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Potential Powertrain Configurations to Achieve Future CO_2 Goals in 2040

The goal currently being implemented in the EU Parliament of only allowing climate-neutral vehicles on the roads by 2035 is often associated with the conversion of motorized private transport to battery-electric vehicles. In the research project “Antriebsstrang 2040” (FVV No. 1355), which was initiated in 2018, scenarios were investigated at the University of Stuttgart that compare different powertrain architectures with the purely battery-electric drive in passenger cars and light commercial vehicles in terms of greenhouse potential.

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1 RESEARCH

Detailed powertrain simulations and technology assessments were carried out at the Institute of Automotive Engineering Stuttgart (IFS) of the University of Stuttgart. At the Institute for Acoustics and Building Physics (IABP), Department of Life Cycle Engineering (GaBi), which is also part of the university, scenarios for life cycle analyses were evaluated in relation to Global Warming Potential (GWP) and the associated costs from the user's perspective. The analysis covers 57 vehicles in three different type classes: sedan, SUV and heavy-duty vehicle with 7.5 t maximum gross weight.

2 VEHICLE VARIANTS

For this paper, six representative powertrain variants in sedan configuration were selected, whose powertrain configurations are shown schematically in **FIGURE 1** and the associated performance data in **TABLE 1**. Variant (1) is a hybrid vehicle with P0 arrangement (P0 Hybrid Electric Vehicle, P0-HEV). The combustion engine is a gasoline engine with pre-chamber ignition and variable compression ratio. Variant (2) is a P2-HEV. The combustion engine has the same characteristics as in (1) and runs on Compressed Natural Gas (CNG). Variant (3) is a P2 plug-in (P)HEV. Its gasoline engine has a pre-chamber ignition, but without a variable compression ratio. Variant (4) is a serial (S)PHEV. The hydrogen-powered fuel cell system has a maximum system efficiency of 61 % – based on the lower heating value of hydrogen. The fuel is supplied via a pressurized tank at 700 bar. Variant (5) is a serial/parallel (S/P)2 PHEV. The combustion engine is a diesel engine with an injection pressure of 2800 bar and a two-stage Selective Catalytic Reduction (SCR) system. Variant (6) is a Battery Electric Vehicle (BEV).

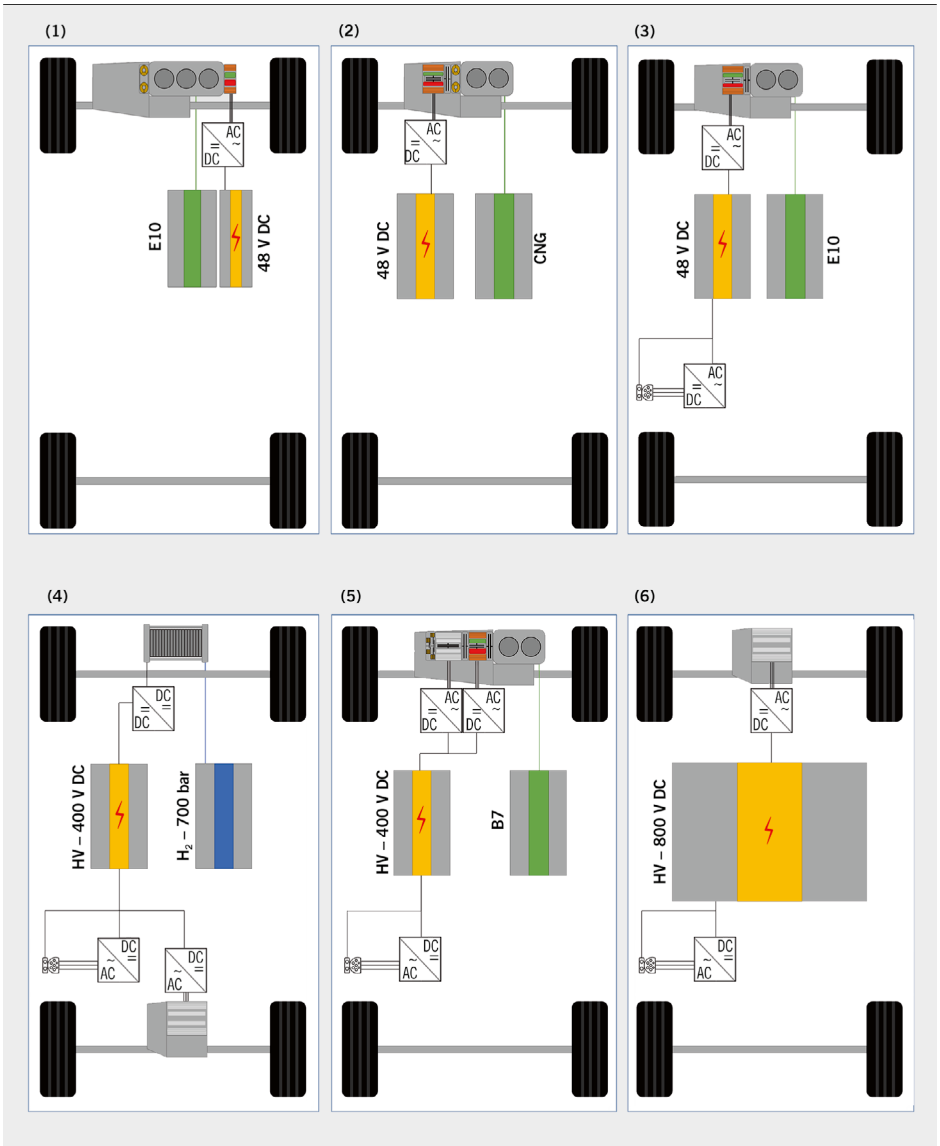

FIGURE 1 Representative powertrain variants: (1) P0-HEV-48-V-E10 (gasoline); (2) P2-HEV-400-V-CNG (natural gas); (3) P2-PHEV-400-V-E10 (gasoline); (4) S-PHEV-400-V-H_2 (fuel cell); (5) S/P2-PHEV-400-V-B7 (diesel); (6) BEV-800-V (© FKFS)

	Units	(1)	(2)	(3)	(4)	(5)	(6)
Power Internal Combustion Engine (ICE)	kW	100	75	60	–	60	–
Electric drive power	kW	12	25	40	100	160	100
Power Fuel Cell (FC) system	kW	–	–	–	60	–	–
Fuel	-	E10	CNG	E10	H_2	B7	–
Battery capacity	kWh	0.5	1.8	16	30	16	140
Mean intermediate circuit voltage	V	48	400	400	400	400	800
Total vehicle mass with driver	kg	1651	1677	1700	1798	1752	2049

TABLE 1 Performance data of the selected powertrain variants (© FKFS)

3 POWERTRAIN SIMULATION

The six powertrain variants are operated with an optimally adjusted version of the Equivalent Consumption Minimization Strategy (ECMS). This shows comparably good results as the optimization generated with the Dynamic Programming (DP) algorithm, but can be configured more flexibly [1]. The powertrain variants are evaluated representatively for two driving cycles: for a highly dynamic Real Driving Emission (RDE) cycle – with operation in Charge-sustaining (CS) mode – and with an urban cycle corresponding to the Worldwide harmonized Light duty Test Cycles (WLTCs) low and medium – with operation in purely electric mode up to the lower charge state limit (Charge-depleting (CD) mode). Fuel consumption and local CO_2 emissions for both driving cycles can be found in **TABLE 2**. The results for local CO_2 emissions show that the PHEVs with Internal Combustion Engine (ICE) (3) and (5) as well as PHEV with fuel cell (FC) (4) and BEV (6) can be operated locally in urban traffic free of CO_2 emissions. Variants (4) and (6) are also locally CO_2 emission-free under all operating conditions. For variants (1) and (3), the fuel consumption in the RDE cycle decreases significantly as the degree of hybridization increases. Variant (2) has low local CO_2 emissions due to the use of CNG as fuel. The diesel engine (5) shows slightly higher CO_2 emissions compared to the gasoline PHEV (3) due to the simpler powertrain architecture and the complex exhaust gas aftertreatment.

4 LIFE CYCLE ASSESSMENT

The Life Cycle Assessment (LCA) part of this study is prepared according to the steps specified in DIN EN ISO 14040 and 14044 [2, 3]. The software GaBi Professional with database version 2021.2 [4] is used for the modeling and CML2001 Version 2016 [5] is used as the characterization method. Greenhouse Gas (GHG) emissions are used as the impact category.

In order to map the GWP of future production processes of both the vehicles themselves and the fuels, two electricity scenarios are applied for the EU region: an optimistic scenario with electricity from photovoltaic plants with a GWP of 5 g CO_2-eq/kWh and a Business as Usual (BAU) scenario with 213 g CO_2-eq/kWh. These energy scenarios are used for the production of the vehicle manufacturing materials most relevant for the GWP. Then the reduction potentials through material production are estimated. For steel production, on the other hand, the GWP reduction potential is estimated on the basis of literature by means of future technological development [6, 7]. The vehicles are modeled on the basis of the material data. The GWP of fuel production is calculated using the two energy scenarios via the energy efficiency factors from the “FVV Fuel Study III” [8]. Only e-fuels obtained from electricity and CO_2 through direct air capture are assumed. In the use phase, a lifetime milage of 200,000 km is assumed.

Variables	Units	(1) HEV		(2) HEV		(3) PHEV (ICE)	
		RDE cycle	City cycle	RDE cycle	City cycle	RDE cycle	RDE cycle
Fuel type	-	E10 gasoline		CNG		E10 gasoline	
Fuel consumption	l/100 km	4.23	3.84	–	–	2.89	0.02
Fuel consumption	kg/100 km	–	–	2.49	1.89	–	–
Electric energy consumption	kWh/100 km	–	–	–	–	0.64	8.43
Local CO_2 emissions	g/km	93	85	68	52	64	0
Variables	**Units**	**(4) PHEV (FC)**		**(5) PHEV (ICE)**		**(6) BEV**	
		RDE cycle	**City cycle**	**RDE cycle**	**City cycle**	**RDE cycle**	**RDE cycle**
Fuel type	-	Hydrogen		B7 diesel fuel		–	
Fuel consumption	l/100 km	–	–	2.96	0.00	–	–
Fuel consumption	kg/100 km	0.52	0.00	–	–	–	–
Electric energy consumption	kWh/100 km	-0.09	9.81	-0.02	7.29	13.44	9.80
Local CO_2 emissions	g/km	0	0	78	0	0	0

TABLE 2 Fuel consumption and local CO_2 emissions of the powertrain variants (© FKFS)

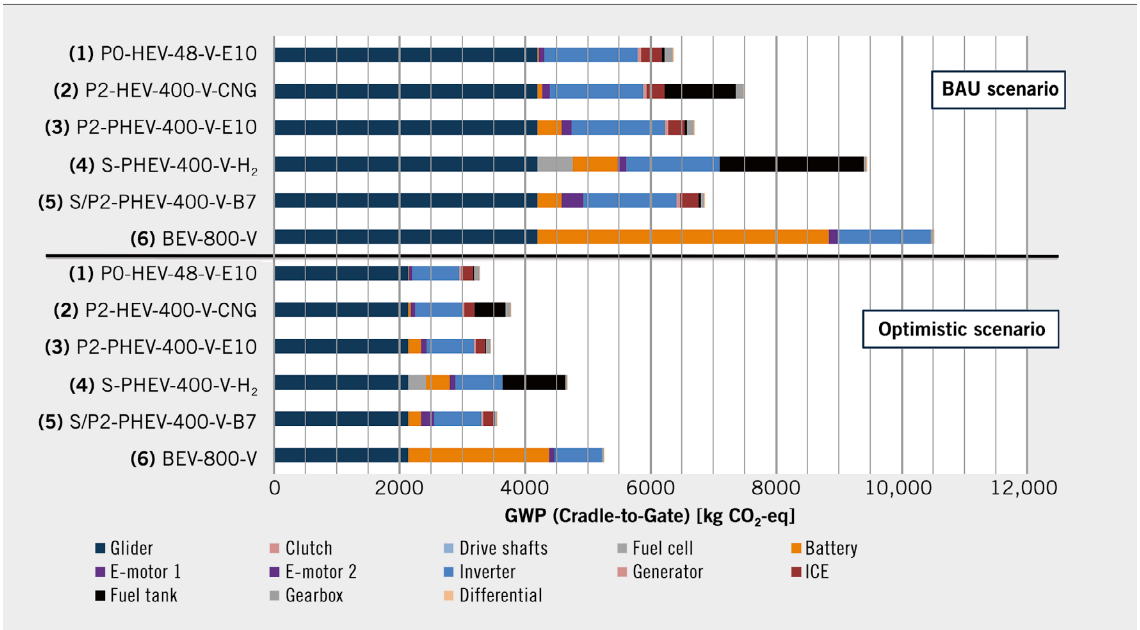

FIGURE 2 GWP in the production of the different vehicle variants in the BAU scenario and the optimistic scenario (© IABP)

FIGURE 2 shows the GWP through the production of all vehicle variants, broken down by the respective vehicle parts. The glider has the largest share of the total GWP, which also has the largest weight share of the total vehicle. Summing up, the highest GWP is for the BEV. It has the highest total weight, with the battery taking the largest share. The fuel tanks of the CNG and hydrogen-powered variants have relatively high shares of the total GWP because they are made of carbon fibers, which in turn are manufactured with high emission levels. The most significant reduction in GWP compared to current values can be achieved with the fuel cell. This can be explained by the high possible reduction in GWP for the platinum mass in the electrodes. In the optimistic scenario, an overall reduction of 50 % in GWP can be seen compared to the BAU scenario.

The analysis from production to use (Cradle-to-Wheel, CtW) for both driving cycles is shown in **FIGURE 3**. The GWP values for the CtW phase simulated in the RDE driving cycle are highest for HEVs (1) and (2) and conventional PHEVs (3) and (5) in the BAU scenario. Due to the energy-efficient fuel production and the high powertrain efficiency, the FCEV and the BEV show the lowest impact per kilometer driven. In the city cycle, the conventional PHEVs (3) and (5) show the lowest GWP. This is due to the small battery and the resulting lower energy consumption during production. In the optimistic scenario, the low GWP in vehicle and fuel production makes the total GWP of HEV (1) and (2) and the conventional PHEVs (3) and (5) significantly lower than for the PHEV (FC) (4) and the BEV (6). In contrast to the BAU scenario, there is hardly any differ-

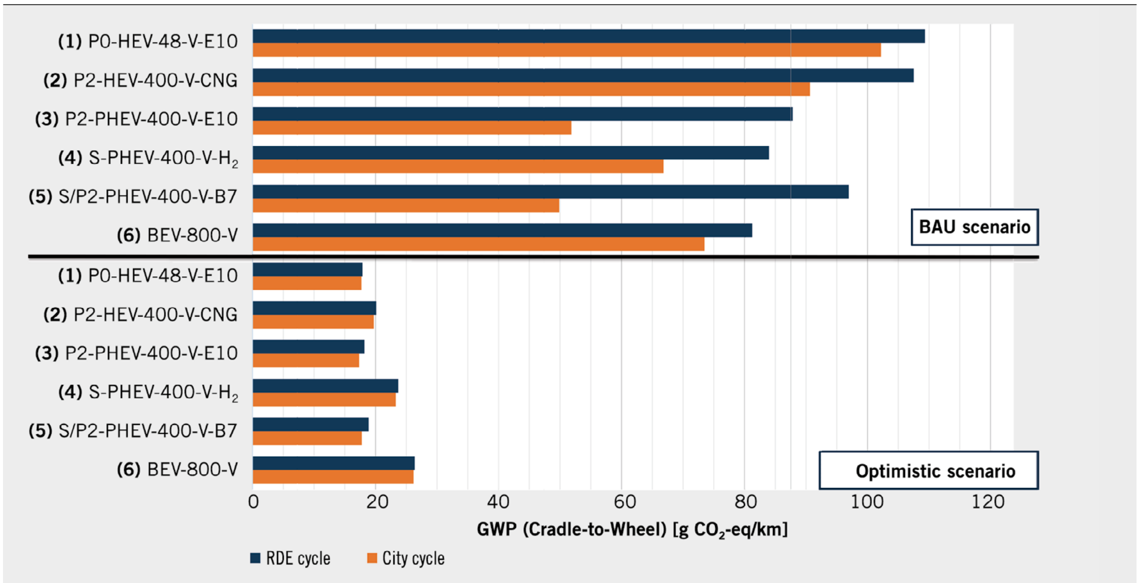

FIGURE 3 CtW results of the vehicle variants for the RDE and city cycle in the BAU scenario and the optimistic scenario (© IABP)

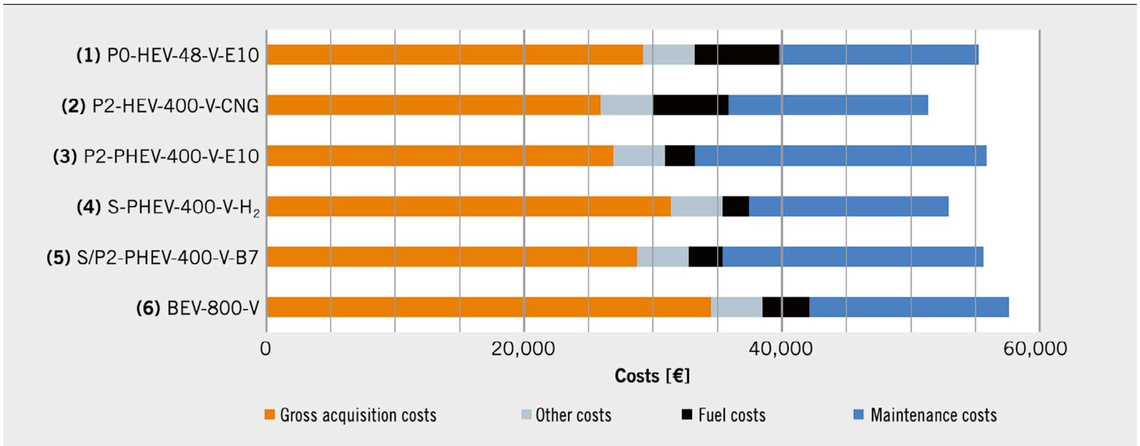

FIGURE 4 TCO results for the vehicle variants (© IABP)

ence in GWP between the two driving cycles for the optimistic scenario, which can be explained by the low electricity GWP.

5 TOTAL COST OF OWNERSHIP

In addition to the GWP associated with technical development forecasts, this study also assesses the economic aspects. For this purpose, the Total Cost of Ownership (TCO) is used for each vehicle variant, as it includes the acquisition costs, the operating and maintenance costs as well as the resale profit including decrease in value. The assumed costs are literature-based. For example, for the acquisition costs, a university study on the cost drivers of different vehicle configurations is used [9] and offset with a depreciation calculation according to Bähr & Fäss Forecasts based on their residual value forecasts for 2019 [10]. For the fuel costs, it should be noted that no taxes or profit margins are included here, as these depend heavily on the (economic) political situation, which is hardly predictable. Therefore, the forecast fuel costs from the current FVV fuel studies are used [8, 11]. For the operating and maintenance costs, current average values from the ADAC are used [12].

FIGURE 4 shows the TCO calculations for the six variants. The total costs are dominated by the gross acquisition costs, while fuel costs account for the smallest share. This is due to the abovementioned lack of inclusion of taxes and margins. Maintenance costs account for the second largest share, especially for the variants that require battery replacement over the total lifetime.

6 SUMMARY

The representative powertrain variants presented show that locally CO_2 emission-free transport is only possible with fuel cells and battery electric vehicles. However, hybridization with external charging offers potential for urban, locally CO_2 emission-free transport. In general, it can be seen that fuel consumption can be reduced with an increasing degree of hybridization and optimized, but thus also more complex, powertrain technology. Globally CO_2 emission-free transport becomes possible with the use of synthetic fuels based on CO_2 from direct air capture, even for powertrain architectures with combustion engines. By using electricity from renewable sources, the GWP profiles of the vehicles can be reduced by 49 to 52 % between the BAU scenario (213 g CO_2-eq/kWh) and the optimistic scenario (5 g CO_2-eq/kWh). The political situation as well as the availability of resources will continue to be decisive for the calculation of the operating costs of the vehicles.

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