Applied Energy 289 (2021) 116621

Contents lists available at ScienceDirect

Applied Energy

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

The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications

Öivind Andersson [a,*], Pål Börjesson [b]

[a] Energy Sciences, Lund University, Sweden
[b] Environmental and Energy Systems Studies, Lund University, Sweden

HIGHLIGHTS

- LCA of the GHG performance of a passenger car with various degrees of electrification.
- Sensitivity analysis regarding the electricity mix and renewable fuel content.
- Renewable fuels may lead to lower GHG emissions than a low carbon electricity mix.
- Both electrification and renewable fuels are needed to reach the sector's climate goals.
- Policy instruments favor electrification over renewable fuels and need corrections.

ARTICLE INFO

Keywords:
Electric vehicles
Renewable fuels
Life cycle assessment
Greenhouse gas emissions

ABSTRACT

A life cycle assessment is presented for a current vehicle's greenhouse gas impact when using a combination of electrification and renewable fuels. Three degrees of electrification are considered: a hybrid electric vehicle, a plug-in hybrid electric vehicle, and a battery-electric vehicle. These are combined with fuels with various degrees of renewable content, representing a fossil fuel, a first-generation biofuel and a second-generation biofuel. For charging, the 2020 European electricity mix is used and compared with an electricity mix of low greenhouse-gas intensity. Renewable fuels are found to have a greater potential to reduce the life-cycle greenhouse gas emissions than a low carbon electricity mix. The results are discussed in terms of the supply potential for renewable fuels on the fleet level. It is found that plug-in hybrid vehicles may enable the automotive sector to reach more ambitious climate goals than battery-electric vehicles. An assessment is also made of how the life cycle greenhouse gas emissions compare with the emissions as measured by current policy instruments. The discrepancies indicate that current climate policy instruments are inadequate for minimizing the automotive sector's climate impact and suggestions for improvements are made.

1. Introduction

The transport sector accounts for a quarter of the greenhouse gas (GHG) emissions in the European union (EU), and the share is growing [1]. In 2017, cars were responsible for 44.3% of these emissions [2]. A 90% reduction in transport emissions is needed to achieve climate neutrality by 2050, and for this reason, the European Commission (EC) proposes a revision of the CO_2 legislation standards for cars and vans by June 2021 to ensure a clear pathway from 2025 onwards towards zero-emission mobility [1].

As electrification is widely perceived as the most effective route towards decreased GHG emissions, public policy instruments tend to favor electric vehicles. This is illustrated by the definition of battery-electric vehicles (BEVs) as zero emission vehicles, subjecting these to super credits during phase in of the EU 95 g/km limit for CO_2 emissions (*i.e.* counting each BEV as two zero-emission vehicles) [3], and subsidies designed to increase market shares of BEVs. These policies have prompted vehicle manufacturers to make focused efforts on electrification, often at the expense of vehicles capable of using renewable fuels.

The GHG mitigation efficacy of both electrification and renewable fuels has been discussed in recent years. For BEVs, both the GHG intensity of the electricity used for charging and the GHG emissions associated with battery production have been debated. Biofuels, on the other hand, have been discussed in terms of their indirect GHG

* Corresponding author.
E-mail address: oivind.andersson@energy.lth.se (Ö. Andersson).

https://doi.org/10.1016/j.apenergy.2021.116621
Received 1 November 2020; Received in revised form 20 January 2021; Accepted 4 February 2021

emissions *e.g.* due to potential indirect land-use change (ILUC) when growing feedstock crops.

Analyses of BEV emissions have suffered from large uncertainties in the estimated GHG emissions from battery production, with published figures spanning from 30 to 494 kg CO_2-equivalent per kWh of battery capacity [4]. A 2017 metastudy narrowed this span to 150–200 kg/kWh [5]. With GHG emissions of this magnitude, the batteries have been estimated to contribute 31–46% of the total GHG impact from manufacturing a BEV [6]. More recently, the span was shifted significantly downwards to 61–106 kg/kWh, due to access to more transparent data [7]. This new span includes the level indicated in the widely used Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (see *e.g.* [8]), but excludes end-of-life emissions, which were included in the previous span.

Uncertainties about the GHG reduction potential of renewable fuels are also decreasing. To avoid potential negative ILUC effects, current policies (*e.g.* within EU [9]) promote biofuels from non-crop biomass feedstock, such as residues from agriculture and forestry. Studies from IPCC [10], the EC [11] and several journal articles (*e.g.* [12–14]) also show the potential of producing energy crops without causing negative ILUC effects, for example, in regions with excess arable land not used for food or feed production or by integrated food and energy crop production systems. Furthermore, renewable fuels do not have to be sourced directly from biomass but can be synthesized using renewable electricity (so-called e-fuels) [15]. While *e.g.* IPCC [10,16] and IEA [17] state that the global potential for biofuels is limited by the quantity of biomass that can be sustainably produced, the production potential for renewable e-fuels is fundamentally limited by the supply of renewable electricity [18].

Biofuels are not unique in facing sustainability limitations. A significant scaleup of the BEV fleet could entail challenges such as shortage of minerals for battery production. Mining already gives BEVs significantly higher impact on human toxicity and freshwater ecotoxicity than conventional vehicles [19] and the growing demand for battery minerals have lately prompted an interest in deep-sea mining, which could have severe impacts on sensitive, deep sea ecosystems [20]. This stresses that any technology based on limited resources – whether it be biomass or minerals – may face sustainability challenges when implemented on a global level. For this reason, a combination of measures is likely to be needed when shifting the car fleet towards low GHG emission technologies. This motivates an assessment of electrification and renewable fuels in the same context.

GHG emissions from BEVs have been compared to those of internal combustion engine vehicles (ICEVs) in a large number of studies. For example, Hawkins et al. found that a small BEV powered by European electricity offered a decrease in global warming potential (GWP) compared to an ICEV. Since much of the GWP of a BEV was associated with the battery production, the magnitude of the decrease was sensitive to assumptions about the vehicle lifetime. On the other hand, the study associated BEVs with significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion – impacts largely emanating from the vehicle supply chain [21]. Faria et al., widened the perspective by also considering a range of electricity mixes in a detailed study of economic and environmental balances for mid-sized HEVs, PHEVs, and BEVs. Based on real-world drive cycles, the BEV was found to have the lowest GWP of the vehicle set [22]. Ma et al. studied a range of vehicles operated in the UK and California. Even when accounting for an increased electricity demand, the BEVs tended to emit less GHG emissions than an ICEV, although high speed and load conditions reduced the difference, especially when using marginal electricity [23]. Onat et al. considered the spatial and temporal variation in GHG intensity of the electricity production across the USA. Based on average electricity mixes, BEVs were found to be the best option in 24 states. Use of marginal electricity substantially increased the BEV GHG emissions, whereas renewable electricity substantially decreased them [24]. All of these studies were based on small BEVs with small batteries, typically a Nissan Leaf with a 24 kWh battery pack. Bauer et al. assumed larger batteries for a set of current and future mid-size passenger vehicles, where a 2030 BEV model was expected to have a battery capacity of 73 kWh. In this study, a 2012 diesel HEV was found to have a similar GWP as a BEV powered with EU electricity, whereas the 2030 BEV had about half the GWP of the diesel HEV, due to reduced GHG intensity of the electricity mix. Similarly to [21], the authors noted that BEVs are not necessarily better than ICEVs in terms of other environmental impacts and therefore advocated integration of life cycle management in policies to counter potential environmental drawbacks [25]. Ellingsen et al. explicitly addressed the effects of vehicle and battery size, studying vehicles weighing 1100–2100 kg, having battery capacities in the 17.7 to 59.9 kWh range. Life cycle GHG emissions were compared between BEVs and ICEVs in four vehicle classes over a total driving range of 180,000 km. Although the BEVs had elevated production phase emissions, these were found to be offset by decreased emissions during the use phase for all considered electricity mixes except coal power [6].

The works above represent the most widely cited life cycle assessment (LCA) comparisons between BEVs and ICEVs published during the last decace (*i.e.* during the period when market-viable BEV technology has become available). Despite the variety of perspectives offered in these studies, a fundamental flaw is that they exclusively evaluate ICEVs in the context of fossil fuels. Only a few LCA comparisons involving renewable fuels were published in the last decade, most of which indicate that biofuels compare well with electrification in terms of GHG emissions. Boureima et al. made a comparative LCA of conventional and alternative vehicles, finding that a BEV powered with Belgian electricity emits less GHG than the alternatives, except for a vehicle fueled with sugarcane-based E85 [26]. Relatively small battery packs were assumed for the BEV and as the energy consumption for battery production was withheld from the article, it is difficult to assess how relevant this analysis is to current BEVs. Tessum et al. compared air quality impacts of 10 alternatively powered vehicles. First-generation ethanol was found to result in lower GHG emissions than US grid average electricity, and second-generation ethanol resulted in lower GHG emissions than renewable electricity [27]. Due to the assumptions about vehicle energy consumption and battery capacity not being explicitly mentioned in the study, it is difficult to translate these results into a current EU context. Furthermore, up to half the battery production emissions were stated to occur outside the spatial modeling domain (USA) and therefore excluded from the analysis. Meier et al. benchmarked 27 scenarios against a 50% petroleum-reduction target and an 80% GHG-reduction target in USA. At a relatively high rate of electrification (40% of miles and 26% by fuel), an 80% GHG reduction could only be achieved with significant quantities of low-carbon liquid fuel in cases with low or moderate travel demand growth [28]. Messagie et al. compared BEVs to ICEVs using a range of fuels, including first-generation biofuels. They noted that the feedstock of the fuel affects the outcome: sugarcane ethanol was found to result in a far smaller GWP than a BEV charged with EU electricity, whereas sugar-beet ethanol resulted in a slightly greater GWP [29]. Picarelli de Souza et al. compared ICEVs fueled with gasoline and sugarcane ethanol to BEVs in a Brazilian context and found that, in terms of GWP, the ethanol vehicle was the best vehicle in this set, followed by the BEV [30]. Glensor et al. reverses the picture: in a Brazilian passenger transport system consisting of cars and urban buses, biofuels yielded similar or higher GHG emissions than a business-as-usual scenario, whereas electric vehicles significantly reduced them [31]. This study only considered first-generation biofuels (ethanol from sugarcane and biodiesel from soybeans) and the major contributor to their GHG emissions was negative ILUC effects. Interestingly, the electrification scenario was credited with positive ILUC effects. From an EU perspective, potential negative ILUC effects of the use of biofuels has been assessed during the last two decades in connection to the revision of the Renewable Energy Directive (REDII), which will be implemented in 2021. The overall conclusions from this assessment are that palm oil is currently the only feedstock identified as a high ILUC-risk feedstock for biofuels, whereas other feedstocks, such as cereals, are seen as low ILUC-risk feedstocks [11]. However, REDII limits the contribution of conventional biofuels based on food and feed crops to avoid future risks of negative ILUC effects and suggest a gradual phase-out of high ILUC-risk feedstock (*e.g.* some palm oil) until 2030 [9]. A future expansion in the use of biofuels within EU will therefore be based mainly on non-food crop feedstock thereby avoiding risks of negative ILUC effects.

This article presents a life cycle assessment of the GHG impact of a current car model using three degrees of electrification: a hybrid electric vehicle (HEV), a plugin hybrid electric vehicle (PHEV), and a BEV having a battery capacity representative of modern mid-sized cars. In contrast to the comparisons cited above, this study addresses the combination of electrification and renewable fuels. The hybrid vehicles are therefore combined with fuels with various degrees of renewable content to assess how the combinations compare with electrification alone. The baseline fuel is a fossil fuel (gasoline). This is compared with a first-generation biofuel (ethanol, mainly based on cereals). In contrast to the studies cited above, the study also includes a second-generation biofuel (hydrotreated vegetable oil, HVO, mainly based on residues and waste products). All fuels are widely available at filling stations in Sweden. The 2020 European electricity mix is used for charging and is compared to a potential 2050 European electricity mix, based on modeling scenarios used by the EC. The results are analyzed in relation to the EU 95 g/km limit for CO_2 emissions to provide a perspective on how the legislated GHG emissions (measured tank-to-wheel) compare with the life cycle emissions of the studied vehicles. Finally, the potential to achieve climate neutrality in the automotive sector using these options and the associated policy implications are discussed.

2. Methodology

The Kia Niro is a subcompact HEV manufactured by Kia Motors since 2016. With a service weight of just above 1500 kg it is heavier than the average European car (1397 kg in 2018 [32]), but it is still a moderately sized car. A PHEV version of the Kia Niro was introduced in Europe in 2017, and a BEV version was introduced in 2018 [33]. The Kia Niro thus offers three powertrain alternatives with various degrees of electrification in the same base vehicle, making it ideal for assessing the GHG impact of powertrain choices independently of other vehicle factors.

This LCA is based on the manufacturer's vehicle specification for the 2020 Kia Niro model, combined with typical data from the literature as described below. The analysis should thereby not be seen as a detailed assessment of a specific vehicle, but of the impacts of various technology choices using a currently available vehicle as a model. For example, it is assumed that the model vehicle can be powered with the biofuels ethanol (in the form of E85) and biodiesel (in the form of HVO), which is not possible with the Kia Niro. Key technical data of the three Niro versions are given in Table 1. Note that the battery capacity of the BEV model is 64 kWh, adding more than 400 kg to the vehicle as compared to the HEV model. This illustrates the trend towards larger batteries as battery technology develops. For example, the Nissan Leaf (comparable to the Niro in size) was equipped with a 24-kWh battery when introduced in 2010. Over the years, its battery pack has grown to 62 kWh in the current Leaf e + model [34]. This 260% increase more than offsets the recently reduced estimates of GHG emissions from battery production.

Table 1
Technical specifications of the vehicle models.

Powertrain	HEV	PHEV	BEV
Engine	1.6 l 4 cyl gasoline	1.6 l 4 cyl gasoline	
Battery type	Li ion polymer	Li ion polymer	Li ion polymer
Battery capacity (kWh)	1.6	8.9	64
Battery mass (kg)	33	117	457
Fuel consumption WLTP (l/100 km)	4.8	1.4	0
Electricity consumption WLTP (kWh/100 km)	0	no data	15.9
CO_2 WLTP (g/km)	110	31	0

As schematically illustrated in Fig. 1, the global warming potential (GWP) of the vehicles is assessed as g CO_2-equivalent per kilometer from the production, usage, and end-of-life phases. A weight-based relationship was used to estimate the GHG emissions from the production of the car excluding the battery. The relationship was determined by linear regression based on data from LCAs of 11 modern ICEVs in the A, B, C, and F segments [6]. It should be noted that the vehicle production emissions include the production of the ICE. As the ICE contributes a minor part of the production GHG impact (7% according to the inventory of [21]), the same production data were used for all three vehicles. This gives the BEV a slight advantage in the comparison as the GHG impact of the powertrain production is greater for a BEV than for an ICEV [21]. Since the battery production emissions are so dominant for the BEV, however, this simplifying assumption does not affect the conclusions. The GHG emissions from battery manufacturing were estimated separately using the updated assessment of 61–106 kg CO_2-eq per kWh, where the lower value represents production with a renewable electricity mix and the higher represents production with a fossil-rich mix similar to the Chinese electricity mix [7]. In the diagrams presented in this article, the bars are based on the midrange value for battery production (83.5 kg/kWh) and the error bars display the outcome using the lower and higher values of the range, respectively.

The GHG emissions from the usage phase were based on the total fuel and electricity consumption during the vehicle life. Many previous LCA comparisons between BEVs and ICEVs have used a 150,000 km usage phase to avoid having to account for a potential battery replacement (see *e.g.* [4,19,21]). As this is probably too conservative and would give the HEV an unfair advantage, a vehicle life of 200,000 km is assumed. The official WLTP (worldwide harmonized light vehicle test procedure) energy consumption was used for each vehicle version. This test cycle has replaced the NEDC (new European drive cycle) in the EU vehicle certification and results in higher energy expenditure due to steeper speed-load transients. It could still be argued that the WLTP cycle is less transient than the driving styles of many real-world drivers, but such effects are assumed to affect the energy consumption of all vehicles in the same way. They will not affect the conclusions, as this assessment is a comparison of powertrains and fuels.

The contributions from the fuel to the usage phase emissions were based on statistics from the Swedish Energy Agency on fossil and renewable fuels delivered to the road transport sector in Sweden in 2018 [35]. The GHG emissions are determined from a well-to-wheel perspective in accordance with the EU RED. This means that emissions from the whole production process are included, as well as from combustion of the fossil-based components. As discussed previously in Section 1, no negative ILUC effects are assumed to be associated with the current use of biofuels. The emissions of the fuels are given in Table 2.

The fuels were chosen to represent various degrees of renewable content. As the Kia Niro HEV and PHEV models have spark ignition engines, Swedish Mk1 gasoline was used as the baseline fuel, which on

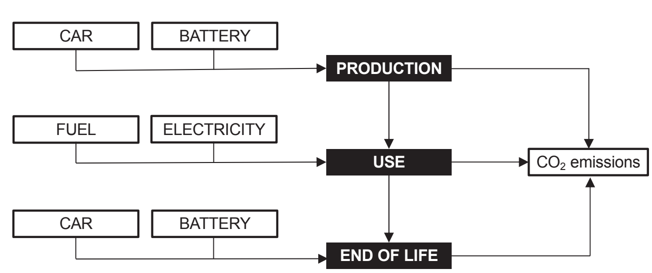

Fig. 1. Product tree for the LCA.

Table 2
Specific CO_2-equivalent emissions of the energy carriers.

Energy carrier	CO_2-eq g/MJ	CO_2-eq g/l	CO_2-eq g/kWh
Gasoline	90.2	2930	
E85	48.5	1120	
HVO	8.8	295	
2020 electricity			429
2050 electricity			38

average has 6.3% renewable content (low blend ethanol). E85, which is a mix of 85% ethanol (mainly produced from cereals) and 15% gasoline, is available at filling stations throughout Sweden and is used in this assessment to represent a first-generation biofuel. Due to the lower energy content of ethanol, a 30% higher fuel consumption was assumed for this fuel compared to the gasoline engine. HVO, or hydrotreated vegetable oil, is a drop-in biobased diesel fuel mainly produced from by- and waste products (*e.g.* from the forest, agriculture and food industry) and represents a second-generation biofuel. Like E85, HVO is widely available at filling stations in Sweden. It should be noted that part of the HVO sold in Sweden in 2018 was based on palm fatty acid distillate (PFAD), which is a by-product from palm oil production that will be gradually phased out along with the previously discussed phase out of palm oil in the EU by 2030 [11]. Unexploited resources of, for example, forest residue feedstocks in Sweden and the EU are expected to replace PFAD in future HVO production. The carbon footprint of future HVO produced from forest residue feedstocks is calculated to be similar as todaýs HVO shown in Table 2. This is also valid for forest residue-based ethanol which will have a significantly lower carbon footprint than the current crop-based ethanol presented in Table 2 [36]. As HVO is typically used in compression ignition engines, which have higher energy efficiencies than spark ignited engines, a 25% lower fuel consumption is assumed with this fuel compared to the baseline fuel [37]. As will become clear in the discussion section, these first- and second-generation biofuels are seen as steps in a gradual transition towards e-fuels, which will increase the total potential for sustainable production of renewable fuels.

The electricity contribution to the usage phase emissions is based on an LCA of the GHG intensity for the EU-28 electricity mix used in the recent European Commission (EC) report on LCA of vehicles [38]. The production chains for this electricity mix are taken directly from two EC modelling scenarios: the baseline scenario (accounting for all currently planned and/or implemented EU and national policies) and the Tech1.5 scenario (consistent with keeping the global temperature increase below 1.5 °C). By removing the emission contribution from the infrastructure, GHG intensities that are directly comparable to the well-to-wheel emissions of the fuels are obtained. The midrange of values of the two scenarios is used. This results in 429 g/kWh for the 2020 electricity mix, and in 38 g/kWh for 2050. As there are no data for the electricity consumption of the PHEV, it is assumed to be equal to the BEV electricity consumption in electric drive mode. Note that non-fuel and non-electricity contributions to the usage phase emissions are omitted from the assessment as they are both negligible and similar for ICEVs and BEVs [21].

For the end-of-life emissions of the car (excluding the battery), a weight-based relationship was used, determined by linear regression of LCA data for vehicles in the A, B, C, and F segments [6] which, in turn, was based on the inventory in [21]. For the batteries, the end-of-life emissions were estimated to be 12% of the production value [7].

The following assessment begins by a comparison of life cycle GHG emissions from the vehicles using various combinations of powertrains, fuels and electricity mixes. This is, in effect, a sensitivity analysis of the life cycle GHG emissions of the vehicles with respect to the varying GHG intensities of the fuels and the electricity mix. After this, the effect of the share of driving in electric mode on the PHEV GHG emissions is assessed using the same combinations of electricity mixes and fuels. Finally, an aggregated calculation of how the share of BEVs in the car fleet affects the emissions on a fleet level is performed. All these analyses are presented in the following section.

3. Results

3.1. 2020 EU electricity

Fig. 2 shows the GHG emissions from the three powertrain alternatives when using 2020 EU electricity. The contribution from the production phase is given in blue, where light blue represents the vehicle excluding the battery and dark blue represents the battery. The usage phase emissions are given in purple, where reddish purple represents the fuel contribution and the bluish purple represents the charging electricity. The end-of-life contributions are represented by the top, olive parts of the bars. There is also an error bar displaying the effect of the span in GHG emissions from battery production, since this has an significant impact on the results compared with other factors in car manufacturing [7]. As seen in the figure, only the BEV estimate is significantly affected by this span, due to its large battery pack.

The grey, horizontal line in Fig. 2 represents the European fleet average limit of 95 g CO_2 per km. Exceeding this limit will incur fines for the vehicle manufacturer. The limit is not strictly relevant in an LCA context, as the CO_2 legislation only applies to the tank-to-wheel (TTW) emissions. For this reason, the BEV produces no CO_2 emissions according to the certification method. For the same reason, the certification CO_2 emissions of the HEV and PHEV are lower than indicated by the reddish-purple part of the gasoline bar, as this part accounts for the well-to-wheel (WTW) emissions of the fuel, of which the TTW emissions are only a part. Although the grey line is not completely relevant, it is displayed as a reference to illustrate the small portion of the vehicle CO_2 emissions that is accounted for by the EU certification method.

Note that the PHEV bars show contributions from both fuel and electricity. During certification, a PHEV is tested once in electric drive mode (*i.e.* with zero TTW emissions) and once in ICE drive mode. In ICE mode, the batteries may be used for regenerative braking and the vehicle thereby effectively works as a HEV. The certification CO_2 emissions are determined as a weighted average of the results in the two modes, with the weighting factor determined by the vehicle's electric range [39]. The contributions of fuel and electricity to the PHEV GHG emissions in Fig. 2 are calculated using this weighting factor.

As seen in Fig. 2, the HEV represents both the top and bottom of the emission range. It is the highest emitter when fueled with gasoline and the lowest when fueled with HVO. The PHEV has a slightly smaller carbon footprint than the BEV when fueled with gasoline (131 and 139 g/km, respectively), but none of them meet the 95 g/km limit. With E85, the HEV emissions decrease below the BEV level. With HVO, both the HEV and PHEV meet the 95 g/km limit. It can be noted that both the HEV and PHEV benefit greatly from using renewable fuels, but the PHEV is less sensitive to the fuel type. This is due to a relatively large CO_2-contribution from the electric drive mode, which remains constant when the fuel is altered. It is also clear that electrification is not sufficient in itself to meet the 95 g/km limit in a life cycle perspective with current EU electricity. The CO_2 footprint of the BEV is merely 24% lower than that of the gasoline powered HEV.

3.2. 2050 EU electricity

Fig. 3 illustrates how the results in Fig. 2 are affected by using the predicted EU electricity mix in 2050. The life cycle emissions for E85 and HVO are unchanged and thereby include neither potential future improvements in the fuel production efficiency nor negative effects from ILUC etc. To isolate the effect of the GHG intensity of the electricity mix, it is also assumed that the fuel and electricity consumption of the vehicles remain the same. Viewed in relation to the 95-gram CO_2 limit, the BEV now meets the target, once again stressing that decreasing the GHG

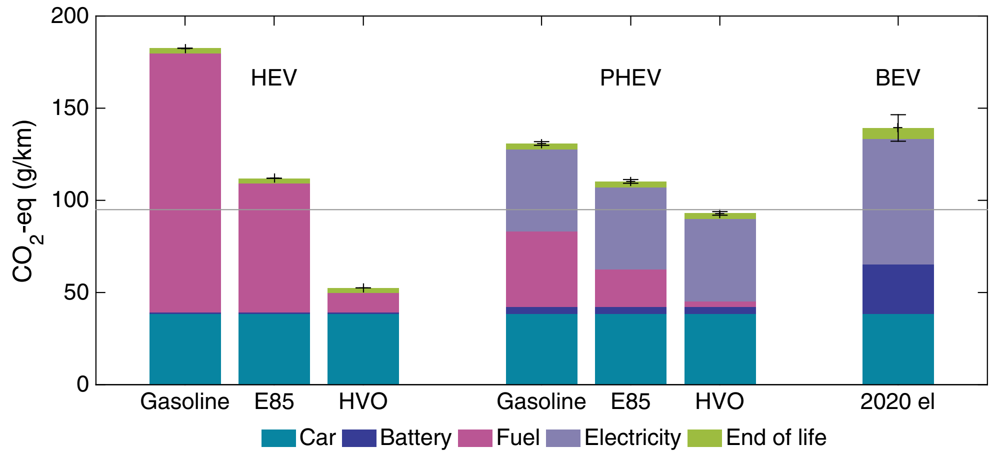

Fig. 2. Life cycle CO_2 emissions from the HEV, PHEV, and BEV model when using 2020 EU-28 electricity. The colors represent, from bottom to top, production phase emissions from the car and battery, usage phase emissions from the fuel and electricity, and end-of-life emissions. The error bars indicate how the span in battery production emissions affects the overall emissions.

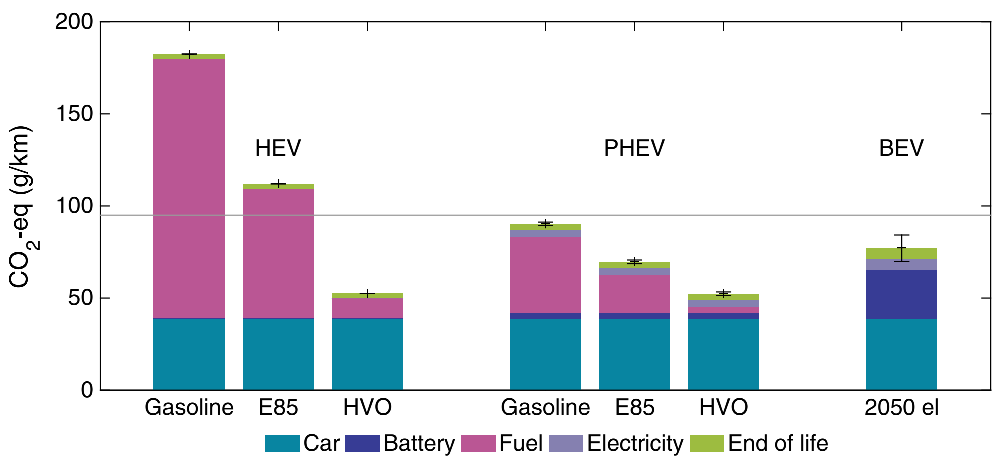

Fig. 3. Life cycle CO_2 emissions from the HEV, PHEV, and BEV model when using 2050 EU-28 electricity.

intensity of the grid is a prerequisite for achieving a substantial GHG reduction by electrification. The PHEV vehicle also meets the target, regardless of the fuel used. It is still less sensitive to the fuel type than the HEV due to its large share of electric drive. It can be noted that the PHEV now emits slightly more CO_2 than the BEV when fueled with gasoline (90 and 77 g/km, respectively). Its emissions break even with the BEV at an electricity GHG-intensity of 276 g/kWh, but the difference remains relatively small regardless of the electricity mix used. Fueled with E85, the PHEV emits less than the BEV. Fueled with HVO, it is on par with the HEV, which meets the 95 g/km limit by a factor of two with this fuel. In summary, regardless of the electricity mix used in this study, the renewable fuels consistently have a larger GHG reduction potential than electrification. The HEV and PHEV reduce GHG emissions below the BEV level due to their smaller battery packs, which more than offsets the emissions from the ICE drive mode for a renewable fuel with low GHG intensity.

3.3. Impact of the electric drive share

As a PHEV can be operated either in electric drive mode (charged from the grid) or in ICE mode (powered by fuel), it is interesting to study how the electric drive share (EDS) affects the GHG emissions. EDS here denotes the percentage of the total distance that is covered in electric drive mode.

The GHG emissions of the PHEV in Figs. 2 and 3 were based on the EDS prescribed by the WLTP based on its electric range. The EDS in actual use may be different and Fig. 4 illustrates how this affects the

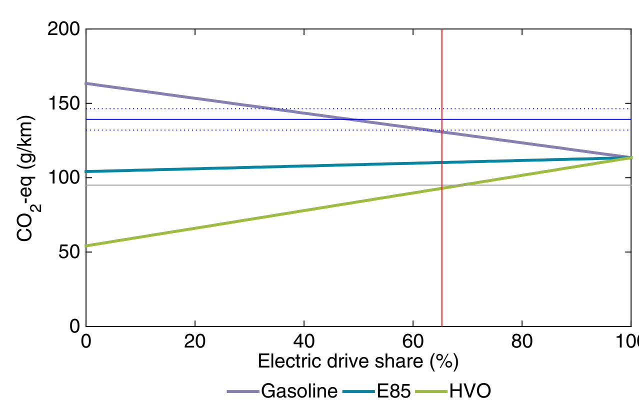

Fig. 4. PHEV CO_2 emissions as function of electric drive share (EDS) with 2020 EU electricity. The slanting lines show the emissions when fueling the PHEV with gasoline (purple line), E85 (turquoise), and HVO (olive). The horizontal blue line shows the BEV CO_2 emissions, with dotted blue lines representing the BEV error bars in Fig. 2. The horizontal grey line represents the EU 95 g/km limit and the vertical red line represents the EDS prescribed for the model vehicle in the WLTP.

GHG emissions using 2020 EU electricity. Three slanting lines represent the PHEV emissions when powering the ICE with gasoline (purple line), E85 (turquoise line), and HVO (olive line). The horizontal blue line shows the BEV emissions (139 g/km) with dotted blue lines representing the error bars due to the range in battery production emissions. The horizontal grey line represents the 95 g/km limit, and the vertical red line represents the EDS prescribed by the WLTP.

The three slanting lines converge at 100% EDS, since the fuel effect vanishes when the PHEV is operated in electric drive mode. As seen at the far right of the diagram, the GHG emissions from the PHEV lie below the BEV band in 100% electric mode. This is due to the significantly smaller battery pack reducing the PHEV's production phase emissions. The gasoline-powered PHEV requires at least 49% EDS to reduce the emissions below the BEV level. As will be pointed out in the discussion section, this is a typical EDS for the average PHEV customer. In practice, therefore, the PHEV carbon footprint is on par with that of the BEV when using 2020 EU electricity, even when operated with fossil fuel. With the renewable fuels, the GHG emissions *increase* with increasing EDS. The emissions of the E85-fueled PHEV lie below the BEV level in all drive modes. The HVO-fueled PHEV is the only vehicle that meets the 95 g/km limit during some conditions (at less than 69% EDS).

Fig. 5 shows how the results presented in Fig. 4 are affected when using 2050 EU electricity instead. The horizontal blue BEV line is now located below the grey 95-gram line at 77 g/km (cfr Fig. 3). At 100% EDS, all the PHEVs continue to outperform the BEV. With gasoline, a 77% EDS is required to reduce the PHEV GHG emissions below the BEV level. With E85, the corresponding figure is 52%, while HVO is relatively unaffected by the EDS and outperforms the BEV in all driving modes. In summary, even with 2050 electricity, a PHEV can reduce the GHG emissions below the BEV level, granted that it is mainly used in electric drive mode or operated with an adequate renewable fuel.

3.4. Impact of BEV share in the overall fleet

Car manufacturers are required to report the average CO_2 emissions of the cars they sell in EU each year. Failing to meet the 95 g/km limit will incur penalty payments in proportion to the excess emissions. When calculating the average, BEVs are defined as zero emission vehicles and PHEV emissions are determined as a weighted average of the emissions from the ICE and electric drive modes, as described above. During the phase-in of the 95 g/km limit, electric vehicles are also granted so-called super credits, meaning that each BEV sold during 2020 is counted as two zero-emission vehicles. The factor then decreases to 1.67 in 2021 and 1.33 in 2022 [39]. A super credit cap of 7.5 g/km per manufacturer applies over the three years.

As both the zero-emission definition and the super credits are policy instruments designed to increase the BEV share of the fleet, it is interesting to investigate how effective they are at reducing the fleet emissions when upstream life cycle emissions are included. In this section, the CO_2 emissions according to the policy (*i.e.* based on WLTP emissions and 2020 super credits) are compared to the life cycle CO_2 emissions of a hypothetical fleet, consisting of a mix of the HEV and BEV previously studied. A real-world fleet will naturally be a more complex mix of vehicles, but this simplified analysis still provides an illustration of some important effects.

Fig. 6 shows the average GHG emissions as a function of the share of BEVs in the fleet. At 0% BEV share, all vehicles are HEVs powered by either gasoline, E85 or HVO. At 100% BEV share, all vehicles are BEVs powered by 2020 EU electricity. The horizontal grey line again marks the 95 g/km limit for CO_2.

Starting with the dotted lines in Fig. 6, these show the fleet average GHG emissions as determined by the WLTP. The grey dotted line does not account for super credits. At 0% BEV share it attains the WLTP emissions of the HEV powered by gasoline, *i.e.* 110 g/km (see Table 1). It then decreases linearly with increasing BEV share to zero emissions at 100% BEVs. The grey dotted line shows that, without super credits, 14% BEVs are required to meet the 95-gram target with this hypothetical fleet. The black dotted line accounts for the 2020 super credits (*i.e.* each BEV is counted twice) and therefore drops twice as fast until the cap of 7.5 g/km reduction has been attained. After this point, it follows the same slope as the grey dotted line. When accounting for super credits, only 7% BEVs are required to meet the 95-gram target.

Turning to the solid lines in Fig. 6, these represent the life cycle emissions of the fleet. When fueling the HEVs with gasoline (purple line), the average emissions are considerably higher than the WLTP level, which only includes the TTW emissions. Moreover, the slope with increasing BEV share is not nearly as steep, and the line never drops below the 95 g/km limit. Note that increasing the BEV share from 0 to 100% merely decreases the emissions by 24% in the life cycle fleet-emission perspective, as compared to 100% according to the certification method. While selling 7% BEVs would meet the 95 g/km limit according to the super credit calculation, this merely reduces the life cycle fleet-emissions by 1.6%. For E85 (turquoise) and HVO (olive), the life cycle fleet-emissions are equal to or lower than the WLTP emissions at the far left of the diagram. Interestingly, they then increase with increasing BEV share for these fuels. HVO is the only fuel for which the 95 g/km limit can be met, provided that the BEV share does not *exceed* 49%. In summary, for small shares of BEVs, electrification has modest effects on fleet GHG emissions, whereas renewable fuels can have large, immediate effects. With the current electricity mix, this renders policy measures that favor electrification relatively ineffective, and even

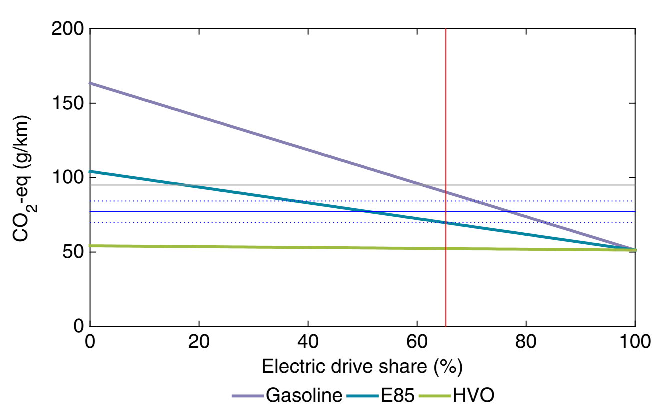

Fig. 5. PHEV CO_2 emissions as function of electric drive share (EDS) with 2050 EU electricity. The lines are color coded as in Fig. 4.

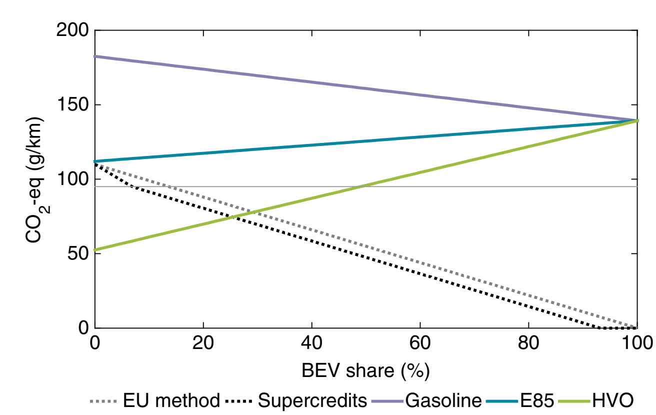

Fig. 6. Fleet CO_2 emissions as function of the share of BEVs using 2020 EU electricity. The slanting lines correspond to the HEV part of the fleet being fueled with gasoline (purple), E85 (turquoise), and HVO (olive line). The dotted lines represent the emissions as measured by the EU vehicle certification method. The grey dotted line is based on official WLTP emissions, counting BEVs as zero emission vehicles; the black dotted line also includes 2020 supercredits for BEVs.

counterproductive if the HEV part of the fleet uses renewable fuels with low carbon footprint.

Fig. 7 shows the results when using 2050 EU electricity. At this reduced grid GHG intensity, it is possible to reach the 95-gram limit with all of the fuels studied. The limit is attained at 83% BEV share when using gasoline in the HEV part of the fleet, at 49% BEV share when using E85, and for all BEV shares when using HVO. This illustrates the potential of renewable fuels to decrease GHG emissions below the BEV level, even in a future scenario where the electricity GHG intensity has dropped significantly.

4. Discussion

4.1. The potential of electrification

The EC states that a 90% reduction in transport emissions is needed to achieve climate neutrality by 2050 [1]. Here, the potential of electrification to achieve this goal in the car segment of the transport sector is discussed.

As seen in Fig. 3, the life cycle GHG emissions of the studied HEV are 182 g/km. At 77 g/km with 2050 electricity, the BEV achieves a 58% reduction from the HEV level. Even considering that the HEV achieves 20–28% fuel savings compared to a conventional vehicle [40], it is unlikely that a BEV powered by 2050 electricity will approach a 90% reduction in life-cycle GHG emissions compared to a conventional vehicle.

Besides limited GHG reduction potential, it is questionable whether it is possible to achieve a 100% penetration of BEVs in the car fleet by 2050. For example, assuming a BEV market share of 5% and a 15-year turnover time of the EU car fleet, only 5% of the 2035 car fleet would consist of BEVs. It is likely that falling prices and increased subsidies will increase the BEV market share from today's level of about 2% [41], but even in the exceptional case of Norway (where a BEV effectively is less expensive to buy than a corresponding ICEV), about half the customers still choose to buy non-chargeable vehicles [42]. Even with costly incentives and perhaps forcing measures to increase the BEV share in the EU fleet, it is likely to be a lengthy process.

Another challenge for substantially increasing the BEV share of the fleet is that a global scale-up of BEV production will increase the supply risk of important battery minerals. Achieving a 30% global market share of electric vehicles by 2030 requires a tripling of the current global supply of lithium, more than a doubling of the cobalt supply, and an almost 50% increase of the nickel supply [42]. Switching 100% of today's automotive production to BEVs based on state-of-the-art NMC 811 batteries (requiring considerably less cobalt and manganese than current NMC 111 cathodes) would deplete the current known and economically exploitable land reserves of lithium, cobalt, nickel, and manganese within 2 to 33 years [20]. This estimate does not account for

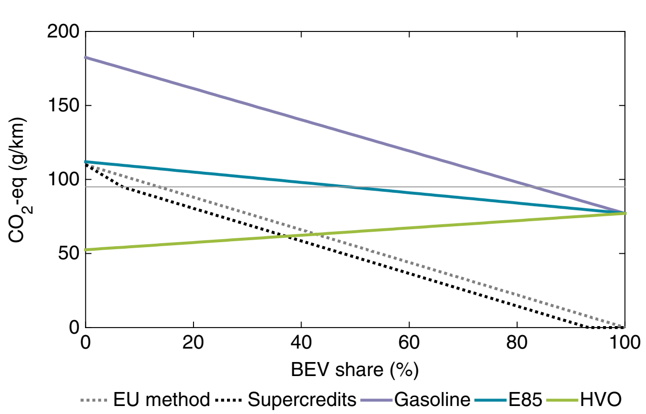

Fig. 7. Fleet CO_2 emissions as function of the share of BEVs using 2050 EU electricity. The lines are color coded as in Fig. 6.

battery use in freight vehicles or indeed for any applications where these minerals are currently used.

Apart from land resources, there are untapped resources of minerals in the deep oceans that may eventually be able to economically supply enough cobalt and other minerals for widespread automotive electrification [20]. Considering the amounts of minerals required, however, deep sea mining would have to be implemented on an immense scale. For example, extracting the cobalt required for a fully electrified global automotive industry from the richest sites would mean mining about 5 000 square kilometers of seabed annually [20]. The associated ecological impact is a significant concern. Deep sea ecosystems, already under stress from climate change and its side effects, are characterized by slow reproduction and growth, making recovery from loss or damage difficult or even improbable over human timeframes. Apart from these ecosystems having value as a potential source of new pharmaceuticals, biomaterials, and other genetic resources, they contribute critical carbon sequestration, reducing GHG concentrations in the atmosphere [43]. While deep sea mining would enable full electrification of the automotive sector, it could be at the cost of potentially catastrophic effects on ocean ecosystems and subsequent carbon release. This would hardly be compatible with the European Green Deal's strive to "increase the value given to protecting and restoring natural ecosystems" and "the sustainable use of resources" [1].

Recycling of minerals from scrapped batteries may offset the need for mining, but time is an important factor also here. The target lifetime for batteries in vehicles is 15 years [44]. After this, batteries typically maintain 80% of their capacity and they are therefore predicted to be used in second-life applications such as energy storage in an electric grid that has significant contributions from intermittent renewable sources. The delay between a global scale-up of BEV production and the time when substantial amounts of recycled battery minerals can become available in the market will thereby be significant.

To minimize the sustainability issues of battery production for a large BEV fleet, policies should favor technologies that combine adequate vehicle range with small battery packs. One such technology is electric road systems (ERS), which enable vehicles to be charged while in motion. When fully implemented, ERS enable BEVs to operate with smaller batteries, as the battery is needed only when travelling off the ERS, *e.g.* into urban areas. Studies have shown ERS to be technically and economically feasible [45] but, as they require massive infrastructure investments, it is still an open question whether and when they will become available across the continent. Therefore, hybrid technology seems to be an appealing option for combining a small battery with range. As shown in this study, when combined with renewable fuels, hybrid technology can also reduce GHG emissions below the BEV level.

A few caveats about the 2050 scenario should be mentioned before moving on. It should be noted that the 2050 electricity is only applied to the vehicle usage phase, as prediction of how vehicle production technology evolves through 2050 is outside the scope of this study. The error bars of the battery production emissions do account for a span of electricity mixes covering the 2050 mix, but only for Li-ion batteries. A widespread industrialization of alternative battery technologies before 2050 may change the battery contribution. On the other hand, current vast investments in production capacity suggest that Li-ion batteries will remain dominant in the foreseeable future, and a potential technology shift is anyhow likely to occur over an extended time. It is also assumed that the vehicles have the same usage phase energy consumption in 2050. Concerning the vehicle production emissions, they are weight-based (dominated by material production) and assumed to be substantially unaffected by the EU electricity mix. Moreover, a change in production emissions (*e.g.* due to increased use of lightweight materials) would be identical for all the studied vehicles. Thereby, it would not affect the relative comparison, except perhaps for reduced energy consumption in the usage phase, which would be more significant for the ICE vehicles. In summary, our 2050 projection should be seen as an illustration of how a predicted decrease in electricity GHG-intensity affects the comparison between the vehicles in a Li-ion battery technology scenario.

4.2. The potential of renewable fuels

In Figs. 2 and 3, it can be seen that fueling the HEV with HVO yields a 74% reduction of the GHG emissions, *i.e.* a larger reduction than that offered by the BEV. The PHEV GHG emissions are comparable to those of the BEV when fueled with gasoline, regardless of the electricity mix, whereas renewable fuels reduce the PHEV emissions below those of the BEV, also in the 2050 electricity scenario. This means that renewable fuels can potentially accelerate the reduction of the car fleet's GHG emissions in two ways. First, they can be used with immediate effect in the vast portion of the car fleet that is likely to remain non-chargeable during decades to come. Second, even when the GHG intensity of the electricity mix has dropped significantly from today's levels, renewable fuels maintain their potential to reduce GHG emissions below the BEV level, provided that they can be produced in a long-term sustainable way and with continued low life cycle GHG emissions.

A central question is therefore how large a share of the demand for transportation fuels can be supplied with sustainably produced renewable fuels. The regulatory framework for this is set by the European Renewable Energy Directive (REDII) [9], according to which renewable fuels must be characterized by GHG emission savings of 65% (biofuels) and 70% (other fuels) from 2021. First-generation biofuels (based on food crops) are limited to 7% of the final energy demand in transport from 2020 [9]. This means that second-generation fuels with low carbon footprint are favored in REDII, which covers the time period to 2030. In a global perspective, the sustainable biomass potential mainly based on residues and forest biomass has been estimated to be two to three times higher than current use of biomass energy, *i.e.* 100 to 150 EJ per year compared with today's use of approximately 50 EJ [10,17]. Biomass could then contribute up to roughly 20–25% of the total global energy supply by 2050. If, for example, one third of this biomass potential is utilized for biofuel production (and the remaining part is utilized for heat and power production), this would correspond to approximately one third of the current global use of transportation fuels. Today, the global use of biofuels amounts to some 3% [40].

Prognoses by the international energy agency (IEA) [46] and OECD-FAO (food and agriculture organization of the united nations) [47] show that the production and use of biofuels will increase during the coming years, that crop-based biofuels will represent the largest increase, and that this increased production will take place mainly outside of the EU. The supply of second-generation biofuels based on lignocellulosic biomass is estimated to be doubled within the coming five years, but still only represent a few per cent of the global biofuel volume [46]. HVO is estimated to be the individual second-generation biofuel that shows the fastest increase due to its technical and practical advantages as a drop-in fuel. The EU REDII target is that new advanced biofuels should supply 3.5% of the total use of transportation fuels by 2030 [9]. In some countries, such as Sweden, the production and use of second-generation biofuels are, however, estimated to be much higher due to current national policy tools which promote a rapid commercial development of forest residue-based biofuel production plants [48]. Today, the production costs of first-generation biofuels are often half of those of second-generation biofuels, but the cost reduction potential of second-generation biofuels is estimated to be substantial when a large-scale commercial production is developed [49]. Still, more efficient policy tools are needed on a global scale also taking into account the GHG performance to make second-generation biofuels competitive, thereby promoting such a large-scale commercial development.

To conclude, the biomass feedstock potential for an increased production of biofuels on a global level is substantial. In a short-term perspective, the main increase in biofuel volumes will be in the form of first-generation biofuels outside of EU, but long-term policies target increased volumes of second-generation biofuels. To make second-generation biofuels more competitive, however, these policies need to be implemented with much more effective instruments than today. It is therefore not the availability of lignocellulosic feedstock, such as forest and agriculture residues, that limits the commercial development today, but commercial investments in production capacity.

Renewable fuels are not limited to fuels sourced directly from biomass. They can also be synthesized from CO_2 and water using renewable electricity to produce so-called electrofuels (e-fuels). The process is often referred to as power-to-gas/liquids and can be used to produce various energy carriers, *e.g.* methane, methanol, gasoline, and diesel. Together with hydrogen, e-fuels constitute a practical option for storing large quantities of electricity at high energy density and transporting it over long distances. The CO_2 needed for e-fuel production can be captured directly from the atmosphere or from various point sources, including industrial processes. Interestingly, utilizing CO_2 from biofuel production sites in this way may allow increased use of biofuels (see *e.g.* [50,51,52]). If e-fuels are produced from renewable electricity and biogenic carbon dioxide (so called biogenic carbon capture and utilization, bio-CCU), they can reduce GHG emissions by 95% compared to fossil fuels [53], *i.e.* more than HVO (see Table 1). Due to high production costs, e-fuels are currently significantly more expensive than their fossil counterparts, but the prices are predicted to approach that of fossil gasoline over the next couple of decades [15] and are affected by coming policy measures.

A common argument against e-fuels is the limited overall energy efficiency in using electricity to produce hydrogen for synthesizing fuels, instead of using it directly to charge BEVs (see *e.g.* the literature review in [15]). In such comparisons, it is often forgotten that a power production system based on variable, renewable electricity sources have an inherent need for storing electricity during periods of high production. This is partly due to the need for so-called peak shaving, *i.e.* storing electricity when production exceeds the demand and restoring it to the grid when production fails to meet the demand. Another reason is that electricity prices tend to drop during periods of high production (*e.g.* during windy periods). Negative electricity prices have become more frequent *e.g.* in the German spot market as the capacity for renewable electricity production has increased [54]. Storing surplus electricity in the form of hydrogen is thereby a means for producers to maintain profitability in a renewable electricity system. Hydrogen production consumes electricity, reducing the excess supply to the grid and keeping electricity prices up. Hydrogen thereby becomes a cheaply produced commodity that, in turn, can be sold at a profit.

In a scenario where such an energy storage system is in place, one can choose between converting the hydrogen into electricity or into an e-fuel. As liquid fuels can be produced from hydrogen at about 92% efficiency [53], the hydrogen-to-wheel efficiency for a HEV fueled with an e-fuel is comparable to that of a BEV charged with electricity produced from stored hydrogen (assuming thermal or electrochemical conversion of hydrogen to electricity at about 45% efficiency). If e-fuels are seen as a means for storing excess electricity, this is the relevant efficiency comparison to be made.

The production potential for e-fuels is theoretically vast but is in practice limited by the supply of renewable electricity. Hansson et al. found that, if all the recoverable CO_2 from point sources in Sweden were used to produce e-fuels, the yield would correspond to 2–3 times the current Swedish demand for transportation fuels, but the electricity required would correspond to about 3 times the current Swedish electricity supply [18].

In summary, there is a large unexploited potential for sustainable production of renewable fuels, including biofuels and e-fuels. While these fuels are not likely to replace a major share of today's demand for transportation fuels, they can contribute with a valuable part of the energy need for tomorrow's automotive sector. E-fuels from bio-CCU are especially interesting in this context as they provide double services to the energy system: both as a storage medium for surplus renewable electricity and as an enabler for increased production of sustainable biofuels. As various forms of electrification gradually reduce the demand for fuels, the supply gap will diminish over time. As discussed in the next subsection, PHEV technology could play an interesting role in this scenario.

4.3. The potential of PHEVs

The typical daily driving distance for most cars is short enough to be powered by a PHEV battery, which is typically one order of magnitude smaller than that of a BEV. This means that the major portion of a BEV's battery is seldom used and, during most trips, effectively only adds weight to the vehicle. PHEVs are often considered to be a transitional technology on the path towards full electrification, but this study indicates that PHEVs may rather be an enabler for reaching the climate goals of the automotive sector. First, smaller battery packs enable a limited supply of battery minerals to electrify a larger fleet, allowing a greater number of fleet kilometers to be powered by electricity. Second, smaller battery packs significantly reduce each vehicle's production phase GHG footprint. Third, if mainly driven in electric mode, a fleet of PHEVs could reduce the need for fuels to the point where it is possible to meet the demand with sustainably produced renewable fuels. Finally, reduced battery mass will translate directly into greater equivalent fuel economy. The main drawback of the PHEV is that it produces local emissions in the ICE mode (although these are today limited to ultra-low levels by state-of-the-art aftertreatment technology). On the other hand, these emissions are reduced at the same rate as the demand for fuel is reduced. If the PHEV is mainly used in electric mode in urban areas where many humans are exposed, these emissions will be significantly reduced compared to a HEV or a conventional ICEV.

The extent to which PHEVs are actually driven in electric mode was investigated by Plötz et al. In a systematic overview of a sample of 73,000 PHEVs in USA and Germany, they found a clear relationship between the average EDS and the vehicle's electric range [55]. For the Niro's electric range (47 km) the average EDS exceeded 50%, which would put its real world GHG emissions below that of a BEV, even when fueled with gasoline (see Fig. 4). At 60 km electric range, the study showed that a 75% EDS was reached. As seen in Fig. 5, this would put a gasoline-powered PHEV on par with the BEV when using 2050 electricity. Switching from gasoline to HVO or an e-fuel would reduce the PHEV GHG emissions vastly below the BEV level at this EDS.

This study indicates that electrification is not sufficient in itself to achieve a 90% reduction of the car fleet's GHG emissions, even in a scenario when the GHG intensity of the electricity mix has been significantly reduced from the current level. It also indicates that PHEV technology combined with renewable fuels has greater potential for GHG reduction than BEV technology. Several avenues should therefore be pursued in parallel to achieve a 90% GHG reduction: First, a drastic reduction of the grid GHG intensity is necessary to attain any substantial GHG benefits with electrification. Second, increasing the production of sustainable, renewable fuels has the potential to reduce GHG emissions beyond what is allowed by electrification alone. Lastly, reducing the demand for transport and transferring transport work from the car fleet to less energy-intense modes of transport, such as public transport, bicycling and walking, can contribute to reducing GHG emissions beyond the limits of automotive technology.

4.4. Policy implications

This study focuses on vehicles' life cycle GHG emissions impact when using a combination of electrification and renewable fuels, and do not consider other types of tailpipe emissions from ICEVs. Examples of such emissions having a negative impact are nitrogen oxides, particulate matter and organic gases. Depending on the fuel used, gasoline or biofuels such as E85, these various emissions could both increase or decrease. For example, Ginnebaugh and Jacobson assessed the air quality impacts of using E85 instead of gasoline in an urban setting when fog is present and showed that E85 could slightly increase the ozone level and thereby smog formation depending on actual atmospheric conditions [56]. Therefore, the policy implications discussed below only cover policy tools focusing on climate impact. Further environmental systems studies should therefore also include other categories of emissions in addition to GHG emissions, both upstream and tailpipe emissions.

The comparison in this study would look different when using the conventional method of carbon accounting. This is because the conventional method only attributes the TTW CO_2 emissions to the transportation sector. The production and recycling emissions are normally attributed to the industry sector, and the emissions from producing the fuel and electricity are attributed to the energy sector. The implementation of the EU RED has, however, expanded the system boundaries for biofuels used for road transport by also including the upstream GHG emissions from fuel production. This policy tool has thereby partly introduced the life-cycle perspective in carbon accounting in transport policies, but only regarding biofuels. As BEV technology displaces much of the carbon emissions upstream in the value chain and energy system as well as overseas (notably the emissions from producing the batteries), its emissions would seem to approach zero in such an analysis. There is thus an obvious discrepancy regarding system boundaries in the carbon accounting of current transportation policies.

It can be argued that the current method of carbon accounting is relevant for a car fleet consisting of ICEVs fueled with fossil fuels, where the usage phase is the dominant contributor to the GHG emissions. Even though the TTW perspective underestimates the GWP of such vehicles, it provides a means for relevant relative comparisons. This is not the case when different vehicle types are compared, since variation in both usage and production phase emissions may strongly affect the life cycle emissions of a vehicle. This limited study only compares three powertrain options and demonstrates that current policy instruments fail to favor the most effective GHG reduction technology. As further technologies enter the market, for instance fuel cell electric vehicles and ERS, a policy that ignores all GHG sources besides the TTW contribution will have increasing difficulties to effectively minimize the automotive sector's climate impact.

Policy instruments that focus on indirect metrics (*e.g.* BEV sales) rather than direct metrics (*e.g.* the climate impact of the vehicle fleet) risk becoming ineffective or even counterproductive. For example, a recent study found that the US policy instruments favoring sales of alternative fuel vehicles (including zero emission vehicles) resulted in each alternative vehicle increasing the fleet level GHG emissions by up to 60 tons of CO_2 [57]. The risk for such unexpected effects is likely to increase with increasing complexity in the mix of available vehicle technologies. To effectively minimize the automotive sector's climate impact, policy instruments should therefore adopt a life cycle perspective on GHG emissions and be technology neutral.

This study also demonstrates the urgent need to increase the supply of sustainably produced renewable fuels. A number of policy measures could promote such a development. Fossil fuels are still heavily subsidized in the EU [58]. A phase-out of these subsidies and increased CO_2 taxes on fossil fuels would improve the prospects for renewable alternatives. Decreasing the CO_2 taxes on renewable fuels in proportion to their GHG reduction potential would serve the same purpose. Reduced power taxes and surcharges for renewable hydrogen production would improve the prospects to economically supply e-fuels to the market. Finally, a targeted market introduction program for e-fuels and implementation of more ambitious targets for advanced renewable fuels in the EU RED would provide the member states with valuable strategic goals.

5. Conclusions

The European Commission proposes revisions of the automotive CO_2 emission legislation by June 2021 "to ensure a clear pathway from 2025 onwards towards zero-emission mobility" [1]. The current definition of zero emissions poses an imminent risk that this pathway will lead to emissions that approach zero only on paper.

This study finds that electrification in itself is unlikely to reduce the greenhouse gas emissions from the EU car fleet by 90% until 2050. A combination of electrification and renewable fuels, such as biofuels and e-fuels, is needed to approach climate neutrality in the automotive sector. By favoring electrification over renewable fuels, current policy instruments reduce the potential to reach this goal.

Specifically, it is found that plug-in hybrid electric vehicles, rather than being viewed as transitional, can be seen as an enabling technology for meeting ambitious climate goals. This is because their moderately sized battery packs reduce production phase greenhouse gas emissions compared to battery-electric vehicles. They also enable a limited supply of battery minerals to electrify a larger fleet, reducing the sustainability concerns around extracting sufficient amounts of minerals for a large fleet of battery-electric vehicles. If mainly driven in electric mode, a fleet of plug-in hybrids also reduce the need for fuels to the point where it may be possible to meet the demand with sustainably produced renewable fuels that have low life cycle greenhouse gas emissions.

Considering the slow rate at which the carbon intensity of the EU electricity mix is reduced, as well as the slow turnover rate of the car fleet, renewable fuels are a key element in meeting the climate goals of the automotive sector. This means that, apart from a technology-neutral, life-cycle based vehicle certification method, there is an urgent need for policy measures targeting an increased supply of sustainably produced renewable fuels.

CRediT authorship contribution statement

Öivind Andersson: Conceptualization, Methodology, Investigation, Software, Formal analysis, Writing - original draft, Visualization. **Pål Börjesson:** Methodology, Investigation, 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.

Acknowledgements

The research underlying parts of this work was funded by the Swedish Energy Agency.

References

[1] European Commission. Communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal. COM (2019) 640. Brussels; 2019.
[2] European Environment Agency. Greenhouse gas emissions from transport in Europe. 2019. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-ofgreenhouse-gases/transport-emissions-of-greenhouse-gases-12.
[3] European Commission. Climate Action. Reducing CO2 emissions from passenger cars, 2019. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en.
[4] ICCT 2018. Briefing. Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions.
[5] Mia Romare, Lisbeth Dahllöf. The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, IVL Swedish Environmental Research Institute, 2017. http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf.
[6] Ellingsen Linda Ager-Wick, Singh Bhawna, Strømman Anders. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environ Res Lett 2016;11(5). http://iopscience.iop.org/article/10.1088/1748-9326/11/5/054010.
[7] Emilsson Erik, Dahllöf Lisbeth. Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling. IVL Swedish Environmental Research Institute; 2019.
[8] Dai Qiang, Kelly Jarod C, Gaines Linda, Wang Michael. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries 2019;5:48. https://doi.org/10.3390/batteries5020048.
[9] EU. European Union Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, 2018.
[10] IPCC 2019. Climate Change and Land. Special Report. https://www.ipcc.ch/srccl/.
[11] European Commission. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and Committee of the Regions on the status of the production expansion of relevant food and feed crops worldwide. COM (2019) 142. Brussels, 2019.
[12] Englund O, Dimitriou I, Dale V, Kline K, Mola-Yudego B, Murphy F, et al. Multifunctional perennial production systems for bioenergy: performance and progress. WIRE's Energy Environ 2020:375.
[13] Alcantara C, Kuemmerle T, Baumann M, Bragina E, Griffiths P, Hostert P, et al. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. Environ Res Lett 2013;8.
[14] Berndes G, Ahlgren S, Börjesson P, Cowie A. Bioenergy and land use change – state of the art. WIREs Energy Environ 2013;2:282–303.
[15] Yugo Marta, Soler Alba. "A look into the role of e-fuels in the transport system in Europe (2030-2050). Concawe Rev 2019;28(1).
[16] IPCC. Renewable energy sources and climate change mitigation. Bioenergy 2011;2.
[17] IEA. Technology Roadmap – Delivering Sustainable Bioenergy, 2017.
[18] Hansson J, Hackl R, Taljegard M, Brynolf S, Grahn M. The potential for electrofuels production in Sweden utilizing fossil and biogenic CO_2 point sources. Front. Energy Res 2017;5:4. https://doi.org/10.3389/fenrg.2017.00004.
[19] EEA 2018. EEA report no 13/2018. Electric vehicles from life cycle and circular economy perspectives, TERM 2018: Transport and Environment Reporting Mechanism (TERM) report. doi:10.2800/77428.
[20] Muelaner JE. Unsettled Technology Domains for Pathways to Automotive Decarbonization. SAE EDGE Report EPR2020014, 2020. doi: 10.4271/EPR2020014.
[21] Hawkins Troy R, Singh Bhawna, Majeau-Bettez Guillaume, Strømman Anders Hammer. Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 2012;17(1). https://doi.org/10.1111/j.1530-9290.2012.00532.x.
[22] Faria Ricardo, Moura Pedro, Delgado Joaquim, de Almeida Anibal T. A sustainability assessment of electric vehicles as a personal mobility system. Energy Convers Manage 2012;61. https://doi.org/10.1016/j.enconman.2012.02.023.
[23] Ma Hongrui, Balthasar Felix, Tait Nigel, Riera-Palou Xavier, Harrison Andrew. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. Energy Policy 2012;44. https://doi.org/10.1016/j.enpol.2012.01.034.
[24] Onat Nuri Cihat, Kucukvar Murat, Tatari Omer. Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. Appl Energy 2015;150. https://doi.org/10.1016/j.apenergy.2015.04.001.
[25] Bauer Christian, Hofer Johannes, Althaus Hans-Jörg, Del Duce Andrea, Simons Andrew. The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. Appl Energy 2015;157. https://doi.org/10.1016/j.apenergy.2015.01.019.
[26] Boureima F, Messagie M, Sergeant N, Matheys J, Van Mierlo J, De Vos M, et al. Environmental assessment of different vehicle technologies and fuels. WIT Trans Built Environ 2012;128. https://doi.org/10.2495/UT120021.
[27] Tessum Christopher W, Hill Jason D, Marshall Julian D. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. PNAS 2014;11(52). https://doi.org/10.1073/pnas.1406853111.
[28] Meier Paul J, Cronin Keith R, Frost Ethan A, Runge Troy M, Dale Bruce E, Reinemann Douglas J, et al. Potential for electrified vehicles to contribute to U.S. petroleum and climate goals and implications for advanced biofuels. Environ Sci Technol 2015;49. https://doi.org/10.1021/acs.est.5b01691.
[29] Messagie Maarten, Boureima Faycal-Siddikou, Coosemans Thierry, Macharis Cathy, Van Mierlo Joeri. A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. Energies 2014;7. https://doi.org/10.3390/en7031467.
[30] La Picirelli Lidiane, de Souza Electo, Lora Eduardo Silva, Palacio José Carlos Escobar, Rocha Mateus Henrique, Renó Maria Luiza Grillo, et al. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. J Cleaner Prod 2018;203. https://doi.org/10.1016/j.jclepro.2018.08.236.
[31] Glensor Kain, María Rosa Muñoz B. Life-cycle assessment of Brazilian transport biofuel and electrification pathways. Sustainability 2019;11:6332. https://doi.org/10.3390/su11226332.
[32] ICCT 2019. European vehicle market statistics, pocketbook 2019/20. http://eupocketbook.theicct.org.
[33] https://press.kia.com/eu/en/home/media-resouces/press-releases/2019/Kia_to_reveal_upgraded_Niro.html.
[34] https://www.greencarreports.com/news/1121758_2019-nissan-leaf-plus-vs-2011-nissan-leaf-5-takeaways-over-8-years.
[35] Energimyndigheten 2019. ER 2019:14. Drivmedel 2018: Redovisning av rapporterade uppgifter enligt drivmedelslagen, hållbarhetslagen och reduktionsplikten.
[36] Soam Shveta, Börjesson Pål. Considerations on potentials, greenhouse gas and energy performance of biofuels based on forest residues for heavy-duty road transport in Sweden. Energies 2020;13:6701. https://doi.org/10.3390/en13246701.

[37] Andersson Ö. Diesel combustion In: Lackner, Winter, Agarwal, editors. Handbook of combustion vol. 3. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim; 2010. p. 415–40.
[38] European Commission 2020. Final Report for the European Commission, DG Climate Action. Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA. doi: 10.2834/91418.
[39] ICCT 2017. Briefing. Too low to be true? How to measure fuel consumption and CO2 emissions of plug-in hybrid vehicles, today and in the future.
[40] Seyed Amir H, Zahabi Luis Miranda-Moreno, Barla Philippe, Vincent Benoit. Fuel economy of hybrid-electric versus conventional gasoline vehicles in real-world conditions: A case study of cold cities in Quebec, Canada. Transp Res Part D 2014; 32. https://doi.org/10.1016/j.trd.2014.07.007.
[41] European Commission 2020. Climate Action News. https://ec.europa.eu/clima/news/average-co2-emissions-new-cars-and-vans-registered-europe-increased-2018-requiring-significant_en.
[42] IEA 2019. Global EV Outlook 2019: Scaling-up the transition to electric mobility.
[43] Levin Lisa A. Sustainability in deep water: the challenges of climate change, human pressures, and biodiversity conservation. Oceanography 2019;32(2).
[44] Xiaosong Hu, Le Xu, Lin Xianke, Pecht Michael. Battery lifetime prognostics. Joule 2020;4(2). https://doi.org/10.1016/j.joule.2019.11.018.
[45] Taljegard M, Thorson L, Odenberger M, Johnsson F. Large-scale implementation of electric road systems: Associated costs and the impact on CO_2 emissions. Int J Sustainable Transport 2020;14(8). https://doi.org/10.1080/15568318.2019.1595227.
[46] IEA (2019). Renewables 2019. http://www.iea.org/reports/renewables-2019.
[47] OECD-FAO (2019). Agricultural Outlook. Chapter 9. Biofuels. http://www.agri-outlook.org/commodities/Biofuels.pdf.
[48] Swedish Energy Agency. Kontrollstation 2019 för reduktionsplikten. Reduktionspliktens utveckling 2021-2030. Eskilstuna; 2019.
[49] Bioenergy IEA. Advanced Biofuels – Potential for Cost Reduction. IEA Bioenergy Task 2020;41(2020):01.
[50] Mignard D, Pritchard C. On the use of electrolytic hydrogen from variable renewable energies for the enhanced conversion of biomass to fuels. Chem Eng Res Des. 2008;86:473–87. https://doi.org/10.1016/j.cherd.2007.12.008.
[51] Hannula I. Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: performance and cost analysis. Biomass Bioeng 2015;74:26–46. https://doi.org/10.1016/j.biombioe.2015.01.006.
[52] Hannula I. Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: a techno-economic assessment. Energy 2016;104:199–212. https://doi.org/10.1016/j.energy.2016.03.119.
[53] Albrecht Friedemann Georg, Nguyen Tuong-Van. Prospects of electrofuels to defossilize transportation in Denmark – A techno-economic and ecological analysis. Energy 2020;192. https://doi.org/10.1016/j.energy.2019.116511.
[54] Hinderks WJ, Wagnera A. Factor models in the German electricity market: Stylized facts, seasonality, and calibration. Energy Econ 2020;85. https://doi.org/10.1016/j.eneco.2019.03.024.
[55] Plötz P, Funke SA, Jochem P, Wietschel M. CO_2 mitigation potential of plug-in hybrid electric vehicles larger than expected. Sci Rep 2017;7:16493. https://doi.org/10.1038/s41598-017-16684-9.
[56] Ginnebaugh Diana L, Jacobson Mark Z. Examining the impacts of ethanol (E85) versus gasoline photochemical production of smog in a fog using near-explicit gas- and aqueous-chemistry mechanisms. Environ Res Lett 2012;7(8). https://doi.org/10.1088/1748-9326/7/4/045901.
[57] Jenn Alan, Azevedo Inês ML, Michalek Jeremy J. Alternative Fuel Vehicle Adoption Increases Fleet Gasoline Consumption and Greenhouse Gas Emissions under United States Corporate Average Fuel Economy Policy and Greenhouse Gas Emissions Standards. Environ Sci Technol 2016;50(5).
[58] European Parliament (2017). PE 595.372. Fossil Fuel Subsidies.