When, Where and How can the electrification of passenger cars reduce greenhouse gas emissions?

Sacchi, R.[1*], Bauer, C.[1], Cox, B.[2], Mutel, C.[1]

1 = Technology Assessment group, Laboratory for energy systems analysis, Paul Scherrer Institut, Villigen, Switzerland

2 = INFRAS, Bern, Switzerland

**Corresponding author: email - romain.sacchi@psi.ch, telephone - +417 67 62 19 22, fax - +41 56 310 21 99*

Word count excluding Abstract, Software and data availability, Acknowledgement and References: 7'580

Abstract

Reducing the climate impacts of passenger cars has a high priority on the political agenda, especially in the EU. However, there is disagreement on how this can best be achieved – with battery or fuel cell electric vehicles, or rather with combustion engine vehicles using electricity-based synthetic liquid fuels. To answer this question and to quantify potential environmental co-benefits and trade-offs, this paper introduces *carculator*, a Python library to conduct environmental life cycle assessments of current and future passenger vehicles. Because *carculator* is open-source and equipped with an easy-to-use online graphical user interface, it produces context-specific results, deemed more relevant than results otherwise published in more static formats. *carculator* supports for several powertrains, vehicle size categories and fuel types, for any year between 2000 and 2050, as well as error propagation from input parameters. We demonstrate *carculator* with an analysis of the expected evolution of life-cycle greenhouse gas emissions of hybrid vehicles powered by fossil or synthetic gasoline and battery electric vehicles between 2020 and 2050, for all European countries and Brazil, China, India, Japan and the United States. Results show that current battery electric vehicles perform better than gasoline-powered vehicles in 26 out of the 35 countries considered. In the future, electricity-based synthetic fuels show the potential to reduce climate impacts due to the expected massive decarbonization of electricity supply. However, due to their comparatively inefficient supply and use, limited renewable resources represent a challenge and should better be used for other purposes.

Highlights

- Transparent life cycle assessment for current and future passenger vehicles
- Time-adjusted foreground and background inventories, from 2000 to 2050

- Battery electric vehicles already cause less GHG emissions than gasoline-fueled vehicles in most EU countries
- Climate impacts of cars using synthetic gasoline crucially depends on electricity supply
- Synthetic fuel production poses a huge challenge in terms of renewable resource use

Keywords: Life Cycle Assessment (LCA), open-source, battery electric, synthetic fuels, mobility, projection, error propagation.

Abbreviations

Acronym	**Description**
BEV	Battery electric vehicle
HEV-p	Gasoline-fueled hybrid electric vehicle
HEV-syn	Synthetic gasoline-fueled hybrid electric vehicle
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gases
GWP	Global warming potential
HBEFA	Handbook emission factors for road transport
IAM	Integrated assessment model
ICEV	Internal combustion engine vehicle
LCA	Life cycle assessment
LCIA	Life Cycle Impact Assessment
NEDC	New European driving cycle
NMC	Lithium nickel manganese cobalt oxide battery
WLTC	Worldwide harmonized light vehicles test cycles
WLTP	Worldwide harmonized light vehicles test procedure

1 Introduction

The European Commission recently announced the goal to achieve a “net-zero” Greenhouse Gas (GHG) emissions level by 2050 [1]. Currently, more than 20% of the EU’s GHG emissions are due to transport activities [2] and almost 50% of those are caused by passenger vehicles [3]. As opposed to other energy-intensive sectors, such as electricity generation and industry, emissions from transportation activities have been growing in the past years [2]. Therefore, effective measures to reduce these emissions are urgently needed.

The electrification of powertrains using battery electric vehicles (BEV) is seen as a promising option and a large number of stakeholders including governments and car manufacturers recently signed a declaration at the COP26 to phase-out combustion engine vehicles by 2035 or 2040 [4]. However, several large economies such as Germany, France and the United States, as well as major car manufacturers like Volkswagen and Toyota, did not sign this declaration due to – among other reasons – the fact that it excludes the option of using synthetic low-carbon fuels based on renewable electricity (“synfuels”) in internal combustion engine vehicles (ICEV). None of the options – be it BEV, fuel cell electric vehicles (FCEV) or synfuel ICEV – is free of environmental burdens: while BEV and FCEV offer the advantage of removing exhaust emissions, other aspects of their life cycle, such as the supply of electricity or the production of the vehicle frame and components, may still lead to substantial GHG emissions and other environmental impacts. And while synfuel production pathways – which use hydrogen from electrolysis and CO_2 from the atmosphere or biomass, to synthesize liquid gasoline or diesel – allow in principle for a closed carbon cycle, they are rather inefficient in both supply and use and thus can cause substantial indirect environmental burdens [5].

Life Cycle Assessment (LCA) is a tool fit for characterizing such impacts along the life cycle of vehicles. Several recent LCA studies have shown that BEV substantially reduce life cycle GHG emissions compared to conventional internal combustion engine vehicles (ICEV) fueled with gasoline or diesel provided that the electricity supply is associated with low GHG emissions [6–28]. At the same time, a few studies claimed that current BEV lead to higher GHG emissions than ICEV [29–31] in countries where most analyses show the opposite. In addition, popular news articles raised doubts on the environmental performance of BEV [32–39]. These studies and news articles cause confusion. The assumptions made in such studies often lack adequate grounds, and are rapidly exposed by the scientific community, as a press article demonstrates [40] in the case of the work by Buchal et al. [41]. Such phenomenon reveals an important aspect of LCA of BEV: in contrast to ICEV using fossil fuels, much of the environmental performance of BEV depends on the complex modeling of

upstream services in time and space as well as some parameters specific to the conditions of use of the vehicle. Similar caveats apply to synfuel ICEV, as upstream activities mostly dominate life-cycle burdens and they can exhibit substantial variability from factors like electricity supply, CO_2 sources and synthesis processes [5,42–44].
As such, most LCA studies on passenger vehicles never fully fit a precise context as several sensitive parameters depend on the geography (e.g., the electricity mix used for charging the battery), on the temporal scope (e.g., weight reduction of the vehicle glider over time), and user behaviour (e.g., number of kilometers driven per year). There is a clear need for transparent and comprehensive LCA models able to adjust foreground and background parameters to deliver relevant results that fit many different contexts. This largely fails to be commonplace nowadays among available LCA models of passenger vehicles.

Indeed, only a few prospective analyses with a flexible temporal and geographical dimension exist. The few future-oriented studies available conclude that a reduction of the environmental burden of both BEV and (synfuel) ICEV should be expected due to improved technology performance, engine hybridization, and progressive integration of renewable sources of energy in the electricity supply for battery charging [7,10,24,26,43,45–48]. Three LCA studies of passenger vehicles have considered the effects of potential changes in the global economy, but all were limited to the expected changes in the global power supply [23,24,49]. A fourth and more recent publication by Knobloch et al. [20] also attempts to include the effects of economy-wide changes in the power supply on the life cycle GHG emissions of BEV, but leaves out the life cycle emissions of the power-producing technologies, using instead a regional average GHG emission factor based on direct emissions only. None of these four studies includes synthetic electricity-based fuels, which are in general poorly covered in the literature. A general agreement on their environmental performance is that it crucially depends on the origin of power for electrolysis, the nature of the heat to sustain the fuel production, and the source of CO_2 [5,42–44,50].

This paper introduces *carculator*, an LCA library written with the programming language Python. It assesses the environmental and economic life cycle footprint of passenger vehicles by adjusting the life cycle inventories (LCI) across time, location, and other user-defined preferences, to provide a tailored basis for decision-making. Based on an open and well-documented source code, the tool offers transparency as to which input parameters are used and how results are calculated. *carculator* is designed to perform fast calculations while allowing the user to adjust the model to their own context of vehicle production, use and disposal. *carculator* addresses the following shortcomings of existing literature:

- Key parameters of passenger vehicle models are not always easy to identify, nor are they always reported. Sensitivity analysis on these key parameters is also often missing. In contrast to this, *carculator* allows to perform one-at-a-time sensitivity analyses to identify the most influential parameters.
- Epistemic uncertainty in the input parameters and the model are often not addressed. *carculator* allows for stochastic uncertainty in input parameters and its numeric propagation to end-results.
- Several literature studies are based on outdated information, while *carculator* relies on updated based on the most recent scientific literature to ensure that results are always at the cutting edge. This is specifically the case for battery electric and fuel cell-based vehicles, as well as for a number of fuel pathways, for which the publication source and date are listed in the Electronic Supplementary Information document.
- In most studies, the electricity mix used to charge batteries or produce hydrogen is not time-distributed but instead corresponds only to the year of the vehicle production. Given the number of years of use defined by the user, *carculator* produces instead a kilometer-distributed electricity mix for future battery charging and electrolysis-based hydrogen and synthetic fuel production.
- Comparisons of different drivetrains are often based on biased assumptions and input parameters (e.g., energy density for battery cells, power-to-area density of fuel cells, etc.). *carculator* does not prevent biases as such, but discloses them. Its open-source status allows the wider audience to suggest corrections.
- Results from studies in the literature are hard to reuse as the LCI datasets are not available or clearly described. *carculator* has several export functions, which allow to reuse the LCI in common LCA software, such as Brightway2 [51] or Simapro [52].
- Finally, few if any prospective studies adjust both the vehicle LCI and the background LCI over time to reflect progress in terms of material and energy use efficiency: *carculator* considers the expected progress in the automotive industry as well the penetration rate of renewable sources of energy in the electricity network of different regions of the world by coupling the LCI database ecoinvent [53] and the Integrated Assessment Model (IAM) REMIND [54,55], though other IAMs could also be used.

As a case study to demonstrate the capabilities of the calculation framework, this study quantifies country-specific climate change impacts, expressed in terms of GHG emissions per km, of BEV, synfuel ICEV, FCEV, and conventional ICEV between 2020 and 2050. This analysis is based on several electricity supply scenarios (details provided in section 2.2.3), with varying degrees of climate policy ambition, both at the country level and globally. Hence, this case study aims to answer whether, when and under which conditions electric or electricity-based powertrains provide GHG benefits in Europe, in addition to Brazil, China, India, Japan and the United States. Further, the overall demand for electricity, water, and land, as well as health impacts due to particulate matter emissions from a hypothetical European car fleet in 2050 is quantified to identify co-benefits and trade-offs of the different powertrain and fuel options.

2 Method

The structure of the tool can be described in terms of *foreground* and *background* models. The foreground model is concerned with calculating the physical attributes of the vehicles, such as the sizing of the vehicle components and the motive energy requirements, as well as quantifying direct exhaust and non-exhaust emissions. The background modeling deals with the provision of upstream goods and services necessary to support the life cycle of the vehicle. It generally includes the supply of fuel or electricity, the infrastructures, and the provision of the different material fractions necessary to the manufacture and assembly of the vehicle components.

The next subsections describe the main principles governing the foreground and background models of *carculator*. A detailed description of the model and assumptions are available in the Supplementary Information document.

2.1 Vehicles foreground model

carculator is based on the model initially used in the work of Cox et al. [23], which has been expanded and refactored into a Python library. It has been extended with the addition of several calculation modules (e.g., noise and exhaust emissions modelling), an improved handling of projected electricity mixes for battery charging, an increased range of vehicle production years to choose from, as well as a wider catalogue of powertrain and fuel types and pathways. These additional features are presented in the following sections. The calculation framework of *carculator* includes a large portfolio of powertrains, size categories, and years – see Table 1. They represent up to 324 pre-set vehicle configurations (9 powertrains x 9 size categories x 50 production years), in addition to numerous fuel pathways, stored in a four-dimensional numerical array: *powertrain*, *size*, *year* and *parameter*, where the dimension *parameter* stores *input* and *calculated* parameters.

Table 1 Powertrain and size categories, and year of production offered by *carculator*

Powertrain	**Fuel pathways**	**Size**	**Year**
Internal combustion engine vehicle, diesel-powered (ICEV-d), including a mild engine hybridization in the future	Conventional diesel, bio-diesel (from micro-algae as well as used cooking oil) and synthetic diesel (from hydrogen, combined with different CO_2 routes).	Micro, Mini, Small, Lower, medium Medium, Large, Medium SUV, Large SUV and Van	2000 to 2050
Internal combustion engine vehicle, gasoline-powered (ICEV-p), including a mild engine hybridization in the future	Conventional gasoline, bio-ethanol (from maize starch, sugar beet, forest residues and wheat straw) and synthetic gasoline (from methanol).		
Internal combustion engine vehicle, compressed natural gas-powered (ICEV-g), including a mild engine hybridization in the future	Compressed natural gas, bio-methane (from livestock manure), and synthetic methane.		
Battery electric vehicle (BEV)	Over 90 country-specific electricity mixes.		
Hybrid electric gasoline-powered vehicle (HEV-p)	Hydrogen from electrolysis, from steam methane reforming of natural gas, biogas, as well as from coal gasification, with and without Carbon Capture and Storage.		
Hybrid electric diesel-powered vehicle (HEV-d)			
Plug-in hybrid electric gasoline-powered vehicle (PHEV-p)			
Plug-in hybrid electric diesel-powered vehicle (PHEV-d)			
FCEV (hydrogen fuel cell)			

Operations are performed based on *input* parameter values to obtain *calculated* parameter values. For example, the calculated parameter *power* (i.e., the required power output of an engine) is defined by the following relation:

$$power\ [kW] = \frac{\left(power - to - mass\ ratio\ \left[\frac{W}{kg}\right] * curb\ mass[kg]\right)}{1000\ [W/kW]}$$

Here, *power-to-mass ratio* is an *input* parameter, while *curb mass* is another *calculated* parameter. Input parameter values are initially given for current and future vehicles, along with uncertainty information (i.e. uncertainty information is represented by a distribution type and parameters). Values for input parameters are defined for the current period (i.e., 2020) and an expected future realizable between 2040 and 2050. Input parameters are then linearly interpolated to the period 2000-2050. While it is possible to extrapolate vehicle models beyond 2050, the results would be highly uncertain.

Seven modules are used to obtain all the different calculated parameter values:

- the driving cycle module,
- the mass module,
- the auxiliary energy module,
- the motive energy module,
- the noise emissions module,
- the abrasion emissions module
- and the exhaust emissions module.

Should the default values provided seem inappropriate for the scope of analysis, or simply for the purpose of sensitivity analysis, those can be changed. This can range from modifying the number of passengers in the vehicle to adjusting the charge and discharge efficiency rate of the battery of a BEV or the engine hybridization level of future ICE vehicles (i.e., the share of the overall power output of a powertrain provided by an electric engine).

2.1.1 Motive energy and vehicle emissions

The functional unit of the model is the driving distance of 1 kilometer, given a user-specified driving cycle. The concept of driving cycle, which defines vehicle speed for every second of driving, is central to the foreground model. The driving cycle characterizes the conditions of driving, sets the requirements in terms of acceleration and is the basis for calculating the motive and auxiliary energy needs, onboard energy storage requirements, and related noise, tire abrasion, and exhaust emissions. The motive energy is summed together with the auxiliary energy, the energy required to operate the heating and cooling systems of the vehicle as well as the onboard electronics, to obtain the *tank-to-wheel* energy consumption of a vehicle given a specified driving cycle. Regarding abrasion emissions, five sources are distinguished: engine, brake, tire and road wear, as well as re-suspended road dust. For engine wear characterization, the methodology presented the EEA's 2019 Air pollutant emission inventory guidebook [56] is used. For the other types of abrasion emissions, the methodology presented by Beddows and Harrison [57] is used. The Handbook Emission Factors for Road Transport (HBEFA) database 4.1 [58] is used to calculate five sources of fuel-related emissions: exhaust, cold start, diurnal, hot soak and evaporation emissions. HBEFA provides emission factors based on engine maps created from emission measurements, and shows the relationship between fuel consumption and emission of pollutants for a given emission standard. *carculator* uses this relation to quantify the amount of pollutants emitted along the driving cycle for a number of emission standards (i.e., EURO-2 to EURO-6d). The tool also considers the degradation of the exhaust treatment system on ICEVs over time, as indicated by the HBEFA database. This leads to increased emissions of CO, NOx and hydrocarbons over time, especially on older vehicles (e.g., kilometric emissions of CO and NOx can be multiplied by a factor 2 on EURO-5 vehicles by the time they reach their end of life). More information on the approach to quantifying emissions is given in the Supplementary Information document. *carculator* does not consider future emission standards beyond EURO-6d. Rather, a hybridization of ICEV vehicles is assumed. This allows to use a smaller engine that operate more often at a higher load point, thereby increasing the fuel efficiency of the powertrain and decreasing exhaust-related emissions.

The driving cycle is also an important input parameter to the noise emissions model used by *carculator*. Noise levels (in dB) are calculated for eight frequency ranges for each second of the driving cycle to obtain propulsion and rolling noise levels, based on coefficients developed from the CNOSSOS project [59]. However, this model has several limitations. One of them is that it does not differentiate noise emission levels within the different types of ICEV (i.e., diesel, gasoline, compressed natural gas) or size categories.

The speed zones of the driving cycle are also used to distribute abrasion, exhaust and noise emissions between urban, suburban and rural regions, allowing for population density-specific characterization factors – mostly relevant for toxicity-related impact categories – at the impact assessment level.

2.1.2 Sizing of vehicles

Another important calculated parameter to define the motive energy is the curb mass, which is the mass of the vehicle without passengers or cargo. The model sizes the different vehicle components. This includes the mass of the fuel tank, the glider, the engine, etc. The sum of the mass of these components, in addition to the mass of the passengers and cargo, amounts to the *driving mass*. The driving mass calculated, the model defines the requirements in terms of engine power and engine mass, themselves feeding back into the calculation of the driving mass. This iterative work is performed until the driving mass of the vehicle stabilizes. While the driving mass could instead be exogenously given, this bottom-to-top approach provides a granularity at the component level, which is then validated against external sources (i.e., passenger vehicles database). A detailed description of the approach used is given in Section 2.3 of the Supplementary Information document.

2.2 Vehicles background model

When all the material and energy attributes of the vehicle are defined (e.g., mass and size of components, energy consumption), the required amounts of material and energy normalized over 1 kilometer are calculated, to be further characterized against midpoint environmental and economic indicators.

2.2.1 Life cycle inventories for vehicle components

The model uses specific LCI from the literature for some of the vehicle components, initially detailed in [23]. Additional specific LCI relating to fuel pathways have been added and are listed in the Section 3.7 of the Supplementary Information document. *carculator* also sources some data from a time-adjusted version of the ecoinvent database version v.3.8, cut-off by classification system model, as described in the next section. Specific LCI entail data for onboard energy storage (e.g., batteries of different chemistries, fuel tank for liquid and gaseous fuels, and manufacture of carbon fiber), energy transformation (e.g., hydrogen-powered fuel cell stack) and fuel pathways (e.g., production and distribution of hydrogen, biogas, synthetic fuels, etc.). LCI for the vehicle glider, powertrain and road infrastructures are sourced from the time-adjusted ecoinvent database. In the absence of better public data, we build on a bill of materials for a 2006 VW Golf IV vehicle [60], adjusting the use of lightweighting aluminium and advanced high strength steel for current and future vehicles. It is to note that *carculator* considers the use of light weighting materials to be about twice as prevalent on battery electric vehicles as on other powertrain types, to compensate for the additional weight represented by the battery. Being more carbon-intensive to produce than steel, light weighting materials increase the carbon footprint of the glider but help reduce the energy needed to move the vehicle. More information on the approach to calculating the use of light weighting materials is available in Sections 2.3 and 2.6 of the Supplementary Information document.

2.2.2 Time- and climate scenario-adjusted life cycle inventories

Using the Python library *premise* [61], multiple time- and climate scenario-adjusted versions of the ecoinvent database are produced. A similar endeavor has been realized before in the work of Cox et al. [24], where the ecoinvent database has been coupled to the integrated assessment model IMAGE [62], to modify life cycle datasets that relate to electricity generation. In this work, electricity, heat, steel and cement are aligned with the scenario outputs of the integrated assessment model REMIND [55]. Modification to the ecoinvent database include the energy efficiency of power plants, the availability of secondary steel in the future, the share of biomass-derived and synthetic fuels in the conventional fuel blend, etc. Details on the coupling between ecoinvent and REMIND are available in the *premise* documentation and associated publication [61]. For the purpose of this study, the “SSP2-Baseline” and the “SSP2-PeakBudget1300” energy scenario outputs of REMIND are used [63]. The “SSP2-Baseline” scenario lets the market regulate the development of energy technologies, without any specific climate policies enforced, leading to an increase in the global atmospheric temperature of more than 3.5 ºC, compared to pre-industrial levels by 2100. The “SSP2-PeakBudget1300” scenario is target-driven, limiting the cumulative release of GHG emissions to 1’300 Giga-tons and limiting the increase of the global atmospheric temperature to well-below 2 ºC by 2100. Additionally, emissions of non-GHG of power plants are aligned with the projections of the air emissions model GAINS [64]. *carculator* chooses LCI from the REMIND-based time-adjusted ecoinvent database that corresponds to the year of the vehicle production and the climate scenario defined by the user.

Finally, a number of improvements are modelled along the fuel chains as well. For example, the electricity required to operate the electrolyzers per kg of hydrogen produced reduces from 55 kWh today, to 44 kWh in 2050, based on [65].

2.2.3 Electricity supply

The electricity supply mix used for charging the battery of BEV and PHEV, producing hydrogen via electrolysis for FCEV, or any other electricity-based synthetic fuels, can be selected from a list of over 90 countries. A user-defined electricity mix can also be specified.

Current country-specific electricity mixes originate from the ecoinvent database [66] – itself based on statistics from the IEA – and include electricity trade. Future electricity mixes for European countries are based on ENTSO-e’s latest TYNDP projections following the *National Trends* scenario [67], the JRC TEMBA’s model for African countries [68] and on the IEA Energy Outlook STEPS scenario projections for other countries [69,70]. Unfortunately, these projections do not include imports in the supply mix.

To capture the effect of a changing electricity system during the vehicle’s lifetime, *carculator* uses an electricity supply mix which results from weighting equally the supply mix of each year comprised in the vehicle’s lifetime, starting from the vehicle’s first year of use, on the basis that the same amount of kilometers are driven each year. We refer to this mix as the “lifetime-weighted” electricity supply mix. An example for Poland is given in the Supplementary Information, Table 24. After 2050, the electricity system does not change in our model. Figure 1 shows the carbon intensity of the lifetime-weighted electricity supply mixes for European countries, as well as Brazil, China, India, Japan and the United States.

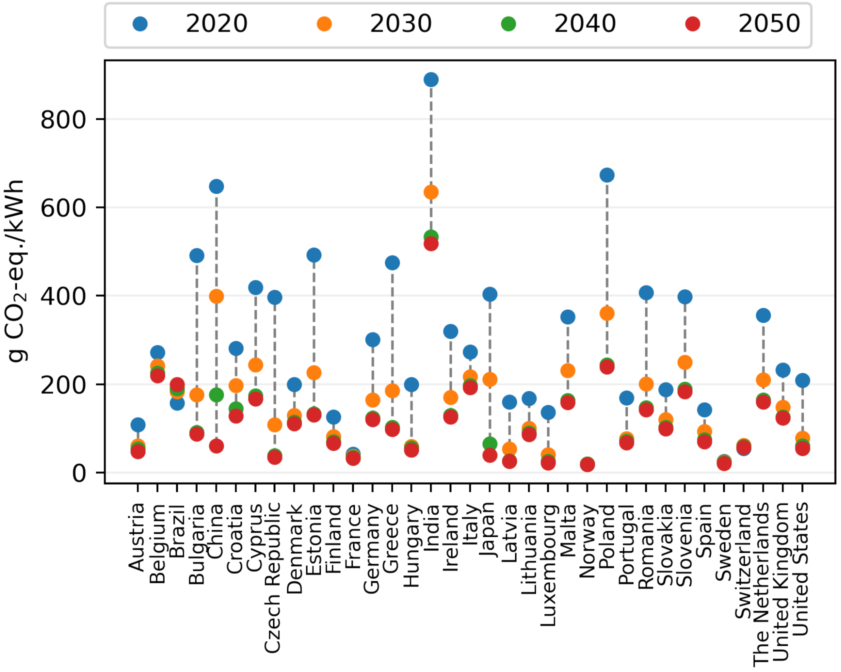

Figure 1 Country-specific lifetime-weighted carbon intensity of electricity supply mix for vehicles starting operation in specific years. Calculated with a vehicle lifetime of 16 years.

2.3 The case study

The case study investigates whether electric vehicles perform better than vehicles equipped with a combustion engine using fossil or electricity-based synthetic fuel, across different time and location-specific contexts, while considering uncertainty at the level of the vehicle technology development and climate scenarios. For this case study, a battery electric vehicle (BEV) of medium size is compared to a performant hybrid gasoline-powered vehicle (HEV) equivalent in size, from today until 2050, using the WLTC test cycle. The gasoline blend of the HEV includes some residues-based bio-ethanol for each country, based on country-specific IEA statistics. As it is not known how such blends will progress in the future and because biomass residues are constrained in supply (i.e., their availability does not react to a change in demand), the fuel blend composition remains constant until 2050. An alternative hybrid vehicle using synthetic gasoline (HEV-syn) is also considered. The synthetic gasoline is produced from synthesized methanol, using electrolysis-based hydrogen and carbon dioxide from direct air capture (DAC). To produce such fuel and to charge the battery of the electric vehicle, the country-specific lifetime-weighted electricity mix is used. Combustion engine vehicles are likely to not be sold past 2035 in Europe [4], China [71], the United States [72] and Japan [73]. And while India and Brazil have not made such commitment, the technological development of the HEV in this analysis is "frozen" past that point in time (i.e., efficiency-related parameters do not improve after 2035). This assumption is based on the authors' opinion that the lack of incentive to invest in R&D for ICEV and HEV past 2035 will translate into moderate to no gain in efficiency in the future for these vehicles.

To fully explore the possible results, we compare vehicles across two climate scenarios (SSP2 Baseline, called here "3.5 ºC" and SSP2 PeakBudget1300, called here "<2 ºC"), 30 years (2020-2050), and 1'000 Monte Carlo input parameter uncertainty iterations. We also define a best and worst case based on the sorted impacts over all time periods, where lower scores represent less environmental damage. The best case is the 25th percentile of the Monte Carlo analysis results under the "<2 ºC" scenario, while the worst case is the 75th percentile of the Monte Carlo analysis results under the "3.5 ºC" scenario. 1'000 results are obtained for each vehicle, using different input parameter values for each iteration. The input parameter values chosen are conditioned by the uncertainty distribution associated with each input. For example, the energy density of NMC battery cells in 2020 is associated to a triangular distribution with the minimum, mode and maximum values of 0.18, 0.2 and 0.22 kWh/kg, respectively. This indicates that while the "most likely" value for this parameter is 0.2 kWh/kg, the tool can generate any value between 0.18 and 0.22 for each iterations. The random values for this parameter are generated independently from the other input parameters. In addition, regarding the manufacture of synthetic gasoline for the HEV-syn vehicle, the heat used for the distillation of methanol and the regeneration of the sorbent in the DAC process comes from natural gas in the "worst" case, while excess waste heat (i.e., free of burden) is used in the "best" case.

3 Results

Before the life cycle GHG emissions can be calculated, the specifications of the vehicles to compare have to be modelled. Figure 2 shows the development of a number of vehicle parameters over time. A few important assumptions are made in terms of future development that deserve an explanation. The progress considered in terms of gravimetric energy density of battery cells means that 4 kg of battery are necessary to store 1 kWh of electricity in 2050, against 8 kg today – reflecting a battery cell energy density of 0.2 kWh/kg today, against 0.5 in 2050, based on NMC-622 cell chemistry. With the idea of maximizing range, BEVs are foreseen to maintain their driving mass, converting every gain in mass reduction from the glider (through the use of light weighting materials) and increase in the energy density of the battery cells, into additional energy storage, going from 50 kWh in 2020, to a little over 100 kWh in 2050. This has the almost proportionate effect of tripling the range autonomy (from 200 km today, to 600 km in 2050). This increasing difference in mass over time also plays in disfavor of the BEV: its electricity consumption stagnates while its emissions of particles during driving (which depend on the vehicle mass) do not decrease – and remain higher than those of the hybrid vehicle. This analysis is extended to conventional gasoline, diesel and fuel cell electric vehicles in the Section 5 of the Supplementary Information document.

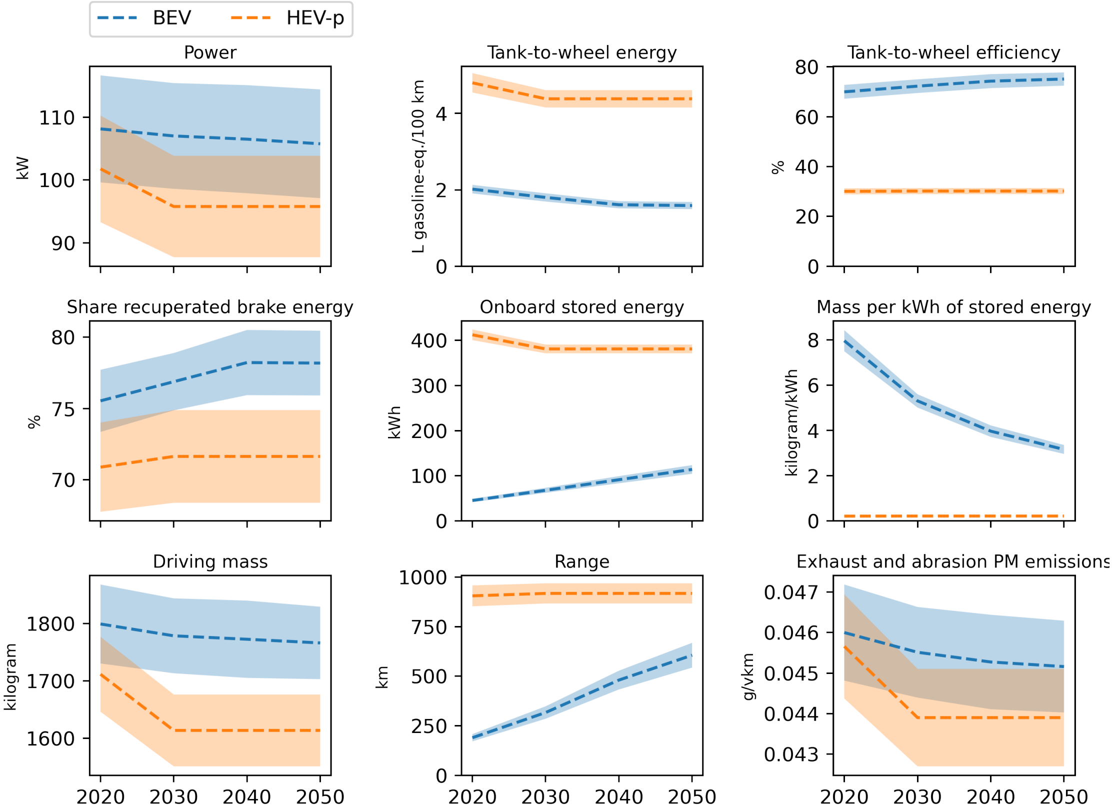

Figure 2 Calculated parameters for a mid-size gasoline hybrid and battery electric vehicle. Results are calculated over a Monte Carlo analysis (1’000 iterations). The upper and lower bounds represent the 25th and 75th quantiles. The dashed line represents the median.

Figure 3 shows the life cycle-based GHG emission totals from the comparative analysis for the two vehicles, with the HEV using either fossil or synthetic gasoline (similar results for other drivetrains are provided in the Supporting Information document, Section 5). In Europe today, the benefits in terms of GHG emission reductions from using BEVs as opposed to HEV-p are not visible in Estonia, Bulgaria and Poland. To that list, one can add Romania, Greece and Cyprus, as the difference is visible, but probably not statistically significant. However, the situation for these countries changes by 2025-2030, provided ENTSO-e *National Trends* scenario projections materialize. The prospects for synthetic gasoline are not obvious. This fuel option (HEV-syn) seems to be able to compete with BEVs, but only if sustained by very low-carbon electric networks (e.g., Norway, Sweden, France, Luxembourg) combined with the provision of heat "free of burden", and rather late in time (i.e., past the planned ban on combustion engine vehicle sales). This option remains very energy intensive, where 23 MJ of primary energy are necessary per MJ of fuel energy delivered at the wheels (as opposed to 4.8 MJ for the fossil gasoline-fueled hybrid vehicle, or 4.1 MJ for the battery electric vehicle), of which three quarters are lost between the tank and the wheels. Outside of Europe, results indicate a potential GHG emission reduction from using BEV as opposed to HEV-p in the United States as well as Brazil, but much less so in Japan and China for the time being. As for India, the country will have to wait 2035 before seeing parity between the BEV and HEV-p, since the electricity supply relies predominantly on inefficient coal power plants and the transformation towards low-carbon electricity needs time. Similarly to European countries, synthetic gasoline does not seem to be a very promising option in any of these countries, allowing for – compared to BEV – only minor reduction of GHG emissions (if any). Overall, considering the expansion of residues-based biofuels limited, the progress to be reasonably expected for the HEV-p mainly stem from reducing the fuel consumption via decreasing the vehicle's weight. However, this is not the trend observed so far, as vehicles in Europe have gotten 10% heavier between 2000 and 2016 [74]. Similarly, synthetic gasoline does not really offer a viable strategy, as it only delivers benefits under very specific conditions that will likely be met too late in time, and relying on the constrained supply of waste heat. It is also important to note that, if a country were to adopt synthetic fuels to satisfy the needs of its fleet of vehicles, the increase in demand for electricity would be such that it would impact the nature and capacities of the electric network, resulting in a different electricity supply mix that what has been used here.

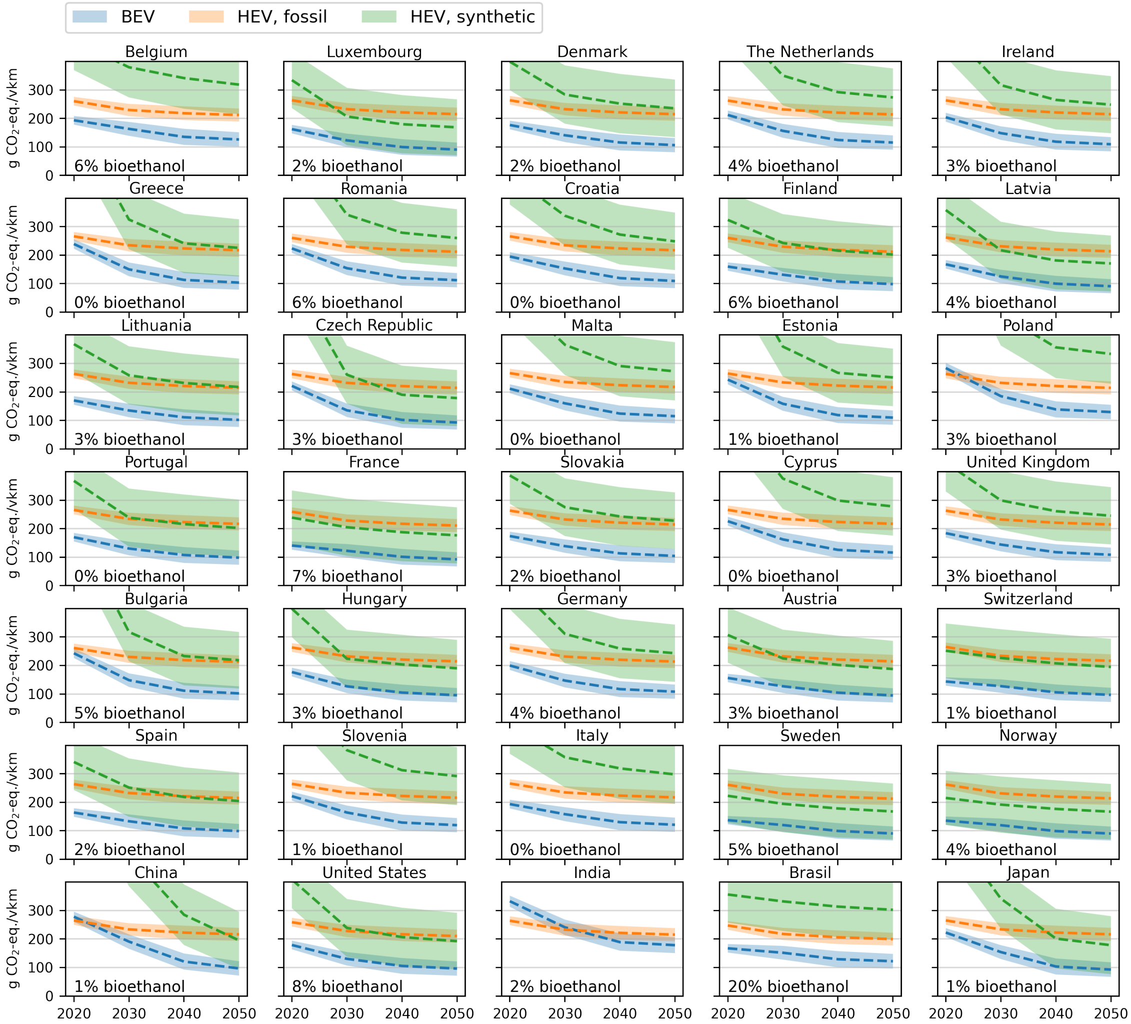

Figure 3 Life cycle GHG emissions of a mid-size BEV and gasoline HEV (using both fossil and synthetic gasoline) in European countries, as well as Brazil, China, India, Japan and the United States, including error propagation analysis. The amount of bioethanol in the gasoline blend is indicated for each country. Lower interval boundary: 25th percentile of Monte Carlo distribution using the "<2 ºC" climate scenario in the background LCI database. Upper interval boundary: 75th percentile of Monte Carlo distribution using the "3.5 ºC" climate scenario in the background LCI database. In the case of HEV-syn, the upper boundary considers the use of natural gas as the source of heat, while excess "free-of-burden" heat is considered in the lower boundary.

Figure 4 provides a closer look at the life cycle phases' contribution to the total GHG emissions in France and Poland, selected to showcase countries with high and low shares of fossil power generation, respectively, following the "<2 C" climate scenario. The hard coal and lignite-dominated electricity supply mix of Poland penalizes both the BEV and HEV-syn options today. By 2050, BEVs become a viable option in Poland thanks to the expansion of solar, wind and nuclear power. It is to note that embodied emissions in the vehicle components (i.e., glider, powertrain, energy storage) significantly reduce as well. This reduction is not country-specific, but rather depends on the REMIND climate scenario selected: it conditions the level of de-carbonization and gains in efficiency experienced by the industries (i.e., steel, cement, liquid fuels and electricity) along the supply chain of the vehicle components. In 2050, based on the "<2 C" climate scenario, these embodied emissions constitute most of the life cycle GHG emissions of BEV, both in France and Poland. Should the world head for a "3.5 ºC" climate scenario (see horizontal red bars), the life cycle GHG emissions of BEV would increase by 15 to 25% comparatively, while that increase is of a factor 2 to 3 for HEV-syn, mostly explained by a "worst case" use of natural gas-based heat to sustain the production of the synthetic fuel.

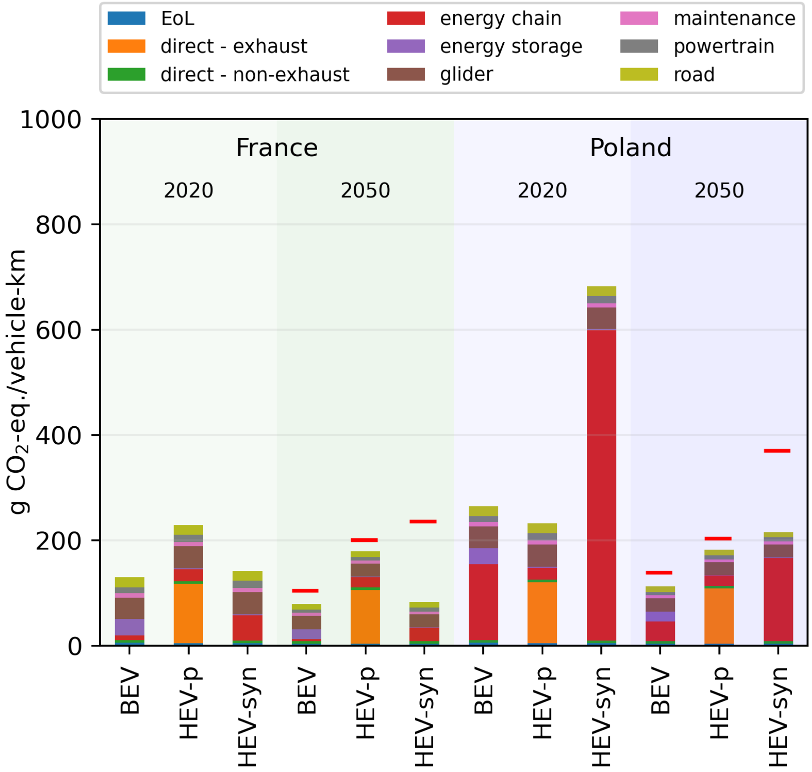

Figure 4 Life cycle GHG emissions comparison for a mid-size passenger car used in France and Poland, in 2020 and 2050, powered by electricity, gasoline and synthetic gasoline, respectively, in a world heading for the "<2 C" climate scenario. The red horizontal bars in 2050 indicate the sum of GHG emissions if the world heads for a "3.5 ºC" climate scenario. The carbon intensity of the kilometer-distributed electricity supply mix in France in 2020 is 42 g CO_2-eq./kWh in 2020, against 28 in 2050 in the "<2 ºC" climate scenario. Similarly, the carbon intensity of the kilometer-distributed electricity supply mix in Poland in 2020 is 668 g CO_2-eq./kWh in 2020, against 230 in 2050 in the "<2 ºC" climate scenario. "Net-emissions" are shown for the HEV-syn, meaning that

the exhaust CO_2 emissions and the equivalent CO_2 extraction from the atmosphere for synfuel production are not shown.

3.1 Sensitivity analysis

This section briefly describes the input parameters of the model that can influence the results presented so far.

3.1.1 Electricity supply mix

Life cycle GHG are most sensitive to a few calculated parameters. For BEV and HEV-syn, the carbon intensity of the electricity supply mix is the most important. Figure 5 depicts the effect of the carbon intensity of the electricity mix used for battery charging, hydrogen production on the potential climate change impacts of BEVs and HEV-syn, respectively, compared to that of HEV-p, in 2020 and 2050. Unlike the previous analysis, the production of synthetic gasoline is here fully electrified: the provision of heat along the fuel chain is performed by heat pumps, with a coefficient of performance (CoP) of 2.9. The figure shows that GHG emissions of BEV reduce dramatically for each additional percent of electricity share provided by wind turbines (i.e., with a carbon intensity of 25 g CO_2-eq./kWh), at the expense of coal-based electricity (i.e., with a carbon intensity of 790 g CO_2-eq./kWh). This translates into an electricity supply mix with a lower carbon intensity, as shown in the secondary x axis of the graph. The same holds true for any other type of renewable energy source with similarly low GHG emissions (e.g., large photovoltaic panel installations). In 2020, the intersection between the BEV and HEV-p slopes indicates that a minimum contribution of wind power of 50% -- or a maximum coal-based power contribution of 50% --, is required for BEV to perform better than HEV-p in regard to potential climate change impacts, and on the basis of one kilometer driven. This corresponds to a maximum carbon intensity of the electricity mix of 400 g CO_2-eq./kWh. By 2050, the minimum share of wind power in the electricity mix required for BEV to start performing similarly to HEV-p is 35% -- or around 550 g CO_2-eq./kWh. Regarding HEV-syn in 2020, the fuel needs to be produced with an electricity supply mix associated to a carbon intensity below 50 g CO_2-eq./kWh. By 2050, considering uncertainties in terms of vehicle development and background climate scenario, the carbon intensity of the electricity must be at a maximum of 150 g CO_2-eq./kWh to start yielding gains in GHG emissions reduction, compared to using HEV-p.

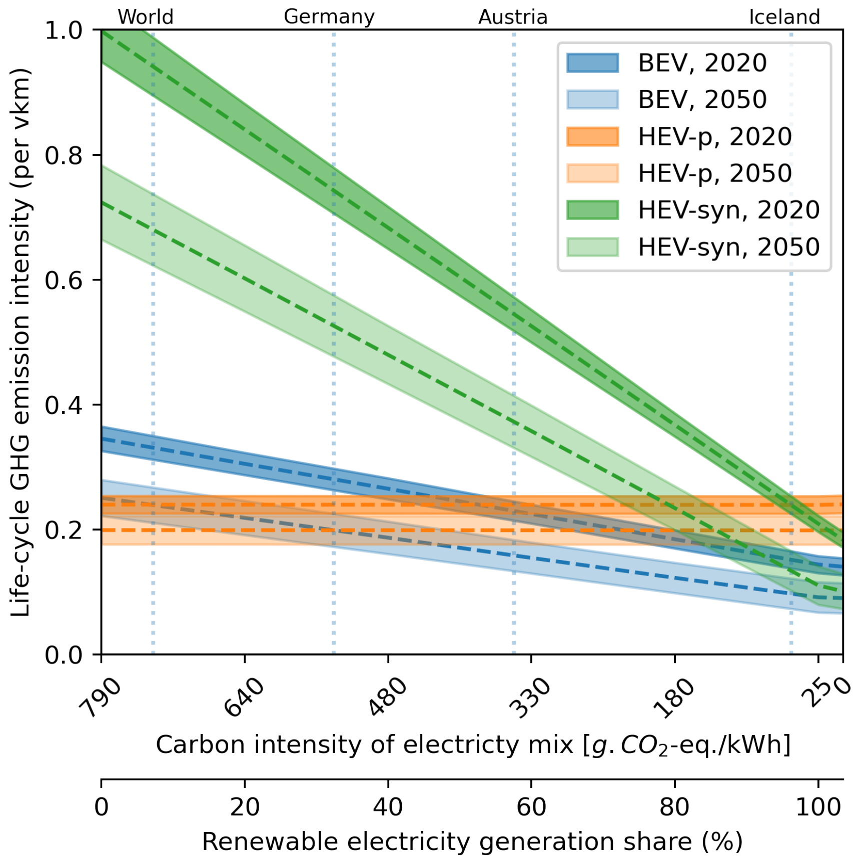

Figure 5 Effect of the carbon intensity of the electricity mix used for charging the battery of a BEV as well as for producing the synthetic gasoline for a HEV-syn (including the provision of heat via heat pumps), on their GHG emissions, compared to a gasoline-fueled HEV-p. Lower interval boundary: 25th percentile of Monte Carlo distribution using the “<2 ºC” climate scenario in the background LCI database. Upper interval boundary: 75th percentile of Monte Carlo distribution using the “3.5 ºC” climate scenario in the background LCI database.

3.1.2 Other vehicle parameters

Calculated results may also be sensitive to other vehicle parameters. *carculator* includes functions to perform “one-at-a-time” sensitivity analyses on all vehicles. By default, the tool increases each input parameter by 10% individually and measures the changes on the end-results. Such analysis is shown for the HEV-p and BEV with the production year of 2020, with respect to GHG emissions, in Figure 6. For the HEV-p, increasing the engine or drivetrain efficiency would decrease kilometric GHG emissions by a little over 4%, while increasing the mass of the glider, the aerodynamic drag, or the frontal area of the vehicle would increase them by 2 to 5%. For the BEV, such changes in the charge and discharge efficiencies of the battery can reduce GHG emissions by almost

4%. The motor and drivetrain efficiencies are also parameters that can "positively" impact GHG emissions, although in practice, the efficiency of the electric motor, already high, is not expected to improved significantly in the near future. On the other hand, GHG emissions are "negatively" impacted by any parameter that adds mass to the vehicle, such as a larger vehicle frame or battery. This aspect is important to keep in mind as current policies push to electricity vehicle fleets: if the tendency of manufacturing heavier vehicles is sustained over time, electrifying passenger cars may not lead to a substantial reduction in GHG emissions [75].

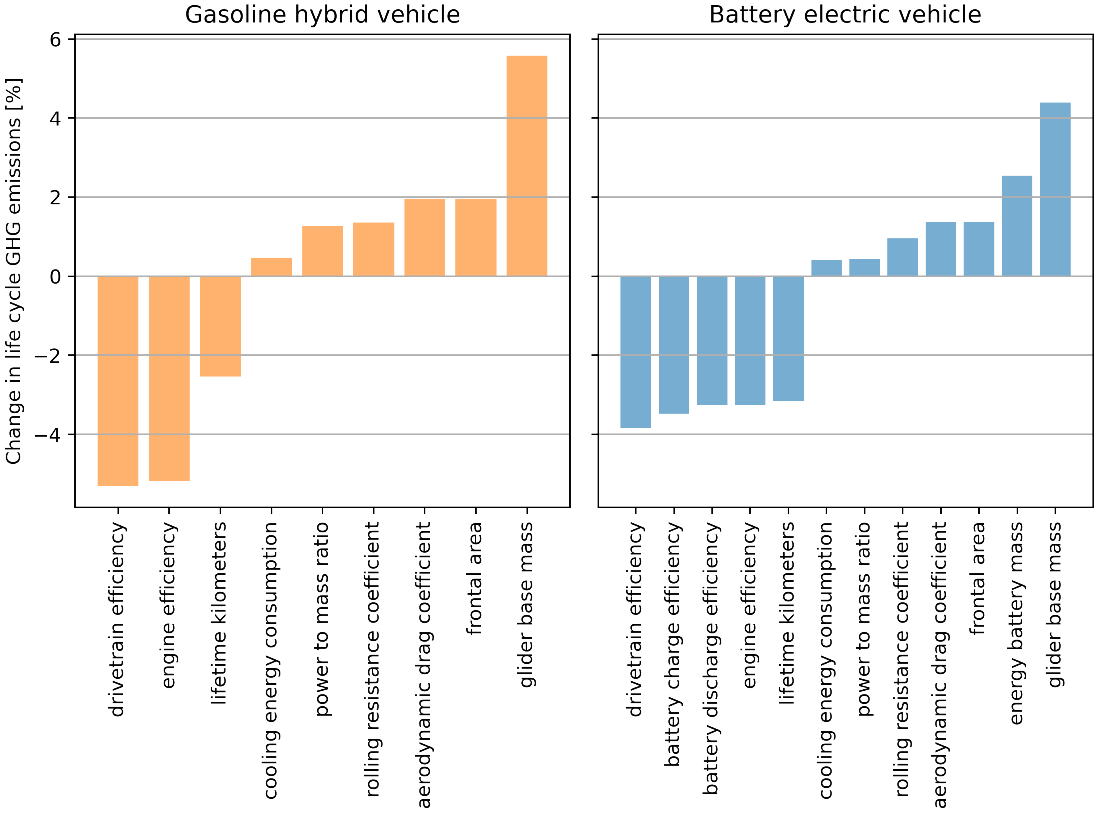

Figure 6 Sensitivity of GHG emission results in regard to vehicle input parameters

4 Discussion

Our calculator LCA tool provides a robust, open, transparent and comprehensive model. As a model, however, it has by definition limitations. A first limitation is that *carculator* quantifies life-cycle environmental burdens (and costs) of generic vehicles of specific size-categories, but not of real world models. The analysis of a specific model is possible, provided that input parameters specific to the vehicle model are known and default values adjusted accordingly.

A second limitation is related to the use of the ecoinvent database. As this database is proprietary, we can only release aggregated results for some supply chain components, instead of providing complete process models. This means that modifying these supply chains to account for region- or technology-specific parameters is not possible. Inventory datasets can be exported from carculator, and one can make such changes in generic LCA software, but two-way data transfer is still relatively cumbersome.

Moreover, environmental impacts often depend on the location of emissions of specific pollutants. While the current version of the tool is able to discern different emission compartments for exhaust emissions based on the driving cycle, it does not have such geographical resolution for emissions that occur during the production phase of the vehicle and its components. This may impede the accuracy of the model, especially in regard to the extraction and refining of metals required for the battery and onboard electronics, for example.

The inventory data used for the production of the vehicle glider also represent a limitation as they are relatively old and are therefore unlikely to represent modern vehicles very well, especially with regards to on-board electronics. This should, however, not have a major impact on potential climate change impacts. Other impact categories might be affected to a larger extent.

Finally, it is worth noting possible inconsistencies between model analyses and the IAM scenarios. The future scenarios assume certain levels of production and demand, both for mobility services and electricity. Analyses which depart from these levels could have significantly larger impacts, especially for the energy-intensive production of synthetic fuels. This limitation is underlined by the use of average electricity mixes, which don’t take into account the effect of marginal changes in demand on infrastructure, which can also be substantial. This limitation applies to any prospective LCA tool which does not include a dynamic IAM.

With all these limitations being considered, the case study shows that battery electric vehicles cause lower life-cycle GHG emissions than gasoline hybrid vehicles in most European countries today, and even more so in the future. GHG emissions reduction caused by switching from HEV-p to BEV is substantial in countries with large shares of renewable energy or nuclear power, which can also provide sufficient additional generation with these sources. This seems, for example, to be the case in France, Iceland, Norway, and Sweden. In the case of Bulgaria, Estonia and Poland, three countries with a large share of electricity supplied by coal-fired power plants, operating a BEV does not currently lead to a reduction of GHG emissions. However, the situation is expected to change in 5 to 10 years, if de-carbonization goals are reached. The climate impacts of HEV-syn are even more sensitive to the GHG intensity of electricity supply than those of BEV, since overall – considering fuel supply and use in the vehicle – BEV are 4-5 times more efficient in using electricity than HEV-syn. Thus, their climate benefits are more limited and occur later in time only after substantial progress regarding the de-carbonization of power generation.

In general, the prospective analysis shows that benefits associated to the electrification of powertrains are expected to increase. This is due to two main dynamics. On one side, there is the expected progress in the automotive sector in terms of material and energy efficiency. On the other side, the European decarbonization goals push forward the deployment of renewable energy sources, at the expense of fossil-based technologies. Notwithstanding a great potential for GHG emissions reduction, replacing combustion engine vehicles with battery electric vehicles will not be sufficient to reach the EU's "zero-emission" target for the transport of passengers. Indeed, the GHG emissions associated with the vehicle production can only be eliminated if the energy supply world-wide would refrain from using fossil fuels, especially as vehicles tend to become heavier. These results underline the importance of embodied GHG emissions in imported goods and services. Alternatives to individual transport must therefore be expanded and become more attractive.

Finally, while BEV – and HEV-syn given a very low GHG intensity of electricity supply – appear beneficial in terms of GHG emissions, it is important to consider other indicators, notably those relating to resource use in the context of upscaling technologies. Figure 7 shows an estimation where the European passenger cars fleet in 2050 is assumed to be equivalent to 2010 in terms of demand (i.e., 3'110 billion vehicle-kilometers) and size composition (i.e., 39%, 30%, 14% and 17% of the demand driven by small, lower medium, medium and large cars, respectively) [76], and satisfied by a single powertrain technology. For HEV-syn, the provision of hydrogen and carbon dioxide for producing the synthetic gasoline is ensured by electrolysis and DAC, respectively, as they are believed to be the most scalable supply routes (as opposed to Steam Methane Reforming of natural gas or bio-methane for hydrogen, or industrial point source capture for carbon dioxide). Additionally, the heat needed for DAC and methanol distillation is provided by heat pumps, deemed more scalable than waste heat, and less carbon intensive than natural gas. GHG emissions significantly reduce when considering BEVs, as opposed to HEV-p/syn, as do emissions of particulate matter. However, the latter may remain important if no effort is made to reduce the size and mass of battery electric vehicles, despite the absence of emissions from the exhaust and a reduction in emissions of brake wear particles. Direct (i.e., BEVs) or indirect (i.e., HEV-syn and FCEVs) electrification of passenger cars may also become a challenge in terms of freshwater use. In the case of BEV, the freshwater footprint is dominated by the extraction of cobalt that requires significant of hydropower-based electricity in the Democratic Republic of the Congo. Hydroelectric reservoirs leads to the dissipation of large amounts of freshwater, which becomes no longer available to natural aquifers. A better modeling of future recycling rates of cobalt and other metals entering the composition of the battery may decrease this figure. The effect on land occupation across powertrains is less clear and easily falls within the error margin of the model. The required expansion of renewable (or nuclear) power generation capacity is the biggest hurdle for indirect electrification, especially considering the HEV-syn option. The required electricity demand in 2050 for a European HEV-syn fleet would be beyond the power generation of the five largest countries in the EU in 2018. Installing the required generation capacities in Europe in addition to those which are in any case required to replace fossil fuels in the power sector as such seems unrealistic. And considering limited renewable potentials, synthetic fuels should primarily be used for applications which are hard or impossible to directly electrify, such as aviation [5].

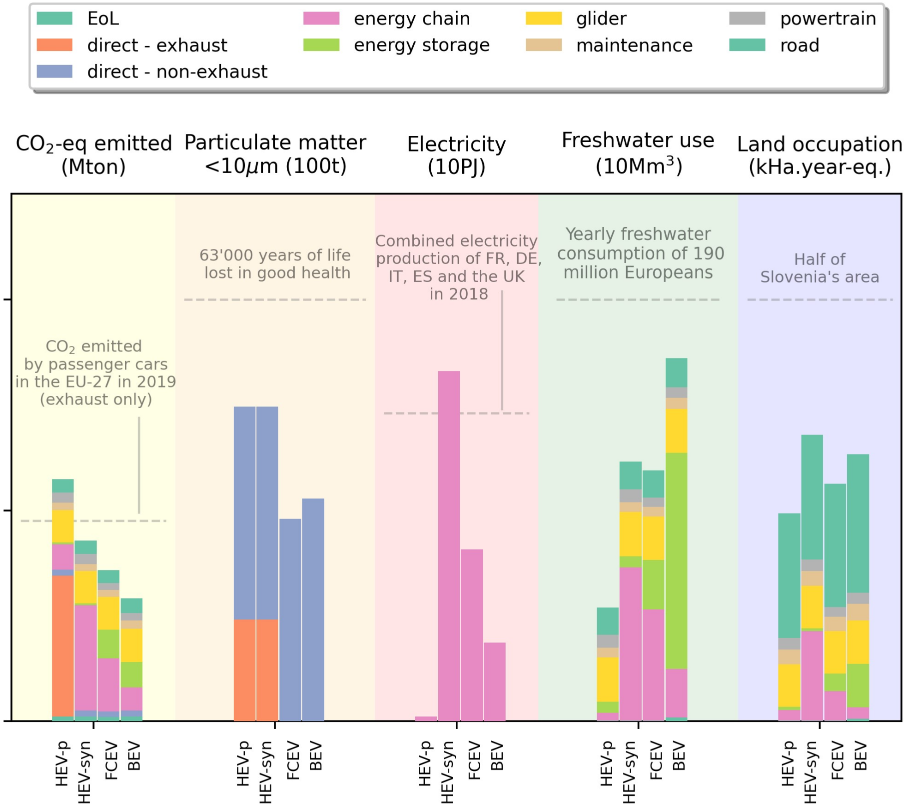

Figure 7 Resource and pollution indicators for different mid-size vehicles in 2050, in a “<2 ºC” climate scenario. For the “Particulate matter” and “Electricity” indicators, only use-related impacts are shown. The “Land occupation” indicator comprises agricultural and urban land occupation. Years of life lost in good health are

calculated based on the ReCiPe 2016's dose-response relationship of 6.29e-4 disability-adjusted life years (DALY) per kg of $PM_{2.5}$-eq. emitted.

Software and data availability

- Name of software: carculator
- Version: 1.6.4
- Developers: Romain Sacchi, Christopher Mutel, Brian Cox
- Online repository: https://github.com/romainsacchi/carculator
- Documentation: https://readthedocs.org/projects/carculator/
- Online graphical user interface: https://carculator.psi.ch/
- Contact information: carculator@psi.ch
- Year first available: 2020
- Software required: Python 3.9
- Availability: Open source
- Cost: Free
- Program language: Python
- Program size: 38 megabytes
- Archive: https://zenodo.org/record/5879787
- DOI: 10.5281/zenodo.5879787
- Size of archive: 1,900 kilobytes

Acknowledgment

The authors thank Gunnar Luderer and Alois Dirnaichner from the Potsdam Institute for Climate Impact Research (PIK) for the insights given on the integrated assessment model REMIND.

Funding: This research was primarily supported by the Swiss Competence Center for Energy Research (SCCER) Efficient Technologies and Systems for Mobility, funded by the Swiss Innovation Agency (Innosuisse), and the Volkswagen Group Sustainability Council. Further contributions are due to PSI's Energy System Integration platform and the "Enabling a Low-Carbon Economy via Hydrogen and CCS" (ELEGANCY) project, which has received funding from DETEC (CH), BMWi (DE), RVO (NL), Gassnova (NO), BEIS (UK), Gassco, Equinor and Total, and is co-funded by the European Commission under the Horizon 2020 programme, ACT Grant Agreement No 691712.

References

[1] European Commission. The European Green Deal. Brussels: 2019.

[2] European Environment Agency. Greenhouse gas emissions by aggregated sector 2019.

[3] European Environment Agency. Greenhouse gas emissions from transport in Europe 2019.

[4] Department for Transport. COP26 declaration on accelerating the transition to 100% zero emission cars and vans . GovUk 2021. https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans (accessed January 17, 2022).

[5] Ueckerdt F, Bauer C, Dirnaichner A, Everall J, Sacchi R, Luderer G. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat Clim Chang 2021 115 2021;11:384–93. https://doi.org/10.1038/s41558-021-01032-7.

[6] Ajanovic A, Haas R. Economic and Environmental Prospects for Battery Electric- and Fuel Cell Vehicles: A Review. Fuel Cells 2019. https://doi.org/10.1002/fuce.201800171.

[7] Bauer C, Hofer J, Althaus H-J, Del Duce A, Simons A. 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.

[8] Helmers E, Weiss M. Advances and critical aspects in the life-cycle assessment of battery electric cars. Energy Emiss Control Technol 2016;2017:5:1–18.

[9] Marmiroli B, Messagie M, Dotelli G, Van Mierlo J. Electricity generation in LCA of electric vehicles: A review. vol. 8. MDPI AG; 2018. https://doi.org/10.3390/app8081384.

[10] Miotti M, Hofer J, Bauer C. Integrated environmental and economic assessment of current and future fuel cell vehicles. Int J Life Cycle Assess 2015;22:94–110.

[11] Miotti M, Supran GJ, Kim EJ, Trancik JE. Personal Vehicles Evaluated against Climate Change Mitigation Targets. Environ Sci Technol 2016;50:10795–804. https://doi.org/10.1021/acs.est.6b00177.

[12] Moro A, Lonza L. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transp Res Part D Transp Environ 2018;64:5–14. https://doi.org/10.1016/j.trd.2017.07.012.

[13] Rosenfeld DC, Lindorfer J, Fazeni-Fraisl K. Comparison of advanced fuels—Which technology can win from the life cycle perspective? J Clean Prod 2019;238:117879. https://doi.org/10.1016/j.jclepro.2019.117879.

[14] Wu Z, Wang M, Zheng J, Sun X, Zhao M, Wang X. Life cycle greenhouse gas emission reduction potential of battery electric vehicle. J Clean Prod 2018;190:462–70. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.04.036.

[15] Wu Z, Wang C, Wolfram P, Zhang Y, Sun X, Hertwich E. Assessing electric vehicle policy with region-specific carbon footprints. Appl Energy 2019;256:113923. https://doi.org/10.1016/j.apenergy.2019.113923.

[16] Nordelöf A, Messagie M, Tillman A-M, Ljunggren Söderman M, Van Mierlo J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 2014;19:1866–90. https://doi.org/10.1007/s11367-014-0788-0.

[17] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J Ind Ecol 2013;17:53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x.

[18] Bicer Y, Dincer I. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resour Conserv Recycl 2018;132:141–57. https://doi.org/10.1016/j.resconrec.2018.01.036.

[19] Del Pero F, Delogu M, Pierini M. Life Cycle Assessment in the automotive sector: A comparative case study of Internal Combustion Engine (ICE) and electric car. Procedia Struct Integr 2018;12:521–37. https://doi.org/10.1016/j.prostr.2018.11.066.

[20] Knobloch F, Hanssen S V., Lam A, Pollitt H, Salas P, Chewpreecha U, et al. Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat Sustain 2020:1–11. https://doi.org/10.1038/s41893-020-0488-7.

[21] Transport & Environment. How clean are electric cars? 2020.

[22] Bigazzi A. Comparison of marginal and average emission factors for passenger transportation modes. Appl Energy 2019:1460–6. https://doi.org/10.1016/j.apenergy.2019.03.172.

[23] Cox B, Bauer C, Mendoza Beltran A, van Vuuren DP, Mutel C. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl Energy2 2020.

[24] Cox B, Mutel CL, Bauer C, Mendoza Beltran A, van Vuuren DP. Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. Environ Sci Technol 2018;52:4989–95. https://doi.org/10.1021/acs.est.8b00261.

[25] DelDuce A, Gauch M, Althaus H-J. Electric passenger car transport and passenger car life cycle

inventories in ecoinvent version 3. Int J Life Cycle Assess 2016;21:1314–26. https://doi.org/https://doi.org/10.1007/s11367-014-0792-4.

[26] Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, et al. Current and Future United States Light-Duty Vehicle Pathways: Cradle-to-Grave Lifecycle Greenhouse Gas Emissions and Economic Assessment. Environ Sci Technol 2018;52:2392–9. https://doi.org/10.1021/acs.est.7b06006.

[27] Ellingsen LA-W, Singh B, Strømman AH. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environ Res Lett 2016;11:54010.

[28] He X, Zhang S, Wu Y, Wallington TJ, Lu X, Tamor MA, et al. Economic and Climate Benefits of Electric Vehicles in China, the United States, and Germany. Environ Sci Technol 2019. https://doi.org/10.1021/acs.est.9b00531.

[29] Kawamoto R, Mochizuki H, Moriguchi Y, Nakano T, Motohashi M, Sakai Y, et al. Estimation of CO2 Emissions of internal combustion engine vehicle and battery electric vehicle using LCA. Sustain 2019;11. https://doi.org/10.3390/su11092690.

[30] Buchal C, Karl H-D, Sinn H-W. Kohlemotoren, Windmotoren und Dieselmotoren: Was zeigt die CO2-Bilanz? 2019.

[31] Ferroni F, Reichmuth A. Energieverschwendung der Extraklasse. Die Weltwoche 2017.

[32] Wade L. Tesla's Electric Cars Aren't as Green as You Might Think 2016.

[33] Watts A. Tesla car battery production releases as much CO2 as 8 years of gasoline driving 2017.

[34] McGee P. Electric cars' green image blackens beneath the bonnet. Financ Times 2017.

[35] Fischer H, Keating D. How eco-friendly are electric cars? Dtsch Welle 2017.

[36] Häne S. Kampf um das Image der Elektroautos. Tages-Anzeiger 2019.

[37] Rotter C. Australian: New Report: Electric Cars Have 'Higher CO2 Emissions' 2019.

[38] Lesser J. Short Circuit: The High Cost of Electric Vehicle Subsidies. 2018.

[39] AutoVista Group. Conflicting reports on the carbon footprint of EVs 2019.

[40] EUfactcheck. Mostly false: "Electric cars generate higher emissions than diesel cars" – eufactcheck.eu 2019. https://eufactcheck.eu/factcheck/mostly-false-electric-cars-generate-higher-emissions-than-diesel-cars/ (accessed April 9, 2020).

[41] Buchal C, Karl H-D, Sinn H-W. Kohlemotoren, Windmotoren und Dieselmotoren: Was zeigt die CO 2-Bilanz? 2019.

[42] Bongartz D, Doré L, Eichler K, Grube T, Heuser B, Hombach LE, et al. Comparison of light-duty

transportation fuels produced from renewable hydrogen and green carbon dioxide. Appl Energy 2018;231:757–67. https://doi.org/10.1016/J.APENERGY.2018.09.106.

[43] Ricardo Energy & Environment. Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA - Final Report. 2020.

[44] Hombach LE, Doré L, Heidgen K, Maas H, Wallington TJ, Walther G. Economic and environmental assessment of current (2015) and future (2030) use of E-fuels in light-duty vehicles in Germany. J Clean Prod 2019;207:153–62. https://doi.org/10.1016/J.JCLEPRO.2018.09.261.

[45] Bauer C. Environmental impact of passenger cars - today and tomorrow. Bern: 2020.

[46] Bekel K, Pauliuk S. Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. Int J Life Cycle Assess 2019. https://doi.org/10.1007/s11367-019-01640-8.

[47] Bauer C, Cox B, Heck T, Hirschberg S, Hofer J, Schenler W, et al. Opportunities and challenges for electric mobility: an interdisciplinary assessment of passenger vehicles Final report of the THELMA project in co-operation with the Swiss Competence Center for Energy Research “Efficient technologies and systems for mobility.” 2016.

[48] Petrauskienė K, Skvarnavičiūtė M, Dvarionienė J. Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. J Clean Prod 2019. https://doi.org/10.1016/j.jclepro.2019.119042.

[49] Mendoza Beltran A, Cox B, Mutel C, Vuuren D van, Vivanco DF, Deetman S, et al. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. J Ind Ecol 2018. https://doi.org/https://doi.org/10.1111/jiec.12825.

[50] Rüdisüli M, Bach C, Bauer C, Beloin-Saint-Pierre D, Elber U, Georges G, et al. Prospective life-cycle assessment of greenhouse gas emissions of electricity-based mobility options. Appl Energy 2022;306:118065. https://doi.org/10.1016/J.APENERGY.2021.118065.

[51] Mutel C. Brightway: An open source framework for Life Cycle Assessment. J Open Source Softw 2017;2:236. https://doi.org/10.21105/joss.00236.

[52] SimaPro | LCA software for informed-change makers n.d. https://simapro.com/ (accessed January 9, 2022).

[53] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21:1218–30.

[54] Bertram C, Luderer G, Popp A, Minx JC, Lamb WF, Stevanović M, et al. Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. Environ Res Lett 2018;13:064038. https://doi.org/10.1088/1748-9326/aac3ec.

[55] Luderer G, Leimbach M, Bauer N, Kriegler E, Lavinia Baumstark, Christoph Bertram, Anastasis G. Description of the REMIND Model (Version 1.6). Rochester, NY: 2015.

[56] European Environment Agency. Air pollutant emission inventory guidebook 2019 2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view (accessed November 2, 2020).

[57] Beddows DCS, Harrison RM. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. Atmos Environ 2021;244:117886. https://doi.org/10.1016/J.ATMOSENV.2020.117886.

[58] INFRAS. Handbook Emission Factors for Road Transport 2019.

[59] Kephalopoulos S, Paviotti M, Anfosso-Lédée F. Common Noise Assessment Methods in Europe (CNOSSOS-EU). 2012.

[60] Althaus H-J, Gauch M. Vergleichende Ökobilanz individueller Mobilität: Elektromobilität versus konventionelle Mobilität mit Bio-und fossilen Treibstoffen 2010.

[61] Sacchi R, Terlouw T, Siala K, Dirnaichner A, Bauer C, Cox B, et al. PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective Life Cycle Assessment using Integrated Assessment Models. Renew Sustain Energy Rev n.d.

[62] Stehfest E, van Vuuren D, Bouwman L, Kram T. Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL); 2014.

[63] Aboumahboub T, Auer C, Bauer N, Baumstark L, Bertram C, Bi S, et al. REMIND - REgional Model of INvestments and Development 2020. https://doi.org/10.5281/ZENODO.3730919.

[64] International Institute for Applied Systems Analysis (IIASA). The GAINS Model 2016:2–3. https://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html (accessed January 31, 2020).

[65] Bauer C, Desai H, Heck T, Schneider S, Terlouw T, Treyer K, et al. Electricity storage and hydrogen: Technologies, costs and environmental burdens. 2021.

[66] Steubing B, Wernet G, Reinhard J, Bauer C, Moreno-Ruiz E. The ecoinvent database version 3 (part II):

analyzing LCA results and comparison to version 2. Int J Life Cycle Assess 2016;21:1269–81. https://doi.org/10.1007/s11367-016-1109-6.

[67] Entso-e. ENTSO-E Ten-Year Network Development Plan 2020 – Main Report – November 2020 – Version for public consultation 2020.

[68] Pappis I, Howells M, Sridharan V, Gardumi A, Ramos E. Energy projections for African countries. 2019. https://doi.org/10.2760/678700.

[69] International Energy Agency (IEA). World Energy Outlook 2017. IEA 2017. https://www.iea.org/reports/world-energy-outlook-2017 (accessed January 26, 2020).

[70] IEA. World Energy Outlook 2021 - revised version October 2021 2021.

[71] Tabeta S. China plans to phase out conventional gas-burning cars by 2035. Nikkei Asia 2020. https://asia.nikkei.com/Business/Automobiles/China-plans-to-phase-out-conventional-gas-burning-cars-by-2035 (accessed January 19, 2022).

[72] Milman O. Biden faces pressure to drive gasoline and diesel cars out of the US. Guard 2021. https://www.theguardian.com/us-news/2021/apr/30/biden-administration-cars-emissions (accessed January 19, 2022).

[73] Reuters Staff. Japan may ban sale of new gasoline-powered vehicles in mid-2030s: media. Reuters 2020. https://uk.reuters.com/article/us-japan-autos-gasoline/japan-may-ban-sale-of-new-gasoline-powered-vehicles-in-mid-2030s-media-idUKKBN28D044 (accessed January 19, 2022).

[74] Mock P. Footprint versus mass: How to best account for weight reduction in the european vehicle CO2 regulation. vol. 2020. 2017.

[75] Shaffer B, Auffhammer M, Samaras C. Make electric vehicles lighter to maximize climate and safety benefits. Nat 2021 5987880 2021;598:254–6. https://doi.org/10.1038/d41586-021-02760-8.

[76] Papadimitriou G, Ntziachristos L, Wüthrich P, Notter B, Keller M, Fridell E, et al. TRACCS : Transport data collection supporting the quantitative analysis of measures relating to transport and climate change. 2013.