HDV CO_2 Comparator — a life-cycle assessment tool for heavy-duty vehicles in real-world conditions

This article summarises a study to create an interactive life-cycle assessment tool for heavy-duty vehicles. The tool enables users to compare the CO_2 emissions intensity of various heavy-duty transport technology options in order to determine the best options for decarbonisation for a range of vehicle categories and use cases. The tool can be accessed via the Concawe website.

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Introduction

The Concawe HDV CO_2 comparator is an interactive life-cycle assessment (LCA) tool for heavy-duty vehicles (HDVs), developed by IFP Energies nouvelles (IFPEN) and commissioned by Concawe. It was first published on the Concawe website in July 2023, and some data source and interface updates are scheduled for early 2025. Users are provided with an easy-to-use interactive tool to compare the CO_2 intensity of various heavy-duty transport technology options.

Understanding the benefits and drawbacks of each solution from a life-cycle perspective for a given use case is difficult. The LCA tool described in this article aims to improve this understanding and assist in decision-making.

HDVs have numerous vehicle categories and use cases, and have access to many powertrains and energy carrier combinations. The tool combines the following parameters to define specific use cases:

- Six powertrains and their efficiencies: ICEV, fuelled by diesel or diesel-like fuels, gas (compressed natural gas (CNG) or liquefied natural gas (LNG), or hydrogen; HEV; PHEV; FCEV; and BEV (and CEV).
- Five vehicle categories: long-haul truck (Class 5); delivery truck (Class 2); city bus; coach; and refuse truck (for waste collection).
- Five categories of energy carriers: diesel (petroleum-based diesel and partially renewable blends such as B7, B30, B7+25%HVO[1]); renewable diesel-like fuels (including HVO, B100 (100% FAME[2]), e-diesel, biomass-to-liquid, etc.); hydrogen (grey, blue or green); CNG and LNG (fossil-based, bio-based, e-fuel based); and electricity (with variations in carbon intensity).
- Sensitivities around battery, fuel cell capacity and hydrogen tank production emissions.
- Number of battery packs used in the lifetime of the vehicle.
- Use cases (payload, trip profile, charging frequency).

All of this provides the user with a comprehensive yet simple tool to make direct comparisons on the same free-to-use platform via the Concawe website.

Context

Transport-related greenhouse gas (GHG) emissions represent approximately one quarter of European Union (EU) GHG emissions, of which commercial road transport represents approximately one third of this. In the context of aiming to reach carbon neutrality in 2050, reducing heavy-duty transport-related GHG emissions is important. Technology neutrality is an important consideration for achieving carbon neutrality whilst simultaneously retaining functionality within the diverse range of heavy-duty transport needs.

[1] Hydrotreated vegetable oil

[2] Fatty acid methyl ester

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When looking at each vehicle individually, there are several ways to consider their GHG emissions:

- The tank-to-wheel (TTW) approach, which only accounts for the tailpipe emissions.
- The well-to-wheel (WTW) approach, which is more comprehensive and takes into account the GHG emissions related to the production of the energy carriers.
- The LCA approach, which is holistic and also takes into account the GHG emissions related to the production of capital goods that are necessary for the transport system.

The LCA approach is the most relevant to climate-related issues. However, it is also challenging and dependent on the scenarios and use cases studied (i.e. combined assumptions). In this context, the passenger cars LCA tool[1] commissioned by Concawe in 2022 proved itself to be very useful as it allowed a complex set of options to be combined in a simple way, following the user's own approach.

Concawe received feedback from numerous external users of the passenger car LCA tool, who requested a similar tool to evaluate the life-cycle emissions of heavy-duty vehicles. This led to the development of the HDV CO_2 Comparator described in this article.

Scope and objectives

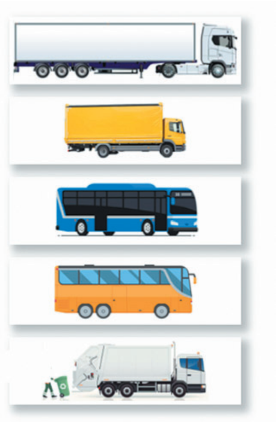
The objective of this study was to develop a life-cycle assessment online interactive tool for heavy-duty vehicles in real-world conditions, similar to the one previously developed for passenger cars. This includes:

- LCA CO_2-equivalent emissions (g/km) segregated by stage of life (vehicle manufacture, electricity, fuel production (well to tank, or WTT), TTW emissions, and absorbed CO_2 during the production of the fuel);
- overall energy consumption: fuel consumption TTW (l/100 km or kg/100 km), and electrical consumption (kWh/100 km); and
- the facility to specify the following conditions:
  - powertrains used and their efficiencies;
  - vehicle categories;
  - sensitivities around battery, fuel cell and hydrogen tank capacity and emissions during their production;
  - number of battery packs used in the lifetime of the vehicle;
  - use cases (payload, trip profile, charging frequency);
  - fuels used; and
  - carbon intensity of the electricity mix.

Overview of the tool functionality

As powertrains diversify in their electrification levels, energy carriers and fuel production pathways, the carbon footprint over their life cycle depends on their use cases. This interactive tool is user centric, allowing scenarios where multiple parameters can be combined to compare their environmental performance. The tool consists of a welcome page where the vehicle category can be selected by clicking on the corresponding picture for long-haul truck, delivery truck, city bus, coach or refuse truck (see Figure 1).

Figure 1: Vehicle categories available for selection



Long haul — Class 5

Delivery truck — Class 2

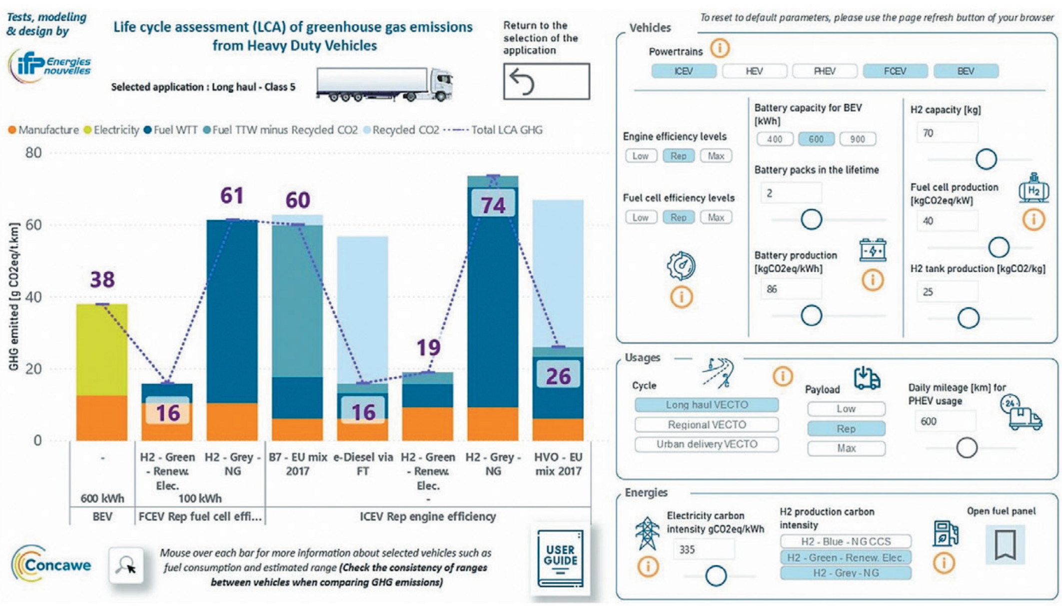
City bus

Interregional coach

Refuse truck

Once a selection is made, this is followed by a page composed of two main panels: the results panel (on the left-hand side) and the configuration panel (on the right-hand side), as shown in Figure 2.

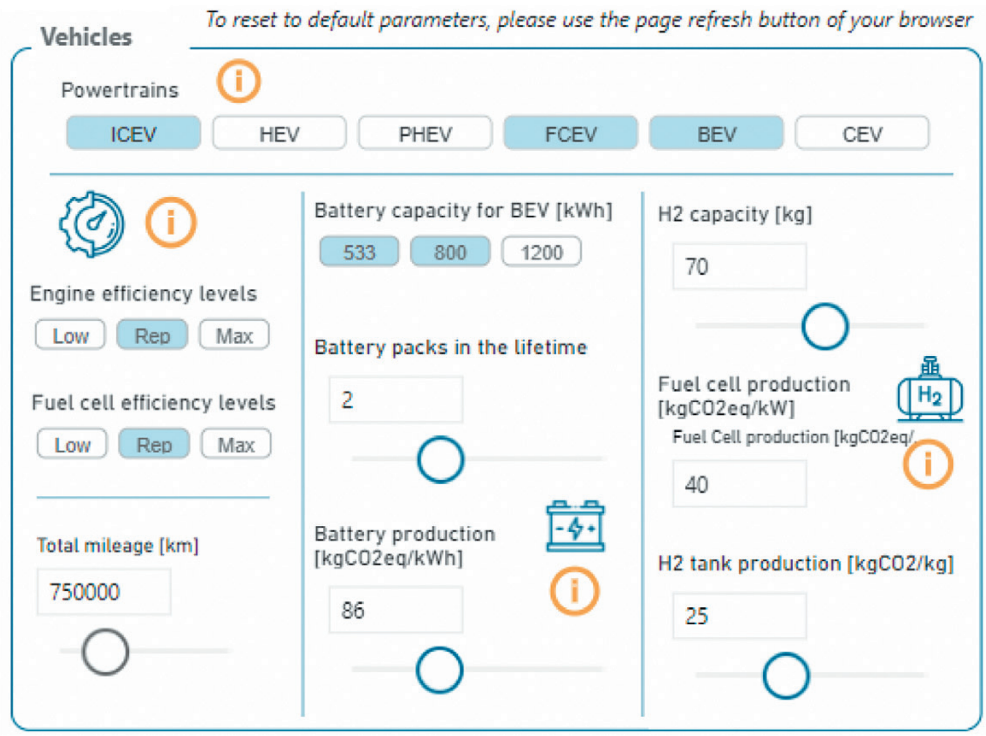
Figure 2: Main user interface of the tool



Vehicle configuration

On the configuration panel found on the right-hand side of the page, the user is presented with options to set up the desired comparison, starting with the vehicle itself (see Figure 3).

Figure 3: Details of the vehicle configuration user interface



Powertrains

Six powertrain options can be selected, and once selected their results appear as a bar chart in the results panel. The choice of powertrain options includes:

ICEV = internal combustion-engine vehicle
HEV = hybrid electric vehicle
PHEV = plug-in hybrid electric vehicle
FCEV = fuel cell electric vehicle
BEV = battery electric vehicle
CEV = catenary electric vehicle

The technical details of the powertrains modelled are shown in Table 1 on page 33. The user can select any number of these options and they will immediately appear on the results panel on the left-hand side.

Table 1: Powertrain sizing details and efficiencies

Powertrain	Energy carrier	Long-haul truck Class 5	Delivery truck Class 2	City bus 12 m	Coach/ interurban bus	Refuse truck
ICE	Diesel	12.8 litres / 400 kW / 46% / 2,700 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / 6 gears
	CNG/LNG	12.9 litres / 340 kW / 36.5% / 2,000 Nm / 12 gears	7.1 litres / 225 kW/ 36% / 1,150 Nm / 12 gears	7.1 litres / 225 kW / 36% / 1,150 Nm / 6 gears	7.1 litres / 225 kW / 36% / 1,150 Nm / 6 gears	7.1 litres / 225 kW / 36% / 1,150 Nm / 6 gears
	H_2	15.2 litres / 410 kW / 44.1% 1,950 Nm / 12 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 12 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 6 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 6 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 6 gears
HEV	Diesel	12.8 litres / 400 kW / 46% / 2,700 Nm / battery 20 kWh / e-motor 150 kW / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 30 kWh / e-motor 100 kW-280 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 20 kWh / e-motor 35 kW-250 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 25 kWh / e-motor 120 kW-800 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 25 kWh / e-motor 120 kW-8,000 Nm / 6 gears
PHEV	Diesel/ electricity	12.8 litres / 400 kW / 46% / 2,700 Nm / battery 130 kWh / e-motor 250 kW-1,100 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 100 kWh / e-motor 250 kW-1,100 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 100 kWh / e-motor 160 kW-400 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 100 kWh / e-motor 250 kW-1,100 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 100 kWh / e-motor 250 kW-1,100Nm / 6 gears
BEV	Electricity	Battery 533 kWh / e-motor 350 kW-2,000 Nm-5 krpm / 2 gears	Battery 400 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Battery 533 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Battery 667 kWh / e-motor 300 kW-1,500 Nm / 2 gears	Battery 400 kWh / e-motor 300 kW-1,500 Nm / 2 gears
FCEV	H_2	Fuel cell 225 kW / 65% / H_2 50 kg / battery 100 kWh / e-motor 350 kW-2,000 Nm-5 krpm / 2 gears	#1: Fuel cell 225 kW / 65% / H_2 30 kg / battery 20 kWh / e-motor 250 kW-1,100 Nm / 2 gears #2*: Fuel cell 75 kW / 65% / H_2 15 kg / battery 100 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Fuel cell 75 kW / 65% / H_2 35 kg / battery 75 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Fuel cell 225 kW / 65% / H_2 35 kg / battery 75 kWh / e-motor 300 kW-1,500 Nm / 2 gears	Fuel cell 75 kW / 65% / H_2 25 kg / battery 75 kWh / e-motor 300 kW-1,500 Nm/ 2 gears
CEV	Electricity	Battery 130 kWh / e-motor 250 kW-1,100 Nm / 12 gears	Battery 100 kWh / e-motor 250 kW-1,100 Nm / 12 gears	Battery 100 kWh / e-motor 160 kW-400 Nm / 6 gears	Battery 100 kWh / e-motor 250 kW-1,100 Nm / 6 gears	Battery 100 kWh / e-motor 250 kW-1,100 Nm / 6 gears

Engine and fuel cell efficiency levels

Engine and fuel cell efficiency data are sourced either from the IFPEN engine database or the generic engine database within the EU VECTO tool (a simulator for HDVs developed by the European Commission).[2] The default setting is 'Representative' which corresponds to the efficiencies in Table 1.

For diesel, gas and H_2 engines, 'Low' and 'Max' correspond to peak efficiencies of 40% and 50%, respectively. For the fuel cell, 'Low' and 'Max' correspond to peak efficiencies of 55% and 70%, respectively.

Battery production (kgCO_2eq/kWh)

Battery production GHG intensity is mostly related to the material extraction and production process. In the tool, the user can set the GHG intensity for the production of 1 kWh of battery capacity. The value can be adjusted here as a user input with the following guideline from literature (users can view the explanation by clicking on the information icon near each parameter):

Given the dynamic nature of the sector, it is relevant to consider technological, geographical and environmental developments in battery production, which may reduce the emission factor over time for this key component. Xu *et al.*[3] built a prospective life-cycle assessment model for lithium-ion battery cell production for various chemistries, production regions and time frames. This work provides emission factor values for current and future battery production in different contexts. A value of 86 kgCO_2/kWh was ultimately set as the default value since current solutions are largely produced in China.

Fuel cell and H_2 tank production (kgCO_2eq/kWh)

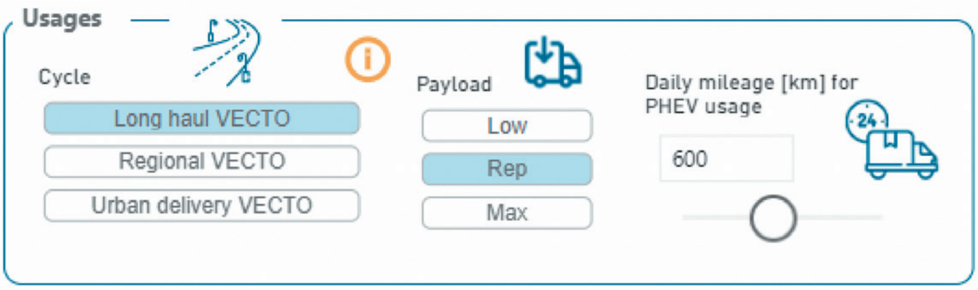
For the fuel cell, a power of 225 W/cell was considered (IFPEN assumption). The fuel cell modelling is based on the studies of Evangelisti[4] and Miotti[5] for bipolar plates. Regarding fuel cell auxiliary equipment, the study by Stropnik[6] was used. For platinum, an Ecoinvent emission factor of 69,500 kgCO_2eq/kg is considered. This leads to an estimated emission factor of 40 kgCO_2eq/kW_fuel_cell for the fuel cell as a whole, which is set as a default value for the corresponding input field.

The amount of H_2 carried in vehicles can be modified. This parameter has an impact on the vehicle's estimated range (visible by hovering the mouse over the results bar chart). It also has an impact on the emissions associated with the carbon fibre tank, whose emission factor can also be modified using a slider (25 kgCO_2eg/kg_tank is set as a default value according to IFPEN LCA modelling). It was assumed that to store 1 kg of H_2, a 26.3 kg tank is needed.

Usage configuration

Once the vehicle parameters are set, the next step is to set the usage parameters with the following options.

Figure 4: Details of the usage configuration user interface



Cycle

VECTO is a new simulation tool developed by the European Commission to determine CO_2 emissions and fuel consumption from HDVs, and the cycles used in VECTO are considered to be the most representative for the purposes of this comparator. For the long haul and delivery truck, three cycles are considered coming from the VECTO database[2]: a 'long-haul' cycle representative of highway driving conditions; a 'regional delivery' cycle including a mix of highway and intercity driving conditions at lower speed; and an 'urban delivery' cycle at a lower average speed for deliveries in cities.

For the city bus two cycles are considered: a medium average speed cycle, 'Urban' from VECTO, as well as a lower average speed cycle representative of very dense urban usage, the 'TfL UIP cycle', proposed by Concawe and courtesy of Transport for London.

For the interurban bus, a medium average speed cycle, 'InterUrban', as well as a higher average speed cycle including highway driving portions, 'Coach', both from the VECTO database, are considered.

Finally, for the refuse truck, a specific cycle including driving displacement and power take-off (PTO) work called 'Municipal Utility PTO' is considered. This cycle is an urban driving cycle with several standstill phases using a PTO cycle consistent with a refuse collecting phase.

Payload

Alongside driving cycles, variations in payload are considered for the vehicle from low to maximum payload. Payload is the weight of goods transported for Class 5 and Class 2 trucks and the refuse truck. For the city bus and interurban coach it corresponds to the number of passengers. Maximum payload is adjusted to stay within the maximum vehicle weight according to the vehicle type. The maximum payload is defined for a conventional ICE configuration, but can be adjusted for other powertrain configurations considering the vehicle curb mass effect of the powertrain (e.g. the battery mass impact for BEVs). 'Low' and 'representative' payloads are taken from the VECTO definitions.

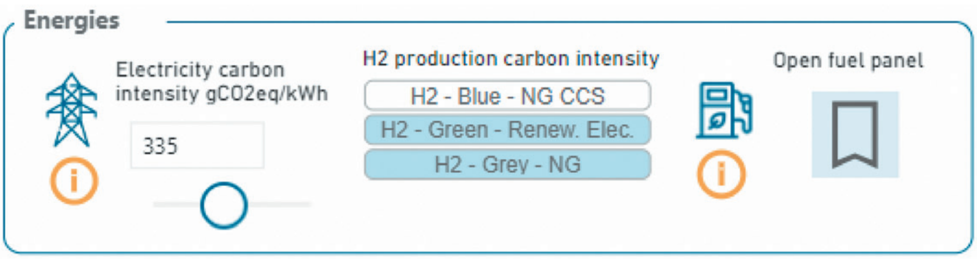
PHEVs fuel calculation

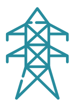
For PHEV consumption, a weighting of ‘charge depleting’ and ‘charge sustaining’ consumption is used. The weighting coefficient is called the ‘utility factor’ and is defined as the ratio between the all-electric range and the vehicle’s daily distance (which can be directly selected by the user), assuming that drivers will recharge their PHEV every night between two driving days.

Energy configuration

The remaining panel is used to select energy parameters (see Figure 5).

Figure 5: Details of the energy configuration user interface



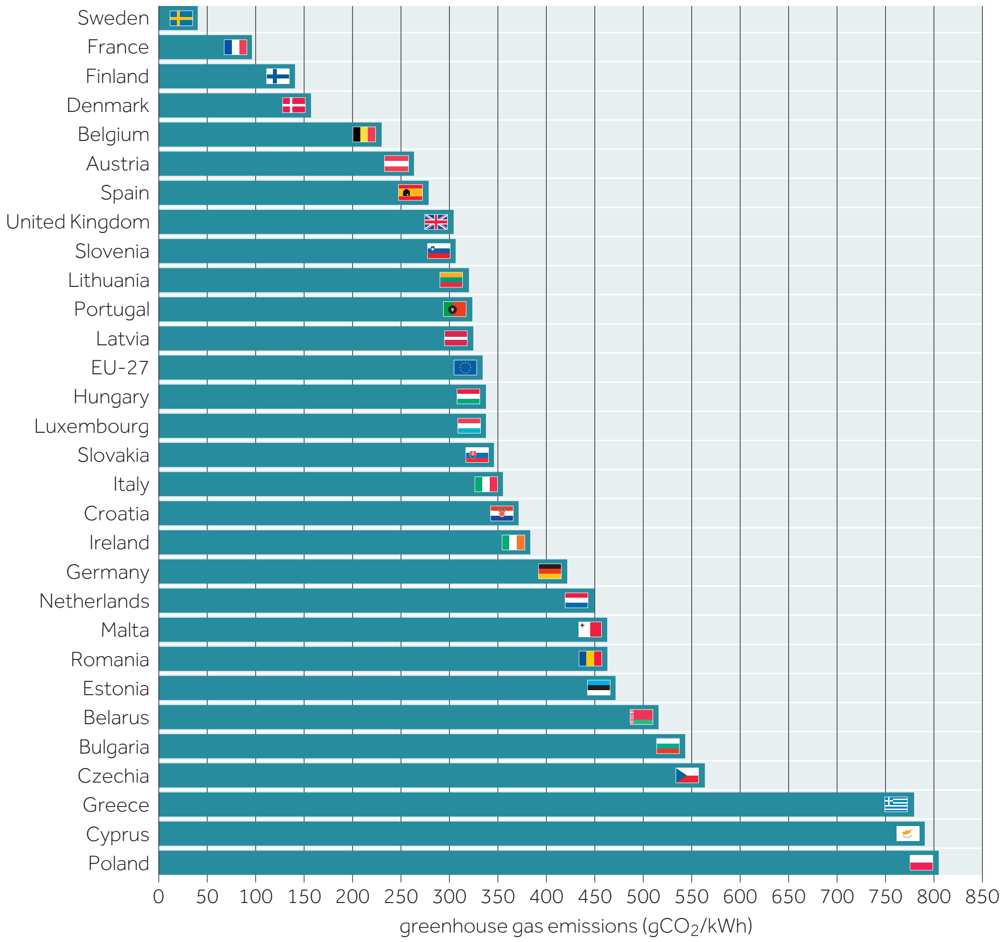


Electricity carbon intensity (gCO_2/kWh)

The user needs to input a value based on where the electricity will be coming from. The GHG intensity of electricity for European countries can be used as a guideline to help users set this value. This key parameter is used to calculate CO_2-equivalent emissions related to the vehicle electricity consumption.

These values are extracted from Scarlat *et al.*,[7] which presents an LCA-based methodology to quantify the produced and the consumed electricity carbon intensities of European countries. The default value chosen for used electricity carbon intensity is the EU-27 average for 2019, which is 334 gCO_2eq/kWh (see Figure 6 on page 37). This is down from approximatively 650 gCO_2/kWh in 1990, and is expected to decrease further in the coming decades. As newer sources become available this will be updated, so users should refer to the orange information icon to see the source used in the current version.

Figure 6: Greenhouse gas emissions intensity of used electricity for 2019 (gCO_2/kWh)



H_2 production carbon intensity

Where hydrogen is considered, the user can choose between three different hydrogen production sources:

- H_2-blue (natural gas reforming coupled with carbon capture and storage (CCS));
- H_2-green (electrolysis using renewable electricity); and
- H_2-grey (natural gas/methane reforming with no CCS).

Fuels

A variety of diesel- and CNG-like fuels can be selected. Fuels selected here are displayed in the results panel.

Table 2: Fuels available for selection in the tool

Diesel-like fuels	CNG-like fuels
B100—EU mix 2017	CNG[g]—fossil EU mix 2017
B100—rapeseed	Compressed biomethane—EU mix 2
B100—UCO[a]	Compressed biomethane—manure
B30—EU mix 2017	Compressed biomethane—municipal
B7—EU mix 2017	Compressed e-methane
B7—EU mix 2017 with 25% HVO[b]	Liquefied biomethane—EU mix 2017
BtL[c] via FT[d]	Liquefied biomethane—manure
BtL via FT and BECCS[e]	Liquefied biomethane—municipal waste
BtL via HTL[f]	Liquefied biomethane—waste wood
e-diesel via FT	Liquefied e-methane
HVO—EU mix 2017	LNG[h]—fossil EU mix 2017
HVO—UCO	

[a] UCO = used cooking oil [b] HVO = hydrotreated vegetable oil [c] BtL = biomass to liquid
[d] FT = Fischer Tropsch [e] BECCS = bioenergy with carbon capture and storage [f] HTL = hydrothermal liquefaction
[g] CNG = compressed natural gas [h] LNG = liquefied natural gas

The primary properties of the fuels considered for the vehicle simulations are provided in Table 3. These properties are specifically related to parameters that have an impact on the energy analysis, including density, lower heating value (LHV) and the air/fuel ratio (AFR). Additional attributes such as carbon content and carbon intensity, pertaining to the production of petroleum fuels, derivatives and renewable fuels, are described in the section on *Life-cycle assessment* on pages 41–46.

Table 3: Primary fuels properties

Fuel	Density (kg/m^3)	LHV (kJ/kg)	AFR
B7	835	42,580	14.39
Gas	0.66	42,700	17.24
H_2	0.08	120,000	34.2

Vehicle simulation methodology

In the vehicle simulation phase of the study, typical figures for the energy consumption of current and future propulsion systems for HDVs were assessed. This part of the study is related to the TTW analysis providing the vehicle energy consumption, a technical definition of the selected HDV and the associated powertrain as the input for the LCA. This focuses on energy consumption and GHG emissions, therefore pollutant emissions were not included in the vehicle simulations. However, GHG contributions from CH_4 and N_2O emissions were factored in. These additional GHG emission contributions were added to the other emissions based on data collected in the literature.

Vehicle simulations aim to estimate the overall energy consumption (kWh/100 km) of HDV vehicles as well as the fuel consumption (l/100 km for liquid fuels and kg/100 km for gaseous fuels) or electrical consumption (kWh/100 km) depending on the considered powertrains.

Five typical categories of HDVs, representative of the European HDV market, were identified in the scope of the study by Concawe members:

- An HDV, also referred to as a long-haul vehicle, with a maximum weight of around 44 tonnes.
- A medium-duty vehicle (MDV), also referred as a delivery truck, with a maximum weight of around 19 tonnes.
- A 12-metre non-articulated city bus.
- An interregional coach (bus).
- A 26-tonne utility truck, also referred to as a refuse truck.

For each of these vehicles, five categories of powertrains were evaluated:

- Conventional powertrain for ICEVs.
- Hybrid electric powertrain for HEVs.
- Plug-in hybrid electric powertrain for PHEVs.
- Hydrogen fuel cell powertrain for FCEVs.
- Battery electric powertrain for BEVs.
- Catenary electric power for CEVs.

Furthermore, four categories of energy carriers were considered:

- Diesel-type fuels (for ICEVs, HEVs and PHEVs): petroleum-based with renewable blend components such as B7, B30 or B7+25% HVO, and renewable diesel-like fuels such as HVO, B100 (100% FAME), e-diesel, BtL, etc.
- Hydrogen (for ICEVs and FCEVs): grey, blue or green.
- Gas (for ICEVs): CNG and LNG, fossil-based, bio-based or e-fuel-based.
- Electricity (for PHEVs and BEVs), with variations in carbon intensity.

Energy consumption figures of the vehicles were evaluated considering vehicle representative cycles depending on vehicle category:

- For the HDV long-haul truck:
  - 'High speed' cycles corresponding to national and international travel.
  - Local/urban trips for last-mile delivery.
- For the MDV delivery truck:
  - 'High speed' cycles corresponding to national and international travel.
  - Local/urban trip for last-mile delivery.
- For the city bus:
  - Urban transport including medium- and low-speed travel.
- For the interregional bus:
  - 'High speed' cycles corresponding to national and international travel.
- For the refuse truck:
  - Local/urban low- and medium-speed trip including garbage collection phases.

A nominal simulation matrix including vehicle categories, powertrain architectures, and the selected energy carrier was considered as a nominal simulation set. In addition, a sensitivity analysis was considered around nominal configurations (default vehicle and powertrain sizing). For the sensitivity analysis, the following parameters were investigated:

- Vehicle payload.
- Vehicle driving cycle.
- ICE peak efficiency (for ICEVs, HEVs and PHEVs).
- Battery capacity (for BEVs).
- Fuel cell efficiency (for FCEVs).
- Charging frequency (for PHEVs).

Note: all the simulations were operated at nominal temperature (20°C) with an ambient start.

Vehicle simulations were developed using Simcenter Amesim™ sketches. First, the simulations were calibrated using the VECTO tool[2] on the 'mainstream' ICEV configurations; this showed a good fit, with a less than 2% difference in fuel consumption on typical driving cycles.

The simulations were then expanded to alternative powertrains (HEV, PHEV, FCEV, BEV). The vehicle configurations (powertrain characteristics, weight, efficiencies, battery capacity, etc.) and their conditions of use (driving cycles, payload) were selected based on a literature review of existing vehicles. The simulation results (energy consumption) were cross-checked with data found in the literature and showed a fairly good consistency considering that the driving cycles used in the literature may vary and are not always described. The vehicle simulations provided an energy consumption (expressed in l/100 km, kg/100 km or kWh/100 km) for each vehicle configuration featuring the combined parameters mentioned above.

This energy consumption is converted to CO_2eq emissions using the emission factors (TTW, WTT and recycled CO_2 contributions) of the different energy carriers (liquids, gases and electricity). Added to that are the non-CO_2 exhaust emissions (i.e. CH_4 and N_2O contributions — powerful GHGs even when emitted in small quantities) and the emissions from manufacturing the vehicle (powertrain, chassis, battery, tank, tyres), giving the life-cycle emissions of the vehicles expressed in gCO_2eq/t.km (where 't' represents tonnes of goods transported).

An in-depth Concawe report on the vehicle simulation details and LCA methodology was published in March 2024.[8]

Life-cycle assessment

The GHG emission factors used in the simulator are summarised below. Three categories of emission factors are considered: fuel emission factors; carbon intensity of the electricity mix; and emission factors associated with vehicle production and recycling (for chassis, tyres and battery).

These emission factors were obtained using LCA methodology. The LCA was performed in accordance with ISO 14040 and 14044 standards. The functional unit is gCO_2eq/t.km, where 't' refers to the payload of the vehicle, not to the total mass of the vehicle.

Fuel emission factors

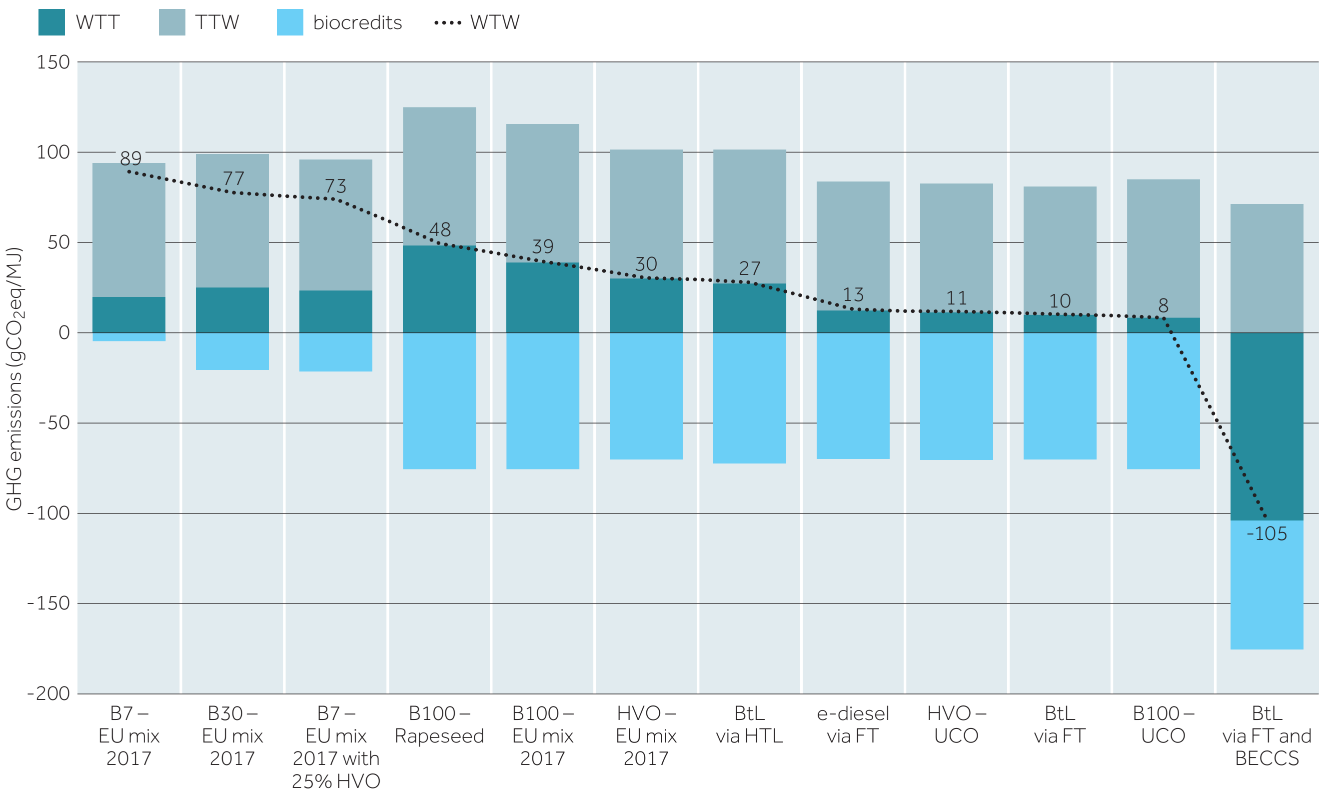
The combustion of fuel generates GHG emissions. However, to assess the life-cycle impact of fuel use, it is also necessary to consider the production and supply phases of the fuel. Therefore, fuel emission factors are generally subdivided in two categories: WTT for the production and supply phases, and TTW for the use phase. The sum of these contributions is the emission factor of the fuel over its entire life cycle, and is usually denoted as WTW.

For some fuels, such as biofuels or e-fuels, CO_2 is captured from the atmosphere to make the fuel. This CO_2 consumption is either absorbed by the plants grown for the biomass used to produce the fuel, or captured directedly from the air (direct air capture, or DAC) or taken from industrial flue gas stacks which would otherwise emit the CO_2 to the atmosphere. This means that some credit (called recycled CO_2) can be applied to the emission factors of these fuels.

Finally, it is sometimes possible to blend different fuels, for example petroleum diesel blended with biodiesel in B7 or B30. Emission factors of such blends can be calculated from the known composition.

Figure 7: Fuel emissions considered in the LCA GHG estimation (gCO_2eg/MJ)

(Shown here for diesel-like fuels. Hydrogen and gaseous fuels are also available in the tool.)



Well-to-tank GHG emitted

'Well to tank' refers to the production, transport, manufacture and distribution of the fuels. This is the scope considered for petroleum-based fuels and biofuels. For further details, please consult the JEC Tank-To-Wheels report v5.[9] For e-fuels (green H_2, e-diesel, e-methane), the emission scope is extended with upstream emissions from infrastructure needed to produce them (mainly solar panels and wind turbines). See the Concawe e-fuels study[10] for further details. It was observed that infrastructure requirements (per unit of energy produced) are significantly higher for e-fuels than for petroleum fuels and biofuels, and could not reasonably be neglected for e-fuels.

Tank-to-wheels GHG emitted

'Tank to wheels' refers to the combustion process within the engine that converts fuel energy into CO_2 emissions. N_2O and CH_4 were added to the total TTW part of the overall LCA GHG results. Based on a literature review, the contribution of N_2O and CH_4 in terms of CO_2-equivalent emissions represents around 6.6% of CO_2 exhaust emissions for diesel fuelled-trucks (essentially from N_2O emissions which are approximately 50 CO_2eq/km[11]) and 2.5% of CO_2 exhaust emissions for CNG fuelled-trucks (essentially from CH_4 emissions which are approximately 500 mg/kWh).[12] For ICE-H_2 fuelled-trucks, it is assumed that the after-treatment system and the N_2O emissions are the same as for diesel-fuelled trucks.

Recycled CO_2

This is the amount of credit related to the CO_2 offset that occurs if CO_2 is consumed during the production of the fuel, resulting in a closed-loop carbon cycle. For example, for biofuels this would be the CO_2 captured by biomass from the air when it grows, or for e-fuels the CO_2 captured from the air via DAC.

Carbon intensity of the electricity mix

BEVs use electricity as the primary energy carrier. Therefore, the GHG emissions per kWh of electricity consumed must be computed to obtain a realistic life-cycle impact of the energy consumption of BEVs. In this study, the carbon intensity of the electricity is set by the user of the web application. Guidelines are given in the tool overview, as shown in Figure 6.

Emission factors due to vehicle production

The GHG emission factors of the various vehicle components: chassis, tyres, battery, fuel cell, electric motor, ICE and tanks are considered and are built into the tool. These emission factors were obtained using the LCA methodology performed in accordance with ISO 14040 and 14044 standards using the commercial LCA software SimaPro®. The database used is Ecoinvent v.3.8. LCA results were obtained using the EF3.0 characterisation method (environmental footprint).

Chassis

For the emission factors related to the production of ICEV (and HEV) chassis, the Ecoinvent data 'Bus production {RER}| producing' has been used and adapted (depending on the types of vehicles). For the interurban bus, the modelling of the chassis is derived from that of the bus (mass difference). Some differences in interior composition were also accounted for, namely the additional steel seats. For the emission factors of the EV and FCEV chassis, a material percentage adjusted in relation to the chassis of ICEVs was considered.

The end-of-life scenario for chassis is modelled from the PE International and Gingko21 report produced for ADEME. Most of the rates provided concerning the proportion of recycling, incineration and landfilling by type of material have been reused. The 2000/53/EC directive of the European Parliament and of the Council relating to end-of-life vehicles (ELVs) has also been followed. An ELV collection rate of 69% was used. The distances from the holder to the demolisher, and then from the demolisher to the crusher, have also been taken into account.

Table 4: Emission factors used for chassis CO_2eq emissions

Application	Chassis emission factor (tCO_2eq/kg)
Class 5	40.1
Class 2	24.4
City bus	33.9
Interurban bus	37.8
Refuse truck	24.4

Tyres

The weight and composition of coach and truck tyres are based on the JRC[3] report, *Environmental Improvement of Passengers Cars (IMPRO-car)*. Tyre life is assumed to be 40,000 km.

The end-of-life scenario for tyres is based in part on a study carried out for ADEME entitled 'Transport and logistics of waste' published in October 2014.

Table 5: Emission factors used for tyre CO_2eq emissions

Application	Chassis emission factor (tCO_2eq/kg)
Class 5	34.0
Class 2	8.4
City bus	10.9
Interurban bus	10.9
Refuse truck	8.4

Powertrain

For the emission factors of thermal and electric motors, the Ecoinvent 'Internal combustion engine, passenger car {GLO}' and 'Electric motor, electric passenger car {GLO}' data were used.

For the fuel cell, a power of 225 W/cell was considered (IFPEN assumption). The fuel cell modelling is based on the studies of Evangelisti[4] and Miotti[5] for bipolar plates. Regarding fuel cell auxiliary equipment, the study by Stropnik[6] was used. For platinum, an emission factor of 69,500 kg CO_2eq/kg is considered ('Ecoinvent: Platinum {GLO}| market for'). This leads to an estimated emission factor of 40.9 kgCO_2eq/kW_fuel_cell for the fuel cell as a whole, that is set a default value for the corresponding slider.

Table 6: Emission factors used for powertrain components CO_2eq emissions

Powertrain	Emission factor ($kgCO_2eq/kg$)
Internal combustion engine	26.6
Electric motor	5.0
Fuel cell	40.9

[3] The European Commission's Joint Research Centre: https://commission.europa.eu/about/departments-and-executive-agencies/joint-research-centre_en

Tank

For diesel tank modelling, 50% steel, low alloy and 50% aluminum, cast alloy was considered.

For hydrogen Type IV tanks, 45% epoxy resin, 55% carbon fibre was considered. This tank can contain a maximum of 5.1 kgH_2 at 700 bar.

Table 7: Emission factors used for tank CO_2eq emissions

Tank type	Tank capacity (kg)	Tank mass, empty (kg)	Emission factor ($kgCO_2eq/kg\_tank$)
Type I — 200 bar	16	93	5.8
Type IV — 500 bar	8	210	22.8
LNG tank steel	115	320	10.0
Diesel steel tank	418	500	3.2

Battery

Battery production GHG intensity is mostly related to the material extraction and production process. In the tool, the user can set the GHG intensity for the production of 1 kWh of battery capacity. In the updated version of the comparator, the battery result is displayed separately and not added to the total vehicle manufacturing result.

Aichberger *et al.*,[13] who analysed 50 publications from the years 2005–2020 about the LCA of lithium-ion batteries, assessed the environmental effects of production, use and end of life for application in electric vehicles. For battery production emissions, the median value was 120 $kgCO_2eq/kWh$.

Given the dynamic nature of the sector, it is relevant to consider technological, geographical and environmental developments in battery production, which may reduce the emission factor over time of this key component. Xu *et al.*[3] built a prospective life cycle assessment model for lithium-ion battery cell production for various chemistries, production regions and time frames. This work provides emission factor values for current and future battery production in different contexts. A value of 86 $kgCO_2/kWh$ was ultimately set as the default value since current solutions are largely produced in China.

Table 8: Emission factors for battery production for different chemistries and regions ($kgCO_2eq$)

	Lithium iron phosphate (LFP)-graphite			Nickel-manganese-cobalt (NMC)-graphite / nickel-cobalt-aluminium (NCA)-graphite		
	China	United States	European Union	China	United States	European Union
2020	69	49.5	39.5	86	65	52
2030	56	40	34	70	52	45
2040	45	32	28	58	42	37
2050	34	24	19.5	44	32	27

(86 $kgCO_2/kWh$ is set as the default value in the interactive tool for current solutions.)

The energy density chosen for the batteries in the LCA tool to calculate the weight of the battery pack system is 200 Wh/kg.[13] It is assumed that the operational battery depth of discharge is 85%. This value is used to calculate the vehicle range shown in the toolbox when hovering the mouse over the bar graph.

The following aspects are not considered in this study:

- Battery production capacity.
- Raw materials availability.
- Externalities generated by mining activities.

Fuel cell and hydrogen tank

The fuel cell is composed of modular packs of 75 kW. From 1 to 3 packs are considered depending on the vehicle category. Three levels of efficiency are considered for the fuel cell: a nominal peak efficiency of 55% (state of the art for the HDV vehicle), a maximum 65% peak efficiency (current state of the art for the LDV) as well as a future 70% peak efficiency (for maximum trend). For fuel cells a 600 W/kg system is considered for the mass estimation, derived from the US Department of Energy (DOE) *Hydrogen and Fuel Cells Program Record* (2020). Hydrogen tank mass impact on vehicle curb mass is also considered with a 60 gH_2/kg density, representative of a Type IV tank (350 or 750 bar).

Conclusion

The interactive digital tool developed from this study is powerful and can provide valuable insights if used correctly as per the guidelines and the deeper understanding outlined in this review.

The use of this LCA tool for HDVs shows that the optimal options for decarbonisation are highly dependent on the use case considered. The best technology and energy options may differ according to the use case, highlighting the importance of technology neutrality when selecting the best option for decarbonisation.

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