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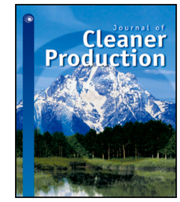

On the road to a sustainable transport mobility in isolated power systems: The role of light-duty powertrain electrification

Óscar García-Afonso *, Itziar Santana-Méndez, Agustín M. Delgado-Torres, Benjamín González-Díaz

Departamento de Ingeniería Industrial, Escuela Superior de Ingeniería y Tecnología (ESIT), Universidad de La Laguna (ULL), Avda. Astrofísico Francisco Sánchez s/n, 38206 La Laguna, Tenerife, Spain

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ABSTRACT

Plug-in vehicles are seen as a promising path to reduce the road transport greenhouse gas (GHG) emissions. However, the singularities of small isolated power systems in terms of the high dependence of fossil fuel-based generation and the relative short distances travelled do require a particular analysis to evaluate the potential emission reduction. This paper describes a simulation study for estimating the energy consumption and the corresponding Well-to-Wheels GHG emissions of different light-duty powertrain architectures subjected to real-world driving conditions, taking the island of Tenerife (Canary Islands) as a test case. The simulations have been carried out with a high-level vehicle powertrain system analysis tool, capable to estimate second-by-second vehicle energy consumption. Road gradient, GHG grid intensity and battery capacity impact on the GHG emission reduction were analysed in detail.

Based on the results, the current high carbon content of the grid and the additional weight of the large battery packs limit the potential benefit of Battery Electric Vehicles (BEVs) with respect to hybrid architectures (HEV). The simulations also reveal that Plug-in Hybrid Electric Vehicles (PHEVs) currently offer a great potential to reduce the GHG emissions. Unlike other geographical areas, the high Utility Factors derived from the short distances travelled ensure the proper use of this technology.

1. Introduction

Passenger cars and light commercial vehicles accounts for approximately 15% of the total CO_2 emissions in the European Union (European Environment agency, 2020). In order to achieve the target of 40% reduction compared with 1990 levels by 2030, the European Commission has expressed their commitment to a low-emission and sustainable mobility (European Commission, 2020). The topics addressed cover the improvement of transport efficiency, the use of low-emission alternative energy for transport, infrastructure deployment for alternative fuels, revision of CO_2 performance standards for light-duty vehicles or a proposal for post-Euro 6 emission standards. In the specific case of Spain, several ambitious targets have been set recently (Gobierno de España, 2020): No tailpipe GHG emissions for light-duty transport by 2050; establishing low emissions zones for medium and big cities; deployment of alternative fuels and the enhancement of the current charging infrastructure for plug-in vehicles.

In this sense, fuel efficiency standards for light-duty vehicles are a proven measure to increase the fuel economy of new platforms. Countries with this type of regulation are able to improve faster the fleet average fuel consumption than countries without policies (IEA, 2019). These standards, together with the corresponding testing procedures, have been able to reduce GHG emissions under lab-based testing. Nevertheless, it is well reported in the literature the gap between lab-based and real-world fuel economy (Uwe Tietge, Sonsoles Díaz, Peter Mock, Anup Bandivadekar and Norbert, 2019). Driver behaviour (aggressiveness) (Neubauer and Wood, 2013, 2014), driving environment (road grade and traffic) (Neubauer and Wood, 2013; Wood et al., 2014; Borlaug et al., 2020a; Rosero et al., 2021) and weather (Alvarez and Weilenmann, 2012) are examples of the main parameters responsible for the fuel economy values variations from the official lab-based numbers reported.

In this context, powertrain electrification does play a key role to reduce the associated GHG emissions. Regenerative braking and a more efficient internal combustion engine (ICE) operation bring along a noticeable fuel economy benefits compared to pure internal combustion engine vehicles (ICEV). Plug-in vehicles are seen as a promising route to reduce the GHG emissions and oil-dependency with respect to

* Corresponding author.
E-mail address: ogarciaa@ull.es (Ó. García-Afonso).

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Nomenclature

a^+	positive acceleration
v	vehicle speed
d	trip distance
R_{CD}	Charge depletion range

Greek

Δt	time step

Abbreviations

TF	Tenerife island
CC	Combined Cycle
ST	Steam Turbine
GT	Gas Turbine
HFO	Heavy Fuel Oil
GHG	Greenhouse Gas
DSO	Distribution System Operator
RE	Renewable Energy
WE	Wind Energy
DI	Diesel
PV	PhotoVoltaic
PHEV	Plug-in Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
UF	Utility Factor
AER	All-Electric Range
WLTC	Worldwide Harmonized Light-duty Vehicle Test Cycle
CD	Charge Depletion
CS	Charge sustaining
SOC	Battery State of Charge
ICE	Internal Combustion Engine
RPA	Relative Positive Acceleration
MHEV	Mild Hybrid Electric Vehicle
TTW	Tank-to-Wheels

hybrid electric vehicle (HEV) based on its higher overall vehicle energy efficiency (Lorf et al., 2013; Genikomsakis and Mitrentsis, 2017). However, determining their potential benefit is a complex task. Besides the aforementioned factors affecting the energy consumption, the benefit of plug-in vehicle mass introduction is affected by the cleanness of the energy source that is used to recharge the vehicles and charging times.

The mass adoption of BEV in isolated power systems has been addressed in the literature by several authors. Pina et al. (2008) and Ramírez-Díaz et al. (2015), Ramirez-Diaz et al. (2016) proposed the use of this vehicle type as a distributed energy storage system to allow further renewable energy (RE) penetration, highlighting the benefits on GHG emission reduction, the total cost of electricity and oil dependence. In this context, *Camus et al.* estimated the number of BEVs required to accommodate additional geothermal capacity in the island of São Miguel (Azores) (Camus and Farias, 2012), outlining the key role of the charging times to ensure enough demand to allow RE penetration. *Guérin et al.* also showed the potential benefit of BEV mass introduction as a potential method to reduce the RE curtailment in Guadalupe island (Guerin and Bucknall, 2016).

Nevertheless, the impact of BEV mass adoption on the grid stability and the charging management is, by far, the topic that has drawn most of the attention. Godina et al. (2015) covered the impact of charging loads on the grid system, highlighting the potential issue of transformer overload after certain number of BEVs. Proposals for recharging structures allowing smart BEV charging based on the Distribution System Operator (DSO) decision (Pina et al., 2014; Ramírez-Díaz et al., 2015; Guerin and Bucknall, 2016) have been proposed. Through this coordinated charging methods, it is possible to reduce the share of conventional energy in the instantaneous generation mix and to match the BEV charging with the availability of RE excess. In this context, the role of vehicle-to-grid (V2G) and vehicle-to-home (V2H) concepts have been studied for many authors as a method to improve the grid stability (voltage and frequency control) and provide spinning reserve under high shares of intermittent RE in isolated systems (Lopes et al., 2009; Pina et al., 2014; Gay et al., 2018).

It is important to note that the numerous quotes presented, related to the decarbonization of the light-duty transport sector in isolated systems, are mainly focused on optimistic virtual scenarios with significant RE and BEV penetration. Nevertheless, the RE energy share is still limited in most of the cases studied and the BEV adoption is low due to the required infrastructure to be deployed or the relative low willingness to pay for this technology without incentives (Ramos-Real et al., 2018). Under these circumstances, short-to-medium term analysis are also key to establish a proper transition to a fully sustainable mobility in the light-duty transport sector. This particular topic is covered in the present paper taking as case study the Metropolitan Area of the island of Tenerife, one of the most populated isolated grid systems in Europe. This choice is based on three main reasons:

- This area accounts for 40% of the daily trips in the island (Cabildo de Tenerife, 2018).
- The relative short distances travelled within this zone fit entirely with the BEV range even for the ones with very limited battery capacity. Therefore, in principle, the lack of range anxiety would not be a barrier for BEV mass adoption by potential customers.
- The significant road gradients between the city centres requires a detailed analysis accounting for road gradient when evaluating fuel economy of different powertrain architectures.

Based on these facts, this study performs a comparison of the vehicle energy consumption and the corresponding Well-to-Wheels (WTW) GHG emissions under real-world driving conditions. The paper is structured as follows: Section 2 covers the methodology, where a detailed explanation of the method applied to gather real-world driving cycles, the simulation work and GHG emission estimation by platform is provided. In Section 3, a WTW analysis of the different platforms subjected to study is performed. Relevant parameters such as powertrain electrification level, local GHG grid intensity and road grade impact are covered in detailed. Finally the All-Electric range (AER) impact on the GHG emission reduction is addressed.

2. Methodology

This section describes the entire simulation method followed in this research. First, the real-world driving data collection and preparation is described whereas the next subsections are devoted to the simulation set-up and the estimation of the island's GHG grid intensity.

2.1. Data-set collection

Tenerife is the largest and most populated island in the Canary archipelago, a group of eight islands located in the Atlantic Ocean at 100 km west of Morocco. Its metropolitan area, located in the north-east part of the island, comprises the two largest urban (interconnected) centres of Tenerife and several medium-low size towns (see Fig. 1). This area, with approximately 440k citizens, contains 40% of the trips within the island (Cabildo de Tenerife, 2018). Besides the overall short distances travelled, the trips are characterized by significant road gradients as Fig. 1 shows. It is worthy to highlight the road gradient

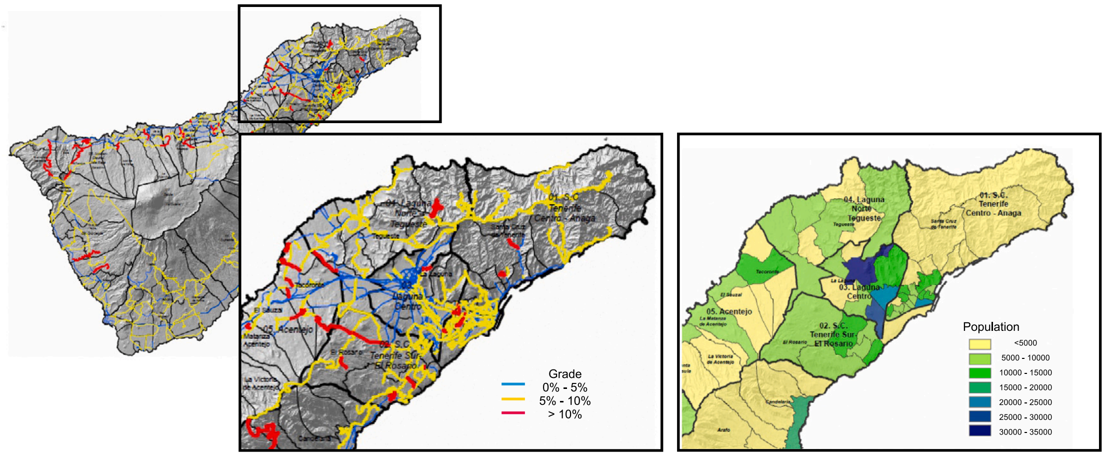

Fig. 1. Road gradient profile and population distribution in Tenerife Metropolitan Area.

above 5% between the two city centres, what accounts for a great number of journeys. The fleet number in the Metropolitan Area reaches 239k of passenger cars. Petrol vehicles dominates the share with a 80% of the total figure. The rest of vehicles are comprised by Diesels (19.7%), LPG (0.17%) and BEV, limited to 0.11% (DGT, 2020).

Representative real-world driving cycles in the Metropolitan Area has been obtained through second-by-second in-vehicle GPS data. 600 trips from 15 drivers of mid-size vehicles were recorded between October 2020 and February 2021. Speed-time profile, location and altitude were available for each trip. Although the sample weight cannot guarantee that the selected sample reflects with accuracy the population, the authors consider that the data collected is enough to perform a preliminary comparison of energy consumption between platforms under real conditions.

The data prepossessing comprised cycle filtering to remove outliers, replacing false zero-speed records and amending signal dropping/gaps. Furthermore, short trips and/or with unrealistic speed profiles were removed from the data-set gathered. As a result, approximately 18% of the cycles were dismissed, with a definitive sample of 490 trips remaining. As an example, Fig. 2 includes the vehicle speed and altitude trace for one of the cycles processed, representative of urban driving within the metropolitan area. Vehicle speed and the gradient, derived from the instantaneous altitude, are the inputs for the subsequent drive cycle simulations.

Fig. 3 shows the distribution of key driving features derived from the processed data. Average vehicle speed, trip distance, idle percentage time, trip average grade, relative positive acceleration (RPA) and mean of square velocity (related to kinetic energy) are shown as histograms. As a matter of comparison, the median of the distribution and the equivalent variables of the World Harmonized Light-duty Vehicle Test Cycle (WLTC) are also included. The relative positive acceleration, what is a good descriptor for the dynamics of a cycle, has been calculated as per Eq. (1):

$$\mathrm{RPA} = \frac{\sum_{i=1}^{n} a_i^+ v_i \Delta t}{d} \tag{1}$$

where a_i^+ accounts for the positive acceleration calculated from the vehicle speed data at time step i, v_i is the vehicle speed at time step i, Δt is the time step and d is the drive cycle distance.

The difference in the median of the average vehicle speed between the data collected and the WLTC, that reaches approximately 10 km/h, reveals larger proportions of urban and rural driving. The reason is the short motorway distances travelled within the metropolitan area. Nevertheless the data seems to be well balanced, as the median of idle percentage time (a good indicator of urban driving) is similar to the WLTC and the number of samples with percentages above 30% is limited.

The driving pattern characteristics previously explained regarding short driving distances and significant road gradients are well captured in the data collected, as both distributions shows. Ruling out the clear differences in the trip distance, the new type approval test is representative of the real-world cycles gathered in terms of cycle dynamic metrics as the RPA evidences.

2.2. Simulation method

The simulation work has been carried out with the open-source code Future Automotive Systems Technology Simulator (FASTSim) tool (Brooker et al., 2015). FASTSim, developed by the National Renewable Energy laboratory (NREL), is a high-level vehicle powertrain system analysis tool capable of estimating the fuel economy of a wide range of powertrain architectures. Taking as input the vehicle speed trace and making use of power-to-efficiency maps for the different components, FASTSim captures the most relevant factors that describe the vehicle road load and energy consumption. Based on its good compromise between model accuracy and complexity, this tool has been extensively used to perform high-level assessment over large datasets (Laberteaux et al., 2019; Borlaug et al., 2020b; Chen et al., 2018; Zhang et al., 2020). Example of tool validation over real-world driving and laboratory-based data can be found in Gonder et al. (2018), Ji and Tal (2020).

2.3. Powertrain architectures subjected to study

To insure fair comparisons, the fuel economy of the powertrain architectures was established based on vehicles of similar size and class. 4 common and mass-produced light-duty powertrains have been modelled: Mid-size conventional petrol engine vehicle (ICEV); full hybrid vehicle (HEV), parallel plug-in hybrid vehicle (PHEV) and Battery electric vehicle (BEV). 48 V MHEVs vehicles have not been modelled in this research, as they will be considered as an evolution of the current ICEV.

The main parameters of the powertrain architectures subjected to study are summarized in Table 1. Although the four models represent real vehicle platforms, the commercial names have been replaced by its powertrain architecture to avoid commercialism issues. The similarities in terms of acceleration time (vehicle performance) guarantee a fair comparison between models. With regard to the fuel-type, only petrol will be considered as both Diesel and LPG represent less than 20% of the passenger vehicle fleet in the island (DGT, 2020).

Table 1 also includes the comparison of the EPA simulated and label fuel economy/energy consumption for each architecture, what demonstrates that the tool is able to capture the vehicle energy consumption with acceptable accuracy.

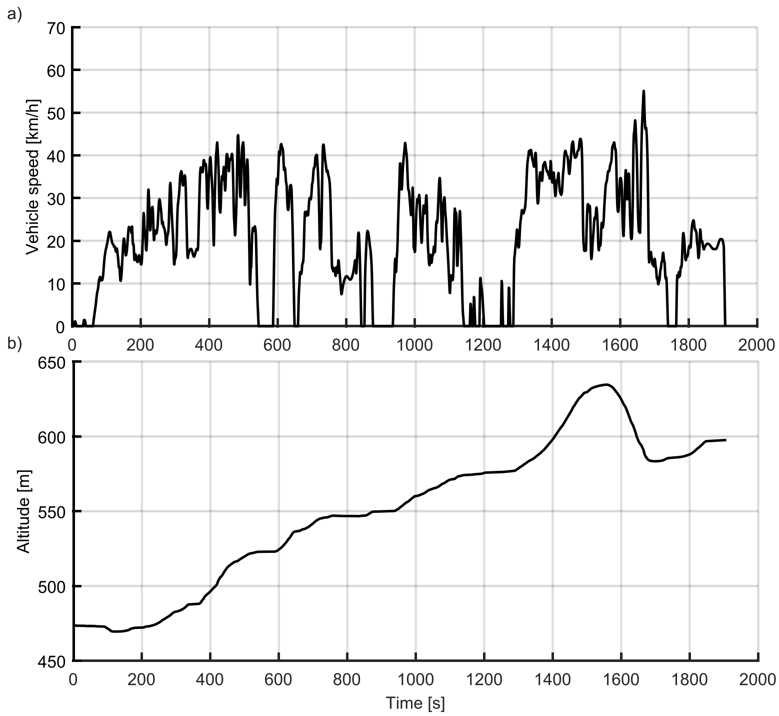

Fig. 2. Example of driving cycle: a) vehicle speed and b) altitude.

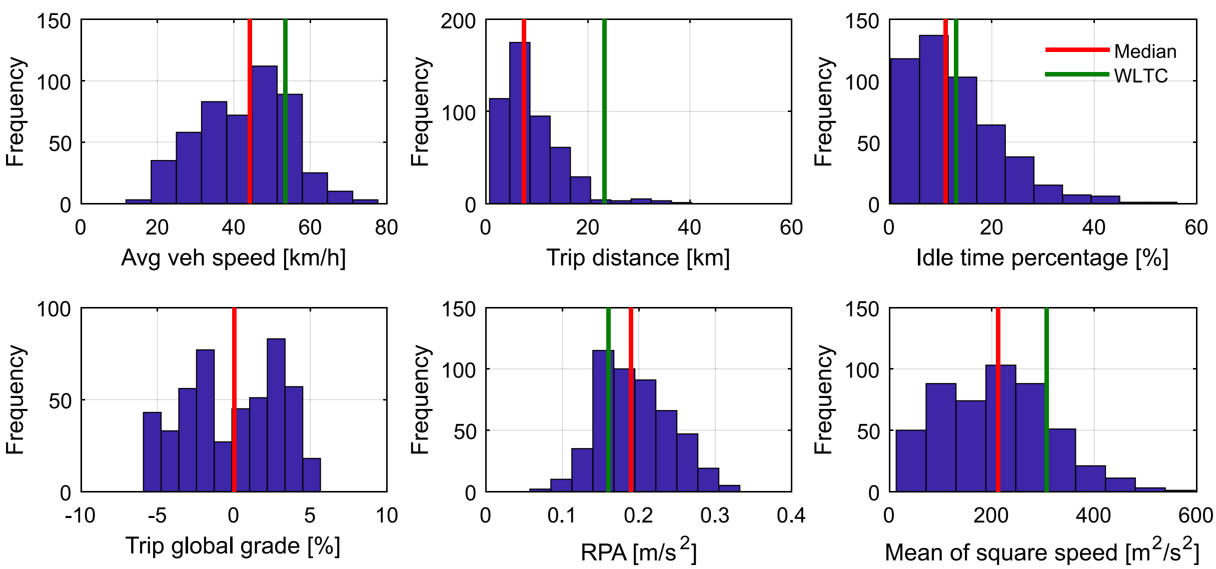

Fig. 3. Driving feature distribution in the collected data-sets.

Table 1
Baseline model parameters for the different powertrain architectures studied.

Parameter	Mid-size ICEV	Mid-size HEV	Mid-size PHEV	Mid-size BEV
Frontal Area [m^2]	2.5	2.52	2.58	2.7
Drag coefficient [–]	0.29	0.29	0.27	0.3
ICE power [kW]	103	73	71	–
Motor power [kW]	–	53	53	110
Battery capacity [kWh]	–	1.3	8.8	40
EV range [km]	–	–	40	240
Acceleration time (0 to 100 km/h)	8.5	10.5	10.5	8
Simulated mass [kg]	1476	1505	1662	1715
Fuel	Petrol	Petrol	Petrol	–
EPA simulated (Actual) comb FE [L/100 km; kWh/100 km]	7.4 (7.2)	4.8 (4.5)	CS: 4.5 (4.4) CD: 16.25 (15.53)	17.5 (18.75)

Table 2
Description of Tenerife power system (Gobierno de Canarias, 2020).

Technology	Gross installed [MW]	Generation [GWh]	Share [%]	Fuel	Average thermal efficiency [%]
Combined Cycle (CC)	456.8	1569.4	42.3	Diesel	47
Steam turbine (ST)	240	1146.9	30.9	HFO	33
Gas Turbine (GT)	265.7	105.6	2.9	Diesel	24
Diesel engine (DI)	84	192.7	5.2	HFO	43
Wind energy (WE)	195.65	495.3	13.3	–	–
Solar photovoltaic (PV)	116	189.1	–	–	
Small hydropower	1.2	3.5 0.1	–	–	
Biogas plant	1.6	8.1	0.2	Biogas	–

2.4. GHG emission estimation

The present study is based on a WTW analysis. Under this condition, the GHG estimation for any architecture accounts for both the vehicle energy use and the upstream emissions related to the supply chain (fuel production, transport and distribution). The WTW emission factor for petrol has been set to 0.314 tCO_2eq/MWh, according to the EU CoM Default Emission Factors (Koffi et al., 2017).

The grid carbon intensity has been estimated based on the current generation-mix in the island, included in Table 2. Generation-set technology, gross installed capacity, share of electrical energy generated, fuel used and the actual annual average thermal efficiency are given (Gobierno de Canarias, 2020). This isolated power system is characterized by a great dependence of fossil fuels for electricity generation due to the low penetration of RE. Diesel is fed to open cycle gas turbines and combined cycles, whereas heavy fuel oil (HFO) is used in the steam boilers and the DI engines. From the 10 min-based power registered by the DSO, the average efficiency of the different units (Gobierno de Canarias, 2020) and the fuel emission factor (set to 0.306 tCO_2eq/MWh for Diesel and HFO based on the EU CoM Default Emission Factors (Koffi et al., 2017)) the equivalent GHG emissions (gCO_2eq/kWh) can be estimated. The contribution of the small hydropower and the biogas plant to the total generation is negligible, so it has not been taken into account in the calculations. Finally, a 7.2% losses associated to the transport and distribution of electricity has been included based on data provided by the DSO (Gobierno de Canarias, 2020).

Fig. 4(a) shows the real time covering of electrical energy demand in the island by technology, registered by the DSO. The data corresponds to 3 consecutive days in the first week of 2019. More recent data has been dismissed as it is not considered representative due to the current low activity in the island derived from the COVID-19 pandemic. Fig. 4(b) shows the corresponding estimated GHG grid intensity. Without any large-scale energy storage facility in place, the conventional generator-sets must modify significantly their load to cover the power demand of the island. This is clearly shown during valleys (overnight), where there is no PV contribution and the total amount of non-conventional power is supplied by the WE. This is an unusual scenario for ST and CC in continental regions, where the main role is to provide based power supply. This off-design operation explain the low efficiency values shown previously in Table 2, particularly by the CC.

As a result of the power plant load control a highly variable GHG grid intensity is found, what is function of both the demand and the RE resource availability. With the current generation-mix technology, overnight charging presents high GHG grid intensity levels, becoming extremely high in events of low WE generation. As a consequence, plug-in vehicles do not get benefit of the low GHG intensity levels that can be found in connected power systems with alternatives power-generation mixes (Robinson et al., 2013). This fact does limit their potential for GHG emissions reduction.

Table 3 includes the annual average GHG grid intensity, estimated in 680 gCO_2eq/kWh. In order to validate this result, the island's generation mix has been modelled with GREET, an analytical tool able to simulate the energy use and emissions of a wide variety of vehicle and fuel combinations (Argonne National Laboratory (ANL), 2018). Examples of tool application to carry out similar WTW and LCA analysis can be found here (Rosenfeld et al., 2019; Shi et al., 2019; Wang et al., 2020). Based on the thermal efficiency of the generation units, the annual share of generation by technology and Greet's emission factors database, the grid intensity result is 710 gCO_2eq/kWh. The similarities between both results ensure the robustness of the input data to conduct the subsequent powertrain comparisons.

Table 3
Grid GHG intensity in the island.

Period	Grid GHG intensity [gCO_2eq/kWh]
2019 TF	680
2019 TF daytime (8 am–8 pm)	645
2019 TF evening/Overnight (8 pm–8 am)	716
2019 TF (GREET)	710
2019 Spain	240

The annual average for daytime and overnight is also included in Table 3. An 11% reduction is found during day-time due to the PV contribution. This reduction is expected to be even higher in the near future due the noticeable incentives that this technology is going to have in this decade, aligned with Energy and Climate National Integrated Plan 2021–2030 proposed by the Spanish Government (Plan Nacional Integrado de Energia y Clima, PNIEC) (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020). This behaviour states that the plug-in vehicles charging patterns might have a significant impact on the indirect GHG emissions in the future. As a matter of comparison the GHG emission of electricity in Spain is also included. Due to the complexity of modelling the entire system, the data has been extracted from direct emissions based on EEA (2020) and corrected to take into account the upstream emissions related to the fuel supply chain. The important differences in terms of grid carbon content between the island and mainland are related to the presence of natural gas, nuclear, hydropower and higher penetration of the rest of RE in the latter. Therefore, plug-in vehicles in the island will not get benefit of the low carbon grid intensity levels as in mainland, what would limit considerable their potential for GHG emission reduction.

2.5. Baseline simulation and modelling assumptions

The 4 powertrain architectures described in 2.3 were simulated using FASTSim across the 490 trips considered. The vehicle models have been configured with the parameters described in Table 1. Every simulation has been performed twice, with a without taking into account the road gradient. This would allow estimating its impact on vehicle energy efficiency.

The following assumptions have been considered during the simulation process:

- Plug-in vehicles (PHEVs and BEVs) are fully charged at the beginning of each trip. This means that PHEVs do start in charge depletion (CD) mode in each test. In case of battery depletion, the strategy switches to charge sustaining (CS) mode, operating from this moment as a HEV.

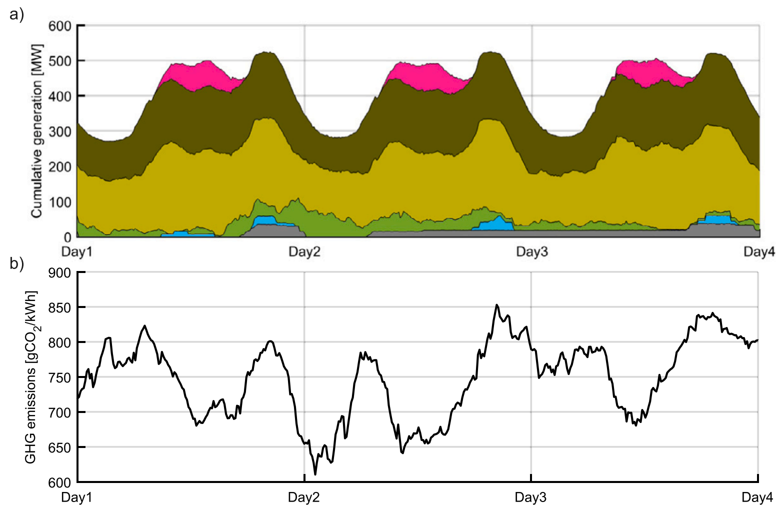

Fig. 4. Cumulative generation (a) and estimated grid GHG intensity (b) for 3 consecutive days in 2019: Week1.

- A Battery round-trip efficiency of 95% has been used for all electrified platforms (ITP Renewables, 2020).
- Additional losses from cabin and battery pack thermal management have not been taken into account.
- Due to the low numbers of BEVs and PHEVs in the island, there is a lack of representative recharging profiles than could be applied. Instead, profiles representing private users from the research of *Robinson et al.* have been used (Robinson et al., 2013). Based on this work, the proportion of day-time recharging events would be 30%, whereas the evening/overnight charging would represent the other 70%. This scenario would result in an overall GHG grid intensity of 694 gCO_2eq/kWh, used as input to estimate the WTW GHG emissions of plug-in vehicles.

3. Results

As a result of the baseline simulation process, a wide range of energy consumption values are available for each case. The equivalent WTW GHG emission values (calculated based on the methodology described in 2.4) for each trip and architecture are shown in vertical box plots in Fig. 5. Only charge depletion (CD) mode for PHEV is shown, as the AER of the PHEV model was large enough to cover any cycle. However, this fact does not mean that the ICE has been switched-off the whole time. Under events of high power demand, the ICE can be turned on even at high levels of battery SOC.

Driving behaviour and the average trip gradient explain the important variability in estimated GHG emissions for each architecture. The first quartile corresponds to low demanding drive cycles associated with negative average gradient and low cycle dynamics. The opposite trend is found in the Q4 region with noticeable GHG emissions, corresponding to drive cycles characterized by positive road gradient and high cycle dynamics.

The benefits of powertrain electrification are clearly seen in the large reduction of GHG emissions that HEV brings compared to ICEV. Regenerative braking and e-motor assistance allow the ICE to operate at higher efficiencies. As a result, looking at the median of both distributions, up to a 40% GHG reduction might be achieved shifting from solely ICE-based powertrain architectures to HEV.

Higher levels of electrification bring along a further GHG emission reduction due to the superior e-motors average efficiency and the higher hardware capacity to recover energy from regenerative braking. However, the large carbon content of the grid in the island does prevent these powertrain architectures from reaching low WTW GHG emissions. This result points out that promoting high level of electrification, in particular plug-in vehicles, which require a massive investment in both infrastructure and subsides must come with the de-carbonization of the grid system. Simulations reveal reduction levels of 53% and 50% for PHEVs in CD mode and BEVs respectively. With this energy-mix, vehicle class and drive cycles modelled, PHEV is the powertrain architecture that achieves the largest GHG emission reduction. Several authors have also suggested the better PHEV performance for GHG emission reduction under high carbon intensity grids (McLaren et al., 2016; Plötz et al., 2017; Laberteaux et al., 2019).

Fig. 6 shows the overall GHG emission as function of the powertrain architecture and GHG grid intensity. Although it is expected a continuous improvement in the ICE technology (injection systems, turbocharging, energy management, electrification or waste heat recovery) (Serrano et al., 2019), only GHG reduction based on grid intensity is considered.

Based on the predicted energy consumption, the trends reveal that the gap between HEVs and PHEVs/BEVs is not relevant up to an average GHG grid intensity below 600 gCO_2eq/kWh. This is not possible with the current power-generation mix, therefore plug-in vehicles mass introduction would not enhance the emission reduction in the light-duty transport sector. For reference, the GHG grid intensity of the isolated grid systems of La Gomera (LG), calculated with GREET, is also included. In this island, characterized by a negligible penetration of RE energy, a massive adoption of BEV would result in a GHG emission penalty with respect to similarly sized HEV. A completely different scenario can be found in mainland Spain, included also in Fig. 6. In this case, with a much lower carbon grid intensity, rightly sized BEV/PHEV architectures could bring the WTW GHG emissions in the transport sector down.

Fig. 6 also includes a Tenerife 2030 scenario, proposed by the authors. It is important to note that the main aim of this exercise is not to predict the real trend in the decarbonization of the power-generation sector of the island, but to set a basis for obtaining an average GHG grid intensity that allows high-level powertrain comparisons. Aligned with the PNIEC, a maximum share of 50% for fossil fuel-based generation in the Archipelago is targeted. Based on this objective, Table 4 includes the results of the proposed scenario taking several assumptions aligned with the feasibility assessment carried out by Monitor Deloitte and supported by Deloitte (2020). The annual RE capacity is increased by 118 MW/year, as a PV/WE ratio of 80–20. The same capacity factor for PV technology has been kept, due to the mass introduction of storage capacity for both utility scale and self-production (Gobierno de Canarias, 2021). On the contrary, as a result of such a tremendous increase in WE capacity, noticeable rates of curtailment are expected. In this simple exercise, it has been assumed that a 25% of the total WE generation must be taken out of the grid (Deloitte, 2020). Finally,

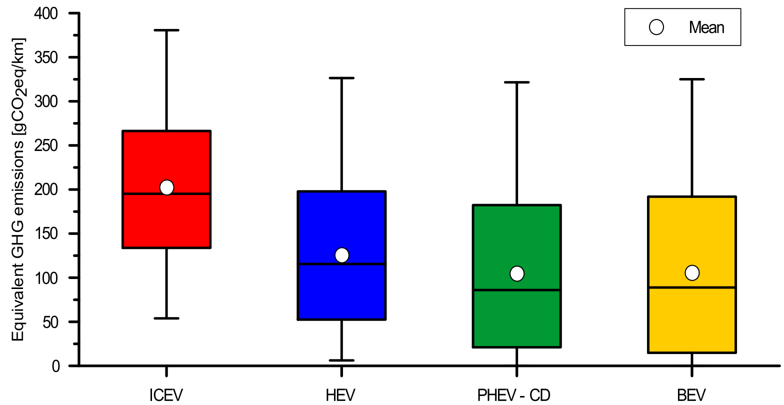

Fig. 5. Equivalent WTW GHG emission box plots of all powertrain architectures subjected to study.

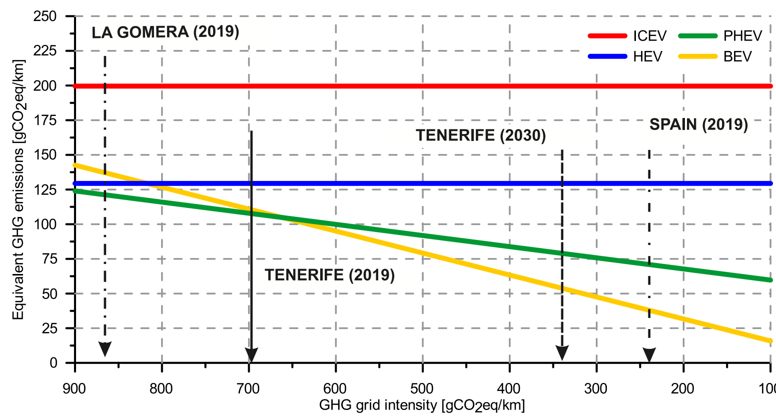

Fig. 6. GHG emission based on powertrain electrification level and GHG grid intensity.

a 3.5% increase in electrical energy demand has been considered, what accounts for a higher share of electricity in the final energy consumption.

Based on this scenario, where fossil-fuel technologies would satisfy 50% of the electrical energy demand of the island, a restructure of the conventional generator-set would be required. Such a complex work is out of the scope of this work, as it requires a deep analysis covering the spinning reserve, response to frequency changes, etc. Instead, it has been assumed that ST and DI are to be taken out of service permanently and GT would only operate to cover potential peak demands. Therefore, applying the same methodology described in 2.4, Tenerife 2030 scenario would reach a GHG grid intensity of 340 gCO_2eq/kWh. Despite the economical and technological challenge that the reduction of fossil fuel-based generation share to 50% in isolated systems implies, the GHG grid intensity would still be noticeably higher than the current one in mainland Spain or Europe. This fact evidences that the electrification strategy in the Canary Islands for GHG reduction in the light-duty sector should be different. Based on the trends analysed, promoting BEVs should be shifted to mass introduction of efficient hybrid platforms as a short-to-medium strategy to achieve important GHG reductions.

Table 4
Current and future (estimated) description of Tenerife power system.

Power generation mix	TF (2019)	TF (2030)
Conventional power capacity [MW]	1046.5	–
Conventional generation [GWh]	3015	2502
RE capacity [MW]	312	1487
RE generation [GWh]	684	2539
Curtailment [%]	–	24 (only WE)
Average GHG grid intensity [gCO2eq/kWh]	694	340

3.1. Road grade impact on CHG emissions

The sensitivity of each platform to the road grade is explored in this subsection. Fig. 7 shows the GHG emissions of every cycle simulated with each architecture as function of the trip average gradient. A second order polynomial has been fitted to the each set of data for a better comparison between vehicles. The trends clearly show that for any simulated powertrain architecture, energy consumption and therefore GHG emissions increase or decrease considerably depending on the road grade characteristics.

Powertrain electrification gets benefit from regenerative braking during downhill deceleration events in driving cycles with negative average road gradients. This hardware capacity does explain the extremely low GHG emissions for HEV, PHEV and BEV. MHEVs, considered as an ICEV evolution and therefore not included in this study, could also benefit from their 48 V system. Although limited compared to the high voltage systems counterparts, these architectures would also bring along a GHG emission reduction.

Nevertheless, as the average road gradient becomes positive the aforementioned positive effect dwindles and the gap in the emissions is reduced with respect to ICEV, tending to collapse at high average road gradients. The reason resides in the additional battery weight, which damages the vehicle energy efficiency. This behaviour is especially noteworthy in BEVs, presenting higher emissions than HEV and limited benefit compared to ICEV.

The previous analysis is complemented with a gradient penalty estimation for each architecture, calculated as the difference between the GHG emissions with and without taking into account the gradient in the simulation. These results, included in Table 5, intend to provide a general overview of the sensitivity of each platform to the gradient.

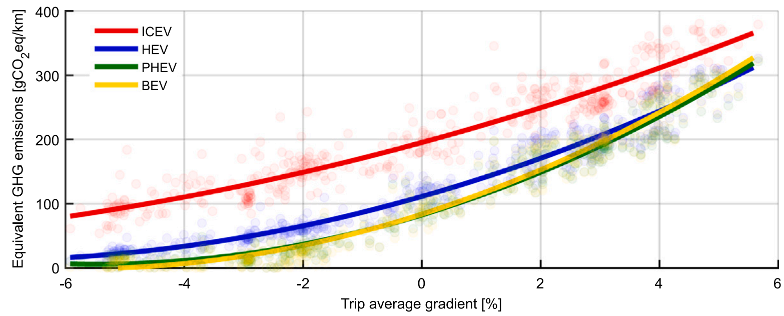

Fig. 7. Road gradient impact on powertrain performance: GHG emissions as function of the powertrain architecture and road gradient.

Table 5
GHG emission penalty when road gradient is considered.

Platform	Penalty [gCO2eq/km]	Penalty [%]
ICEV	20.1	14.5
HEV	19.4	23.3
PHEV	22.8	34.4
BEV	15.3	19.2

Similar absolute penalty numbers in the range of 15–23 gCO_2eq/km are found, without a clear trend with the electrification level. The results are a balance between the benefit of regenerative braking during downhill deceleration and the penalty during uphill (additional weight). It is worth mentioning the slightly higher sensitivity the PHEV platforms present. The reason resides in the larger number of times that the ICE must start, which degrades slightly the overall vehicle efficiency. Nevertheless, this behaviour is closely related to the energy management strategy, which is simplified in FASTSim. More precise results would required a detailed description of the hardware and software.

3.2. All-electric range capacity impact on GHG reduction potential

Increasing the AER of PHEVs results in higher shares of CD mode, whereas in BEVs reduces the driver's range anxiety. Larger battery capacities are required to meet this requirement, leading to both higher vehicle cost and weight. Besides the larger e-motor size to meet the vehicle performance requirements, heavier vehicles do have a negative effect on vehicle efficiency. This AER–vehicle energy efficiency trade-off, closely related to the driving distances patterns, is discussed in this section.

To get a perception of the optimum range of plug-in vehicles, additional architecture models have been simulated. The baseline PHEVs and BEVs models have been used to generate new plug-in vehicles with different battery pack capacity. Changes in battery size will have an impact on the AER and the overall vehicle energy efficiency, that will be estimated by FASTSim. E-motor power has also been modified to keep the same power-to-weight ratio than baseline vehicle in order to maintain vehicle performance. As a result, 6 new plug-in vehicles are available for comparison:

- PHEVs with battery packs of 8.8 (baseline), 10 and 13 kWh. This range covers a large part of the current available plug-in hybrid battery packs in the market (Julius Jöhrens, Dominik Räder, 2020).
- BEV with battery packs of 30, 40 (baseline), 50 and 60 kWh, what is a representative range of mid-size class full electric vehicles.

The overall equivalent GHG emission and AER results as function of the battery pack capacity after simulating the new vehicle models over the entire set of data are shown in Fig. 8. The AER estimation for both PHEVs and BEVs have been done based on the EPA Federal Test Procedure to keep consistency with the data shown in Table 1. Although ICEV and HEV do not have all-electric range capability (or very limited in the case of HEV), their GHG emissions have been included as a matter of comparison.

Based on the simulation results, HEV (ICE with a small battery pack) allows a 35% GHG emission reduction. Although higher electrification levels provide further reductions, the GHG reduction per unit increase in battery capacity drop considerably as Fig. 8 clearly shows. This result highlights the important role of the ICE-based vehicle development as a transition path for a sustainable road-transport. Highly efficient ICE and advanced energy management strategies together with renewable fuels, such as e-fuels from RE excess and CO_2 capture, shows a great potential to achieve solid GHG emission reduction in light-duty road transport.

Increasing PHEV AER through battery capacity is a common trend (Laberteaux et al., 2019) and industry approach. Nevertheless, no benefit is found in the set of data analysed due to the short distances travelled. None of the trips evaluated present travel distances above the shortest PHEV AER. Therefore, increasing battery capacity to provide an additional 15 km under CD result in a slight GHG emission penalty of 3.5%. The impact of the Industry trends to tackle BEV range anxiety by increasing battery capacity is also observed in Fig. 8. Enlarging the battery capacity from the baseline (40 kWh) to the upper range (60 kWh), what is representative of the battery pack size options of the same vehicle model that an OEM might offer, result in a GHG penalty of 7.2% and very limited GHG reduction with respect to HEV.

Previous analysis are based on individual cycles, assuming a fully charged plug-in vehicle before each trip. However, intermediate charging events are not always possible, either due to short stops or because there is not an available charging point. Therefore, it is a common practice to evaluate the AER requirements based on the total daily travel distance. With this aim, an additional data-set statistically relevant collected via GPS during 2018 has been used. This information is part of a global mobility study carried out every decade by the local authorities of the island (Cabildo de Tenerife, 2018). Fig. 9 shows the estimated daily travel distance distribution in a working day from private passenger car users in the metropolitan area. 90% of the daily trips present travel distances below 27 km, whereas half of the vehicles travel less than 12 km per day.

As a matter of comparison, data analysis from large data-sets in European regions such as Modena, Firenze, Paris, Amsterdam or Luxembourg by Paffumi et al. (2018) showed that the median is set in the range of 30–40 km/day and the 3rd quartile ranges from 50 to 60 km/day. This comparison points out the significant differences in terms of travel distance between Continental Europe and small islands such as Tenerife, what eventually sets a completely different AER requirements for plug-in vehicles.

The AER of the baseline BEV (40 kWh) meets 4 times (see Fig. 8) the 50 km daily distance that covers more than 99% of the drivers in the area. The GHG emission penalty for not including a smaller battery pack (30 kWh) that covers approximately 3 times the previous requirement, reaches the 3.8%. This result points out that promoting

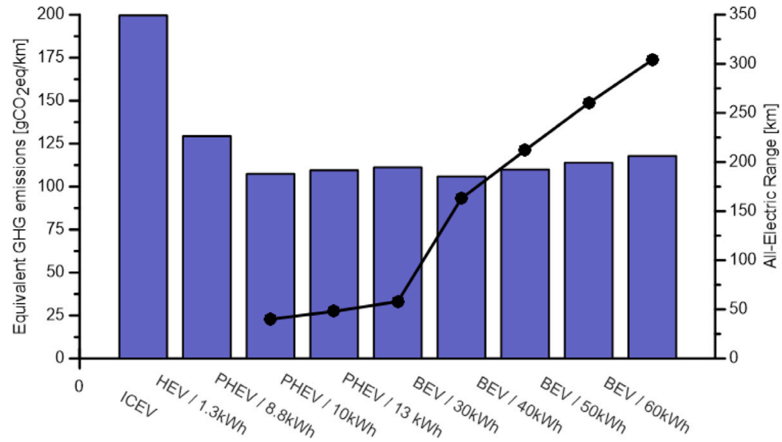

Fig. 8. Overall equivalent GHG emissions and AER as function of the battery pack capacity.

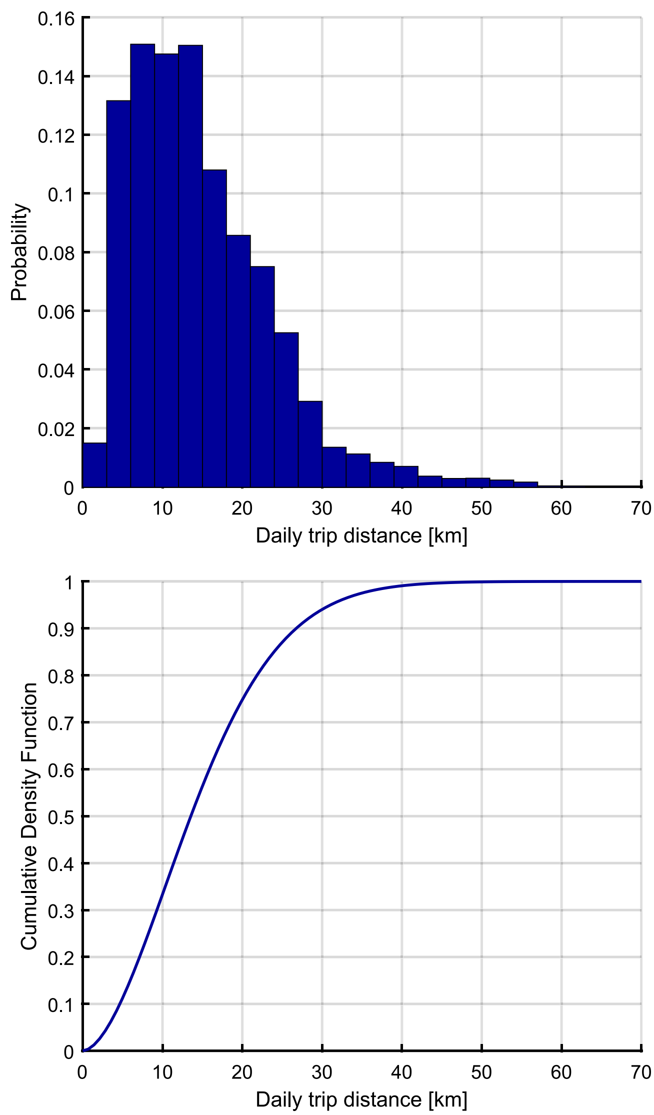

Fig. 9. Daily travel distance distribution in Tenerife Metropolitan Area.

plug-in vehicles, in special BEVs, must be accompanied by a detailed evaluation of the local driving pattern to ensure an effective GHG emission reduction.

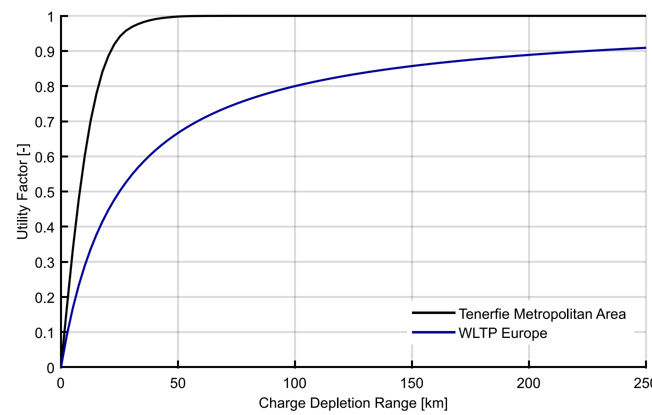

Fig. 10. Fleet Utility Factor calculation for the Tenerife Metropolitan data-set compared to the European WLTP.

PHEV architectures have demonstrated the highest capacity for GHG emission reduction based on the current and near future power-generation mix. Nevertheless, the potential benefit depends heavily on the CD share of the total distance travelled, usually quantified by the Utility Factor (UF). The standardized J2841 UF (Society of Automotive Engineers, 2010) is calculated according to Eq. (2):

$$UF = \frac{\sum_{k}^{n} min(d(k), R_{CD})}{\sum_{k}^{n} d(k)} \quad (2)$$

where $d(k)$ is the daily distance travel of the vehicle k in the corresponding data-set and R_{CD} is the charge depletion range.

This method assumes that the vehicle is fully charged before the first trip of the day is performed, and it is not charged until the end of the same day. Low Utility factors derived from travel distances far beyond the AER capacity between charging events involves longer periods under charge sustained mode, what eventually impact vehicle emissions. Fig. 10 shows the SAE J2841 UF calculated for Tenerife Metropolitan Area. The corresponding European WLTP has been also included, based on the Regulation 101 of the UNECE (UNECE, 2020). The short trips characterizing this geographical area explain the high UF depicted in Fig. 10, above 80% at 20 km. To get the same UF in the European WLTP it is required a 100 km AER, what is out of the parallel PHEV architecture design philosophy.

The PHEV AER numbers previously shown correspond to the EPA Federal Test Procedure. In order to get the real-world AER in Tenerife Metropolitan Area, a charge depletion test has been performed with the baseline PHEV model (8.8 kWh battery pack). The drive cycle selected is characterized by a nearly 0% global road gradient, but with

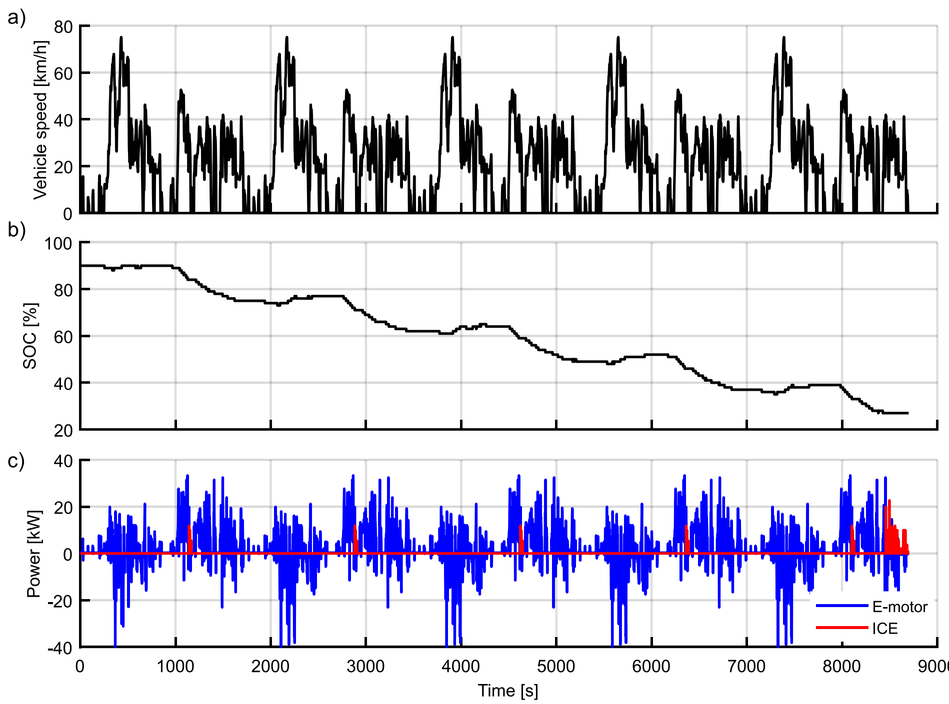

Fig. 11. Charge depletion test: (a) Vehicle speed, (b) Battery SOC and (c) ICE and e-motor power.

significant local gradients. In terms of energy consumption, this test covers the 75% of the samples (first data-set). Fig. 11(a), (b) and (c) show the instantaneous profiles of vehicle speed, SOC and powertrain operation respectively. The test consists of repeating the drive cycle from fully charged battery conditions until battery depletion.

At the end of the last part of the 5th cycle repetition the SOC reaches the lower limit and the ICE is turned on, working in CS mode. From this moment, the PHEV operates as a HEV where the ICE maintains the battery SOC. Although the PHEV has been operating under CD mode, it can be observed short periods in which the strategy turns the ICE on when the e-motor power cannot satisfy the power demand. This behaviour, coming from a simplified energy management strategy in FASTSim, has been reported previously by Ji and Tal (2020).

From this test, the estimated AER from a mid-size PHEV under real-world driving conditions is 50 km, what is a 25% higher than the EPA procedure. Hence, based on the UF profile shown previously in Fig. 10, a mid-size PHEV with a battery pack of 8.8 kWh (low range of the market (Julius Jöhrens, Dominik Räder, 2020)) would have almost 100% UF. This result points out that promoting PHEV with larger battery packs would not be translated in lower GHG emissions, but totally the opposite. This result reaffirms PHEVs as a clear alternative to reduce GHG emission in the area subjected to study. The high UFs exhibited ensure the correct use of the technology at any time, even under the conservative definition of the UF where intermediate recharging events are not considered.

4. Conclusions

This paper explores the WTW GHG emission of different light-duty powertrain alternatives in the island of Tenerife under real-world driving conditions. This test case is representative of small isolated power systems with a large proportion of conventional generation and where high levels of RE penetration present a technical challenge. Second-by-second vehicle speed and altitude profile from several drivers were available to feed the high-level vehicle powertrain simulation tool FASTSim. The main conclusions from the simulation work are the following:

- The current high GHG grid intensity and the heavy weight of the battery packs limit the potential of BEVs to reduce significantly the GHG emission. Although the differences are limited with respect to BEVs, PHEVs (ICE and a relative small battery pack) provide the lowest GHG emission levels across the entire set of trips analysed.
- The regenerative braking in downhill deceleration events allows the electrified powertrains to reduce significantly the GHG emissions. Nevertheless positive gradients narrow this reduction down, with limited benefit provided by electrified powertains above average road gradients above 5%.
- The parametric study of the GHG grid intensity evidences the long route and the high investment required to reduce notably the GHG intensity of the grid. This is currently a barrier to maximize the benefit of plug-in vehicles. Efficiency increase, the use of cleaner fuels in conventional generator-sets and an effective RE energy penetration must be set as a first step prior to establish government-based strategies to deploy a large number of plug-in vehicles across the island. Even in the optimistic 2030 scenario, where RE share might reach 50%, mid-size BEV GHG emissions would still be in the range of 50 $gCO2eq/km$. This result points out the need of complementary routes to achieve a further reduction of GHG emissions in the light-duty transport sector. HEVs running with fuels from renewable energy source (minimizing curtailment) and carbon capture might be a promising route for a medium-long term. In this context, life-Cycle Analysis (LCA) of a wider range of powertrain architectures and fuels, together with more precise energy-mix scenario would be the right methodology to assess potential alternatives.
- The impact of the battery size on plug-in vehicle efficiency was also studied across the real-world driving cycles. The short daily travel distances in the metropolitan area ensure high UFs for PHEVs even with small battery packs. Therefore, industry trends to reduce fleet CO_2 emissions enlarging battery packs would not result in a further GHG emission reduction for PHEVs in the geographical area subjected to study. Similar results are found for BEVs. Current mid-size BEV battery packs allows an AER that is in the range of 3-to-6 times the daily requirements of Tenerife

Metropolitan Area. The fact of not selecting a rightly-sized battery capacity would result in a penalty of 7.6%, presenting similar GHG emissions than HEV.

CRediT authorship contribution statement

Óscar García-Afonso: Investigation, Conceptualization, Methodology, Writing – original draft. **Itziar Santana-Méndez:** Investigation, Conceptualization, Writing – review & editing. **Agustín M. Delgado-Torres:** Conceptualization, Methodology, Writing – review & editing. **Benjamín González-Díaz:** Conceptualization, Methodology, Writing – review & editing.

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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