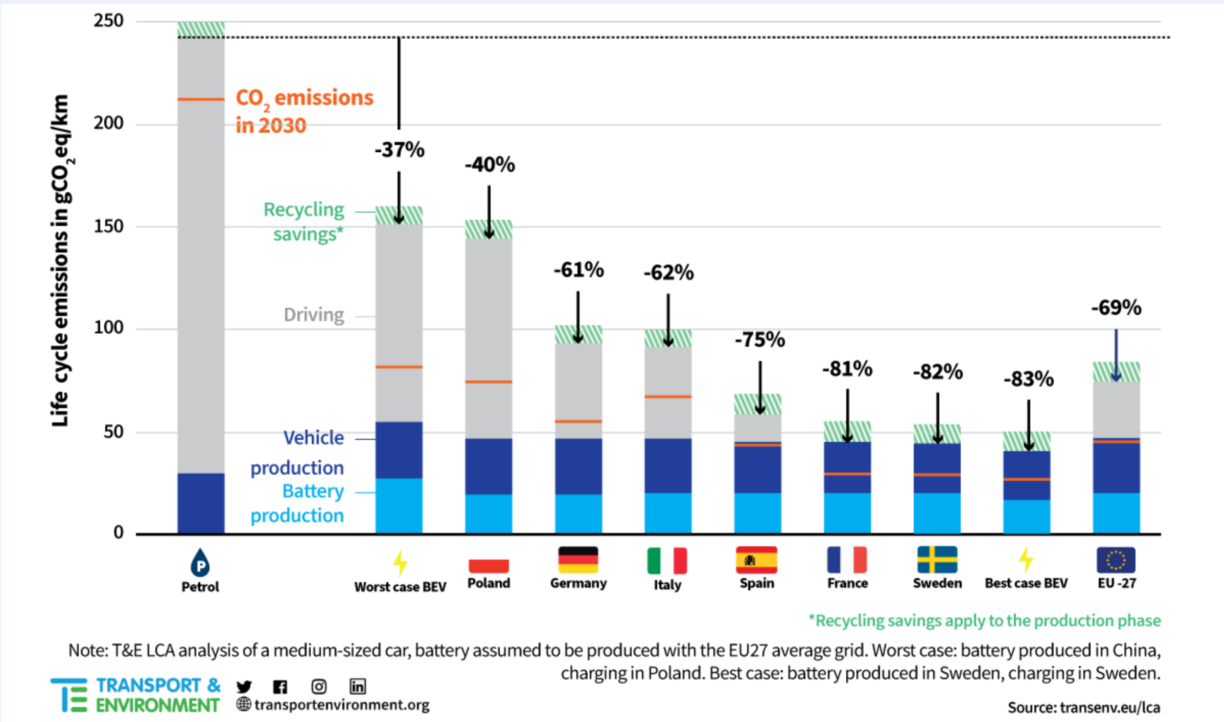
UPDATE - T&E's analysis of electric car lifecycle CO_2 emissions

May 2022

Summary

Following the entry into force of the 2020/21 EU car CO_2 standards, battery electric cars (BEVs) have stepped into the mass market much faster than previously expected and one out of ten cars sold in the European area were battery electric in 2021. In parallel, the sales of plug-in hybrid vehicles (PHEVs) and full hybrids (HEV) also grew in recent years and there are still some misbeliefs about their lifecycle greenhouse gas emissions performance.

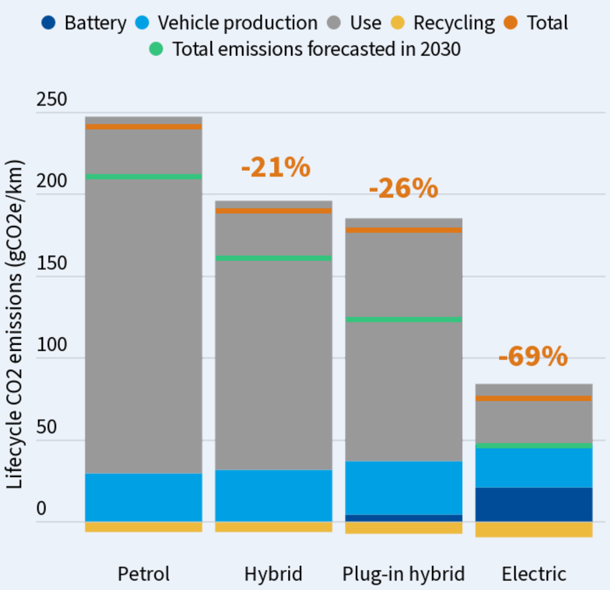
To bring clarity to the subject, T&E has updated its online tool comparing the lifecycle CO_2 emissions of different powertrains over the lifetime of vehicles sold in 2022 and 2030 and has added PHEVs and hybrids. This lifecycle assessment (LCA) is based on the latest available real world direct emissions data, real world share of distance driven electrically by PHEVs, as well as the latest data and forecast of the carbon intensity of the European country's electricity grid. Technologies such as solid-state batteries and synthetic fuels ("e-fuels") which may be available in limited quantities from 2030 have also been added to the tool.



Petrol cars emit more than 3 times more CO_2 than average EU electric cars

This new analysis shows that the average European BEV is more than three times cleaner than equivalent petrol cars in 2022 (-69%). In the best case where the battery production and the charging use the cleanest electricity grid, a medium-sized BEV is nearly six times cleaner (-83%). On the other hand, in the worst case where the battery is produced in China and the car is charged in Poland, a BEVs is still 37% cleaner than petrol. Based on an average battery, an electric car driven in Germany or Italy is slightly more than 2.5 times cleaner than a conventional car (-61% and -62%) while BEVs in France and Sweden have an impact more than five times lower (-81% and -82%). In 2030, BEVs will fully benefit from the cleaner electricity grid (renewable electricity is expected to make up 62% of the EU electricity in 2030) and are expected to be 4.6 times cleaner than petrol.

Lifecycle emissions per powertrain



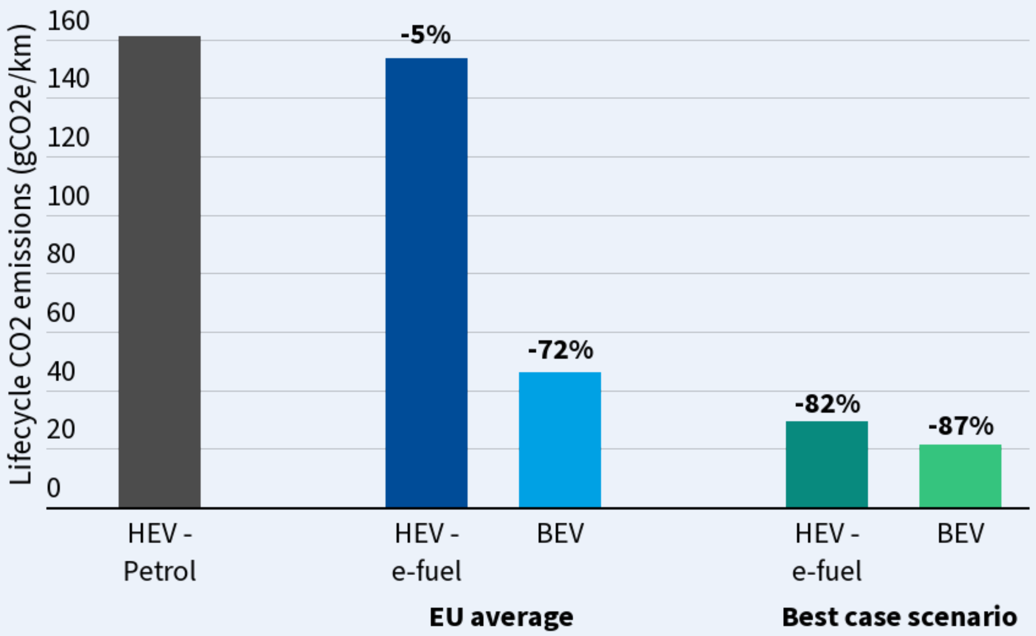
Source: T&E LCA analysis of a medium-sized car, battery assumed to be produced with the EU27 average grid, BEV/PHEV charging with the EU27 average grid

Despite their green credentials, HEVs and PHEVs lifecycle emissions are much closer to polluting conventional petrol than to BEVs. The results show that HEVs only achieve a 21% reduction in LCA emission compared to an equivalent petrol car while PHEV improvements are limited to 26%. As a result PHEVs are more than two times more polluting than BEVs. This poor performance of PHEVs is caused by the fact that in real world operations, only about 37% of the kilometres are driven in electric mode.

In 2030, PHEVs are expected to be driven more on the electric powertrain but thanks to the rapidly decarbonising grid, BEVs would be 2.7 times cleaner than PHEVs.

Running a petrol hybrid car on a blend of synthetic and conventional petrol would only reduce emissions by 5%-7% in 2030. The blend modelled by T&E is based on forecasts done by the fuel industry where 0.4% of the fuel available at the pump would be synthetic fuel in 2030 (3% in 2035). Looking at a more theoretical scenario where a car is powered entirely by e-fuels, the emissions would be reduced more significantly: -53% if the e-fuel is made from 100% renewables and -82% if it is made under the RED II fuel sustainability criteria (where 15%-30% of the energy required for the e-fuel production could still come from non-renewable sources). Nonetheless, in the best case scenario, a BEV would still be 27% cleaner than the best case for combustion engines (HEV running on 100% e-fuel made from 100% renewable energy) mainly due to the low efficiency of the e-fuel production process. Nevertheless, results with 100% e-fuel could only be applicable to a marginal part of the car fleet as only about 3% of internal combustion engine vehicles (ICEs) could run on 100% e-fuel in 2035 (according to the optimistic forecast from the fuels industry). With such strong supply constraints, e-fuels will be better used in hard to decarbonize sectors such as aviation and shipping, where no better alternatives exist.

Electric vehicles are cleaner than cars running on e-fuel



Average use: e-fuel produced according to the regulation criteria (REDII) and blended with petrol based on industry fuel production forecast. Average EU grid used for battery production and charging, and average supply-chain impacts.
Best case scenario: pure e-fuel produced from 100% renewable. Swedish electricity grid used for battery production and charging, and low supply-chain impacts.
BEVs are cleaner: even under the best case scenario, the production of e-fuel has low energy efficiency and requires a greater amount of energy, meaning it has higher lifecycle emissions due to indirect emissions from the electricity infrastructure.
Source: T&E LCA analysis of a medium-sized car bought in 2030

In 2030, the LCA emissions of BEVs can be reduced further with different levers. First, the use of cleaner electricity for battery production would enable a 5% savings on the BEV lifecycle emissions. Second, the battery supply chain is also getting cleaner; with best-in-class supply chains used for the sourcing of lithium, nickel or graphite, BEVs lifecycle emissions could be decreased by 13%. Therefore, BEVs still have the highest potential for CO_2 emissions reductions over their lifecycle in 2030.

This latest evidence highlights that battery electric cars remain the most promising and mature technological solution to accelerate the transition to carbon neutrality. Given the urgency to decarbonise all sectors of our economy, the EU should not delay this transition with sub-optimal technology such as hybrids nor with rare, expensive and inefficient synthetic fuels. The phase out of all internal combustion engines by 2035 without any credits for e-fuels is the safest way to stay in line with the EU's Green Deal ambition.

1. Methodology

The methodology for T&E's electric vehicle (EV) Life Cycle Assessment (LCA) of CO_2 emissions was described in April 2020 in the report entitled '*How clean are electric cars?*'[1]. The following sections explain methodological modifications that were included in April 2022. (For any data or method not mentioned in this briefing, please refer to the April 2020 report.)

1.1 Electricity sources emissions factors and electricity mixes

In the previous version of this LCA analysis, T&E's calculation of the carbon intensity of a country's electricity grid was made using of a bottom-up calculation based on the electricity generation mix evolution forecasted in 2020 and the Intergovernmental Panel on Climate Change (IPCC) global emissions factors for different energy sources. In this latest version, new EU-specific emissions factors derived from the 2021 UNECE report[2] have been included. The electricity generation mix is now based on ENTSO-E's TYNDP 2022 Draft Scenario Report[3].

Life-cycle carbon intensity of electricity sources

To replace IPCC emissions factors that were defined in the Fifth Assessment Report (2014), T&E derived new emissions factors from a recent LCA analysis published by UNECE in 2021. This study (based on more recent data sources) provides results customised to the European region instead of global averages. The following emissions factors were included in T&E analysis[4] based on hypotheses described in Annex 1. Compared to the previously used 2014 IPCC data, results derived from UNECE lead to a lower carbon intensity for hydroelectric, solar and nuclear power.

Table 1 - Life-cycle carbon intensity of electricity sources

LCA CO_2eq. emissions	Coal	Gas	Solar PV	Offshore Wind	Hydro	Onshore Wind	Nuclear
(gCO_2e/kWh)	997	434	34	14	11	12	5

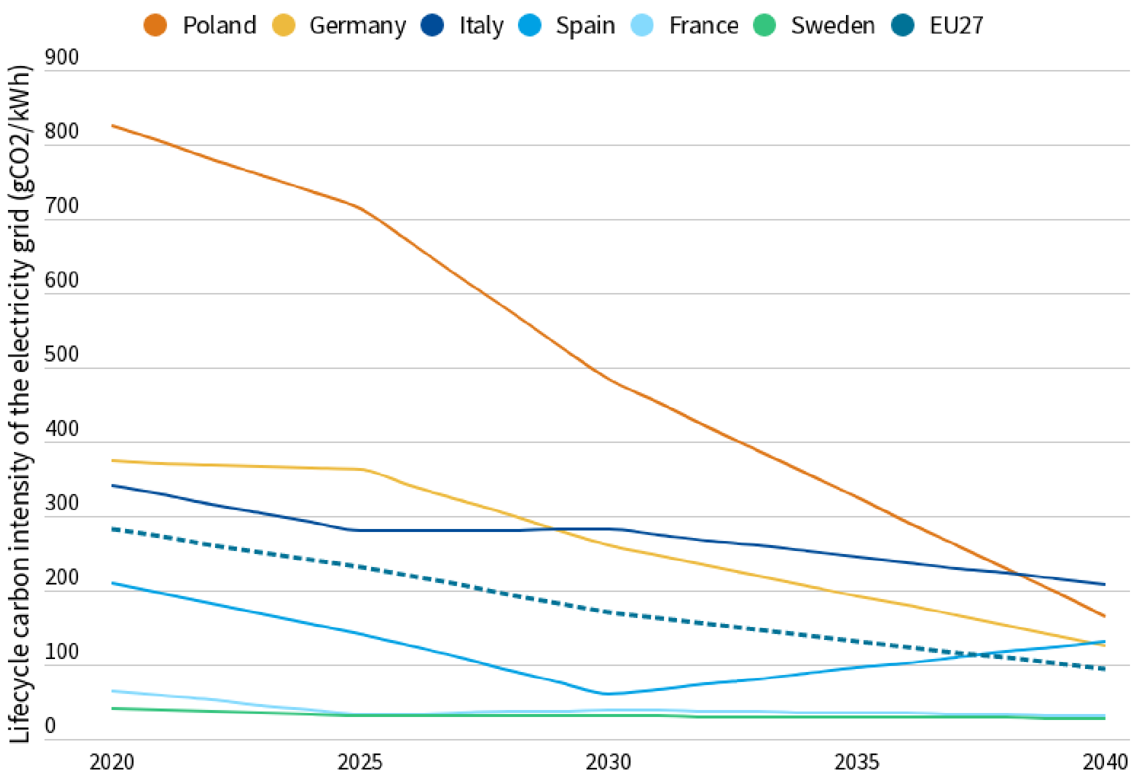
EU countries electricity grid

For each country, the lifecycle carbon intensity of electricity was assumed to evolve linearly between 2020 and 2025, between 2025 and 2030 and between 2030 and 2040. Data from 2020 are historic data from Ember[5] while forecasted data are from ENTSO-E's TYNDP 2022 Draft Scenario Report. ENTSO-E's scenarios depict European energy futures up to 2050. The scenarios used are the 'National Trends'

[1] https://www.transportenvironment.orgCO2e/discover/how-clean-are-electric-cars/
[2] https://unece.org/sites/default/files/2021-10/LCA-2.pdf
[3] https://2022.entsos-tyndp-scenarios.eu/
[4] Other electricity sources emissions are unchanged compared to T&E 2020 report
[5] https://ember-climate.orgCO2e/insights/research/eu-power-sector-2020/

for 2025 and the 'Global Ambition' for 2030 and 2040, taken from the official European network of Transmission System Operators (TSOs), ENTSO-E's scenarios, and particularly the 'Global Ambition' scenarios. We consider these forecasts to be the most credible pathways, best reflecting the European net-zero carbon ambition for 2050.

Taking into account the above update of emissions factors and country generation mixes, the calculated EU27 average life-cycle carbon intensity of the electricity grid is 261 gCO_2e/kWh[6] in 2022, 171 gCO_2e/kWh in 2030 and 93 gCO_2e/kWh in 2040. Vehicles sold in 2022 are used as the default option of the LCA model whereas the previous version of the model used vehicles sold in 2020 with 319 gCO_2e/kWh taken as the EU27 average carbon intensity of the electricity grid (based on IPCC emissions factors and a previous estimate of the EU grid mix). The methodology accounts for yearly change in carbon intensity over the lifetime of the vehicles. This update leads to a 18% improvement of the electricity carbon intensity in the default option, which explains the improvement of BEVs lifecycle emissions referred to in section 2.1. Results for key EU countries are shown in the figure below:



Source: T&E modelling based on future electricity generation from ENTSOE TYNDP 2022 Draft Scenario Report and lifecycle emissions factors derived from UNECE LCA report (2021)

Figure 1 - BEV lifecycle emissions savings in T&E updated model

[6] Lifecycle carbon intensity including transport and distribution losses

1.2 Fuel consumption and vehicle data

Fuel consumption used for the 2022 baseline option

The latest real-world fuel consumption data was extracted from the spritmonitor.de database, a German website that collects information about the fuel consumption of vehicles under real-life conditions. In addition to petrol and diesel cars, full hybrid vehicles (HEVs[7]) and plug-in hybrids have been added to the analysis. In order to gather representative averages for each vehicle segment, a sufficient number of models were included to cover at least 70% of sales for each segment[8], related to each powertrain. Overall, the extracted data amounts to 74% of petrol car sales, 86% of diesel sales and 86% of HEV sales (EU27 sales figures from 2021).

Regarding plug-in hybrid electric vehicles (PHEVs), the real world fuel and electricity consumption depends on the share of distance driven on electricity (utility factor) or the use pattern for the car (private or company car drivers don't have the same utility factor). T&E analyses of PHEV consumption data are detailed in Annex 2. Real-world consumption is estimated from the carmaker's fuel and electricity consumption and the electric range values measured on the Worldwide Harmonised Light Vehicles Test Procedure (WLTP), a type-approval test. Correction factors are used to estimate real-world fuel consumption from WLTP values and realistic utility factors (UF) are included to be representative of the average user of a PHEV. These realistic utility factors were calculated by Fraunhofer ISI[9] based on the average range driving on electricity by real PHEV users.

The fuel and electricity consumption, as well as the battery capacity used in the model are provided in the table below:

Table 2 - Powertrains parameters in the 2022 model

Segment	Gasoline (L/100km)	Diesel (L/100km)	HEV (L/100km)	PHEV (L/100km)	PHEV (kWh/100km)	PHEV battery capacity (kWh)	BEV (kWh/100km)	BEV battery capacity (kWh)
Small	6.5	5.4	4.8	NA[10]	NA	NA	16.0	45
Medium	7.5	6.2	5.7	4.5	7.8	12	17.5	60
Large	8.8	6.7	6.6	5.2	8.2	13	19.0	75
Executive	8.5	6.9	7.0	5.3	11.5	15	20.5	90

[7] In this analysis, HEVs refer only to full hybrid vehicles as mild hybrids are grouped with conventional ICE.
[8] Based on T&E analysis of 2021 registration data in EU27 provided by Dataforce
[9] https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/BMU_Kurzpapier_UF_final.pdf
[10] Very few PHEV models are sold in segment B (small) and the methodology defined to assess real world consumption is not applicable to individual models but only to an average model. For that reason, results would not be representative in this segment and thus they have been omitted.

2030 fuel consumption forecast

A forecast of emissions by powertrain based on latest industry trends was defined by T&E in the *Electric car boom at risk* report[11]. Based on this analysis, the following assumptions are used to calculate expected emission reductions by powertrain:

- Pure ICE fuel consumption by body type, such as hatchbacks and SUVs, is assumed to follow a downward trend of 1.5% each year between 2021 and 2025 and is expected to stagnate as from 2025. Mild hybrid fuel consumption is assumed to follow a similar downward trend of 1.5% each year between 2021 and 2025, and then 1% each year from 2026. The growth of the SUV share is expected to follow the historical trend and grow from 40% in 2020 to 63% in 2030. However, this anticipated SUV growth would slow the emissions reductions. Moreover, the sales of mild hybrids among ICE is estimated to grow from 11% in 2020 to 91% in 2030. Together with improvements in fuel consumption, these changes in the mild hybrid share would lead to an average ICE fuel consumption decrease of 1.1% every year from 2022 to 2030.
- Full hybrid fuel consumption is assumed to decrease by 1.5% each year between 2021 and 2025 and 1% each year from 2026.
- BEV electricity consumption is assumed to decrease by -0.5% each year.
- Regarding PHEVs, fuel consumption is expected to decrease in line with HEVs and the electricity consumption trend should decrease, in line with BEVs. However, the utility factor of PHEVs is likely to increase since their range is planned to rise. Another factor is that the share of private users (who have a higher electric driving share vs. company car users) is also expected to increase, see Annex 2 for all assumptions. The increase of PHEV battery capacity is based on industry trends analysed by T&E in the *Promises, but no plans* report[12].

The forecasted values are provided in the following table:

Table 3 - Powertrains: parameters in the 2030 model

Segment	Gasoline (L/100km)	Diesel (L/100km)	HEV (L/100km)	BEV (kWh/100km)	PHEV (L/100km)	PHEV (kWh/100km)	PHEV Battery capacity (kWh)
Small	5.9	4.8	4.3	15.3	NA	NA	NA
Medium	6.8	5.7	5.1	16.7	3.2	10.6	17
Large	8.0	6.1	5.9	18.2	3.7	12.2	22
Executive	7.7	6.2	6.3	19.6	3.6	16.7	23

[11] https://www.transportenvironment.orgCO2e/discover/electric-car-boom-at-risk/

[12] https://www.transportenvironment.orgCO2e/discover/commitments-but-no-plans-how-european-policymakers-can-make-or-break-the-transition-to-zero-emission-cars/

Emissions from production of glider and powertrain
From the analysis in the 2020 Ricardo LCA report[13], T&E estimates that the production of HEV glider and powertrain is 5.9% more carbon intensive (battery included[14]) than its petrol equivalent (provided in T&E 2020 LCA report), and that PHEV glider production is 9.6% more carbon intensive (battery excluded[15]).

1.3 Carbon footprint of battery production

T&E's battery carbon footprint model was calibrated based on results from an LCA report[16] that T&E commissioned from Minviro. In this report, Minviro calculated a 77 gCO_2e/kWh carbon footprint for a NMC-811 lithium-ion battery (LIB) produced in 2021 with the average EU27 electricity grid. Based on this data, T&E estimated that an NMC-622 battery produced with the EU grid in 2022 would have a 78 gCO_2e/kWh carbon footprint. In 2030, we expect the footprint of an NMC-811 battery to decrease to 55 gCO_2e/kWh based on the grid carbon intensity forecast described in section 1.1.

Minviro analysed the impact of using best-in-class material sourcing for key materials of an NMC battery, for instance by using lithium from geothermal sources, nickel from a bioleaching process and synthetic graphite produced in Europe. By integrating Minviro results into the model, it was estimated that an NMC-622 battery produced with the 2022 EU27 electricity grid and a low impact supply chain would have a 48 gCO_2e/kWh carbon footprint.

Moreover, Minviro estimated the carbon footprint of future battery technologies such as solid state batteries (SSB). The SSB formulation with the lowest carbon footprint would be based on a NMC-811 cathode, lithium metal anode and an oxide-based solid electrolyte. T&E estimated that his formulation would achieve a carbon footprint of 43 gCO_2e/kWh with the 2030 electricity EU grid.

Each battery type (LIB or SSB) and sourcing option (standard or low impact supply chain) was modelled based on different production locations detailed in Annex 3, so as to assess the impact of the local electricity grid (2022 or 2030 electricity grid) used for manufacturing processes.

The different battery options are presented in the table below:

[13] https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1
[14] Emissions from HEV battery production are expected to be relatively small, their impact is not modelled explicitly.
[15] PHEV battery capacity is expected to increase significantly in 2030, therefore PHEV battery carbon footprint is modelled explicitly based on battery capacity(same hypotheses as BEV described in section 1.3).
[16] Report not yet published at the time of writing

Table 4 - Carbon content of batteries (kgCO_2e/kWh)

Year	Battery production	Li-ion battery (NMC622 in 2022, NMC811 in 2030)		Solid state battery (NMC 811 - oxide)	
		Standard	Low supply chain impact	Standard	Low supply chain impact
2022	EU average	78	48		
	Sweden	64	35		
	Germany	85	55		
	China	105	75		
2030	EU average	55	33	43	33
	Sweden	47	25	37	27
	Germany	61	39	47	37
	China	81	59	63	53

According to T&E tracking of battery factory plans in Europe, Germany could produce around 40% of European batteries in 2030. The German grid is expected to be 56% more carbon intensive than the European average in 2030. Therefore, Germany is now included in the tool to study sensitivity for a higher-than-average carbon intensity of the grid.

1.4 Greenhouse gas emission reductions from e-fuels

Production of e-fuels

The lifecycle analysis of ICEs powered by e-fuels[17] differs from conventional fuel as the e-fuel well-to-wheel (WTW) emissions are lower thanks to the use of renewable energy in the fuel production processes. In this study, two e-fuel production alternatives are considered: (1) e-fuel produced under the RED II sustainability criteria (see further details below) as the baseline option: and (2) e-fuel produced using 100% renewable electricity.

In option (1), the Renewable Energy Directive (RED II) sustainability criteria is used to determine how much renewable electricity is necessary to produce the e-fuel. The RED outlines a regulatory

[17] Synthetic fuels (or e-fuels) are produced by combining hydrogen and carbon in order to create a hydrocarbon (like petrol or diesel) which can be used to propel a conventional petrol or diesel vehicle. The hydrogen can be produced via electrolysis by splitting water into hydrogen and oxygen molecules while the carbon can be obtained via direct carbon capture. Only synthetic fuels produced from electricity are considered in this paper.

framework to ensure the sustainability of so-called renewable fuels of non-biological origin (RFNBOs) by requiring at least 70% greenhouse gas[18] savings compared to their fossil fuel equivalent (using a WTW accounting). In effect, this implies that a high share of renewable electricity will be needed to meet this threshold. Around 86% of the electricity will have to come from renewables if a combination of renewable electricity and gas is used.

In the 100% renewable electricity scenario, T&E assumes that the e-fuel is produced with a mix of different renewable sources which is derived from the BloombergNEF[19] electrolyser forecast: 34% offshore wind, 31% onshore wind, 28% solar and 7% hydro. The lifecycle CO_2 emissions from fuel production are calculated based on this electricity carbon intensity and an overall 55% e-fuel production efficiency[20]. Based on the expected electrolyser capacity in Europe in 2030 and their electricity source, T&E estimated that the carbon intensity of the electricity used for the e-fuel production would reach 19 gCO_2/kWh (assuming that the electricity source used for electrolysis is representative for the electricity used for the e-fuel production). This lifecycle emissions analysis thus provides a complete picture, including indirect upstream emissions (e.g. fuel production and refining) as well as indirect emissions from the necessary infrastructure (e.g. emissions for the production of renewables infrastructure such as solar panels and wind turbines). Since these upstream sources are not zero emission even under the 100% renewable scenario e-fuel CO_2 intensity is 19 gCO_2/kWh.

Blending of e-fuel

E-fuels are drop-in fuels, which means they can substitute petrol and diesel in conventional cars and can be used under different fuel blends ratios, according to industry with a blend ratio anywhere from 0-100%[21]. T&E defined two e-fuel blending scenarios for petrol cars:

- Industry e-fuel blending scenario: This is the baseline scenario, based on the assumption that the available e-fuel is sold blended with petrol. Under this scenario it can be expected that an increased quantity of e-fuels would be gradually added to conventional fuels as the e-fuel industry ramped-up its production over time. This blending scenario is based on the Concawe's (division of the European Petroleum Refiners Association) 'Alternative 1.5°C' scenario[22] where e-fuels would be used in all transport modes including road transport. Concawe forecasts both the overall liquid fuel demand and the installation of new units for

[18] In this analysis T&E assumes that the 70% GHG reduction criteria for e-fuels is calculated based on WTW emissions from energy sources (i.e. not lifecycle emissions, which means that renewables are counted as zero - no infrastructure related emissions). In this methodology, direct air capture of CO_2 is assumed and the different point source possible is not considered (only the energy used to perform carbon capture and utilisation is accounted for).
[19] BloombergNEF tracks the announced electrolyser nameplate capacity and the electricity source type of these projects.
[20] https://www.transportenvironment.org/sites/te/files/publications/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf
[21] https://www.efuel-alliance.eu/efuels/costs-outlook
[22] Scenario 1 from https://www.concawe.eu/wp-content/uploads/Rpt_21-7.pdf

e-fuel production. From this, they allocated part of the e-fuel production between transport modes to achieve an accelerated substitution of fossil-derived fuels. Concawe assumed that 1 Mtoe of e-fuel would be attributed to road transport in 2030, and that this amount would increase to 6 Mtoe in 2035, 21 Mtoe in 2040 and 46 Mtoe in 2050. T&E assumed that the average blending of e-fuels would be aligned with the e-fuel share of all liquid fuel demand in road transport from the Concawe study. This would lead to an average blending of 0.4% e-fuels in 2030, then successively 3% in 2035, 16% in 2040 and 50% in 2050 . Over the lifetime of a car bought in 2030, which stays on the road for 15 years, the average lifetime e-fuel blend would thus be limited to around 10%.

- 100% e-fuel: The scenario assumes a direct use of the e-fuel in a car (100% e-fuel). This scenario is highly theoretical since the e-fuel supply dedicated to cars is expected to be very limited in the future and to be blended with conventional petrol (see baseline scenario). The e-fuel supply allocated to road transport is expected to cover a minor part of the demand. Without blending, only about 2% of the non-electric car fleet in 2035 would be able to run on 100% e-fuel.

Both scenarios assume that part of EU e-fuel production -and the green hydrogen used in its production- are allocated to road transport. Consequently, this would divert production and supply of synthetic fuels or green hydrogen from other sectors such as aviation, shipping or heavy industry where they are most needed as no better decarbonisation solutions exist for these sectors. Both scenarios are highly inefficient and the 100% e-fuel scenario is given for indicative purposes but it cannot be scaled to cover a significant part of the car fleet.

1.5 Estimate of recycling credits

While recycling processes consume energy and initially increase emissions, they ultimately prevent new raw materials from being extracted from the ground for future vehicles. Results from Ricardo's[23] LCA (commissioned by the EU Commission) shows that recycling enables a reduction of the production carbon footprint of a car of about 19% in 2020 and 22% in 2030. Recycling credits were added in the update of T&E's methodology following the same methodology and findings for recycling credits. These credits are negative GHG emissions given at the end of life to account for the benefits from avoiding raw material extraction. CO_2 credits are given based on the difference between the recycled content of materials used for production and the total recycling rate at the end of life. This conservative method implies that credits are only given when the recycling rate significantly exceeds the content of secondary material used in input. Based on Ricardo results, T&E applied a simplified methodology to account for recycling credits for all powertrains which are estimated to be about 19% of the production carbon footprint in 2022 and 22% in 2030. This

[23] Ricardo's recycling methodology is based on the Product Environmental Footprint 'Circular Footprint Formula' methodology for vehicle recycling and GREET data for battery recycling. https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1

estimate with relative value enables to scale Ricardo results and have consistent order of magnitude applicable to T&E's assumptions and methodology for the production carbon footprint.

2. Results

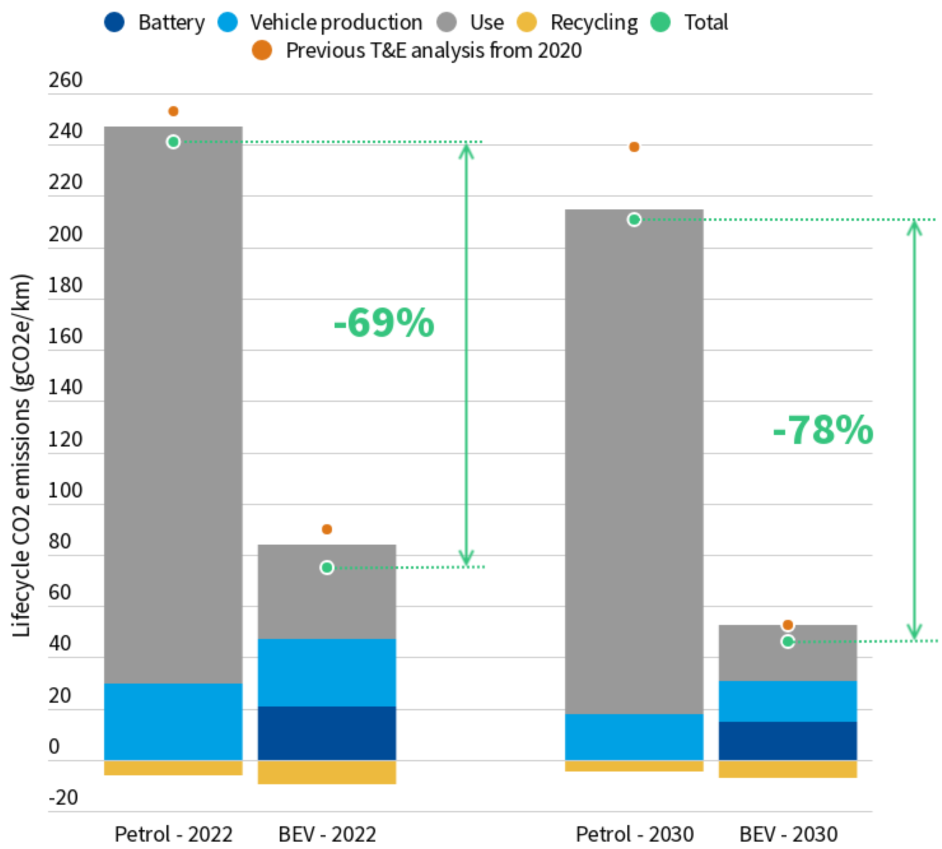
2.1 Comparison with T&E's EV LCA from 2020

For cars sold in 2022, a medium-sized EU-average electric car emits 75 gCO_2e/km over its lifetime, while a petrol car emits 241 gCO_2e/km, including all upstream emissions and end-of-life credits. This shows that BEVs emit about 3.2 times less than petrol cars. These results are slightly better than what was previously shown by T&E in 2020 (BEV were found to emit 90 gCO_2e/km over the lifetime, or 2.8 less than petrol). The changes in the results are primarily explained by improvements in the European electricity grid since 2020, the update of the electricity sources emission factors and the addition of recycling credits in the model. For large and executive categories, average EU electric cars are between 3.4 and 3.6 times better than the petrol equivalent.

When the battery is produced with the cleanest electricity grid, the impact of electric cars decreases to 71 gCO_2e/km or 3.4 times less than petrol. In the best case, if the electric car runs mostly on renewable electricity (e.g. Sweden hydro power) and the battery produced with the cleanest electricity grid, then the GHG impact decreases to 41 gCO_2e/km which is 5.9 times less than petrol equivalents.

In the worst-case scenario, the battery would be produced in China and the EV would run on the EU's most carbon intensive grid (Poland). In this situation, the BEV impact increases to 151 gCO_2e/km and would still be 37% cleaner than the petrol counterpart. This is an improvement compared to T&E's previous estimate (28%), partly explained by the fact that more recent data is used for China's electricity grid (see Annex 3).

In 2030, thanks to rapidly decarbonising electricity, the BEV impact decreases down to 46 gCO_2e/km for an average EU medium electric car (4.6 times cleaner than a petrol car).

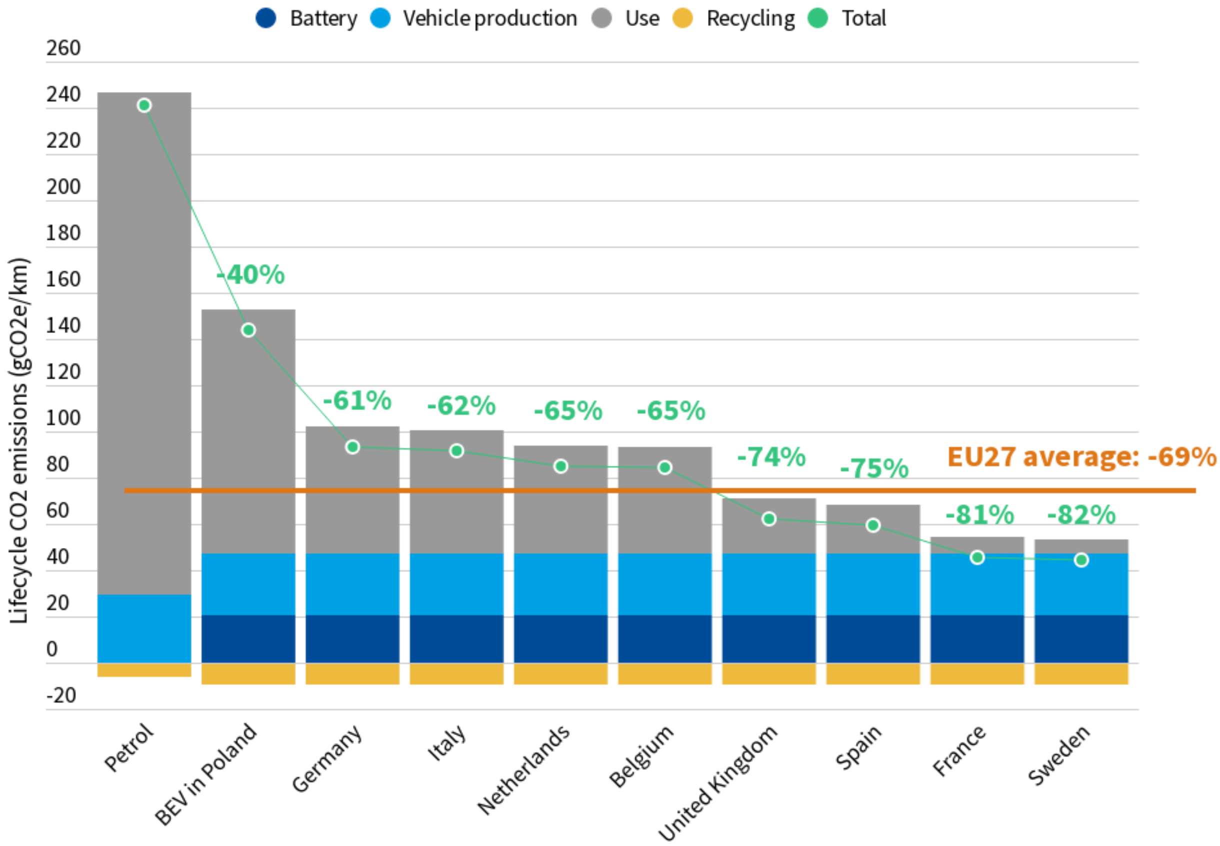


Source: T&E LCA analysis of a medium-sized car, battery assumed to be produced with the EU27 average grid and BEV charged with the average EU27 electricity grid.

Figure 3 - BEV lifecycle emissions savings in T&E updated model

2.2 Influence of national electricity grid over the use phase

The carbon intensity of the electricity used to charge the vehicle over its life has the highest impact over the lifecycle CO_2 emissions of electric cars. The results in this section correspond to a situation where the battery is produced with EU average electricity, so only the electricity used to charge the vehicle changes. The 2022 electricity grid carbon intensity of each country is defined based on a linear growth between 2020 data derived from EMBER and 2025 from ENTSO-E 'National Trends' scenarios. If an EV is recharged in Poland, which has the most carbon intensive electricity grids in Europe, an EV is still 40% cleaner than a petrol car, see Figure 4 below). In Germany, Italy, the Netherlands and Belgium, an electric car is slightly more than 2.5 times cleaner than a conventional car while EV in France and Sweden have impacts more than five times smaller (around 45 gCO_2e/km).



Source: T&E LCA analysis of a medium-sized car, battery assumed to be produced with the EU27 average grid

Figure 4 - Lifecycle emissions in key European countries

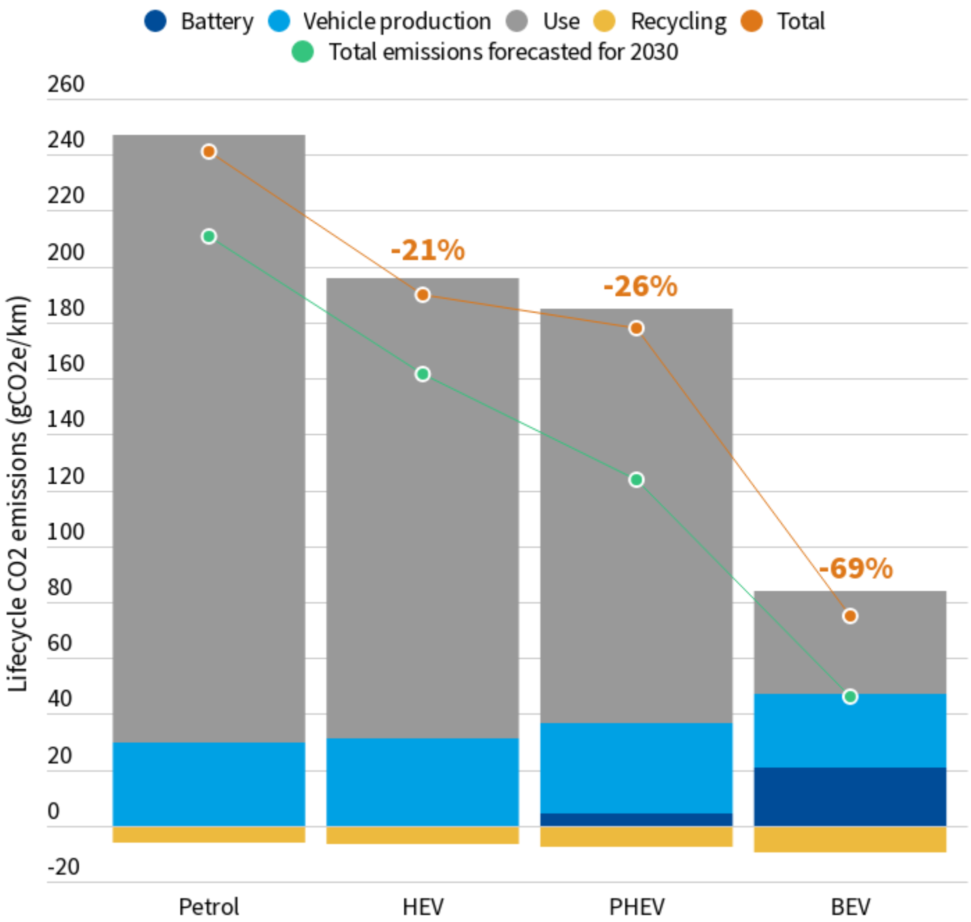
2.3 Lifecycle emission of hybrid vehicles

As described in section 1.2, HEVs and PHEVs were included in the T&E LCA model. The results show that the HEV powertrain used in a medium-sized car only achieved a 21% reduction in LCA emission compared to a petrol equivalent. For large and executive categories, the reductions are 23% and 16% [24] respectively. Regarding PHEVs[25], their improvements compared to petrol cars are limited to 26% for medium cars (32% for large vehicles and 25% for executive vehicles). This shows that the lifecycle emissions of an average HEV and PHEV are much closer to conventional petrol engines and falls short of emission reduction from BEVs. For instance, PHEVs have 2.4 times larger lifecycle emissions than BEVs for medium cars.

[24] The lower reduction in the case of the executive segment is explained by the relatively lower consumption from executive petrol cars where mild hybridisation already enables significant savings (mild hybrids are included in the "petrol" powertrain while HEV refers to full hybrids).

[25] As reported by ICCT in https://theicct.org/publication/ghg-benefits-incentives-ev-mar22/, there are large variations of LCA emissions between different PHEV models. T&E methodology outlined in this report is applicable to an average PHEV for each segment used by an average user. This methodology does not pretend to be accurate for specific models or specific user behaviour.

In 2030, all powertrain benefits for LCA emissions reductions due to improvement of fuel and electricity consumptions. HEVs are expected to be 23% cleaner than petrol equivalent in 2030. PHEVs efficiency and utility factors are expected to improve so that their lifecycle emissions are projected to be 41% lower than petrol vehicles. But even with these improvements, the average PHEV real world utility factor would still be limited to around 56%, so their lifecycle emissions are still expected to be 2.7 times larger than BEVs footprint that fully benefit from the grid decarbonisation.

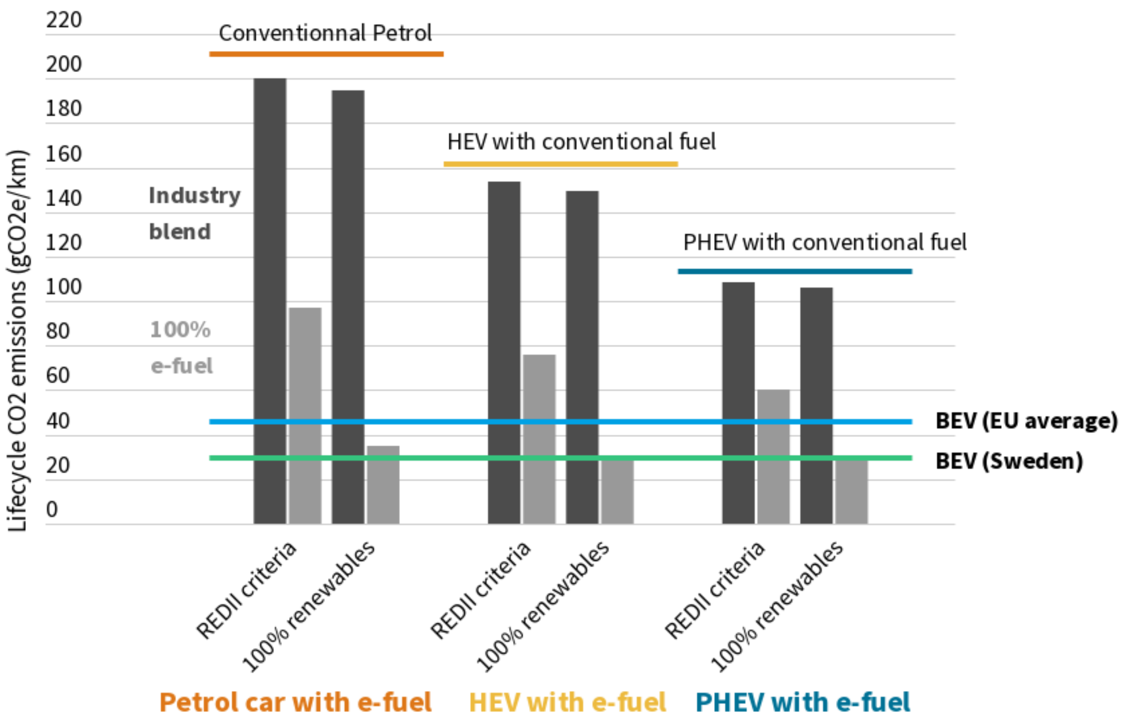


Source: T&E LCA analysis of a medium-sized car, battery assumed to be produced with the EU27 average grid, BEV/PHEV charging with the EU27 average grid

Figure 5 - Lifecycle emissions per powertrains

2.4 Life cycle emissions of cars running on e-fuels

Lifecycle emissions of cars running on e-fuels highly depend on the energy source used to produce the fuel and the blending of fuel in the final fuel available at the pump as shown in the different options in Figure 6 below. In the base case ("Industry blend"), the blending is chosen to be representative of the average blending of fuel in the market (according to the fuel industry forecast of the e-fuel production dedicated to road transport). When the e-fuel is produced according to the REDII criteria and blended with conventional petrol, the lifecycle emissions of a petrol car would be reduced only by 5% compared to conventional fuel (5% for HEV and 4% for PHEV). In the scenario when the e-fuel is produced from 100% renewables, this reduction reaches 8% for medium petrol cars and 7% for HEVs and PHEVs.



REDII criteria: the electricity used to produce the e-fuel is based on a 70% CO2 reduction of the WTW fuel emissions.
100% renewables: based on the forecast of renewable energy sources used by electrolysers.
Source: T&E LCA analysis of medium-sized car in 2030, batteries assumed to be produced with the EU27 average grid and PHEV charged with the cleanest electricity grid (Sweden).

Figure 6 - Lifecycle emissions of cars running on e-fuels in 2030

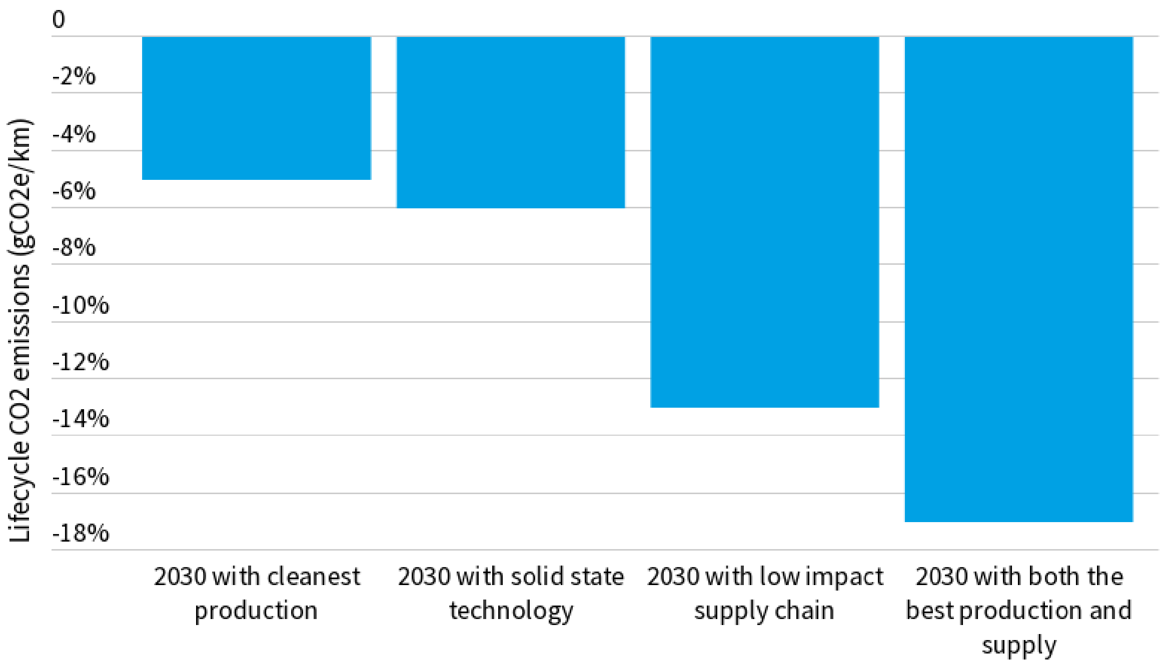
In the theoretical scenario where a petrol car runs on pure e-fuel produced with 100% renewable electricity, its lifecycle emissions would be 20% lower than a BEV charged with the EU average. Nevertheless, if the e-fuel is produced in the best conditions from renewables, a fair comparison would need to take into account the cleanest energy grid available in 2030 for BEV. In this instance, a petrol car running on the cleanest e-fuel still has 18% higher lifecycle emissions than BEVs charged in

Sweden. If the e-fuel is used in a full hybrid vehicle, it would have a similar lifecycle emissions than BEV. If the e-fuel is used in a PHEV that is also charged with the Sweden electricity grid, the lifecycle emissions would be 5% higher than BEV.

Even in the best conditions, a car running solely on efuels is not cleaner through its lifecycle compared to a BEV running on the cleanest electricity grid and more realistic blending forecasts from the industry show that the low expected quantity of e-fuel would only enable marginal savings.

2.5 Sensitivity on battery supply-chain, technology and production

This section analyzes the impact of changes in different battery parameters now available in the LCA tool. The baseline is a medium-sized BEV charged with EU average grid in 2030 and a NMC-811 battery produced with EU average, this 2030 baseline is already 39% cleaner than 2022 average BEV. First, the results displayed in Figure 7 shows that the use of the cleanest country electricity grid (Sweden) for production would enable a 5% decrease of the lifecycle emissions. Then, if a new technology such as solid-state batteries is used, the lifecycle emissions could decrease by 6% compared to the baseline. Finally, the parameter which has the highest influence on the results is the production route of battery materials: with best-in-class supply chains used for the sourcing of lithium, nickel or graphite, the lifecycle emissions of BEV could be decreased by 13%. With the lowest production impact where a LIB battery is produced in Sweden and a low impact supply chain, the lifecycle emissions of BEVs would be reduced by 17% compared to the baseline.



Baseline: Medium-sized BEV with battery produced in 2030 with EU27 average electricity grid, charged with the EU27 average grid, battery chemistry NMC-811. LCA emissions: 46 gCO2e/km

Sensitivities: - Cleanest battery production with the Swedish electricity grid

- SSB technology with a NMC811 cathode, lithium metal anode and oxide based solid electrolyte

- Low impact supply chain cumulating best practices for battery mineral extraction

Source: T&E LCA model and battery carbon footprint estimated by T&E from a LCA carried out by Minviro

Figure 7 - BEV lifecycle emissions sensitivity to battery parameters

In the most ambitious conditions where the lowest production and supply chain impacts are cumulated with the cleanest electricity grid in the use phase, the lifecycle emissions of BEV could become as low as 21 gCO_2e/km. This is 27% lower than the best case for combustion engines where a HEV runs with pure e-fuel made from 100% renewable energy. This difference is mainly explained due to the low efficiency of the e-fuel production. Based on a 55% overall efficiency[26] to convert electricity into efuel, a HEV running on e-fuel would need much more electricity compared to the direct use of electricity in a BEV, so it generates much more indirect emissions. This shows that BEVs have the highest potential of emission improvements over their lifecycle in 2030.

26 https://www.transportenvironment.org/sites/te/files/publications/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf

Annex

1. Emission factors hypotheses

As the UNECE provides different values depending on technologies, the following assumptions were taken:

- For coal, the majority of power plants today use the "pulverised coal" (PC) technology" which is also the one with the highest carbon intensity. It is assumed that 80% of the EU coal generation uses the PC technology and 20% of other technologies mentioned by UNECE (subcritical, supercritical and integrated gasification combined cycle).
- Carbon dioxide capture and storage (CCS) is not included for any electricity source.
- For solar photovoltaic (PV), the overwhelming majority of panels are polycrystalline silicon according to UNECE. It is assumed that 90% of photovoltaic panels are silicon-based (the average between rooftop-mounted and ground-mounted options from UNECE is used) and 10% other new technologies (thin-film PV).
- Regarding hydroelectricity, as stated by UNECE, the 360 MW plant is considered as the most representative.
- The offshore wind emission factor is the average between the "concrete foundation" and "steel foundation" options provided by UNECE.

2. PHEV methodology

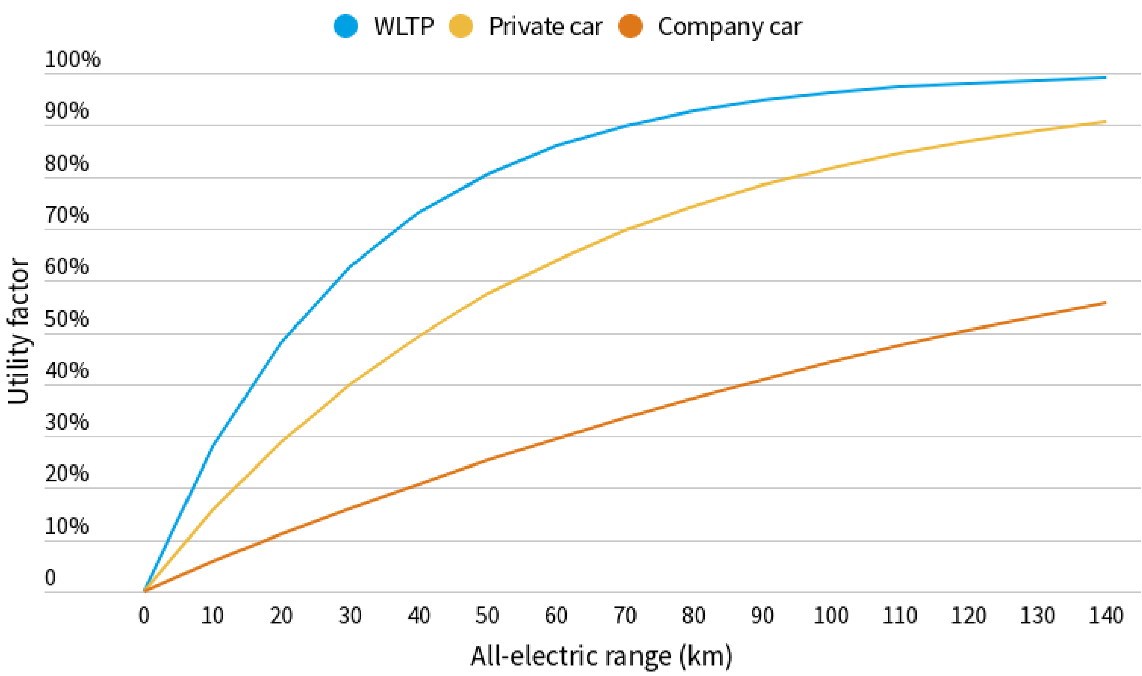
The lifecycle analysis of PHEVs relies on their real world fuel and electricity consumption data. The average real world fuel and electricity consumption can be calculated based on PHEVs consumption in different driving modes (charge depleting CD and charge sustaining CS) and the share of the distance driven on electricity (utility factor UF).

Data shows that the real world fuel consumption of PHEVs is two to four times higher than type-approval values. The gap between real world and type approval values can mainly be explained by overly optimistic UF in the WLTP regulation compared to the real world performance of PHEVs. Moreover, the WLTP utility factor does not discriminate between private and company users. T&E has developed a methodology to derive the real world consumption of PHEVs.

As inputs, the methodology relies on data made available by carmakers on their websites for the latest PHEV models: carmakers usually provide fuel and electricity consumption and the Equivalent All Electric Range (EAER) as determined by the WLTP. For cars where the electricity consumption is not advertised, the values are extracted from the EEA dataset. T&E extracted data from carmakers' websites and the EEA for a large number of models. The sales volumes of the chosen models amounts to 81% of volume of 2021 EU PHEV sales. The methodology is as follows:

1. The WLTP theoretical utility factor is calculated based on the WLTP EAER.

2. The real world estimates of the fuel consumption in CS and CD mode are derived from the input data (WLTP average fuel and electricity consumption) and the WLTP UF.
3. Additional correction factors are included to convert WLTP fuel and electricity consumption into real-world estimates.
4. The utility factor of PHEVs in real-world driving conditions is derived from Fraunhofer ISI's UF real world estimates[27] described in Figure 8.
5. Finally, knowing the estimate of all fuel and electricity consumption in the different phases (CD and CS) and the real world utility factor, the average real world fuel and electricity consumption can be derived.



Source: Plötz, P. and Jöhrens, J. (2021): Realistic Test Cycle Utility Factors for Plug-in Hybrid Electric Vehicles in Europe. Karlsruhe: Fraunhofer Institute for Systems and Innovation Research ISI

Figure 8 - Fraunhofer ISI's realistic UF curve for private and company cars

The outline of the method is depicted in Figure 1 below.

[27] https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/BMU_Kurzpapier_UF_final.pdf
Fraunhofer ISI used the UF function from the WLTP and fitted it to empirical PHEV usage for 1,385 private PHEV from Germany and 10,872 company cars from Germany and the Netherlands to define representative UF functions for both company and private cars.

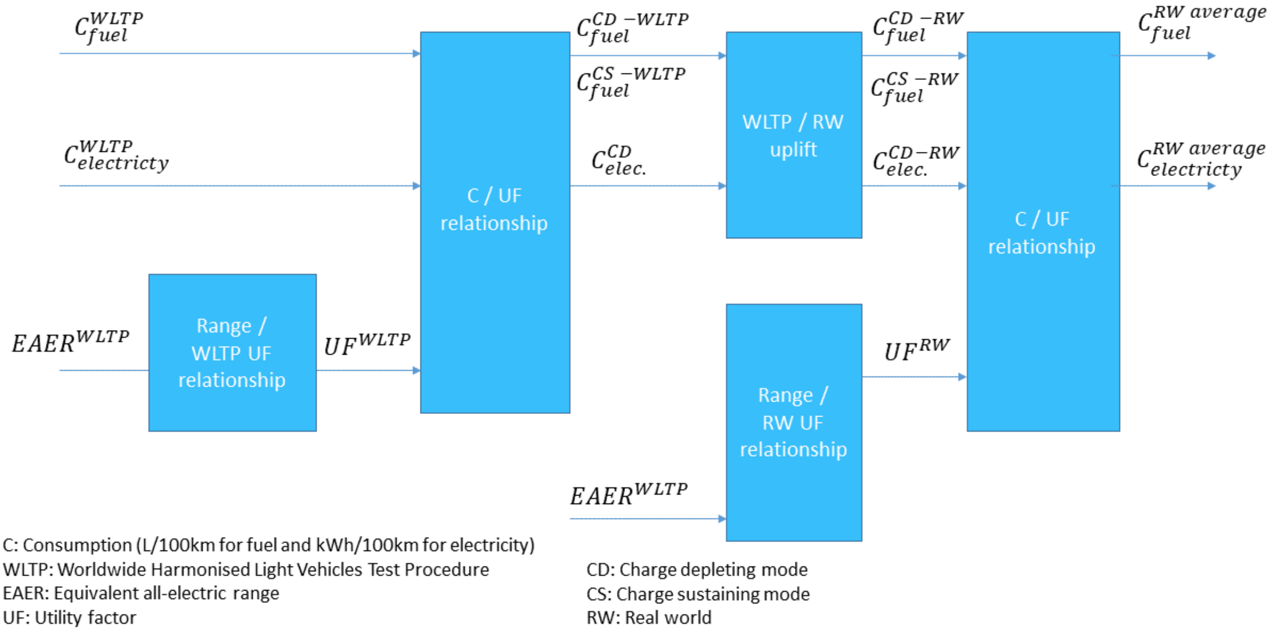


Figure 1 - Real-world PHEV fuel and electricity consumption calculation methodology

The detailed methodology with each calculation steps is detailed below:

1. **WLTP utility factor calculation:**

In the WLTP methodology, the utility factor is defined based on the range in charge depleting mode until the end of the transition cycle (R_CDC). The transition cycle is the WLTC where the transition from charge depleting to charge sustaining modes is considered to have taken place. The R_CDC is not publically available, however it may be estimated based on the WLTP equivalent all electric range (EAER) provided by carmakers. The EAER is defined as the part of the total range in charge-depleting mode that can be attributed to the use of the electric energy from the battery.

The R_CDC and EAER differ because the test cycle carries on after the vehicle reaches its EAER so that the distance driven at the end of the transition cycle is larger than the EAER. In this report, T&E assumes that, on average, the EAER is reached during the transition cycle[28]. So, for the purpose of this analysis the R_CDC is assumed to be the distance reached at the end of the test cycle in which the EAER is reached. With this hypothesis, the WLTP utility factor can only take discrete values defined from the R_CDC as shown in table 5 (each test cycle of the WLTP has a fixed distance of 23 km). For instance, for a PHEV with an advertised EAER of 55km, we assume that the test cycle 3 is the transition cycle and we use a UF of 84%.

[28] Depending on PHEV models, the EAER can be reached during the transition cycle or in the preceding cycle. It is assumed that the average PHEV model reaches the EAER during the transition cycle.

Table 5 - WLTP utility factor value depending on the test cycle

WLTC	Range in charge depleting mode until the end of transition cycle (km)	UF
1	23	51%
2	47	73%
3	70	84%
4	93	89%
5	116	92%
6	140	94%

2. WLTP consumptions calculation:

Having determined an approximation for the utility factor, the WLTP fuel and electricity consumption in CS and CD mode can be derived from the WLTP combined consumptions using the following relationship:

$$C^{WLTP\ combined} = UF^{WLTP}.C^{CD-WLTP} + (1 - UF^{WLTP}).C^{CS-WLTP}$$

Where:
$C^{WLTP\ combined}$= weighted consumption (L/100km for fuel and kWh/100km for electricity) from carmakers data
UF^{WLTP}= WLTP utility factor as a function of the range in CD mode R_CDC
$C^{CD-WLTP}$ consumption in charge depleting mode
$C^{CS-WLTP}$ consumption in charge sustaining mode

In the WLTP, the value of the fuel consumption in charge depleting mode is not generally zero as the ICE usually starts before the battery reaches a minimum state of charge and the end of the transition cycle. In order to simplify this formula, we assume that the fuel consumption in charge depleting mode is about 10% of the consumption in charge sustaining mode. This assumption can be compared to results from the ADAC Ecotest reported by ICCT[29] for 9 vehicles. By using an average of the ratio of CD and CS consumption weighted by each vehicle's 2021 sales, T&E estimate that the fuel consumption in CD mode is about 15% of the consumption in CS mode in the ADAC Ecotest conditions. Nevertheless, the ADAC Ecotest expands the WLTC by an additional highway cycle and stronger accelerations in the transition. So, the fuel consumptions (CD mode and CS mode) measured in these conditions may be overestimated compared to

[29] https://theicct.org/publication/ghg-benefits-incentives-ev-mar22/

WLTP test conditions. Therefore a reduced 10% ratio was used as the ratio of CD mode fuel consumption and CS mode fuel consumption in WLTP test in order to account for the lower average CD consumption in WLTP conditions compared to ADAC. This ratio is applied here to a theoretical average vehicle but individual vehicles can have a wide range of values. For instance, it ranges from only 7% for the Kia Optima Sportswagon to 32% for the BMW 225xe based on values from ADAC reported by ICCT, the large difference can be attributed to the different carmaker designs of PHEVs.

The WLTP fuel consumption in CS mode can be estimated with the following formula:

$$C_{fuel}^{CS-WLTP} = \frac{C_{fuel}^{WLTP\ combined}}{1 - 90\%.UF^{WLTP}}$$

The WLTP electricity consumption in CS mode is assumed to be equal to zero, as according to the regulation the state of charge of the battery may fluctuate during the charge sustaining test but overall all the vehicle should maintain the same state of charge. Therefore the value in CD mode can be calculated from the relationship:

$$C_{electricity}^{CD-WLTP} = \frac{C_{electricity}^{WLTP\ combined}}{UF^{WLTP}}$$

3. **Real-world estimates from WLTP consumptions**:

The CD and CS mode fuel consumption in real-world driving conditions can be derived from their respective estimated WLTP value by applying a corrective factor. ICCT calculated that, on average, the real world fuel consumption of ICEs is 14% larger than the consumption achieved on the WLTP test[30]. T&E's methodology assumes that this relationship can be applied to PHEVs. Regarding electricity consumption, T&E calculations from efficiency data of BEVs provided by EV-Database[31] show that electricity consumption in real world conditions are on average 5% higher than WLTP values. It is assumed that this relationship is also applicable for PHEVs used in CD mode.

30
https://theicct.orgCO2e/publication/on-the-way-to-real-world-co2-values-the-european-passenger-car-market-in-its-first-year-after-introducing-the-wltp/
31 https://ev-database.orgCO2e/

4. Real-world estimate of the utility factor:

$$UF = 1 - exp\left(-\sum_{i=1}^{10} c_i \left(\frac{AER}{d_n}\right)^i\right)$$

Where:
AER is the WLTP all-electric range in km
c_i parameters are constants from the WLTP regulation (EC 2017)

The utility factor is defined based on the distance driven electrically and can therefore be describedas a function of the all-electric range[32]. Fraunhoher defined a methodology to derive these UF curves based on real world data. This UF function is based on the official UF function from the WLTP regulation where the dn parameter is scaled to fit empirical data using a standard statistical method. Fraunhofer ISI found that the best real world estimate leads to the following values of dn : , dn = 1544 km for private cars and dn = 4500 km for company cars[33]. As a comparison, the WLTP regulation use dn = 800 km. Empirical data used by Fraunhofer ISI shows that private and company cars do not have the same utility factors. This difference is due to different charging and driving behaviour: company car drivers often own a fuel card from the employer and have no incentive to charge their car regularly and on average company cars drive more than double the km's of private cars.

Each PHEV car segment had a different share of private and company cars according to T&E analysis of 2021 registration data in EU27 provided by Dataforce. The share of private and company cars for each segment are provided in the Table 6 below. Using this data the average UF can be calculated for each segment.

Table 6 - Private / company car share in Europe

	2021 company car share	2021 private share
C	62%	38%
D	81%	19%
E	83%	17%

[32] Strictly speaking, the UF in the WLTP definition measures the share of km driven in charge depleting mode. Fraunhofer ISI expects their method of estimating the relationship between pure electric range and the share of km driven in pure electric mode to result in a very similar UF-curve compared to estimates based on the relationship between charge depleting range and share of km driven in charge depleting mode. However, Fraunhofer ISI outlined that more research on the relation between pure-electric UF and CD-mode UF is required.
[33] The 2022 update of these parameters carried-out by ICCT -not published at the time of writing- is expected to lead to a larger deviation compared to the WLTP regulation, meaning lower utility factors with more recent PHEV models compared to data reported by Fraunhofer ISI in April 2021.

All PHEVs	70%	30%

An average UF can be calculated for each segment by weighting the UF of private and company cars by their respective share of sales in the given segment[34]. The larger share of company cars sold in the segment D and E implies that the UF will be lower in those segments as the UF function of company cars has lower values than private cars (private car users tend to charge their cars more often than company car users and drive less). Average utility factor results are provided in table 7 below. On average over all segments, the UF is estimated to be 37%.

5. **Real-world average of fuel and electricity consumptions:**

The real world estimate of the average fuel and electricity consumption can be derived thanks to the relationship detailed in step 2 using the average real world UF of each segment and the real world consumption estimates calculated in step 3. In that case, we assume that the real-world fuel consumption in CD mode is about 15% of the fuel consumption in CS mode as derived per the ADAC Ecotest results. Average fuel and electricity consumption values are provided in table 8.

6. **Projection for 2030:**

T&E's model assumes that PHEV fuel consumption in CS and CD mode will decrease by 1.2% a year in line with our forecast for HEV described in section 1.2 and that the electricity consumption would decrease by 0.5% (in line with our hypothesis for BEV). In addition the UF of PHEVs in 2030 is modelled to increase for two reasons:

- Based on T&E analysis[35] of carmakers production plans and the trend of the PHEV battery capacity increase, the electric range of PHEVs is expected to increase by 40% in 2030 compared to 2021.
- Following historical trends, the share of company cars among the new sales of PHEVs is expected to decrease in the future. For instance, 91% of PHEVs sales were company cars in 2015 and this share decreased to 77% in 2019 and 70% in 2021. Based on a linear forecast, T&E assumes that 50% of new PHEVs sales will be company cars in 2030.

This leads to the following change in the UF by segment:

Table 7 - Real-world utility factor per segment

	2022 real world UF	**2030 real world UF**
C	40%	57%

[34] This analysis is applicable for the average new car of each segment and is not representative of specific individual user behaviour for a given model.

[35] https://www.transportenvironment.orgCO2e/discover/commitments-but-no-plans-how-european-policymakers-can-make-or-break-the-transition-to-zero-emission-cars/

D	33%	51%
E	37%	57%

The segment C shows the largest utility factor as it has the highest share of private cars. The company car share is higher in segment D and E, but segment E PHEVs have larger batteries and longer electric ranges[36], so it has a higher UF than segment D. In 2030, the combination of the longer electric range and larger share of private cars results in an increase of the UF in each segment. On average over all segments, the UF would increase from 38% in 2022 to 56% in 2030.

The final fuel and electricity consumption used in the LCA model are shown in the following table:

Table 8 - Fuel and electricity consumption per segment

	Average fuel consumption (L/100km)		**Average electricity consumption (kWh/100km)**	
	2022	2030	2022	2030
C	4.5	3.2	7.8	10.6
D	5.2	3.7	8.2	12.2
E	5.3	3.6	11.5	16.7

3. Location for battery production

The life cycle carbon intensity of the electricity grid options used for battery manufacturing are the following:

Table 9 - LCA carbon intensity of electricity used for battery production in gCO_2e/kWh

	2022	**2030**
EU average	245	160
Sweden	35	30
Germany	355	250
China	680	580

[36] The WLTP ranges of each segment are: 57km for segment C, 55km for segment D and 68km for segment E.

The EU cleanest option is based on the electricity grid from Sweden.
The option with higher than average carbon intensity is now based on the German grid.
China electricity grid life cycle carbon intensity is based on IEA's Stated Policy (STEPS) scenario[37]. This result is a significant improvement as the 2020 value was assumed to be 919 gCO_2e/kWh in T&E's LCA previous version based on Knobloch et al. (2020)[38].

Further information

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[37] T&E estimates from values reported by ICCT in https://theicct.orgCO2e/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/
[38] https://doi.org/10.1038/s41893-020-0488-7