✓	✓	✓		✓	✓
Peng et al. (2017)	Chemical Engineering Research and Design	BEV, ICEV, PHEV	Canada, China, Europe, Japan, US	✓	✓				✓	
Asaithambi et al., 2017	International Climate Protection	BEV, ICEV	China, Germany, Japan, US		✓		✓		✓	
Le Petit (2017)	Transport & Environment	BEV, ICEV	Belgium, EU, France, Germany, Italy, Poland, Spain, Sweden, The Netherlands		✓		✓		✓	
	IEA Report		China, Europe, France, Japan, US		✓				✓	

(*continued on next page*)

Table 1 (*continued*)

Author(s) & Year	Source	Vehicle type	Geographical area (use phase)	Theoretical development	Empirical development	Phases of the vehicle's life cycle covered				
						Material extraction	Manufacturing	Transport	Use	EoL
International Energy Agency (2017)		BEV, ICEV, PHEV								
Tagliaferri et al. (2016)	Chemical Engineering Research and Design	BEV, HEV, ICEV, PHEV	Europe		✓		✓		✓	✓
Hooftman et al. (2016)	Energies	BEV, ICEV	Belgium		✓				✓	
Ellingsen et al. (2016)	Environmental Research Letters	BEV	Europe	✓	✓		✓		✓	✓
International Energy Agency (2016)	IEA Report	BEV	World		✓				✓	
Egede et al. (2015)	Procedia CIRP 29	BEV	Brazil, Germany, Spain	✓	✓				✓	
Rangaraju et al., 2015	Applied Energy	BEV, ICEV	Belgium		✓				✓	
Hawkins et al. (2013)	Journal of Industrial Ecology	BEV, ICEV	Europe	✓			✓		✓	
Helmers and Marx (2012)	Environmental Sciences Europe	BEV, ICEV	Germany	✓	✓				✓	
Notter et al. (2010)	Environmental Science & Technology	BEV, ICEV	Europe	✓	✓		✓		✓	✓
Sullivan et al. (2010)	Journal of Industrial Ecology	BEV, HEV, ICEV, PHEV	US (manufacturing and EoL phases)	✓	✓		✓			✓

150,000 km (Saxena et al., 2015). Possibilities for EVs and ICEVs typically cover the disposal of the vehicle's body and the recycling or reuse of EVs batteries (Tagliaferri et al., 2016). The disposal of a vehicle's body (both for ICEVs and EVs) requires a specific energy consumption of around 0.37 MJ/kg (Kukreja, 2018).

For battery recycling, with reference to LiBs (i.e., the reference technology adopted today in EVs (Peters et al., 2017), the two reference techniques are hydrometallurgical and pyrometallurgical ones. The former allows to considerably reduce the amount of emissions and energy required for primary materials processing, with a specific energy consumption equal to 0.5 MJ/kg (Romare and Dahllöf, 2017). The latter is the most frequently adopted technique due to its ease of implementation, despite the higher specific energy consumption, equal to around 2.88 MJ/kg (Tagliaferri et al., 2016).

Once an EV battery reaches its end-of-life for its use inside an EV, it can be exploited in second life applications (so-called Battery Second Use - B2U), e.g., the integration with renewable energy plants, thus postponing its recycling. Despite the fact that many car manufacturers have started projects to test the feasibility of B2U and develop viable business models (Reinhardt et al., 2019), a broad set of challenges in implementing B2U on a large scale still exist (Jiao and Evans, 2018; Olsson et al., 2018).

In general, the EoL provides the lowest contribution to a vehicle's GHG emissions and, in some cases (e.g., battery recycling), it can enable to achieve energy and resources savings (European Environment Agency, 2018; Tagliaferri et al., 2016). GHG emissions associated to such phase vary between −5% and 14% of a vehicle's life cycle emissions (de Souza et al., 2018; Ellingsen et al., 2014, 2018; European Environment Agency, 2018; Tagliaferri et al., 2016).

2.2. *Emerging gaps*

The literature review brings into light a limited coverage of all the phases of a vehicle's life cycle among studies analysing GHG emissions associated to vehicles. Indeed, existing contributions mainly focus on the manufacturing and use phases, often neglecting the other phases of a vehicle's life cycle such as material extraction, transportation and EoL phases. Therefore, the implementation of an LCA approach, which involves all the phases during a vehicle's life cycle, would require the development of a comprehensive evaluation framework.

In addition, the geographical areas covered in existing contributions – with reference to the vehicle use phase - are quite heterogeneous, ranging from contributions that evaluate one specific country to contributions evaluating different countries or even continents (such as Europe). To the best of our knowledge, none of them focuses on Italy. Furthermore, most of the studies considered a multi-country analysis, i.e., assuming different countries in which the different phases of a vehicle's life cycle take place. Only a few papers perform a one-country analysis (e.g., de Souza et al., 2018; Hooftman et al., 2016), i.e., assuming all the phases of a vehicle's life cycle taking place in a single country, to estimate the impact on GHG emissions related to the creation of national supply chains.

Vehicle use is one of the most impactful phases in terms of GHG emissions along a vehicle's life cycle. However, the impact on the vehicle specific energy consumption due to several factors, such as vehicle use patterns (e.g., urban or extra-urban driving behaviour and auxiliaries use) and contextual factors (e.g., different land morphology) is typically overlooked. From the study that deeply addresses such factors, their relevant impact on GHG emissions emerges (Egede et al., 2015) and it deserves further analysis. Furthermore, in most of the studies analysed, measures are based on lab driving conditions or on data provided by car manufacturers, rather than on real world driving conditions.

Finally, given the huge impact of the energy mix (and related emission levels) on a vehicle's GHG emissions during its life cycle and the recent dramatic development of RES in many countries (IRENA, 2019), a lack of contributions addressing such a recent trend emerges. Interestingly, some scholars emphasize that, as the RES will gain a higher share, it is expected that the amount of GHG emissions savings of EVs compared to ICEVs will increase (Ellingsen et al., 2016; Gómez

Vilchez and Jochem, 2020).

3. The LCA-based evaluation framework

The LCA-based evaluation framework developed in this study enables to assess the environmental impact of EVs (with reference to BEVs) and ICEVs, by estimating the CO_2 emissions associated to each phase during a vehicle's life cycle. Among GHG, CO_2 represents by far the most relevant one, in terms of both quantity and Global Warming Potential (GWP) (European Environment Agency, 2019). As a limitation of this study, we acknowledge the presence of other GHG such as N_2O and CH_4 that are not taken into account within the evaluation framework, due to lack of data availability. The evaluation framework has been then applied to different scenarios, as reported in Section 4. Fig. 1 illustrates the methodological process that has been followed.

The following sub-sections illustrate the phases of a vehicle's life cycle that have been included in the framework (Section 3.1) and the metrics identified to estimate CO_2 emissions associated to each phase (Section 3.2).

3.1. Life cycle phases identification

Fig. 2 shows the phases of a vehicle's life cycle included in the framework, distinguishing between the ones that are relevant for EVs and ICEVs.

The battery manufacturing phase includes emissions associated to the battery manufacturing process, which is computed only for EVs. LiBs are considered as the reference battery technology that equip EVs (assuming average values for the chemistries reviewed, mainly based on Nickel Cobalt Manganese - NCM - and - Lithium Iron Phosphate - LFP), while it is supposed that no battery change occurs during the life cycle of an EV. Given the huge impact of battery manufacturing on the total emissions of an EV (Ellingsen et al., 2018; Notter et al., 2010), this factor is considered separately from the other components manufacturing. Moreover, consistently with the extant literature, this phase includes emissions related to the extraction of materials required to manufacture a battery (European Environment Agency, 2018).

The other components manufacturing and vehicle assembly phase includes emissions associated to the manufacturing of other vehicle's components (apart from the battery) and their assembly. Consistently with the extant literature, this phase includes emissions related to the extraction of materials required to manufacture the other vehicle's components (European Environment Agency, 2018).

The transportation phase includes emissions associated to the transportation of the vehicle's components (with particular reference to the battery) to the location in which the assembly phase takes place and the transportation of the assembled vehicle to the country in which the use phase takes place (Kukreja, 2018).

The use phase includes emissions associated to the vehicle use. For ICEVs, emissions are subject to the different types of fuel used for powering the vehicle (e.g., petrol, diesel), while for EVs emissions are associated to the electricity used, as a function of the national energy mix.

Finally, the EoL phase includes emissions associated to the EoL management. In particular, it refers to the disposal alternatives for the vehicle's body and battery recycling (Tagliaferri et al., 2016).

3.2. Metrics identification

After the identification of the phases of a vehicle's life cycle included in the framework, we set ad hoc metrics for the estimation of the CO_2 emissions associated to each phase, as detailed in the following sub-sections. They are expressed in gCO_2/km, as a function of the total km range that has been set equal to 150,000 km (Egede et al., 2015; Hall and Lutsey, 2018; Le Petit, 2017; Tagliaferri et al., 2016).

3.2.1. Battery manufacturing

CO_2 emissions due to battery manufacturing can be estimated by Eq. (1):

$$\mathrm{BME}_{ij} = \frac{BW_j \,\%\, SER_{BM} \%\ \mathrm{SCO2E}_i}{150,000\ km} \tag{1}$$

Three variables are included in Eq. (1):

- battery weight (BW_j), which depends on the specific vehicle segment "j" under investigation (Concawe, 2019; Ellingsen et al., 2016). The evaluation framework enables to simulate all the car segments currently available in the market (European Commission, 2009), however the application of the evaluation framework (Section 4.4) focuses on the four most relevant segments in Italy, i.e., A, B, C, and D (UNRAE, 2019);
- specific energy requirements for battery manufacturing (SER_{BM}), expressed as kWh of energy required to manufacture a kg of battery, including the energy required for related materials extraction. An average value of 28 kWh/kg is chosen (Ellingsen et al., 2014), however due to the huge variance that emerged from the literature review (Majeau-Bettez et al., 2011; Notter et al., 2010; Philippot et al., 2019; Zackrisson et al., 2010), a sensitivity analysis is proposed to quantify the impact of a variation of the SER_{BM} on the CO_2 emission levels due to battery manufacturing;
- specific CO_2 emission level ($SCO2E_i$), i.e., the amount of CO_2 released per kWh of energy used, which depends on the energy mix of the specific country "i" in which the phase of the vehicle's life cycle takes place (Concawe, 2019).

3.2.2. Other components manufacturing and vehicle assembly

CO_2 emissions due to other components manufacturing (different from batteries, as detailed in section 3.2.1) and vehicle assembly can be estimated by Eq. (2):

$$\mathrm{OCMVAE}_{ij} = \frac{VW_j \ \%\mathrm{SER}_{\mathrm{OCMVAE}}\ \%\ \mathrm{SCO2Ei}}{150,000\ km} \tag{2}$$

Three variables are included in Eq. (2):

- vehicle weight (VW_j), which depends on the specific vehicle segment "j" under investigation (Concawe, 2019; Ellingsen et al., 2016);

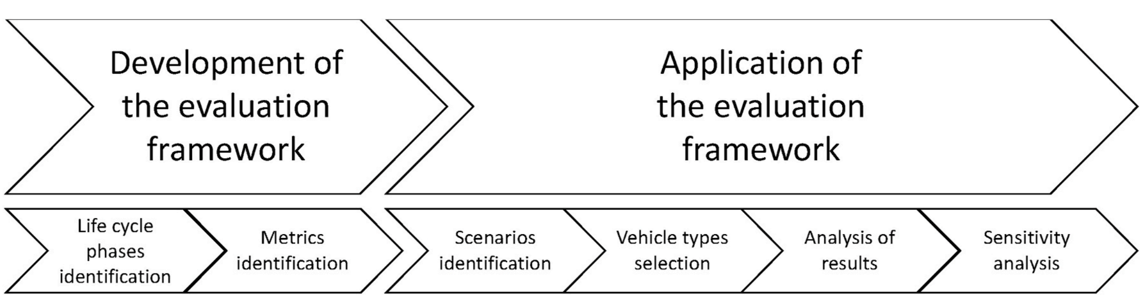

Fig. 1. The methodological process.

	Battery manufacturing (including material extraction)	Other components manufacturing and vehicles assembly (including material extraction)	Transportation	Use	EoL
EV	√	√	√	√	√
ICEV	-	√	√	√	√

Fig. 2. Phases of a vehicle life cycle included in the framework.

- specific energy requirements for other components manufacturing (SER_{OCMVAE}), expressed as kWh of energy required to manufacture a kg of vehicle (battery excluded), including the energy required for related materials extraction (Li et al., 2019). A value of 30 MJ/kg is chosen (Sullivan et al., 2010), then converted into kWh/kg through the coefficient 0.277 kWh/MJ;
- specific CO_2 emission levels associated to energy ($SCO2E_i$), i.e., the amount of CO_2 released per kWh of energy used, which depends on the energy mix of the specific country "i" in which the phase of the vehicle's life cycle takes place (Hall and Lutsey, 2018; Le Petit, 2017).

3.2.3. Transportation

CO_2 emissions due to transportation take into account two different contributions (Kukreja, 2018): (i) battery transportation emissions (BTE), addressing battery transportation from the country in which it is manufactured to the country in which the vehicle is assembled; (ii) vehicle transportation emissions (VTE), addressing vehicle transportation from the country in which it is assembled to the country in which it is used by the owner. The CO_2 emissions associated to the EV transportation take into account both contributions, while the CO_2 emissions associated to the ICEV only consider the second contribution.

The two contributions can be estimated by Eqs. (3) and (4), respectively:

$$BTE_{ji1i2} = \frac{(BW_J \% D_{i1i2}) \% [(\%_{rail} \% \mathrm{SCO2T}_{rail}) + (\%_{road} \% \mathrm{SCO2T}_{road}) + (\%_{sea} \% \mathrm{SCO2T}_{sea})]}{150,000\ km} \quad (3)$$

$$VTE_{ji1i2} = \frac{(VW_J \% D_{i1i2}) \% [(\%_{rail} \% \mathrm{SCO2T}_{rail}) + (\%_{road} \% \mathrm{SCO2T}_{road}) + (\%_{sea} \% \mathrm{SCO2T}_{sea})]}{150,000\ km} \quad (4)$$

On the one hand, four variables are included in Eq. (3):

- battery weight (BW_j), which depends on the specific vehicle segment "j" under investigation;
- distance from the country in which the battery is manufactured (i1) to the country in which the vehicle is assembled (i2) (D_{i1i2}). Such distance is computed taking into account the typical transportation routes among countries (Velandia et al., 2019);
- share of the transportation distance covered by the different transportation modes, i.e., by rail ($\%_{rail}$), road ($\%_{road}$) or sea ($\%_{sea}$). Each share is estimated according to the typical transportation modes applied to specific routes among countries (Kukreja, 2018);
- specific CO_2 emission levels associated to the different transportation modes, i.e., the amount of CO_2 released per kg of battery transported and km covered by rail ($SCO2T_{rail}$), road ($SCO2T_{road}$) or sea ($SCO2T_{sea}$) (Kukreja, 2018).

On the other hand, four variables are included in Eq. (4):

- vehicle weight (VW_j), which depends on the specific vehicle segment "j" under investigation;
- distance from the country in which the vehicle is assembled (i1) to the country in which the vehicle is used (i2) (D_{i1i2}). Such distance is computed taking into account the typical transportation routes among countries (Velandia et al., 2019);
- share of the transportation distance covered by the different transportation modes, i.e., by rail ($\%_{rail}$), road ($\%_{road}$) or sea ($\%_{sea}$). Each share is estimated according to the typical transportation modes applied to specific routes among countries (Kukreja, 2018);
- specific CO_2 emission levels associated to the different transportation modes, i.e., the amount of CO_2 released per kg of battery transported and km covered by rail ($SCO2T_{rail}$), road ($SCO2T_{road}$) or sea ($SCO2T_{sea}$). Specific CO_2 emission values are set equal to 16, 139, and 135 gCO_2/ton-km, respectively (European Environment Agency, 2015).

3.2.4. Use

CO_2 emissions due to EV use can be estimated by Eq. (5):

$$UE_{ji} = [SVC\_EV_j \% (1 + Aux)] \% [1 + (1 - \eta_{charge})] \% (1 + EL) \% \mathrm{SCO2E}_i \quad (5)$$

Five variables are included in Eq. (5):

- specific vehicle consumption (SVC_EV_j), expressed as kWh of energy required to drive one km with an EV, according to the specific vehicle segment "j" under investigation. As stated above, the application of the evaluation framework focuses on the four most relevant segments in Italy, i.e., A, B, C, and D (UNRAE, 2019). Values for specific vehicle consumption are set equal to 12.9, 16.8, 13.1, and 18.3 kWh/100 km, respectively for segments A, B, C, and D, based on technical specifications issued by car manufacturers (as further detailed in Section 4.2). Furthermore, due to the huge variance that emerged from the literature review (Ellingsen et al., 2016; Mock, 2018; Peng et al., 2017), a sensitivity analysis is proposed to quantify the impact of a variation of the specific vehicle consumption on the CO_2 emission due to EV use (as showed in Section 4.4.2);

- specific vehicle consumption increase due to auxiliaries (AUX_i), such as heating and air conditioning, which are required according to the specific country of use and the relative temperatures throughout the year. An average value of 15% is chosen (Notter et al., 2010), nevertheless it is worth mentioning that their impact can range from 10% to even 30% (Notter et al., 2010);
- charging efficiency (η_{charge}), to take into account the amount of energy lost during the charging process. A value of 96% is chosen (Peng et al., 2017), nevertheless it is worth mentioning that its impact can range between 90% and 96% (Peng et al., 2017);
- energy loss (EL), to take into account the amount of energy lost owing to energy transmission and distribution from the production plant to the charger. A value of 7% (representative of the average EU energy loss) is chosen (Peng et al., 2017), nevertheless it is worth mentioning that its impact can range between 5% and 10% (EVE IWG, 2016; Peng et al., 2017);
- specific CO_2 emission levels associated to energy ($SCO2E_i$), i.e., the amount of CO_2 released per kWh of energy used, which depends on the energy mix of the specific country "i" in which the phase of the vehicle's life cycle takes place.

The amount of CO_2 emissions due to ICEV use can be estimated by Eq. (6):

$$UE_{ji} = SVC\_ICEV_j \% \text{SCO2F} \tag{6}$$

Two variables are included in Eq. (6).

- specific vehicle consumption (SVC_ICEV_j), expressed as litres of fuel required to drive a km with an ICEV. As stated above, the model focuses on the four most relevant segments in Italy, i.e. A, B, C, and D (UNRAE, 2019), being segments A and B petrol-fuelled while segments C and D are diesel-fuelled. Values for specific vehicle consumption are set equal to 4.9 and 5.3 L/100 km for segments A and B, while 5.1 and 4.8 L/100 km are set for segments C and D (UNRAE, 2019).
- specific CO_2 emission levels associated to fuel (SCO2F), i.e., the amount of CO_2 released per litre of fuel used, which depends on the overall WTW emissions associated to the specific fuel, i.e., taking into account fuel production and use. Values of 2,767 gCO_2/L and 3,118 gCO_2/L have been chosen for petrol and diesel, respectively (Asaithambi et al., 2019; Eriksson and Ahlgren, 2013; European Commission, 2015; Mock, 2018; Peng et al., 2017; Wu et al., 2018).

3.2.5. EoL

The amount of CO_2 emissions due to EoL management takes into account two different contributions (de Souza et al., 2018; European Environment Agency, 2018; Romare and Dahllöf, 2017; Tagliaferri et al., 2016): (i) battery recycling (BR) and (ii) vehicle disposal (VD). The CO_2 emissions associated to the EV take into account both contributions, while the CO_2 emissions associated to the ICEV only consider the second contribution.

The two contributions can be estimated by Eqs. (7) and (8), respectively:

$$BR_{ij} = \frac{\text{BWj} \% \, SER_{BR} \% \, \text{SCO2Ei}}{150,000 \, km} \tag{7}$$

$$VD_{ij} = \frac{VW_j \% \, SER_{VD} \% \, \text{SCO2Ei}}{150,000 \, km} \tag{8}$$

Three variables are included in Eq. (7).

- battery weight (BW_j), which depends on the specific vehicle segment "j" under investigation;
- specific energy requirements for battery recycling (SER_{BR}), expressed as kWh of energy required to recycle a kg of battery. Among the different techniques to recycle batteries, such as hydrometallurgy, hydrothermal, pyrolysis, and pyrometallurgy (European Environment Agency, 2018) the latter recycling process has been chosen being the most widespread, considering a value of 2.88 MJ/kg (Tagliaferri et al., 2016), then converted into kWh/kg through the coefficient 0.277 kWh/MJ;
- specific CO_2 emission levels associated to energy ($SCO2E_i$), i.e., the amount of CO_2 released per kWh of energy used, which depends on the energy mix of the specific country "i" in which the phase of the vehicle's life cycle takes place.

Three variables are included in Eq. (8).

- vehicle weight (VW_j), which depends on the specific vehicle segment "j" under investigation;
- specific energy requirements for vehicle disposal (SER_{VD}), expressed as kWh of energy required to dispose a kg of vehicle. A value of 0.37 MJ/kg is chosen (Kukreja, 2018), then converted into kWh/kg through the coefficient 0.277 kWh/MJ;
- specific CO_2 emission levels associated to energy ($SCO2E_i$), i.e., the amount of CO_2 released per kWh of energy used, which depends on the energy mix of the specific country "i" in which the phase of the vehicle's life cycle takes place.

Table 2 summarizes the main assumptions for the estimation of CO_2 emissions associated to each phase of a vehicle's life cycle included in the framework. Multiple information sources were used to collect data (e.g., scientific literature and official documents issued by car manufacturers). Furthermore, regarding some variables considered in our framework, we formulated several conservative and robust assumptions.

4. Results and discussion

4.1. Scenarios identification

The developed comparative LCA-based evaluation framework is applied to four scenarios, as shown in Table 3. In particular, scenarios differ from each other by country in which the upstream phases of a vehicle's life cycle take place (i.e., battery manufacturing, other components manufacturing and vehicle assembly, and transportation), while Italy is chosen as the country in which the vehicle use and EoL phases take place in all four scenarios. This enables to estimate the differences in terms of CO_2 emissions due to geographical locations of the upstream phases of the vehicle supply chain (Kukreja, 2018).

In order to select countries, focusing on the three most relevant areas in the world for what concerns the e-mobility sector, i.e., Asia, North America, and Europe, we chose the three most relevant countries (one for each area) in terms of EV and EV batteries manufacturing capacity, i.e., China, US, and Germany.

In Scenario 1, upstream phases take place in China. Chinese OEMs currently lead the global EV market in terms of manufacturing capacity (International Energy Agency, 2020), covering around 20% of EVs production worldwide (International Energy Agency, 2019). Moreover, the most part of global battery manufacturing installed capacity, which was equal to 103.7 GWh in 2017 with reference to LiBs (Philippot et al., 2019), is located in Asian countries, mainly China, Japan, and Korea, which hosted 88% of total global Li–Ion cell manufacturing capacity (Chung et al., 2016; Philippot et al., 2019).

In Scenario 2, upstream phases take place in Germany. German OEMs are massively pushing EV diffusion, also through an overall € 50 bn investment to being able to offer more than 150 EV models by 2023 (Sillitoe et al., 2019). Moreover, together with France, Germany is the

Table 2
Assumptions for the estimation of CO_2 emissions associated to each phase of a vehicle's life cycle.

Phase	Assumption	References
Battery manufacturing (including related materials extraction)	Specific energy requirements for battery manufacturing (SER_{BM}) = 28 kWh/kg	Ellingsen et al. (2014)
Other components manufacturing and vehicle assembly (including related materials extraction)	Specific energy requirements for other components manufacturing (SER_{OCMVAE}) = 30 MJ/kg	Sullivan et al. (2010)
Transportation	Specific CO_2 emission levels associated to rail ($SCO2T_{rail}$) = 16 gCO_2/ton-km	European Environment Agency (2015)
Transportation	Specific CO_2 emission levels associated to road ($SCO2T_{road}$) = 139 gCO_2/ton-km	European Environment Agency (2015)
Transportation	Specific CO_2 emission levels associated to sea ($SCO2T_{sea}$) = 135 gCO_2/ton-km	European Environment Agency (2015)
Use	Vehicle lifetime = 150,000 km	(Egede et al., 2015; Hall and Lutsey, 2018; Le Petit, 2017; Tagliaferri et al., 2016)
Use	Specific vehicle consumption (SVC_EVj) = 12.9 kWh/100 km (segment A)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption (SVC_EVj) = 16.8 kWh/100 km (segment B)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption (SVC_EVj) = 13.1 kWh/100 km (segment C)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption (SVC_EVj) = 18.3 kWh/100 km (segment D)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption increase due to auxiliaries (AUX_i) = 15%	Notter et al. (2010)
Use	Charging efficiency (η_{charge}) = 96%	Peng et al. (2017)
Use	Energy loss (EL) = 7%	Peng et al. (2017)
Use	Specific vehicle consumption (SVC_ICEV_j) = 4.9 L/100 km (segment A)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption (SVC_ICEV_j) = 5.3 L/100 km (segment B)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption (SVC_ICEV_j) = 5.1 L/100 km (segment C)	Technical specifications issued by car manufacturers
Use	Specific vehicle consumption (SVC_ICEV_j) = 4.8 L/100 km (segment D)	Technical specifications issued by car manufacturers
Use	Specific CO_2 emission levels associated to fuel (SCO2F) = 2,767 gCO_2/L (petrol)	(Asaithambi et al., 2019; Eriksson and Ahlgren, 2013; European Commission, 2015; Mock, 2018; Peng et al., 2017; Wu et al., 2018)
Use	Specific CO_2 emission levels associated to fuel (SCO2F) = 3,118 gCO_2/L (diesel)	(Asaithambi et al., 2019; Eriksson and Ahlgren, 2013; European Commission, 2015; Mock, 2018; Peng et al., 2017; Wu et al., 2018)
EoL	Specific energy requirements for battery recycling (SER_{BR}) = 2.88 MJ/kg	Tagliaferri et al. (2016)
EoL	Specific energy requirements for vehicle disposal (SER_{VD}) = 0.37 MJ/kg	Kukreja (2018)
All (transportation excluded)	Specific CO_2 emission levels associated to energy (SCO2Ei) = depending on the analysed country, see Section 4.1	(ISPRA, 2018; Enerdata, 2018)

Table 3
Overview of the scenarios analysed.

Scenarios	Phases included in the evaluation framework				
	Battery Manufacturing	Other components manufacturing and vehicle assembly	Transportation	Use	EoL
Scenario 1	China	China	China -> Italy	Italy	Italy
Scenario 2	Germany	Germany	Germany -> Italy	Italy	Italy
Scenario 3	US	US	US -> Italy	Italy	Italy
Scenario 4	Italy	Italy	Italy -> Italy	Italy	Italy

Table 4
Specific CO_2 emission levels associated to energy (SCO2Ei) in the selected countries (values expressed in gCO_2/kWh) (Enerdata, 2018; ISPRA, 2018).

Country	SCO2Ei [gCO_2/kWh]
China	650
Germany	403
US	408
Italy	313

Table 5
Transportation characteristics.

Transportation route	Distance covered [km]	Transport modes		
		Rail [%]	Road [%]	Sea [%]
China -> Italy	10,000	30%	20%	50%
Germany -> Italy	10,000	75%	25%	0%
US -> Italy	1,500	5%	5%	90%
Italy -> Italy	1,000	75%	25%	0%

European country with the highest number of production plants for batteries, vehicles, and components (Unique Energy Hub, 2018; International Energy Agency, 2019).

In Scenario 3, upstream phases take place in US. US car manufacturers retain consistent global EV market shares (EV-volumes, 2019; International Energy Agency, 2019). Moreover, with the above-mentioned Asian countries, USA is among the first countries worldwide in terms of LiB production (International Energy Agency, 2019).

Finally, we introduced a fourth scenario (Scenario 4) in which the upstream phases take place in Italy. Even though Italy cannot be included among the countries with the highest EV and EV battery manufacturing capacity, it has been selected to evaluate the potential impacts on a vehicle's CO_2 emissions that would derive from the creation of a fully-Italian supply chain.

Table 4 shows the specific CO_2 emission levels associated to energy (SCO2Ei) in the selected countries (Enerdata, 2018; ISPRA, 2018),

Table 6
Vehicle assumptions for EVs and ICEVs.

Vehicle segment	EV					ICEV		
	Type	SVC_EV_j [kWh/km]	BC_j [kWh]	BW [kg]	VW_j [kg]	Type	SVC_ICEV_j [L/km]	VW_j [kg]
A	BEV	0.129	17.6	160	925	Petrol	0.049	1,015
B	BEV	0.168	41	305	1,175	Petrol	0.053	1,040
C	BEV	0.131	40	303	1,277	Diesel	0.051	1,505
D	BEV	0.183	65	480	1,367	Diesel	0.048	1,568

which depend upon the national energy mix. Selected countries in each scenario, i.e., China, Germany, US, and Italy, show very different energy production mix and RES penetration levels, the latter (expressed in terms of share of renewables in electricity generation) being equal to 25.9%, 33.9%, 17.6%, and 38%, respectively (Enerdata, 2018). Moreover, as far as the transportation phase is concerned, the distance covered from the country in which the battery is manufactured to the country in which the vehicle is assembled and from the country in which the vehicle is assembled to the country in which the vehicle is used are illustrated in Table 5. Distances refer to typical transportation routes between the two countries in each scenario (Velandia et al., 2019), while the share of each transportation mode is related to specific routes among countries (Kukreja, 2018). Due to the substantial absence of scientific contributions addressing this topic, estimations are based on a review of transportation practices implemented by a set of OEMs.

4.2. *Vehicle types selection*

The analysis of the CO_2 emissions during a vehicle's life cycle focuses on the four most relevant vehicle segments in Italy, in terms of annual car registrations, i.e., A, B, C, and D (UNRAE, 2019). Table 6 shows the input data for EVs and ICEVs belonging to each vehicle segment provided by car manufacturers, which refer to the best-selling vehicles in Italy in 2018 (UNRAE, 2019). For what concerns ICEVs, vehicles belonging to segments A and B are petrol-fuelled, while segments C and D are diesel-fuelled vehicles. For what concerns EVs, the BEV typology is chosen. Consistently with the literature, a charging efficiency equal to 96%, energy loss equal to 7% and auxiliaries' consumption equal to 15% are assumed, irrespective of the specific vehicle segment.

4.3. *Results*

Table 7 shows the specific CO_2 emission levels (expressed in gCO_2/km) estimated for each scenario, with reference to four vehicle segments analysed.

It emerges that specific CO_2 emissions associated to EVs over the entire vehicle's life cycle are always lower than the ones associated to a comparable ICEV (i.e., in terms of vehicle segment in the same scenario). EV CO_2 emissions reduction against ICEV ranges between 60% and 97% for the vehicle segment A, between 22% and 55% for the vehicle segment B, between 53% and 99% for the vehicle segment C and between 12% and 40% for the vehicle segment D. The outcomes are consistent with the extant literature (e.g., Van der Zwaan et al., 2013; Ellingsen et al., 2014; Knobloch et al., 2020), however the specific CO_2 emission values obtained should be carefully compared with the ones presented in the other contributions for several reasons. First, many contributions are characterized by a limited coverage of all the phases of a vehicle's life cycle, while the evaluation framework developed in this paper takes into account all the phases of a vehicle's life cycle, in accordance with the LCA approach (ISO, 2006). Second, to the best of our knowledge, this paper is the only one assuming that the vehicle use and EoL phases take place in Italy, i.e., a country characterized by a peculiar energy mix with a high level of RES penetration (Ministero dello Sviluppo Economico, 2019).

Table 7
Scenario results overview (values expressed in gCO_2/km).

Scenarios	Vehicle type	Vehicle segment			
		A	B	C	D
Scenario 1	EV	112.1	157.25	146.54	194.18
	ICEV	179.12	191.26	223.58	216.93
Scenario 2	EV	85.33	117.92	105.29	141.88
	ICEV	158.94	170.58	193.64	185.74
Scenario 3	EV	94.58	130.60	118.81	157.77
	ICEV	167.49	179.34	206.33	198.96
Scenario 4	EV	77.86	106.71	93.59	126.72
	ICEV	153.72	165.23	185.91	177.68

By comparing the four scenarios, it emerges that the geographical location in which the upstream phases of the vehicle's life cycle take place (i.e., battery manufacturing, other components manufacturing and vehicle assembly, and transportation) exerts a huge impact on a vehicle's CO_2 emissions. Results show that, for all the vehicle segments, the worst scenario is the one assuming the upstream phases of a vehicle's life cycle occurring in China (Scenario A), i.e., the country with the highest $SCO2E_i$ among the analysed ones (see Table 4), also due to the relatively low level of RES penetration. Conversely, the best scenario is the one assuming the upstream phases of the vehicle's life cycle occurring in Italy (Scenario D), i.e., the country with the lowest $SCO2E_i$ among the analysed ones. Such evidences confirm the current and expected positive role played by RES on the better environmental performance of EVs against ICEVs, as highlighted by several scholars (Ellingsen et al., 2016; Gómez Vilchez and Jochem, 2020). Moreover, being this paper one of the few performing a one-country analysis, i.e., assuming all the phases of a vehicle's life cycle taking place in one country (Italy), it emerges that the development of a national EV supply chain in a country with a high level of RES penetration may enable to achieve considerable environmental benefits (Tagliaferri et al., 2016).

Finally, by comparing the four vehicle segments analysed in each scenario, it emerges that, moving from small-sized vehicles to larger ones (i.e., from Segment A to D), specific CO_2 emission levels increase. This is due to the progressive increase of some parameters included in the evaluation framework that strongly affect the results, i.e., battery size, vehicle weight, battery energy consumption, and fuel consumption.

Table 8 shows the specific CO_2 emissions (expressed in gCO_2/km) associated to each phase of a vehicle's life cycle in each scenario, for all the vehicle segments analysed. For what concerns EVs, irrespective to the specific vehicle segment, the most impactful phase during the vehicle's life cycle is the use phase, followed by vehicle and battery manufacturing phases. The impact of the use phase on the overall CO_2 emissions of an EV during its life cycle ranges from 45% to 66% for segment A, from 42% to 63% for segment B, from 35% to 56% for segment C and from 37% to 57% for segment D. Upper and lower values within each range refer to Scenarios 2 and 4, respectively, i.e., the ones in which the upstream phases of a vehicle's life cycle take place in China and Italy. Interestingly, moving from segment A to D, the gap between CO_2 emissions associated to vehicle and battery manufacturing phases decreases, and for segment D the contribution of battery manufacturing is even higher than the one associated to vehicle manufacturing.

The transportation phase shows a limited contribution to the overall CO_2 emissions of an EV during its life cycle, ranging from 0 to 1% in Scenarios 2 and 4 to around 10–11% in Scenario 3. Significant differences in absolute terms among scenarios are due to distances to be

Table 8
Cross-scenario analysis overview (values expressed in gCO_2/km).

	EV						ICEV				
Segment A		Battery manufacturing	Other components manufacturing and vehicle assembly	Transportation	Use	EoL		Other components manufacturing and vehicle assembly	Transportation	Use	EoL
	Scenario 1	19.41	33.31	7.24	51.67	0.46	Scenario 1	36.55	6.77	135.68	0.22
	Scenario 2	12.04	20.65	0.51	51.67	0.46	Scenario 2	22.66	0.47	135.68	0.22
	Scenario 3	12.19	20.91	9.35	51.67	0.46	Scenario 3	22.94	8.75	135.68	0.22
	Scenario 4	9.35	16.04	0.34	51.67	0.46	Scenario 4	17.60	0.32	135.68	0.22
Segment B		Battery manufacturing	Other components manufacturing and vehicle assembly	Transportation	Use	EoL		Other components manufacturing and vehicle assembly	Transportation	Use	EoL
	Scenario 1	37.01	42.31	9.88	67.29	0.76	Scenario 1	37.45	6.94	146.65	0.22
	Scenario 2	22.94	26.23	0.69	67.29	0.76	Scenario 2	23.22	0.49	146.65	0.22
	Scenario 3	23.23	26.56	12.79	67.29	0.76	Scenario 3	23.51	8.96	146.65	0.22
	Scenario 4	17.82	20.37	0.46	67.29	0.76	Scenario 4	18.03	0.32	146.65	0.22
Segment C		Battery manufacturing	Other components manufacturing and vehicle assembly	Transportation	Use	EoL		Other components manufacturing and vehicle assembly	Transportation	Use	EoL
	Scenario 1	36.76	45.98	10.54	52.47	0.78	Scenario 1	54.2	10.04	159.02	0.32
	Scenario 2	22.79	28.51	0.74	52.47	0.78	Scenario 2	33.6	0.70	159.02	0.32
	Scenario 3	23.08	28.87	13.61	52.47	0.78	Scenario 3	34.02	12.97	159.02	0.32
	Scenario 4	17.70	22.14	0.49	52.47	0.78	Scenario 4	26.10	0.47	159.02	0.32
Segment D		Battery manufacturing	Other components manufacturing and vehicle assembly	Transportation	Use	EoL		Other components manufacturing and vehicle assembly	Transportation	Use	EoL
	Scenario 1	58.24	49.23	12.33	73.30	1.09	Scenario 1	56.46	10.46	149.66	0.34
	Scenario 2	36.11	30.52	0.86	73.30	1.09	Scenario 2	35.01	0.73	149.66	0.34
	Scenario 3	36.56	30.90	15.91	73.30	1.09	Scenario 3	35.45	13.51	149.66	0.34
	Scenario 4	28.04	23.70	0.58	73.30	1.09	Scenario 4	27.19	0.49	149.66	0.34

covered and transportation modes, in addition to vehicle weight, which determines, *coeteris paribus*, a higher level of CO_2 emissions associated to the transportation phase for vehicle segments C and D. In general, this evidence brings into light the importance of including such phase in the evaluation of the CO_2 emissions associated to EVs, whose impact is not negligible, despite the poor coverage within the extant literature.

Finally, the EoL phase is responsible for a negligible contribution, as already stated within the literature (European Environment Agency, 2018; Tagliaferri et al., 2016).

For what concerns ICEVs, the most impactful phase during a vehicle's life cycle is the use phase too, followed by vehicle manufacturing and transportation, while the contribution due to EoL is still negligible. The impact of the use phase on the overall CO_2 emissions of an ICEV during its life cycle ranges from 75% to 88% for segment A, from 76% to 88% for segment B, from 71% to 85% for segment C and from 69% to 84% for segment D. It is worth highlighting the huge gap in terms of CO_2 emissions between an ICEV and an EV related to the use phase, which are 2–3 times higher for ICEVs compared to EVs in all the analysed scenarios. This gap more than offsets CO_2 emissions due to the EV battery manufacturing, which are absent for an ICEV. As a result, specific CO_2 emissions over the entire vehicle's life cycle associated to an EV are always lower than the ones associated to a comparable ICEV.

4.4. Sensitivity analysis

A sensitivity analysis is proposed by addressing two of the most impactful phases during an EV's life cycle, i.e., vehicle use and battery manufacturing phases. In particular, CO_2 emissions associated to such phases are affected by two variables, whose quantification through the literature review shows a significant variance, i.e.:

- specific energy requirements for battery manufacturing (SER_{BM}), which affect CO_2 emissions associated to the battery manufacturing phase;
- specific vehicle consumption (SVC_EV_j), which affects CO_2 emissions associated to the vehicle use phase.

Furthermore, as many scholars emphasize that CO_2 emissions savings related to EVs compared to ICEVs will increase as RES will gain a higher share (Ellingsen et al., 2016; Gómez Vilchez and Jochem, 2020), a third sensitivity analysis is proposed on the specific CO_2 emission levels associated to energy ($SCO2E_i$), which affect CO_2 emissions associated to the vehicle use phase. This variable also affects other phases during an EV's life cycle, however the sensitivity analysis only focuses on the vehicle use phase.

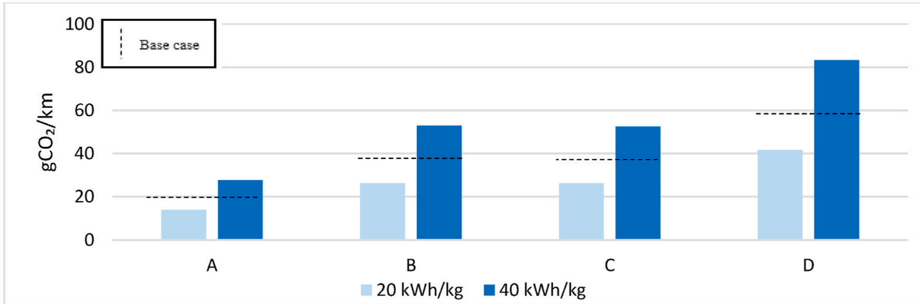

Fig. 3. Sensitivity analysis – Specific energy requirements for battery manufacturing, scenario 1 (values expressed in gCO_2/km).

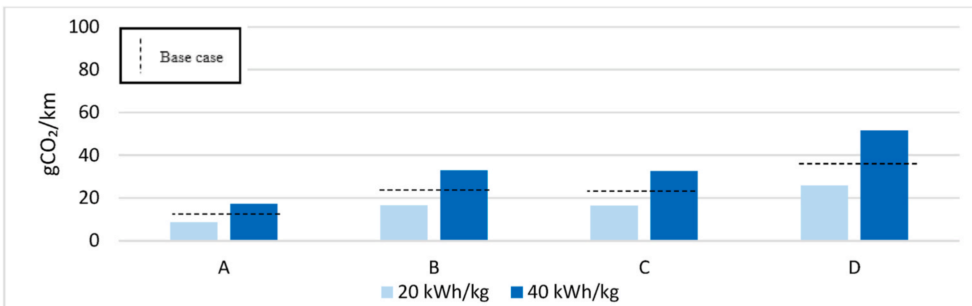

Fig. 4. Sensitivity analysis – Specific energy requirements for battery manufacturing, scenario 2 (values expressed in gCO_2/km).

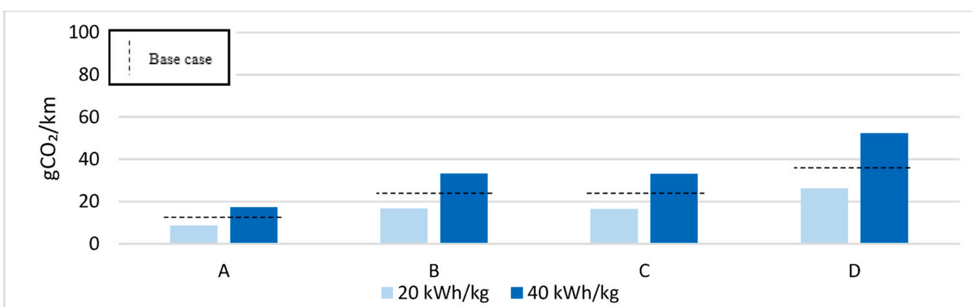

Fig. 5. Sensitivity analysis – Specific energy requirements for battery manufacturing, scenario 3 (values expressed in gCO_2/km).

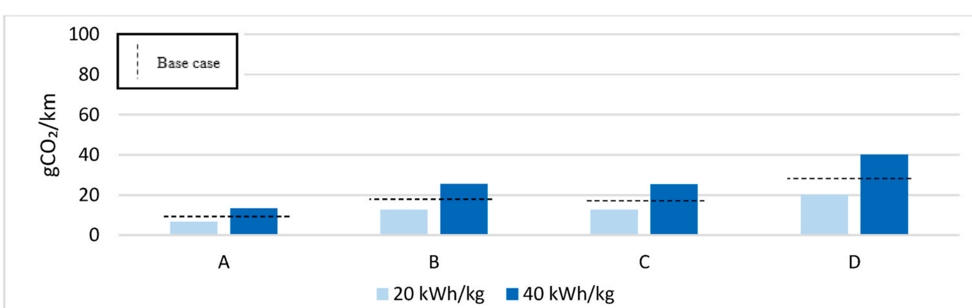

Fig. 6. Sensitivity analysis – Specific energy requirements for battery manufacturing, scenario 4 (values expressed in gCO_2/km).

4.4.1. Specific energy requirements for battery manufacturing

Results presented in Section 4.3 assume a SER_{BM} value equal to 28 kWh/kg (Ellingsen et al., 2014), however the literature review shows a huge variance of such value among the different studies (Majeau-Bettez et al., 2011; Notter et al., 2010; Philippot et al., 2019; Zackrisson et al., 2010). Therefore, two extreme cases are evaluated, in which the SER_{BM} is equal to 20 or 40 kWh/kg. Figs. 3–6 show the results of the sensitivity analysis for each vehicle segment and each scenario.

SER_{BM} variation significantly affects (either positively or negatively) the overall EV CO_2 emissions. On the one hand, a value of 20 kWh/kg (−29% compared to the base case, i.e., 28 kWh/kg) determines an EV CO_2 emissions reduction compared to the base case equal to 4%, 5.5%, 6.1%, and 7.2%, for segments A, B, C, and D, respectively. On the other hand, a value of 40 kWh/kg (+43% compared to the base case) determines an EV CO_2 emissions increase equal to 6%, 8.3%, 9.1%, and 10.8% compared to the base case, for segments A, B, C, and D,

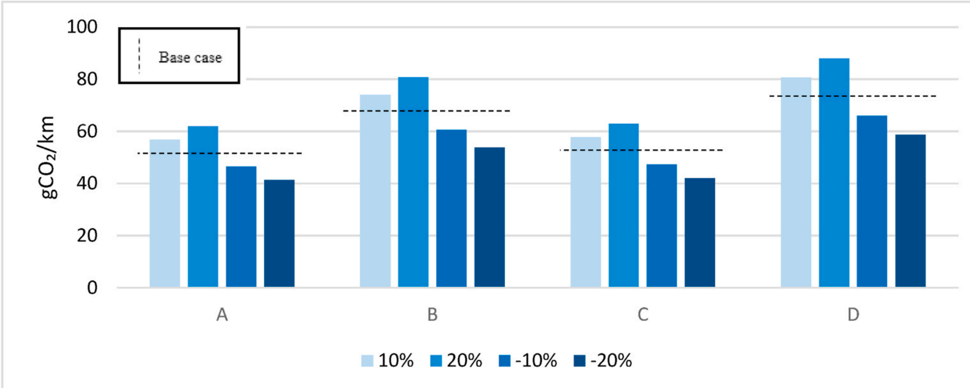

Fig. 7. Sensitivity analysis - Specific vehicle consumption (values expressed in gCO_2/km).

respectively.

4.4.2. Specific vehicle consumption

Results presented in Section 4.3 assume SVC_EV$_j$ values for each vehicle segment showed in Table 4, however the literature review shows that many factors such as vehicle's characteristics, specific energy and fuel consumptions, use of auxiliaries, driving behaviour, land morphology and weather conditions dramatically affect such value (Egede et al., 2015; Notter et al., 2010). Therefore, consistently with previous studies (Egede et al., 2015; Kukreja, 2018; Notter et al., 2010), four cases are evaluated, in which the SVC_EV$_j$ values vary between −20% and +20% against the values chosen in the base case. Fig. 7 shows the results of the sensitivity analysis for each vehicle segment.

Specific vehicle consumption variation significantly affects (either positively or negatively) the overall EV CO_2 emissions, even more than the SER_{BM}. On the one hand, a 10% increase of the SVC_EV$_j$ values determines an increase of the EV CO_2 emissions compared to the base case equal to 5.7%, 5.4%, 4.6% and 4.8%, for segments A, B, C and D, respectively, while a +20% increase determines an increase of the EV CO_2 emissions compared to the base case equal to 11.4%, 10.7%, 9.3% and 9.7%, for segments A, B, C, and D, respectively. On the other hand, negative variations of the SVC_EV$_j$ values determine the same variations presented above, but with negative signs.

4.4.3. Specific CO_2 emission levels associated to energy

Results presented in Section 4.3 assume a SCO2E$_i$ value (related to vehicle use taking place in Italy) equal to 313 gCO_2/kWh, as a result of the current Italian energy mix (ISPRA, 2018), which is characterized by a RES penetration equal to 38%. To evaluate CO_2 emissions reduction associated to vehicle use due to an increase of RES penetration (as expected in Italy in the next years), two cases are evaluated:

- SCO2E$_i$ value equal to 230 gCO_2/kWh. It corresponds to a RES penetration equal to 55%, that is expected to be reached in Italy by 2030 (Ministero dello Sviluppo Economico, 2020). Such value also takes into account the national objectives in terms of energy mix set by the Integrated National Energy and Climate Plan, e.g., with reference to the progressive phasing out of coil plants.
- SCO2E$_i$ value equal to 180 gCO_2/kWh. It correspond to a RES penetration equal to 65%, that is expected to be reached in Italy by 2040, according to one of the most respected evolutionary scenario jointly developed by the national electricity and natural gas Transmission System Operators (TSO) (Snam & Terna, 2019).

Fig. 8 shows the results of the sensitivity analysis for each vehicle segment.

The expected reduction of SCO2E$_i$ values, as a result of the progressively higher levels of RES penetration in the Italian energy mix, would determine a significant improvement of the overall EV CO_2 emissions. An increase of RES penetration by 17% (from the current 38%–55%) would reduce the EV CO_2 emissions associated to the vehicle use phase by 27% compared to the base case, while an increase by 27% would reduce the EV CO_2 emissions associated to the vehicle use phase by 43% compared to the base case.

Analysing the whole emissions during the EV's life cycle, the first case entails a CO_2 emissions reduction of 15.1%, 14.2%, 12.3% and 12.8% for segments A, B, C and D respectively, and a 24.2%, 22.8%, 19.7% and 20.6% reduction in the second case. This evidence highlights the extent to which the further diffusion of RES worldwide will further increase the CO_2 emission spread between EV and ICEV.

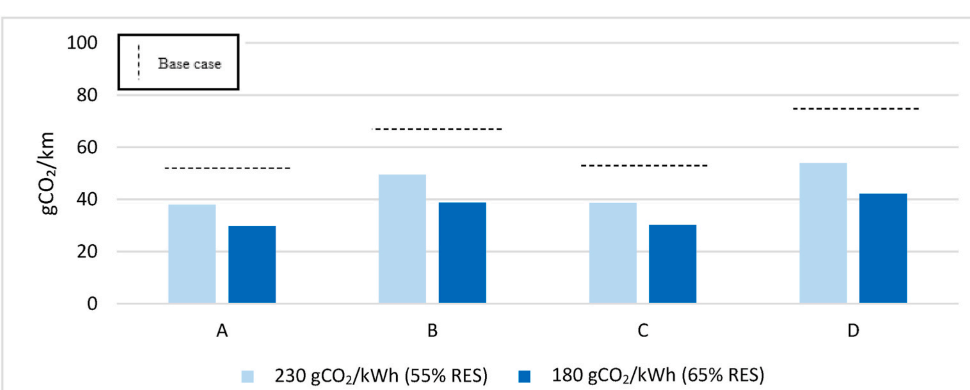

Fig. 8. Sensitivity analysis - Specific CO_2 emission levels associated to energy (values expressed in gCO_2/km).

5. Conclusions

The paper provides a comparison of the CO_2 emissions associated to EVs and ICEVs during their life cycle, through the development of a novel LCA-based evaluation framework and its application to four different scenarios. Results show that CO_2 emissions associated to an EV over its life cycle are always lower than the ones associated to a comparable ICEV, i.e., comparing the same vehicle segment in the same scenario. The most impactful phase during the life cycle of an EV is the use phase, irrespective to the specific vehicle segment, followed by vehicle and battery manufacturing ones, while the impact associated to transportation and EoL phases is quite limited. For an ICEV, the most impactful phase during life cycle is the use phase as well, followed by vehicle manufacturing and transportation, while the contribution due to EoL is negligible. Moreover, it emerges that, *coeteris paribus*, moving from small-sized vehicles to larger ones (i.e., from Segment A to D), the CO_2 emission levels increase, due to the values of some impactful input variables such as battery size, vehicle weight, specific battery energy consumption and specific fuel consumption. Results also bring into light the huge impact on a vehicle's CO_2 emissions of the geographical location in which the upstream phases of the vehicle's life cycle take place, as a function of the energy mix and the RES penetration that characterize the countries analysed in each scenario. Finally, it emerges that variations of the specific energy requirements for battery manufacturing, the specific vehicle consumption, and the specific CO_2 emission levels associated to energy exert a huge impact on the overall CO_2 emissions of an EV.

The paper contributes to the extant literature by reaffirming the better environmental performance of EVs compared to ICEVs, in terms of CO_2 emissions over their entire life cycle. As the main contribution of this study, the developed evaluation framework takes into account all the phases of a vehicle's life cycle, in accordance with the LCA approach, thus overcoming the limited coverage of such phases that characterizes most of the existing contributions. To this aim, ad hoc metrics to estimate CO_2 emissions associated to the most neglected phases of a vehicle's life cycle, i.e., material extraction, transportation, and EoL phases, are proposed and discussed. Second, to the best of our knowledge, the study is the first one focusing on Italy as the country in which the vehicle use phase takes place, i.e., one of the major automotive markets worldwide with the highest level of RES penetration in the national energy mix. Furthermore, as most of the studies adapt a single multi-country analysis (i.e., assuming different countries in which the different phases of a vehicle's life cycle take place), the one-country scenario evaluated in the paper brings into light the possibility to achieve considerable environmental benefits through the development of local supply chains in countries with a high level of RES penetration, such as Italy. Third, this study is one of the first attempts to quantify the positive impact on an EV's CO_2 emissions associated to the higher diffusion of RES that is expected in the near future, as shown in the sensitivity analysis. It is confirmed that the further RES diffusion will expand the spread between EV and ICEV in terms of CO_2 emissions during their life cycle.

Our findings offer suggestions for policymakers on the opportunity to promote the spread of EVs as a means to tackle environmental issues. Indeed, the study provides a comprehensive picture of the CO_2 emissions associated to EVs and ICEVs during their life cycle, also bringing into light the variables that mostly affect these emissions, such as the specific CO_2 emission levels associated to energy production. A more sustainable transportation sector, through the spread of EVs, would require a higher level of RES penetration, therefore policy makers are called to draft consistent policies (e.g., in terms of mandatory targets and incentive schemes) to concurrently promote EVs and RES diffusion. Moreover, given the huge impact on a vehicle's CO_2 emissions related to the upstream phases of the life cycle, policy makers should promote the development of local supply chains in countries characterized by a high level of RES penetration, to achieve considerable environmental benefits in addition to economic ones. Finally, since the study shows an increase of CO_2 emissions moving from small-sized vehicles to larger ones (i.e., from Segment A to D), policy makers should carefully design provisions supporting the EV diffusion in order to make small-sized vehicles more appealing, thus reversing customers preferences that seem to be currently oriented towards large-sized vehicles.

Some limitations of the proposed evaluation framework should be highlighted, which could lead to further improving the framework itself. First, the framework focuses only on the estimation of CO_2 emissions associated to EVs and ICEVs during their life cycle, which represent by far the most relevant ones among GHG, in terms of both quantity and GWP. The inclusion of other GHG such as N_2O and CH_4 may add an important improvement to our framework, albeit quite complex. Second, the estimation of CO_2 emissions associated to the vehicle use phase is based on average values of the input variables collected through the literature review. Given the huge impact of such phase on the overall CO_2 emissions associated to a vehicle, more sophisticated metrics for their estimation could be introduced, e.g., by taking into account the different vehicle use patterns (such as urban or extra-urban driving behaviour and auxiliaries use) and other contextual factors (e.g., different land morphology). Moreover, the contribution of maintenance activities could be added within the framework, even though it is substantially negligible for EVs. Third, as most of the studies analysed, values of input variables are based on lab driving conditions or are provided by car manufacturers. An input data collection based on real world driving conditions would add a further important improvement to the application of the proposed framework, despite the undeniable increasing effort it would require. Another avenue for future research is the application of the proposed evaluation framework in other countries in which vehicles are used. However, since each country is characterized by specific peculiarities (e.g., energy loss in the energy system owing to energy transmission and distribution), input data should be carefully revised. Moreover, the analysis focuses on one EV typology, i.e., BEV, and two ICEV typologies, i.e., petrol- and diesel-fuelled vehicles. As the options currently debated to achieve a more sustainable mobility go beyond such typologies, e.g., with reference to other EV typologies such as PHEV and FCEV or to methane-fuelled vehicles among ICEVs, it would be useful to enrich the proposed evaluation framework to enable a comparison with other vehicle types. The last avenue for future research refers to a deeper implementation of the Circular Economy (CE) principles in the proposed evaluation framework, with particular reference to the vehicle EoL. The EV industry, with particular reference to batteries, seems to fit well the CE principles, e.g., with reference to battery recycling and B2U. It would be beneficial to evaluate the impact of emerging recycling technologies on the whole CO_2 emissions associated to EVs and the one related to the implementation of B2U.

CRediT authorship contribution statement

Simone Franzò: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Alessio Nasca:** Methodology, Investigation, Data curation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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