A look into the life cycle assessment of passenger cars running on advanced fuels

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Abstract: This joint study between Aramco and Concawe uses a Cradle-to-Grave approach to assess the life cycle impacts of passenger car vehicles including emissions related to the manufacturing and infrastructure set up. These vehicles are analysed running with advanced fuels, like synthetic fuels produced from renewable electricity (e-fuels) and advanced biofuels produced from different waste sources like wheat straw and used cooking oil.

Multiple parameters are taken into account to get a comprehensive overview of the range of available solutions, especially different levels of vehicle electrification that include thermal hybrid and plug-in hybrid vehicles. The sensitivity to the electricity sources used in the utilisation phase for either direct consumption or synthetic fuel production is also considered. The study analyses also the sensitivity to methodological aspects of carbon allocation on biofuels. The results obtained are finally compared with other alternative passenger car technologies such as battery electric (BEV) and fuel cell hydrogen electric vehicles (FCEV).

Keywords: Life cycle assessment, power-to-liquid, e-fuels, advanced biofuels, greenhouse gases, passenger cars.

1. Introduction

This paper is an update to an earlier vehicles life-cycle assessment (LCA) study that was presented at the 2020 SIA Powertrains & Energy conference [1]. As a joint collaboration between Concawe and Aramco, several of the previous assumptions have been updated, added plug-in hybrid electric vehicles (PHEV) and diesel hybrid electric vehicles (HEV) to the scope, and conducted sensitivity analyses on a range of parameters. The previous scope has also been broadened including, amongst others, the utilisation of advanced, low-carbon fuels, the effects of the battery manufacturing location, consumer behaviour reflected in the PHEV e-drive mode use, and the methodology chosen when estimating the greenhouse gases (GHG) impact of advanced fuels. We expanded the definition of *advanced* fuels in the RED II [2] Annex IX A to include also waste-based fuels and Power-to-Liquid (PtL) fuels (also referred to as e-fuels). These updates close the gaps in the earlier 2020 study, and offers significant new insights to inform the debates on future low-carbon mobility in the EU.

2. Model and Methodology

The present study follows the standard of ISO 14040 [3] and 14044 [4] to evaluate the life-cycle impacts of fuels, electricity, batteries and vehicles. The LCA modelling platform used was the GaBi software system for life-cycle engineering [5]. The JEC WTT v5 report [6] was also used in the Well-To-Tank (WTT) part for comparison of different methodologies (CO_2 and co-product allocation) of biofuels production, as well as in the definition of fuel properties (Tank-To-Wheels emissions, energy contents) and the fuel's infrastructure-related emissions). Finally, the vehicle fuel and power consumptions values are taken from JEC TTW v5 report [7] as well.

The main focus of the present study is on the impact category Climate Change, for which we have used characterization factors from the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) considering a time frame of 100 years [8]. This impact is analysed on a Cradle-to-Grave (CTG) rather than a WTW basis, which means that it includes the emissions from power and fuel infrastructure construction and end-of-life.

3. Fuel Production Pathways

3.1. Biofuels from residues and waste-based

As part of the assessment, four different feedstocks and conversion routes were investigated when looking into future biofuel production pathways (Well-To-Tank):

- Hydrotreated Vegetable Oil (HVO) from Used Cooking Oil (UCO) [9] [10]
- Fermentation of wheat straw for the production of cellulosic ethanol [11] [12] [13]
- Fischer-Tropsch diesel from wheat straw gasification (FT biodiesel) [14] [15] [16] [17]
- Gasoline from plastic waste pyrolysis (HPO) [18]

For each of these pathways, the required steps from feedstock collection, transport to the conversion site, fuel production and transport of final fuel to the filling station have been modelled. Different scenarios were modelled to explore effects of various parameters including methodological approaches (e.g., treatment of co-products) and process-related assumptions (e.g., maximisation of renewable electricity and transport distance). Table 1 provides a summary of the assumptions for each fuel pathway and the resulting WTT GHG emissions intensity. LCA software GaBi was used as a life-cycle inventory modelling tool to implement the fuel pathways, in collaboration with consulting firm *Sphera*.

Table 1: Summary of waste-based and biofuels results – scenarios explored (WTT)

Fuel	**HVO**	**Cellulosic ethanol**	**FT biodiesel**	**HPO**
Feedstock	UCO	Wheat straw	Wheat straw	Non-recyclable plastic waste
Conversion	Hydro-treating	Fermen-tation + Distillation / Dehydra-tion	Gasifica-tion + Fischer-Tropsch + Hydro-cracking	Pyrolysis + Hydro-cracking
Selected scenario to WTW integration	No impact / SMR H_2	Only baling / 50 km transport to site	Only baling / Internal Use of LPG & CH_4	150 km transport to site / SMR H_2 / No credit from energy recovery
WTT energy expended (MJ/MJ_{fuel})	0.210	0.290	0.043	0.048
CTT GHG emissions (gCO_2eq/MJ)	17.0	20.9	7.6	9.7
Range of CTT GHG (*) (gCO_2eq/MJ)	8.3 to 22.3	20.9 to 47.4	7.3 to 24.5	9.7 to 55.7

(*) Range of the scenarios explored in this analysis. Variation due transport methodological choices (e.g. credits/co-products considerations), transport distances and other factors. Negative values imply credits from avoided incineration or power production. Additional potential savings related to full replacement of fossil-based sources used in the production/conversion steps not considered within the scope of this analysis.

Key general assumptions:

- The current electricity mix includes around 30% renewables (total life cycle carbon intensity 406 g CO_2eq/kWh electricity), including upstream emissions and GHG linked to the manufacturing of the electricity generation based on data from the latest version of the EC Reference Scenario [19] combined with GHG emissions data from GaBi database 2021.1 [5]. The same mix is used for biofuel production and the credits estimate in case of surplus electricity (electricity from the EU mix is replaced).
- Supply of residues is attributed with no environmental impact when it is considered as a waste and not defined as product, but the effort to collect and condition is considered (e.g. wheat straw baling).

3.2. Power-to-X fuels

3.2.1. Hydrogen

In the present study, hydrogen can be used directly in Fuel Cell Electric Vehicles (FCEVs) in high-purity form, but also as a feedstock, together with CO_2 to produce PtL fuels or as hydrogenation agent to produce HVO.
Steam methane reforming (SMR) is the most utilised hydrogen production method used in the pathways modelled, also referred to as “grey hydrogen”. Carbon capture technologies can be combined with SMR to produce a hydrogen with a lower GHG intensity, also known as “blue hydrogen”. This can lead to CO_2 emissions reductions of up to 90% when applied to both process and energy emission streams [20]. On the other hand, electrolytic hydrogen, when produced from renewable electricity is often referred to as “green hydrogen”, in reference to its low carbon emissions.

In this study we assume that, at the 2030 time horizon, hydrogen as a fuel for FCEVs is by default a mix of 25% green hydrogen produced from wind electricity, and 75% grey hydrogen [21]. The carbon intensities of the different hydrogen types shown in Table 2 (green) and Table 3 (grey and blue) take into account emissions from the supply chain including natural gas transportation, hydrogen compression, conditioning and dispensing at retail site. For PtL and advanced biofuels production, we assume the use of 100% green hydrogen with no transportation emissions, assuming that the fuel production sites are close to a renewable energy source.

3.2.2. Power-to-Liquid (PtL) fuels (e-fuels)

For PtL fuels synthesis, a carbon source is required, typically in the form of CO_2, which can be extracted from ambient air or from flue gases and gas mixtures containing CO_2 [22]. The direct capture of carbon dioxide from the air (DAC), was chosen as carbon source for this study.

Different types of PtL fuels (e-fuels) are considered within the scope of the current analysis:

- Methanol-to-gasoline (MtG), using a synthesis gas feedstock (two-step route) or a one step process that uses CO_2 directly (direct route) as the basis for this study [23].
- Fischer-Tropsch (FT) diesel. The process modelled for this study, based on the work of König [17] and de Klerk [24], considers the heat integration of the FT process with direct air capture by recovering the heat from the exothermic reaction at a rate of 80%.
- OME_{3-5} as an example of poly(oxymethylene) dimethyl ethers. OME_{3-5}, are synthetic, diesel-like fuels synthesized from methanol that have shown potential in reducing vehicle pollution, in particular soot formation and NO_x [24], including in dual fuel applications [25].

The characteristics of the PtL fuels considered are presented in Table 2.

Table 2: Summary of Power-to-X fuels

Fuel	**Green hydrogen** [6]	**Methanol-to-Gasoline** [5]	**Fischer-Tropsch diesel** [5]	**$OME_{3,5}$** [5]
Feedstock	Water	Green hydrogen, DAC CO_2	Green hydrogen, DAC CO_2	Green hydrogen, DAC CO_2
Conversion	Electrolysis (alkaline)	Methanol synthesis (direct) + Methanol-to-Gasoline synthesis	Reverse Water-Gas Shift+ Fischer-Tropsch synthesis + Hydro-cracking	Methanol synthesis (direct CO_2 conversion) + $OME_{3\text{-}5}$ synthesis
Energy source (including heat)	Wind electricity	Wind electricity + Synthesis reaction heat	Wind electricity + Synthesis reaction heat	Wind electricity + Synthesis reaction heat
WTT energy expended, MJ/MJ_{fuel}	0.87	1.45	1.68	2.84
CTT (WTT) GHG emissions, gCO_2eq/MJ	9.5 (9.2)	9.9 (2.6)	10.8 (3.1)	16.0 (5.0)

Note. Cradle-to-Tank (CTT) values incorporate to the Well-to-Tank values (between brackets), the GHG impact due to the infrastructure required to produce the fuel throughout its entire lifecycle, including the material, energy and resources for the construction of refineries, fuel synthesis plants and power plants for renewable power generation.

3.3. Conventional fuels

Conventional gasoline and diesel fuels are obtained by distillation and upgrading of crude oil in oil refineries, while grey and blue hydrogen come from steam reforming of methane. As a reference for comparison with alternative fuels included in the scope of this analysis, fossil-based fuels taken from the JEC WTT report [6] have been considered with the Well-To-Tank GHG emissions shown in Table 3, referring when relevant to the selected allocation method (consequential or average).

Table 3: Summary of fossil-based fuels

Fuel	Feedstock & Conversion	WTT GHG emissions [6], gCO_2eq/MJ
Diesel	Crude oil refining	Consequential: 18.9 Average: 11.6
Gasoline		Consequential: 17.0 Average: 17.8
Grey hydrogen	SMR	113.0
Blue hydrogen	SMR + Carbon Capture	39.7

3.4. Electricity source

Electricity and thermal energy sources are used throughout all the processes of fuel production and vehicle manufacturing. The sources vary in terms of location and carbon intensity, depending on the process. The assumed carbon intensities for the electricity supply are shown in Table 4.

Table 4: Summary of electricity sources

Electricity source	Description	CTG carbon intensity [5], gCO_2eq/kWh
EU mix 2030 (base case)	Electricity mix as defined in the IEA SDS for 2030.	151.4
Norway wind	Average wind electricity produced in Norway	6.6
Poland mix 2017	Electricity mix reported in Poland for 2017	936.7
China mix 2030	Electricity mix as defined in the IEA SDS for 2030.	483.2

Note. Cradle-to-Grave (CTT) values incorporate the GHG impact due to the infrastructure required to produce the electricity.

For the electricity consumed in PtL processes, we assume the use of 100% renewable electricity (average wind electricity, assumed 10.4 gCO_2-eq/kWh) as a default value for PtL production in this study based on the GaBi database 2021.1 [5].

4. Vehicles

4.1. Parameters for vehicle/battery manufacturing

The reference vehicle assumed for all the vehicles of the study is based on a C-Segment medium car, like VW Golf, Ford Focus or Opel Astra.

Powertrains: The study includes eight variants of five types of powertrains: Battery electric (BEV), fuel cell hydrogen electric (FCEV), internal combustion engine (ICEV), hybrid electric (HEV), and plug-in hybrid electric (PHEV). Thermal engines can run on either gasoline or diesel fuel, conventional or advanced.

Battery type: Lithium-ion batteries used by BEVs, PHEVs, HEVs and FCEVs were assumed to be built with chemistry technology NMC 622. The assumed battery manufacturing location is China, with specific carbon intensities of aluminium, electricity and thermal sources consistently calibrated to reflect this. The weights of the batteries were calculated from the life cycle inventory model, taken from the Argonne National Laboratory's BatPac [26] model.

4.2. Fuel and energy consumption of vehicles

The main assumptions and input parameters to calculate TTW GHG emissions are summarized in Table 5. TTW emissions in gCO_2eq/km are calculated based on energy consumption of vehicles (MJ/km) and fuel emission factors (gCO_2eq/MJ). Vehicle energy consumptions (MJ/km in WLTP) were derived from 2015 and 2025+ figures in the JEC TTW study v5 [7]. The lifetime average vehicle mileage is assumed to be 200,000 km for all vehicle types. For PHEVs, the annual mileage on e-driving mode is determined by the electric driving mode share, also referred to as *utility factor*. Based on JEC TTW v5 data, with a battery size of 20.8 kWh for PHEVs, the utility factor would be around 90% (in WLTP without any adjustment in the baseline to reflect consumer behaviour in real driving). The impact of a lower utility factor is presented in the sensitivity case, section 6.2.4.

Table 5: Energy consumptions and battery sizes

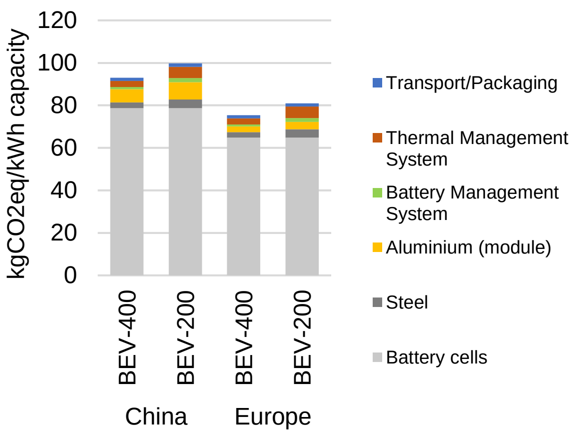
Powertrain	**Energy consumption, MJ/km (WLTP)** [7]		**Battery size, kWh** [7]	
	2015	**2030**	**2015**	**2030**
ICE Gasoline	1.99	1.41	--	--
HEV Gasoline	1.69	1.10	1.5	1.2
ICE Diesel	1.76	1.30	--	--
HEV Diesel	1.55	1.09	1.5	1.2
Gasoline PHEV (e-mode) (*)	0.71	0.52	14.0	20.8
Gasoline PHEV (fuel mode) (*)	1.73	1.15	--	--
Diesel PHEV (e-mode) (*)	0.67	0.51	14.0	20.8
Diesel PHEV (fuel mode)(*)	1.58	1.14	--	--
BEV-150(**)	0.57	--	26.2	--
BEV-200(**)	--	0.43	--	24.7
BEV-400(**)	--	0.45	--	49.4
FCEV(***)	0.88	0.70	--	1.2

(*) The total energy consumption of a PHEV will be estimated prorating both individual fuel and electricity consumption based on its *utility factor*.
(**) Battery powered driving range (km)
(***) Assuming fuel cell power of 100 kW.

The Li-ion battery production is a major contributor of CO_2eq embedded emissions for solutions requiring large electricity storage capacities (BEV and PHEV). The lifecycle inventory of the batteries is taken from Argonne National Laboratory's BatPac model [26]. We also assume that the battery's lifetime is of 200,000 km and that part of its constituent materials can be recycled.

Figure 1 compares the carbon intensities of four NMC 622 batteries calculated with the developed GaBi LCA model, assuming production in China and in Europe of two different battery sizes in 2030 (see Table 4 for carbon intensity values of the electricity used). The figure shows differences of around 8% in the battery carbon intensity depending on the reference size used when comparing directly figures in units of $kgCO_2eq/kWh$.

Figure 1: Calculated battery carbon intensities by size and manufacturing location



5. Summary of base case assumptions and sensitivities

5.1. Summary of assumptions for the base case.

The following parameters were analysed in the study:

Time horizon: The reference year used is 2030.

Electricity: The carbon intensities of all the electricity sources are shown in Table 4.

Fuels: The study considers a wide range of fuels, including hydrogen (blue and green), conventional fossil fuels (gasoline, diesel), advanced biofuels (ethanol, FT biogasoline and HVO) and synthetic drop-in (e-)fuels produced using PtL technologies (Methanol-to-gasoline, e-Fischer Tropsch diesel and $OME_{3,5}$). Details of the fuel production pathways can be found in section 3.

Vehicles: Considering the vehicle parameters presented in sections 4.1 and 4.2, the main results related to vehicle and battery manufacturing and end-of-life (EoL) for all powertrains are presented in Table 6. For PHEVs, the e-drive share (utility factor) we considered is 90%.

Table 6: Calculated emissions associated to vehicle manufacturing and end-of-life

Powertrain	**Vehicle (Battery) manufacturing emissions, $kgCO_2eq$**		**Vehicle (Battery) end-of-life credits, $kgCO_2eq$**	
	2015	**2030**	**2015**	**2030**
ICE Gasoline	4,641	4,395	521	495
HEV Gasoline	5,184 (135)	4,699 (135)	615 (7)	590 (7)
ICE Diesel	4,937	4,699	565	540

Powertrain	Vehicle (Battery) manufacturing emissions, $kgCO_2eq$		Vehicle (Battery) end-of-life credits, $kgCO_2eq$	
	2015	2030	2015	2030
HEV Diesel	5,478 (135)	5,424 (135)	659 (7)	655 (7)
PHEV Gasoline	7,619 (2,205)	7,370 (2,205)	767 (85)	728 (85)
PHEV Diesel	7,985 (2,205)	7,624 (2,205)	807 (85)	767 (85)
BEV-150	7,445 (2,687)	—	656 (95)	—
BEV-200	—	7,172 (2,553)	—	639 (92)
BEV-400	—	9,378 (4,758)	—	686 (138)
FCEV	7,870 (131)	7,341 (131)	761 (7)	703 (7)

5.2. Sensitivities

Following the assumptions described in Sections 3 and 4, a total of 89 cases were executed in the LCA modelling platform. The main parameters tested in the sensitivity analyses are the following:

Utilisation of advanced (bio and e-) fuels: For all vehicles fuelled with conventional gasoline or diesel (ICEV, HEV, PHEV), the default fuel was partially or fully replaced with low carbon fuel alternatives (blends or total drop-in fuels).

Electricity source: The 2030 EU mix electricity used by default for all electrified powertrains (BEV, PHEV) were replaced by sources with very low or very high carbon intensity (see Table 4).

Hydrogen production source for FCEV: The hydrogen mix (25% green and 75% grey hydrogen) fuelling FCEV is replaced by a source of 100% green and 100% blue hydrogen (SMR+CCS).

PHEV key sensitivities: PHEV were studied in detail by applying sensitivities to the use of advanced fuels, a change in the electricity source, the vehicle weight, the origin of battery and a group of parameters specific to PHEVs, including energy consumption and the share of electric-driving mode of PHEVs (i.e. utility factor) reflecting consumer behaviour.

6. Main results

6.1. Base case

Figure 2 shows the first set of results for the 8 vehicle types under the base case conditions as specified in section 5.1. Despite having a significant carbon burden from its manufacturing stage, BEV appears as having the lowest level of cumulated lifetime GHG emissions of the set at 10.5 tCO_2eq. The main factor in favour of this position is the high powertrain energy efficiency, reflected in the slope of the curve during its use phase. On the other side, ICE passenger vehicles display the highest levels of GHG emissions in the base case as a result of the combination between the fossil source and a lower thermodynamic efficiency. However, the results for ICE vehicles are those that show the highest variability in our sensitivity analyses (see Figure 3), especially when alternative advanced fuels (bio/waste and e-fuels) are used in the analysis.

Figure 2: Base case GHG LCA cumulated emissions during the vehicle lifetime (base case – 2030). Conventional fossil fuels used.

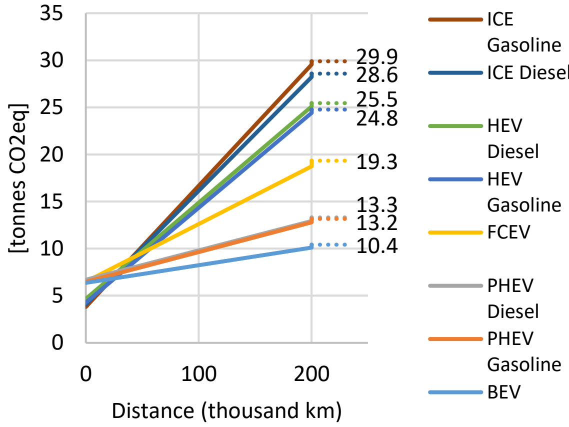
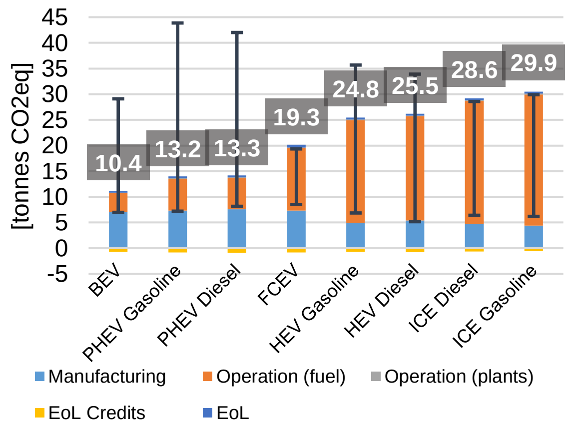


Figure 3 shows with error bars the variability of the GHG emission due to the sensitivity cases explored around the base cases described in section 5.2. The figure also breaks down the sources of GHG emissions for each type of vehicle by stage: i) Manufacturing, ii) Operation (use phase) related to the fuel production and to the new plant infrastructure and iii) EoL, differentiating actual emissions from the credits obtained from material recycling or energy production from incineration.

Figure 3: Sensitivity of GHG cumulated emissions of the base cases during the lifetime (LCA); error bars showing the min/max values from all key sensitivities evaluated



6.2. Sensitivities

6.2.1. Utilisation of advanced fuels

We analysed the impact of displacing conventional fuels with advanced fuels (bio/waste and e-fuels). For the purpose of this analysis, this term groups PtL fuels (MtG, $OME_{3,5}$) with fuels produced from waste of biological (used cooking oil or biomass waste) or non-biological origin (plastic waste) as illustrative examples of the technologies. We compared the use of these advanced fuels, in the form of blends of conventional fuels (with e-$OME_{3,5}$ as an example for diesel-fuelled powertrains), or by complete substitution with advanced fuels.

Figure 4: Sensitivity of lifetime GHG emissions of fossil diesel-fuelled vehicles to advanced fuels

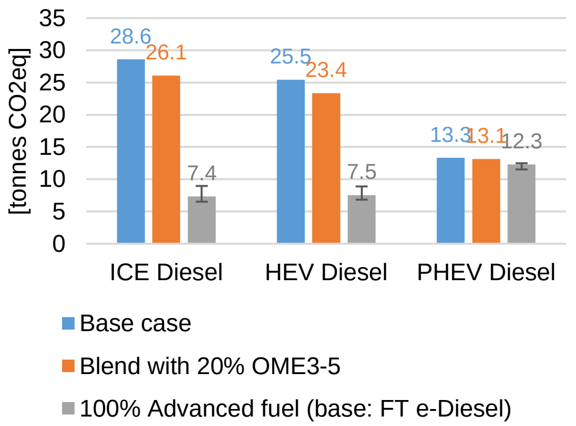


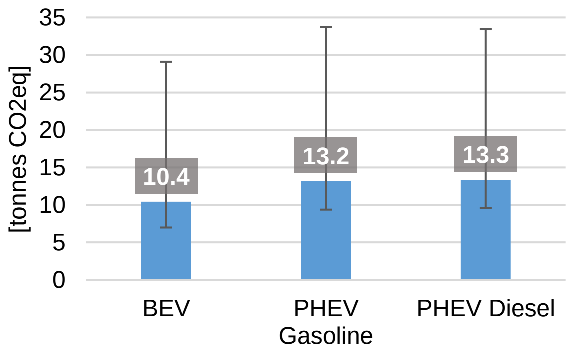
Figure 4 shows the big impact of the substitution of fossil-based fuels by their advanced equivalent diesel like ones (similar results are obtained for gasoline). In both ICE and HEV cases, the reduction of lifetime GHG emissions is ~70% for the 2030 scenarios considered with a small variability due to the type of advanced fuel considered. The impact on PHEV is lower due to the utility factor (90%) assumed.

6.2.2. Electricity source

The carbon intensity of the electricity mix is one of the most relevant parameters impacting BEVs and PHEVs when the CTG impacts are assessed, with a wide variability depending on the electricity source used (see Figure 5).

As stated in the JEC WTW v5 report, it is important to mention that the EU electricity mix applied to the base case can only be used as an approximation for deriving a back-of-the-envelope evaluation. When electricity for BEVs/PHEVs vehicles is taken from the grid, this can lead to either an increase or a reduction in emissions compared to the baseline depending on the marginal electricity source used for that purpose. These aspects are country, regional, company and time-specific and they are not explored in detail in this analysis and the range explored (from a 30% reduction up to tripling the LCA GHG value versus the base case) is given as an indication of plausible GHG variability options in our analysis.

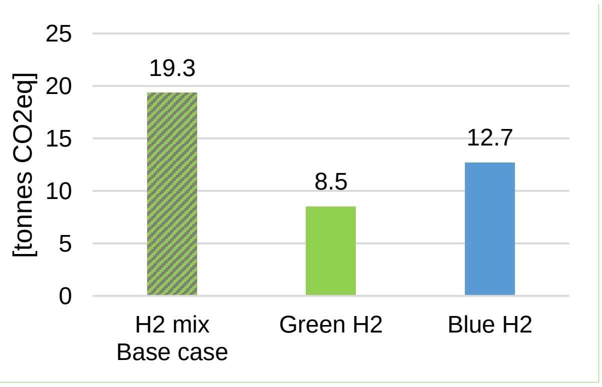
Figure 5: Sensitivity of lifetime GHG emissions (LCA) of electrified vehicles to the source of electricity



6.2.3. Hydrogen production source for FCEVs

As for the other powertrains, the source of hydrogen as energy carrier in these vehicles is deemed the most relevant parameter impacting on the lifetime GHG emissions of the FCEVs. The sensitivity analysis explored in Figure 6 shows that ~50% benefit could be reached by switching to a fully renewable (green) electricity-based hydrogen and ~35% for the blue hydrogen (SMR+CCS) case.

Figure 6: Sensitivity of lifetime GHG emissions of FCEV to hydrogen source



6.2.4. Sensitivity analysis for PHEVs

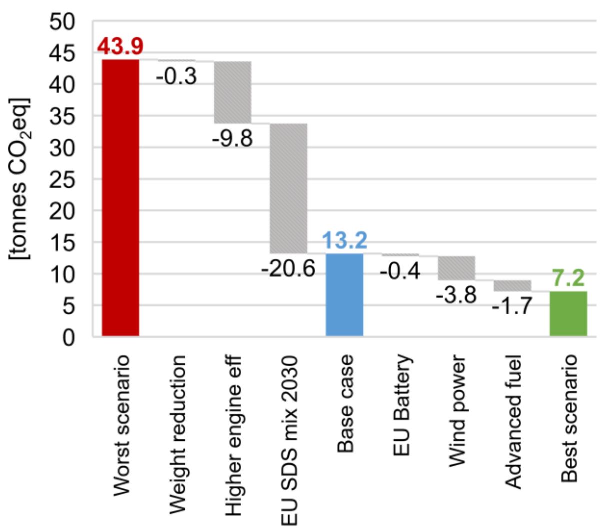
The impact of different parameters for one specific vehicle/fuel combination is explored in this case in which key parameters deemed to influence the LCA performance of PHEV are considered. The parameters are detailed in Table 7.

Table 7: PHEV combined scenarios

Parameter	Worst scenario	Base case	Best scenario
Vehicle weight	Reference 2015	Reference 2030	Reference 2030
Energy consumption	WLTP 2015	WLTP 2030	WLTP 2030
Utility factor	90%	90%	90%
Electricity mix in use phase	Poland mix 2017	EU SDS mix 2030	Norway wind
Battery manufacturing location	China	China	EU
Fuel in use phase	Fossil	Fossil	Advanced

Figure 7 shows the impact of a step-by-step transition from the worst scenario to the best scenario. The contribution from the source of the electricity used in the e-drive mode, the origin of the fuel, and the engine efficiency are deemed to be the key parameters reducing GHG emissions, highly dependent on the utility factor considered.

Figure 7: Sensitivity of lifetime GHG emissions of plug-in hybrid vehicles to multiple parameters – **Utility factor: 90%**



Note. A utility factor of 50% in combination with the role of advanced fuels, despite their opposite individual impact, show very similar results at the end of the life (Best scenario with 50% utility factor: 7.9 tonnes CO_2eq).

7. Conclusions and Recommendations

This paper aims at conducting a life cycle analysis of different alternative fuels and powertrains towards 2030, expanding the scope of the JEC WTW v5 report with focus on advanced fuels (bio/waste and e-fuels). Different sensitivities around some of the main key factors identified have also been presented, summarizing the main conclusions below:

1. From a lifecycle assessment viewpoint, climate change mitigation should not be associated to a particular technology by itself.
   - Within the vehicle related measures, fuel efficiency is just one of many parameters that have an impact on lifetime environmental aspects. Other aspects such as battery manufacturing or consumer behaviour show a potential relevant impact.
   - An integrated and holistic view considering different vehicle-related aspects with low carbon intensity energy carriers/fuels is deemed to have the biggest impact when reducing cradle-to-grave GHG emissions.
   - For bio/waste fuels, GHG reduction potential varies between 65-95% (WTW) depending on the methodological and low carbon energy sources used during the conversion process.
2. When compared with internal combustion engines powered by fossil fuels, BEVs are presented as the lowest lifetime GHG emission option, assuming a SDS EU electricity mix in 2030 (IEA).
3. The electricity sources used for battery manufacturing and especially during the use phase are fundamental in determining the impact of electrified passenger car vehicles. Access to renewable electricity is also presented as a way to further reduce the GHG emissions linked to the production of biofuels.
4. Conventional internal combustion vehicles running on advanced fuels show a potential to provide similar or even better effects on cumulated GHG emissions than electrified technologies depending on the scenarios considered. Factors such as fleet scenarios and potential availability of bio/waste and e-fuels have not been considered in the scope of this analysis.
5. PHEV potential to reduce GHG emissions depends on the combination of multiple factors among which are the source of electricity, the engine efficiency, the battery manufacturing location, the fuel source and the utility factor (representative of consumer behaviour).
6. Having access to low carbon intensity hydrogen sources is fundamental to the impact of FCEV. Blue, and especially green hydrogen, allow reductions going from 35% to 56% when compared with fossil-based grey hydrogen (considered as the main technology also in the fuel production routes within the 2030 timeframe). These low-carbon sources could be efficiently developed in parallel and play an essential role in the energy transition process of the hydrogen-based alternatives.

7. As a final conclusion, holistic GHG emission reduction strategies are presented as complementary options and their implementation should be applied based on timing, cost and relevance to specific regional contexts.

8. Acknowledgements

The authors would like to thank Alexander Stoffregen and Oliver Schuller from *Sphera* for their valuable contribution to this paper.

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10. Glossary

BEV:	Battery Electric Vehicle
CCS:	Carbon Capture and Storage
CTT/G:	Cradle-to-Tank/Grave
DAC:	Direct Air Capture
EoL:	End of Life
FT:	Fischer-Tropsch
FCEV:	Fuel Cell (Hydrogen) Electric Vehicle
GHG:	Greenhouse Gases
HPO:	Heavy Pyrolysis Oil
HEV:	Hybrid Electric Vehicle
HVO:	Hydrogenated Vegetable Oil
ICE:	Internal Combustion Engine Vehicle
LCA/I:	Life-Cycle Assessment/ Inventory
MtG:	Methanol-to-Gasoline
NMC:	Nickel-Manganese-Cobalt battery
OME_x:	Poly(oxymethylene) dimethyl ethers
PHEV:	Plug-in Hybrid Electric Vehicle
PtL:	Power-to-liquids
SDS:	Sustainable Development Scenario (IEA)
SMR:	Steam Methane Reforming
UCO:	Used cooking oil
WLTP:	Worldwide Harmonized Light-duty Vehicle Test Procedure
WTT/W:	Well-to-Tank/Wheels