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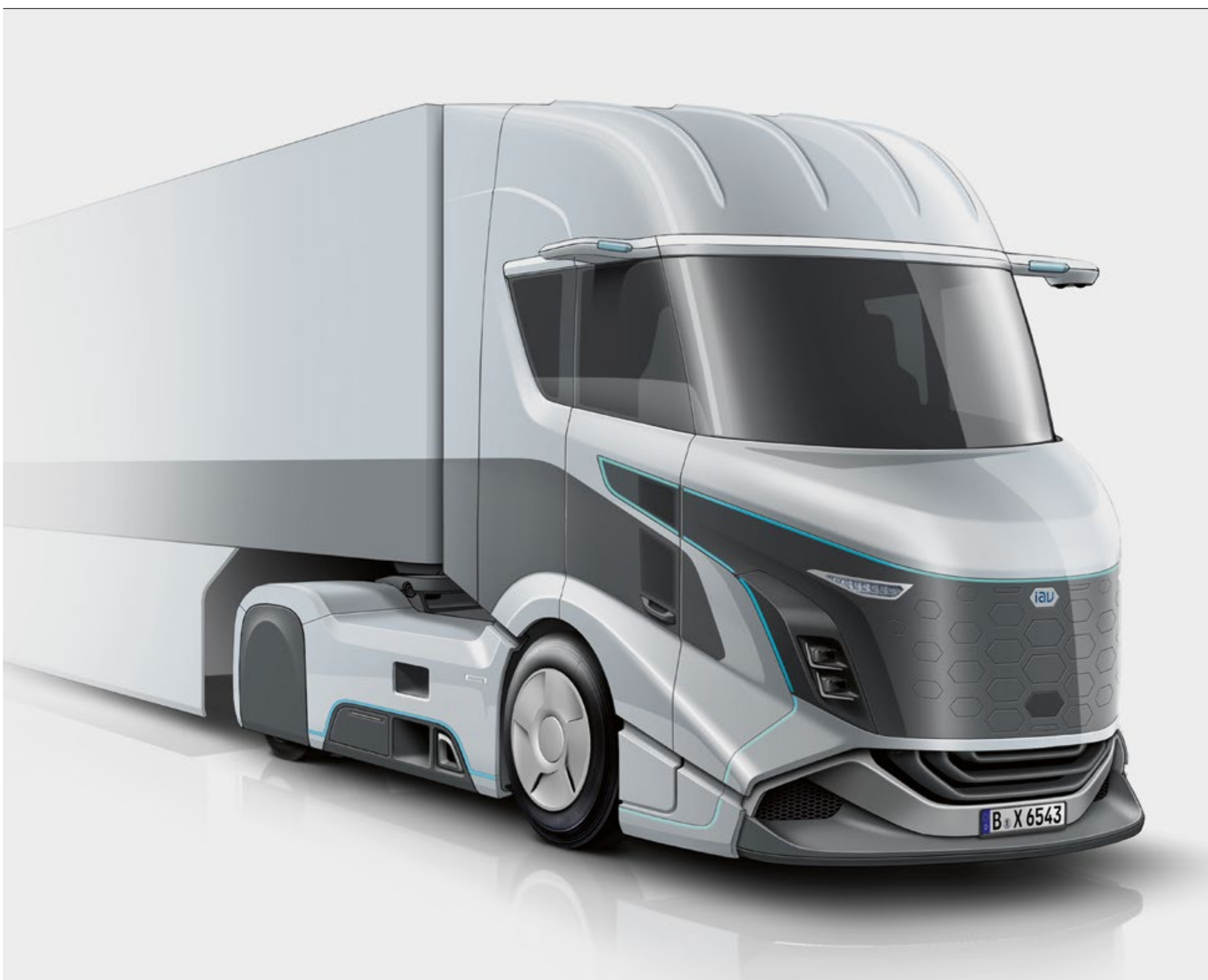
Technical Evaluation and Life Cycle Assessment of Long-haul Heavy Duty Vehicles in 2050

Alternative drive concepts are currently being researched in many places and some are already ready for the market. However, the activities in this area are mainly to be seen in passenger cars. It is not yet clear where heavy-duty trucks are headed. The University of Stuttgart and IAV, in a research project of the Research Association of Internal Combustion Engines, have investigated the powertrains of future heavy-duty trucks for long-distance transport, which should emit as little CO_2 as possible.



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1 MOTIVATION

The search for low emission vehicle concepts is becoming more and more urgent in light of the current discussion about the emission of greenhouse gases and the continuing growth in freight transport on the roads in the future. In order to be able to make a suitable selection from a large number of possible powertrains for long-haul heavy duty trucks in 2050, five powertrains were selected for a detailed evaluation. Two of them are Plug-in Hybrid Electric Vehicles (PHEV) with combustion engines optimized for synthetic fuels (Fischer-Tropsch Diesel (FTD) and Synthetic Natural Gas (SNG)). The other three vehicles all have an electric powertrain, but with different power supplies. The Battery Electric Vehicle (BEV) draws its power from the battery, while the Catenary Electric Vehicle (CEV) is supplied with electrical energy via an overhead line on the highway. In contrast, the Fuel Cell Electric Vehicle (FCEV) converts chemical energy (hydrogen (H_2)) in a Polymer Electrolyte Membrane (PEM) fuel cell into electrical energy while driving.

2 BOUNDARY CONDITIONS AND TECHNICAL PROPERTIES OF THE POWERTRAINS

Before the detailed investigations, it was necessary to define the framework conditions for the year 2050. The following assumptions were postulated for energy generation and distribution:
- Emissions for the construction of infrastructure are not considered.
- Electricity comes 100 % from renewable sources with 21.8 g CO_2 equivalents/kWh electric energy in the EU and 27.4 g CO_2 equivalents/kWh electric energy in the MENA (Middle East, North Africa) region.
- BEV and CEV obtain renewable energy from the EU, taking into account electricity storage with Power-to-Gas.
- The hydrogen required for FCEV is produced locally in the EU via electrolysis.
- SNG and FTD are produced in the MENA countries using Power-to-X technology.

The following framework conditions were assumed for the vehicle models and their use on the road:
- All vehicles can drive autonomously on level 5 between 6 a.m. and 10 p.m. At other times there is a night driving ban in which refueling and recharging can be done.
- As a typical, multi-day, international long distance route Almería (Spain) – Berlin (Germany) was chosen.
- BEV and FCEV refuel/recharge once during the day, the other vehicles can drive through without stopping.
- Trucks comply with the EMS (European Modular System) standard of 25.25 m length.
- The two trailers are identical for all powertrains and have a transport volume of 140 m³.
- On the basis of assumed emission-free urban zones, all vehicles except FCEV have a minimum purely battery electric range of 100 km.

The battery technology is lithium high-energy nickel-manganese-cobalt (Li-HE-NMC) with solid electrolyte. The cell storage density of 400 Wh/kg or 1200 Wh/l is significantly higher than today's battery cells [1]. Since it was assumed that the state of charge is between 10 and 90 %, the gross storage capacity is 20 % greater than the required net capacity, **TABLE 1**.

Due to the hybridization of the powertrain, the output of the combustion engines was limited to 250 kW. With a maximum brake mean effective pressure of 29 bar, 8 l displacement and four cylinders are sufficient. The maximum efficiency, taking into account reduced friction, optimized combustion process and waste heat recovery, is 55 % for the FTD and 54 % for the SNG combustion engine. On the vehicle side, it was assumed that driving resistances would be significantly lower than at present. A c_W value of 0.35 was assumed for the air drag and a c_R value of 3.5 ‰ for the rolling resistance.

	BEV	CEV	FCEV	SNG-PHEV	FTD-PHEV
Power ICE/FC [kW]	–	–	180	250	250
Power electrical machine [kW]	330	330	330	210	210
Battery gross capacity [kWh]	1238	166	63	166	166
Cruising range [km + electrical km]	864	∞ + 100	864	1536 + 100	1536 + 100
Weight powertrain [t]	4.26	1.44	1.78	3.14	2.81
Curb weight including drive [t]	18.57	15.75	16.09	17.43	17.10
Maximum payload [t]	31.43	34.25	33.91	32.57	32.90

TABLE 1 Technical data of assessed powertrains concepts (© University of Stuttgart)

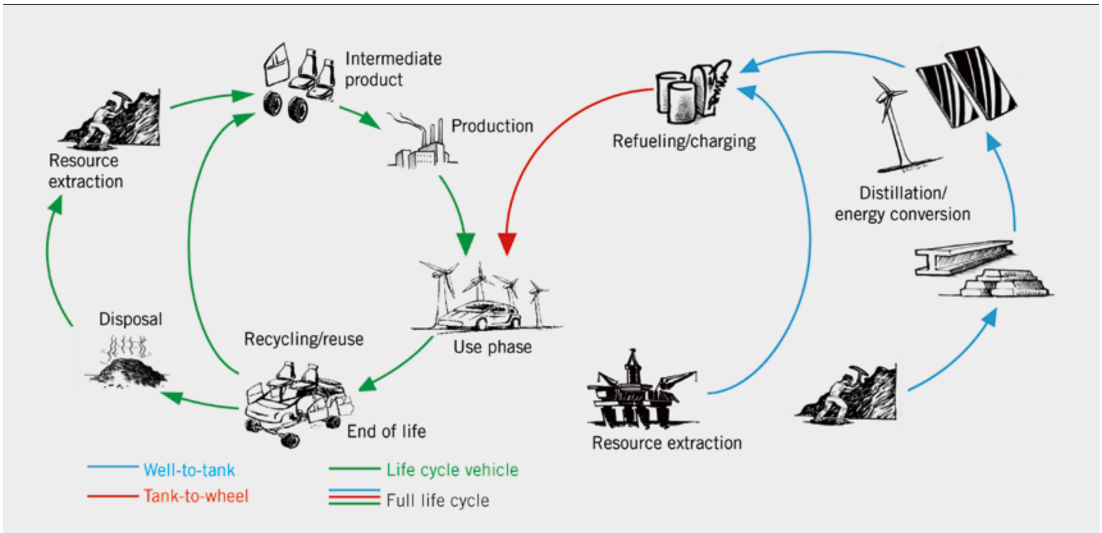

FIGURE 1 Overview well-to-wheel and full life cycle [4] (modified) (© University of Stuttgart | Fraunhofer IBP)

All consumption calculations were accomplished with the overall weight of 50 t. The calculation of the payload was based on the implementation of lightweight design measures with materials already used today. On this basis, a weight of 4.75 and 4.95 t was determined for the trailers. Due to the different powertrains, individual curb weights were calculated for the trucks, **TABLE 1**. The CEV has the lightest powertrain as the battery is comparatively small and the electric drive axle weighs less than a combustion engine

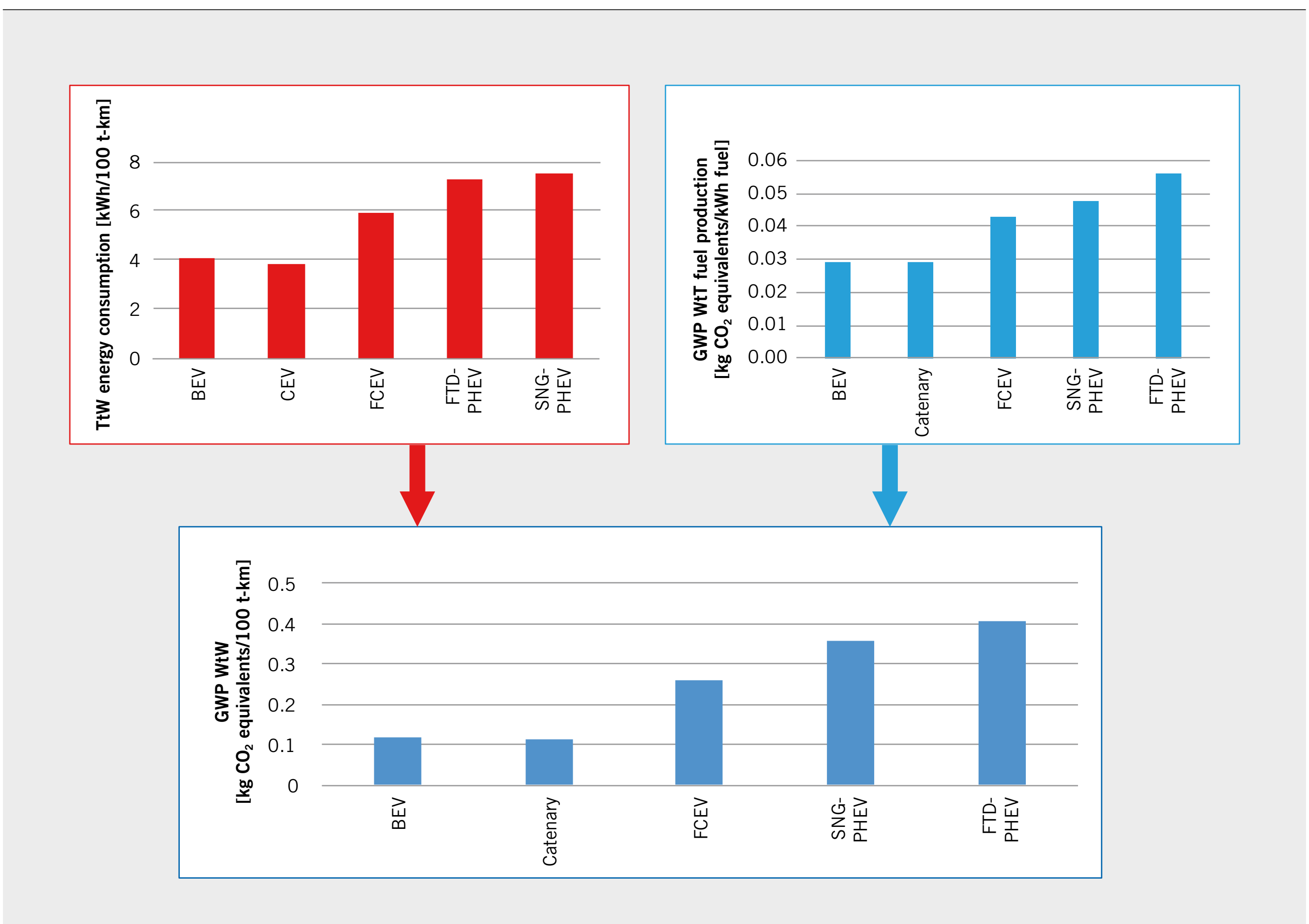

FIGURE 2 Greenhouse gas well-to-wheel evaluation (© University of Stuttgart, Institute for Acoustics and Building Physics)

with gearbox. This also applies to the FCEV, which has an even smaller battery but the fuel cell and 500 bar hydrogen pressure tanks on board. The high weight of the BEV results mainly from the large and heavy battery. This makes it considerably heavier than the two PHEV vehicles with their combustion engines and 4×2 gear box. The higher weight of the SNG-PHEV results from the lower storage density of the liquid SNG and the necessary cryogenic tanks. Despite the differences mentioned above, the payload of all the vehicles examined lies within a relatively narrow scatter band.

3 LIFE CYCLE ASSESSMENT

The life cycle assessment (LCA) was carried out according to ISO 14040 and 14044 [2, 3]. The environmental impacts of the various inputs and outputs are cumulated and considered in relation to 100 ton-kilometers (t-km). In **FIGURE 1** (blue arrows) the Well-to-Tank (WtT) fuel production is shown. For the fossil fuel production, which is not considered for 2050, this includes crude oil/natural gas exploration as well as further processing and transport to the vehicle tank. With e-fuels, it starts with the construction and erection of renewable energy plants, including the necessary raw materials, and continues with water and (if necessary) CO_2 from air to produce the fuels. The next step is Tank-to-Wheel (TtW) shown in **FIGURE 1** (red arrows), which is largely determined by the fuel, respective energy consumption of the vehicles. Furthermore, **FIGURE 1** (green arrows) shows the vehicle life cycle. It also begins with the extraction of raw materials, further processing into intermediate products and vehicle manufacture. The end of life with recycling and landfilling is not considered, as common for life cycle assessments of vehicles [5].

4 RESULTS

4.1 TANK-TO-WHEEL

For the TtW consumption calculation, the driving profile of the Vehicle Energy Consumption calculation TOol (VECTO) long-distance traffic cycle was used several times in a row. The first and last 50 km were simulated in the regional delivery traffic cycle as purely electrically driven. In order to make the different consumption of FTD, SNG, hydrogen and electricity comparable taking into account the different payloads, the consumption was converted into kWh/100 t-km. **FIGURE 2** (upper left diagram) shows that BEV and CEV have the lowest energy consumption due to the high efficiency of the electric motor. The slightly higher consumption of the BEV results from the lowest payload in the comparative field caused by the high battery weight. The FCEV is in between BEV, CEV and PHEV, since the efficiency of the fuel cell and electric motor is somewhat better than that of the hybridized combustion engines. In addition, the FCEV has the second highest payload of the vehicles compared here due to the small battery.

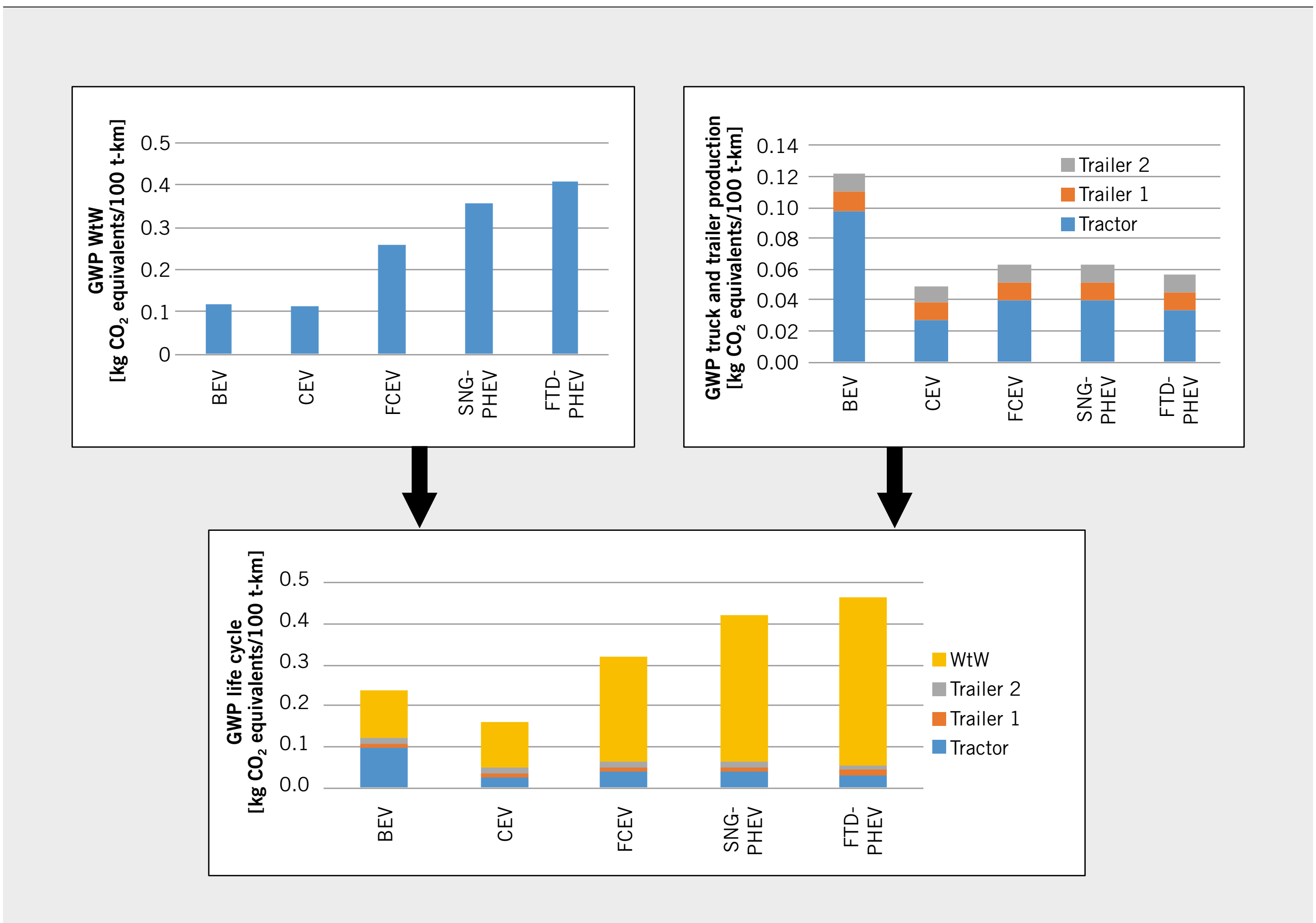

FIGURE 3 Greenhouse gas potential for the whole life cycle (© University of Stuttgart, Institute for Acoustics and Building Physics)

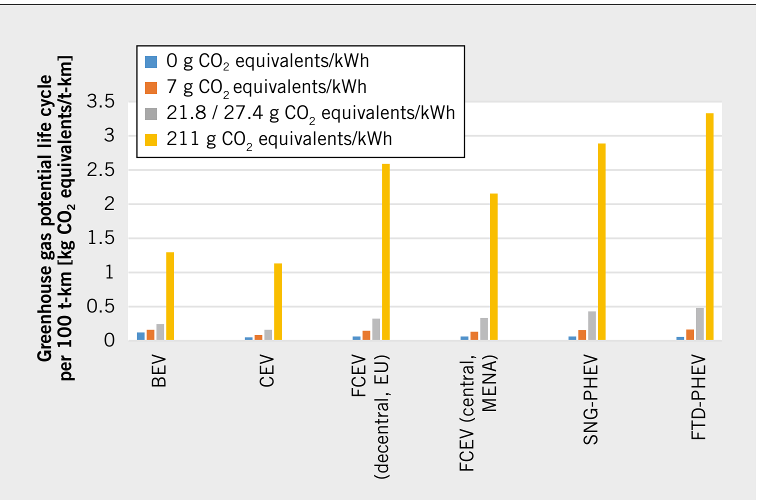

FIGURE 4 Greenhouse gas potential over the life cycle for different energy scenarios (© University of Stuttgart, Institute for Acoustics and Building Physics)

4.2 WELL-TO-WHEEL

The Global Warming Potential (GWP) of WtT fuel production is shown in **FIGURE 2** (upper right diagram). The electricity supply for BEV and CEV is the same. H_2, SNG and FTD differ in the fuel production efficiency and thus in their GWP results. **FIGURE 2** (below) shows the combination of WtT and TtW to a WtW consideration. The low results of BEV and CEV at WtT and TtW are shown in the lowest WtW results. The distance to FCEV, SNG-PHEV and FTD-PHEV has increased compared with TtW analysis.

4.3 LIFE CYCLE RESULTS

FIGURE 3 shows the combination of GWP WtW emissions, **FIGURE 3** (top left), already described in **FIGURE 2** and truck and trailer production, **FIGURE 3** (top right), for the entire life cycle. In order to calculate the results from truck and trailer production per 100 t-km, the detailed GWP results are first calculated vehicle-specifically and then combined with the expected life time of 1.5 million km and the powertrain specific payload, **TABLE 1**. The vehicles are manufactured using renewable energies and future production processes for the materials.

The BEV has the highest emissions in vehicle production, which is mainly due to the largest batteries among the assessed vehicles. For the FCEV the production of the fuel cell and the tanks is relevant, for the SNG-PHEV the cryogenic tanks are also crucial. The CEV has the lowest emissions due to the lightest drive and the lowest technical effort in the vehicle. In the GWP life cycle results, the CEV has the lowest results. BEV emissions increase in comparison to CEV because of the battery production. The FCEV is somewhat in the middle. The SNG-PHEV and FTD-PHEV have the highest GWP results over the whole life cycle.

4.4 ENERGY SCENARIOS FOR THE FUEL PRODUCTION

The influence of fuel production, which can be seen in the WtW and life cycle results, is mainly due to the CO_2 balance of the electricity supply plants produced with today's electricity mix. Therefore, the GWP of the electricity supply was varied in further scenarios, **FIGURE 4**. On the one hand, a conservative "business as usual" scenario of the EU is presented in which fossil energy is still used in 2050, resulting in 211 g CO_2 equivalents/kWh electricity [6]. On the other hand, it was calculated to which GHG threshold (break-even) the electricity supply would have to fall in order for vehicles running on e-fuels to have the same life cycle GHG emissions as the BEV:

- break-even BEV versus FCEV: 10 g CO_2 equivalents/kWh electricity supply (above BEV is better, below FCEV)
- break-even BEV versus SNG-PHEV: 8 g CO_2 equivalents/kWh electricity supply (above BEV is better, below SNG-PHEV)
- break-even BEV versus FTD-PHEV: 7 g CO_2 equivalents/kWh electricity supply (above BEV is better, below FTD-PHEV).

Compared to the "business as usual" scenario, all other results are much lower and the differences between the powertrains are of minor importance. The use of 100 % renewable electricity is therefore absolutely necessary for a climate-friendly future.

5 SUMMARY AND OUTLOOK

Five different powertrains were evaluated for 2050, taking into account potential further developments within the next decades. Based on the assumption that there will be 100 % renewable energy in 2050, represented by current installations, the CEV has the lowest GWP results followed by the BEV. The FCEV is in the medium range and the combustion engines have the highest GWP values. This ranking remains stable for electricity generation with higher GWP emissions. For a certain, very low threshold, GWP emissions from vehicles with e-fuels are equal to those of a BEV. Generally, the provision with low GWP electricity is crucial.

For a final evaluation of the concepts, it is furthermore necessary to consider not only the costs for vehicle production and energy consumption, but also the GHG balance of future power generation plants and the infrastructure for an overhead line network as well as charging points and second life concepts for batteries. This will be done in a follow-up project.

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