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Integration of Drivers' Routines into Lifecycle Assessment of Electric Vehicles

Apostolos Vavouris[a,*], Lina Stankovic[a], Vladimir Stankovic[a]

[a] *Department of Electronic & Electrical Engineering, University of Strathclyde, 16 Richmond St., Glasgow G1 1XQ, United Kingdom*

Abstract

With the aim of minimising Green House Gases (GHGs) emissions, older Internal Combustion Engine Vehicles (ICEVs) are being banned from circulating in city centres around the world. Different legislations have been passed to phase-out ICEVs with the parallel introduction of cleaner means of transportation such as Battery Electric Vehicles (BEVs), Plug-In Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). While different Life Cycle Assessment (LCA) models that calculate the carbon footprint of vehicles exist, these models tend to average the carbon footprint per energy unit throughout the day—instead of measuring the actual carbon footprint during charging times, which is directly correlated to the generation mixture at that specific point—and therefore fail to accurately map emissions. In this paper actual time of charging is incorporated in LCA aiming to increase the accuracy and the fairness of the comparison of the different technologies, using actual consumption data gathered from different countries in Europe.

Keywords: Electric Vehicles (EVs); Life Cycle Assessment (LCA); Electricity Sources; Smart Charging; Non-Intrusive Load Monitoring (NILM)

1. Introduction

The profound climate crisis combined with Net Zero targets is accelerating the introduction of novel vehicular technologies that utilise electricity instead of common fossil fuels such as petrol and diesel. According to the International Energy Agency (IEA), at the end of the 2021 more than 16.5 million Electric Vehicles (EVs) were in use with the Net Zero Emissions Scenario expecting more than 300 million EVs to be in circulation by 2050 (International Energy Agency (2022)). In the UK alone, as of March 2023, there are approximately 735,000 Battery Electric Vehicles (BEVs) and 480,000 Plug-In Hybrid Electric Vehicles (PHEVs), a number that is expected to sky-rocket in the coming years (Society of Motor Manufactures and Traders (2023)). The vast increase in the number of EVs has led to installation of charging points both privately and a publicly. By January 2023 there were more than 37,000 public

* Corresponding author.
E-mail address: apostolos.vavouris@strath.ac.uk

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charger points installed throughout the UK with 19% of them rated as "rapid" chargers (25-100kWh), 57% as "fast" chargers (7-22kWh) and the rest of them as "slow" (3-6kWh) or "ultrarapid" (+100kWh) chargers (Department for Transport (2023)).

Although the manufacturing and recycling process—powertrain, batteries, and end-of-life—of these vehicles is more carbon intensive, the usage of electricity instead of fossil fuels can compensate for the higher manufacturing and recycling process CO_2 emissions (Transport & Environment (2022)), especially when electricity is generated using renewable sources of energy. To compare Green House Gases (GHGs) emissions between technologies, different Life Cycle Assessment (LCA) models have been proposed to quantify vehicles' lifetime carbon footprint. These models, in general, focus on different parts of the lifecycle of EVs, including mining and processing of raw materials, manufacturing of the powertrain, usage and end-of life. Although a lot of research has been performed on LCAs and estimation of total CO_2 emissions during a vehicle's production and recycling stage (Marmiroli et al. (2018); Verma et al. (2022)), there is still a research gap regarding factors influencing GHG emission quantification during usage, which contributes to a significant share of emissions (Transport & Environment (2022)). Compared to ICEVs where fuel's footprint is not affected by the time of refuelling, EVs fuel impact to the GHGs is dynamically changing and directly correlated to the generation mixture during the charging period. Furthermore, in general, electrical vehicular technologies, are more carbon intensive during the production stages of the vehicle and therefore the reduction of carbon emissions is based on the usage period of the vehicle. Therefore, an accurate estimation of the carbon footprint of the usage cycle, taking into account different parameters such as end-users' specific information is of paramount importance, as they can greatly affect the total emissions.

The objective of this paper is to augment existing EV LCA models and enhance their accuracy by including usage factors that impose specific time of charging patterns. Results are compared with current LCA models that do not take into account these parameters. The rest of the paper is organised as followed: Section 2 presents the state-of-the-art of LCA models as well as on GHGs estimation for vehicles; Section 3 expands on the methodology followed to integrate the end users' specific routines to current LCA models and in Section 4 the results of the proposed methodology are presented. Lastly, in Section 5 a brief discussion and the conclusions are drawn.

2. Literature Review

The LCA assessment of different models has been the topic of discussion of several research papers throughout the years with research focusing both on the modelling and simulation of different vehicular technologies—Internal Combustion Engine Vehicles (ICEVs), BEVs and PHEVs—as well as on studies that aim to estimate the emissions during different stages of a vehicle's life including the production and the recycle stage. LCA is methodology that is standardised worldwide based on the ISO 14040:2006 Standard (International Organization for Standardization (ISO) (2009)). The European Platform of Life Cycle Assessment (European Commission (2023))—a European Commission's project that aims in providing good practice in LCA use and interpretation—is widely used in business and policy making for solutions towards sustainable production and consumption. As EVs have only emerged during the last decade there is insufficient data for full-cycle large scale deployment—i.e., production, usage and recycling—and therefore, research is focused on methods to compare the actual carbon footprint of the EVs to that of current fossil-fuelled vehicles.

Xia and Li (2022) presented an extended review of the different LCA models available for the comparison of the different vehicular technologies with a focus on effects of the batteries to the total carbon footprint of the EVs. Complimentary to that, Verma et al. (2022) presented a comparison between the different proposed LCA models for EVs and ICEVs as well as between the different Life Cycle Cost models for the same technologies. Authors concluded that although the introduction of EVs would be beneficial to the environment as the GHGs will decrease, the toxicity caused to human activities is increased due to the more demanding production of the electric powertrains and high voltage batteries. The LCA estimation of a vehicle takes into account different parts of the vehicle's life, including the production stage—i.e., raw material extraction, vehicles' components manufacture and vehicles assembly—the usage stage—i.e., the carbon footprint of the production of the fuel used and the vehicles emissions—and lastly the recycling stage—i.e., the carbon recovered during recycling/reusing and the carbon footprint produced due to materials being buried in landfills. The majority of the different LCA models that have been proposed in the literature, can be grouped in one of the following categories:

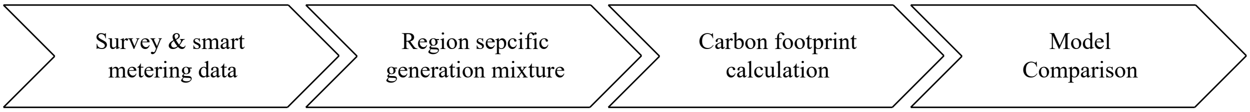

Fig. 1. Methodology Summary

- Cradle to Gate (CTGa): assessment of the production stage, i.e. from the raw materials to the production of the vehicle. Kim et al. (2016) presented the first CTGa model for the assessment of the mass-production of a battery used in an EV. For a typical 24kWh battery of an EV it was estimated that a total of 3.4 metric tonnes of CO_2eq will be emitted;
- Cradle to Cradle (CTC): assessment of the production, usage and recycling stage with materials' recovery for reusage;
- Cradle to Grave (CTGr): the same approach as with CTC, but with the difference that the assessment ends right after the recycling stage and therefore does not take into account the repurpose of materials. Burchart-Korol et al. (2018) presented a CTGr approach in estimating the LCA of EVs in Poland and the Czech Republic, with the results for the EVs ranging between 172–276 gCO_2eq/km for Poland and 132–214 gCO_2eq/km for the Czech Republic;
- Well to Tank (WTT): assessment of the carbon footprint of the supply of different fuels used to run a vehicle. Girardi et al. (2015) used a WTT LCA assessment model with EVs emitting 155gCO_2eq/km and petrol cars 300gCO_2eq/km;
- Tank to Wheel (TTW): assessment of the carbon footprint due to the operation of a vehicle, and lastly,
- Well to Wheel (WTW): assessment that combines bot the WTT and the TTW methods. Bicer and Dincer (2018) introduced a WTW LCA model, with results ranging from 160 gCO_2eq/km for EVs, 270 gCO_2eq/km for petrol-powered vehicles and 230 gCO_2eq/km for diesel-powered vehicles.

In general, literature tends to tackle the LCA problem by different methods that consider the production, usage and end-of-life withdrawal of the vehicles. Assessment models, as summarised by Verma et al. (2022) and Xia and Li (2022) are either performed in a generic way or are focused on a specific country and therefore the carbon footprint of the electricity used to charge the EVs is calculated based on a regional average. However, models do not take into account the intraday variability of the carbon footprint of the electricity produced in a network that is correlated with the generation mixture at that specific moment. Considering that, as well as the fact that end-users are not charging their vehicles uniformly throughout a day, assuming that the average carbon footprint of the electricity is representative is leading to under-and/or over-estimations of the actual impact of the EVs. Therefore, the integration of users' routines within the LCA models would greatly improve the accuracy of them and at the same time improve the fairness when comparing different vehicular technologies. Lastly, as current LCA models assume a national average when estimating the footprint of the electricity used to charge the EV batteries, the variance in generation mixture of different regions in a national level is not taken into account, a fact that is very timely especially considering the EV initiatives to reduce GHGs emissions that are being deployed in different countries around the world—which by nature have a finite budget—and therefore do not fully optimise the deployment of these initiatives.

3. Methodology

This section presents the methodology followed to augment current LCA models in order to increase the precision of the usage estimation of the different technologies and therefore increase the trustworthiness of the solutions and the fairness in the comparison of the different technologies. A novel LCA model is introduced, a summary of the steps followed to estimate the carbon footprint of each technology are presented in Figure 1. As this study focuses on the effects of the EVs' usage compared to ICEVs' under different charging profiles and different regions—both national and international—carbon emissions involved during the battery and vehicle production and end-of-life stages were calculated based on the updated CTGr LCA model of the European Federation for Transport and Environment (Transport & Environment (2022)) and therefore the rest of the section will only focus on the methodology followed to calculate the carbon footprint of the usage cycle and how this is affected based on different charging times, different charging speeds and different regions.

3.1. Time of Charging

In order to integrate end-users' routines in the LCA models, different types of data were collected across different countries, including survey data and actual energy consumption data. Countries that were considered in the research were the United Kingdom, Norway and Germany.

3.1.1. United Kingdom

In the United Kingdom, as there are no publicly available datasets of EV usage, time of charging was based on the 2022 smart chargepoint survey (Department for Business, Energy and Industrial Strategy (2022)) commissioned by the Department of Business Energy and Industrial Strategy (BEIS) where 1,000 EV drivers participated in the research as well as on the Department of Transport report on Electric Vehicle Charging Research (Department for Transport (2022a)). According to the responses of this survey, the majority of the respondents have access to private driveway, garage or other form of off-street parking with only 6% parking on-street, a fact that is detrimental to the selection of charging technology and charging place. A total of 66% of end-users own a dedicated chargepoint, 26% use a standard 3-pin cable which is directly plugged into the mains socket and 1% use a private access communal dedicated chargepoint. Therefore, a total of 93% of the participants have access to charging at home and select to do so. According to the Department for Transport (2022a) the vast majority of people with dedicated chargepoints prefer charging their vehicle during night-time, with 78% of the participants reporting to charge their EV overnight regularly. Therefore, in this research, two different users' profiles with BEVs are studied: 1) a user with a 3-pin cable that charges directly after normal working hours at 18:00 with an average total duration of 11 hours and a user with a dedicated chargepoint that charges overnight with an average duration of 3 hours. As the United Kingdom comprises of the Great Britain (GB) and the Northern Ireland – where a different electricity system operator (ESO) exists – assessment was only carried for the GB.

3.1.2. Norway

In Norway, a field study was performed by the GECKO project (GECKO MSCA ITN (2023)). Based on smart metering data, comprising BEVs and on closed-format questionnaires in a smart-home district in the greater area of Frederikstadt, two charging profiles were created for: (1) homeowners that own a dedicated chargepoint (11kW) with scheduling capabilities—as the energy price in that area varies on an hourly basis user opted to charge during the night hours at midnight with an average duration for a full charge of 3 hours, when the energy is cheaper, (2) homeowners that do not own a dedicated chargepoint and therefore charge their cars 3-pin cable (3kW) based on their daily routines—i.e. after returning from work, circa 17:00—with an average total charge duration of 11 hours.

3.1.3. Germany

Vavouris et al. (2022b) presented a household in Germany that was monitored for a period of 1 year—1 January 2021 to 31 December 2021—where an EV was present with an installed fast EV charger of 11kW. The aggregate readings as well as the annotated BEV chargers' activations at 30 min resolution were used for creating the Germany's user profile. The average charging duration was approx. 3 hours. The data can be accessed at)Vavouris et al. (2022a)).

3.2. Fossil Fuels & Electricity Carbon Footprint

Fossil fuels carbon footprint is correlated with the penetration of renewable fuels that made up 7% of the total road and non-road machinery fuel in the UK in 2022 (Department for Transport (2022b)). Renewable fuels are produced with the use either of crops or wastes known as feedstocks. When comparing the GHGs emissions of fossil fuels to the renewable ones, there is a total saving of 81%. Considering the Indirect Land-Use Change (ILUC)—i.e. the not intended consequence of switching land use for the generation of renewable fuels—this percentage is slightly less at 77%. These renewable sources were included into to proposed LCA model.

Compared to ICEVs, whose fuel refill timing is not correlated to their carbon footprint, EVs use energy that is instantaneously produced in the grid. Therefore, data regarding the generation mixture as well as their CO_2 emissions

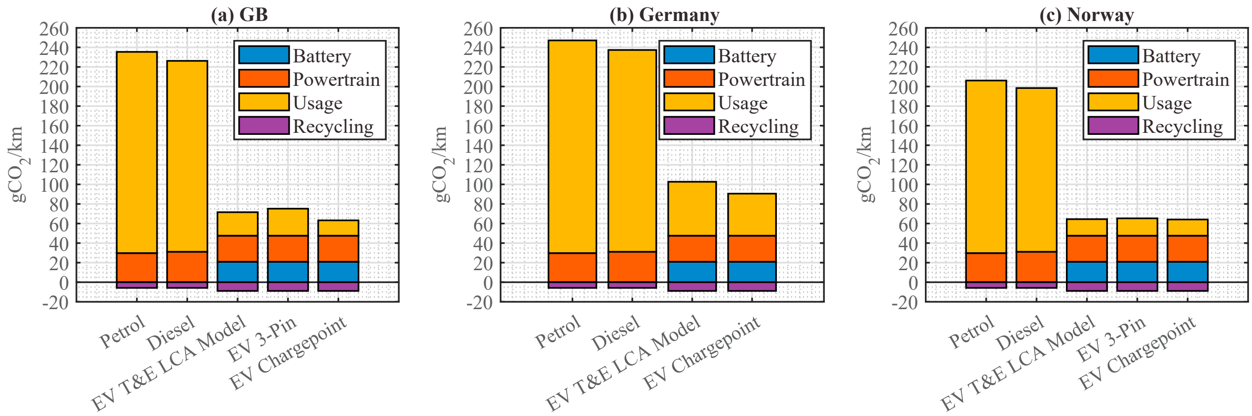

Fig. 2. LCA Assessment Comparison for: (a) GB, (b) Germany and (c) Norway

were gathered through the Electricity System Operators (ESOs) on a half-hourly interval for a period of 1 year, starting on the 1 January 2022 to 31 December 2022. For the GB, the carbon intensity API (National Grid ESO (2023)) was used to retrieve the carbon footprint of the produced energy on a regional and national level. For Norway and Germany, the generation mixture obtained through the European Network of Transmission System Operators for Electricity (2023) was used and then translated to an approximate carbon footprint based on the updated work of Transport & Environment (2022) for the parameters of Schlömer et al. (2014) to better capture the actual European region instead of global averages, i.e. 997 gCO_2eq/kWh for coal, 434 gCO_2eq/kWh for gas, 34 gCO_2/kWh for solar PVs, 14 gCO_2eq/kWh for offshore winds, 11 gCO_2/kWh for hydro, 12 gCO_2/kWh for onshore wind and lastly 5 gCO_2eq/kWh for nuclear.

3.3. LCA Model

A one-year simulation of the actual footprint based on the charging time—as identified through the surveys and the actual electricity consumption of different households – was performed. Results were then extrapolated to a vehicle's full lifetime—i.e., the total expected mileage before withdrawal from circulation.Powertrain parameters for the LCA model of a medium-sized vehicle are presented in Table 1 as obtained through Transport & Environment (2022).

Table 1. Powertrain parameters for a medium-sized vehicle

	Petrol [l/km]	Diesel [l/km]	BEV [kWh/100km]	BEV (capacity) [kWh]
Medium-sized	7.5	6.2	17.5	60

4. Results

In this section the results obtained followed the methodology in Section 3 are presented. Results are both on the national level for the GB, Norway and Germany, as well as on a regional level for the GB.

4.1. National - Level

Figure 4.1 illustrates a comparison of the GHG emissions between the ICEV and EV model of Transport & Environment (2022) compared to the proposed model, where user-charging-routine information is integrated into the models. A medium-sized vehicle—as presented in Table 1—with an estimated usage of 225,000 km in its lifetime is assessed in three different households. In the GB household, based on the two scenarios—i.e. a user with a 3-pin system and a user with a dedicated chargepoint—a 5.8% increase (i.e. an increase of ~0.8 tCO_2 in the vehicle's lifetime emissions) and a—13.3% decrease (i.e. a decrease of ~1.9 tCO_2 in the vehicle's lifetime emissions) is observed for Scenarios I and II, respectively. In the 3-pin scenario the increase in the carbon footprint, is expected due to the peaking power plants that are introduced to the grid to meet the increased demand that is usually exhibited during the evening hours. In the German household, based on the smart metering data, the BEV is charged mainly during night—when the grid is less stretched and therefore base power plants can handle the load. A reduction of 12.9% (i.e., a decrease of ~2.7 tCO_2 in the vehicle's lifetime emissions) is observed. Lastly, for Norway's scenarios, according to smart metering and interview data, in the 3-pin Scenario a slight increase is observed of 1.5% (i.e. an increase of ~0.2 tCO_2 in the vehicle's lifetime emissions) whereas in Scenario II, in which a similar behaviour with German household is exhibited—i.e., charging during night hours—a negligible reduction of 0.6% (i.e. a decrease of ~0.1 tCO_2 in the vehicle's lifetime emissions) is observed. This is due to the particular nature of Norway's generation mixture which consists almost exclusively of hydro generation and therefore peak demand is not covered with the use of carbon intensive peaker plants.

4.2. GB Regional Level

In Table 2, a summary of the results obtained for the two different scenarios for the GB are presented. In general, it can be observed that a dedicated chargepoint, with an ability to charge during the night hours in a faster pace can greatly reduce the emissions when compared with the common 3-pin charger. In addition, England exhibits almost the same level of carbon footprint as the GB average, Scotland exhibits ~16% and ~27% reduced emissions in the first and second scenario, respectively, and lastly Wales exhibit an increased carbon footprint of ~15% and ~13% increased emissions in the two scenarios. The difference between the regions of Britain can be attributed to the different generation mixture as well as due to the different levels of energy imports. In Figure 3, the increase or decrease in a vehicle's lifetime emissions when compared with the GB average for the two scenarios is presented. This was calculated based on the carbon footprint per km as presented in Table 2. The divergence of the carbon footprint from the GB average is given as:

$$DV(reg, i) = (E_{reg,i} - E_{GB,i}) \times R \times 10^{-6} [tCO_2], \tag{1}$$

where $E_{reg,i}$ is the CO_2 emissions on region *reg* for scenario *i* in grams, $E_{GB,i}$ is the average CO_2 emissions of GB for scenario *i* in grams, and *R* is the range in km.

In GB, Scotland is the only country that exhibit a better than average carbon footprint. England falls slightly above average whereas Wales exhibit the highest carbon footprint due to the increased usage of fossil fuels in electricity generation. In general, areas of the Northern Britain—i.e. North-East England, North-West England, South Scotland, North Scotland and North Wales and Merseyside—exhibit higher levels of CO_2 savings due to higher penetration of renewable energy sources, including wind and solar. On the other hand, areas of the South and South-East Britain—i.e., South Wales, East Midlands, South England, South-West England and South-East England—exhibit the worst performance.

5. Conclusions

In this paper, a methodology for increasing the accuracy of the LCA models as well as the fairness of the comparison of different vehicular technologies was presented. Results, obtained for different charging routines as well as different users' locations, were presented. Particular attention was given in quantifying the effect of different geographical areas, both on regional and national level, to the actual carbon footprint of each technology, a factor that can greatly affect the actual carbon footprint of each technology. In contrast with ICEVs, where refuelling timing does not affect the carbon emissions, EVs' charging routines can greatly affect the actual GHGs emissions during its lifetime. From the results presented, lifecycle emissions per vehicle type can vary from -12.9% up to +3.8% considering the different users' charging routines. This research is especially timely given the introduction of load-shifting initiatives throughout the world with an aim to reduce CO_2 emissions, as well as the introduction of smart chargers that can be programmed to charge during specific time periods. In addition, in different parts of the world initiatives that support the purchase of EVs through subsidies and withdrawals of ICEVs are being rolled out in order to reduce the countries'

Table 2. Carbon footprint estimation of the usage parameter for the regions of the GB

Region	3-pin Charger (18:00 – 05:00) [gCO_2/km]	Dedicated Chargepoint (01:00 – 04:00) [gCO_2/km]
Great Britain	66.279	54.327
England	67.944	54.969
Scotland	48.464	45.400
Wales	75.946	61.181
South-East England	71.947	58.423
London	69.434	55.887
South England	80.018	62.526
South-West England	74.265	57.924
East England	65.217	52.866
East Midlands	82.851	62.321
West Midlands	67.118	53.526
South Wales	86.849	67.373
North Wales & Merseyside	56.865	49.500
Yorkshire	66.555	54.438
North-East England	43.657	41.874
North-West England	49.470	44.300
South Scotland	46.315	44.467
North Scotland	49.679	47.402

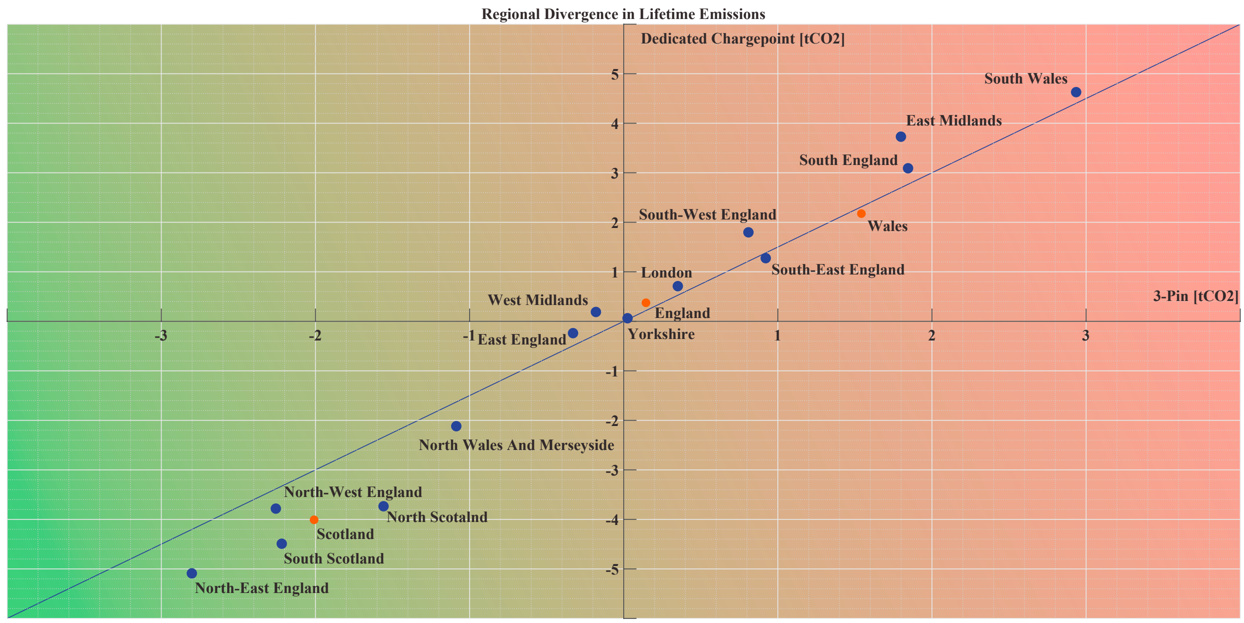

Fig. 3. Regional Divergence in Lifetime Emissions When Compared with GB Average, Scenario I & II

GHGs. Therefore, it is essential, to first target specific areas that demonstrate the lowest carbon footprint per kWh of electricity as in this case the reduction of the GHGs will be faster as well as the compensation of the increased carbon unleashed during the production of an EV. Further research should perform to expand in more regions around the world as well as in different end-users' profiles. In addition, as the EV market share is expected to rapidly increase with a plethora of different vehicles available to the consumers, it is crucial to introduce novel recommender system solutions that will be able to identify the best candidate vehicle based on the bespoken requirements of an end-user.

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