Hydrogen Powertrains in Competition to Fossil Fuel based Internal Combustion Engines and Battery Electric Powertrains

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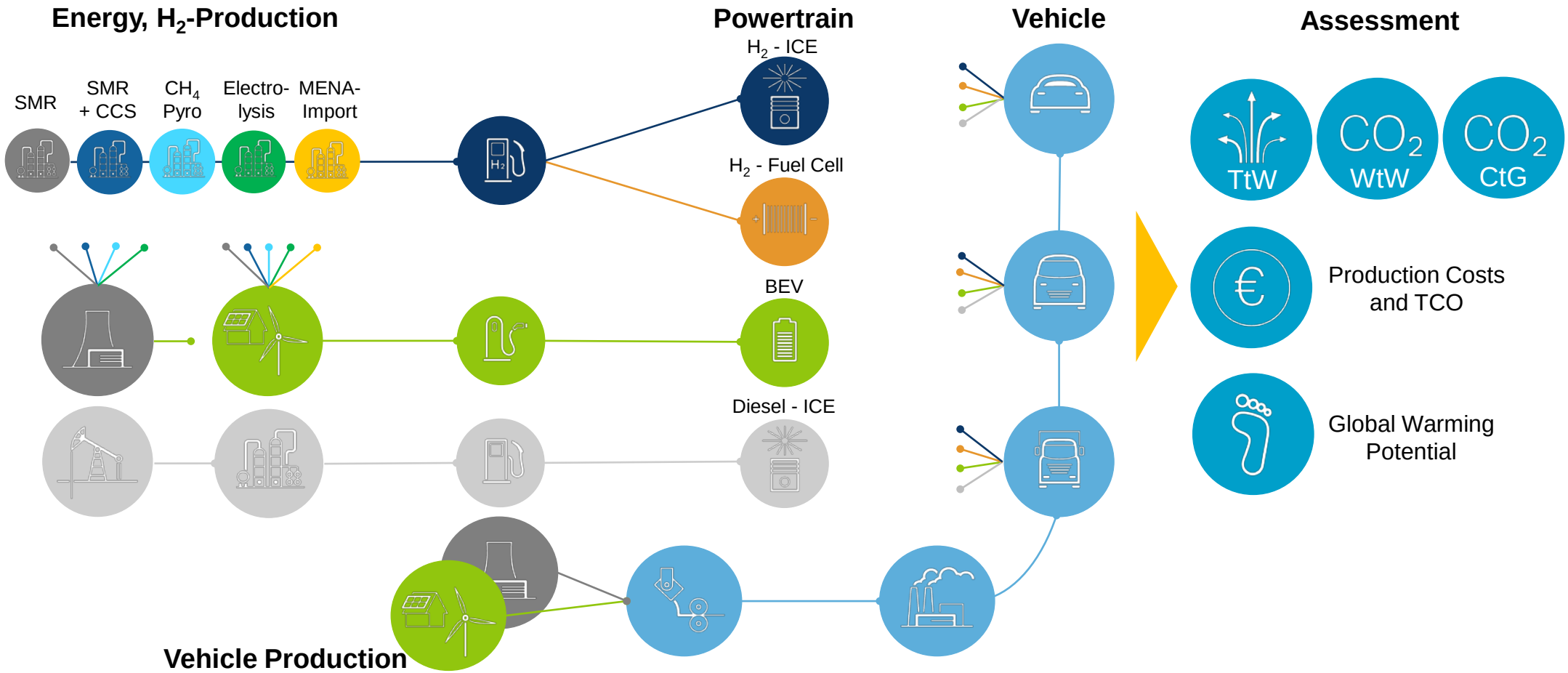
A Techno-Economical Study – LCA based Approach

Procedure and Focus of the Study



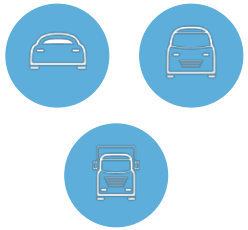
→ Holistic study for understanding the potential of H_2 powertrains on CO_2 and cost over lifetime (TCO) was performed

Techno-Economical Study

Some Important Boundary Conditions

- **Study focus: 2030, Germany**

- **Electricity mix is based on German Umweltbundesamt “Rescue Ee1” Scenario which leads to a electricity footprint of:**
  - **220 g CO_2e/kWh for general electricity**
  - **24 g CO_2e/kWh for renewable electricity (Assumption: 25 % PV / 75 % Wind)**



- **Tank and storage size is scaled on a fixed cruising range for all vehicles and powertrains**
- All powertrain configurations are optimized with focus on minimum consumption by hardware optimization and operating strategies (hybrid and shifting)
- **The fuel consumption values include typical “all season factors” for climatization: ICE = +6 %, Fuel Cell = +7 %, BEV = +26 %**
- Fossil based ICE-references generally considered with Diesel fuel
- TCO boundary conditions are valid for the specific vehicle class
- Assumption for production numbers:
  - PC, LCV: 500,000 units/year for H_2-ICE, FC-Stack, BEV-Battery and Diesel
  - HDV: 10,000 units/year for H_2-ICE, 500,000 units/year for FC-Stack, BEV-Battery and Diesel
- Hybridization or additional energy recuperation system (e.g. WHR) are not considered for the ICE-powertrains
- Charging losses considered for TCO calculation

Techno-Economical Study

Vehicles and Technology

Passenger Car

- SUV segment
- 1.600 kg basic curb weight
- FWD
- **500 km range**
- v_{max}= 180 km/h
- H_2-ICE: 2.0l DI H_2, 90 kW
- FCEV: PEM 1 x 90 kW Stack
- **700 bar CGH_2**
- BEV: 400 V NMC

Light Commercial Vehicle

- Van
- 2.250 kg basic curb weight
- RWD
- **500 km range**
- v_{max}= 170 km/h
- H_2-ICE: 2.0l DI H_2, 130 kW
- FCEV: PEM 2 x 65 kW Stack
- **700 bar CGH_2**
- BEV: 400 V NMC

Heavy Duty Commercial Vehicle

- Long-haul tractor vehicle
- 35 t simulation weight
- RWD
- **800 km range**
- H_2-ICE: 12.5l DI H_2, 310 kW
- FCEV: PEM 2 x 110 kW Stack
- **700 bar CGH_2 / LH_2**
- BEV: 800 V NMC

→ All components of all powertrain types are efficiency-optimized and rightsized on the vehicle performance requirements.

Techno-Economical Study

Results: TtW Potential of H2 Powertrains vs. Diesel ICE and Battery Electric Vehicle

IAV Powertrain Synthesis Process
(Brute Force Approach)

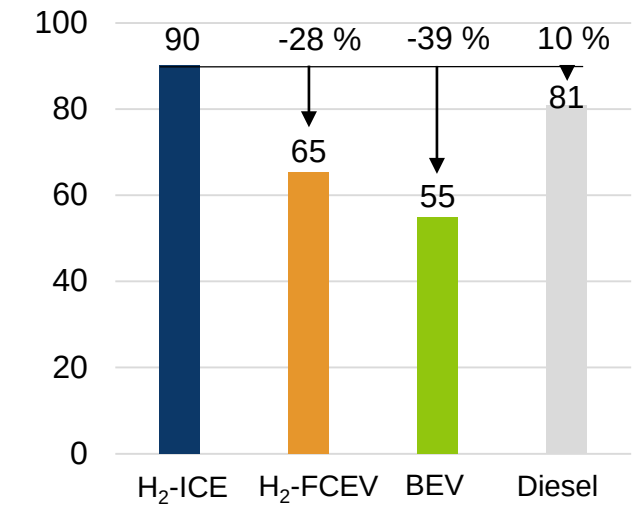
Combination of all component-parameters and maps to powertrain systems

Simulation of all powertrain configurations

Analyzing “Best-Off” solutions with filters and weighting process

Visualization of effect and systematical assessment of alternatives

Vehicle, Range, Cycle	2030	**Light Commercial Vehicle** 2.250 kg basic curb weight, RWD 500 km range, WLTP
Powertrain	**Optimal System Specification**	**Consumption energy for WLTP, TtW [kWh/100km]***
H_2 ICE	**ICE:** H_2-DI, 2.0l 130 kW, 350 Nm, 2-Stage VTG, Max. Efficiency = 45 % **Transmission:** 7-Speed AT 16.50 / 11.93 / 8.63 / 6.24 / 4.51 / 3.26 / 2.36 **Storage System:** 700 bar CGH_2 **/** 13.5 kg H_2	
H_2 FCEV	**Fuel Cell System:** PEM 2x65 kW, Double Stack Max. FC-System Efficiency = 65 % **E-Motor:** 240 kW Peak, 500 Nm Peak **Transmission:** 2-Speed, 21.0 / 10.5 **Battery:** NMC**,** 400 V, 9.25 kWh **Storage System:** 700 bar CGH_2 **/** 9.8 kg H_2	
BEV	**E-Motor:** 170 kW Peak, 450 Nm Peak **Transmission:** 2-Speed, 23.0 / 14.4 **Battery:** NMC**,** 400 V, 302 kWh	
Diesel	**ICE:** DI, 2.0l, 150 kW, 400 Nm **Transmission:** 7-Speed AT	



*Consumption values consider powertrain-individual factors for All-Seasons-Operation: +6% ICE, +7% FC, +26% BEV

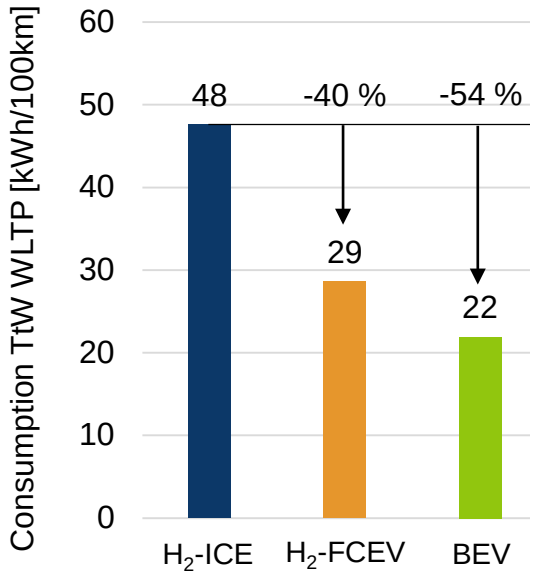
- → H_2-ICE is slighty behind the fossil Diesel ICE – due to better efficiency level of Diesel ICE (even estimated to 2030)
- → Better Fuel Cell efficiency leads to an advantage of FC over H_2-ICE (around 25-30% better)
- → Based on highest energy conversion efficiency BEV is in the lead (suffering from worst all season behavior)

Techno-Economical Study

Results: TtW Fuel Cell Efficiency in all Vehicle always in Advantage over H_2-ICE

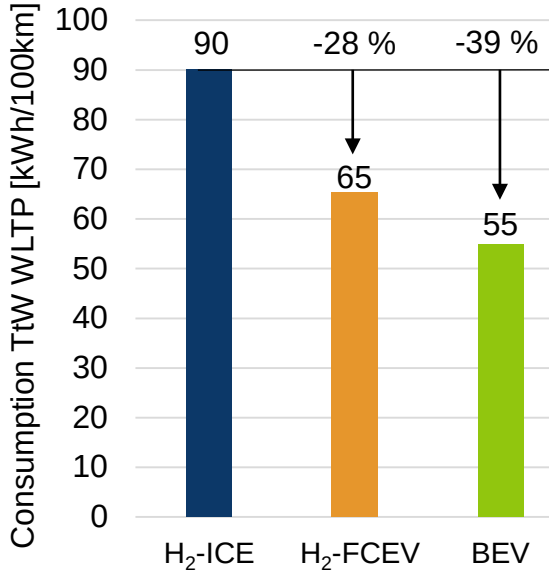
Passenger Car

1.600 kg basic curb weight, FWD
PEM Single Stack 90kW,
500 km range



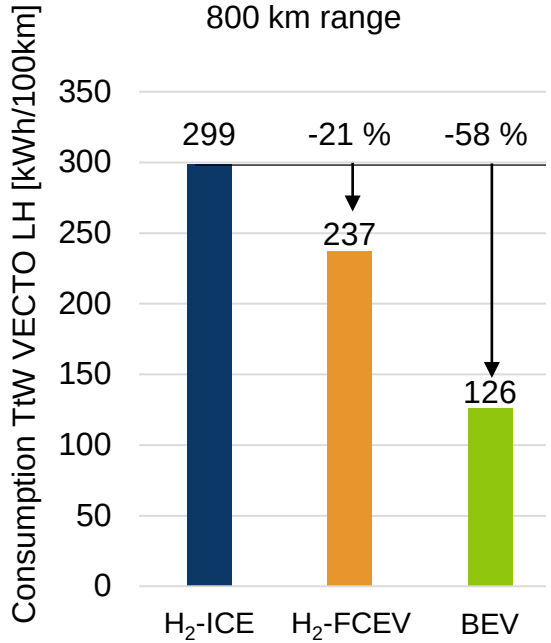
Light Commercial Vehicle

2.250 kg basic curb weight, RWD
PEM Double Stack 2 x 65 kW Stack
500 km range



Heavy Duty Commercial Vehicle

Tractor vehicle, 35 t Simulation mass,
PEM Double Stack 2 x 110 kW
800 km range



- → TtW efficiency of FC in all vehicle classes always in advantage compared to H_2-ICE powertrains and relatively close to BEV
- → As for the heavy CV no all season factors are applied and therefore the BEV is more in advantage over the H_2 powertrains
- → As higher the power demand from the powertrain is, as smaller the advantage of the FC compared to the H_2-ICE is
- → TtW assessment is showing an advantage for the BEV in all vehicle classes
- → However, the H_2-ICE allows further efficiency gains to achieve by introducing other fuel efficiency technologies into powertrain

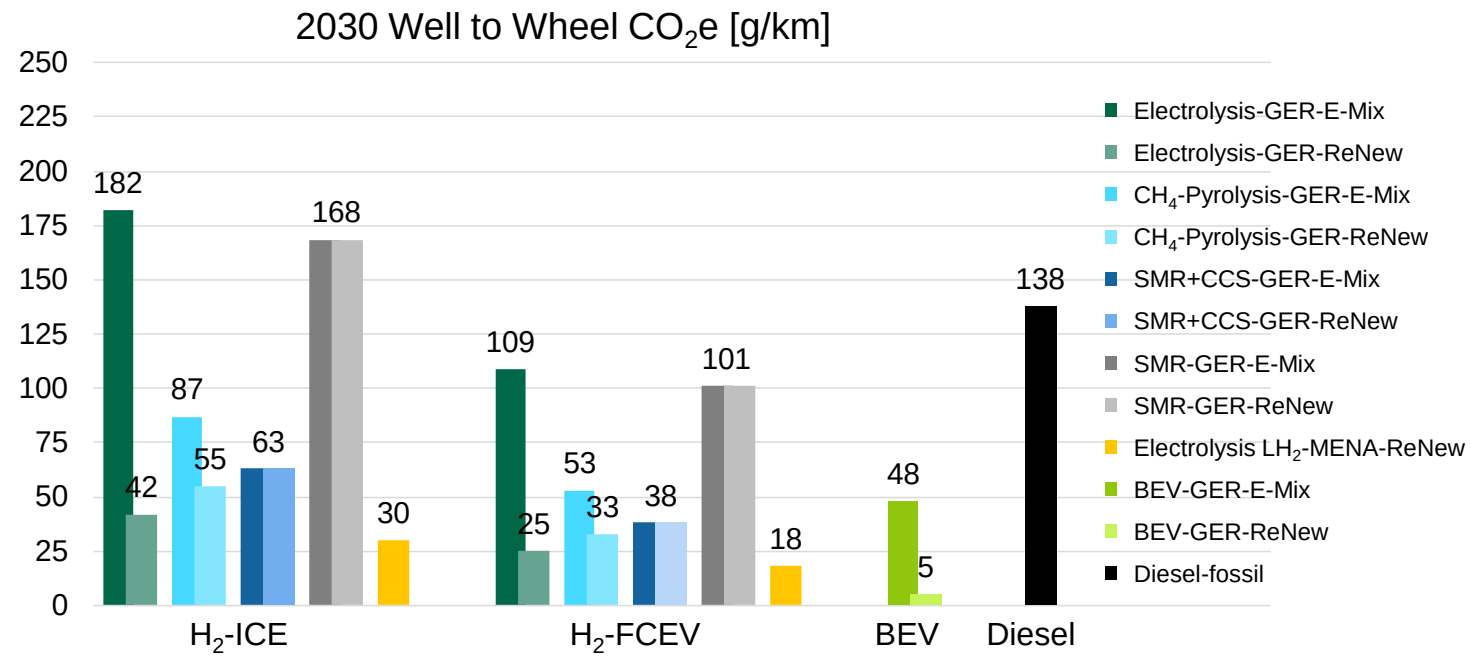
Techno-Economical Study

Results: Impact of Hydrogen Production Path on CO_2 Footprint of H_2 Powertrains (WtW)

SUV Passenger Car

2030 Electricity Mix
220 g CO_2e/kWh

Renewable Mix
24 g CO_2e/kWh

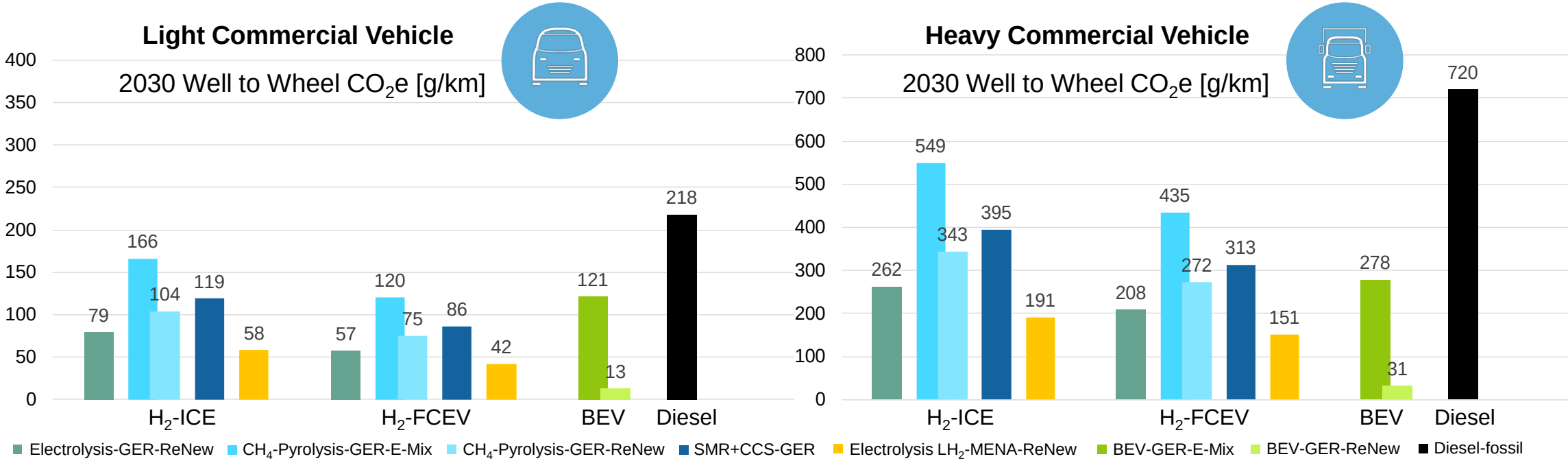


- → Grey and electrolysis based H_2, both produced with 2030`s german electricity mix and used in the ICE is not favourable at all
- → However, when used in a FC it is at least better than the fossil fuel based Diesel ICE and worse than the BEV
- → Blue H_2 (SMR+CCS) in a FC enables WtW CO_2 emissions lower than BEV's operated with the german 2030 electricity mix.
- → Green H_2 produced in Germany or imported from MENA-region and used in Fuel Cell`s or the H2-ICE are in advantage over the BEV with Germany's 2030 electricity mix and very close the the renewable BEV
- → BEV´s are in advantage over all hydrogen concepts for WtW as soon 100 % renewable electricity will be used.

* SMR – Steam Methane Reforming
* CCS – Carbon Capture and Storage
* BEV – Battery Electric Vehicle

Techno-Economical Study

Results: Impact of Hydrogen Production Path on CO_2 Footprint of H_2 Powertrains (WtW)



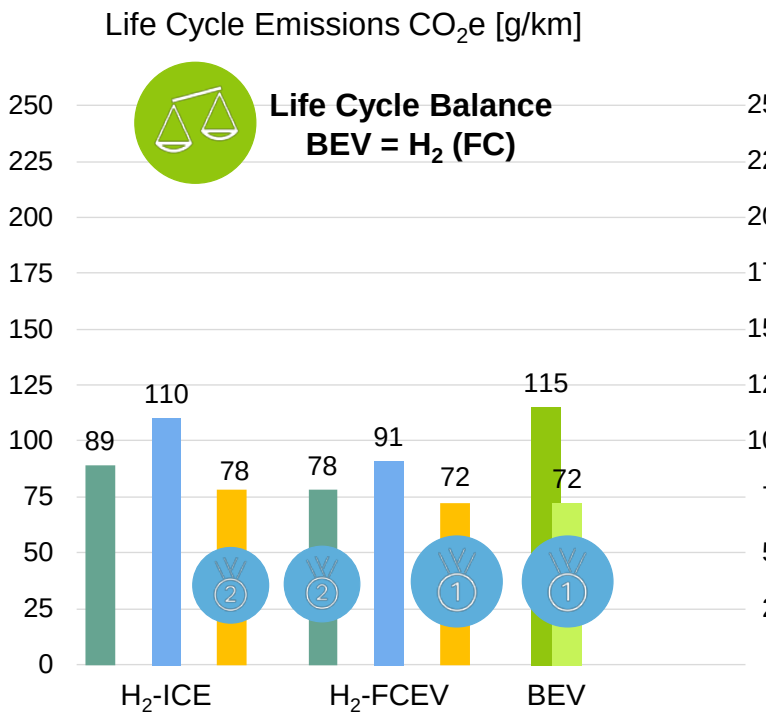
- → LCV: very similar picture as for the passenger car
- → LCV: blue H_2 fueled ICE or FC is more in advantage over BEV operated with Germany's 2030 electricity mix – BEV TtW eff.
- → LCV: turquoise H_2 from Germany's electricity mix is when used in a FC at the same level as the BEV with same electricity mix
- → HDV: BEV with Germany's electricity mix 2030 is in advantage over the blue H_2 fueled FC and ICE – all season factors
- → HDV: green hydrogen with electricity from Germany or imported from MENA enables with both H_2-ICE and FC-powertrains lower WtW CO_2 emissions compared to BEV´s charged with 2030 German electricity mix.
- → Take away: based on a WtW assessement H_2 powertrains are as good as BEV's in contributing to a lower transport CO_2

* SMR – Steam Methane Reforming
* CCS – Carbon Capture and Storage
* BEV – Battery Electric Vehicle

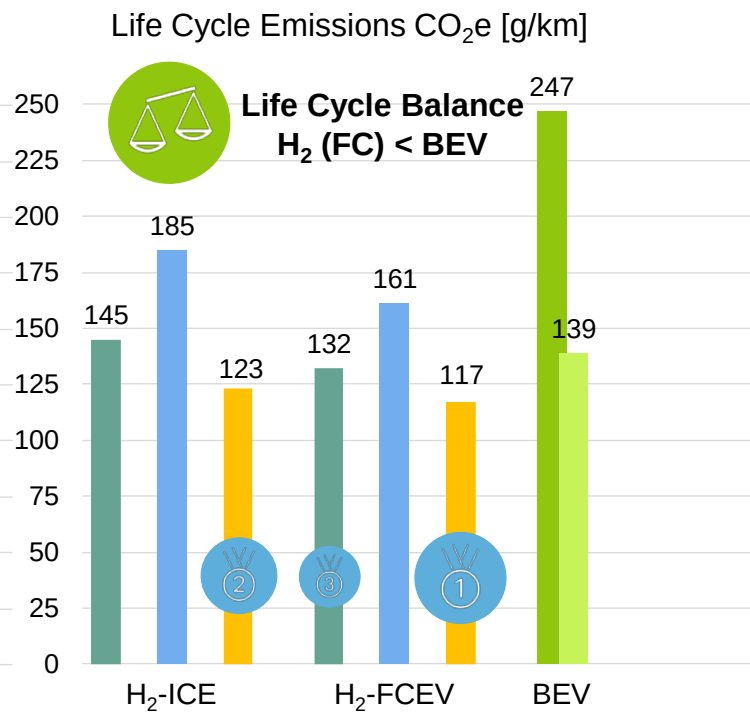
Techno-Economical Study

Results: Break-even of BEV Production Footprint vs. CO_2 Emissions of Hydrogen over Life Cycle (CtG)

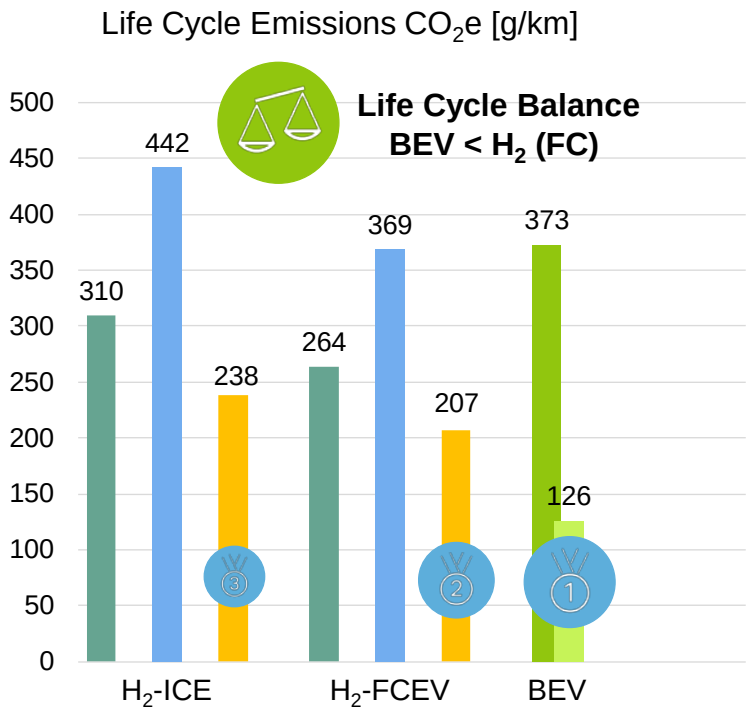
Passenger Car



Light Commercial Vehicle



Heavy Duty Commercial Vehicle



Electrolysis-GER-ReNew | SMR+CCS-GER-ReNew | Electrolysis LH_2-MENA-ReNew | GER-E-Mix | GER-ReNew

- → For PC´s the life cycle emissions of H_2-ICE, FC and BEV are at the same level if all are operated with fully renewable electricity
- → In LCV´s the FC-powertrain is the most sustainable one, H_2-ICE is very close, both have lower CO_2 footprint than the BEV
- → In Heavy Duty Trucks the usage phase with high mileage dominates the life cycle. This leads to an advantage of the BEV´s charged with 100 % renewable energy. So the battery CO_2-backpack of the BEV pays off at the end of life.

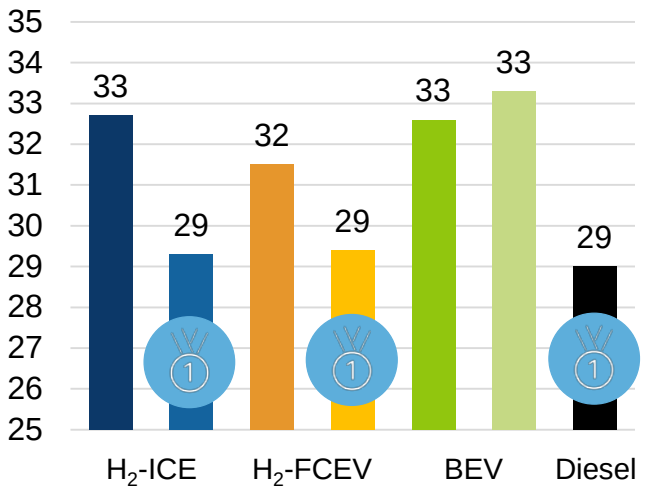
Techno-Economical Study

Results: How TCO-competitive Hydrogen Powertrains are compared to BEV´s and Fossil Diesel

Passenger Car

TCO-Ranking:
H_2-ICE = FC = Diesel

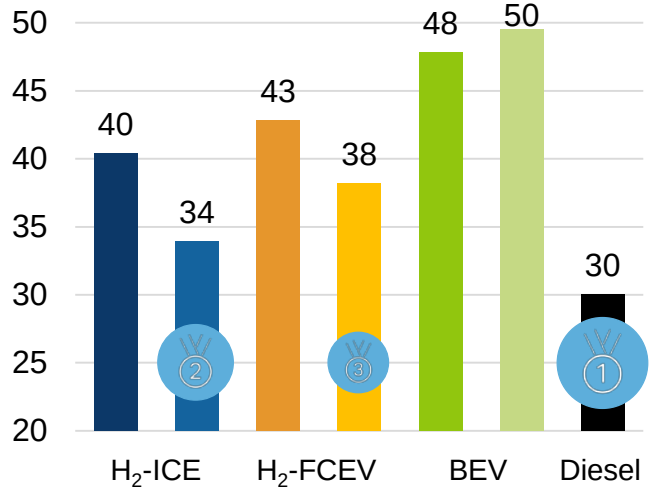
TCO, 160 Tkm, 4 years [€ct/km]



Light Commercial Vehicle

TCO-Ranking:
Diesel < H_2-ICE < FC

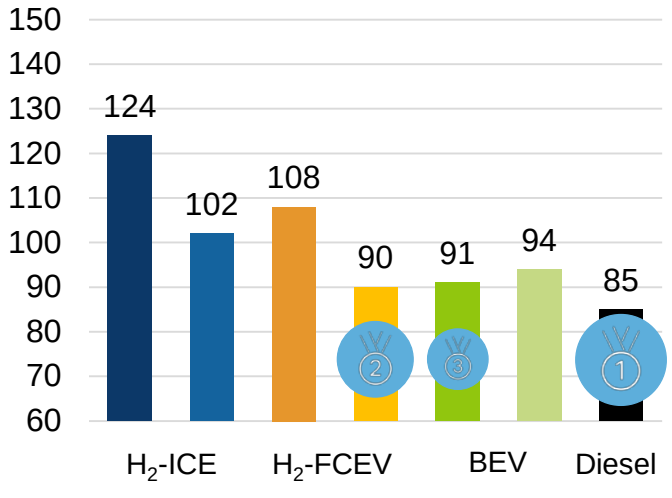
TCO, 400 Tkm, 4 years [€ct/km]



Heavy Duty Commercial Vehicle

TCO-Ranking:
Diesel < FC < BEV

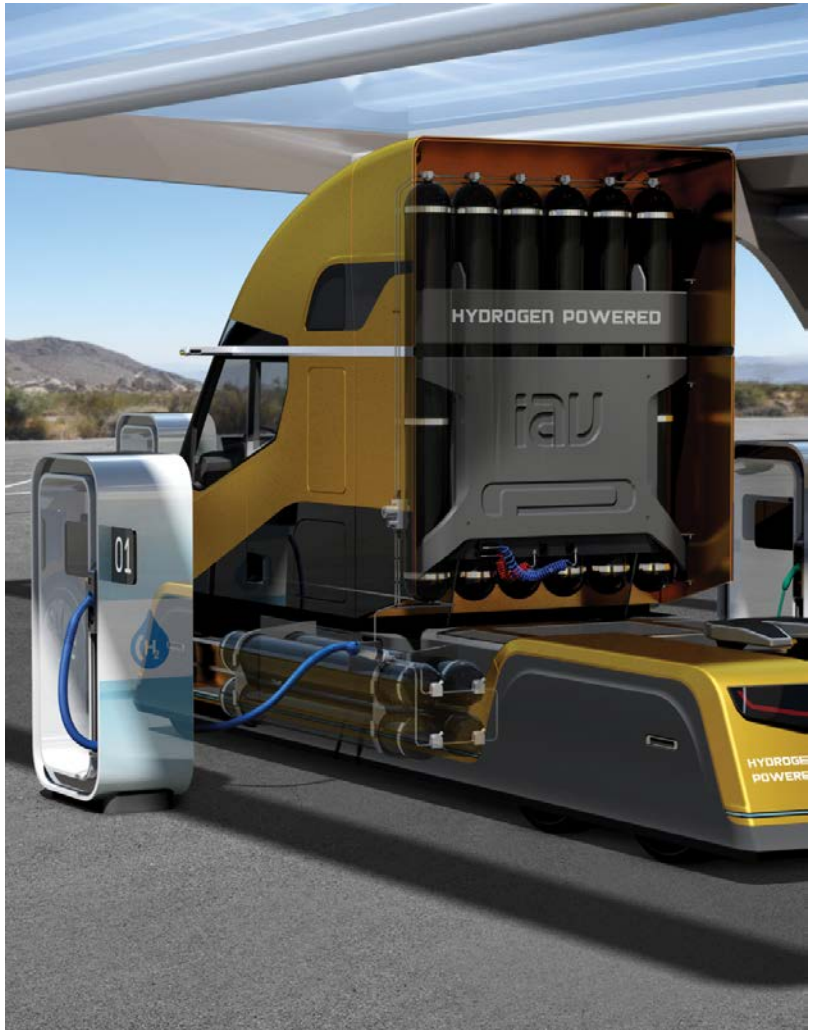
TCO, 600 Tkm, 5 years [€ct/km]



H_2-ICE-Electrolysis-GER | H_2-ICE-Electrolysis-MENA | H_2-FCEV-Electrolysis-GER | H_2-FCEV-Electrolysis-MENA | BEV-2030-E-Mix | BEV-2030-ReNewable-Mix | Diesel

- → For PC´s the TCO of H2-ICE, FC and Diesel will be on the same level. Depending on the electricity prices in 2030 the BEV-powertrain is also competitive.
- → In LCV´s the ICE powertrains dominates the TCO ranking. H2-ICE will be competitive with Diesel beyond 2030.
- → In Heavy Duty Trucks the low energy consumption of FC and BEV pays off over the high mileage.

For Take Away…LCA is the basis for strategic decision making!



- Hydrogen Powertrains are ecological and economical a meaningful alternative to other zero CO_2 propulsion concepts.
- Fuel cells offer an advantage over battery-electric drives in certain vehicle segments, e.g. commercial vehicles, when looking on WtW or CtG basis
- In a long term scenario the FC is in advantage over the H_2-ICE, however the H_2-ICE is a very interesting short and midterm solution in LCV and HDV applications
- Green hydrogen, produced domestic or imported from i.e. MENA is the goal
- Waiting for sufficient quantities of green hydrogen takes too long
- With blue hydrogen (SMR + CCS) a very shortterm and significant WtW CO_2 reduction potential compared to fossil fuel based propulsion concepts of up to around 70%, depending on the vehicle class, is possible
- To promote the use of hydrogen in powertrains, different, CO_2-free or low-carbon hydrogen production pathways must be enabled, incl. import – let's push for a hydrogen society as well in mobility applications now.
- In order to achieve the highest and quickest possible CO_2 reduction, Hydrogen Powertrains should be definitely considered as a parallel path to battery electrical mobility concepts

For the Authors Team...

…,and in case you want to start a deeper discussion with us!

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