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Lifecycle assessment and environmental impacts of hybrid electric vehicles fuelled by bioethanol and biogas

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ABSTRACT

This work presents an assessment of the environmental impacts of hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) by integrating cradle-to-grave (C2G) and well-to-wheel (WTW) evaluations. GREET, GASEQ and SimaPro software were applied to assess HEV and PHEV production models available in the UK, Spain, and Brazil, fuelled by 100 % sugarcane bioethanol, blends of gasoline with bioethanol concentrations of 5 % (E5), 10 % (E10), and 27 % (E27), and dual-fuel operation of those fuels with 50 % and 80 % biogas. In comparison with conventional vehicles, the results reveal that PHEVs and HEVs reduce WTW carbon dioxide emissions from 59 to 68 % and 23–54 %, respectively, for all countries and fuels evaluated. The use of PHEVs in Brazil, where renewable sources account for 83 % of the electricity matrix, demonstrated lower overall environmental impacts than their operation in the UK and Spain. The findings conclude that HEVs and PHEVs operating with the biofuels are instrumental to reduce the carbon footprint of the transportation sector as transitionary or complementary technology to battery electric vehicles (BEVs).

1. Introduction

Electric vehicles (EVs) are alternative replacements internal combustion engine vehicles (ICEVs) to mitigate greenhouse gas (GHG) emissions during the operation phase, since they have lower fuel consumption, in the case of hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicle (PHEVs), or use exclusively electrical energy, when it comes to battery electric vehicles (BEVs). On the other hand, there are concerns regarding the high environmental impacts of EVs during their production phase. From an assessment of land disturbance caused by mining activities, EV production was found to require twice the natural resources used for ICEV production [1].

A lifecycle assessment (LCA) can point out the advantages and disadvantages of EVs as replacement to ICEVs at specific locations, considering their production, operation, and end-of-life phases. Despite the differences of electricity generation, traffic conditions, driving patterns and road infrastructure of different countries, most of previous studies applying LCA reveal that EVs present lower carbon emissions than ICEVs [2]. Local assessments may also reveal disadvantages, such as a well-to-wheel (WTW) analysis showing that EVs present lower energy efficiency than ICEVs in Japan [3].

Regarding recommendations of EV types, it has been pointed out that large deployment of BEVs should not be incentivised at the expense of HEVs and PHEVs, as these can still play a significant role to reduce GHG emissions during the period of infrastructural upgrades [4]. HEVs and PHEVs are particularly valuable as transitional technologies, providing a smoother shift towards zero-emission transportation by leveraging existing refuelling infrastructure and addressing the limitations of BEVs, such as range anxiety and dependency on a fully developed charging network. BEVs present better environmental performance during urban operation, but they are underperformed by PHEVs in motorway driving and combined driving cycle with moderate and low traffic conditions [5,6]. This adaptability makes HEVs and PHEVs crucial for bridging the gap between ICEVs and full electrification, reducing emissions without requiring abrupt changes in vehicle fleets or infrastructure.

Battery is the main EV component; its lifecycle carbon footprint needs to be analysed considering its stage of production, use, second use and recycling, which is predominantly affected by battery lifetime [7]. The production of batteries significantly impacts the environment [8], mainly in the toxicity categories, due to the use of metals [9]. The demand for natural resources for lithium-ion (Li-ion) battery production

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List of abbreviations

- BEV - battery electric vehicles
- c - fuel consumption correction factor (non-dimensional)
- C2G - cradle-to-grave
- CH_4 – methane
- CO_2 - carbon dioxide
- CO_{2eq} - equivalent carbon dioxide
- $e_{CO_{2eq}}$ - emission related to the generation and transmission of electricity (gCO_{2eq}/kWh)
- EC - electricity consumption (kWh/km)
- ER - electric range with fully charged battery (km)
- EV - electric vehicle
- f_{CH4} - methane emission factor (kg_{CO2eq}/kg_{fuel})
- f_{CO_2} - carbon dioxide emission factor (kg_{CO2eq}/kg_{fuel})
- $f_{CO_{2eq}}$ - equivalent carbon dioxide emission factor (gCO_{2eq}/kg fuel)
- f_{N2O} - nitrous oxide emission factor (kg_{CO2eq}/kg_{fuel})
- FC - fuel consumption declared by the manufacturer (km/L)
- FEu - freshwater eutrophication
- FWE - freshwater ecotoxicity
- FPMF - fine particulate matter formation
- FR - fuel range with full tank (km)
- FRS - fossil resource scarcity
- GHG - greenhouse gas
- GW - global warming
- GWP - global warming potential
- HCT - human carcinogenic toxicity
- HEV - hybrid electric vehicles
- HNCT - human non-carcinogenic toxicity
- ICEV - internal combustion engine vehicle
- IR - ionising radiation
- LCA - lifecycle assessment
- LU - land use
- ME - marine ecotoxicity
- MEu - marine eutrophication
- MRS - mineral resources scarcity
- N_{ER} - number of full battery recharge in the same period of one full tank refuelling
- N_2O - nitrous oxide
- NO_X - oxides of nitrogen
- OFHH - toxicity affecting human health
- OFTE - damage to terrestrial ecosystems
- PHEV - plug-in hybrid electric vehicle
- PM – particulate matter
- SOD - stratospheric ozone depletion
- TA - terrestrial acidification
- TE - terrestrial ecotoxicity
- TTW - Tank-to-Wheel
- TTW_{1f} - TTW emissions for single-fuel mode (gCO_{2eq}/km)
- TTW_{2f} - TTW emissions for dual-fuel mode (gCO_{2eq}/km)
- WC - water consumption
- WTP - Well-to-Pump
- WTP_{1f} - WTP emissions for single-fuel mode (gCO_{2eq}/km)
- WTP_{2f} - WTP emissions for dual-fuel mode (gCO_{2eq}/km)
- WTW - well-to-wheel
- y - fuel mass fraction (non-dimensional)
- ρ_f - density of fuel used for declared FC (kg/m^3)

accounts for almost half of all resources explored for EV manufacturing [10]. Battery recycling and remanufacturing have achieved considerable economic and environmental values, especially with the use of electricity produced from clean energy sources [8]. Carbon intensities of Li-ion batteries have been quantified as 51 $kgCO_{2,eq}$/kWh for materials production, 34 $kgCO_{2,eq}$/kWh for battery preparation, and 33.7 $kgCO_{2,eq}$/kWh for end-of-life battery recycling stages [11].

Battery degradation during electric bus operation showed a drop in performance of over 5 % annually [12], meaning that for a hybrid powertrain configuration there is a corresponding increase of fuel consumption and carbon emissions. The minimisation of the battery size can significantly decrease EV lifecycle cost [13] and, in this line, encouraging the uptake of smaller EVs helps to mitigate their environmental impact [14]. The optimum battery size of PHEVs is about 10–20 kWh depending on vehicle size and user behaviour [15].

1.1. Worldwide LCA of EVs and the use of biofuels

Cradle-to-grave (C2G) and WTW emission analyses have been performed to compare EV types with ICEVs, focusing on a component [16,17] or the full vehicle [9,18,19]. A WTW analysis using GREET software for different car segments representatives of 27 European countries demonstrated that BEV emissions of equivalent carbon dioxide (CO_{2eq}) per km is about 58 % lower for B- and C-segment cars and 64 % lower for A-segment cars, in comparison with their gasoline-fuelled counterparts [20]. Also using GREET software, hybrid electric buses in Finland and California, USA, have demonstrated carbon emission reduction from 25 % to 33 % while battery electric busses reduced carbon emissions from 76 % to 86 % in comparison with diesel and compressed natural gas fuelled buses [21]. In China, a C2G analysis pointed out to only 6 % of CO_2 emissions from EVs in comparison with ICEVs, with the difference to other results being attributed to several factors including the emission parameters used [22]. A C2G approach was conducted to evaluate the environmental impacts of ICEVs fuelled by gasoline, ethanol, and gasoline-ethanol blend (flexible fuel vehicle) compared with PHEVs and BEVs in Brazil, alongside a WTW emission analysis [23]. The results showed that BEVs have the lowest impact compared to the other vehicles analysed, followed by ICEVs fuelled by ethanol, encouraging the use of this fuel. Nevertheless, depending on the electricity mix, PHEVs can demonstrate lower global warming potential (GWP) than BEVs at certain locations [24].

The advantages of EVs depend on the composition of the electrical matrix, making the large use of renewable energy sources necessary. If the electrical matrix is not clean, the deployment of EVs presents risks of increasing categories of environmental impacts, such as the formation of fine particulate matter (PM), human carcinogenic and non-carcinogenic species, and terrestrial ecotoxicity (TE) with a greater proportion than gasoline fuelled ICEVs [25]. A LCA carried out in eight Canadian cities with various electricity generation mix concluded that the promotion of PHEVs should be incentivised in regions of higher use of renewable energy sources to promote the largest CO_2 emission savings [26]. Elsewhere, it has been pointed out that PHEVs only emits less CO_2 emission than BEVs if the emission factor of electricity generation and the internal combustion engine efficiency are high [27]. Through a projection of different scenarios in Lithuania, the global warming impacts of BEVs are expected to decrease by 40 % in thirty years due to the expansion of renewables in the power generation mix [28].

BEVs produce 92 % more lifecycle mercury emissions than ICEVs powered by gasoline if electricity generation is coal-based. Mercury emissions from material production and manufacturing of vehicle components account for 50–60 % of lifecycle mercury emissions from BEVs and about 90 % from ICEVs [29,30]. The emissions associated with BEVs are significantly influenced by the electricity generation mix, as coal-fired plants are a major source of mercury emissions. However, depending on the charging strategy and the share of renewable energy in the grid, mercury emissions from BEVs can be reduced by as much as 50

% [31]. These findings underscore the need to consider not only the direct emissions from vehicles but also the upstream emissions from electricity generation when evaluating the environmental impacts of BEVs. While this work primarily focuses on HEVs, PHEVs, and ICEVs, this discussion highlights the critical role of energy sources and grid decarbonisation in reducing the environmental footprint of EVs.

The use of biofuels is also an alternative to help the transition to a decarbonised transport sector, taking advantage of the potential for their production from waste and renewable sources. Additionally, the use of biofuels can contribute to reduce emissions from ICEVs without a sudden change in the current fleet composition. Methanol, propanol, bioethanol, and butanol were analysed as alternative fuels for ICEVs, showing that bioethanol can potentially be used to reduce oxides of nitrogen (NO_X) and smoke emissions [32]. ICEVs and HEVs fuelled with bioethanol presented lower emissions per kilometre than BEVs, proving the fuel as a viable option for transitional reduction of emissions in the short term and medium term [33]. However, in the long term BEVs can become a better alternative [34]. The use of bioethanol depends on each country's production potential, land use and resource availability [35, 36].

Recent studies highlight the importance of focusing on the operational phase of EVs, as well as their energy demand. A research in China demonstrates that while PHEVs show promising potential for reducing carbon emissions, real-world data reveals that their operational energy use and carbon dioxide emissions can significantly exceed model estimates, indicating the need for more accurate regional data and tailored policies [37]. Similarly, studies on BEVs in China report growing operational energy demand and emissions, particularly in regions with high intensity of electricity consumption, pointing to the importance of grid decarbonisation to reduce the environmental impacts of EVs [38]. Moreover, integrating the decarbonisation of the building sector in EV-related research provides a significant opportunity for further emissions reduction [39]. As result, it is possible to develop more effective carbon-neutral pathways that include both transportation and building decarbonisation as complementary strategies.

1.2. Novelty of this work

While prior research has devoted to the integration of C2G and WTW methodologies for evaluating environmental impacts of vehicles [40], there is still a lack of studies to use these approaches in assessing HEVs, PHEVs, and ICEVs across diverse national contexts, taking into account variations in fuel availability and electrical matrices, and analysing a broader spectrum of impact categories beyond GHG emissions [41–43]. As an example, HEVs displayed the best combined results of price, emission and maintenance in Indonesia, but from a different approach to LCA [44]. Moreover, there is a scarcity of published studies applying LCA to evaluate the use of ethanol in hybrid vehicles and most of them compare carbon emissions between two or more vehicle technologies or power propulsion systems but do not consider multiple scenarios defined by local energy and transportation systems [24]. Further research on EVs, including HEVs and PHEVs, are still required to fully understand their roles to attain sustainable transportation [45].

To bridge this knowledge gap, the present study introduces a novel combination of C2G and WTW emission analyses by utilizing three software tools: SimaPro, GREET, and GASEQ. This approach enabled a comprehensive LCA of the environmental and human health impacts of HEVs, PHEVs, and ICEVs, in both single- and dual-fuel modes, with a particular focus on Brazil, the UK, and Spain. The study encompasses the evaluation of fuels such as bioethanol and biogas from sugarcane, alongside gasoline blends containing 5 % (E5), 10 % (E10), and 27 % (E27) ethanol. GREET software contributes to critical insights into the Well-to-Pump (WTP) emissions, while GASEQ enhances the WTW analysis with detailed Tank-to-Wheel (TTW) emissions data. These GASEQ-derived values are then integrated into SimaPro for the vehicle usage phase analysis, implying on a broad understanding of the environmental impacts throughout the entire vehicle lifecycle.

The selection of the UK, Spain, and Brazil as case study countries is particularly insightful due to the diverse characteristics of their transportation and energy sectors. The UK and Spain were chosen due to their advanced EV infrastructure, strong government commitments to decarbonise their transportation sectors, and the increasing adoption of renewable energy sources in their electricity grids. These countries provide an interesting perspective on the integration of hybrid technologies within an electrified transport system, where HEVs and PHEVs can help to reduce emissions during the transition to a fully electric fleet.

In contrast, Brazil's transportation sector is heavily reliant on biofuels, especially ethanol, which is widely used to reduce emissions from ICEVs. Brazil also faces unique challenges related to the infrastructure required for the widespread adoption of EVs. This combination of biofuel reliance and the need for EV infrastructure development presents a distinct opportunity to assess the adoption of HEVs and PHEVs in Brazil, where they could play a crucial role in facilitating a smoother transition towards zero-emission vehicles. The analysis of these three countries provides valuable insights into how HEVs and PHEVs can be strategically deployed to support the global move towards sustainable transportation while addressing regional challenges.

2. Material and methods

Two types of EVs were chosen for comparison with a ICEV, HEV and PHEV. The same models were selected according to their availability in Brazil, the UK, and Spain. Toyota Corolla Hybrid was the selected HEV, however, different versions were found in the three countries analysed: Corolla Hybrid Hatchback, Corolla Hybrid Business Hatchback, and Corolla Altis Hybrid were used for the British, Spanish, and Brazilian scenarios, respectively. The technical specifications of all versions are similar, except for the Brazilian model, which is a flexible fuel vehicle able to operate with gasoline or ethanol pure or blended at any proportion. Volvo XC60 T8 Recharge Plus Hybrid fuelled by gasoline was the selected PHEV, available in all three countries with the same model version. Toyota Corolla GLi was the ICEV model used to compare against the HEVs and PHEVs.

In this study, two types of evaluation methods were integrated to assess the environmental impact of the selected vehicles: C2G and WTW. The C2G approach accounts for the entire vehicle lifecycle, from raw material extraction to disposal, while the WTW methodology focuses specifically on fuel production and use, evaluating the environmental effects associated with vehicle energy consumption. By combining both approaches, more comprehensive picture of the total environmental footprint of the vehicle can be obtained.

GASEQ software was employed to calculate the exhaust emissions from the different vehicle technologies considered in the study during the operation stage. GREET software was used to assess the lifecycle emissions of the vehicles, specifically the emissions associated with fuel production and consumption. SimaPro provided a detailed environmental footprint of the vehicle technologies throughout their lifecycle, encompassing various impact categories such as GWP, ozone depletion, and resource depletion.

2.1. Tank-to-wheel and well-to-pump analysis

TTW emissions were calculated from simulation of vehicle operation with the base fuels bioethanol, biogas (70 % methane content), and gasoline using GASEQ software to calculate the exhaust gas composition, applying the same methodology described in Ref. [46]. The exhaust emissions for operation with gasoline-ethanol blends - E5, E10 and E27 – and dual-fuel mode – 50 % bioethanol +50 % biogas, 20 % bioethanol +80 % biogas, 50 % E5 + 50 % biogas, 50 % E10 + 50 % biogas, and 50 % E27 + 50 % biogas – were determined proportionally to the concentrations of the base fuels. E5 and E10 blends were specifically selected because they are commonly used fuels in the UK and Spain. E27 blend, on the other hand, is widely used in Brazil. The dual-fuel modes were considered to explore the potential of bioethanol-biogas combination to further reduce emissions, since biogas is available as automotive fuel in regions of Brazil.

Fuel consumption for vehicle operation with fuel blends and dual-fuel mode were computed based on an energy analysis and the fuel consumption declared by the vehicle manufacturer for a given fuel. For the Brazilian scenario, the manufacturer provides consumption values for hydrous ethanol and E27, since most of the light vehicle fleet in the country is powered by flexible fuel engines allowing to use those fuels at any proportion. Therefore, for the chosen Brazilian vehicle, it was necessary to calculate E5, E10 and biogas consumption. For the British and Spanish scenarios, bioethanol, biogas, and E27 consumption were calculated. For all scenarios, the consumption of each blend in dual-fuel mode needed to be determined. TTW emissions were calculated for single-fuel mode, TTW_{1f} (gCO_{2eq}/km), and dual-fuel mode, TTW_{2f} (gCO_{2eq}/km), by:

$$TTW_{1f} = f_{CO_{2eq}} \bullet c \bullet \left(\frac{\rho_f}{FC} \times 10^{-3}\right) \bullet \frac{FR}{FR + N_{ER} \bullet ER} \tag{1}$$

$$TTW_{2f} = \left[\left(y \bullet f_{CO_{2eq}} \bullet c\right)_{pf} + \left(y \bullet f_{CO_{2eq}} \bullet c\right)_{sf}\right] \bullet \left(\frac{\rho_f}{FC} \times 10^{-3}\right) \bullet \frac{FR}{FR + N_{ER} \bullet ER} \tag{2}$$

where $f_{CO_{2eq}}$ is the equivalent carbon dioxide emission factor (gCO_{2eq}/kg fuel), FC is the fuel consumption declared by the manufacturer (km/L), ρ_f is the density of the fuel used for the declared FC (kg/m^3), y is the fuel mass fraction (non-dimensional), and c is the fuel consumption correction factor (non-dimensional), taken as 1.0 for gasoline, 1.35 for ethanol, and 0.83 for biogas [47] (for the fuel blends c is calculated proportionally to the concentrations involved), FR is the fuel range with full tank (km), ER is the electric range with fully charged battery (km), and N_{ER} is the number of full battery recharge in the same period of one full tank refuelling. Index pf stands for primary fuel and sf for secondary fuel. The last term of Eqs. (1) and (2) becomes 1 for HEVs and ICEVs as they do not recharge the battery electrically ($N_{ER} = 0$).

The equivalent carbon dioxide emission factor in the TTW stage is calculated by Ref. [48]:

$$f_{CO2eq} = f_{CO2} + 28 f_{CH4} + 265 f_{N2O} \tag{3}$$

where f_{CO_2} is the carbon dioxide (CO_2) emission factor (kg_{CO2eq}/kg_{fuel}), f_{CH4} is the methane (CH_4) emission factor (kg_{CO2eq}/kg_{fuel}), and f_{N2O} is the nitrous oxide (N_2O) emission factor (kg_{CO2eq}/kg_{fuel}), all related to the vehicle exhaust. TTW emissions for PHEVs operating with only electricity from the battery is taken as 0.

GREET software was used to simulate the production pathways of different fuels, such as bioethanol from sugarcane, biogas from vinasse, and gasoline-ethanol blends E5, E10 and E27. The analysis considered GHG emissions associated with extraction, production, and transport of fuels to the refuelling stations. Bioethanol and biogas from sugarcane were adopted due to their availability in Brazil, one of the largest world producers of sugarcane and with a high potential to produce biofuels from this crop. The UK and Spain do not use bioethanol or biogas as fuel for the transport sector, but they have E5 and E10 as commercially available fuels. The simulation conducted for the Brazilian scenario using bioethanol and biogas from sugarcane was replicated for the European countries.

The lower heating value (LHV) and density of bioethanol were added to the GREET library, as well as the density, carbon rate and sulphur rate of sugarcane vinasse as co-product, with 92.6 % allocation. The ethanol transportation process by heavy-duty truck, rail, and pipeline from the production plant to the bulk terminal, then by heavy-duty truck until the refuelling station was created. Anhydrous bioethanol was considered in the E5, E10, and E27 fuel blends simulation and mixed with 7.5 % water to obtain hydrous bioethanol, in accordance with the Brazilian National Agency for Petroleum, Natural Gas and Biofuels (ANP) [49]. Table 1 shows the parameters inserted to create each bioethanol resource and process in the software. The transportation process of biogas adopted the same parameters applied to natural gas, such as the use of pipeline as distribution mode. The parameters used to create biogas resources and processes are shown in Table 2.

The process for E10 available on GREET database was modified for E5, keeping the same sulphur percentage (%S) and carbon percentage (%C) data and updating LHV and density values, which were calculated by multiplying the respective values of those parameters for gasoline and bioethanol by the proportion of each fuel in the blend. Ethanol from corn was considered for both E5 and E10, as this source is one of the most used in Europe to produce the biofuel. The transportation process of gasoline was considered common for European and Brazilian scenarios for comparison purposes. The existing resource for E10 was also used for E27 by modifying the fuel LHV and density, the production source from corn to sugarcane, and the proportion of bioethanol in the blend with gasoline from 10 % to 27 %. The transportation process was the same as the one used for E5 and E10. Table 3 shows the parameters used to simulate the processes related to E5, E10 and E27.

WTP emission calculation takes into account the extraction of raw materials, fuel production and transportation to the refuelling stations. Data extracted from GREET simulation were used to calculate WTP emissions of different the fuels considering carbon fixation in the biomass, in gCO_{2eq}/km, as follows:

Table 1
Pathway "Anhydrous bioethanol from sugarcane – Production and use in Brazil –Transport to refuelling station".

PRODUCTION PROCESS: "BIOETHANOL FROM SUGARCANE – BRAZIL – WITH VINASSE ALLOCATION"				
NEW RESOURCES	LHV (MJ/kg)	DENSITY (kg/m^3)	%C	%S
Sugarcane vinasse	–	1030 [50]	1.96 [51]	0.0142 [52]
Bioethanol	28.24 [53]	791 [53]	52.2[a]	4.43×10^{-7}[a]
INPUTS	AMOUNT	SOURCE		
Sugarcane straw	0.0029 ton[a]	Primary resource		
Sugarcane bagasse	0.0072 ton[a]	Primary resource		
Sugarcane	0.0467 ton[a]	Output of a previous process		
Lime (CaO)	4.11×10^{-5} ton[a]	Single pathway: production from limestone in Chile		
GROUP INPUT	AMOUNT	SOURCE		
Residual oil	316.5 kJ[a]	Single pathway: production from crude oil (100 % share)		
OUTPUT	AMOUNT	LOSSES		
Bioethanol	3.785 L	0 %		
CO-PRODUCT	AMOUNT	TREATMENT METHOD FOR SELECTED CO-PRODUCT		
Sugarcane vinasse	4.73×10^{-2} m^3 [54]	Allocation type – mass – 94.22 % [54]		

TRANSPORTATION PROCESS: "ANHYDROUS BIOETHANOL TRANSPORTATION (PRODUCED AND USED IN BRAZIL) TO REFUELLING STATION"			
MODE	TRAVEL	DISTANCE[a]	URBAN SHARE[a]
Rail	Ethanol plant to bulk terminal	563 km	10 %
Heavy-duty truck	Ethanol plant to bulk terminal	563 km	68.5 %
Pipeline	Ethanol plant to bulk terminal	563 km	10 %
Heavy-duty truck	Bulk terminal to refuelling station	48 km	68.5 %

[a] Provided by GREET database.

Table 2
Pathway "Biogas from Brazilian sugarcane vinasse to refuelling station".

PRODUCTION PROCESS: "BIOGAS FROM SUGARCANE VINASSE – BRAZIL"				
NEW RESOURCE	LHV (MJ/kg)	DENSITY (kg/m^3)	%C	%S
Biogas from vinasse	27.40[a]	0.784[a]	0.558 [51]	0.0189 [52]
INPUTS	AMOUNT	SOURCE		
Electricity	5.81 kWh[a]	Single pathway: distributed mix – Brazil		
Sugarcane vinasse	4.01×10^{-2} m^3 [55]	Output of a previous process		
OUTPUT	AMOUNT	LOSSES		
Biogas from Vinasse	0.0312 m^3 [56]	2 % (70 % CH_4; 30 % CO_2) [54]		

TRANSPORTATION PROCESS: "BIOGAS FROM SUGARCANE VINASSE TRANSPORTATION THROUGH PIPELINE TO REFUELLING STATION"				
MODE	TRAVEL	DISTANCE	URBAN SHARE	FUEL SHARE
Pipeline	Ethanol plant → Refuelling station	80 km[a]	14 %[a]	Natural gas

[a] Calculated by the authors through values given by Ref. [46].

$$WTP_{1f} = f_{CO_{2eq}} \bullet c \bullet \left(\frac{\rho_f}{FC} \times 10^{-3}\right) \bullet \frac{FR}{FR + N_{ER} \bullet ER} + e_{CO_{2eq}} \bullet EC \bullet \frac{N_{ER} \bullet ER}{FR + N_{ER} \bullet ER} \tag{4}$$

$$WTP_{2f} = \left[\left(y \bullet f_{CO_{2eq}} \bullet c\right)_{pf} + \left(y \bullet f_{CO_{2eq}} \bullet c\right)_{sf}\right] \bullet \left(\frac{\rho_f}{FC} \times 10^{-3}\right) \bullet \frac{FR}{FR + N_{ER} \bullet ER} + e_{CO_{2eq}} \bullet EC \bullet \frac{N_{ER} \bullet ER}{FR + N_{ER} \bullet ER} \tag{5}$$

where $e_{CO_{2eq}}$ is the emission related to the generation and transmission of electricity, in gCO_{2eq}/kWh; and EC is the electricity consumption, in kWh/km.

The equivalent carbon dioxide emission factor $f_{CO_{2eq}}$ for the WTP stage is also calculated by Eq. (3) but the terms f_{CO_2}, f_{CH4} and f_{N2O} assume different values as they now refer to fuel production and transportation.

The baseline condition here considered is one full tank or cylinder gas refuelling per month and daily full battery recharging to reflect the average annual vehicle mileage in the UK, Spain and Brazil, of approximately 12000 km.

2.2. Cradle-to-grave analysis

C2G analysis was conducted through SimaPro software by applying both methods: "ReCiPe 2016 Midpoint (H) World (H)" and "ReCiPe 2016 Endpoint (H) World (H/H)". Midpoint categories are intermediate categories that quantify specific environmental impacts associated with a system or process at a more detailed level. They focus on each environmental aspect, such as GHG emissions, land use (LU), marine and terrestrial toxicity, resource scarcity, and water consumption (WC), among others. Endpoint categories aim to represent the results of the overall environmental impacts of a system or product in broader and more understandable terms, aggregating the midpoint impact categories into a smaller set of more comprehensive categories, which are human health, resources availability, and ecosystems [57]. Each vehicle was simulated considering the production process and end-of-life of their main components, such as battery, powertrain, glider, and engine (Fig. 1).

Firstly, the approximate proportion of each main component to the vehicle total weight was considered, as shown by Table 4. These proportions were then used to quantify the mass of each component, in kg. Each fuel was simulated by inserting the same values used on GREET as inputs, along with the transport modals given by SimaPro, such as inland waterways, light commercial vehicles, lorries, and sea. For the usage

Table 3
Parameters adopted to simulate the E5, E10 and E27 fuels.

PRODUCTION PROCESS: "REFORMULATED GASOLINE (E5) PRODUCTION VIA BLENDING – EU"				
NEW RESOURCE	LHV (MJ/kg)	DENSITY (kg/m^3)	%C	%S
E5	42.75[a]	744[a]	0.8278[b]	9.01×10^{-6}[b]
INPUTS	SHARE	SOURCE		
Gasoline Blend Stock	95 %	Output of a previous process		
Ethanol	5 %	Single Pathway: Ethanol Production from Corn		
OUTPUT	AMOUNT	LOSSES		
E5	455 L[b]	0 %		
PRODUCTION PROCESS: "REFORMULATED GASOLINE (E10) PRODUCTION VIA BLENDING – EU"				
RESOURCE	LHV (MJ/kg)	DENSITY (kg/m^3)	%C	%S
E10	41.99[a]	747[a]	0.8278[b]	9.01×10^{-6}[b]
INPUTS	SHARE	SOURCE		
Gasoline Blend Stock	90 %	Output of a previous process		
Ethanol	10 %	Single Pathway: Ethanol Production from Corn		
OUTPUT	AMOUNT	LOSSES		
E10	455 L[b]	0 %		
PRODUCTION PROCESS: "BRAZILIAN GASOLINE (E27) BLENDING WITH BIOETHANOL FROM SUGARCANE"				
RESOURCE	LHV (MJ/kg)	DENSITY (kg/m^3)	%C	%S
E27	39.33 [28]	754 [28]	0.8278[b]	9.01×10^{-6}[b]
INPUTS	SHARE	SOURCE		
Gasoline Blend Stock	73 %	Output of a previous process		
Bioethanol	27 %	Output of a previous process		
OUTPUT	AMOUNT	LOSSES		
E27	455 L[b]	0 %		
TRANSPORTATION PROCESS: "U.S. CONVENTIONAL GASOLINE WITH ADDITIVES – DISTRIBUTION"				
MODE	TRAVEL	DISTANCE	URBAN SHARE	
Heavy Heavy-Duty Truck	Bulk Terminal → Refuelling Station	48 km[b]	68.5 %[b]	

[a] Calculated by the authors.
[b] Provided by GREET software.

phase, new processes were created for each fuel and the values found on GASEQ for CO_2, CH_4, N_2O, sulphur dioxide (SO_2) and NO_X were inserted as outputs in kg of pollutant per kg of fuel. In addition to fuel consumption, the usage phase of PHEV included electricity consumption as "input from technosphere" and considered a low-voltage electricity mix for the Brazilian, British, and Spanish scenarios, assuming charging at homes. Electricity consumption was calculated by dividing the electrical energy consumption throughout the vehicle life cycle by the vehicle weight so that the result could be found in kWh per kg of vehicle.

For the end-of-life analysis, used glider, engine, battery, and powertrain were added as "output to technosphere". Finally, the process called "Passenger car maintenance" – which already exists in the software with the measurement unit presented as "p" (piece) – was added at the end, after multiplying the result found in 1 kg of vehicle by its weight considering the maintenance process throughout the vehicle useful life of 150,000 km or 10 years, as given by the software.

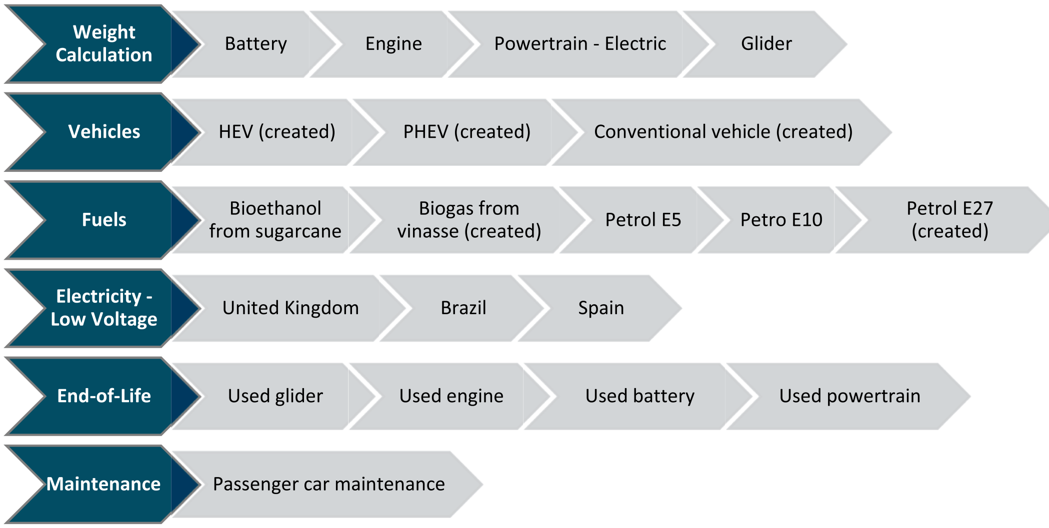

Fig. 1. Flowchart of cradle-to-grave simulation using SimaPro software.

Table 4
Proportions of main components of HEV, PHEV and ICEV.

COMPONENT	HEV	PHEV	ICEV
Glider	80.9 %	83.8 %	74.0 %
Powertrain	7.7 %	8.0 %	–
Battery	4.0 %	3.6 %	–
Internal combustion engine	7.4 %	4.6 %	26.0 %

Table 5
Carbon dioxide and biogenic carbon dioxide related to the production process of different fuels.

FUEL	BIOGENIC CO_2 (kg/m^3 fuel)	CO_2 (kg/m^3 fuel)	CO_2 TOTAL (kg/m^3 fuel)
Bioethanol	−486.61	498.59	11.98
Biogas	−0.045	0.059	0.014
E5	−0.75	783.60	782.85
E10	−0.76	782.80	782.04
E27	−66.31	658.70	592.39

3. Results and discussion

3.1. WTP, TTW and WTW emissions

Fig. 2 shows that bioethanol demonstrates the most favourable WTP emissions in both single-fuel and dual-fuel modes for all vehicle types and countries evaluated. In single-fuel mode, its emissions were up to 78.3 %, 78.5 %, and 70.5 % lower compared to E5, E10, and E27 fuels, respectively. This result is credited to the carbon sequestration capabilities of sugarcane crops, responsible for offsetting 97.6 % of CO_2 emitted through consumption, decomposition, and combustion of sugarcane (see Table 5). The total CO_2 emissions of bioethanol is remarkably low compared to its production emissions due to the substantial biogenic CO_2 absorption during the growth of its biomass. This explains why bioethanol contribute to atmospheric CO_2 reduction despite from a life cycle viewpoint.

Due to the predominant presence of fossil fuel content, E5 and E10 present higher levels of WTP CO_2 emissions than the other fuels (Fig. 2). Because of its larger proportion of ethanol, E27 shows significantly lower CO_2 emissions than E5 and E10. Dual-fuel use of biogas with E5, E10, and E27 achieved WTP emissions up to 35.2 %, 35.4 %, and 29.9 % lower than these fuels in single-fuel mode, respectively. These findings demonstrate the potential of dual-fuel systems of biogas with the gasoline-ethanol blends to reduce GHG emissions. On the other hand,

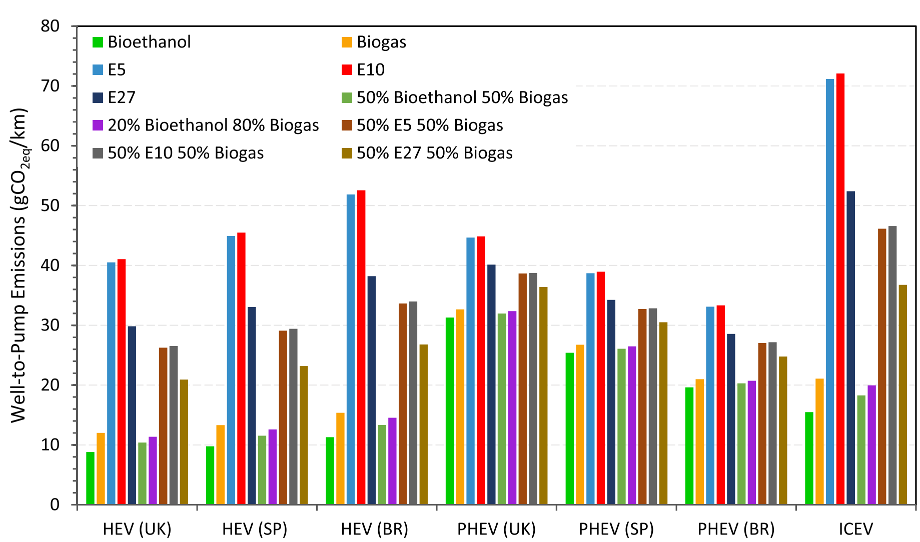

Fig. 2. WTP emissions of HEV, PHEV and ICEV powered by different fuels.

there is no improvement on WTP emissions when biogas is used in single or dual-fuel mode against bioethanol.

In general, WTP emissions from HEVs were 27 %–43 % lower than emissions from ICEVs for all countries and fuels evaluated, providing evidence of the benefits of the embedded hybrid technologies in HEVs (Fig. 2). These results align with the finding of 40 % reduction of well-to-tank emissions from a hybrid electric bus against a conventional diesel bus in Spain [58]. WTP emission from PHEV was higher than that from HEV in the UK due to the large use of natural gas and other non-renewable sources for electricity generation. Similar situation occurs in Spain, where the exceptions were for E5 and E10. Brazilian PHEVs exhibited the lowest WTP emissions among all PHEVs, attributed to predominant use of renewable sources for electricity generation in the country. Electricity generation mix in Brazil is mostly made by renewable sources, where hydroelectric, biofuels, wind and solar photovoltaics account for a share of 89 % [59]. This leads to a substantial reduction in the carbon footprint of electric power, which in turn results in lower WTP emissions for PHEVs when compared to those in the UK and Spain. As result, Brazilian PHEVs become more sustainable options for transportation in comparison to their European counterparts.

PHEV produced less WTP emission than HEV when fossil fuels were used in Brazil, but the opposite occurred for operation with bioethanol, biogas and dual mode operation with these fuels (Fig. 2). Likewise, PHEVs produced less WTP emission than ICEV when fossil fuels were utilised in all countries, with reductions of up to 54 %, but opposing results are observed for operation with the biofuels in single and dual mode. These outcomes encourage the use of the biofuels for transport decarbonisation since their benefits can, in certain scenarios, be even higher than the use of electricity.

Fig. 3 illustrates that PHEVs exhibiting the most favourable TTW emissions, which were calculated considering usage conditions requiring one full tank refuelling per month and daily full battery recharging. In comparison with ICEV, PHEVs reduce TTW emissions from 74 % to 81 % while HEVs cause reductions from 38 % to 56 %. Biogas in single-fuel mode produced the lowest TTW emission levels of all fuels, irrespective of the vehicle type and country. HEVs fuelled by biogas as single-fuel or in dual-fuel mode can attend the 2025-29 EU emissions target of 93.6 gCO_{2eq}/km in all evaluated countries and can also be at this limit if fuelled by bioethanol in the UK. HEVs can only meet the 2030-34 EU emissions target of 49.5 gCO_{2eq}/km when fuelled by biogas in the UK. PHEVs can fully meet both targets in any scenario investigated, while ICEVs cannot reach either target.

TTW emissions from PHEVs are averaged at 23 gCO_{2eq}/km for operation with E27 according to the Brazilian Programme of Vehicle Labelling (PBE) report [60], and 21 gCO_{2eq}/km as specified by the vehicle manufacturer. These figures are 55–60 % lower than the number here found, of 38 gCO_{2eq}/km, meaning that they can just be attained with highly intense operation in electric mode. Regarding Brazilian HEVs, the PBE report indicates emissions of 77 gCO_{2eq}/km for operation with E27, while the vehicle manufacturer specifies the maximum of 84 gCO_{2eq}/km. The results here found are 49 % higher than the PBE report and 36.6 % higher than the manufacturer's declaration. For the UK and Spain, the HEV manufacturers specify 98 gCO_{2eq}/km and 111 gCO_{2eq}/km, respectively, following the World Harmonized Light Vehicle Test Procedure (WLTP). There is a close agreement with the results of this work, which are 97 gCO_{2eq}/km and 110 gCO_{2eq}/km for the British and Spanish models, respectively.

Fig. 4 shows WTW emissions, calculated by summing WTP and TTW emissions, revealing that emissions from PHEVs are from 59 to 68 % lower than ICEVs and from 12 to 46 % lower than HEVs, for all countries and fuels evaluated. These results are in the range of early comparisons of PHEVs against ICEVs, where CO_2 reduction was in the interval of 27–69 % [61]. The reliance of the electricity grid of European countries on fossil fuels leads to higher WTW emissions from PHEVs in the UK and Spain, in comparison with Brazil. WTW emissions from PHEVs using E5 or E10 in the European countries lie around 80–86 gCO_{2eq}/km, while Brazilian PHEVs, when fuelled with the same fuels, emit about 75 gCO_{2eq}/km. Considering the use of commercial gasoline in Brazil (E27), emissions stay below 67 gCO_{2eq}/km, representing up to a 22.2 % reduction compared to their European counterparts using their local fuel E5 or E10. The large use of renewables in the Brazilian electricity generation mix makes the country a viable location for the implementation of PHEVs [62].

Brazilian PHEV fuelled by ethanol reduces WTW CO_2 emissions by 75 % compared with ICEV powered by gasoline E5 (Fig. 4), which is below the figures found elsewhere, of 85 % reduction [63]. An LCA performed for passenger cars in Brazil recommends the country to prioritise HEVs and PHEVs over BEVs, considering its leadership in ethanol production, extensive infrastructure of biofuel distribution, consolidated flexible fuel technology in the light duty vehicle fleet, and the restrictions on expansion of the electricity infrastructure to supply an overloading demand [64]. If the annual changes of electricity mix such as those applied in China [65] is considered, GHG emissions can show reduced figures in Spain and the UK as electricity generation in the European countries becomes cleaner.

WTW emission reductions were more pronounced with higher ethanol content in the fuel blend, as observed when comparing E5 and E27 fuels (Fig. 4). When powered by E27 instead of E5, HEVs achieved

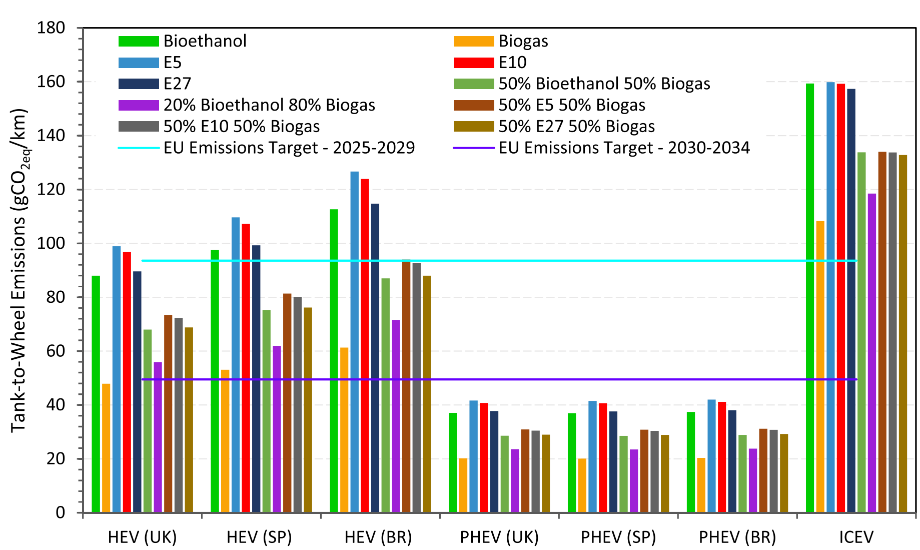

Fig. 3. TTW emissions of HEV, PHEV andICEV powered by different fuels.

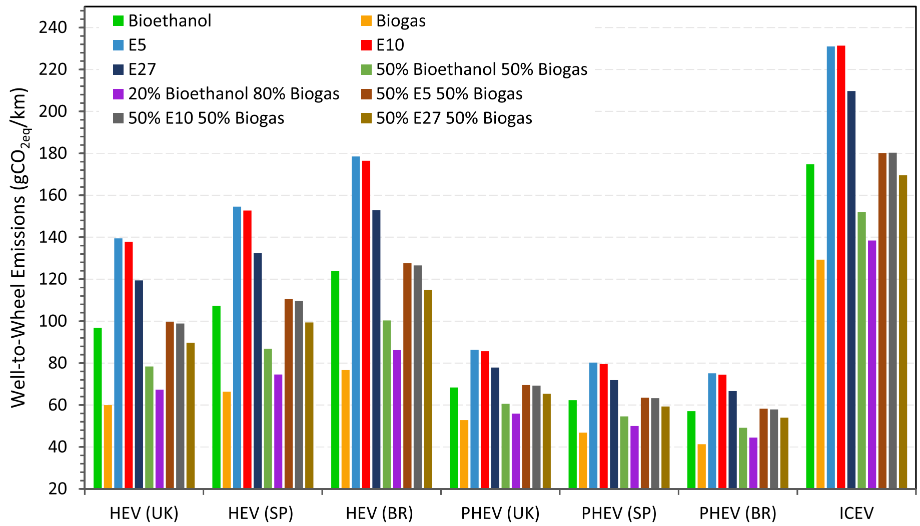

Fig. 4. WTW emissions of HEV, PHEV and ICEV powered different fuels.

reductions of 14.3 % in single-fuel mode and 10.0 % in dual-fuel mode with 50 % biogas. Also in comparison with E5, PHEVs operating with E27 as base fuel reached WTW emission reductions from 9.7 % to 11.3 % in single-fuel mode and from 6.0 % to 7.3 % in dual-fuel mode with 50 % biogas, depending on the country. These results emphasise the specific effects of fuel type and vehicle technology to reduce emissions.

A sensitivity analysis was conducted to examine the effect of refuelling frequency on WTW emissions of PHEVs, considering daily battery recharging (Fig. 5). Changing the refuelling period from four weeks to five and six weeks reduced WTW emissions by up to 8 % and 14.2 %, respectively. Conversely, WTW emissions increased up to 10.7 % when refuelling every three weeks, particularly when using fossil fuels in single-fuel mode, with the smallest increase of 1.6 % observed for biogas. These results confirm that intensified use of electricity and reduced use of fuel are highly beneficial to reduce WTW carbon emissions from PHEVs.

3.2. C2G analysis

3.2.1. Midpoint categories

One of the main issues of EVs is their high emission rate during the production process. This is shown by Fig. 6, where HEVs and PHEVs presented higher values for midpoint impact categories in the production stage than ICEVs, especially the human carcinogenic toxicity (HCT), freshwater ecotoxicity (FWE) and marine ecotoxicity (ME) categories. These categories are related to human and ecosystem toxicity and the high values are due to the environmental and human health challenges inherent to the use of metals in the production of the battery pack [9]. Mining metals such as lithium, cobalt and nickel, main elements of lithium-ion batteries, are associated with environmental issues and miners' health, especially where environmental and work safety regulations are less stringent. The industrial processes of manufacturing batteries also involve the handling of toxic chemicals to which workers are exposed. Furthermore, energy consumption during the production process comes predominantly from fossil fuels, resulting in emissions of CO_2, SO_2, NO_X, and other pollutants. Finally, the large volume of transportation of EV components produces environmental impact due to the use of fossil fuels for cargo transport.

On the other hand, HEVs presented lower levels of midpoint environmental impacts than ICEVs while PHEVs presented similar values to ICEVs when analysing the end-of-life stage (Fig. 6). This is largely due to battery recycling, reducing the need to mine new critical materials, and the reuse of EV components, such as electric motors and electronic components, prolonging their useful life and reducing inappropriate

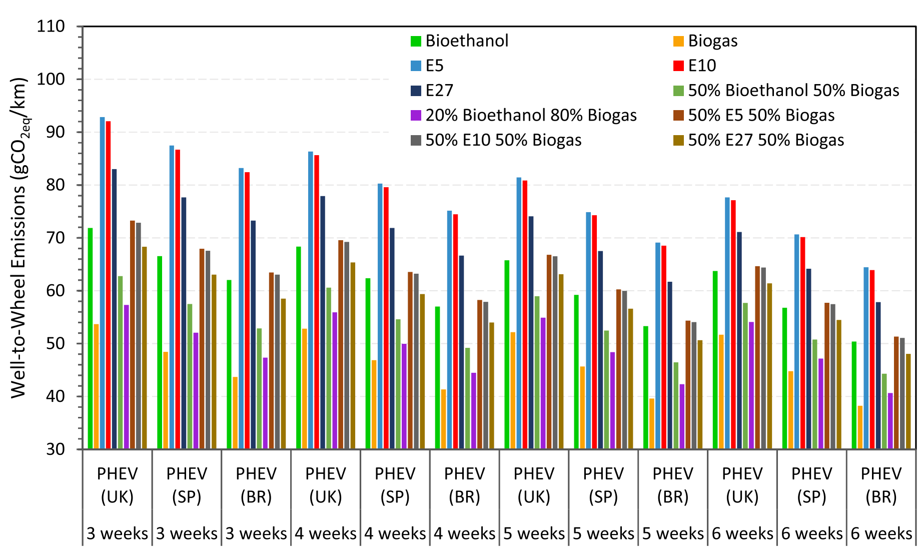

Fig. 5. Sensitivity analysis of WTW emissions for electricity and fuel utilisation in PHEVs.

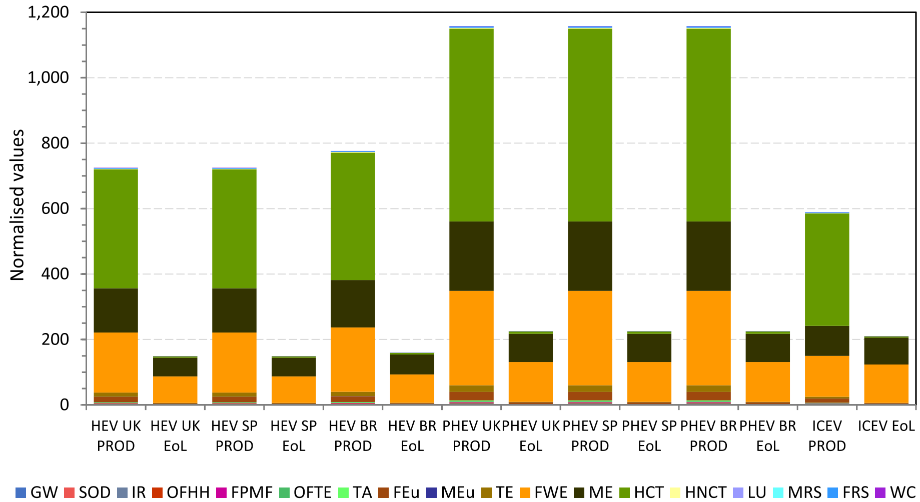

Fig. 6. Normalised midpoint impact categories of production and end-of-life (EoL) of HEVs, PHEVs and ICEV.

disposal. The lowest impact levels presented HEVs can be related to the smaller size of their main components in comparison with PHEVs and ICEVs, such as battery, electric motor and engine.

Through midpoint indicators, the environmental impacts caused by the electricity generation mix in Brazil, the UK and Spain were determined. From Fig. 7, the Brazilian electricity generation mix presented the largest impact in the categories stratospheric ozone depletion (SOD), marine eutrophication (MEu), LU and WC. It can be explained by the predominance of hydroelectric plants in the mix, supplying 55.3 % of internal electricity demand [66]. The construction of hydroelectric plants can alter the flow of rivers in addition to the use of large areas, causing impacts on LU, MEu and, therefore, local aquatic ecosystems. Furthermore, the country faces energy supply uncertainties in periods of prolonged drought and depends on non-renewable sources such as thermoelectric powerplants to meet the energy demand in certain regions, thus causing an impact on the ozone layer.

The Spanish electrical grid presented the highest values for many impact categories due to its high dependence on non-renewable resources (Fig. 7). In 2022, 57.8 % of its electricity was generated by coal, oil, natural gas and nuclear energy, while in the UK and Brazil, these sources represented 58.6 % and 13.0 %, respectively [67]. Due to the large use of nuclear power, the UK and Spain present similar impacts on ionising radiation (IR), which are much larger than in Brazil, where this source is less explored. Also due to the wider presence of nuclear power in Spain, the impacts on ozone formation – which is aggressive in the lower atmosphere layers and, consequently, increases toxicity affecting human health (OFHH) and damage to terrestrial ecosystems (OFTE) – fine particulate matter formation (FPMF), terrestrial acidification (TA), freshwater eutrophication (FEu), HCT and human non-carcinogenic toxicity (HNCT) are larger than in the other countries.

The UK power generation mix presented the highest impact on fossil resource scarcity (FRS), due to its broader dependence on natural gas and coal (Fig. 7). The UK and Spain show similar impacts on global warming (GW), TE, FWE and ME, but higher than Brazil, due to the larger use of non-renewable sources in the European countries. Electricity generation in the UK and Spain also have close impacts on mineral resources scarcity (MRS), higher than in Brazil, as this type of resources is less available in the two European countries.

3.2.2. *Endpoint categories*

Fig. 8 shows the endpoint damage categories of PHEVs, HEVs and ICEVs and the impacts of battery and powertrain on the results. The powertrain plays a significant role in the endpoint damage categories, being more evident in the human health category. The powertrain system of a PHEV has 24.4 % impact on human health while its battery presents 8.4 % impact. The battery and extra powertrain components of HEVs make the difference on human health impact to ICEVs, overcoming the negative impacts caused by the larger engine of the latter.

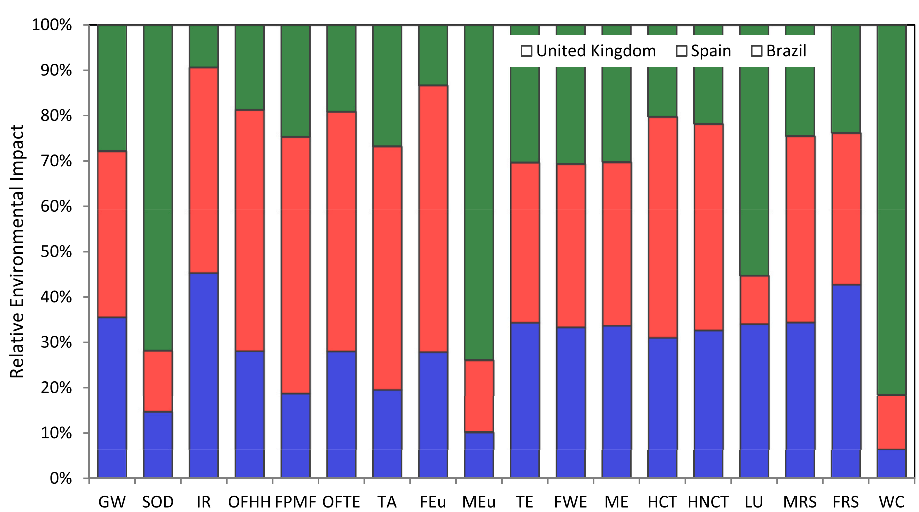

Fig. 7. Midpoint indicators for UK, Spanish and Brazilian electricity generation mixes.

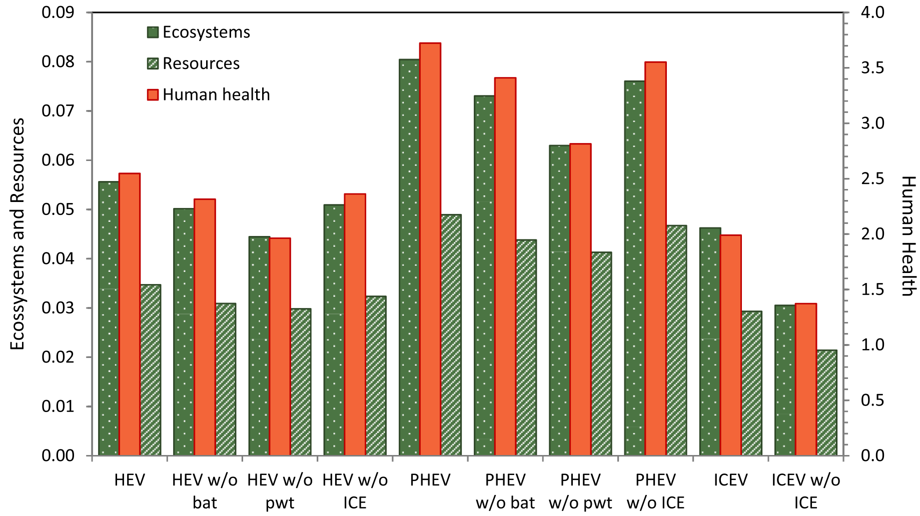

Fig. 8. Normalised endpoint damage categories considering the impact of battery (bat), powertrain (pwt) and engine (ICE) of HEV, PHEV and ICEV.

The engine had smaller influence on the impact caused by HEV and PHEV production, contributing to 7.2 % and 4.6 %, respectively. PHEVs presented the highest ecosystem and resource-related impacts. This is related to the mining of critical materials to produce batteries and electric motors, which directly affects the regional ecosystem with possible water contamination and leads to a scarcity of natural resources.

Fig. 9 shows the impacts on human health, ecosystems, and natural resources of C2G analysis conducted for HEVs, PHEVs and ICEVs. The average consumption of the different fuels here investigated in single-fuel and dual-fuel modes was applied for each vehicle to achieve a comprehensive representation. Even though HEVs and PHEVs have presented high emissions in the production phase of their main components (see Fig. 6) and electricity generation in the countries evaluated are still progressing towards zero carbon emissions, the EVs still present lower impacts than ICEVs in all damage categories when analysing their entire life cycle. Similar results have also been observed in China when comparing EVs against ICEVs [68] and hybrid electric tractors against conventional ones [69]. PHEVs and HEVs show reduced impacts on human health, of 30–38 % and 15–32 %, respectively, in comparison with ICEVs. An analogous approach has shown BEVs in Lithuania reducing the impacts on human health by 55–63 % compared with ICEVs [70], demonstrating a trend of decreased impact with increased electrification. Brazilian HEV presented the highest impact among the HEVs chosen due the technical specifications of the chosen model, which has lower engine power and higher fuel consumption than the Spanish and British models, resulting in higher emissions. On the other hand, Brazilian PHEV presented the lowest impact due to the country's cleaner electricity generation mix, supporting the previous results.

3.3. Final remarks and recommendations

Local energy policies are paramount to support the deployment of EVs and influence their environmental benefits. In 2023, the Brazilian government launched an interim measure to implement a mobility programme which guidelines includes the promotion of the use of bio-fuels and low-carbon fuels, alternative propulsion systems, and appreciation of the energy mix. The programme includes tax relief for vehicle manufacturers and incentives for users, and, according to estimates, it has the potential to reduce emissions by 17 % until 2027 mainly due to the increase of hybrid and fully electric vehicles in the Brazilian fleet. In Spain, the main incentive was a government allowance of up to EUR 9000 for buyers of hybrid and electric vehicles, depending on the vehicle classification. However, this incentive has been scrapped in January 2025 putting in doubt the growth of the electric fleet in the country. In the UK, the government offers a grant to buyers of some types of low-

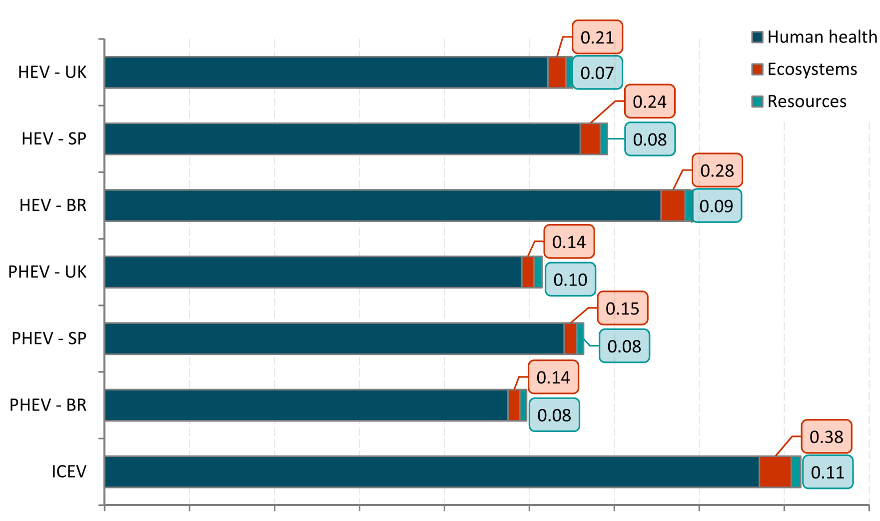

Fig. 9. Normalised endpoint damage categories of production, use and end-of-life phases of HEVs, PHEVs and ICEV.

emission vehicles. The grant is applied as a discount at the act of vehicle purchasing, varying from £500 to £25000 depending on the vehicle category. The types of eligible vehicles include wheelchair accessible vehicles, motorcycles, small and large vans, small and large trucks, and taxis.

The UK government is committed to phase-out the sale of new ICEVs in the country from 2030 in support to zero emission transition. All new cars and vans will need to be 100 % zero emission by 2035. A consultation has been launched to determine what sort of vehicles should be allowed for sale in the 2030–2035 period, with the government proposal to allow PHEVs and HEVs with a 115g CO_2/km vehicle level cap to ensure that the potential emissions reductions are attained. This does not include vans, for which it is proposed a non-ZEV (zero-emission vehicle) fleet average reduction of 10–20 % compared to 2021 manufacturer baseline targets for CO_2 emissions. Spain follows the European Union regulation, which imposes a ban on the sales of new ICEVs from 2035, including cars and vans. Since all new cars cannot produce any CO_2 emissions, the ban will also comprise PHEVs and HEVs. Although Brazil is committed to zero carbon emission by 2050, it does not have a clear plan to phase-out ICEVs yet. However, the Brazilian government incentivises the use of biofuels and alternative propulsion systems that appreciates its clean electricity – an allusion to EVs, especially PHEVs.

The findings of this study highlight the importance of integrating HEVs and PHEVs into carbon reduction strategies, particularly in locations with a high share of renewable energy, which is the case of Brazil. The country supports vehicle manufacturers with tax cuts for the implementation of technologies that increase energy efficiency and reduce carbon emissions. Further promotion of the use of biofuels require subsidies for bioethanol so that car owners can clearly notice advantages on refuelling costs over gasoline. Besides, current tax cuts for car manufacturers should highlight the need to develop technologies that can increase the range of bioethanol-fuelled vehicles closer to what they can achieve when operating with gasoline. There are a few incentives for customers such as reduced road tax, electricity tariff and toll road charges, and low-interest financing for the purchase of a new EV. However, further incentives are recommended for a faster deployment of EVs, especially PHEVs and BEVs, such as the use of bus lanes, car park exemption in urban areas, and government grants to reduce the costs of vehicle purchase and installation of home chargers. Finally, the expansion of public fast-charge infrastructure is vital to increase the confidence of potential EV customers.

Considering the distinct electricity matrices and biofuel availability in the UK, Spain, and Brazil, tailored strategies are essential to maximize the environmental benefits of HEVs and PHEVs in each region. In Brazil, where the energy matrix is predominantly renewable and bioethanol production is well-established, policies should prioritise reduction of bioethanol costs in the pump and incentivise additional development of specific technologies to improve the energy efficiency of vehicle operating with the biofuel. In the UK and Spain, where electricity supply is highly reliant on oil and natural gas, the focus must be on accelerating grid decarbonisation through renewable energy targets and investments in cleaner power generation technologies. For all countries, the expansion of public charge infrastructure is essential to promote larger use of PHEVs and EVs in general.

4. Conclusion

The application of WTW and C2G emissions analyses allowed for a thorough assessment of HEVs and PHEVs carbon footprint. The higher environmental impact during production of these EV types, in comparison with ICEVs, is offset by their superior performance during the use stage, especially when operated with biofuels and in dual-fuel mode. The electricity generation mix significantly influences the environmental impact of PHEVs, with the cleaner Brazilian electricity mix providing reduced emissions. Moreover, EVs have reduced end-of-life impact compared to ICEVs if effective battery recycling is applied to mitigate improper disposal. The main findings of this work are below summarised.

- PHEVs can meet the 2030–2034 EU target for TTW emission of 49.5 gCO_{2eq}/km in any scenario investigated, while HEVs can only attend it when operated with biogas in single-fuel mode in the UK
- PHEVs consistently outperform HEVs and ICEVs in terms of WTW emissions for all countries and fuels considered, with respective reductions of 12–46 % and 59–68 %
- PHEVs present the highest WTW emissions in the UK and the lowest in Brazil for all evaluated fuels, as result of the cleaner electricity generation mix in the South American country
- Due to mining and processing of metals for the battery pack, PHEVs and HEVs cause higher environmental impacts during production than ICEVs, especially in the HCT, FWE and ME midpoint categories
- Mostly based on hydroelectric powerplants, electricity generation in Brazil has higher impacts on SOD, MEu, LU and WC midpoint categories, while the UK and Spain show higher impacts on the toxicity categories due to larger use of fossil fuels and nuclear power.
- Conversely to the midpoint categories, PHEVs and HEVs present lower impacts on human health, ecosystems and resources endpoint categories than ICEVs when considering proper recycling and reuse of batteries.

These findings highlight the potential of HEVs and PHEVs as low-carbon solutions to achieve carbon neutrality targets by reducing emissions in the transport sector. Together with advances in battery technology, expanding use of renewable energy for electricity generation, and extended application of biofuels in specific regions, HEVs and PHEVs can play a key role to contribute to the Paris Agreement pursue to limit the temperature increase to 1.5 °C above pre-industrial levels. The study underscores the importance of tailoring energy and transport policies to local contexts, with a focus on supporting renewable energy adoption and biofuels to maximize the environmental benefits of HEVs and PHEVs.

Further research should focus on exploring the lifecycle environmental impacts of next-generation PHEVs, particularly as battery technology evolves and renewable energy becomes more widespread. An LCA of biofuels from alternative sources in various regional contexts – such as palm oil in Indonesia and Malaysia – is also suggested to provide valuable insights into their potential to locally reduce emissions from HEVs and PHEVs.

CRediT authorship contribution statement

Laene Oliveira Soares: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Jose Ricardo Sodre:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Visualization, Supervision. **Ronney Arismel Mancebo Boloy:** Conceptualization, Methodology, Resources, Visualization, Investigation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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