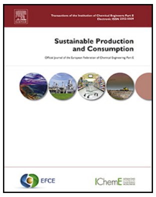
Sustainable Production and Consumption 36 (2023) 49–61

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



# A feasibility analysis on adopting electric vehicles in the short food supply chain based on GHG emissions and economic costs estimations

Antonino Galati [a],[*], Nino Adamashvili [b], Maria Crescimanno [a]

[a] Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, Building 4, 90128 Palermo, Italy
[b] Department of Economics, University of Foggia, Via Romolo Caggese, 1, 71121 Foggia, Italy

## ARTICLE INFO

*Article history:*
Received 12 October 2022
Received in revised form 29 December 2022
Accepted 1 January 2023
Available online 5 January 2023

Editor: Prof. Raymond Tan

*Keywords:*
Electric vehicles
Internal combustion engine vehicles
Sustainable transportation
Comparative study
Environmental impact
Economic impact

## ABSTRACT

The transition toward electric mobility is recognised as a powerful contributor to reaching the goal of reducing environmental pressure from the transport sector minimizing greenhouse gas emissions. Over recent years several studies analysed the economic convenience of adopting electric vehicles as well as its impact on greenhouse gas in the atmosphere. However, very few studies evaluated both economic cost and environmental emissions in a real-life environment. This study aimed to investigate the economic costs of battery electric vehicle adoption in the short food supply chain and its impact on the environment in terms of greenhouse gas emissions when compared to corresponding petrol-powered vehicles. It also aimed to examine the influence of policy measures on this transition process. To achieve these objectives, data were obtained from market research and the testing phase of a project co-funded by the European Interreg Med Programme. Based on collected data, economic cost and greenhouse gas emission of both battery electric vehicle and internal combustion engine vehicle use were determined. The results emphasise that when compared to corresponding petrol-powered vehicles, the economic convenience of electric vehicles as well as their positive impact on greenhouse gas emissions is evident after a finite distance is covered, which grows thereafter. Simulated scenarios confirm the importance of the incentives for vehicle acquisition promoted by governments to reduce their economic cost, whilst also confirming the influence that an energy mix consisting of renewable energy sources could have on achieving the environmental benefits of adopting electric vehicles over a shorter period and distance. In light of these results, some recommendations can be provided to promote the spread of battery electric vehicles in the short food supply chain. In detail, financial support is needed to both purchase battery electric vehicles and support projects to obtain lower-cost batteries. At the same time, a great effort should be made by policymakers to create an efficient network of recharging infrastructures also powered by alternative energies to further reduce greenhouse gas emissions.

## 1. Introduction

Sustainable development is a major global challenge of the modern world. Ecosystem degradation hampers the progress of different sectors, causes climate change and ruins the socio-economic system (OECD, 2019). Current business activities have a notable impact on the environment. Specifically, they consume valuable natural resources, emit hazardous pollution and pose a threat to human health and biodiversity (Zelazna et al., 2020). The impact of greenhouse gas (GHG) emissions on the environment is especially noteworthy. The massive amount of GHGs in the atmosphere—especially $CO_2$—may cause additional heat retention, thereby resulting in global warming. As pointed out by the European Energy Agency, the transport sector represents one of the main sources of environmental pressure. In 2020, transportation was responsible for over a quarter of total GHG emissions—of these, road transport produced more than 70 % of total emissions (EEA, 2020). These data show that transport pollution is now a global priority. Since the early 1990s, starting with the United Nations Earth Summit and up to the 2030 Agenda for Sustainable Development, the sustainability of the transport sector has increasingly become a central theme. Specifically, the 2030 agenda states that '*sustainable transport systems, along with universal access to affordable, reliable, sustainable and modern energy services, quality and resilient infrastructure, and other policies that increase productive capacities, would build strong economic foundations for all countries*' (UN, 2015, para. 27). This highlights how sustainable transport can contribute to the achievement of the objectives of sustainable development, particularly of energy efficiency (objective 7.3), sustainable infrastructure (objective 9.1) and access to a system of safe, sustainable, convenient and

---

[*] Corresponding author.
*E-mail addresses:* antonino.galati@unipa.it (A. Galati), nino.adamashvili@unifg.it (N. Adamashvili), maria.crescimanno@unipa.it (M. Crescimanno).

https://doi.org/10.1016/j.spc.2023.01.001

**Nomenclature**

| | |
|---|---|
| $C_{BEV}$ | The cost of BEV |
| $C_{ICEV}$ | The cost of ICEV |
| EP | the electricity price in Italy |
| FP | the price of fuel in Italy |
| EC | the observed energy consumption of the BEV |
| VC | the vehicle fuel consumption |
| $\Delta x$ | the number of kilometres travelled during the testing phase |
| $A_{EV}$ | the purchase cost of the EV |
| $A_{ICEV}$ | the ICEV purchase cost |
| $E_{BEV}$ | greenhouse gas emissions of BEV |
| $E_{mix}$ | the emission cost of the Italian energy mix |
| BPE | the emissions value during the production process |

accessible transport (objective 11.2) (UN, 2015). These objectives were recently discussed at COP26 to facilitate the transition to zero-emission means of transport as a tool to help reduce global warming. In this scenario, the adoption of battery electric vehicles (BEVs) represents an opportunity that can contribute to the aforementioned aims. Currently, there are numerous initiatives for shifting from fossil fuel-based to battery electric vehicles (BEVs). The European Union seeks to achieve a more than 80 % share of EVs among total vehicles by 2030. To fulfil this ambitious plan, Guzović et al. (2022) assumed that major technological changes should occur. Also, Rohe and Mattes (2022) argued that for economic and environmental strength, it is crucially important to develop not only global or national strategies but also regional technological innovation systems since all regions differ from one another and an individual approach is thus required.

Over the last few years, a growing interest in the use of BEVs in response to the marked environmental pressure of the transport system has attracted the attention of academics and practitioners aiming to understand as the economic convenience of adopting BEVs as an alternative to traditional internal combustion engine vehicles (ICEVs) as well as its impact on GHGs in the atmosphere. In many studies, feasibility analyses have been based on data from national and/or international databases (Fevang et al., 2021; Hoekstra, 2019; Hawkins et al., 2013) as well as vehicle technical information provided by manufacturers (Hoekstra, 2019). However, few studies have evaluated both - economic cost and emissions analysis based on empirical data (Siragusa et al., 2020; Ouyang et al., 2021). The results of these studies are conflicting, which highlights the need to rely on experimental data (Hoekstra, 2019). Furthermore, only a few studies have examined commercial vehicles for the transport of goods (Siragusa et al., 2020; de Mello Bandeira et al., 2019) and none has involved the transportation of agri-food products using BEVs. In the latter sector, several authors have emphasised that the transportation of foods is a major direct contribution to GHG emissions (Alp et al., 2022; Fernández-Ríos et al., 2022). For instance, Chen et al. (2021) calculated a 64 % reduction in GHG emissions during the food transport and logistics stage when applying sustainable fuel in a salmon system. The same authors observed a 50 % reduction in GHG emissions during the consumption and end-of-life stage by reducing the fuel-based transportation caused by food waste. In light of this, by modeling a food delivery scheme in New York City, Elangovan et al. (2021) discovered that electric trucks (e-trucks) consume about 1/3 of the energy consumed by diesel-based whilst also generating 60 % less GHGs. Moreover, Alp et al. (2022) proved that the adoption of e-trucks by firms—along with investment in charging infrastructure—can be environmentally friendly and economically convenient. These authors also discussed the importance of the way the energy is obtained and noted that the role of the policy-makers is important.

In light of this context, the present study aimed to investigate the impact of shifting from fossil fuel-based to electric vehicles on sustainable development. Specifically, this study sought to evaluate the economic feasibility of BEV adoption in the short food supply chain (SFSC) in Italy and its impact on GHG emission. The study focuses on the experiments carried out under the EnerNETMob project funded by the Interreg-Med program, which explores 'last-mile' connections for the distribution of agri-food products over short distances between rural and metropolitan areas, and in particular between the coastal area of eastern Sicily and the regional hinterland. This focus on the SFSC can be attributed to the fact that despite a general consensus on the social and ecological benefits associated with short supply chains (SSCs), some authors (Malak-Rawlikowska et al., 2019; Coley et al., 2011) have raised concerns about the environmental impact of the transportation system, which makes the entire process less sustainable. Indeed, establishing SFSCs has been considered as another solution for reducing the harmful environmental impact of the food delivery (Forssell and Lankoski, 2015). However, the impact of SFSC on the environment is heterogeneous and should be studied separately (Chiffoleau and Dourian, 2020; Kiss et al., 2019). Moreover, Malak-Rawlikowska et al. (2019) argue that if impact is calculated per unit of production, it will be evident that the SFSCs are less environmentally friendly than conventional food supply chains since the less products are transported at a time. Therefore, the reduction of food miles is not enough (Coley et al., 2011) and further measures are necessary, such as EVs adoption (Franzò and Nasca, 2021).

Recently, only few research have been published investigating the experience with BEV for commercial transport and distribution and, especially the prospective of the adoption of sustainable transport system in the SFSCs (Galati et al., 2022). To the best of our knowledge, this is the first study to deal with the economic convenience of commercial EV adoption in the food distribution system and simultaneously giving insight to its impact on GHG emissions. Furthermore, compared to previous studies, which are mainly based on BEV general parameters and simulations, this study offers a comprehensive and comparative environmental and economic analysis based on a real-life test. This allows us to identify potential advantages and obstacles to the use of commercial BEVs in the short food supply chain.

Although this research is based on a case study within a particular area of focus and under specific operative conditions, the proposed methodological approach can be extended to other geo-political contexts. Further real-life tests and pilots, comparing BEVs under different market and political conditions, which modify the scenario's parameters, can deliver important insight for a deeper understanding of the usefulness of introducing BEVs for last-mile deliveries to the agro-food supply chain. Therefore, the research can serve as a stimulus for researchers and a basis for future studies in this field. Moreover, the research results can assist practitioners by providing insights into the comparison of commercial EV and ICEV characteristics, as well as the economic convenience of their adoption and environmental impact in terms of generated GHGs in the atmosphere. Additionally, the study outcomes can be beneficial for policymakers since they highlight the advantages of commercial EVs in the SFSC as well as the main barriers and challenges to their adoption. Thus, policymakers will be able to make more informed decisions and advance relevant laws.

The structure of the article is as follows: it begins with a literature review concerning the economic convenience of EVs adoption and environmental impact in terms of generated GHGs in the atmosphere as well as the factors influencing their adoption. Then, the research methodology is described. Thereafter, the testing phase is reported, followed by the results and discussion. Finally, the conclusion and recommendation section concludes the article.

## 2. Literature review

### 2.1. The impact of electric vehicles adoption on the greenhouse gas emissions

Several studies on the environmental benefits of EV adoption have shown that these are closely linked to the energy sources used for both vehicle manufacturing (i.e., batteries and electronic components) and vehicle power supply (Jeon et al., 2020; Cao et al., 2021; Alp et al., 2022). In light of this, several authors have suggested considering both the energy consumption during the manufacturing process and the energy used by vehicles on the road to evaluate the environmental feasibility of EV adoption whilst avoiding the overestimation or underestimation of emission parameters (Hoekstra, 2019; Hawkins et al., 2013). Pipitone et al. (2021) estimated the impact of ICEVs and BEVs on the GHG emissions over their life cycles and found that the manufacturing of a BEV and the energy sources used to power it during its use lead to a release of 109.6 g/km of $CO_2$eq—41.4 % less than the emissions released by an ICEV. A similar approach was used by Costa et al. (2021), who compared a BEV and an ICEV with similar characteristics. By considering the GHG emissions during the manufacturing of both vehicles, these authors found that the amount of GHGs emitted is greater for the ICEVs than for the BEVs, attributing this result to the greater quantity of components that must be produced for the ICEVs when compared to a BEV; however, this environmental benefit is dependent on the energy mix. Consistent with this, Siragusa et al. (2020) considered the entire life cycle of a vehicle (raw material and component acquisition and processing, maintenance and disposal) by adopting the LCA to estimate the GHG emissions. These authors found that the adoption of EVs allows a reduction in GHG emissions ranging from 17 to 54 % in relation to the number of kilometres travelled.

Nevertheless, some authors have found that the adoption of BEVs leads to a reduction in $CO_2$ emissions and lower energy consumption. On the other hand, this contributes to emitting a greater amount of fine dust. For instance, Ji et al. (2012) compared the impact in terms of $CO_2$ and particulate matter (PM2.5) emissions after the adoption of ICEVs (petrol or diesel) and EVs in 34 major cities in China. They found that the emissions of an EV are similar to that of a petrol car (Euro IV) for $CO_2$, yet 19 times higher in terms of PM2.5 despites being more efficient than diesel cars.

Other studies have evaluated the feasibility of adopting BEVs in terms of air pollution with the GHGs by only considering the energy sources used to recharge their batteries. Zheng and Peng (2021) found that although BEVs have a lower energy consumption rate than non-plug-in HEVs and diesel cars, the life cycle $CO_2$ emissions are highly variable and depend on the power generation mix. Indeed, in countries such as Norway, where 98 % of energy comes from renewable sources, the $CO_2$ emissions of EVs are significantly lower than those of ICEVs. Meanwhile, in China, where a lot of coal is used to produce electricity, EVs are more polluting. These results highlight the need to develop clean power generation mixes to support the development and diffusion of electric cars. Indeed, as Nimesh et al. (2020) pointed out, the conversion of a fleet from ICEV to BEV is feasible but could become unsustainable due to an exponential increase in EVs. A similar result was obtained by Siragusa et al. (2020).

Finally, other authors have also suggested considering battery wear in evaluating the benefits of EVs compared to ICEVs. In particular, a study carried out by Yang et al. (2021) in different U.S. regions analysed BEV battery degradation under different conditions of use over a period of 5 and 10 years. Their results were as follows: i) a reduction in battery charge capacity leading to an increase in EV energy consumption; ii) an increase in GHG emissions due to the possibility of replacing the battery pack; iii) a simultaneous reduction of the economic and environmental advantages when compared to ICEV use. As some authors noted, recycling or transferring the unused capacity of batteries to another sector can significantly reduce the negative environmental impact and provide stability to the grid through the integration of other storage devices, with a consequent reduction in harmful waste (Wesseh and Lin, 2022; Park et al., 2021; Zheng et al., 2018). Since the amount of lithium in nature is very limited, the recycling of lithium-ion batteries (LIBs) would allow the recovery of important materials (Wang et al., 2022; Mirza et al., 2021). In addition to the sustainable use of resources (Zhao et al., 2022; Yanamandra et al., 2022), the recycling and reuse of LIBs lead to environmental conservation through responsible disposal since this type of waste can significantly damage nature (Kotak et al., 2021; Wang et al., 2020). Chen et al. (2022) considered lithium recycling to be beneficial to both the environment and the economy. In this direction, Gu et al. (2021) discussed the role of government subsidies to promote the use of second-life batteries. Undoubtedly, the use of these new technologies—whose key principle is respect for the environment—should be analysed with particular attention to understanding their potential or limits in relation to the pursued environmental benefits.

### 2.2. Economic feasibility of electric vehicles adoption

Turning to the analysis of the economic feasibility of adopting BEVs compared to ICEVs, some studies have found that purchase price is the most influential factor for car purchases, with high cost being one of the main barriers slowing the spread of EVs (Gómez Vilchez et al., 2019; Dumortier et al., 2015). This high cost is attributable to the price of the batteries, which accounts for 75 % of the total cost of the vehicle. This is mainly due to the cost of raw materials (60–80 % of the total cost) and electrodes since they require noble materials (Berckmans et al., 2017). In light of this, Neubauer and Pesaran (2011) suggested that giving batteries a second life can reduce the cost of EVs and increase interest in them. Jiang et al. (2017) proposed a new screening strategy to assess the ageing state of battery packs and the cost-effectiveness of using spent EV batteries by analysing consistency and ageing characteristics and hypothesising alternative uses. Moreover, additional studies (Pagliaro and Meneguzzo, 2019; Cusenza et al., 2019) proposed using end-of-life batteries in energy storage systems (ESSs). This solution would significantly reduce waste that is hazardous to human health and the environment whilst being economically viable, thereby allowing a reduction in the cost of EVs. Indeed, Richa et al. (2017) showed that the benefit of using ESSs with end-of-life EV batteries is about 10 times higher than producing new ones. Additionally, considerable progress has been made in recent years regarding the useful life of batteries. In particular, it is estimated that they currently last from 1500 to 3000 charging cycles before reducing their storage capacity by 20 %. Thanks to technological progress, it is estimated that by 2030, batteries will be able to reach 10,000 cycles (Hoekstra, 2019; Few et al., 2018).

Compared to ICEVs, BEVs have the advantage of requiring little maintenance, having no moving parts except the rotor, and ensuring greater longevity than vehicles powered by fossil fuels (Berckmans et al., 2017; Crabtree et al., 2017). In line with this, several authors have noted that due to lower operating and maintenance costs, it is expected that EVs will be more profitable than ICEVs by 2050 (Gambhir et al., 2015; Liu et al., 2021a) and the market share of ICEV will decrease from 99 to 68 % (Berckmans et al., 2017).

Therefore, an increase in the useful life of batteries and low maintenance costs will make EVs more advantageous in the long run. In accordance with this, Siragusa et al. (2020) compared electric vans and ICEVs for last-mile deliveries. In particular, this study highlighted numerous positive aspects regarding the use of EVs: 40 % lower repair and maintenance costs, 60 % lower refuelling costs, 35 % lower insurance costs, no road tolls and no property tax. Ultimately, the operating costs for EVs and ICEV were 35 and 73 % of their total cost of ownership (TCO), respectively. In this scenario, it emerged that the use of EVs is economically convenient when compared to ICEV starting from 4.5 years of ownership. Consistent with this, Costa et al. (2021) identified how the economic benefits depend on the mobility profile of the end user. In particular, in relation to the acquisition cost of electric and combustion vehicles and the costs of power supply (electricity and fuel costs), the authors assumed that the greater the price difference between the two types of vehicle, the greater the travelled distance required to make the EV an advantageous solution from an economic perspective, consequently leading to an increase in the payback time. In contrast, de Mello Bandeira et al. (2019) compared the conventional strategy for postal deliveries in the city of Rio de Janeiro with an alternative model that adopts an electric LDV (Light Duty Vehicle), which highlighted the economic unsustainability of an EV when compared to an ICEV. The authors found that despite the environmental benefits arising from the use of EVs, the total delivery cost per route increases by 6.16 % compared to the traditional system due to the significantly higher cost of the electrical LDV.

### 2.3. Government policies toward electric vehicle based transportation systems

Currently, given the increasing global concern regarding climate change and oil dependency, the adoption of BEVs has become a critical path toward an updated transport system for modern society (Zelazna et al., 2020; Guo et al., 2022; Galati et al., 2022). Indeed, transport electrification is the main focus of European and single countries' transportation policies. The EU initiative 'Fit for 55' for 2030 means that by 2030, no more than 20 % of total vehicles should be based on pure internal combustion engines (ICEs; i.e., petrol and diesel). This seems quite ambitious because EVs represented only 18 % of the vehicle market in 2021 (EAFO, 2022). If this initiative turns into legislation with the requirement of reducing fossil fuel-based vehicles and substituting them with EVs, this type of policy will likely result in difficulties to produce an ever-increasing amount of EVs and supplying electric parts for vehicle production. The achievement of the aforementioned objectives could also be possible due to the incentives provided by governments. In light of this, Ebrie and Kim (2022) argued that tax breaks and directly subsidising EV purchases have significant effects on EV adoption. Similarly, Guo et al. (2022) reviewed Irish policies and found out that governmental subsidies for purchasing EVs and installing home chargers resulted in a 26 and 42 % lower TCO when compared to their equivalent petrol and diesel ICEVs, respectively, during a 4-year ownership period. However, as Ouyang et al. (2021) found in China, despite the purchase costs of BEVs and PHEVs decreasing by 31–36 % and 16–18 %, respectively, most BEV models will not reach cost parity with ICEVs by 2030.

Additionally, several authors have emphasised that financial stimuli for customers and technical improvements are necessary from the governmental side. Allahmoradi et al. (2022) listed the main factors influencing buyers' decisions, in which policymakers may intervene as follows: decreasing the difference between EV and ICEV prices by subsidising EVs; increasing fuel prices; extending EV travel ranges by improving charging infrastructure and/or battery capacity; increasing the top speeds of EVs. In line with this, Thiel et al. (2020) studied EV adoption trends in Italy and noted that buyers choose to purchase an EV if it is economically convenient for them. Similarly, Peiseler and Cabrera Serrenho (2022) argued that improvements in governmental incentives are required. Precisely, the authors proposed differentiating vehicles by their emissions and considering emissions not only in subsidy schemes but also in the road taxation system. Also, they suggested reviewing end-of-life vehicle directives.

Besides using policy incentives to minimise the price gap between EVs and ICEVs, additional policy measures for reducing range anxiety by establishing a relevant number of publicly accessible charging points are crucial (Thiel et al., 2020). Similarly, Tsakalidis et al. (2019) argued that adequate charging infrastructure significantly increases EV adoption. Similarly, Rosenberger et al. (2022) investigated the city of Hamburg by using the example of commercial EVs and concluded that reviewing the policies regarding EV charging infrastructure and expanding it would increase electrification by 35 %. ICCT's (2022) research proved the same for Italy. Precisely, to shift toward an EV-based transport system, extensions to public charging infrastructure are crucially important. Additionally, appropriate charging systems need to be developed. Notably, Petrauskienė et al. (2020) considered that the further development of transportation policies by improving charging infrastructure and strictly controlling the energy sources for EVs to support the use of renewable energy can have a desirable result. Consistent with this, Sommer and Vance's (2021) study of the German market revealed that the most important barrier to EV uptake is the low territorial coverage of charging infrastructure, even though Germany significantly exceeds the EU's recommended minimum ratio of one charging point to ten EVs. Some authors have argued that an increase in the number of charging points is positively correlated with EV adoption. Indeed, White et al. (2022) investigated metropolitan areas of Los Angeles, Dallas/Fort Worth and Atlanta in the United States and found out that government incentives to expand charging infrastructure ensure customers' free mobility without restrictions and play a crucial role in the wider adoption of EVs.

With regard to commercial vehicles, Newman et al. (2014) argued that the electrification of transportation has a positive impact on society, yet substantial challenges appear when it comes to commercial vehicles due to the need to deliver products in rural areas. In this context, Napoli et al. (2021) discussed the importance of EV adoption in the logistics sector since this is the most effective step toward decarbonisation. The case of the UK is noteworthy in that this country is the earliest adopter of EVs in delivery services. UK parliament passed a law regarding net-zero greenhouse gas emissions by 2050. To reach this goal, the UK government announced a ban on the sale of new ICEs from 2035 onward. This is a part of the UK's '10-point Plan for a Green Industrial Revolution' (GOV.UK, 2020). Besides grants for purchasing EVs, the government provides high-skilled green working places, investments in alternative sources of energy and support for the replacement of traditional commercial transport with zero-emission alternatives. Additionally, it is attempting to transition to EVs as smoothly as possible by investing £1.3 billion in charging infrastructure. Notably, the UK logistics sector is willing to shift to a green and safe transportation system. However, in 2019, electric vans only made up 1 % of the total number of vans sold in the UK. Newman et al. (2014) suggested new policies for suburban and rural areas and more comprehensive research in the field to overcome the aforementioned issue. When studying the Australian market, Allan (2014) posed the same problem for policymakers and considered that without appropriate charging infrastructure, the country will not be able to meet the EV market requirements. This is because EVs have 80–90 % less capacity when compared to their fossil fuel-based equivalents, with a significantly longer recharge time. Therefore, this author suggested reviewing infrastructure investments and transport policy in Australia.

## 3. Methodological approach

### 3.1. Emission and economic benefits analysis

This study analysed the GHG emission and economic costs of using BEVs compared to ICEVs based on empirical data obtained in the testing phase of a project co-funded by the European Interreg Med programme and aimed to draft, test and improve 'Sustainable Electromobility Plans' for the SFSC. The EV adopted in the testing phase, VAN Nissan e-NV200 (40 kWh) with 80/109 CV, was compared to an ICEV vehicle with similar characteristics: the Fiat Doblò 1.4 T-Jet PC-TN Cargo Easy with 120 CV, petrol-powered (Mezzicommerciali, n.d.). ICEV technical information was provided by the car manufacturer. It was decided to compare the EV exclusively with the corresponding petrol-powered vehicle and not a diesel vehicle for two reasons: i) diesel vehicles are notoriously more polluting and ii) more expensive than petrol vehicles. Thus, diesel vehicles would not allow a correct evaluation of the economic and environmental benefits.

The data analysis was performed according to the approach proposed by Costa et al. (2021). For the analysis of the economic benefits, data relating to the purchase cost of vehicles, consumption, electricity and fuel costs in Italy, as well as the kilometres travelled, were acquired.

The cost of BEV use ($C_{BEV}$) was calculated based on the following formula (1):

$$C_{EV}(€) = EP\left(\frac{€}{kWh}\right) * EC\left(\frac{kWh}{km}\right) * \Delta x(km) + A_{EV}(€) \tag{1}$$

where EP is the electricity price in Italy based on the single national price (i.e., the reference price of energy registered on the Italian stock exchange (a2aenergia)); EC is the observed energy consumption of the BEV, given by the ratio between the kWh absorbed during the recharging phase and the number of kilometres travelled; Δx is the number of kilometres travelled during the testing phase; $A_{EV}$ is the purchase cost of the EV obtained through market analysis. It is important to emphasise that, following the formulas proposed by Costa et al. (2021), maintenance costs are not taken into consideration. The academic literature offers conflicting results regarding these costs. Several authors have demonstrated that BEVs have significantly lower maintenance costs than ICEVs for the least number of components that need to be treated (Costa et al., 2021; Burnham et al., 2021; Wilken et al., 2020). By contrast, Alotaibi et al. (2022) argue that the lack of qualified labour in this new market and the vehicles' high consumption of real power leads to the maintenance costs of EVs exceeding those of ICEVs.

The cost of ICEV use ($C_{ICEV}$) was calculated using the following formula (2):

$$C_{ICEV}(€) = FP\left(\frac{€}{l}\right) * VC\left(\frac{l}{km}\right) * \Delta x(km) + A_{ICEV}(€) \tag{2}$$

where FP is the price of fuel in Italy, obtained from the website of the Italian Ministry of Ecological Transition (MET); VC is the vehicle fuel consumption, obtained from the vehicle technical sheet; Δx is the number of kilometres travelled during the testing phase; $A_{ICEV}$ is the ICEV purchase cost, obtained through market analysis.

For the analysis of environmental benefits in terms of GHGs generated in the atmosphere—and in line with Costa et al. (2021)—it was assumed that in the analyses, only the production emissions of the EV battery (approximately 3.44 t of $CO_2$-eq) are considered since the emissions from the manufacturing of an ICEV are similar to those of an EV (Bieker, 2021; Andersson and Börjesson, 2021). Furthermore, these authors point out that the end-of-life emissions of both vehicles are negligible and similar to each other. During the use phase, the emissions of the ICEV were calculated using the vehicle's average emission value of 165 g/km.

With reference to the GHG emissions of BEV use ($E_{BEV}$), the following formula was used (3):

$$E_{EV}(gCO_2eq) = E_{mix}\left(\frac{gCO_2eq}{kWh}\right) * EC\left(\frac{kWh}{km}\right) * \Delta x(km) + BPE(gCO_2eq) \tag{3}$$

where $E_{mix}$ is the emission cost of the Italian energy mix supplied by ISPRA (2021); $EC$ is the BEV energy consumption; $\Delta x$ is the number of kilometres travelled; BPE is the emissions value during the production process.

Starting from the results obtained through the experimentation data, a break-even analysis was used as a tool to understand the risk of BEV adoption compared to ICEV use. Specifically, the break-even point refers to the minimum number of kilometres that must be travelled for the use of the EV to be convenient from economic and emission perspectives.

### 3.2. Battery electric vehicle testing phase and data collection

The experimental activity was performed in Sicily within the territory between the municipalities of Troina (EN; in the hinterland of the island) and Acireale (CT; located on the Eastern coast of the island). The exchange of agri-food products between these two municipalities, approximately 90 km apart, has, in line with the logic of the short food supply chain, always been active, connecting the products of the Acireale area, mainly fruit and vegetables, with inland markets, above all for the products of livestock farming. The decision to conduct the experiment in this area, along the axis connecting the two municipalities, was linked not only to the flow of agri-food products but also to the willingness of the two municipalities to install two charging stations as envisaged by the EnerNETMob project. As previously mentioned, a Nissan e-NV200 was hired (long-term rental) for the testing phase. This vehicle, approved according to Directive 2007/46/EC, was chosen based on the characteristic of having an exclusively electric power supply (i.e., zero carbon dioxide emissions). The vehicle is a van with a 4.2 $m^3$ cargo capacity that guarantees enough room for 2 Euro Pallets or 705 kg of cargo. Due to its new 40kWh battery, the e-NV200 can cover between 190 (WLTP City) and 300 km (Combined cycle) on a single charge. These vehicle features are in line with the needs of farmers operating in SSCs. In this regard, according to Galati et al. (2021), farmers transport an average of approximately 100/200 kg of agro-food products per trip (including the equipment necessary to prepare the selling point in the farmers' markets). Also, a Fiat Doblò 1.4 T-Jet Pc-Tn Cargo Easy was chosen for the comparative analysis because it has similar characteristics to the BEV, including payload.

The BEV was used by a Sicilian social farm (Rete Fattorie Sociali Sicilia) and its associated partners for the distribution of local agri-food products in the area under study for a period of 4 months. To monitor the movements of the BEV, monitoring sheets were drawn up to record useful information for assessing the emission and economic costs of an EV compared to a conventional means of transport. In particular, two sheets were created: the 'trips booklet' and the 'recharges booklet'. The first sheet contains information on the date, departure time, mileage at departure (on the odometer), place of departure, arrival time, mileage on arrival (on the odometer), destination, active electrical devices (AC, heating), vehicle load (% of total volume), and the type of products transported. The 'recharges booklet' contains information on the following aspects: charging start date and time; charging end date and time; total mileage (on the odometer); place of charging; type of charging (domestic, normal, fast); battery level at the start of charging (percentage); battery level at the end of charging (percentage). Moreover, drivers of the BEV used an RFID card provided by the Enel X operator to recharge the vehicle. This system enables the recharging infrastructure to dispense and account for energy expenditure by placing the card in the provided slot. The choice of Enel X for the RFID cards is linked to the number of charging stations managed by Enel X in the regional territory. Through the Enel X website, it was possible to obtain additional information related to the location of the charging station used, the start and end time of the charging process, the duration of the charging process, the cost of the service, the energy delivered (kWh), the type of plug used, and the amount of $CO_2$ saved. This collected information was used to analyse GHG emission and economic cost of the BEV compared to the ICEV.

### 3.3. Simulation scenarios

Based on the empirical analysis, two scenarios were simulated relating to the incentive policies for the purchase of BEVs by the Italian government and the use of an energy mix consisting of 100 % renewable energy, respectively. In particular, the first scenario concerns the assessment of the economic cost of the BEV in comparison to the ICEV by applying the BEV incentives provided for category N1 vehicles in Italy via the Budget Law of 2021. This assessment was based on the data analysed in the testing phase after amending the cost of the vehicle in this case. This particular incentive varies according to the total mass on the ground (MTT), the power supply of the vehicle and the eventual scrapping. With reference to our study, since the MTT of the examined vehicle falls within the range of 2–3299 t, the law provides for an incentive of € 5600 and € 4800 with and without scrapping, respectively, to be applied to the sale price of the vehicle (VAT included at 22 %).

With regard to the second scenario, since the economic convenience of an EV adoption as well as the impact on GHG emissions also depends on the energy mix used for electricity production, it was assumed that the power supplied is exclusively from renewable sources. Starting from the analysis of the GHG emission and economic costs of BEV use based on the data collected in the testing phase, the same analysis was repeated considering an energy mix consisting exclusively of renewable energies.

For both scenarios, it was possible to calculate the break-even point and verify the effect on the standard situation in terms of the economic incentives when supplying the EV with energy originating from renewable sources.

## 4. Results and discussion

### 4.1. Economic cost analysis

During the testing phase of the project, the BEV used for the distribution of agri-food products covered a total of 1505 km. Based on the experimental data, data obtained through a market analysis for the ICEV, and the formulas outlined in chapter 3, it was possible to calculate the cost of using the two studied vehicles in both economic and GHG emission terms.

In economic terms, the results summarised in Table 1 show that the $C_{BEV}$ value is greater than the $C_{ICEV}$ value (+77 %), which highlights that purchasing the BEV compared to the ICEV for the delivery of agri-food products in the SFSC is not a cost-effective solution. In particular, the initial acquisition cost of the vehicle, being much higher for the BEV, significantly affects this result and slows down the adoption of EVs since economic convenience is the main factor affecting buyers' purchasing decisions (Gómez Vilchez et al., 2019; Dumortier et al., 2015). Several studies have emphasised that reducing the difference between BEV and ICEV acquisition costs is the main driver facilitating the spread of BEVs (Allahmoradi et al., 2022), which can be achieved via purchase subsidies, among other mechanisms (Ebrie and Kim, 2022; Guo et al., 2022).

As highlighted in various studies, the high cost of BEVs is linked to the production of batteries, which accounts for 75 % of the total cost of the vehicle due to the precious materials required for their manufacture (Berckmans et al., 2017; Chakraborty et al., 2022). If the cost of replacing the battery is also added to this cost, it would further reduce the economic convenience of a BEV compared to an ICEV (Yang et al., 2021; Ouyang et al., 2021). Consistent with our results, Soysal et al. (2015) revealed a cost increase of 10.8 % resulting from the introduction of EVs. A result confirmed by de Mello Bandeira et al. (2019) suggests that the use of an electric LDV for postal deliveries resulted in a cost increase of 6.16 % when compared to a petrol-powered vehicle, which is attributed to the higher cost of BEV acquisition. On the contrary, Siragusa et al. (2020) experimented with electric vans for last-mile e-commerce deliveries in the city of Milan and highlighted their economic convenience. Over time, technological and scientific progress will undoubtedly contribute to reducing the existing gap between the acquisition costs of BEVs and ICEVs, which will largely be due to a decrease in battery prices (Costa et al., 2021). Concerning the latter aspect, Berckmans et al. (2017) performed a projection of the costs of LIBs and predicted that by 2030, innovative battery packs with a silicon alloy anode combined with a nickel-rich cathode will be on the market. These new technologies will allow improvements in terms of energy density (storage capacity) and result in a 30 % cost reduction per kWh. These factors will have a significant impact on the overall price of BEVs and will thus contribute to the reduction of the time required to recover the initial investment, thereby improving the competitiveness of BEVs in comparison to ICEVs.

**Table 1**

Costs of the battery electric vehicle ($C_{BEV}$) and internal combustion engine vehicle ($C_{ICEV}$) use.

| Variables | BEV | Variables | ICEV |
|---|---|---|---|
| Electricity price – EP (€/kWh) | 0.26 | Fuel price – FP (€/l) | 1.78 |
| Energy consumption - EC (kWh/km) | 0.19 | Vehicle fuel consumption - VC (l/km) | 0.09 |
| Distance covered (km) | 1505 | Distance covered (km) | 1505 |
| Purchase cost - $A_{BEV}$ (€) | 38,985.10 | Purchase cost $A_{ICEV}$ (€) | 21,838 |
| **$C_{BEV}$ (€)** | **39,057.63** | **$C_{ICEV}$ (€)** | **22,068.21** |

BEV = Battery Electric Vehicle; ICEV = Internal combustion engine vehicle; $C_{BEV}$ = Cost of Battery Electric Vehicle; $C_{ICEV}$ = Cost of Internal combustion engine vehicle.

By neglecting the acquisition cost of the vehicle and considering only management costs, the BEV is cheaper than the ICEV since electricity has a lower cost than fossil fuels (Petrauskienė et al., 2021). In line with this, Siragusa et al. (2020) studied the use of electric vans as an alternative to ICEVs for B2C deliveries and found—in addition to lower vehicle refuelling costs—a major difference in management costs for the two types of vehicles (i.e., maintenance, insurance, tolls and property taxes), which represent 35 and 73 % of the TCO for EVs and ICEVs, respectively.

Some authors have underlined that the economic convenience of adopting an EV instead of an ICEV is achieved over time. For instance, Siragusa et al. (2020) calculated the economic convenience of EVs over time and found out that they are more beneficial than ICEVs after 4.5 years of use. In this study, starting from the collected data, we calculated the distance necessary to reach the economic convenience of an EV. Fig. 1 shows the break-even point obtained when considering variations in $C_{BEV}$ and $C_{ICEV}$ in relation to the number of kilometres travelled. More specifically, starting from the break-even point, EVs are more advantageous than ICEVs, thus offsetting the high initial cost. In relation to the data collected and analysed, 163,616.41 km of travel are required to achieve the economic benefit of purchasing an EV compared to an ICEV. This result confirms the lack of cost-effectiveness in adopting this type of vehicle without any incentive measures.

### 4.2. Effects of incentives on economic feasibility

To overcome the criticalities emphasised in the previous section, many governments are defining policies to support the transition toward electric mobility. In Europe, this situation is very heterogeneous since some countries have established incentives to lower the list prices of cars whilst others simply apply tax benefits (ACEA, 2021a). In Italy, the eco-bonus is the measure promoted by the Ministry of Economic Development to promote the purchase of low-emission vehicles. With the 2021 budget law, contributions were also recognised for two new categories of vehicles: N1 and M1 special. In this case, the contribution varies from 4000 to 8000 euros with scrapping, and from 3200 to 6400 euros without scrapping, whilst also differing based on the fully loaded mass of the vehicle. At the tax level, there is an exemption of up to 5 years for EVs from the first registration; thereafter, there is a 75 % reduction in the tax rate applied to equivalent petrol vehicles (ACEA, 2021b). In relation to the new measures adopted with the 2021 Budget Law, the influence of this incentive on the economic cost and break-even point was analysed. In particular, our findings demonstrate that the introduction of incentives reduces the cost of EV ownership, which remains too high when compared to that of ICEVs for short distances. These results are in line with the research outcomes of Ebrie and Kim (2022) and confirm the key role of purchase incentives on the cost-effectiveness of adopting an EV compared to an ICEV. Indeed, applying the contribution to the end price of the vehicle contributes to the reduction of the number of travelled kilometres necessary to reach the break-even point, which changes to 110,181.30 km in case of scrapping (Fig. 2) and 117,814.89 km in the case of not scrapping the vehicle (Table 2, Fig. 3).

This highlights how the TCO of EVs compared to ICEVs decreases over time and confirms the results of the research conducted by Gambhir et al. (2015) and Liu et al. (2021a). Moreover, the outputs of this study emphasise that the policy based on purchase subsidies is an effective strategy to guide consumer choices toward electric mobility, whilst also strengthening the research results of Chen et al. (2019) as well as Ebrie and Kim (2022). In Canada, Azarafshar and Vermeulen (2020) estimated the effect of financial incentives on EV and PHEV

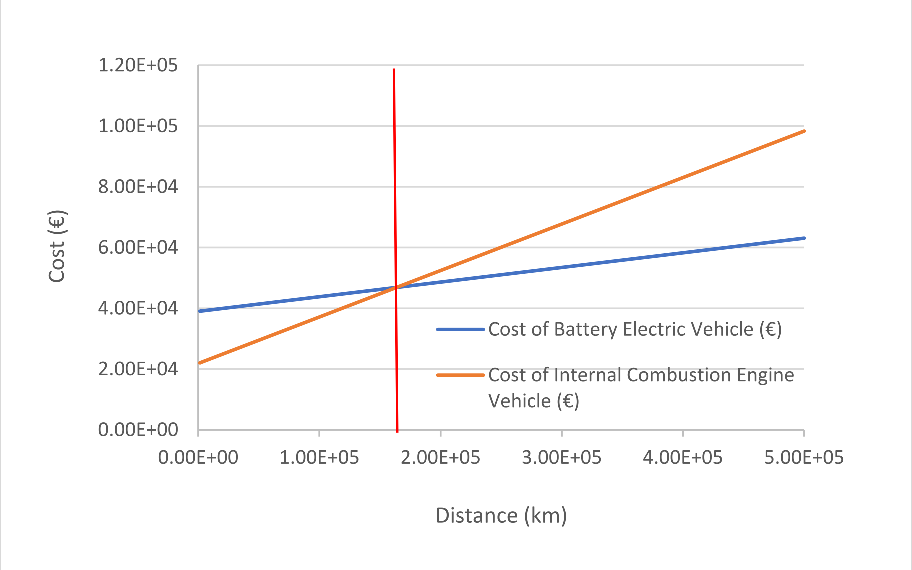


**Fig. 1.** Breakeven point of costs combustion engine vehicle ($C_{ICEV}$) use.
Source: our elaboration on collected data.

sales between 2012 and 2016 and find that the incentives resulted in a 35 % increase in EV sales. In line with previous studies, Liu et al. (2021b) explored the effectiveness of BEV support policies implemented in China between 2009 and 2018 and found that incentives play a key role, especially in the introduction phase. When BEV adoption reached the maturity stage, sales were positively influenced by the increase in recharging points and the increased price of fossil fuels. In light of this, several authors have emphasised that other factors affecting the adoption of BEVs are related to the adoption of additional policy measures that address the establishment of a relevant number of publicly accessible charging points (Thiel et al., 2020; Tsakalidis et al., 2019). Therefore, there is a need to review and further develop the transport policies regarding EV charging infrastructure (Rosenberger et al., 2022; Petrauskienė et al., 2020), which positively affect the adoption of BEVs.

### *4.3. Greenhouse gas emission analysis*

Hawkins et al. (2013) and Kawamoto et al. (2019) noted that the emissions produced by EVs are greater than those of ICEVs, which are mainly related to the production of various electronic components. In particular, the authors emphasised that only by increasing the number of kilometres travelled can the emissions of EVs be compensated and lower than those of vehicles powered by fossil fuels. As several scholars note, this difference is related to the production and treatment of the battery (Buberger et al., 2022). Bieker (2021) conducted a detailed investigation of the life-cycle GHG emissions of ICEVs and EVs in Europe, the United States, China and India, showing that emissions generated during the manufacturing of these vehicles differ imperceptibly, whilst the difference is obvious in respect of battery manufacturing. Similarly,

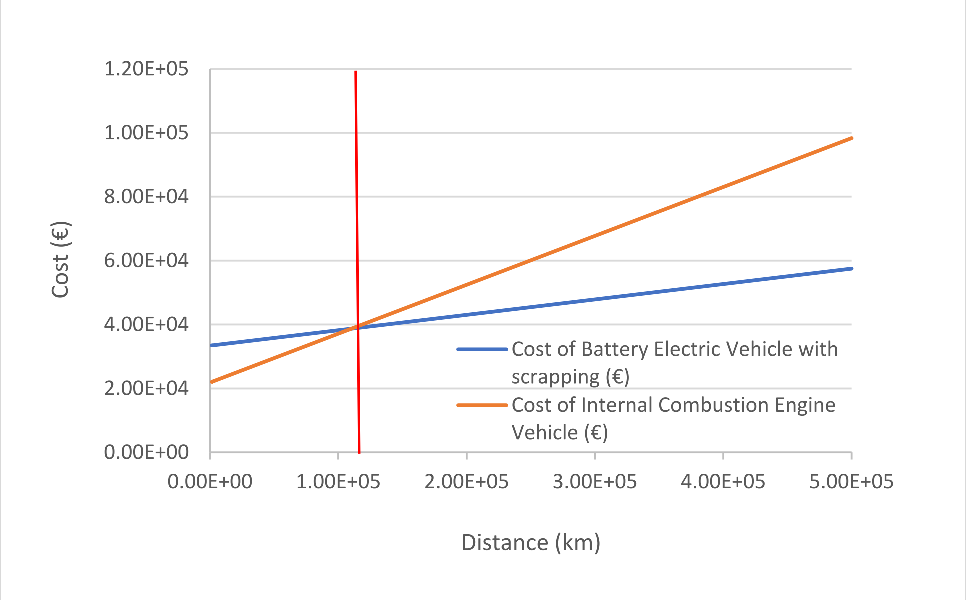


**Fig. 2.** Breakeven point of costs of battery electric vehicle ($C_{BEV}$) and of internal combustion engine vehicle ($C_{ICEV}$) use with incentives (with scrapping).
Source: our elaboration on collected data.

**Table 2**
Cost of the battery electric vehicle use ($C_{BEV}$) with incentives.

| Variables | BEV with scrapping | Variables | BEV without scrapping |
|---|---|---|---|
| Electricity price – EP (€/kWh) | 0.26 | Electricity price – EP (€/kWh) | 0.26 |
| Energy consumption - EC (kWh/km) | 0.19 | Energy consumption - EC (kWh/km) | 0.19 |
| Distance covered (km) | 1505 | Distance covered (km) | 1505 |
| Purchase cost - $A_{BEV}$ (€) | 33,385.10 | Purchase cost - $A_{BEV}$ (€) | 34,185.10 |
| **$C_{BEV}$ (€)** | **33,457.63** | **$C_{BEV}$ (€)** | **34,257.63** |

BEV = Battery Electric Vehicle; ICEV = Internal combustion engine vehicle; $C_{BEV}$ = the Cost of Battery Electric Vehicle; $C_{ICEV}$ = Cost of Internal combustion engine vehicle.

Andersson and Börjesson (2021), in their study of the environmental impact of production, usage and disposal of ICEVs and different kinds of EVs, found that battery manufacturing has the most significant environmental impact. The impacting effect linked to battery manufacturing was also highlighted by Sen et al. (2019). These authors analysed the material footprint (MF), which is defined as the quantity of materials required along the supply chain for the construction of the vehicles—equal to 16 and 42 t, respectively for ICEVs and EVs. This difference is due to battery manufacturing, which is responsible for 80 % of an EV's MF.

Therefore, for the GHG emission analysis, it was assumed that the emissions for the production of both types of vehicles are similar, differing only with respect to EV battery production. In particular, the results of our analysis, which was carried out using data obtained in the testing phase and with reference to the use of the vehicle for 1505 km, show that BEV GHG emissions ($E_{BEV}$) are higher than those of the ICEV vehicle ($E_{ICEV}$)—a result that is consistent with the work of Hawkins et al. (2013) and Kawamoto et al. (2019) (Table 3).

Additionally, as Raugei and Winfield (2019) stressed, the recycling process should also be considered in the environmental impact of batteries, which is relevant and depends on the chemicals used for their construction. Several authors have found that the disposal of end-of-life batteries causes damage to the environment (Kotak et al., 2021; Wang et al., 2020). In particular, if the battery ends up in nature, it has additional harmful environmental impacts, including SOx emissions and water contamination (Dunn et al., 2015). Therefore, this factor should be taken into consideration when the overall environmental impact of EV adoption is discussed (Kotak et al., 2021). These results highlight the importance of studying innovative solutions for the decarbonisation of the production process and the recycling or reuse of batteries at the end of their life. Batteries at the end of their life cycle still contain valuable and critical materials, such as cobalt, lithium and nickel (Ahuja et al., 2020). As such, using them in other industries or in the same battery production industry can be equally beneficial for the environment and the economy (Wesseh and Lin, 2022; Park et al., 2021; Zheng et al., 2018).

In light of this, it is crucial to improve collection systems, traceability throughout the battery's useful life, and standardisation in design; all of these could ensure the effective recycling of batteries. To date, as Lander et al. (2021) argue, the battery recycling process stands out as having substantial economic costs. Scholars have proposed various solutions to overcome this issue, including the provision of policy incentives. Relatedly, Gu et al. (2021) clarify the importance of government subsidies to encourage the refurbishment of batteries and the widespread adoption of second-life batteries. Due to technological advancement, it is desirable to make EVs environmentally and economically competitive in comparison to ICEVs. In this regard, Hoekstra (2019) emphasised that in the near future, emissions stemming from battery manufacturing as well as the production and use of EVs will be lower than those of ICEV technologies.

Fig. 4 shows that with reference to emission data, the break-even point from which the use of the EV is most convenient in relation to the current Italian energy mix is reached at 33,367.07 km. Notably, a similar result was obtained by Pipitone et al. (2021), who evaluated the GWP impact factor as a function of the distance travelled over the useful life of an EV and showed that the environmental advantage in terms of reduced GHG emissions of using the EV can be observed starting from 46,250 km. This confirms the findings of other authors, according to which the positive impact of using an EV on the GHG emissions increase as the number of kilometres travelled increases (Hawkins et al., 2013; Kawamoto et al., 2019). Add to this is the opportunity to reduce the emissions rates of NOx, CO, VOCs, and $PM_{2.5}$ than those of conventional vehicles (Li et al., 2016; Nichols et al., 2015). However, our results contrast with the observations of Costa et al. (2021), who asserted that the manufacturing of ICEVs generates more

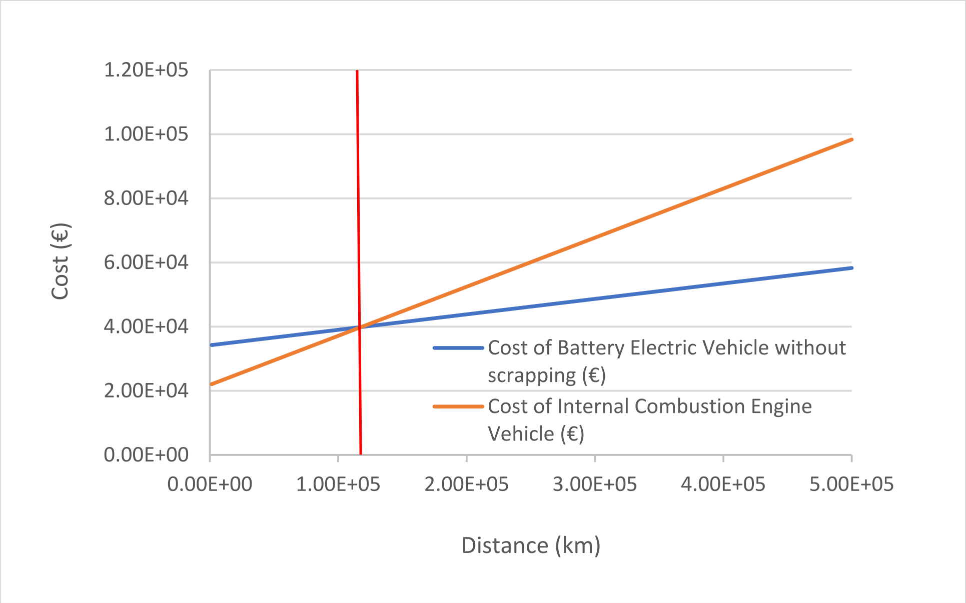


**Fig. 3.** Breakeven point of costs of battery electric vehicle use ($C_{BEV}$) and internal combustion engine vehicle ($C_{ICEV}$) use with incentives (without scrapping).
Source: our elaboration on collected data.

**Table 3**
GHG emissions of battery electric vehicle ($E_{BEV}$) and internal combustion engine vehicle ($E_{ICEV}$) use.

| Variables | BEV | Variables | ICEV |
|---|---|---|---|
| Emission cost of energy mix - $E_{mix}$ ($gCO_{2eq}$/kWh) | 404.60 | | |
| Energy consumption - EC (kWh/km) | 0,19 | Emissions (g/km) | 165,00 |
| Distance covered (km) | 1505 | Distance covered (km) | 1505 |
| Emissions value during the production process - BPE ($gCO_{2eq}$) | 3,440,000 | | |
| **$E_{BEV}$ ($gCO_{2eq}$)** | **3,553,012.40** | **$E_{ICEV}$ ($gCO_{2eq}$)** | **248,325** |

BEV = Battery Electric Vehicle; ICEV = Internal combustion engine vehicle; $E_{BEV}$ = Emissions of Battery Electric Vehicle; $E_{ICEV}$ = Emissions of Internal combustion engine vehicle.

GHGs than EVs since it consists of a higher number of components. Still, authors consider different results to be permissible if the different energy source scenarios are investigated.

The scenario just described, in addition to referring to a real-life environment and specific operating conditions, brings a large number of variables into play and thus does not allow for future developments to be traced. The dynamics of the market for electric cars and state incentives and policies encouraging the adoption of sustainable means and, in particular, the development of new technologies, will significantly influence the dynamics of the sector in the foreseeable future. For instance, in terms of technological innovations, a great effort has already been made in the design of new electrodes, electrolytes and separators to produce high-performance batteries that are also environmentally friendly and at low cost (Yu et al., 2022; Rajaeifar et al., 2022). From this point of view, the reduction of the cost of batteries would lead to the parity of costs between BEVs and vehicles powered by fossil fuels and the success of the BEV sector.

### *4.4. Effect of renewable energy sources on greenhouse gas emissions*

Since the largest share of BEV emissions is a function of the energy mix adopted by a specific country to produce the electricity required to power them (Costa et al., 2021; Nimesh et al., 2020; Frischknecht et al., 2018), the adoption of renewable energy sources could change the current scenario. For instance, Ji et al. (2012) studied the produced emission and found a low performance of EVs compared to ICEVs in China, where 85 % of electricity is produced from fossil sources.

Based on the obtained results, a new scenario was simulated assuming that EVs are powered by an energy mix consisting of 100 % renewable energy. In this specific case, the break-even point is reached at 18,181.82 km (Table 4; Fig. 5). This result confirms what was found in previous studies, according to which the greater the energy derived from renewable sources in the energy mix, the shorter the distance to be travelled by the EVs to compensate for the high impact due to emissions their production (Jeon et al., 2020; Cao et al., 2021; Alp et al., 2022). This highlights that the number of emissions produced by the use of EVs depends on the energy mix of the country where the recharging takes place, as Zheng and Peng (2021) illustrated in their work. For example, in Poland, where the energy economy is based on the use of fossil sources to produce electricity, $CO_2$ emissions due to the use of EVs are comparable to those of ICEVs. On the contrary, since Norway bases its national energy production mainly on renewable sources, this allows it to obtain positive impact on the GHG emissions from the use of EVs starting from 30,000 km when compared to the use of ICEVs (Costa et al., 2021). However, previous assessments and comments did not consider the costs of producing renewable energy, which would inevitably lead to an increase in the price of electricity. Indeed, as Owusu and Asumadu-Sarkodie (2016) emphasised, one of the barriers to the use of renewable energy sources is the cost of technologies, which depend on the policy instruments adopted by each country.

The integration of renewable energy sources for the production of electricity is today, more than ever, a priority, especially to cope with changes in energy scenarios. The ongoing Russian–Ukrainian conflict is causing an unprecedented energy crisis with the relatively large increase in the prices of energy raw materials, causing concern in the electric car sector, for which the power supply is becoming increasingly less sustainable on an economic level.

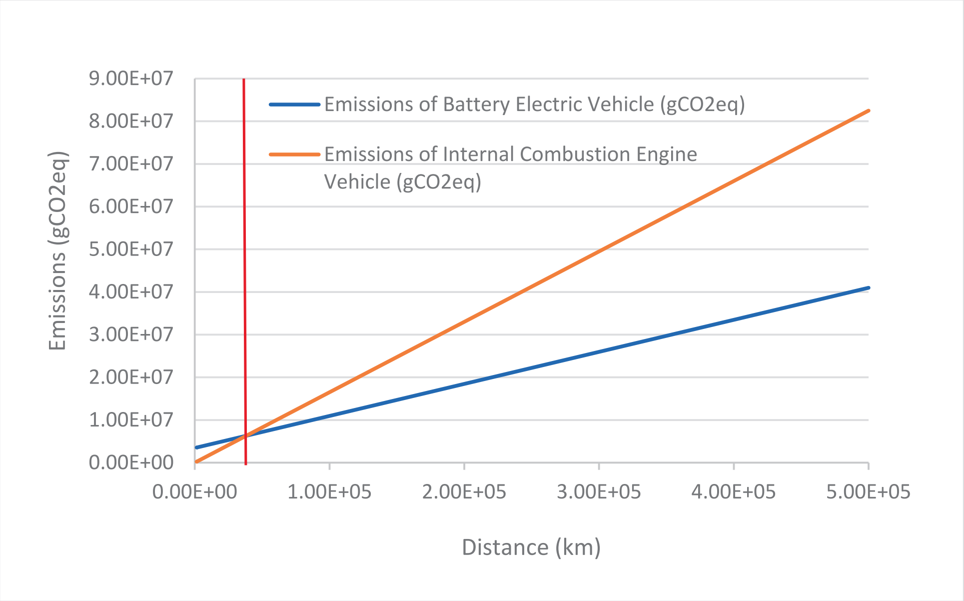


**Fig. 4.** Breakeven point of GHG emissions of battery electric vehicle ($E_{BEV}$) and internal combustion engine vehicle ($E_{ICEV}$) use.
Source: our elaboration on collected data.

**Table 4**
GHG emissions of battery electric vehicle ($E_{BEV}$) and internal combustion engine vehicle ($E_{ICEV}$) with an energy mix based on renewable sources.

| Variables | BEV | Variables | ICEV |
|---|---|---|---|
| Energy consumption - EC (kWh/km) | 0,19 | Emissions (g/km) | 165,00 |
| Distance covered (km) | 1505 | Distance covered (km) | 1505 |
| Emissions value during the production process - ($gCO_{2eq}$) | 3,440,000 | | |
| **$E_{BEV}$ ($gCO_{2eq}$)** | **3,440,279.32** | **$E_{ICEV}$ ($gCO_{2eq}$)** | **248,325** |

BEV = Battery Electric Vehicle; ICEV = Internal combustion engine vehicle; $E_{BEV}$ = Emissions of Battery Electric Vehicle; $E_{ICEV}$ = Emissions of Internal combustion engine vehicle.

## 5. Conclusions

This study compares the economic feasibility of using a BEV compared to an ICEV for the transportation of agri-food products in the SFSC and the impact on the GHG emissions. Results based on empirical data show that the adoption of a commercial EV is not an economically advantageous solution in the short term, mainly due to the initial acquisition cost. Also, from a GHG emission perspective, the findings show that for short distances travelled, BEVs have more impact than ICEVs. However, confirming what was previously found by other authors, our results show that the economic convenience of BEVs compared to ICEVs as well as the positive impact on GHG emissions is reached and grows with an increase in the number of kilometres travelled. On the one hand, the simulated scenarios confirm the importance of the incentive measures for BEV acquisition promoted by governments. On the other hand, they also confirm the influence that an energy mix consisting of renewable energy sources could have on achieving the higher positive impact of adopting EVs on the GHG emissions over a shorter period and distance travelled.

To the best of our knowledge, this is the first study to investigate the GHG emissions and economic convenience of commercial BEV adoption in the food distribution system in a real-life environment. As a case study, the findings here must be read and interpreted with reference to the particular scenario, including the characteristics of the Nissan e-NV200 VAN and corresponding ICEVs, the Italian energy mix, and the characteristics of the road network of the studied area. As such, it is unclear if the findings can be extended to other regions. Changing the type of EV (BEV, PHEV, HEV) and corresponding ICEV (including gas and diesel vehicles), the energy mix, government subsidies, and road and weather conditions might drastically change the output of the study. Although the analysis concerned a particular case study, the proposed methodological approach can be applied in other regions and in similar studies, allowing the expansion of real-life research with important potential insights into the economic and environmental benefits of using BEVs for the transport of foods. Obviously, possible future scenarios are fraught with uncertainties related to market dynamics, new technologies, including battery technologies, and government policies that could significantly change the scenario under consideration.

This study has various theoretical, practical and political implications. First, it enriches the academic literature by providing a comprehensive and comparative analysis of the economic costs and $CO_2$ emissions of both commercial BEVs and ICEVs for last-mile deliveries based on a real-life environment. The critical analysis based on economic and environmental factors allows us to confirm the feasibility of introducing BEVs for the transport of foods in last-mile delivery as compared to commercial vehicles powered by fossil fuels, also highlighting the main barriers to their adoption. Switching to a managerial perspective, results also provide insight and hints to managers in the transport industry by providing relevant information regarding the GHG emissions and economic benefits of BEV adoption in the agri-food supply chain according to a long-term vision. Also, manufacturers and service providers may find these findings useful for optimising the production, use and reuse/recycling of EV batteries in order to reduce costs and improve the level of sustainability of batteries throughout their lifecycle. This requires significant support to R&D and innovation activities for the development of economically and environmentally sustainable production and battery recycling technologies. As emerges from the study, the high economic and environmental costs, in terms

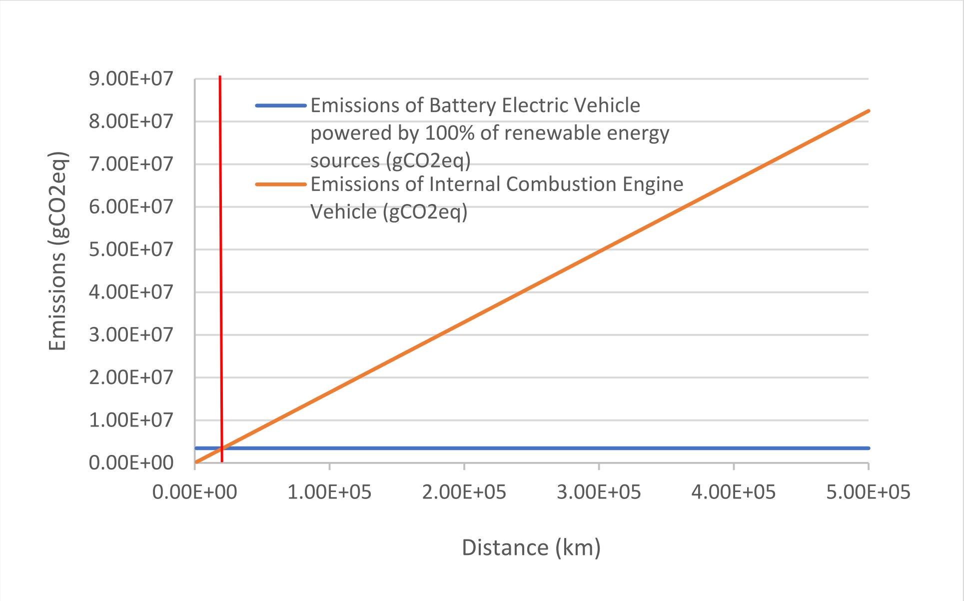


**Fig. 5.** Breakeven point of GHG emissions of battery electric vehicle ($E_{BEV}$) and internal combustion engine vehicle ($E_{ICEV}$).
Source: our elaboration on collected data.

of emissions, especially in the initial stages of use of the BEV, are attributable to the batteries currently used to power them. Political intervention is thus essential to support the development of the sector and promote more sustainable solutions. The results are useful for policy-makers by informing them about the urgency of the field and providing recommendations for further moves to support the spread of electric commercial vehicles. As shown in the present study, it is essential to intervene in the following diverse areas: i) providing incentives for the purchase of EVs; ii) financially supporting projects to obtain lower-cost batteries and give them a second life; iii) promote and support an effective recycling system, through a system of collection and recovery of materials in a circular economy perspective; iv) provide a regulatory framework to facilitate the diffusion of second generation batteries; v) creating an efficient network of recharging infrastructures and adopting political measures aimed at increasing their number; vi) encouraging the construction of recharging points powered by alternative energies to reduce the environmental cost.

Despite its usefulness, the proposed study has certain limitations. For example, it does not consider all the possible variables that could affect the performed evaluations. In particular, the analysis was conducted whilst assuming that the maintenance costs are the same for the two types of vehicles; however, it is known that the maintenance of EVs involves lower costs and that the GHG emissions related to the production phase of these two types of vehicles are the same—although it is also known that in reality, emissions and costs are greater for ICEVs than for EVs due to the large number of components that must be produced. Moreover, this study illustrates the results of comparing only one pair of vehicles in the region of Sicily, Italy. Since vehicles with different classes, price ranges and characteristics differ from each other, similar academic works for other vehicles will deepen the research outputs. Also, an investigation of the disparity between the same vehicles in other regions will provide a more complete picture because landscape and climate affect their functionality.

This study opens the possibilities for future research on the adoption of commercial BEVs in the short food supply chain and, in general, for last-mile food delivery. It would be interesting and useful to use the same methodological approach to compare our findings with those from other real-life experiments in other regions under similar or different technical and political conditions. In addition, it would be interesting to include the effects of recycling or reusing the batteries in the assessment to consider, for example, i) the environmental benefit and economic costs of reusing the lithium through battery recycling in terms of responsible usage of lithium and responsible disposal of batteries, and ii) the environmental benefits of reusing the batteries in other sectors, thereby reducing harmful waste, and the potential financial profit of this for companies.

## Funding

This research was funded under the EnerNETMob project, Cod. 4MED 17_2.3.M123_040, co-funded by the European Regional Development Fund, INTERREG Mediterranean program. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

## 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.

## References

a2aenergia, .. Indice PUN https://www.a2aenergia.eu/area_clienti/tariffe/clienti_non_domestici/energia_elettrica/PUN.html.

ACEA, 2021. Economic and Market Report State of the EU auto industry First three quarters of 2021. https://www.acea.auto/files/Economic_and_Market_Report-First_three_quarters_of_2021.pdf.

ACEA, 2021. Electric vehicles: tax benefits & purchase incentives. In the 27 member states of the European Union (2021). https://www.acea.auto/files/Electric_vehicles-Tax_benefits_purchase_incentives_European_Union_2021.pdf.

Ahuja, J., Dawson, L., Lee, R., 2020. A circular economy for electric vehicle batteries: driving the change. J. Prop. Plan. Environ. Law 12 (3), 235–250. https://doi.org/10.1108/JPPEL-02-2020-0011.

Allahmoradi, E., Mirzamohammadi, S., Naeini, A.B., Maleki, A., Mobayen, S., Skruch, P., 2022. Policy instruments for the improvement of customers'willingness to purchase electric vehicles: a case study in Iran. Energies 15 (12). https://doi.org/10.3390/en15124269.

Allan, A., 2014. The transport policy and planning implications of electric cars for Australian cities. Retrieved from www.eea.europa.eu:Paper Presented at the Australasian Transport Research Forum, ATRF 2012 – Proceedings (last access: 05/08/2022).

Alotaibi, S., Omer, S., Su, Y., 2022. Identification of potential barriers to electric vehicle adoption in oil-producing nations—the case of Saudi Arabia. Electricity 3 (3), 365–395. https://doi.org/10.3390/electricity3030020.

Alp, O., Tan, T., Udenio, M., 2022. Transitioning to sustainable freight transportation by integrating fleet replacement and charging infrastructure decisions. Omega 109. https://doi.org/10.1016/j.omega.2022.102595.

Andersson, Ö., Börjesson, P., 2021. The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: life cycle assessment and policy implications. Appl. Energy 289. https://doi.org/10.1016/j.apenergy.2021.116621.

Azarafshar, R., Vermeulen, W.N., 2020. Electric vehicle incentive policies in Canadian provinces. Energy Econ. 91, 104902.

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., Van Mierlo, J., 2017. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. Energies 10 (9), 1314.

Bieker, G., 2021. A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars. Retrieved fromInternational Council on Clean Transportation (ICCT), Neue Promenade 6, 10178 Berlin, Germany (Last access: 23/12/2022) https://theicct.org/publication/a-global-comparison-of-thelife-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/.

Buberger, J., Kersten, A., Kuder, M., Eckerle, R., Weyh, T., Thiringer, T., 2022. Total CO2-equivalent life-cycle emissions from commercially available passenger cars. Renew. Sust. Energ. Rev. 159. https://doi.org/10.1016/j.rser.2022.112158.

Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., Boloor, M., 2021. Comprehensive Total Cost of Ownership Quantification for Vehicles With Different Size Classes and Powertrains. https://doi.org/10.2172/1780970 United States: N. p., Web.

Cao, J., Chen, X., Qiu, R., Hou, S., 2021. Electric vehicle industry sustainable development with a stakeholder engagement system. Technol. Soc. 67, 101771. https://doi.org/10.1016/j.techsoc.2021.101771.

Chakraborty, P., Parker, R., Hoque, T., Cruz, J., Du, L., Wang, S., Bhunia, W., 2022. Addressing the range anxiety of battery electric vehicles with charging en route. Sci. Rep. 12, 5588. https://doi.org/10.1038/s41598-022-08942-2.

Chen, B., Liu, M., Cao, S., Chen, G., Guo, X., Wang, X., 2022. Regeneration and performance of LiFePO4 with Li2CO3 and FePO4 as raw materials recovered from spent LiFePO4 batteries. Mater. Chem. Phys. 279. https://doi.org/10.1016/j.matchemphys.2022.125750.

Chen, K., Ren, C., Gu, R., Zhang, P., 2019. Exploring purchase intentions of new energy vehicles: from the perspective of frugality and the concept of “mianzi”. J. Clean. Prod. 230, 700–708.

Chen, W., Jafarzadeh, S., Thakur, M., Ólafsdóttir, G., Mehta, S., Bogason, S., Holden, N.M., 2021. Environmental impacts of animal-based food supply chains with market characteristics. Sci. Total Environ. 783. https://doi.org/10.1016/j.scitotenv.2021.147077.

Chiffoleau, Y., Dourian, T., 2020. Sustainable food supply chains: is shortening the answer? A literature review for a research and innovation agenda. Sustainability 12 (23), 9831.

Coley, D., Howard, M., Winter, M., 2011. Food miles: timefor a re-think? Br. Food J. 113 (7), 919–934.

Costa, C.M., Barbosa, J.C., Castro, H., Gonçalves, R., Lanceros-Méndez, S., 2021. Electric vehicles: to what extent are environmentally friendly and cost effective?–Comparative study by european countries. Renew. Sust. Energ. Rev. 151, 111548.

Crabtree, G., Kocs, E., Tillman, B., 2017. Where is transportation going? Europhys. News 48 (3), 21–25.

Cusenza, M.A., Guarino, F., Longo, S., Mistretta, M., Cellura, M., 2019. Reuse of electric vehicle batteries in buildings: an integrated load match analysis and life cycle assessment approach. Energy Build. 186, 339–354. https://doi.org/10.1016/j.enbuild.2019.01.032.

de Mello Bandeira, R.A., Goes, G.V., Schmitz Gonçalves, D.N., D'Agosto, M.de A., Oliveira, C.M.de, 2019. Electric vehicles in the last mile of urban freight transportation: a sustainability assessment of postal deliveries in Rio de Janeiro-Brazil. Transp. Res. Part D: Transp. Environ. 67, 491–502. https://doi.org/10.1016/j.trd.2018.12.017.

Dumortier, J., Siddiki, S., Carley, S., Cisney, J., Krause, R.M., Lane, B.W., Rupp, J.A., Graham, J.D., 2015. Effects of providing total cost of ownership information on consumers'intent to purchase a hybrid or plug-in electric vehicle. Transp. Res. A Policy Pract. 72, 71–86. https://doi.org/10.1016/j.tra.2014.12.005.

Dunn, J.B., Gaines, L., Kelly, J.C., James, C., Gallagher, K.G., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy Environ. Sci. 8 (1), 158–168. https://doi.org/10.1039/C4EE03029J.

EAFO, 2022. Total market share of newly registered passenger electric vehicles in the European Union between 2015 and 2021. Retrieved from www.statista.com https://www.statista.com/statistics/625010/electric-vehicle-market-share-in-eu-annual/ (Last access: 05/08/2022).

Ebrie, A.S., Kim, Y.J., 2022. Investigating market diffusion of electric vehicles with experimental design of agent-based modeling simulation. Systems 10 (2). https://doi.org/10.3390/systems10020028.

EEA, 2020. Greenhouse gas emissions from transport in Europe. Retrieved from www.eea.europa.eu: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport (last access: 05/08/2022).

Elangovan, R., Kanwhen, O., Dong, Z., Mohamed, A., Rojas-Cessa, R., 2021. Comparative analysis of energy use and greenhouse gas emission of diesel and electric trucks for food distribution in Gowanus district of New York city. Front. Big Data 4. https://doi.org/10.3389/fdata.2021.693820.

Fernández-Ríos, A., Santos, G., Pinedo, J., Santos, E., Ruiz-Salmón, I., Laso, J., Lyne, A., Ortiz, I., Irabien, Á., Aldaco, R., Margallo, M., 2022. Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach. Sci. Total Environ. 820. https://doi.org/10.1016/j.scitotenv.2022.153189.

Fevang, E., Figenbaum, E., Fridstrøm, L., Halse, A.H., Hauge, K.E., Johansen, B.G., Raaum, O., 2021. Who goes electric? The anatomy of electric car ownership in Norway. Transp. Res. Part D: Transp. Environ. 92, 102727.

Few, S., Schmidt, O., Offer, G.J., Brandon, N., Nelson, J., Gambhir, A., 2018. Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: an analysis informed by expert elicitations. Energy Policy 114, 578–590.

Forssell, S., Lankoski, L., 2015. The sustainability promise of alternative food networks: an examination through “alternative” characteristics. Agric. Hum. Values 32 (1), 63–75.

Franzò, S., Nasca, A., 2021. The environmental impact of electric vehicles: a novel life cycle-based evaluation framework and its applications to multi-country scenarios. J. Clean. Prod. 315, 128005. https://doi.org/10.1016/j.jclepro.2021.128005.

Frischknecht, R., Messmer, A., Stolz, P., 2018. Aktualisierung Umweltaspekte von Elektroautos. 107.

Galati, A., Giacomarra, M., Concialdi, P., Crescimanno, M., 2021. Exploring the feasibility of introducing electric freight vehicles in the short food supply chain: a multi-stakeholder approach. Case Stud. Transp. Policy 9 (2), 950–957.

Galati, A., Migliore, G., Thrassou, A., Schifani, G., Rizzo, G., Adamashvili, N., Crescimanno, M., 2022. Consumers'willingness to pay for agri-food products delivered with electric vehicles in the short supply chains. FIIB Bus. Rev. https://doi.org/10.1177/23197145221112743.

Gambhir, A., Lawrence, K.C., Tong, D., Martinez-Botas, R., 2015. Reducing China's road transport sector CO2 emissions to 2050: technologies, costs and decomposition analysis. Appl. Energy 157, 905–917.

Gómez Vilchez, J.J., Smyth, A., Kelleher, L., Lu, H., Rohr, C., Harrison, G., Thiel, C., 2019. Electric car purchase price as a factor determining consumers' choice and their views on incentives in Europe. Sustainability 11 (22), 6357. https://doi.org/10.3390/su11226357.

GOV.UK, 2020. The Ten Point Plan for a Green Industrial Revolution. Retrieved from www.gov.uk: (Last access 05/08/2022) https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title.

Gu, X., Zhou, L., Huang, H., Shi, X., Ieromonachou, P., 2021. Electric vehicle battery secondary use under government subsidy: a closed-loop supply chain perspective. Int. J. Prod. Econ. 234. https://doi.org/10.1016/j.ijpe.2021.108035.

Guo, Y., Kelly, J.A., Clinch, J.P., 2022. Variability in total cost of vehicle ownership across vehicle and user profiles. Commun. Transp. Res. 2. https://doi.org/10.1016/j.commtr.2022.100071.

Guzović, Z., Duic, N., Piacentino, A., Markovska, N., Mathiesen, B.V., Lund, H., 2022. Recent advances in methods, policies and technologies at sustainable energy systems development. Energy 245. https://doi.org/10.1016/j.energy.2022.123276.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 17 (1), 53–64.

Hoekstra, A., 2019. The underestimated potential of battery electric vehicles to reduce emissions. Joule 3 (6), 1412–1414.

ICCT, 2022. Preparing Italy's charging infrastructure for rapid vehicle electrification. Retrieved from www.statista.com https://theicct.org/wp-content/uploads/2022/03/Italy-working-paper-16-A4-v3.pdf (Last access: 05/08/2022).

ISPRA, 2021. Indicatori di efficienza e decarbonizzazione del sistema energetico nazionale e del settore elettrico. https://www.isprambiente.gov.it/files2021/pubblicazioni/rapporti/r343-2021.pdf.

Jeon, W., Cho, S., Lee, S., 2020. Estimating the impact of electric vehicle demand response programs in a grid with varying levels of renewable energy sources: time-of-use tariff versus smart charging. Energies 13 (17), 4365. https://doi.org/10.3390/en13174365.

Ji, S., Cherry, C.R., Bechle, J.M., Wu, Y., Marshall, J.D., 2012. Electric vehicles in China: emissions and health impacts. Environ. Sci. Technol. 46 (4), 2018–2024.

Jiang, Y., Jiang, J., Zhang, C., Zhang, W., Gao, Y., Guo, Q., 2017. Recognition of battery aging variations for LiFePO4 batteries in 2nd use applications combining incremental capacity analysis and statistical approaches. J. Power Sources 360, 180–188. https://doi.org/10.1016/j.jpowsour.2017.06.007.

Kawamoto, R., Mochizuki, H., Moriguchi, Y., Nakano, T., Motohashi, M., Sakai, Y., Inaba, A., 2019. Estimation of CO2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA. Sustainability 11 (9), 2690.

Kiss, K., Ruszkai, C., Takács-György, K., 2019. Examination of short supply chains based on circular economy and sustainability aspects. Resources 8 (4), 161.

Kotak, Y., Fernández, C.M., Casals, L.C., Kotak, B.S., Koch, D., Geisbauer, C., Trilla, L., Gómez-Núñez, A., Schweiger, H.G., 2021. End of electric vehicle batteries: reuse vs. recycle. Energies 14 (8). https://doi.org/10.3390/en14082217.

Lander, L., Cleaver, T., Rajaeifar, M.A., Nguyen-Tien, V., Elliott, R.J.R., Heidrich, O., Kendrick, E., Edge, J.S., Offer, G., 2021. Financial viability of electric vehicle lithium-ion battery recycling. IScience 24 (7). https://doi.org/10.1016/j.isci.2021.102787.

Li, N., Chen, J.P., Tsai, I.C., He, Q., Chi, S.Y., Lin, Y.C., Fu, T.M., 2016. Potential impacts of electric vehicles on air quality in Taiwan. Sci. Total Environ. 566, 919–928.

Liu, X., Sun, X., Zheng, H., Huang, D., 2021b. Do policy incentives drive electric vehicle adoption? Evidence from China. Transp. Res. A Policy Pract. 150, 49–62.

Liu, Z., Song, J., Kubal, J., Susarla, N., Knehr, K.W., Islam, E., Nelson, P., Ahmed, S., 2021a. Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles. Energy Policy 158, 112564. https://doi.org/10.1016/j.enpol.2021.112564.

Malak-Rawlikowska, A., Majewski, E., Wąs, A., Borgen, S.O., Csillag, P., Donati, M., Freeman, R., Hoang, V., Lecoeur, J.L., Mancini, L.C., Nguyen, A., Saidi, M., Tocco, B., Torok, A., Veneziani, M., Vitterso, G., Wavresky, P., 2019. Measuring the economic, environmental, and socialsustainability of short food supply chains. Sustainability 11 (15), 4004.

Mezzicommerciali, .. FIAT DOBLÒ 1.4 T-JET PC-TN CARGO EASY http://mezzicommerciali.it/listino-auto/fiat-doblo-1-4-t-jet-pc-tn-cargo-easy-2/ (last access 05/08/2022).

Mirza, M., Abdulaziz, R., Maskell, W.C., Tan, C., Shearing, P.R., Brett, D.J., 2021. Recovery of cobalt from lithium-ion batteries using fluidised cathode molten salt electrolysis. Electrochim. Acta 391, 138846.

Napoli, G., Polimeni, A., Micari, S., Dispenza, G., Antonucci, V., Andaloro, L., 2021. Freight distribution with electric vehicles: a case study in Sicily. Delivery van development. Transp. Eng. 3, 100048. https://doi.org/10.1016/j.treng.2021.100048.

Neubauer, J., Pesaran, A., 2011. The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications. J. Power Sources 196 (23), 10351–10358. https://doi.org/10.1016/j.jpowsour.2011.06.053.

Newman, D., Wells, P., Donovan, C., Nieuwenhuis, P., Davies, H., 2014. Urban, sub-urban or rural: where is the best place for electric vehicles? Int. J. Automot. Technol. Manag. 14 (3–4), 306–323. https://doi.org/10.1504/IJATM.2014.065295.

Nichols, B.G., Kockelman, K.M., Reiter, M., 2015. Air quality impacts of electric vehicle adoption in Texas. Transp. Res. Part D: Transp. Environ. 34, 208–218.

Nimesh, V., Sharma, D., Reddy, V.M., Goswami, A.K., 2020. Implication viability assessment of shift to electric vehicles for present power generation scenario of India. Energy 195, 116976.

OECD, 2019. Prepared by the OECD as input for the 2019 G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth. Retrieved from www.oecd.org: https://www.oecd.org/g20/summits/osaka/OECD-G20-Paper-Innovation-and-Green-Transition.pdf (last access 26/02/2022).

Ouyang, D., Zhou, S., Ou, X., 2021. The total cost of electric vehicle ownership: a consumer-oriented study of China's post-subsidy era. Energy Policy 149. https://doi.org/10.1016/j.enpol.2020.112023.

Owusu, P.A., Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Eng. 3 (1), 1167990.

Pagliaro, M., Meneguzzo, F., 2019. Lithium battery reusing and recycling: a circular economy insight. Heliyon 5 (6). https://doi.org/10.1016/j.heliyon.2019.e01866.

Park, K., Yu, J., Coyle, J., Dai, Q., Frisco, S., Zhou, M., Burrell, A., 2021. Direct cathode recycling of end-of-life Li-ion batteries enabled by redox mediation. ACS Sustain. Chem. Eng. 9 (24), 8214–8221. https://doi.org/10.1021/acssuschemeng.1c02133.

Peiseler, L., Cabrera Serrenho, A., 2022. How can current german and EU policies be improved to enhance the reduction of CO2 emissions of road transport? Revising policies on electric vehicles informed by stakeholder and technical assessments. Energy Policy 168. https://doi.org/10.1016/j.enpol.2022.113124.

Petrauskienė, K., Dvarioniene, J., Kaveckis, G., Kliaugaite, D., Chenadec, J., Hehn, L., Pérez, B., Bordi, C., Scavino, G., Vignoli, A., Erman, M., 2020. Situation analysis of policies for electric mobility development: experience from five European regions. Sustainability 12 (7). https://doi.org/10.3390/su12072935.

Petrauskienė, K., Galinis, A., Kliaugaitė, D., Dvarionienė, J., 2021. Comparative environmental life cycle and cost assessment of electric, hybrid, and conventional vehicles in Lithuania. Sustainability 13 (2), 957.

Pipitone, E., Caltabellotta, S., Occhipinti, L., 2021. A life cycle environmental impact comparison between traditional, hybrid, and electric vehicles in the European context. Sustainability 13 (19), 10992.

Rajaeifar, M.A., Ghadimi, P., Raugei, M., Wu, Y., Heidrich, O., 2022. Challenges and recent developments in supply and value chains of electric vehicle batteries: a sustainability perspective. Resour. Conserv. Recycl. 180, 106144.

Raugei, M., Winfield, P., 2019. Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles. J. Clean. Prod. 213, 926–932. https://doi.org/10.1016/j.jclepro.2018.12.237.

Richa, K., Babbitt, C.W., Gaustad, G., 2017. Eco-efficiency analysis of a lithium-ion battery waste hierarchy inspired by circular economy. J. Ind. Ecol. 21 (3), 715–730. https://doi.org/10.1111/jiec.12607.

Rohe, S., Mattes, J., 2022. What about the regional level? Regional configurations of technological innovation systems. Geoforum 129, 60–73. https://doi.org/10.1016/j.geoforum.2022.01.007.

Rosenberger, K., Tapia, R., Friedrich, H., Flämig, H., 2022. Estimating the potential of electric mobility in commercial transport considering the availability of charging infrastructure – a behavioural model analysis for the city of Hamburg. Res. Transp. Bus. Manag. 43. https://doi.org/10.1016/j.rtbm.2021.100772.

Sen, B., Onat, N.C., Kucukvar, M., Tatari, O., 2019. Material footprint of electric vehicles: a multiregional life cycle assessment. J. Clean. Prod. 209, 1033–1043.

Siragusa, C., Tumino, A., Mangiaracina, R., Perego, A., 2020. Electric vehicles performing last-mile delivery in B2C e-commerce: an economic and environmental assessment. Int. J. Sustain. Transp. 16 (1), 22–33.

Sommer, S., Vance, C., 2021. Do more chargers mean more electric cars? Environ. Res. Lett. 16 (6). https://doi.org/10.1088/1748-9326/ac05f0.

Soysal, M., Bloemhof-Ruwaard, J.M., Bektaş, T., 2015. The time-dependent two-echelon capacitated vehicle routing problem with environmental considerations. Int. J. Prod. Econ. 164, 366–378.

Thiel, C., Tsakalidis, A., Jäger-Waldau, A., 2020. Will electric vehicles be killed (again) or are they the next mobility killer app? Energies 13 (7). https://doi.org/10.3390/en13071828.

Tsakalidis, A., Julea, A., Thiel, C., 2019. The role of infrastructure for electric passenger car uptake in europe. Energies 12 (22). https://doi.org/10.3390/en12224348.

United Nations, 2015. The Sustainable Development Agenda. Retrieved from www/un.org: (Last access 01/03/2022) https://www.un.org/sustainabledevelopment/development-agenda/.

Wang, K., Hu, T., Shi, P., Min, Y., Wu, J., Xu, Q., 2022. Efficient recovery of value metals from spent lithium-ion batteries by combining deep eutectic solvents and coextraction. ACS Sustain. Chem. Eng. 10 (3), 1149–1159. https://doi.org/10.1021/acssuschemeng.1c06381.

Wang, Y., An, N., Wen, L., Wang, L., Jiang, X., Hou, F., Yin, Y., Liang, J., 2020. Recent progress on the recycling technology of Li-ion batteries. J. Energy Chem. 55, 391–419. https://doi.org/10.1016/j.jechem.2020.05.008.

Wesseh Jr., P.K., Lin, B., 2022. A time-of-use pricing model of the electricity market considering system flexibility. Energy Rep. 8, 1457–1470. https://doi.org/10.1016/j.egyr.2021.12.027.

White, L.V., Carrel, A.L., Shi, W., Sintov, N.D., 2022. Why are charging stations associated with electric vehicle adoption? Untangling effects in three United States metropolitan areas. Energy Res. Soc. Sci. 89. https://doi.org/10.1016/j.erss.2022.102663.

Wilken, D., Oswald, M., Draheim, P., Pade, C., Brand, U., Vogt, T., 2020. Multidimensional assessment of passenger cars: comparison of electric vehicles with internal combustion engine vehicles. Paper Presented at the Procedia CIRP. 90, pp. 291–296. https://doi.org/10.1016/j.procir.2020.01.101.

Yanamandra, K., Pinisetty, D., Daoud, A., Gupta, N., 2022. Recycling of Li-ion and lead acid batteries: a review. J. Indian Inst. Sci. https://doi.org/10.1007/s41745-021-00269-7.

Yang, F., Xie, Y., Deng, Y., Yuan, C., 2021. Temporal environmental and economic performance of electric vehicle and conventional vehicle: a comparative study on their US operations. Resour. Conserv. Recycl. 169, 105311.

Yu, X., Li, W., Gupta, V., Gao, H., Tran, D., Sarwar, S., Chen, Z., 2022. Current challenges in efficient lithium-ion batteries'recycling: a perspective. Glob. Chall. 2200099.

Zelazna, A., Bojar, M., Bojar, E., 2020. Corporate social responsibility towards the environment in Lublin Region, Poland: a comparative study of 2009 and 2019. Sustainability 12, 4463. https://doi.org/10.3390/su12114463.

Zhao, S., Quan, J., Wang, T., Song, D., Huang, J., He, W., Li, G., 2022. Unveiling the recycling characteristics and trends of spent lithium-ion battery: a scientometric study. Environ. Sci. Pollut. Res. 29 (7), 9448–9461. https://doi.org/10.1007/s11356-021-17814-7.

Zheng, G., Peng, Z., 2021. Life cycle assessment (LCA) of BEV's environmental benefits for meeting the challenge of ICExit (internal combustion engine exit). Energy Rep. 7, 1203–1216. https://doi.org/10.1016/j.egyr.2021.02.039.

Zheng, X., Zhu, Z., Lin, X., Zhang, Y., He, Y., Cao, H., Sun, Z., 2018. A mini-review on metal recycling from spent lithium ion batteries. Engineering 4 (3), 361–370. https://doi.org/10.1016/j.eng.2018.05.018.