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A comparative evaluation of CO_2 emissions between internal combustion and electric vehicles in small isolated electrical power systems - Case study of the Canary Islands

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ABSTRACT

One of the goals of the European Union (EU) is to reduce greenhouse gas (GHG) emissions. To this end, internal combustion vehicles (ICVs) will be progressively replaced with battery electric vehicles (BEVs) over the course of a transition period that is expected to last until 2035. While GHG reductions have been extensively evaluated for continental territories, this is not the case for territories with isolated electrical power systems, as in some islands of the EU. Emissions generated in these territories are considerably higher than in continental systems because their electricity generation mixes commonly have more polluting fuels. In this study, a calculation is performed of the CO_2 emissions that result from the charging of a reference BEV in the different isolated electrical power systems of the Canary Islands (Spain). The results are then compared with the CO_2 emissions of ICVs. Results show that the Canary electrical power systems that consume the least energy are the most contaminating and that charging a BEV entails higher CO_2 emissions than those generated by an ICV. In addition, no significant differences were observed between BEV- and ICV-related CO_2 emissions in the electrical power systems of the islands with higher energy consumption. A small decrease in CO_2 emissions was only observed in isolated insular systems with energy storage systems and high levels of renewable penetration.

1. Introduction

Transport is responsible for over 30% of CO_2 emissions in the European Union (EU), 72% of which come from road transport (Tsiakmakis et al., 2017). The EU has set itself the goal of reducing the average CO_2 emissions of the European fleet of new vehicles in accordance with the objectives of the 2015 Paris Agreement (Delbeke et al., 2019). The transition to battery electric vehicles (BEVs) is being promoted to ensure private transport generates lower levels of emissions (Rahman et al., 2021). A new law came into force on 1 January 2021, limiting the mean emission value of all newly registered vehicles to 95 g/km de CO_2 (EC, 2019). This value will be further reduced in 2025 by 15% (to 81 g/km), and in 2030 by 37.5% (59 g/km), compared to the 2021 values (EUCO, 2019).

The environmental impact of the emission of greenhouse gases (GHGs) of different types of vehicle (combustion, hybrid and electric) needs to be subjected to full life cycle analyses (Burchart-Korol et al., 2020). Such analyses need to consider the GHG emissions during the different stages of the vehicle: manufacturing, fuel acquirement (extraction, refining and transportation), actual vehicle operation, and the decommissioning process which constitutes the last stage of its life cycle (Basque EcoDesign Center, 2019; IPCC, 2015).

While BEVs do not emit CO_2 on the road, they do indirectly emit CO_2. Around 51% of these emissions takes place in the manufacturing stage (mostly of the batteries), with the remaining 49% attributable to their actual operation (as the result of emissions in the production of electricity with the generation mix in the EU) (Ghandi and Paltsev, 2020; Xiao et al., 2021). The fuel consumption of a medium-sized petrol ICV on the road generates a mean emission of 143 g/km of CO_2, while a similar-sized BEV emits between 47% and 58% less during the charging process based on the current EU electricity generation mix (EEA, 2018). Diesel vehicles emit less CO_2 than petrol ones (IDAE, 2020a). The lower

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GHG emission of electric vehicles justifies their promotion as an energy policy and an R + D + i priority of the member states of the EU. In addition, BEVs that can be plugged into the electrical system -whether these be fully electric or so-called plug-in hybrid electric vehicles (PHEVs)- will facilitate a greater penetration of renewables in the electric sector as they act as a means of surplus energy storage (Clairand et al., 2018; Díaz et al., 2015; Šare et al., 2015). To accelerate the transition to BEVs, the European Commission will suppress the sale of vehicles that directly emit GHGs, both combustion and hybrid, from 2035 onwards (EC, 2019). Other contributory factors in the transition to BEVs include, for example, their greater efficiency, noise reduction and lower maintenance requirements (Duarte Souza Alvarenga Santos et al., 2021). However, various arguments have been put forward against the promotion of BEVs. These include the different battery charging systems and the battery storage technology, with problems of safety, cost, number of charge/discharge cycles and operating temperature ranges, among others (Krause et al., 2016; Schmidt, 2021).

After 1973 and the first oil crisis the decrease in ICV fuel consumption was principally driven by oil shortages and the consequent price increase. Today, the driving force behind reduced ICV consumption is environmental concerns. The New European Driving Cycle (NEDC) was introduced in 1992 and has since been replaced by the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) protocol. Both share the same objectives: the measurement of regulated pollutants like CO_2, hydrocarbons, NOx and particulates, and the measurement of consumption expressed in CO_2 throughout the life cycle of a vehicle. The new WLTP measuring system entered into force in 2021 and aims to measure consumption in conditions as similar as possible to real-life driving. The result has been an increase in emission values compared to those reported by manufacturers under the previous system. The WLTP measurement cycle combines 52% of urban tests with 48% of interurban tests (EC, 2019). The increase in emissions when measured on the basis of the WLTP protocol as opposed to the NEDC is around 30% for ICVs and 21% for BEVs (Tsiakmakis et al., 2017).

The studies undertaken on ICV and BEV emissions have principally been based on a continental geographic situation (Basque EcoDesign Center, 2019; Orsi et al., 2016; Ou et al., 2012; Rangaraju et al., 2015). In an analysis of the BEV transition in Europe which determined the countries with the lowest GHG emissions, it was found that the ICV to BEV transition in France and Norway had a greater impact on GHG emissions reduction than in countries like Germany and the UK (Canals Casals et al., 2016). The EU recently published a report that included the environmental impacts of conventional vehicles and vehicles in the European territory using alternative fuels through life cycle assessments (Hill et al., 2020). The CO_2 emissions of the different EU countries were evaluated taking into consideration each one's electrical energy mix. Special attention has to be paid to the environmental repercussions of the ICV-BEV transition in territories with small and isolated electrical power systems given their different characteristics to those of continental systems. One study which evaluated emissions differences compared to continental territories was undertaken in South Korea, a zone that is highly dependent on oil for electrical power generation (Choi and Song, 2018). Islands represent 6.3% of the emerged surface area of the planet and about 10% of its population live on them. Islands with an isolated electrical power system have a set of specific characteristics that need to be taken into consideration (Kaldellis, 2020). (Wong et al., 2010) studied the life cycles of ICVs and BEVs in Singapore. They established a series of guidelines for the government to make BEVs more economically competitive. However, no data was shown of the electrical energy mix (McKenzie, 2021). studied the impact of the transition of ICVs to BEVs considering an emissions-free electrical energy mix in the year 2050 on the island of Oahu, Hawaii. The work assessed the tank-to-wheel efficiency of ICVs and BEVs (Gay et al., 2018). analysed the different applications in insular systems of BEVs on the island of Barbados. According to the authors, from an emissions perspective BEVs begin to make sense when renewable generation exceeds 50% of total generation and BEVs are incorporated as active elements of the grid (Pina et al., 2014). analysed the benefits of the introduction of BEVs in a small energy system in Floresis (Azores, Portugal). BEVs are incorporated in the grid as an active element to ensure recharging with renewable energy (Suski et al., 2021). evaluated a scenario of 30% BEVs in 2030 in the Maldives. They concluded that BEV charging should be conducted in a coordinated manner in order to reduce energy generation capacity requirements and minimize GHG emissions (Strobel et al., 2021). reported how BEVs offered a wide range of opportunities for greater renewable energy integration and transport-related emissions reductions. The study, carried out in Porto Santo (Madeira), concluded that enhanced charging flexibility for BEVs could increase the share of renewable energy penetration (Meinrenken et al., 2020). used GPS data of vehicle journeys to determine the most significant parameters in the minimization of GHG emissions. The study, carried out in Michigan (US), defined vehicle type, charging technology and driver age. Most of the above studies are based on future scenarios (2030–2050) where it is considered that renewable energies will be predominant in comparison with fuel-based energy sources.

The present study uses as reference the Canary Islands (Spain), an island territory with an isolated electrical power system, a high population density and a high dependency on fossil fuels for electricity production. The population of the islands in 2019 was 2,237,310, with a mean density of 301 inhabitants per km^2 (ISTAC, 2020). Table 1 shows the data relating to surface area, population and installed conventional renewable electrical power on each of the islands that comprise the Canary archipelago. Fig. 1 shows the geographical position of the archipelago and the name of each island. It should be noted that only CO_2 emissions were evaluated since GHG emissions of the power systems in the Canary Islands are mainly CO_2 (99.7%).

The aim of this work is to analyse the CO_2 emissions generated over the entire life cycle of a reference vehicle of three technologies (petrol ICV, diesel ICV and BEV), operating in the different isolated electrical power systems of the Canary archipelago. CO_2 emissions generated as the result of the transport of fuel from the continental territory to the islands are included in the analysis. Firstly, the CO_2 emissions generated by the reference BEV per km are calculated, and these values are then compared with the CO_2 emissions generated by the reference ICVs.

2. Methodology

EU planning with respect to private vehicle use is aimed at replacing ICVs with BEVs. Below, a definition is provided of the reference vehicle and an evaluation is made of CO_2 emissions over the life cycle of three technologies (petrol ICV, diesel ICV and BEV) (Basque EcoDesign Center, 2019; IDAE, 2020b). For the purposes of the present study a small-sized vehicle is chosen, with the results extrapolatable to larger-sized ones. The environmental impact depends on vehicle size (with the same technology) as larger vehicles are heavier and require a larger amount of raw materials for their manufacture, as well as higher

Table 1
Physical, demographic and energy data of the Canary Islands for 2019. Adapted from (Canary Islands government, 2020; ISTAC, 2020).

Island	Surface area (km^2)	Population (inhabitants)	Installed conventional electrical power (MW)	Installed renewable electrical power (MW)
Gran Canaria	1560.1	870,595	999.18	199.9
Tenerife	2034.3	966,354	1046.5	314.53
Lanzarote	845.9	1545,30	232.26	32.41
Fuerteventura	1659.7	126,227	187.02	41.42
La Palma	708.3	85,840	105.34	12.18
La Gomera	369.7	22,426	21.17	0.37
El Hierro	268.7	11,338	14.91	22.83
TOTAL	7446.7	2,237,310	2606.38	623.64

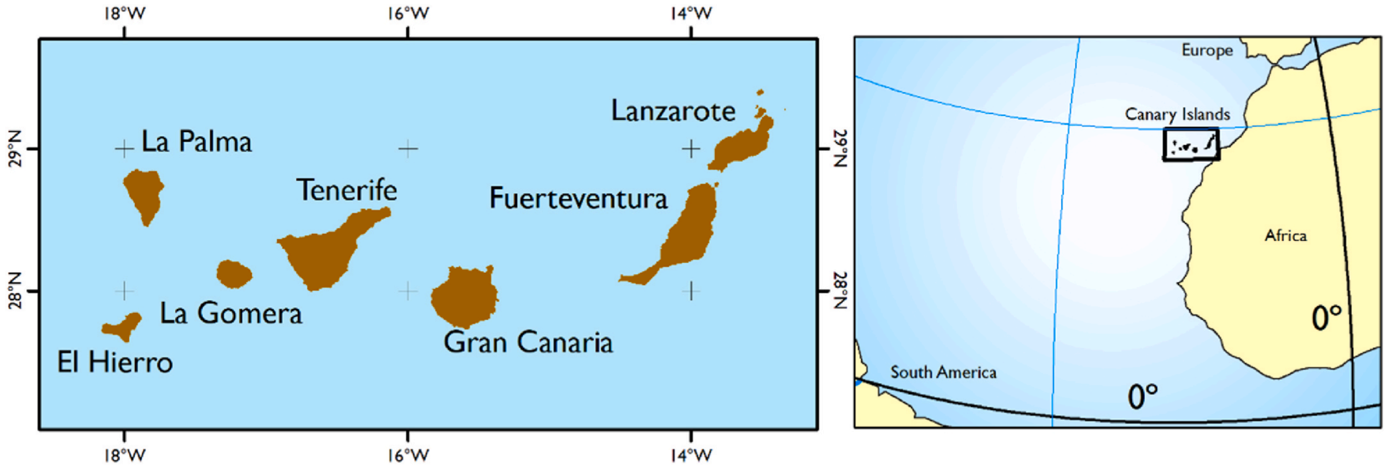

Fig. 1. Geographical position and names of the islands in the Canary archipelago.

quantities of fuel and/or electricity (Hill et al., 2020). The principal characteristics of the reference vehicle are as follows: (1) 15,000 km travelled each year; and (2) life cycle of 10 years. Vehicle size is related to its weight and, for this study, a small-sized vehicle with a weight of 1200 kg is considered. It should be noted that, in the case of BEVs, weight is a factor that could potentially increase the vehicle's autonomy, with a larger size and weight enabling the storage of more batteries, a higher stored charge and, hence, greater autonomy. Table 2 shows the fuel consumption for the three vehicle types (petrol, diesel and electric) (Basque EcoDesign Center, 2019). It should be noted that fuel consumption depends on many factors such as distances travelled, top speeds, etc. To simplify this issue, WLTP values were taken. It should also be noted that these are average value for Spain. Other similar values for Europe and considering small vehicles can be found in the literature (Hoekstra (2019).

The indications valid for the continental territory were taken from two sources ((Basque EcoDesign Center, 2019; EC, 2015)) and used to calculate emissions in the maintenance and decommissioning stages. The environmental impact assessment methodology was based on standards UNE-EN ISO 14040:2006 and UNE-EN ISO 14044:2006. Taking as reference the aforementioned reports and methodologies, Table 3 shows the CO_2 emission values of the reference vehicle for the three technologies considered (petrol ICV, diesel ICV and BEV). The values provided in Table 3 for the BEV are close to others calculated by other authors (Hoekstra, 2019; Hoekstra et al., 2017).

Table 3 also shows the estimated total gCO_2/km emissions for the three vehicle types. The BEV values are only valid for the Spanish mainland territory, with an electricity generation mix that emitted in 2019 an average 241 gCO_2/kWh (REE, 2020a). The mainland electricity generation mix in 2019 was as follows: photovoltaic (4.96%), wind (18.74%), hydropower (13.11%), cogeneration (10.09%), natural gas (13.55%), other fossil fuels (16.35%), nuclear (20.67%) and other renewables (2.53%). Some of the data shown in Table 3 were directly used for calculation of emissions in the Canary archipelago, with only the fuel transport data needing to be adapted. The data of the third column (Fuel extraction, refining and transport) in Table 3 were obtained considering a transport distance of 500 km for fuel delivery (for the Spanish continental territory - from refinery to gas station). However, the actual distances between the refineries and the Canary territory are considerably higher. According with (Prussi et al., 2020) emissions of 2.04 gCO_2/MJ (MJ of petrol or diesel) for a transport distance of up to 2000 km (average distance from a refinery in the Spanish continental territory to the Canary islands), the total fuel transport emissions of refined fuel to the islands amounts to 71 gCO_2/l for gasoline and 78.85 gCO_2/l for gasoil. These data were used in the calculation of the CO_2 emissions of BEVs due to fuel extraction, refining and transport (third column in Table 3). To determine the CO_2 emissions due to fuel extraction, refining and transport it was also necessary to calculate the emissions of the islands' power plants. The importance of the values of these emissions in the territory under study cannot be underestimated as they are fundamental for the subsequent calculations that are made, unlike the situation for BEVs in the Spanish mainland territory.

An analysis of the environmental impact over the course of the life cycle comprises various steps. Firstly, the CO_2 generated during the vehicle manufacturing stage are evaluated, and secondly those generated in the fuel extraction, refining and transport stage. The production, transport and refining of crude oils into fuels like gasoline or diesel represent ~15–40% of the life cycle CO_2 emissions (Masnadi et al., 2018). In the third step, an evaluation is made of the CO_2 generated in the petrol or diesel combustion stage. Finally, it is necessary to evaluate the CO_2 emitted as the result of parts and decommissioning. It is during the third stage, combustion, that the highest amount of CO_2 per kilometre are emitted in the life cycle of ICVs. The technical specifications of the fuels used by the ICVs are shown in Table 4.

Diesel generates more energy per litre than petrol, which explains the lower fuel consumption in diesel engines. ICVs are studied and evaluated in different ways, including efficiency evaluations according to the manufacturer's datasheet or actual road tests. Usually, the type of journey is varied in consumption assessment tests, alternating interurban journeys at constant speed with urban journeys and their more frequent stops and starts. Such tests for standard private vehicles provide a considerable amount of information (Ecoinvent, 2007; IDAE, 2020a).

In the present study, the BEV life cycle is divided into various CO_2

Table 2
Reference vehicle fuel consumption (Basque EcoDesign Center, 2019).

Vehicle type	Manufacturer's data		NEDC data		WLTP data
	Urban consumption	Interurban consumption	Urban consumption	Interurban consumption	Reference consumption
Petrol (l/100 km)	6.94	5.21	5.6	4.2	5.47
Diesel (l/100 km)	5.17	4.79	4.1	3.8	4.84
Electric (kWh/100 km)	10.74	15.63	8.54	12.43	14.9

Table 3
CO_2 of the reference vehicles for the Spanish continental mainland territory. Adapted from (Basque EcoDesign Center, 2019).

Vehicle	CO_2 emission percentages in the life cycle stages				
	Manufacture (%)	Fuel extraction, refining and transport (%)	Kilometres travelled (%)	Maintenance and decommissioning (%)	Total gCO_2/km
ICV petrol	21.15	17.31	55.77	5.77	226
ICV diesel	19.79	17.71	58.33	4.17	212
BEV	49.12	–	43.86	7.02	124

Table 4
Petrol and diesel technical specifications. Adapted from (Spanish Government, 2010).

Fuel	Density	Calorific value		CO_2
	kg/l	kWh/kg	kWh/l	gCO_2/l
Petrol	0.7475	12.3056	9.1984	2350
Diesel	0.8325	11.9444	9.9438	2640

emission stages. Firstly, an evaluation is made of the CO_2 emitted in the manufacturing stage, and secondly of those emitted in the extraction, refining and transport processes of the fuel used in the electricity generation mix. Thirdly, an evaluation is made of the CO_2 emitted in the battery charging process. Finally, emissions as the result of the decommissioning process are evaluated. Possible second uses or battery recycling are not considered as the corresponding evaluation procedures have not yet been developed (Hensher et al., 2021). It is in the first (manufacturing) and third, (battery energy consumption) stages that the highest amount of CO_2 are generated in the BEV life cycle.

Mean power plant bar emissions of the electricity generation mix in 2019 amounted to 652 gCO_2/kWh (Canary Islands government, 2020), with a large variation between islands. It should be noted that the emissions are calculated with respect to plant output, and so energy losses that occur between the plant and the energy stored in batteries are not included. To calculate BEV-related CO_2 emissions in the Canary territory it is necessary to know the origin of the sources used for electrical energy generation. By evaluating the percentages of each technology in the generation of electrical energy in the island, it is possible to determine the CO_2 emission values in each of the insular electrical systems.

The electricity generation mix of each plant (conventional and renewable) needs to be included in the calculation of the CO_2 emissions of a battery-stored kWh of an electric vehicle. Two possibilities were considered for the calculation of the emissions of the electrical energy mix: the mean annual mix and the mix during the cheapest electricity tariff (tariff B) timeslot (from 01:00 to 07:00) for BEVs. The following aspects were taken into account for each battery-stored kWh:

a) Battery charger and battery losses in the charge.
b) Losses in electrical energy transport and distribution from plant to consumer.
c) Evaluation of the mix of each technology to obtain the energy in power plant bars.
d) Inclusion of the auxiliary services necessary for the operation of each technology.
e) Incorporation of the thermal efficiency of each technology.
f) Calculation of the fuel required to obtain the energy.
g) Calculation of the CO_2 emissions of each type of fuel.

A description is provided below of the methodology used with respect to each of the above aspects for the calculation of CO_2:

a) Battery charger and battery losses in the charge.

A slow or rapid charging system can be used to charge an electric vehicle. For the purposes of this study a slow charging system was adopted. This system generates fewer Joule type losses and hence is more favourable in terms of efficiency (Ryu et al., 2014). Fast charging of BEVs increases losses in comparison with slow charging for the same power and, in consequence, also increases CO_2 emissions (Yuan et al., 2021). BEV chargers based on smart systems or renewable sources can lower emissions, but have not been considered in the present study. The equipment required in the vehicle to transform the AC electrical energy of the grid and adapt the energy to charge the batteries has an associated efficiency. Lithium batteries, which are the most widely used, generate heat each time they are charged/discharged. The efficiencies for this stage are considered together (charger, battery in the charging process, battery-inverter in the discharging process) and have been estimated at between 80% and 90% (Kanstad et al., 2019; Mali et al., 2021; Srivastava et al., 2018). The efficiency value used for the purposes of the present study was 85%.

b) Losses in electrical energy transport and distribution from plant to consumer.

The energy is transported from the different generator sets, including that from renewable sources, to the consumer. The system operator calculates the transport losses in each insular system (Canary Islands government, 2020). An annual average was used for each of the insular systems (REE, 2020a). Distribution losses in the Canary territory were based on government data (Ministry of Industry, 2016). The percentage values of transport and distribution losses by island are shown in Table 5.

c) Evaluation of the mix of each technology to obtain the energy in power plant bars.

Each insular system has a different electricity generation mix. All the conventional technologies (steam turbine, diesel engine, gas turbine and combined cycle) are used in the islands of Gran Canaria and Tenerife. Diesel engine (consuming fuel oil) and gas turbine (consuming gasoil) technologies are present In Lanzarote, Fuerteventura and La Palma. Only diesel type plants are used in La Gomera and El Hierro (Canary Islands government, 2020). The different technologies and fuel employed in the plants of each island are shown in Table 6.

Lanzarote and El Hierro have other renewable energy sources in addition to photovoltaic and wind. On Lanzarote a waste renewable energy system is used and on El Hierro a wind-pumped hydro system (Garcia Latorre et al., 2019). The participation of each technology was calculated for electrical energy generation, with the results shown in Table 7 (Canary Islands government, 2020).

d) Inclusion of the auxiliary services necessary for the operation of each technology.

For each of the conventional plants, calculation was made of the required percentage of electrical energy used in auxiliary services (Table 8). Thus, the energy fed into the grid is less than that generated in the generator terminals.

Consideration was also given to the consumption of auxiliary services on Fuerteventura and Lanzarote. As these two islands are interconnected via an underwater cable, the information supplied by the system operator was combined (REE, 2020a). The electrical energy

Table 5
Electrical energy transport and distribution losses in the insular systems of the Canary archipelago. Adapted from (Ministry of Industry, 2016; REE, 2020a).

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
Transport losses	5.30%	7.20%	4.40%	5.80%	5.30%	6.40%	5.40%
Distribution losses	7.61%	10.33%	6.31%	8.32%	7.61%	9.18%	7.75%
Total losses in transport and distribution	12.91%	17.53%	10.71%	14.12%	12.91%	15.58%	13.15%

Table 6
Technologies and fuel used in the Canary power plants. Adapted from (Canary Islands government, 2020).

Insular electrical energy systems	Conventional technologies				Renewable technologies		
	Steam turbine (ST)	Diesel engine (DE)	Gas turbine (GT)	Combined cycle (CC)	Wind turbine (WT)	Photovoltaic (PV)	Other
Gran Canaria	*Fuel oil*	*Fuel oil*	*Gasoil*	*Gasoil*	✓	✓	
Tenerife	*Fuel oil*	*Fuel oil*	*Gasoil*	*Gasoil*	✓	✓	
Lanzarote		*Fuel oil*	*Gasoil*		✓	✓	✓
Fuerteventura		*Fuel oil*	*Gasoil*		✓	✓	
La Palma		*Fuel oil*	*Gasoil*		✓	✓	
La Gomera		*Diesel*				✓	
El Hierro		*Diesel*					✓

Table 7
Participation of each technology in the Canary electricity generation mix in 2019. Adapted from (Canary Islands government, 2020).

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
Steam turbine	34.43%	30.91%					
Diesel engine	4.62%	5.20%	89.80%	77.03%	89.44%	99.80%	48.40%
Gas turbine	0.89%	2.85%	1.41%	11.80%	0.21%		
Combined cycle	44.60%	42.29%					
Renewable	15.46%	18.76%	8.79%	11.18%	10.35%	0.20%	51.60%

Table 8
Mean consumption in the auxiliary service of the conventional Canary plants in 2019. Adapted from (Canary Islands government, 2020).

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
Auxiliary services	5.82%	5.44%	5.51%	5.51%	7.85%	3.91%	3.91%

systems of La Gomera and El Hierro have the same percentage (3.91%) in auxiliary services (Canary Islands government, 2020). The consumption of auxiliary services for renewable generators was not taken into consideration.

e) Incorporation of the thermal efficiency of each technology.

Calculation was performed of the fuel required with each technology to produce the corresponding energy fraction. The technologies used in each island depend on the configuration of the island's electrical energy system (Table 5). The thermal efficiency data of each technology are shown in Table 9 (Canary Islands government, 2020).

f) Calculation of the fuel required to obtain the energy.

Knowing the thermal energy used in each of the conventional technologies, it is possible to obtain the fuel consumption values, measured in grams of fuel oil and litres of gasoil (Table 4).

g) Calculation of CO_2 emissions of each type of fuel.

Once the fuel consumption required to obtain 1 kWh in the battery of a BEV is known, it is possible to calculate the grams of CO_2 emitted into the atmosphere. To evaluate CO_2 emissions, the fuels that feed the plants need to be included, as well as the emissions generated in the manufacturing process of the devices used for renewable energy generation. For fossil fuels, emissions resulting from the extraction, refining and transport of the fuels were considered (Table 3). For renewable generation emissions, a mean value of 41 gCO_2/kWh was used in the case of photovoltaic energy and of 11 gCO_2/kWh for onshore wind energy (IPCC, 2015). No value was incorporated for CO_2 emissions from the waste renewable energy plant in Lanzarote given its very low contribution to the system.

The singular nature of the wind-hydro plant of El Hierro requires a specific study to evaluate the CO_2 emissions per kWh. The construction phase of the plant generates emissions that need to be taken into consideration. According to the Intergovernmental Panel on Climate Change (IPCC, 2015), the emissions of a pumped hydro energy storage (PHES) system range from a mean value of 24 gCO_2/kWh up to 2200 gCO_2/kWh. Given that the wind-hydro plant of El Hierro is small in size and that CO_2 emissions of hydroelectric plants can vary significantly

Table 9
Thermal efficiencies of each technology in the production of electrical energy for each island. Adapted from (Canary Islands government, 2020).

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
Steam turbine	33.46%	32.44%					
Diesel engine	41.98%	42.24%	40.28%	39.86%	38.73%	36.54%	36.58%
Gas turbine	19.35%	24.56%	18.59%	18.34%	25.06%		
Combined cycle	42.84%	41.55%					

between projects (de Faria et al., 2015) (Ricardo et al., 2020), using the values for small reservoirs an emissions value of between 400 and 600 gCO_2/kWh can be roughly estimated (Guo et al., 2020). carried out a study of 7 PHES plants and obtained a mean value for the 40 years of useful life of 314.605 kg/CO_2-eq/kW. Taking into consideration that energy production in El Hierro is carried out using a reversible pump-turbine system (Garcia Latorre et al., 2019), a final value of 385 gCO_2/kWh was estimated and used for the purposes of the present study.

3. Results and discussion

3.1. CO_2 emissions of reference ICVs in the canary islands

To evaluate the environmental impact of CO_2 emissions due to ICV use, it is necessary to calculate the g/km of CO_2 for each of the energy sources used. The data of Table 3 can be used for the reference vehicle with the WLTP consumption values. Table 10 shows the emissions generated by petrol and diesel ICVs, including fuel transport from continental mainland Spain to the islands. Emissions due to the manufacturing process have been combined with those due to decommissioning. CO_2 emissions per km of the petrol reference vehicle exceed those of the diesel reference vehicle by 5.5%.

3.2. CO_2 emissions of reference BEV in the Canary Islands

Table 11 shows the results for CO_2 emitted in each of the electrical energy generation mixes of the islands to obtain 1 kWh stored in BEV batteries. The table shows the evolution of efficiency in the transformation of the fuel from the energy source to a BEV battery. The final column shows the grams of CO_2 emissions per kWh for the reference BEV.

Table 12 shows the efficiency of each island in terms of the storage of 1 kWh in the battery of a BEV. For example, to store 1 kWh in a BEV in Gran Canaria, 1.4214 kWh have to be generated in the island's plants, representing an efficiency of 70.35% that includes the losses between gross plant energy generation and the energy stored in the battery.

The mix used for the calculations of Table 11 corresponds to the mean annual value in each island. However, there are important variations of the renewable energy sources in each island which will affect the CO_2 emission values if the hours envisaged for BEV charging are taken into account. Attractive discounts are made available by the electricity companies depending on the time of the day that the vehicle is connected to the grid for charging. Three tariffs are offered. Tariff A is the most expensive (13:00–23:00 horas) and tariff B, envisaged for vehicle charging, the cheapest (01:00–07:00). The remaining hours of the day are covered by tariff C. Table 7 can be recalculated to see the differences between the mean annual values and the renewable percentage in the tariff B timeslot. The results are shown in Table 13. It can be seen how there is a greater impact of overnight charging (timeslot B) in islands with higher PV generation (e.g. Tenerife). The grids of Lanzarote and Fuerteventura are connected by an underwater cable and separate calculations for the two islands with respect to the B timeslot are not possible. Emissions on the island of La Gomera are unaffected as the renewable percentage is very small. The percentage of renewable generation can be seen to increase in El Hierro in the B timeslot, resulting in a decrease in the CO_2 emissions of BEVs compared to the average annual mix.

Table 11 can be recalculated using the new values obtained for the electrical energy mix in the tariff B timeslot in each of the islands. The results obtained for the CO_2 emissions with the new renewable percentages are shown in Table 14.

The first row in Table 14 shows the gCO_2 emitted per battery-stored kWh when calculated on the basis of the annual average mix (taken from the last column of Table 11). The emissions for La Gomera are the highest due to the size of the installations and the low renewable generation levels (REE, 2020b). The high emissions of Fuerteventura are due to the significant proportion of the use of gas turbine technology in the production of electrical energy production. Interestingly, the incorporation of a reversible wind-pumped storage system on El Hierro has resulted in the lowest grams of CO_2 per battery-stored kWh of all the islands. The second row of Table 14 shows how CO_2 emissions are affected when battery charging is performed in the tariff B timeslot. On El Hierro, as renewable energy generation is managed through the wind-hydro plant, it can be seen how there is a consequent decrease in CO_2 emissions due to the greater renewable contribution in the tariff B timeslot.

To complete the emissions that exist in the energy mix, it is necessary to add those that correspond to the extraction, refining and transport of the fossil fuels present in the mix of each island. Table 11 showed the litres and grams of fuel used in the conventional island plants to generate the unit of energy. Using the same fuel extraction, refining and transport data shown in Table 10 for ICVs, it is possible to calculate the corresponding conventional plant emissions values. These include the values corresponding to the emissions generated as the result of the transport of the fuel from the refineries to the islands. The influence can be seen in Table 15 of the electrical energy mix (annual average and tariff B value) on CO_2 emissions.

The lower the renewable energy percentage in the mix, the higher the emissions.

3.3. Discussion

Using the values of Tables 10 and 15, it is possible to calculate the CO_2 emissions for each vehicle type. For petrol and diesel vehicles, it is assumed that emissions are the same in all the islands. Taking into consideration the CO_2 generated for each required kWh in BEVs and in each of the islands, Table 16 shows the CO_2 emission values per km travelled for both ICVs and BEVs using the annual average electrical energy mix.

Most evaluations of emissions only incorporate the combustion stage. The emissions values associated to the continental energy mix in Spain were 241 gCO_2/kWh in 2019. Compared with the results in Table 14, the emissions of the Canary electricity generation mix were three or four times higher than the continental ones, depending on the island. In addition, the fuels used in electrical energy generation in the islands are mostly obtained from extraction, refining and transport processes. Consequently, when the emissions generated as a result of these processes are incorporated, the emissions per km travelled of a BEV increase considerably (Table 15).

Through the analysis of CO_2 emissions per km travelled by ICVs and

Table 10
CO_2 emissions of the reference ICV in the Canary islands.

Vehicle	Life cycle stages				
	Manufacturing and decommissioning (gCO_2/km)	Fuel extraction, refining and transport (gCO_2/km)	Fuel transport from mainland Spain (gCO_2/km)	Combustion emissions (gCO_2/km)	Total (gCO_2/km)
Petrol ICV	60.85	39.89	3.89	128.54	233.17
Diesel ICV	50.79	38.79	3.81	127.77	221.17

Table 11
CO_2 emissions in the Canary island systems per kWh in the reference BEV.

Island (1)	Energy in EV battery	Energy in charger	Energy in transport and distribution	Generation technology (2)	Percentage for each technology	Energy of the technology	Energy including auxiliary services	Thermal energy	Energy/ kg of fuel	Fuel weight or volume		CO2 produced
	kWh	**kWh**	**kWh**		**%/100**	**kWh**	**kWh**	**kWh**	**kWh/kg**			**g CO_2/ kWh**
GC	1	1.1765	1.3509	ST	0.3443	0.4651	0.4938	1.4965	12.122	123.4534	grams	437.00
				DE	0.0462	0.0624	0.0663	0.1578	12.122	13.0158	fuel	
				GT	0.0089	0.0120	0.0128	0.0672	10.768	0.0062	litres	381.22
				CC	0.446	0.6025	0.6397	1.4877	10.768	0.1382	gasoil	
				WT	0.1391	0.1880	0.1880					2.07
				PV	0.0154	0.0209	0.0209					0.86
							1.4214					**821.14**
TF	1	1.1765	1.4265	ST	0.3091	0.4409	0.4663	1.4572	12.122	120.2133	grams	434.29
				DE	0.052	0.0742	0.0784	0.1868	12.122	15.4084	fuel	
				GT	0.0284	0.0405	0.0428	0.1785	10.768	0.0166	litres	425.27
				CC	0.4229	0.6033	0.6380	1.5561	10.768	0.1445	gasoil	
				WT	0.1333	0.1903	0.1903					2.09
				PV	0.0542	0.0773	0.0773					3.17
							1.5086					**864.82**
LZ	1	1.1765	1.3176	DE	0.8980	1.1832	1.2468	3.1169	12.122	257.1308	grams fuel	823.38
				GT	0.0140	0.0184	0.0194	0.1080	10.768	0.0100	litres gasoil	26.48
				WT	0.0748	0.0986	0.0986					1.08
				PV	0.0114	0.0151	0.0151					0.62
				OT	0.0018	0.0023	0.0023					0.00
							1.3822					**851.56**
FT	1	1.1765	1.3699	DE	0.7703	1.0552	1.1167	2.7916	12.122	230.2941	grams fuel	737.45
				GT	0.1180	0.1616	0.1711	0.9503	10.768	0.0883	litres gasoil	232.99
				WT	0.0885	0.1212	0.1212					1.33
				PV	0.0232	0.0318	0.0318					1.30
							1.4407					**973.07**
LP	1	1.1765	1.3509	DE	0.8945	1.2084	1.3113	3.3623	12.122	277.3696	grams fuel	888.19
				GT	0.0025	0.0034	0.0037	0.0147	10.768	0.0014	litres gasoil	3.59
				WT	0.0808	0.1091	0.1091					1.20
				PV	0.0222	0.0301	0.0301					1.23
							1.4541					**894.22**
LG	1	1.1765	1.3936	DE	0.9980	1.3908	1.4474	3.9119	12.54	311.9527	grams diesel	989.26
				PV	0.0020	0.0028	0.0028					0.11
							1.4502					**989.37**
EH	1	1.1765	1.3546	DE	0.4840	0.6556	0.6823	1.8441	12.54	147.0548	grams diesel	466.34
				WH	0.5160	0.6990	0.6990					269.10
							1.3813					**735.44**

(1) GC Gran Canaria, TF Tenerife, LZ Lanzarote, FT Fuerteventura, LP La Palma, LG La Gomera and EH El Hierro.
(2) ST steam turbine, DE diesel engine, GT gas turbine, CC combined cycle, WT wind turbine, PV photovoltaic, WH wind-hydro, OT Other.

Table 12
Efficiency of each island's electrical systems in terms of battery-stored kWh.

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
Efficiency of gross generation to electric vehicle batteries	70.35%	66.29%	72.35%	69.41%	68.77%	68.96%	72.40%

BEVs in the islands of the Canary archipelago, it can be stated that BEVs do not emit less CO_2 in all cases. In the islands of La Gomera and Fuerteventura, the CO_2 emissions of a BEV are 12.54% and 18.54% higher, respectively, than those of an ICV. CO_2 emissions of petrol ICVs and BEVs are very similar on the islands of Gran Canaria and Tenerife. The only significant difference is found on El Hierro, where BEVs emit 13.21% less CO_2. Consequently, given the results obtained, the ICV to BEV transition to decrease CO_2 emissions cannot be fully justified in the territory of the Canary Islands since emissions do not differ significantly between the different technologies. The importance should also be noted of an active charging system to ensure that BEV charging is undertaken with the highest possible renewable energy proportion. For example, it can be seen in Table 17 (comparing its values with those of Table 16) that when the contribution of renewable energy to the electrical energy mix on the island of Tenerife is reduced there is a 5.21% increase in the CO_2 emissions of BEVs.

It should be noted that the variation of some factors would significantly affect BEV CO_2 emissions. These are principally battery capacity, driving pattern and the percentage of renewable energies in the electric mix.

In this work, a BEV battery capacity was considered such that it has the same autonomy as the ICV. There are presently numerous BEVs with

Table 13
Percentages of renewable energy in the island mixes in 2019.

	Annual average % renewable energy generation	Renewable energy generation % by electricity tariff timeslot		
		Renewable in timeslot B	Renewable in timeslot C	Renewable in timeslot A
Gran Canaria	15.46%	14.74%	16.86%	14.86%
Tenerife	18.76%	12.54%	13.75%	25.19%
Lanzarote	8.79%	9.58%	11.21%	9.85%
Fuerteventura	11.18%			
La Palma	10.35%	9.27%	11.98%	9.75%
El Hierro	51.60%	53.66%	51.03%	50.84%

lower battery capacities, which would result in a lower CO_2/km emission due to its manufacture (the lower the battery capacity the lower the CO_2 emissions). In addition, a lower battery capacity would reduce the weight of the BEV and, consequently, its CO_2 emissions per km travelled. Another factor that affects the CO_2 emissions of BEVs as well as ICVs is the driving pattern. A change in the driving pattern of the vehicle to more urban journeys would reduce CO_2/km emissions of BEVs and increase those of ICVs. However, a change to more interurban journeys would have the opposite effect in both cases. BEV battery charging in power systems with a higher renewable energy contribution would reduce CO_2/km emissions in BEVs.

4. Conclusions

The CO_2 emissions of reference petrol and diesel ICVs and BEVs were evaluated in the territory of the Canary archipelago (Spain). The battery charging process of BEVs on the islands is carried out through an electricity generation mix with a significant fossil fuel contribution, directly impacting emissions. Emissions were calculated per km travelled of the three reference vehicle types. It was found that the BEV emissions vary

Table 14
CO_2 generated per battery-stored kWh with annual average and tariff B timeslot.

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
Annual average gCO_2/kWh	821.14	864.82	851.56	973.07	894.22	989.37	735.44
gCO_2/kWh in tariff B timeslot	827.80	927.34	843.98	989.25	903.40	989.37	726.34

Table 15
CO_2 emissions due to the extraction, refining and transport of the fuel used in the energy mix to store 1 kWh in the battery of an electric vehicle.

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro
CO_2 emissions (expressed as gCO_2 per battery-stored kWh) due to extraction, refining and transport of the fuel used in the annual average electricity generation mix	271.43	285.23	280.74	321.22	294.51	329.88	155.51
CO_2 emissions (expressed as gCO_2 per battery-stored kWh) due to extraction, refining and transport of the fuel used in the tariff B timeslot electricity generation mix	273.74	307.07	278.34	326.97	297.89	329.88	148.89

Table 16
CO_2 emissions of the reference vehicles for the Canary territory using the annual average electrical energy mix.

Vehicle		Life cycle stages			
		Manufacture, maintenance and decommissioning (gCO_2/km)	Fuel extraction, refining and transport (gCO_2/km)	Combustion emissions (gCO_2/km)	Total (gCO_2/km)
Petrol ICV		60.85	43.78	128.54	233.17
Diesel ICV		50.79	42.68	127.77	221.16
BEV	Gran Canaria	69.61	40.44	122.35	232.40
	Tenerife	69.61	42.50	128.86	240.97
	Lanzarote	69.61	41.83	126.88	238.32
	Fuerteventura	69.61	47.87	144.99	262.47
	La Palma	69.61	43.88	133.24	246.73
	La Gomera	69.61	49.15	147.42	266.18
	El Hierro	69.61	23.18	109.58	202.37

Table 17
CO_2 of the reference vehicles for the Canary territory using the tariff B timeslot electrical energy mix.

Vehicle		Life cycle stages			
		Manufacture, maintenance and decommissioning (gCO_2/km)	Fuel extraction, refining and transport (gCO_2/km)	Combustion emissions (gCO_2/km)	Total (gCO_2/km)
Petrol ICV		60.85	43.78	128.54	233.17
Diesel ICV		50.79	42.68	127.77	221.24
BEV	Gran Canaria	69.61	40.79	123.28	233.68
	Tenerife	69.61	45.75	138.17	253.53
	Lanzarote	69.61	41.47	125.75	236.83
	Fuerteventura	69.61	48.72	147.40	265.73
	La Palma	69.61	44.39	134.60	248.60
	La Gomera	69.61	49.15	147.41	266.17
	El Hierro	69.61	22.18	108.22	200.01

between islands. The values obtained also show that BEV emissions are practically double those of continental mainland Spain. The emissions generated by BEVs in the islands of lower electrical energy consumption are higher than those emitted by ICVs. For the islands of higher electrical energy consumption, no important difference was observed between the emissions of an ICV and a BEV. In the island with the highest renewable penetration and energy storage systems, it was found that less CO_2 is emitted with BEVs, but also that the life cycles of the storage installations play an important role and condition any reduction in emissions. Another way to lower BEV emissions is to reduce those that are emitted in the manufacturing process.

A decrease in the CO_2 emissions of BEVs in the islands of the Canary territory can be achieved by:

- Increasing renewable energy penetration in the electricity generation mix. A significant decrease can be obtained, as is shown by the case of El Hierro. On this island, with a renewable penetration in electrical energy generation of 51.6%, the CO_2 emissions of a BEV are 12.66% lower than those of an ICV. Electrical energy storage needs to be suitably sized to obtain a true decrease in CO_2 emissions in insular electrical energy generation. The incorporation of BEVs as active elements in the grid can reduce emissions through selection of the most appropriate charging hours.
- Replacing fuel oil and gasoil for electrical energy generation with other less contaminating fuels like natural gas.
- Renewing or replacing conventional generators with new, more efficient, and less contaminating generators.

Bearing in mind that the majority of islands with isolated electrical power systems consume fossil fuels as in the Canary archipelago, it can be argued that the incorporation of BEVs in isolated electrical energy systems can even increase CO_2 emissions depending on the electrical energy generation mix and the consumption of fossil fuels used in conventional power plants. One practical implication of this study is that the results can be generalized to other territories with similar characteristics, opening the way for a future research line. Only small vehicles were considered in this work to evaluate CO_2 emissions in the electrical energy systems of the Canary islands. In future works, vehicles of different sizes could be taken into account, including heavy-duty transport vehicles, as well as different charging systems (rapid, slow or combined).

CRediT authorship contribution statement

I. Nuez: Conceptualization, Methodology, Data curation, Supervision, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing. **A. Ruiz-García:** Supervision, Visualization, Validation, Writing – review & editing. **J. Osorio:** Resources, Supervision.

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.

Data availability

No data was used for the research described in the article.

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