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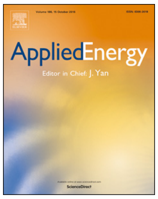


Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios

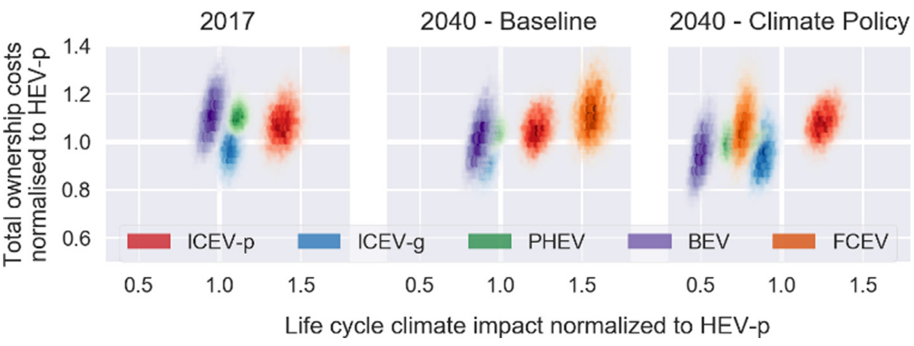
Brian Cox[a,b], Christian Bauer[a,*], Angelica Mendoza Beltran[c], Detlef P. van Vuuren[d,e], Christopher L. Mutel[a]

[a] *Paul Scherrer Institut, Laboratory for Energy Systems Analysis, 5232 Villigen PSI, Switzerland*
[b] *INFRAS AG, Sennweg 2, 3012 Bern, Switzerland*[1]
[c] *Institut de Ciència i Tecnologia Ambientals (ICTA), Autonomous University of Barcelona, 08193 Bellaterra, Barcelona, Spain*[1]
[d] *PBL Netherlands Environmental Assessment Agency, 2594 The Hague, the Netherlands*
[e] *Copernicus Institute of Sustainable Development, Utrecht University, 3584 CB Utrecht, the Netherlands*

HIGHLIGHTS

- European environmental and total costs of ownership of current and future cars.
- Future LCA databases created using SSP scenarios from IMAGE integrated assessment model.
- Battery and fuel cell vehicles exhibit 25–70% lower GHG emissions in 2040.
- Battery vehicles have the highest GHG emission reduction potential independent of the scenario.
- Future battery vehicles will also generally offer cost savings compared to hybrids.

GRAPHICAL ABSTRACT



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ABSTRACT

In this analysis, life cycle environmental burdens and total costs of ownership (TCO) of current (2017) and future (2040) passenger cars with different powertrain configurations are compared. For all vehicle configurations, probability distributions are defined for all performance parameters. Using these, a Monte Carlo based global sensitivity analysis is performed to determine the input parameters that contribute most to overall variability of results. To capture the systematic effects of the energy transition, future electricity scenarios are deeply integrated into the ecoinvent life cycle assessment background database. With this integration, not only the way how future electric vehicles are charged is captured, but also how future vehicles and batteries are produced. If electricity has a life cycle carbon content similar to or better than a modern natural gas combined cycle powerplant, full powertrain electrification makes sense from a climate point of view, and in many cases also provides reductions in TCO. In general, vehicles with smaller batteries and longer lifetime distances have the best cost and climate performance. If a very large driving range is required or clean electricity is not available, hybrid powertrain and compressed natural gas vehicles are good options in terms of both costs and climate change impacts. Alternative powertrains containing large batteries or fuel cells are the most sensitive to changes in the future electricity system as their life cycles are more electricity intensive. The benefits of these alternative

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[*] Corresponding author.
E-mail address: christian.bauer@psi.ch (C. Bauer).
[1] Current affiliation.

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drivetrains are strongly linked to the success of the energy transition: the more the electricity sector is decarbonized, the greater the benefit of electrifying passenger vehicles.

1. Introduction

Decision makers require accurate and detailed information regarding the life cycle environmental burdens of different passenger transport technologies to efficiently decarbonize the passenger transport sector. Much progress has already been made on this front. Previous studies have already shown that Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV) can provide climate benefits, though results depend strongly on several factors including the CO_2 content of the electricity used for battery charging and hydrogen production, the lifetime distance travelled by the vehicle, and the vehicle's energy consumption [1–13]. Recent studies have also shown that the environmental performance of battery electric vehicles is strongly influenced by the size of the battery, the energy required in the battery production phase, and how that process energy is produced [9,10,14–16].

Thus, future developments in the electricity sector must be included in life cycle background databases in order to more accurately understand the environmental impacts of future battery electric vehicles. For example, Cox et al. [15] showed that not considering changes to the energy sector used to build the vehicle, the life cycle climate impacts of battery electric vehicles could be overestimated by up to 75% in scenarios where significant global electricity sector decarbonization (i.e. a shift from coal, gas and oil as dominating energy carriers to renewables, nuclear and carbon capture and storage) is achieved by 2040. Mendoza Beltran et al. [17] showed that the environmental performance of both battery electric and conventional combustion vehicles change strongly depending on the future energy scenario, and that the relative performance of the two powertrains also differs depending on the scenario. Battery electric vehicles are more sensitive to changes in the energy sector than combustion vehicles are. However, Mendoza Beltran et al. [17] considered only two vehicle powertrain options and don't include improvements to future vehicle performance or variability in vehicle parameters such as vehicle lifetime, battery size and other parameters known to influence the relative performance. Meanwhile, Cox et al. [15] included future vehicle improvements and performance uncertainty, but considered only battery electric vehicles. There remains a significant gap in the literature, as all of the remaining studies comparing the environmental burdens of different future passenger vehicle powertrains [1,2,4,6,8,13] miss the impacts of the energy transition on the upstream impacts of producing and operating vehicles. This means that all currently available prospective life cycle comparisons between different future passenger vehicle powertrains likely underestimate the advantages of powertrain electrification.

In order to avoid the introduction of biases and allow for true cost-benefit calculations, a fair comparison of life cycle economic and environmental assessments must use consistent and comprehensive input data sources and scenarios. For example, future electricity prices will be directly tied to future electricity generation mixes. The recent studies which addressed environmental and economic costs in parallel lack this consistency, using disparate models and scenarios for economic and environmental results [3,8,18,19]. Most recent total cost of ownership (TCO) studies showed that current internal combustion vehicles (ICEV) have lowest TCO, while BEV TCO is expected to be lowest in the future [19–24]. Battery and fuel price developments have been identified as major drivers for future TCO rankings [8,18,20].

Moreover, the majority of currently available studies did not adequately address uncertainty in vehicle performance due to factors such as lifetime, mass, battery size etc. Despite their importance for the results, these determining factors were often mentioned only qualitatively or shown in a simple sensitivity or scenario analysis in the majority of studies. The few studies that analyzed this uncertainty and variability with a Monte Carlo analysis or similar, e.g. [6,11], sampled some of the vehicle performance parameters independently. This might lead to incorrect results, as e.g., vehicle mass, energy consumption and emissions are to some extent correlated. Thus, the interplay between these important, yet uncertain, parameters is not yet fully understood.

As a result, the current literature leaves several important issues without robust answers. In order to close these gaps, the following key research questions will be answered:

1. Do battery electric vehicles reduce impacts on climate change compared to other vehicle types in a wide range of likely future energy scenarios, or only in the ones where significant electricity sector decarbonization is achieved?
2. Which environmental and economic co-benefits and trade-offs will come along with vehicle electrification (i.e. the switch from ICEV to BEV and FCEV), depending on future energy scenarios?
3. What role do key parameters such as battery size, vehicle lifetime and vehicle mass play in the relative environmental and economic performances of different powertrains?

The goal of this paper is to present a calculation framework that can provide much more complete and consistent answers to these and similar questions. In order to achieve this, this analysis:

1. Provides robust and consistent estimates of the total cost of ownership and life cycle environmental burdens of current (2017) and future (2040) passenger vehicles with different powertrains based on deep integration of integrated assessment models and life cycle assessment databases under two bounding future electricity scenarios.
2. Examines which vehicle performance parameters have the greatest influence on the environmental and cost performance of different powertrains and their relative ranking using Monte Carlo and global sensitivity analysis.
3. Provides complete input assumptions and calculation methods so that others may build on the results of this analysis, for example in integrated assessment or energy economic models, or may change input assumptions and re-run the model to examine the performance of passenger vehicles under their specific conditions.

The focus is on vehicles operating in European conditions, though enough information is provided in the Supporting Information for results to be generalized. The manuscript also focuses on impacts on climate change and TCO; however, results for further environmental impact categories are included in the Supporting Information and environmental co-benefits and trade-offs are briefly discussed in the conclusions section.

The paper is structured in the following way: The next section contains a description of methods – the vehicle model as basis for LCA and TCO quantification is detailed, including handling of uncertainties and model calibration; also LCA and TCO calculation frameworks are explained. This methods section is followed by one on results and their discussion. Next, limitations are outlined, and as a consequence, implications for further research. The final section draws conclusions.

2. Methods

In this section, the approach to model vehicle performance as well as the Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) model are described. Much more detail and analysis for each of the following sections is found in the Supporting Information, as well as complete executable calculation files in the form of Jupyter notebooks.

2.1. Vehicle modelling

Fig. 1 shows a schematic representation of the framework applied and the step-by-step procedure for LCA and TCO calculations for current and future vehicles. All parameter values used in the vehicle modeling are given in the Supporting Information (excel file “input data”, worksheet “Car parameters”).

2.2. Powertrains considered

The following powertrain variants – deemed relevant for current (production year 2017) and future (production year 2040) operation in Europe – are considered: Internal Combustion Engine Vehicles operating with diesel (ICEV-d), petrol (ICEV-p) or compressed natural gas (ICEV-g), Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV), and Fuel Cell Electric Vehicles (FCEV). Future ICEV are assumed to be mild hybrids with a small 48 V battery system. More information on powertrain definitions can be found in the Supporting Information.

2.3. Uncertainty analysis

Triangular distributions for 233 technological, environmental, or economic parameters are defined. In some cases, these parameters also need to be differentiated by powertrain and vehicle class. Triangular distribution is chosen, because reasonable estimates of the minimum and maximum economic or technological bounds of each parameter are available, while data to describe the shape of the distribution tails are not. In this case, the triangular distribution is conservative, in that its tails have relatively high probabilities. For static analysis, the mode of each distribution is used, as this can be considered to be the most likely value.

Stochastic analysis is calculated using Monte Carlo, which was implemented using standard Python libraries such as numpy and pandas, and is described in detail in the supporting information. Only the basic design parameters for each vehicle are defined as independent input parameters. Dependent parameters are calculated based on these input values. For example, vehicle energy consumption is not defined as an input parameter, but is rather calculated based on input values such as the vehicle mass, driving patterns, aerodynamic characteristics, and rolling resistance. Similarly, inputs such as glider size, lifetime, power-to-mass ratio, cargo load, and heating and cooling demand are specific to a vehicle class, but not a powertrain. In this case, for each iteration, these parameters would be sampled once, and that value applied to all

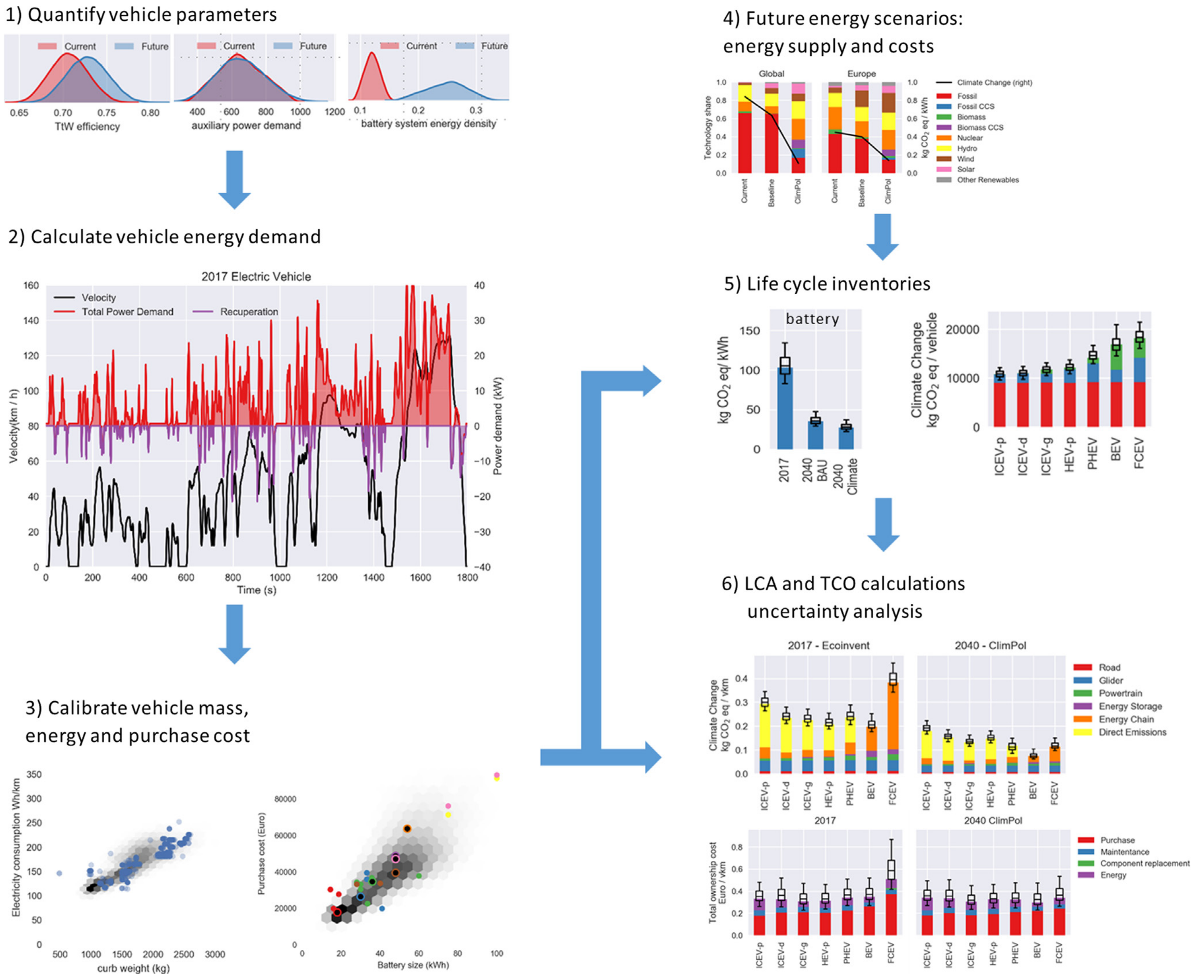

Fig. 1. Schematic representation of the procedure for LCA and TCO calculations for current and future vehicles. The blue arrows indicate information flow.

powertrains. A complete list of input parameters and their distributions is included as an excel table in the Supporting Information.

Uncertainty results here consider only uncertainty and variability of foreground parameters and do not consider uncertainty in the background LCA database or life cycle impact assessment methods. Variation in the driving patterns of the vehicle are not taken into account. While technologies such as autonomous driving and platooning could reduce total energy consumption [15], this effect is independent of powertrain or vehicle size, and therefore is not considered here.

2.4. Vehicle model and calibration

In order to compare vehicle powertrain types as fairly as possible, the base vehicle is considered as a common platform for all powertrain types. This common platform is referred to here as the glider, which contains all components of the vehicle that are not specific to the powertrain or energy storage components, such as chassis, tires, and seats.

Seven different vehicle classes are included in this analysis: mini, small, lower medium, medium, large, van, and SUV. The majority of results shown in the main body of the paper are for lower medium sized cars, which are among the most commonly sold in Western Europe [25]. The vehicle model was calibrated based on mass, power, energy consumption, and purchase cost of new cars available in 2016 and 2017 [26,27]. Calibration results, vehicle parameter values, and results for other vehicles classes are all given in the Supporting Information.

2.5. Vehicle energy demand

Vehicle energy demand is calculated by assuming that the vehicle follows a fixed velocity versus time profile, and calculating the mechanical energy demand at the wheels required to follow this driving cycle based on parameters for vehicle weight, rolling resistance and aerodynamic properties [1]. Additionally, the energy consumption due to auxiliaries such as heating and cooling, lighting and control functions as well as the potential for recuperative braking are considered where applicable for the specific drivetrain. Finally, the efficiency of all drivetrain components is included in the calculation to determine the tank-to-wheel energy consumption of the vehicle. Energy consumption is modeled this way, because it allows endogenous calculation of energy consumption based on variable input parameters upon which energy consumption strongly depends.

Vehicle energy consumption is calculated using the driving pattern defined by the world harmonized light vehicles test cycle (WLTC). This driving cycle is selected because it attempts to model real world driving patterns, which is a common criticism of the New European Driving Cycle (NEDC) [28]. In order to calibrate the model, vehicle energy consumption is also calculated according to the NEDC with the non-essential auxiliary energy demands turned off and cargo and passenger load reduced to a minimum. This allows to make use of the wealth of publically available vehicle energy consumption data based on the NEDC. These results are compared to energy consumption and CO_2 emission monitoring data for all new cars sold in Europe [26,27]; correspondence is good. When recalculating energy consumption results using the WLTC considering auxiliary energy demand, the results are roughly 25% higher than the reported NEDC values. Comparing these vehicle energy consumption results to other data sources with different driving patterns [28–42] also yields reasonable correspondence, though uncertainty is high in the literature values due to the variability of vehicle sizes, production years and driving cycles used. See the Supporting Information, Figures 11 and 12 and the associated text for more information.

2.6. Vehicle component modelling details

In the following section, assumptions regarding the components and environmental flows that have largest impact on the results are provided: lithium ion batteries, fuel cells, hydrogen tanks, tailpipe emissions, and auxiliary power demand due to heating and cooling [1,2,10,43–45]. Also the share of electric versus combustion powered driving for PHEV is discussed.

2.6.1. Lithium ion batteries

The most important component of BEV are the lithium ion batteries used for energy storage, as they are responsible for a significant share of vehicle costs, mass and production impacts [2]. It is assumed that the future battery mass in BEV will decrease compared to current vehicles and remain constant for PHEV. However, the energy storage density is expected to improve significantly in the future - current battery cell energy density is assumed to range from 150 to 250 Wh/kg (most likely value 200 Wh/kg) and with future values ranging from 250 to 500 Wh/kg (most likely value 400 Wh/kg) – resulting in overall increases in energy storage capacity and vehicle range. The specification of the energy storage capacity is an important assumption with strong impact on the results [10]. The rationale behind the best estimate battery size of 55 kWh in 2040 is a substantially expanded charging infrastructure, which will eliminate the current “range anxiety” of drivers, and the positive effect of smaller batteries on vehicle costs and fuel efficiency. However, since there is no way of objectively determining this parameter for 2040, the dependency of the results on battery size is presented in the Supporting Information. Furthermore, the battery size in PHEV can be hugely variable. PHEV have a rather small battery in the most likely case, but include an upper bound on battery size that reflects a “range extender” type of vehicle configuration (see Fig. 2).

Battery lifetime is a highly uncertain parameter, influenced by the number of charging cycles, calendric ageing, charging power, ambient temperatures, and the battery management system. Broad ranges are therefore used, with current batteries expected to have a lifetime of

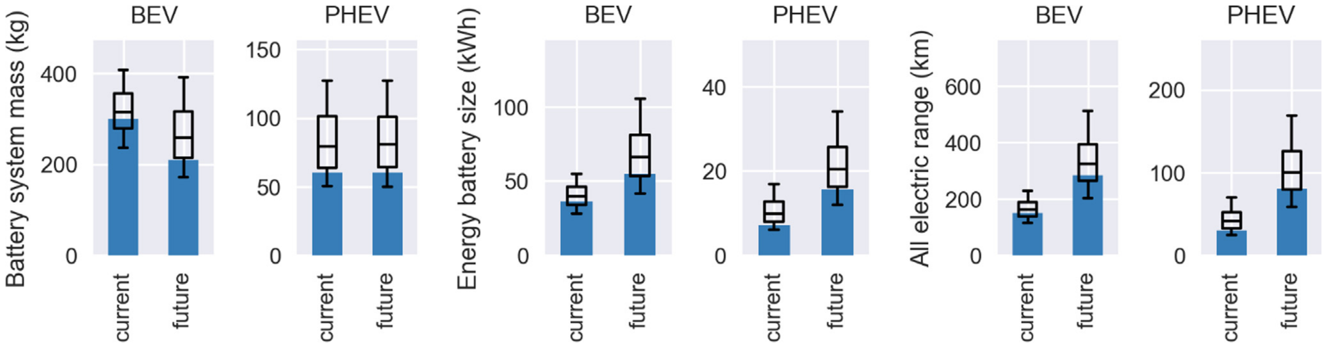

Fig. 2. Energy storage battery mass and capacity, and all electric range of current and future BEV and PHEV lower medium size cars. The box and whisker plots show the 5, 25, 50, 75, and 95 percentiles; the most likely value (mode) is given by the blue bars, and significantly departs from the median as each parameter is modeled with highly asymmetric triangular distributions.

100′000-300′000 km (most likely value 200′000 km) after which they are replaced and recycled, in case the vehicle as such lasts longer [46]. Future batteries are expected to have a lifetime distance of 150′000-350′000 km (most likely value 200′000 km), and show the effect of changes in battery lifetime on LCA results in the Supporting Information. Battery 'second life' is indirectly considered: When a vehicle's battery reaches its end-of-life before the car is retired, the battery is replaced. However, if the car is retired before this replacement battery is expired, the battery is assumed to be used elsewhere, and only the used fraction of the battery is allocated to the car. In short, it is assumed that it is possible to use 1.2 or 2.3 batteries over the lifetime of a BEV, but never less than one complete battery.

The Life Cycle Inventory (LCI) for lithium ion battery production are based on primary data for batteries with a $Li(Ni_xCo_yMn_z)O_2$ (NCM) anode and a graphite cathode [47]. According to the currently available literature, the largest contributing factor to the climate burdens of lithium ion battery production is the energy consumption during the assembly process, though the actual amount of energy required is still under debate as the production facility analyzed in the primary data source [47] was not operating at full capacity and was comparatively small [7,9,14,48–53]. Thus, battery cell energy consumption is included as an uncertain parameter that ranges from 4 to 20 kWh/kg battery cell (most likely 8 kWh/kg) for current batteries and 4–12 kWh/kg battery cell (most likely value 8 kWh / kg battery cell) for future batteries; similarly, a current power density of 1.3–2.3 kW/kg (most likely value 2 kW/kg) is assumed, increasing to a range of 2–3.5 kW/kg (most likely value 3 kW/kg) in the future [46,52]. The lower bound and most likely values for battery production energy consumption are not expected to change significantly in the future, as energy consumption improvements will likely be roughly cancelled out by increasing cell complexity [51]. Conversely, energy consumption of cell production has decreased dramatically in the past decade as factories have increased in size and reached full production capacity [51]. The current upper bound reflects smaller production facilities operating at full production capacity. Furthermore, the share of heat supplied by electricity versus natural gas is also uncertain [52,53]. The outer bounds of this energy share are set to range between 10% and 90% with a most likely value of 50% electricity. The global average electricity mix is used for battery production. Though it is possible to determine where current batteries are produced, it is impossible to determine where batteries will be produced in 2040. Therefore, global average production values are used relying on the different electricity scenarios to examine the sensitivity of results to this assumption.

All other aspects of lithium ion battery production per kilogram are assumed to remain constant in the future. While this is a significant assumption, the current consensus in the literature seems to be that the overall climate burdens of battery production are more dependent on the energy consumed in the manufacturing phase than the battery chemistry [9,14,16] and the environmental burdens in other impact categories are related to battery components that are relatively independent of chemistry, such as the production of the copper current collectors. Specific energy, i.e. energy storage capacity per battery mass, which is partially determined by battery cell chemistry, can be considered as the driving factor regarding environmental burdens associated with battery manufacturing, especially for impacts on climate change [14–16]; other impact categories might be more substantially affected by different cell chemistries or a switch from liquid to solid electrolytes. LCA results per kilogram and kilowatt hour of battery on a system level for selected impact categories are provided in the Supporting Information, Figure 15. With the present inventory data for battery production, the majority of associated impacts on climate change, roughly 70%, are due to material supply chains. This means that the GHG emission reduction potential using renewables for energy supply in battery cell manufacturing – as announced by many car makers – is relatively limited. The same lithium ion battery inventory data is used for all powertrains.

Production costs for lithium ion battery systems are assumed to be 180–270 (most likely value 225) Euro/kWh for current cars, decreasing to 60–180 (most likely value 135) Euro/kWh [54,55].

2.6.2. Fuel cells

The most important component in a fuel cell vehicle in terms of cost, performance and environmental burdens is the fuel cell, and in particular its efficiency and platinum [1,13,44]. FCEV use a Polymer Electrolyte Membrane (PEM) fuel cell designed in a hybrid configuration with a power-optimized lithium ion battery used to help meet peak power demands. Thus, the fuel cell is sized to have a maximum power output of 60–90% (most likely value 75%) of total vehicle power. Current fuel cell stacks are expected have efficiencies of 50–57% (most likely value 53.5%), with an own consumption due to pumps and internal losses of 10–20% (most likely value 15%), improving to 52–63% (most likely value 57%) stack efficiency with own consumption of 8–15% (most likely value 12.5%) in the future [34,56,57].

The LCI model for PEM fuel cells is taken from the 2020 values [44], with a power area density of 800 mW/cm^2, and is comparable to currently available fuel cell vehicles. Uncertainties as well as future improvements in fuel cell design are taken into account by holding the fuel cell stack LCI per unit active area constant, and scaling according to different power area densities. Current fuel cell stacks are modelled to have a power area density of 700–1100 mW/cm^2 (most likely value 900 mW/cm^2), improving to 800–1200 mW/cm^2 (most likely value 1000 mW/cm^2) in the future.

Platinum loading of 0.125 mg/cm^2 of fuel cell active area is assumed to remain constant for varying power area densities [44]. Thus, as the power area density of the fuel cell is scaled, the platinum loading for current and future fuel cells varies from 0.114 to 0.178 g/kW (most likely value 0.139 g/kW) and 0.104–0.156 g/kW (most likely value 0.125 g/kW [1,13,56,57].

Very little data exists regarding actual fuel cell lifetimes in passenger cars. This analysis is based on the assumptions from previous LCA studies [1,13,44], targets from the US Department of Energy [56,57], and reports from fuel cell bus projects [58,59] assuming that current fuel cell systems are replaced and recycled after their lifetime of 100′000-300′000 km (most likely value 150′000) km. This is expected to improve to 150′000-350′000 km (most likely value 200′000 km) in the future, which is roughly the life of the rest of the vehicle. Assumptions for the second life of fuel cells are equal to those for replacement batteries as discussed above.

Current fuel cell system production costs are assumed to cost between 125 and 270 Euro per kW stack power (most likely value 160 Euro/kW), decreasing to 25–135 Euro/kW (most likely value 60 Euro/kW) in the future [13,60].

2.6.3. Hydrogen storage tanks

Hydrogen storage is assumed to be in 700 bar tanks made of an aluminum cylinder wrapped in carbon fiber with stainless steel fittings. The tank is assumed to consist of 20% aluminum, 25% stainless steel, and 55% carbon fiber (of which 40% is resin, and 60% is carbon cloth) [34,61–63].

Per kilowatt hour of hydrogen storage, hydrogen tanks are assumed to weigh between 0.55 and 0.65 kg (most likely value 0.6 kg), improving to 0.45–0.55 kg (most likely value 0.5 kg). These values are consistent with current values available in the literature and commercially available tanks [61,62,64,65].

Current hydrogen tanks are assumed to cost 600–1100 Euro/kg H_2 capacity (most likely value 800 Euro/kg H_2 capacity) decreasing to 350–800 Euro/kg H_2 capacity (most likely value 450 Euro/kg H_2 capacity) [63].

2.6.4. Vehicle exhaust emissions

Tailpipe operating emissions from combustion engines are included using data from the HBEFA version 3.3 [66]. Emissions of CO_2 and SO_x

are linked to vehicle fuel consumption results ("vehicle energy demand" above). For other emissions, average emissions per kilometer for Euro 6 vehicles in average driving conditions are used for the current most likely values; the lowest likely values are assumed to be half of these values, and the highest likely values are double these values. Emissions from future vehicles (except of CO_2 and SO_x, which are correlated to fuel consumption) are assumed to be reduced by 50% compared to current values. This assumed reduction roughly corresponds to the reduction between Euro 3 and Euro 6 emission standards in the past. This assumed reduction is to some extent arbitrary, but LCIA results show that contributions from direct pollutant emissions from exhausts of ICEV are minor if emission standards are met (Figures 30, 32 and 33 in the Supporting Information). However, in light of the recent discovery that real NO_x emissions from Euro 6 diesel cars can be significantly higher than regulatory limits, the upper limit for NO_x emissions from diesel powertrains is increased to 1 g/km according to a report from the ICCT based on measurements in Germany [67,68]. The HBEFA has already been updated to consider increased NO_x emissions from Euro 6 diesel powertrains, so this value (0.085 g/km) is used as the most likely value, which only slightly higher than the regulatory limit of 0.08 g/km for Euro 6.

2.6.5. Auxiliary energy consumption due to heating and cooling

Basic cabin thermal energy demand is assumed to be powertrain type independent, though dependent on vehicle class. For example, all lower medium sized vehicles are assumed to have a thermal heating demand of 200–400 W (most likely value 300 W) and a thermal cooling demand of 200–400 W (most likely value 300 W). In the future, the most likely value for these parameters is decreased by 5% and the lower bound is decreased by 10% due to expected improved cabin insulation.

However, the actual increased load on engine or battery varies for each powertrain. For example, heat demand for combustion and fuel cell vehicles is supplied using waste heat from the powertrain, and thus poses no additional demand on the engine or fuel cell. Conversely, current BEV use energy directly from the battery to provide heat. Future BEV are assumed to use heat pumps and novel concepts such as localized cabin heating to reduce the power demand on the battery to 30–100% (most likely value 80%) of the cabin heat demand. Cooling demands are assumed to be met by an air conditioner with a coefficient of performance between 0.83 and 1.25 (most likely value 1) for all powertrain types, increasing to 1–2 (most likely value 1.25) in the future. For BEV cooling load is assumed to draw directly on the battery, while for the other powertrain types the efficiency of the engine or fuel cell is also taken into account.

2.6.6. Plug in hybrid electric vehicle operation mode

Because PHEV can operate in combustion mode (energy supply from the internal combustion engine) or in all electric mode (energy comes from the onboard battery), assumptions must be taken to define the share of driving in each mode. Here, the concept of a utility factor is used. This factor is defined as the lifetime average ratio of distance driven in all electric mode to the total distance driven, which has been shown to generally correlate with the all-electric range of the vehicle [34,69]. A curve is fit to over 37′000 daily passenger car trip distances reported in Switzerland in 2010 [70] with the assumption that the vehicle starts each day fully charged and is operated in all-electric mode until the battery is depleted. The remainder of the distance travelled that day assigned to combustion mode (see Supporting Information for more information).

3. Life cycle assessment

LCA is a methodology that compiles inventories of all environmentally relevant flows (such as emissions, natural resource use, energy and material demand as well as waste produced) of a products' or services' entire life cycle, from resource extraction to end-of-life and calculates their contribution to known areas of environmental concern, such as climate change, primary energy use, or human health impacts due to fine particulate formation or ground level ozone formation.

In this analysis, attributional LCA according to the ISO standards ISO 14040 and 14044 [71,72] is performed using the ecoinvent v3.4 database with the system model "allocation, cut-off by classification" [73]. The LCA calculations are performed using the Brightway2 software package [74]. The goal of this study is to compare the life cycle environmental impacts of passenger cars with production years 2017 (current) and 2040 (future). The entire life cycle of the vehicle (from raw material production to end-of-life) and energy chain (from well-to-wheel) is included, which corresponds to a 'cradle-to-grave' system boundary. The functional unit of the study is the vehicle kilometer travelled (vkm), averaged over the entire lifetime of the car. Most likely vehicle lifetime is assumed to be 200'000 km, equivalent to 16.7 years at an annual driving distance of 12'000 km, for all drivetrains and for current and future vehicles. Except where explicitly stated, the inventories used for the life cycle assessment are taken from the ecoinvent 3.4 database for European conditions where available and global averages otherwise (i.e. inputs from European or global markets). In the main body of the paper, the focus is on results for impacts on climate change, which are presented in the units of kg CO_2 eq. Characterization factors used are from the most recent IPCC report with the 100 year time horizon [75], as implemented in ecoinvent v3.4. Results for selected ReCiPe [76] impact categories are provided in the Supporting Information.

3.1. Modified LCA databases for future energy scenarios

The procedure described in [15,17] is used to modify the LCA database in order to consider future developments of the electricity sector using scenario results from the IMAGE Integrated Assessment Model [77]. While a larger set of IMAGE scenarios exists based on the Shared Socio-economic Pathways [17,78,79], the focus of this analysis is only on the 'Middle of the Road' scenario, i.e. the SSP2 (Baseline) and a climate policy scenario (ClimPol) leading to radiative forcing in 2100 of 2.6 W/m^2 (giving a likely chance to stay below the 2 °C climate target) [78]. The global and European average electricity mixes and their life cycle climate change impacts for each scenario are shown in Fig. 3. The most important observation is that in 2040 a major share of electricity is produced from low, zero carbon or even negative emission technologies in the ClimPol scenario.

The electricity sector in the ecoinvent database is modified using IMAGE scenario results. This includes changing ecoinvent electricity market shares and fossil, biomass, and nuclear plant performance based on future improvements defined by the IMAGE model for 26 global regions. Electricity generation datasets for carbon capture and storage technologies (from [80]) are added into the database, as they play an important role in the ClimPol scenario. All other production technologies are left unchanged, though their supply chains are also calculated using the modified background database. See [15,17] for details on background database modifications for prospective LCA. LCA results for current and future passenger cars are calculated with the original ecoinvent 3.4 database (current) as well as the future vehicles with each of the two modified databases.[2]

3.2. Vehicle energy supply

Electricity supply used to charge BEV is assumed to be the ENTSO-E average low voltage mix. Also electricity sourced from relevant single technologies is considered: hard coal (modern German hard coal power plant), natural gas (German combined cycle natural gas plant), nuclear

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[2] Results for future vehicles calculated with the current background database are included in the Supporting Information.

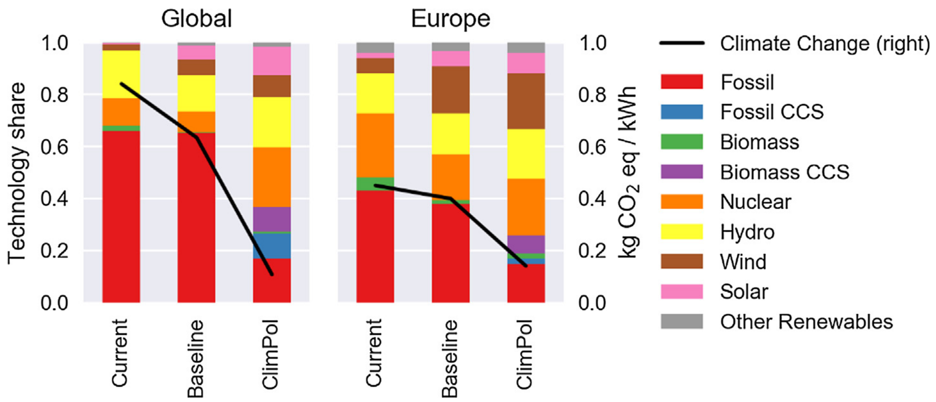

Fig. 3. Global and European electricity mix at low voltage level, and climate change impacts per kilowatt hour for current conditions and two future scenarios in 2040. Electricity generation technologies are grouped together for readability.

(Swiss pressurized water reactor), hydro (Swiss hydroelectricity from reservoir power plants), solar photovoltaic (Swiss slanted-roof installations with multi-crystal silicon), and wind (German 1–3 MW onshore turbines). Losses and emissions associated with converting high voltage to medium and low voltage electricity have been applied according to average Swiss conditions.

Hydrogen is supplied at 700 bar and is assumed to be produced via electrolysis with medium voltage level ENTSO-E electricity. Results for the above mentioned additional electricity sources as well as Steam Reforming of Methane (SMR) are included in the Supporting Information. LCI data for electrolysis is taken from [81], while LCI data for SMR is taken from [82]. Fossil fuel supply chains for petrol and diesel are taken from ecoinvent European conditions, while the CNG dataset is global. None of the fossil fuels contain any biofuel fractions.

3.3. *Total cost of ownership*

Vehicle TCO is calculated from the owners' perspective and includes purchase, energy, maintenance, and component replacement (for batteries and fuel cells) costs. Taxes or subsidies on vehicle purchase and insurance costs are excluded as these can vary strongly depending on location and are not affected by the physical performance of the vehicle. End-of-life costs and values are assumed to be zero. All purchase and replacement costs are amortized with an internal discount rate of 0.03–0.07 (most likely value 0.05) [8,18,20,83]. Vehicle purchase costs are calculated based on estimating production costs for all major components and are converted to purchase costs using an uncertain markup factor that varies depending on vehicle class. For example, the markup factor for lower medium sized vehicles is between 1.2 and 1.7 with a most likely value of 1.4. Model results for vehicle purchase costs are calibrated to 2017 vehicle purchase costs in Switzerland [27], and also agree well with European vehicle costs [25]. Selected calibration results are included in the Supporting Information.

Current gasoline and diesel fuel prices are based on European data for 2017 [84] while CNG prices are taken from an online repository for CNG prices [85]. Electricity prices are also based on European data for 2017 [86]. BEV are charged mostly at home in the current case, and thus assume residential prices, with a 0.02 Euro/kWh surcharge for amortization of infrastructure. Hydrogen for FCEV is produced via electrolysis at fuel stations that pay the industrial electricity price. A current hydrogen infrastructure cost of 0.1 Euro/kWh is used. For all energy prices, the most likely value is defined by the European average, while the minimum and maximum are defined by the European country with the lowest and highest annual average respectively. Future energy prices are taken from IMAGE model results specific for the transport sector. As uncertainty of future energy prices is high, the upper and lower bounds are set at ± 50% of the most likely value. Both hydrogen production and BEV charging could profit from dynamic electricity price schemes with lower than average prices at times of low demand and/or high production. BEV could also generate revenues in systems with vehicle-to-grid concepts in place; these could, however, have negative impacts on battery lifetime with associated economic trade-offs for vehicle owners. These issues are not explicitly taken into account for TCO calculations, but represented by the uncertainty analysis. Energy cost assumptions for all energy types are summarized in Table 1.

4. Results and discussion

4.1. *Climate change*

Fig. 4 shows the life cycle climate change results for lower medium sized cars. The stacked bar chart shows the contribution to the total impacts, calculated with the most likely value of each foreground parameter. The error bars represent the parametric uncertainty and variability of the foreground car description. Results are calculated using the European average electricity mix for battery charging and hydrogen production via electrolysis. Results for BEV, PHEV, and FCEV with other energy chains are available in the Supporting Information along with results for other impact categories, vehicle classes, and results for future cars calculated with the current ecoinvent database.

Advanced powertrain vehicles, especially BEV and FCEV, have higher production impacts than conventional powertrains. However, vehicle production impacts for PHEV, BEV, and FCEV are expected to decrease significantly in the future as battery and hydrogen storage energy density improve and the energy required to produce lithium ion batteries is reduced. Additionally, the environmental burdens of vehicle production for all vehicle powertrain types in most environmental impact categories are expected to decrease in the future due to changes to the global electricity sector, as shown in Figures 16–21 in the Supporting Information. Comparing the baseline and ClimPol scenarios for 2040, advanced powertrains such as PHEV, BEV, and FCEV are found to be most sensitive to changes in the future electricity system as their production phases are more electricity intensive. This indicates

Table 1
Energy costs, Euro per kWh fuel (lower heating value) for total ownership cost calculation.

Euro / kWh	2017			2040 Baseline			2040 ClimPol		
	mode	low	high	mode	low	High	mode	low	high
Electricity	0.22	0.06	0.32	0.16	0.08	0.16	0.21	0.11	0.21
Hydrogen	0.24	0.20	0.33	0.17	0.08	0.17	0.23	0.12	0.23
Petrol	0.16	0.12	0.19	0.18	0.09	0.18	0.27	0.14	0.27
Diesel	0.12	0.10	0.15	0.14	0.07	0.14	0.21	0.11	0.21
CNG	0.07	0.02	0.13	0.12	0.06	0.12	0.18	0.09	0.18

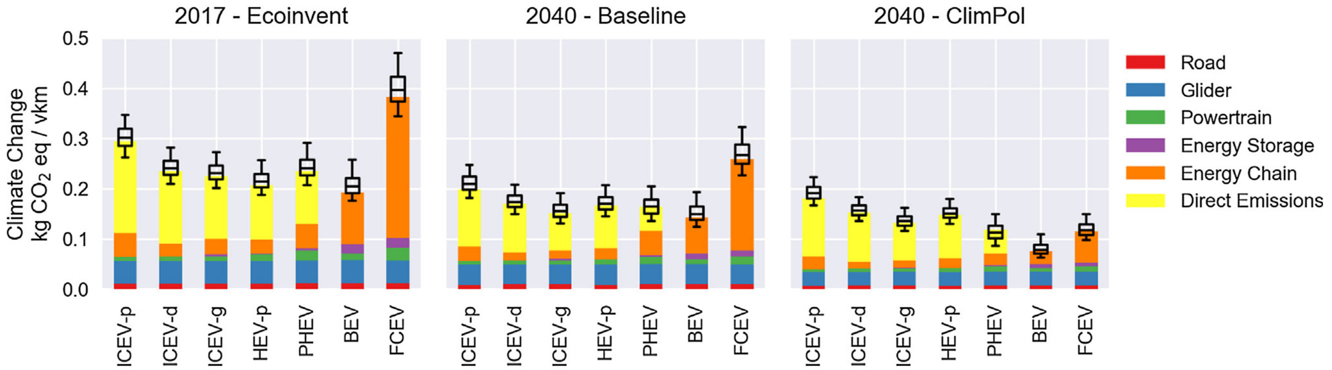

Fig. 4. Life cycle climate change impacts of lower medium size passenger vehicles. The bars represent the most likely vehicle performance, while the whiskers show the 5th and 95th percentiles, the box shows the interquartile range, and the line within the box shows the median. Results are calculated with European average electricity for BEV charging and hydrogen for FCEV is produced via electrolysis with the same electricity mix. "2017 - Ecoinvent" represents current vehicles and LCA results calculated with ecoinvent v3.4 in the background; "2040 - Baseline" and "2040 - ClimPol" represent future vehicles and LCA results calculated with prospective background data as explained above in section "Modified LCA databases for future energy scenarios".

that prospective LCA studies of advanced powertrains that do not include modified background databases for vehicle production likely underestimate the savings potential of advanced powertrains.

In terms of climate change and non-renewable energy consumption, reductions due to vehicle performance improvement are expected to be on the order of 10–30%, depending on the powertrain, as shown in Figure 40 in the Supporting Information. When also future changes to the background electricity sector are included, these improvements are approximately 20–40% for combustion powertrains (highest for conventional powertrains as these are modeled as mild 48-volt hybrids in the future and lowest for regular hybrids as most of the improvement potential has already been achieved) and 25–70% for PHEV, BEV, and FCEV. The large sensitivity of PHEV, BEV, and FCEV to the background electricity scenario is due to a combination of reduced production impacts and reduced impacts due to the cleaner electricity sector used for battery charging and hydrogen production: While life cycle GHG emissions of FCEV are still higher than those of ICEV and emissions of BEV only slightly lower in the 2040 baseline scenario, both FCEV and BEV perform (clearly) better than ICEV in the 2040 ClimPol scenario. The main reason is that GHG intensities of electricity supply drop by factors of around six and three for the global mix – relevant for vehicle production – and European mix – relevant for BEV charging and hydrogen production – respectively (Fig. 4).

When making comparisons across powertrains types in Fig. 4, it is difficult to draw conclusions because the error bars overlap. However, global sensitivity analysis results (shown in the Supporting Information) show that the variability in the results for each vehicle class is most strongly driven by the lifetime distance travelled by the vehicle, and to a lesser degree the mass of the glider. These parameters are, by design of the study, the same for each powertrain for each iteration of the Monte Carlo analysis. Thus, powertrain environmental burdens for each Monte Carlo iteration are normalized by dividing by the HEV-p score. For example, a score of 1.1 would indicate that the powertrain had 10% higher environmental burdens than a HEV powertrain with the same basic parameters, such as lifetime, glider mass, and auxiliary energy demand. The frequency of which each relative score is obtained for each powertrain is shown in a violin plot in Fig. 5. The figure shows that current HEV always have lower greenhouse emissions than comparable ICEV-p and FCEV, and are usually preferable to ICEV–d, ICEV-g and PHEV. On the other hand, BEV are generally preferable to HEV with the same driving profile and vehicle characteristics, though in some cases BEV have higher life cycle greenhouse gas emissions than HEV. In the 2040 ClimPol scenario, i.e. with a very clean electricity sector, BEV and FCEV are always preferable to HEV, and PHEV are nearly always preferable. Similar comparisons for different electricity and hydrogen sources are included in the Supporting Information. Also the influence of certain parameters such as lifetime distance, glider mass and range on the relative performance of BEV and HEV is examined. It can be concluded that, in general, vehicles with smaller batteries and longer lifetime distance travelled have the best relative performance. This means that people who buy an electric car with a long range, but do not use it intensively, would be much better off economically and environmentally buying a (plug-in) hybrid.

4.2. Other impact categories

For impacts other than climate change (figures 29–33 in the

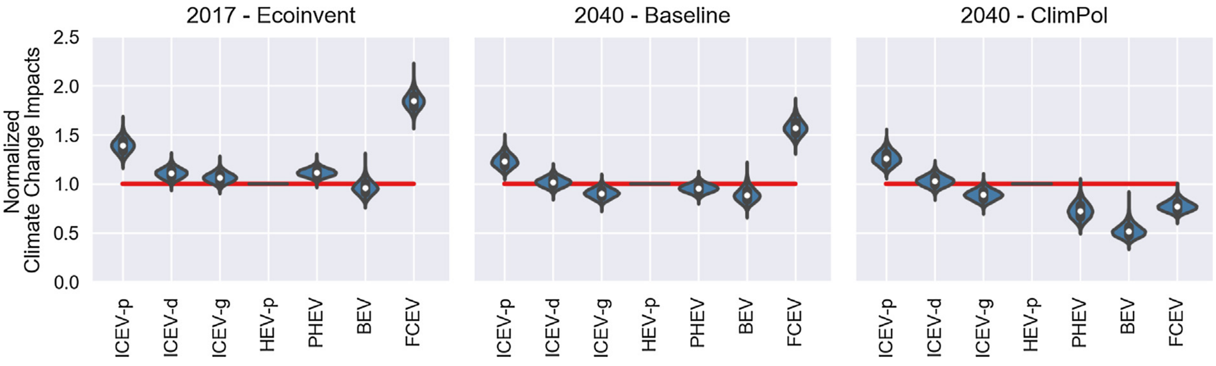

Fig. 5. Normalized climate change impacts of all vehicle classes included in the study, compared for each iteration of the Monte Carlo analysis. A score of less than one indicates better climate change performance than a hybrid vehicle under the same operating conditions. The median is shown with a white dot, the vertical black lines show the interquartile range, and the curves surrounding them show the distribution of the results.

Supporting Information), the performance of BEV and FCEV is often worse than ICEV, especially for current vehicles, and if emission standards are met. However, these results show overall possible burdens along the life cycle, but not actual impacts on human health and ecosystems, which would require a location specific assessment at actual production or usage sites. The analysis for 2040 shows a stronger trend of improvement for BEV and FCEV compared to ICEV. This is due to a combination of improvements to the vehicle such as improved battery, fuel cell, and hydrogen storage technologies (mostly improvements in energy and power density) and improvements in the background electricity sector used for production and recharging/refueling. For PHEV, future improvements are due mostly to more all-electric operation due to the increased all-electric range. Improvements to conventional combustion powertrains are mostly due to the reduction of energy consumption due to mild hybridization and reductions in tailpipe emissions. However, this hybridization comes at a price; impacts are expected to be slightly worse in the human toxicity and metal depletion category due to the additional production requirements of the hybrid drivetrain.

The effect of violated emissions standards can be seen best in terms of photochemical oxidant formation (Supporting Information, Figure 33) for current diesel vehicles. The whisker box and the range of the error bars reflect observed on-road NO_x emissions – as a consequence, the median value of the diesel vehicle is second highest in this category.

4.3. Total cost of ownership

Fig. 6 shows the TCO results for current and future passenger cars: Today, TCO of FCEV are substantially higher than those of all other vehicles, while TCO of BEV are only slightly above those of ICEV. Total ownership costs are dominated by the amortization of the purchase costs. Vehicle purchase costs (shown in more detail in the Supporting Information) are expected to remain roughly constant in the future for most powertrain types, though improvements in batteries will decrease the purchase cost of BEV. The assumed cost reduction for fuel cells is also significant (due mostly to increased economies of scale in production) which leads to much lower total operating costs for FCEV, though they are not expected to reach cost parity with conventional vehicles as BEV are expected to.

The variability in vehicle TCO is dominated by the amortized vehicle purchase cost, with the largest variability being due to the uncertain lifetime of the vehicle, followed by variability of vehicle purchase costs due to factors such as vehicle power or number of special features. Global sensitivity analysis results for total ownership cost are available in the Supporting Information.

In general, life cycle impacts in all categories as well as TCO substantially increase with vehicle category (from mini to large/Van/SUV) (see Figures 34–39 and 61 in the Supporting Information), meaning that smaller vehicles offer clear economic and environmental benefits.

Fig. 7 shows a similar comparison for total ownership cost as Fig. 5 does for greenhouse gas emissions. This figure shows that there is no obvious best option for the lowest cost powertrain technology. Tipping points between BEV and HEV in terms of total ownership costs are compared in the Supporting Information – the largest contributors are battery size and, to a lesser degree, the relative price difference between petrol and electricity.

4.4. Trade-offs and co-benefits (GHG emissions vs. TCO)

Fig. 8 shows vehicle TCO plotted against vehicle climate change impacts, with the score of each Monte Carlo iteration normalized to the HEV-p score. Thus, scores of less than one on the y or x axes indicate lower TCO or a lower climate change impact, respectively. The results are shown in a hexbin plot, so darker areas indicate the most likely results. All vehicle size classes are included in this plot. The left panel shows that BEV have the highest GHG emission saving potential, but at a generally slightly higher cost than HEV-p, though some cases exist where BEV are also preferable in terms of costs. No other powertrains are found to have lower GHG emissions than HEV-p in the current case with European average electricity. In the 2040 Baseline scenario, BEV, ICEV-g, and PHEV are all found to offer climate benefits compared to HEV-p, with both ICEV-g and BEV expected to also offer cost benefits. ICEV-g show a higher potential for CO_2 emission reduction than HEV, since current methane engines are on a comparatively lower technology development level [87]. In the 2040 Climate Policy scenario the relative cost performance of electric vehicles is even higher than in the 2040 Baseline scenario, and the relative climate change performance is much better. In this scenario BEV seem to be clearly the best performer in terms of both TCO and greenhouse gas emissions.

4.5. Impact of the carbon intensity of electricity on life cycle GHG emissions

Fig. 9 shows sensitivity analysis results where an additional uncertain parameter is included in the Monte Carlo analysis.

Here, instead of assuming the average European electricity mix, also the carbon intensity of the electricity mix as an uncertain parameter ranging from 0 to 800 g CO_{2eq}/kWh is included. As expected, ICEV and HEV-p are insensitive to this parameter, but BEV, PHEV, and FCEV are very sensitive to this parameter. Based on this result one may conclude that, all other factors being equivalent, BEV are preferable to HEV-p in terms of climate change as long as the life cycle GHG emissions of the electricity used for battery charging are less than roughly 480 g CO_{2eq}/kWh in the current case less, and less than roughly 500 g CO_{2eq}/kWh in the future. For FCEV, if the life cycle GHG emissions of the electricity used to produce hydrogen are less than 200 g CO_{2eq}/kWh, it is generally better from a climate perspective to use a fuel cell car than a hybrid. However, at this level of grid carbon intensity, BEV are always preferable to FCEV and in the future PHEV will also provide greater climate benefits at this level of grid GHG emissions. Similar plots for both vehicle lifetime distance travelled and vehicle mass are included in the

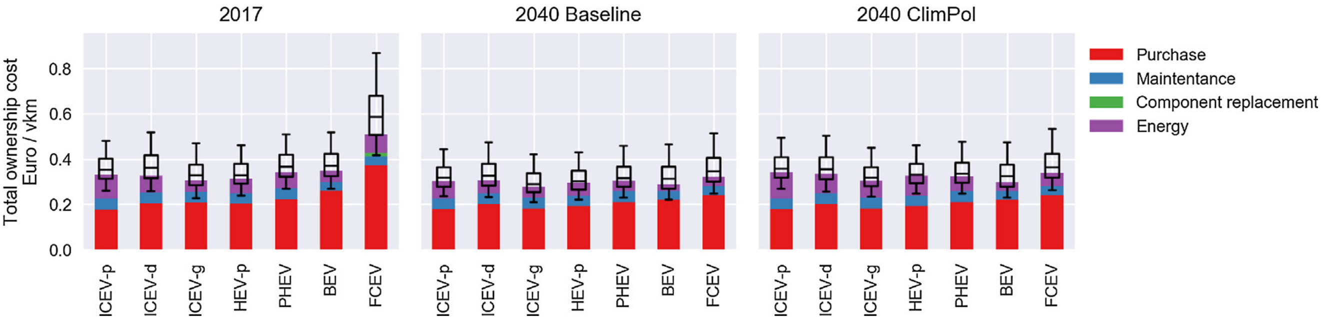

Fig. 6. Total ownership costs of lower medium sized vehicles. The bars represent the most likely vehicle performance, while the whiskers show the 5th and 95th percentiles, the box shows the interquartile range, and the line within the box shows the median. “Energy” refers to fuel costs, i.e. petrol, diesel, natural gas, electricity and hydrogen used as propulsion energy carriers.

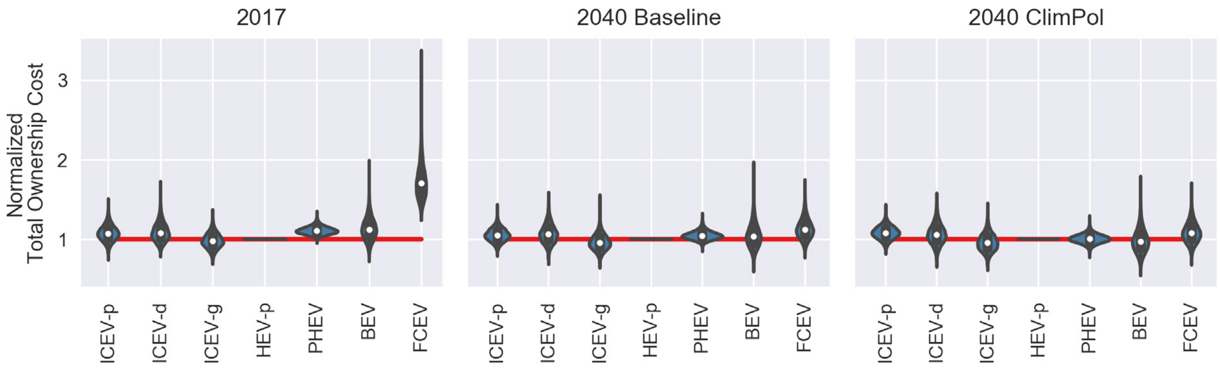

Fig. 7. Normalized total ownership costs of all vehicle classes included in the study, compared for each iteration of the Monte Carlo analysis. A score of less than one indicates lower ownership costs than a hybrid vehicle under the same operating conditions.

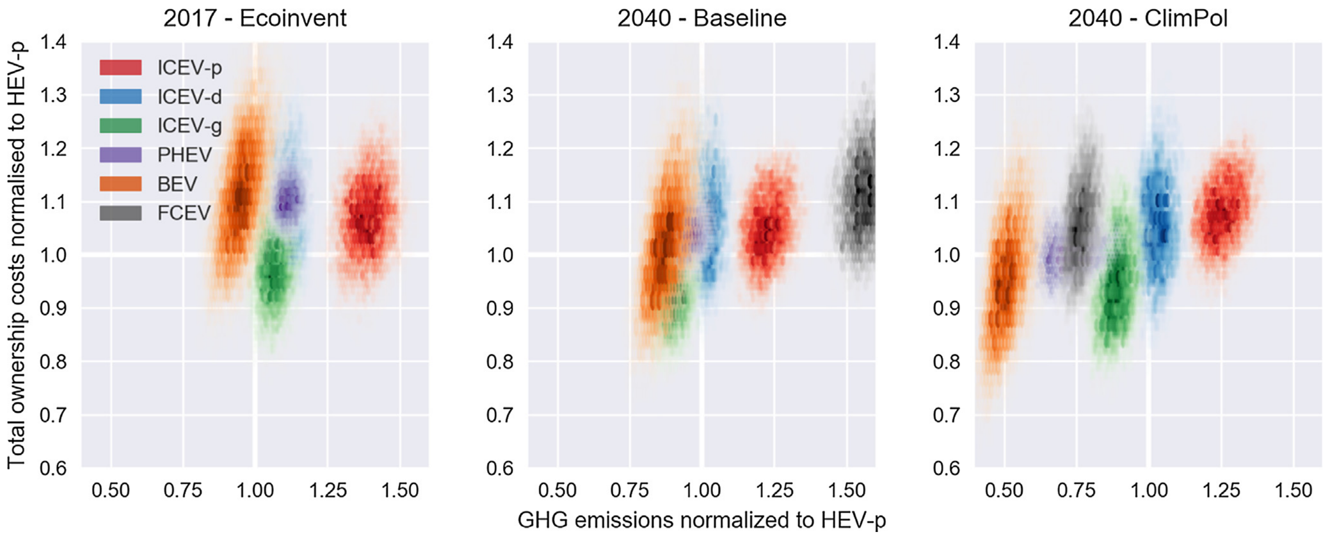

Fig. 8. Comparison of vehicle total ownership costs to life cycle climate change impacts. Both scores are normalized to the score of the HEV powertrain for each iteration of the Monte Carlo analysis. All vehicle sizes are included.

Supporting Information.

4.6. Limitations and further research

There are several important limitations to this study requiring further analysis in the future; these are discussed in three main categories:

4.6.1. Vehicle modelling

It's hard to predict the future. This is mitigated by using reasonable bounds for the uncertainty distributions that describe future car performance, but generally incremental improvements on existing technologies are assumed and it is very likely that some technological breakthroughs are not represented by the future performance estimates. Global sensitivity analysis on the results is used to understand which

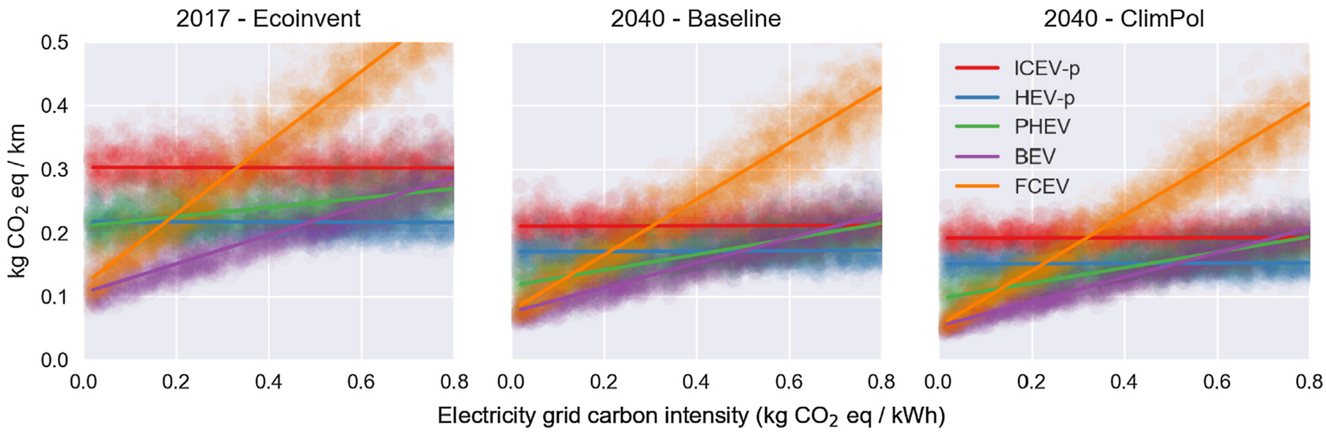

Fig. 9. Life cycle climate change impacts of lower medium size passenger vehicles shown for different electricity grid carbon intensities. Hydrogen is assumed to be produced using electrolysis with grid electricity. The cloud of dots represents the actual Monte Carlo analysis results, while the solid lines represent lines fit to the data to improve visibility.

input parameters are most important to the results. This shows us that the results are only extremely sensitive to a handful of input parameters (see Supporting Information). If these input parameters were wrong, the results could be quite different from what is shown here. For example, it is known that results are very sensitive to the lifetime distance travelled by the vehicle. For this reason, the executable calculation files are provided in the Supporting Information. This way the reader can use the model as a basis to add specialist knowledge to certain input parameters and examine their impact on the results.

One technological breakthrough that the present uncertainty framework currently cannot handle is the potential future use of significantly different materials or amounts of energy to build vehicle components. For example, it is assumed that future batteries will have generally the same life cycle inventory and material composition per kilogram of cell as current battery technologies, though with increasing energy density. This is obviously not likely and it is uncertain how much impact this will have on the results. This is, however, mitigated by the fact that several LCA comparisons across different lithium ion battery chemistries have found similar manufacturing related carbon footprints on a per kg basis [9,14,16], though it is uncertain if this will hold true for future battery chemistries. Differences for other LCIA indicators, for which the contribution of battery manufacturing can be more important (see Supporting Information), might be more substantial.

Different driving cycles as uncertain input parameter are not part of the model. This could be especially important if autonomous driving becomes widespread [15]. The simplistic vehicle energy consumption model used here does not vary component efficiencies with load, so changing the driving cycle would not change the relative results between powertrains, only the absolute values and thus the benefits of considering different driving cycles is limited.

4.6.2. LCA and TCO methodology

There are also several methodological limitations that are worth mentioning. Firstly, recycling is treated very simply in the model, and follows the cut-off principle, meaning that a producer is fully responsible for the disposal of its wastes and does not get credits for the provision of any recyclable materials. This is not expected to change the relative climate change performance of the different powertrains, but it can be expected that including recycling in battery and fuel cell datasets will greatly improve the performance of BEV and FCEV in categories such as mineral depletion and particulate matter formation. A further limitation regarding life cycle inventories is the assumption that all vehicle production processes represent global averages. It would be more accurate to use actual regional vehicle production values and regionalized datasets, but as the future production values are unknown, it is simply assumed that everything corresponds to the global average. Another weakness of the methodology regarding regionalization is that the site-specific impacts of pollutant emissions are not considered. This means that one kilogram of NO_x emitted from a nickel refinery in sparsely populated northern Russia is considered to have the same burdens on humans and ecosystems as one kilogram of NO_x emitted from a diesel car in an urban center. This is obviously not true, though it is methodologically very difficult to implement correctly. Furthermore, uncertainties in life cycle impact assessment methods or in the background database are not taken into account. Environmental burdens of noise emissions, though certainty relevant in this context and likely to give a further advantage to electric powertrains, were not quantified. Frameworks such as that of [88] could be used for this purpose.

Impacts of large-scale fleet transitions to different powertrain types, such as grid expansion or development of an integrated hydrogen supply chain, are neglected. Furthermore, it is assumed that average European electricity is used for hydrogen production and battery charging, and the influence of smart charging or vehicle-to-grid interactions is not quantified.

The cost model applied is admittedly rather simple. However, it is still useful as it allows readers to get TCO and LCA results from one internally consistent source. Future costs are inherently difficult to model as purchase prices can be adjusted by manufacturers to meet sales targets, which may be the case given fleet wide emissions targets.

4.6.3. Scope of study

There are also several limitations regarding the scope of the study. For example, further fuel chains such as power-to-gas, electricity generation with carbon capture and storage and biofuels are all relevant in this context. Power-to-gas fuels can offer substantial environmental benefits from a life cycle perspective [81]; however, due to low energetic efficiency and high investment costs, such fuels are expensive today [89]. Environmental benefits of decarbonisation of mobility via electrification and CCS – apart from reduction of GHG emissions – less obvious [81], but additional costs are expected to be comparatively low in the future [90–92]. It would also be interesting to explore other powertrain types such as diesel, CNG and fuel cell hybrids in future work.

The level of integration between the LCA database and the future scenarios should also be increased. This analysis only considers future changes to the electricity sector, but other sectors such as fossil fuels, metals, concrete and mining should also be included in the future. Furthermore, future work should examine far more scenarios than only two.

5. Conclusions

The main conclusion of this analysis is that electrification of passenger vehicle powertrains is an effective way of reducing greehouse gas emissions without incurring significant cost penalties; to the contrary, it may even provide minor cost benefits in the future. The ideal degree of electrification for minimising GHG emissions depends most strongly on the carbon content of the electricity mix used for charging and to a lesser degree on the lifetime distance driven, mass, and battery size of the car, and the background energy system used to manufacture the vehicles.

In areas and scenarios where electricity has a lifecycle carbon content similar to or better than a modern natural gas combined cycle powerplant (below 500 g CO_{2eq}/kWh), full powertrain electrification with BEV reduces GHG emissions compared to conventional diesel and gasoline vehicles. At a level of 50 g CO_{2eq} per kWh electricity for battery charging, which corresponds to an electricity supply mainly from renewables and/or nuclear, which few countries such as Norway, France, Brazil and Sweden exhibit, BEV reduce GHG emissions by around two thirds today and more than 50% in 2040. If a very large driving range is required, hybrid powertrain and compressed natural gas vehicles are good options. Only in areas with very clean electricity (below 200 g CO_{2eq}/kWh), FCEV fueled with hydrogen from electrolysis provide climate benefits compared to ICEV. In areas and scenarios where clean electricity is not available, ICEV-g and HEV-p are found to have excellent performance in terms of both costs and GHG emissions. However, the carbon intensity of the electricity mix must be higher than that of a combined cycle natural gas powerplant for these technologies to have lower life cycle GHG emissions than an average BEV.

Although powertrain electrification is expected to provide climate benefits compared to conventional combustion powertrains, overall environmental burdens in other impact categories such as mineral depletion, human toxicity, particulate matter formation and photochemical oxidant formation are likely to increase, though uncertainty in these categories is substantial.

While this analysis shows that moving from combustion to electric powertrains is likely to reduce the burdens of passenger vehicle travel in most environmental impact categories, it also shows that gains on a similar scale can be made by selecting smaller vehicles and using them more intensely over their lifetimes. In fact, environmental burdens in all impact categories and total ownership costs are quite sensitive to decreasing vehicle mass and increasing vehicle lifetime.

The main novel contribution made by this paper is that it provides consistent vehicle performance, cost and environmental performance parameters that decision makers and other modellers can use as input for their work. In an effort for full transparency and reproducibility, complete executable calculation files are provided. Readers are encouraged to use and adapt this material to their specific requirements and especially add their own expert knowledge to the model and publish on top of this work.

CRediT authorship contribution statement

Brian Cox: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Christian Bauer:** Writing - review & editing, Supervision, Project administration, Funding acquisition. **Angelica Mendoza Beltran:** Methodology, Writing - review & editing. **Detlef P. Vuuren:** Methodology, Writing - review & editing. **Christopher L. Mutel:** Methodology, Software, Validation, Writing - review & editing, Supervision.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.115021.

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