GREENHOUSE GAS EMISSIONS FOR BATTERY ELECTRIC AND FUEL CELL ELECTRIC VEHICLES WITH RANGES OVER 300 KM

Study commissioned by H2 Mobility

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Freiburg, 13.07.2019

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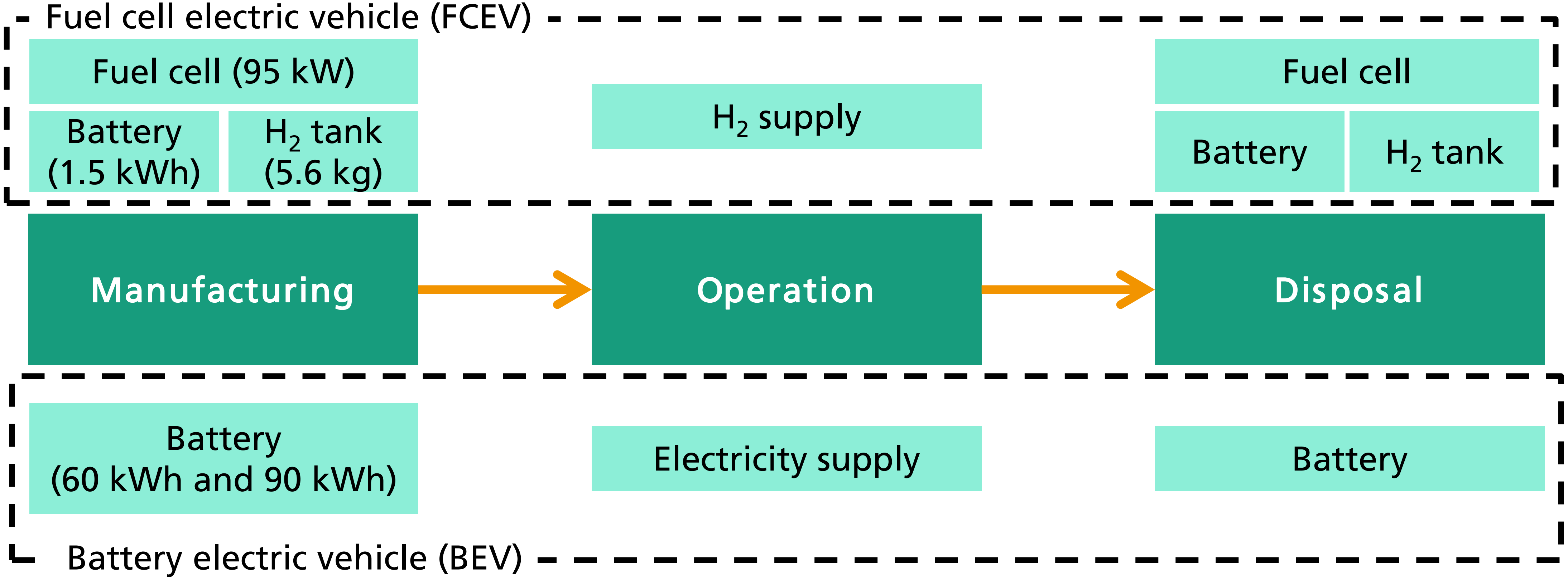
Life cycle analyzed for battery electric vehicle and fuel cell electric vehicle

GHG emissions of vehicle operation for 2020-2030 and 2030-2040



Vehicle type: SUV

Assumptions: all components that are not listed are identical for BEV and FCEV
→ not considered in the first step

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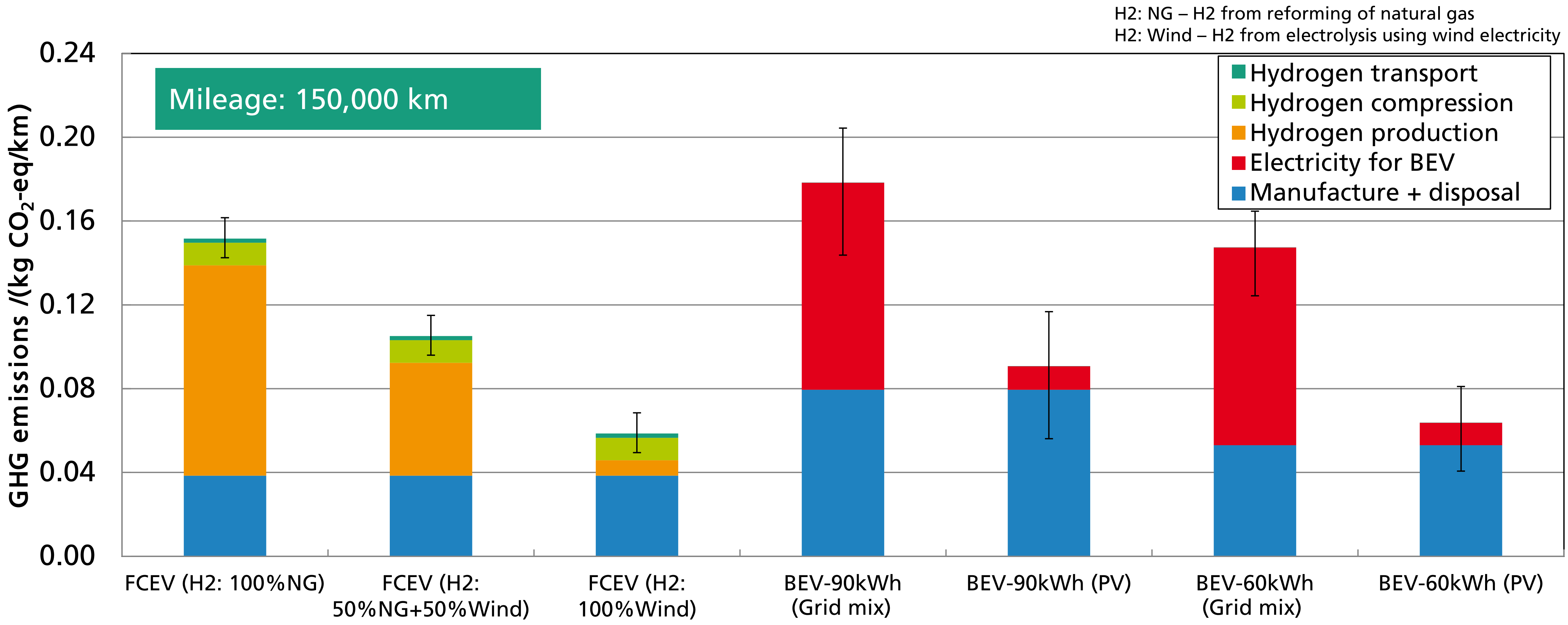
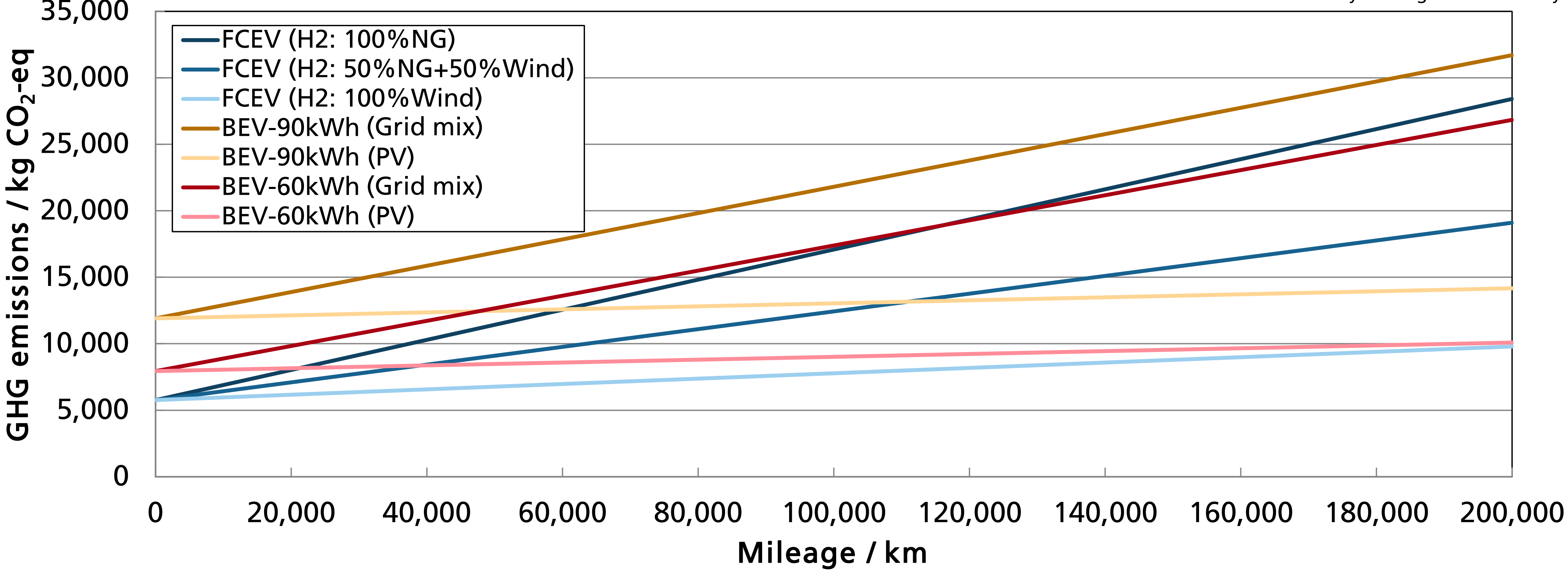
GHG emissions of vehicle operation for 2020-2030 (including manufacture + disposal of battery, fuel cell und H_2 tank)



GHG emissions for manufacture + disposal for base case 2020, for details see appendix
Range considers best case und worst case for manufacture + disposal in 2020

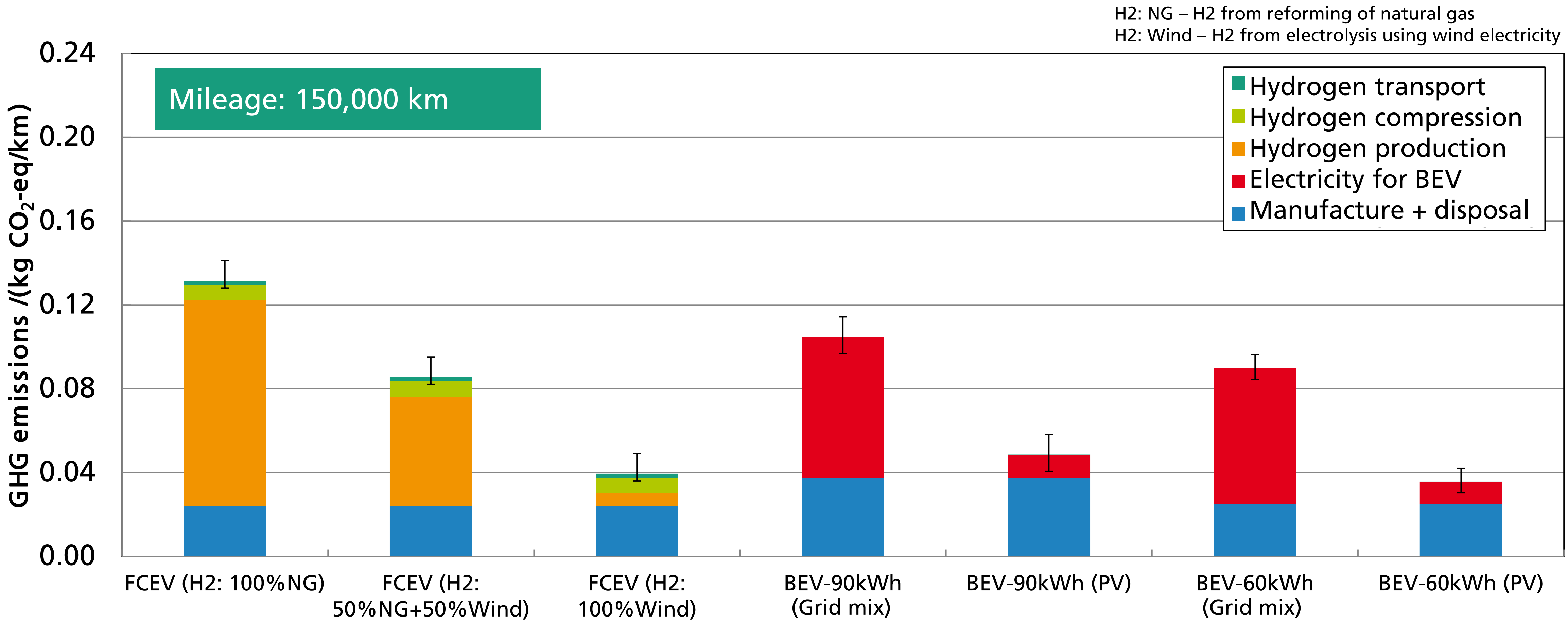
GHG emissions of vehicle operation for 2020-2030 (including manufacture + disposal of battery, fuel cell und H_2 tank)

H2: NG – H2 from reforming of natural gas
H2: Wind – H2 from electrolysis using wind electricity



See appendix for data basis

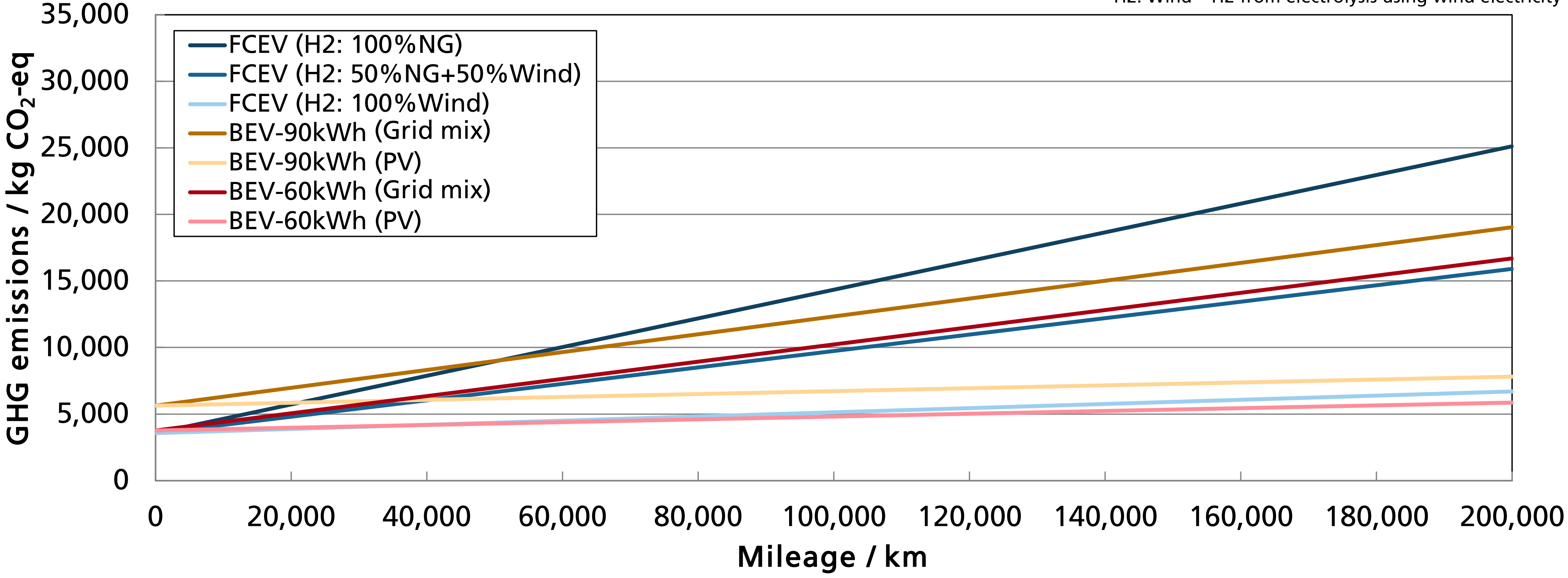
GHG emissions of vehicle operation for 2030-2040 (including manufacture + disposal of battery, fuel cell und H_2 tank)



GHG emissions for manufacture+disposal for base case 2030, for details see appendix
Range considers best case und worst case for manufacture+disposal in 2030

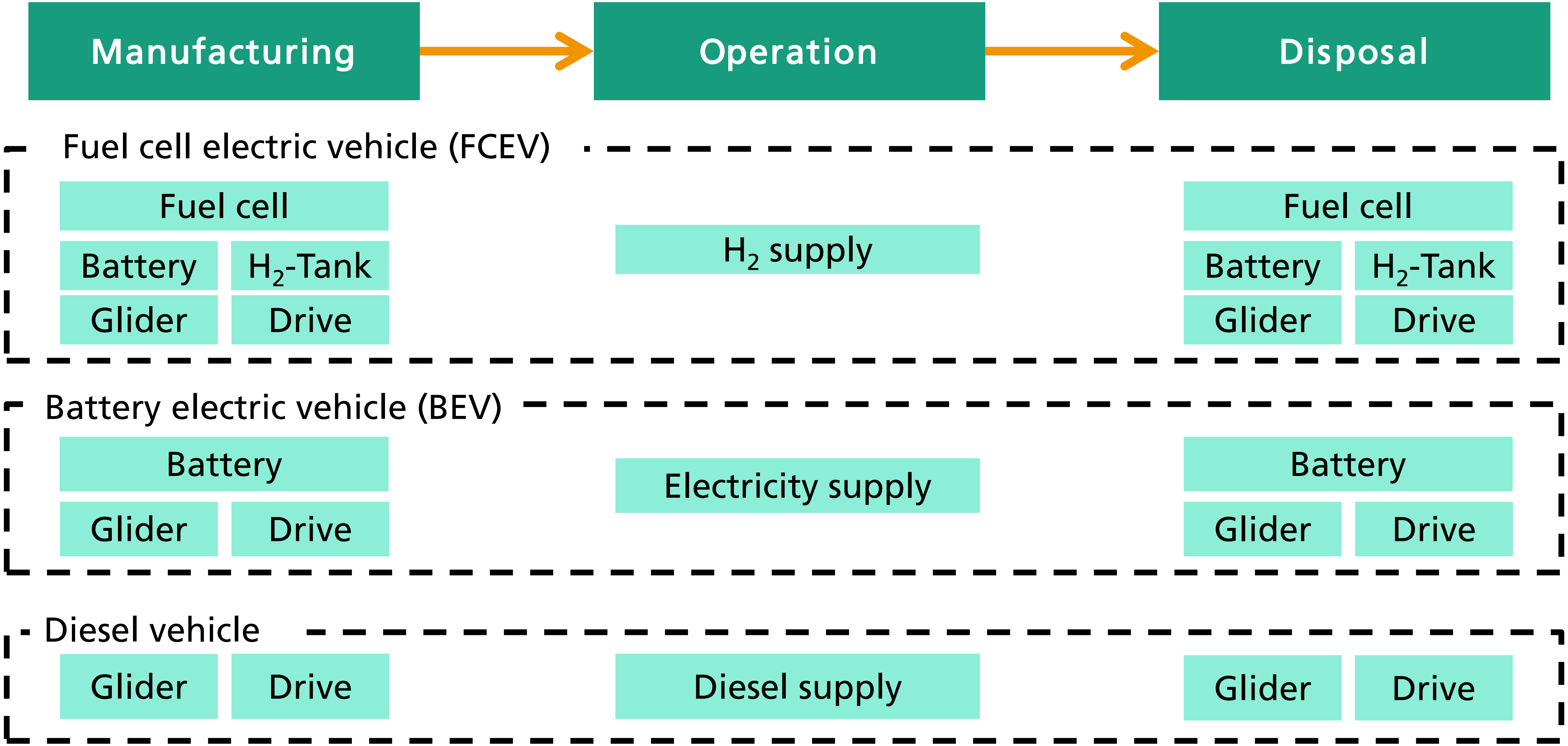
GHG emissions of vehicle operation for 2030-2040 (including manufacture + disposal of battery, fuel cell und H_2 tank)

H2: NG – H2 from reforming of natural gas
H2: Wind – H2 from electrolysis using wind electricity



See appendix for data basis

Comparison with diesel vehicle (100% fossil fuel)

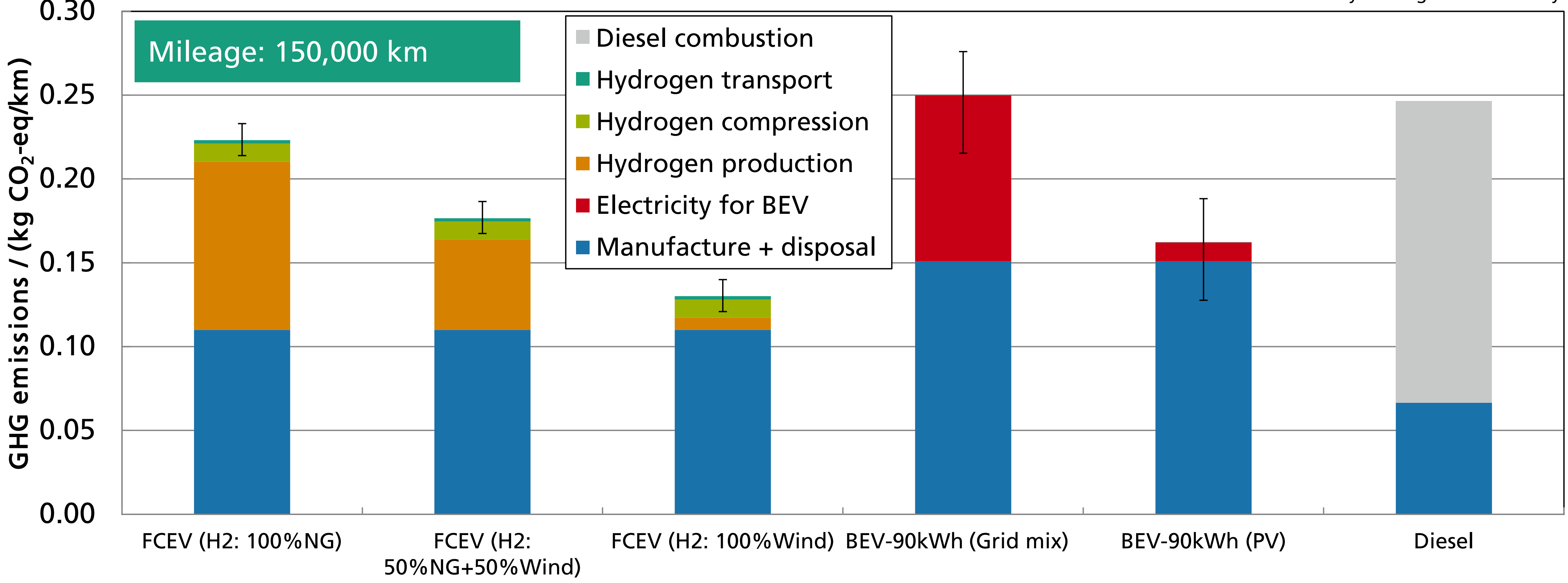


Time horizon: vehicle operation for 2020-2030

Glider and drive (e.g. electric and combustion engine) based on Agora Verkehrswende (2019)
- GHG emissions for manufacturing and disposal scaled by vehicle mass

GHG emissions of vehicle operation for 2020-2030
Comparison with diesel vehicle (100% fossil fuel)

H2: NG – H2 from reforming of natural gas
H2: Wind – H2 from electrolysis using wind electricity



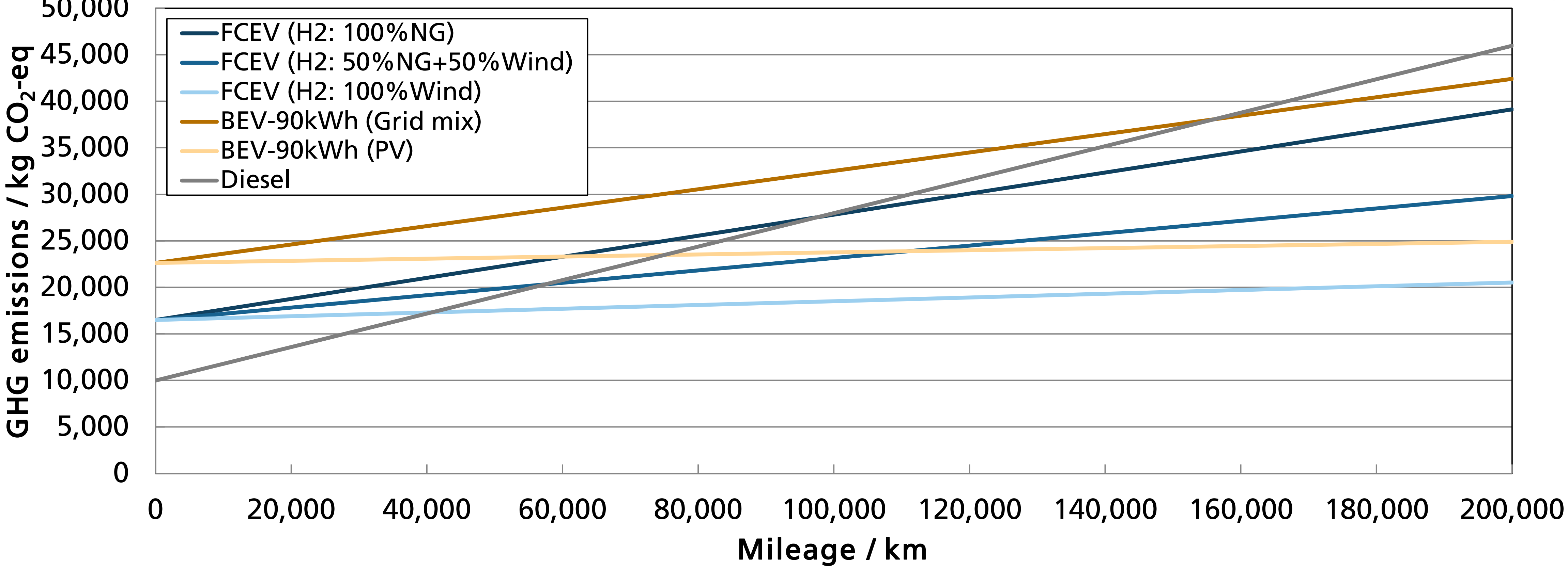
Diesel combustion also includes GHG emissions for diesel supply

Additionally glider and drive considered compared to slide 3

See appendix for data basis

GHG emissions of vehicle operation for 2020-2030
Comparison with diesel vehicle (100% fossil fuel)

H2: NG – H2 from reforming of natural gas
H2: Wind – H2 from electrolysis using wind electricity



Additionally glider and drive considered compared to slide 4

See appendix for data basis

Conclusions

- Manufacturing:
  - Greenhouse gas (GHG) emissions of fuel cell electric vehicles are lower than for considered battery electric vehicles (60 kWh and 90 kWh battery capacity)
    - Crucial factors for battery electric vehicles: Cell production and GHG footprint electricity
    - Crucial factors for fuel cell electric vehicles: Platinum und H_2 tank
- Entire life cycle:
  - Time horizon 2020-2030: lower GHG emissions for fuel cell electric vehicle
    - Higher efficiency of battery electric vehicle cannot offset higher GHG emissions during manufacturing phase
    - Hydrogen supply by wind electricity ➔ Path with lowest GHG emissions
  - Time horizon 2030-2040
    - For similar ranges, fuel cell electric vehicles have lower GHG emissions than battery electric vehicles if both vehicles use renewable electricity
  - Battery electric vehicle with lower battery capacity / range (about < 50 kWh/250 km) have lower GHG emissions than fuel cell electric vehicles

Limitations

- Future improvements in manufacturing process for materials (e.g., platinum and aluminum) were not considered
- Future hydrogen tank concepts could not be considered
- Besides GHG emissions also other environmental impact categories should be analyzed (e.g., land used and water consumption)
- GHG emissions for construction of mobility infrastructure was not considered (e.g., charging infrastructure and hydrogen distribution)
- Interactions with energy system need to be analyzed in more detail
- Analysis of further renewable propulsion concepts required (e.g., hybrid vehicles, combustion engines with synthetic fuels)
- Second life is not considered for battery and fuel cell
- No GHG credit for materials after disposal

Most important references

Battery electric vehicle

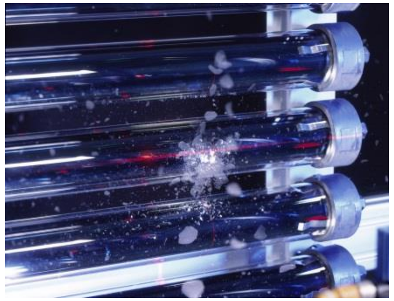
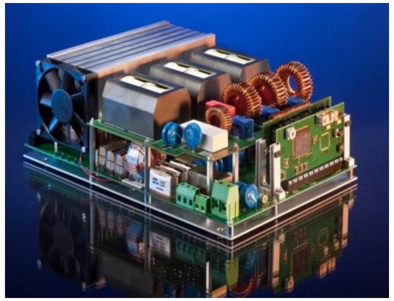
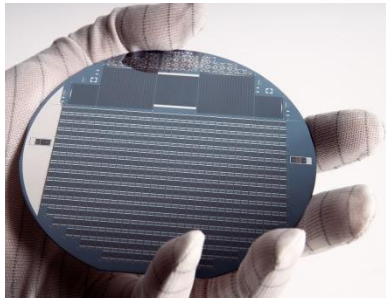
- Ellingsen, Majeau-Bettez, Singh, Srivastava, Valøen und Strømman, Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack *Journal of Industrial Ecology*, 18, 2014, 113-124
  - Department of Energy and Process Engineering, Norwegian University of Science and Technology
- Agora Verkehrswende (2019) *Lifecycle analysis of electric vehicles* (only summary in English)
- Department for batteries at ISE

Fuel cell electric vehicle

- Miotti[1,2], Hofer[1] und Bauer[1] 2017 Integrated environmental and economic assessment of current and future fuel cell vehicles *The International Journal of Life Cycle Assessment*, 22, 2017, 94-110
  - [1]Laboratory for Energy Systems Analysis, Paul Scherrer Institute (PSI)
  - [2]Institute for Data, Systems, and Society (IDSS), Massachusetts Institute of Technology (MIT),
- Department for fuel cells at ISE

Thank you for your Attention!

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APPENDIX

- Assumptions for vehicle operation
- Comparison for manufacturing of battery electric vehicles and fuel cell electric vehicles
- Details for manufacturing of batteries
- Details for manufacturing of fuel cells
- Details for manufacturing of hydrogen tank
- References for scenarios considered

Vehicle operation – assumptions

- FCEV based on Hyundai Nexo
  - Curb weight: 1919 kg
  - Weight without fuel cell and hydrogen tank: 1600 kg [1] (Basis for comparison with BEV)
  - H_2 demand based on WLTP: 0.95 kg H_2/100km (used for 2020); 2030: 0.93 kg H_2/100km
  - Fuel cell power: 95 kW
  - Hydrogen tank: 5.6 kg H2 ➔ Range: > 500 km
- BEV with 60 kWh battery (generic, weight without battery = 1600 kg)
  - Weight, incl. 60 kWh battery: 2044 kg (2020) and 1924 kg (2030)
  - Electricity demand (without charging losses): 19.5 kWh/100km (2020) and 19.0 kWh/100km (2030)
  - Range: ~300 km
- BEV with 90 kWh battery (generic, weight without battery = 1600 kg)
  - Weight, incl. 90 kWh battery : 2266 kg (2020) and 2086 kg (2030)
  - Electricity demand (without charging losses): 20.4 kWh/100km (2020) and 19.7 kWh/100km (2030)
  - Range: > 400 km

[1] Weight of fuel cell and H_2 tank based on Miotti et al., 2017
Electricity demand of BEV was derived from hydrogen demand of FCEV:
Assumptions: - 60% efficiency for fuel cell
- additional electricity demand per kg additional load: 4,2 Wh/100km (Redelbach et al. 2012, Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts)

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Vehicle operation – Assumptions for fuel and electricity supply

- Hydrogen from electrolysis
  - Electricity demand: 54 kWh/kg H_2 (Study IndWEDe, NOW GmbH, Berlin 2019)
  - GHG emissions for manufacturing of electrolysis: 0.18 and 0.08 kg CO_2-eq/kg H_2 (2020 and 2030)
- Hydrogen from reforming of natural gas
  - GHG emissions : 10.6 kg CO_2-eq/kg H_2 (Sternberg et al., Green Chem., 2017, 19, 2244)
- Electricity demand for hydrogen compression from 30 to 1000 bar: 2.7 kWh/kg H_2 [1]
  - Electricity is supplied by grid mix
- GHG emissions H_2 transport (200 km): 0.21 kg CO_2-eq/kg H_2 [2]
- Charging losses for BEV: 15% (Agora Verkehrswende, 2019)
- GHG emissions electricity supply
  - Grid mix 2020-2030: 421 g CO_2-eq/kWh (Agora Verkehrswende, 2019)
  - Grid mix 2030-2040: 296 g CO_2-eq/kWh (Agora Verkehrswende, 2019)
  - PV: 48 g CO_2-eq/kWh (IPCC AR5 WGII Annex III, Wert for „Solar PV – utility“)
  - Wind: 11 g CO_2-eq/kWh (IPCC AR5 WGII Annex III, Wert for „Wind onshore“)

[1] Hydrogen Station Compression, Storage, and Dispensing; Technical Status and Costs; NREL 2014

[2] (Robinius et al., 2018, Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles)
Trailer for GH_2: diesel demand = 0,35 l/km; net H_2 capacity = 1000 kg

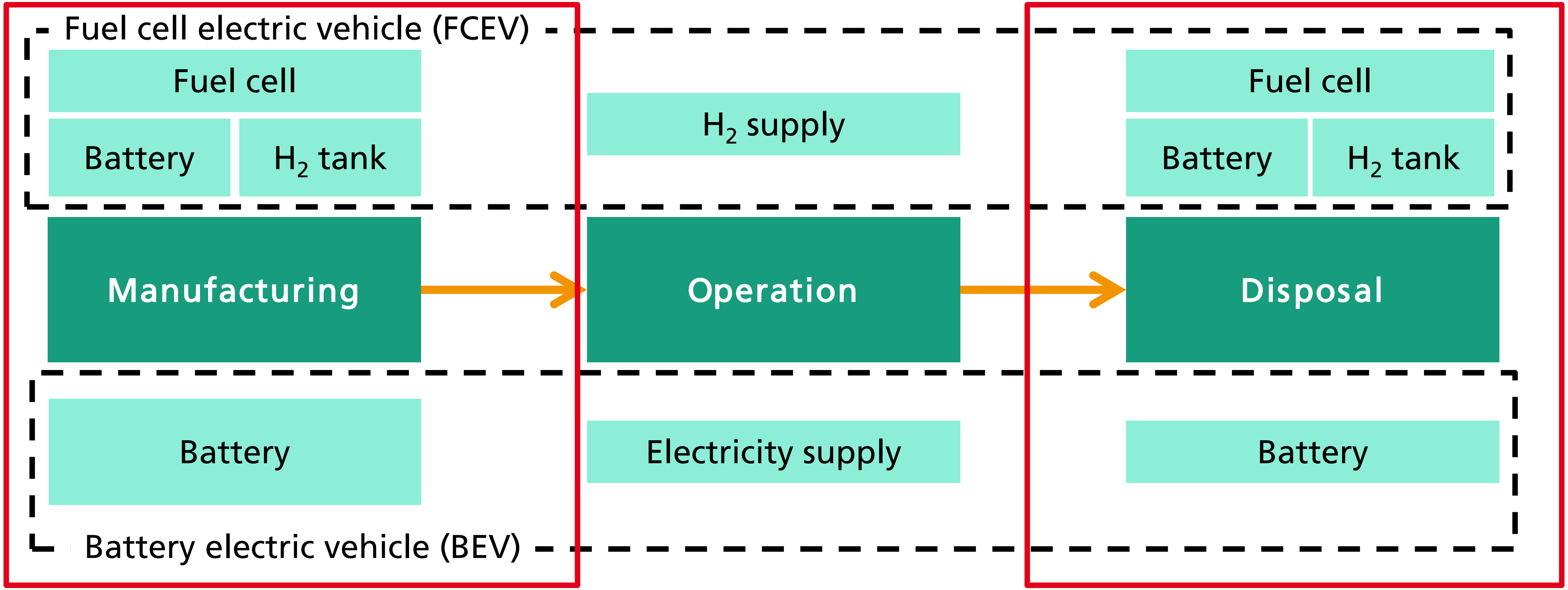
Diesel vehicle: Definition of vehicle weight and consumption

- Reference: Hyundai Tucson 1.6 CRDi (100 kW)
  - Curb weight: 1,683-1,810 kg
  - Consumption based on NEDC[1]: 4.4 l/100km
  - CO2 emissions based on NEDC[1]: 117 g/km
  - CO2-Emissionen based on WLTP: 157 g/km
  - Consumption based on WLTP[2]: 5.9 l/100km
- Considered values:
  - Curb weight : 1,750 kg
  - Consumption based on WLTP: 5.9 l/100km (100% fossil fuel)

[1] Use of WLTP to derive fuel consumption and recalculated to NEDC
[2] Calculated from WLTP CO_2 emissions (2.65 kg CO_2-eq per liter diesel)

Life cycle analyzed for battery electric vehicle and fuel cell electric vehicle

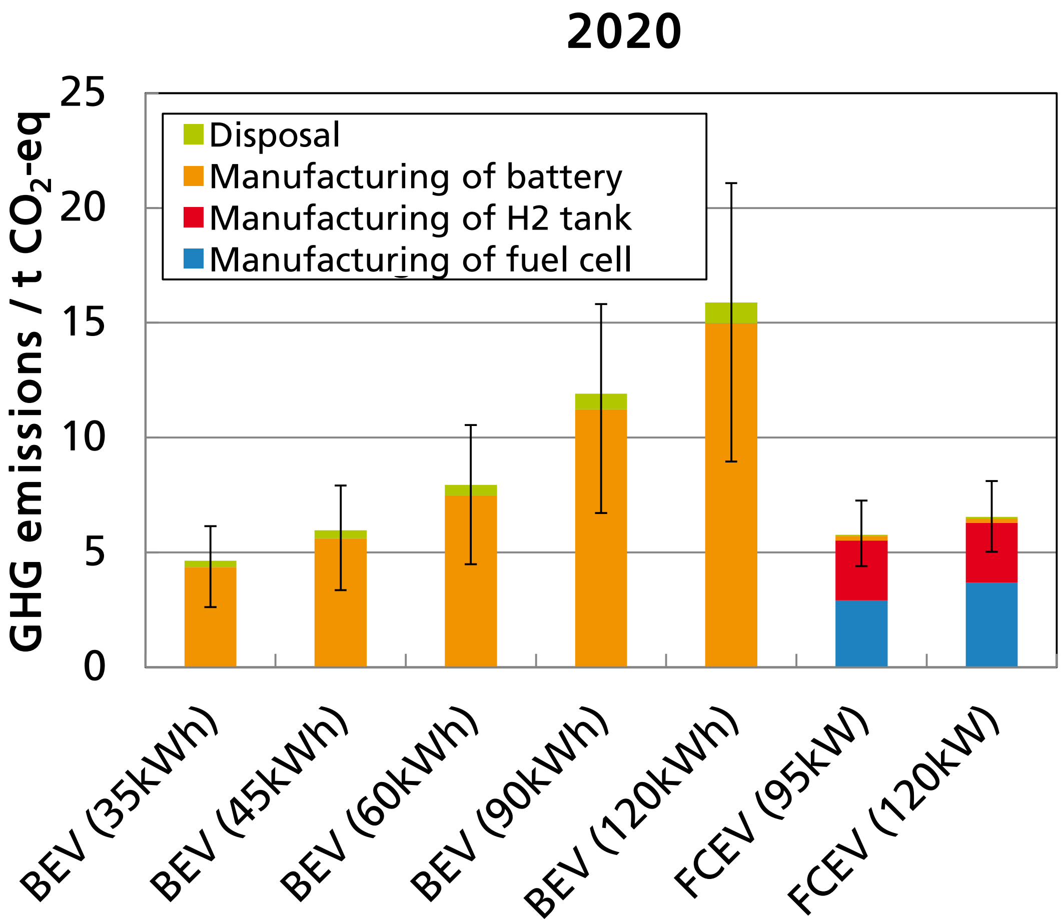
GHG emissions of vehicle operation for 2020-2030 and 2030-2040

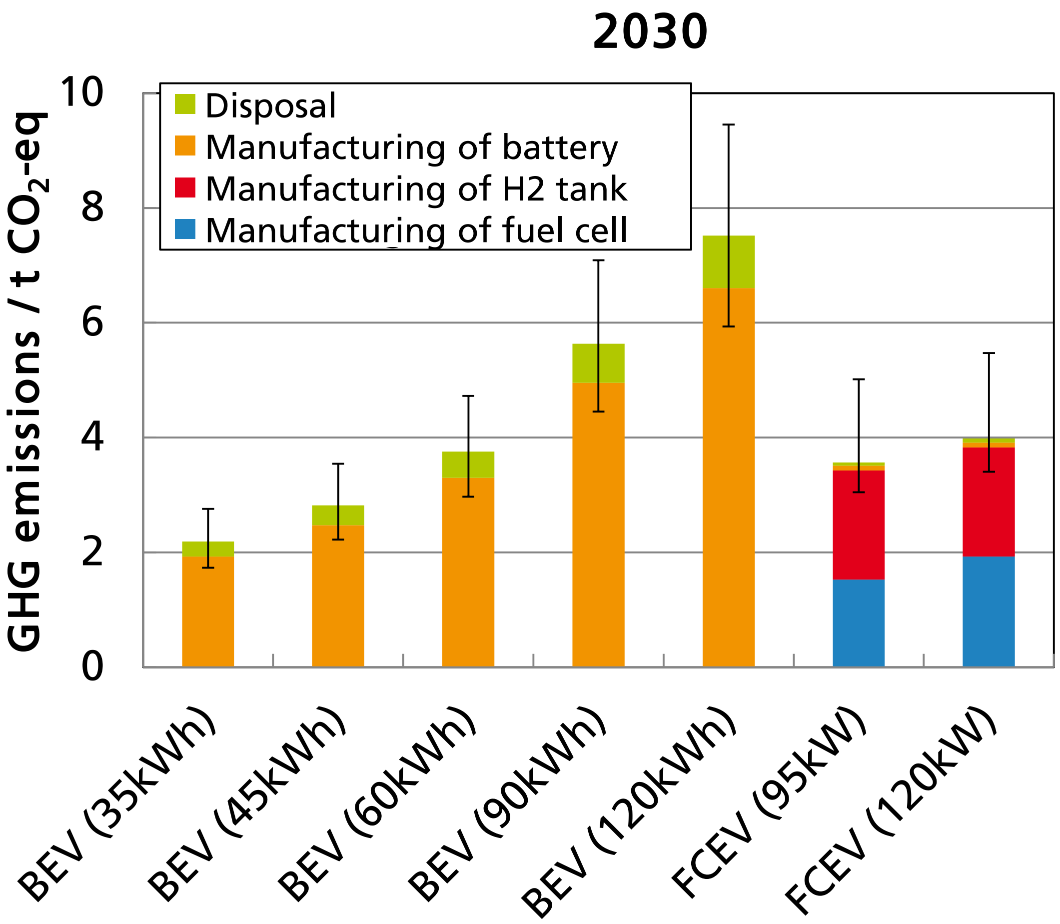


Manufacturing + disposal: greenhouse gas emissions

GHG fuel cell system (95 kW) ≈ GHG battery with 45 kWh

GHG fuel cell system (95 kW) ≈ GHG battery with 60 kWh





FCEV includes fuel cell + 5.6 kg H_2 tank + 1.5 kWh battery

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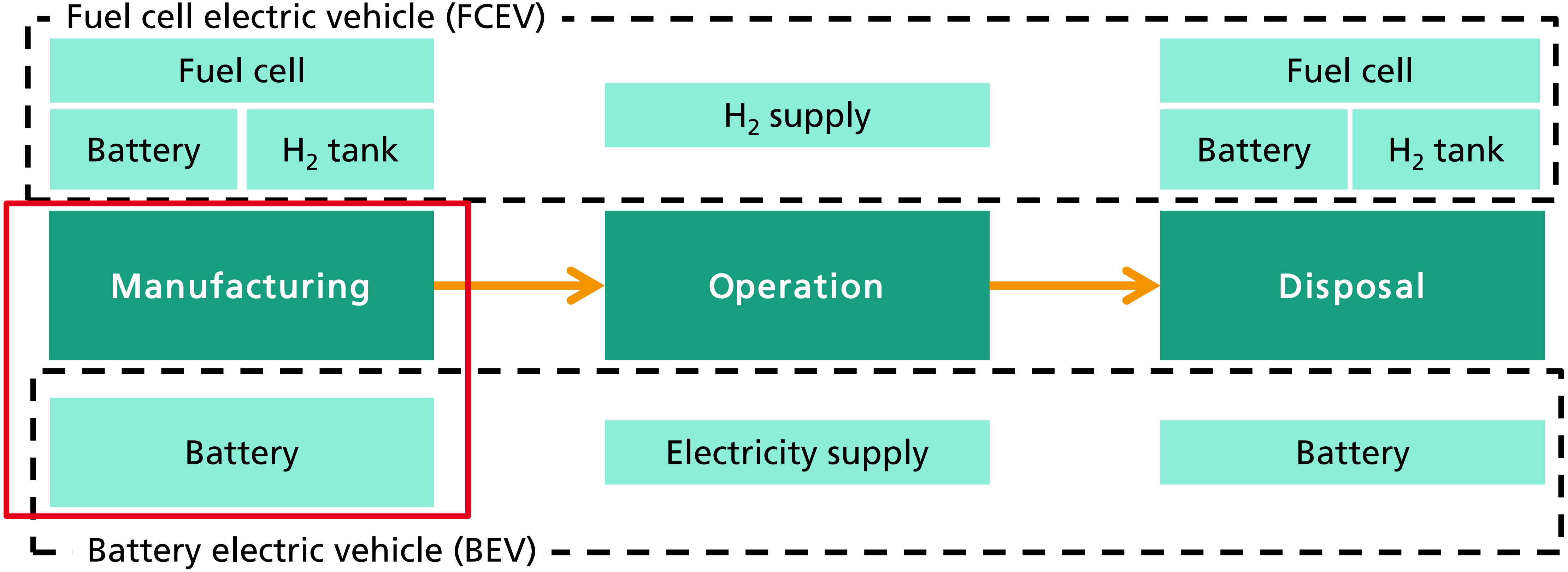

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Most important assumptions for battery

	2020	2030
Cell chemistry [1]	NCM (6:2:2)	NCM (9:0.5:0.5)
Cell container [2]	pouch	
Pack housing [2]	aluminum	
Electrolyte salt [2]	$LiPF_6$	
Solvent [2,4]	n-methyl-2-pyrrolidone	
Energy density (battery pack) [3]	135 Wh/kg	185 Wh/kg

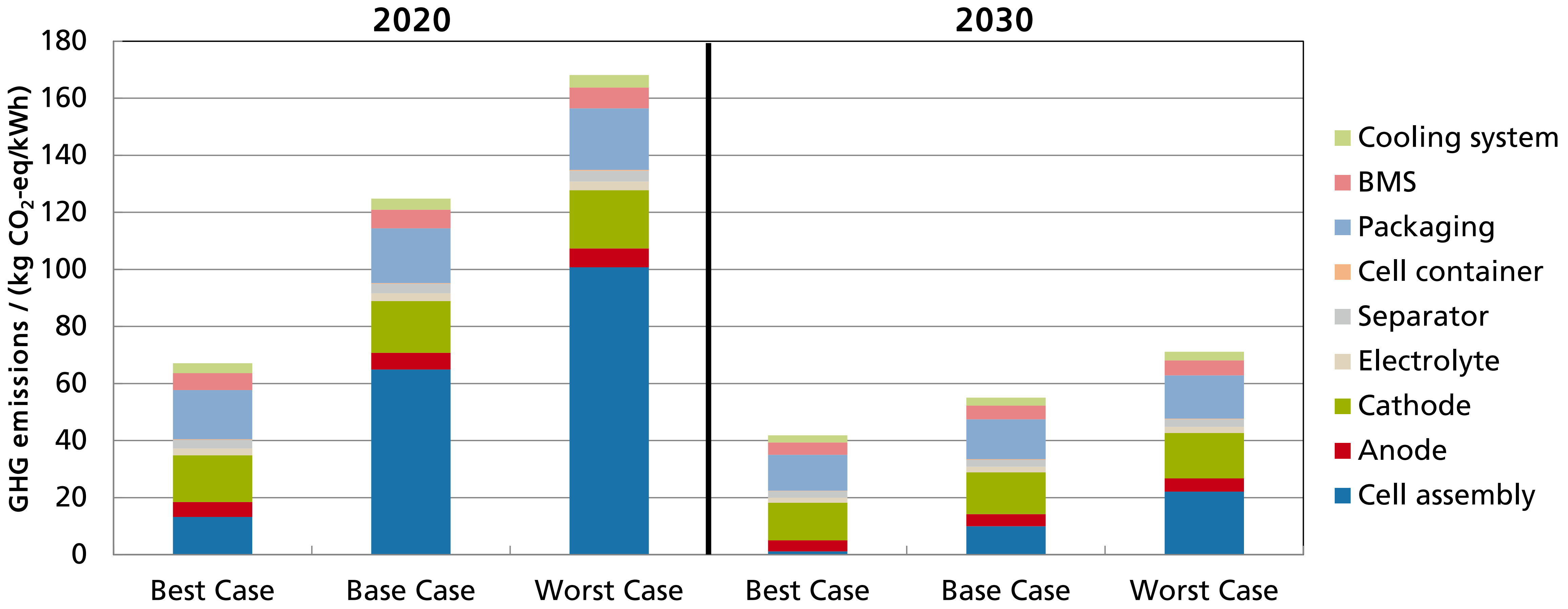
N – nickel
C – cobalt
M - manganese

Battery was modeled in LCA-Software Umberto LCA+ using database ecoinvent 3.5
Data for manufacturing of battery is based on [2]

[1] Cell chemistry with highest market share according to Azevedo et al., Lithium and cobalt – a tale of two commodities, Metals and Mining, June 2018
[2] Ellingsen et al., 2014
[3] see slide „Energy density for battery packs “
[4] based on Agora Verkehrswende (2019) 99.5% are recycled

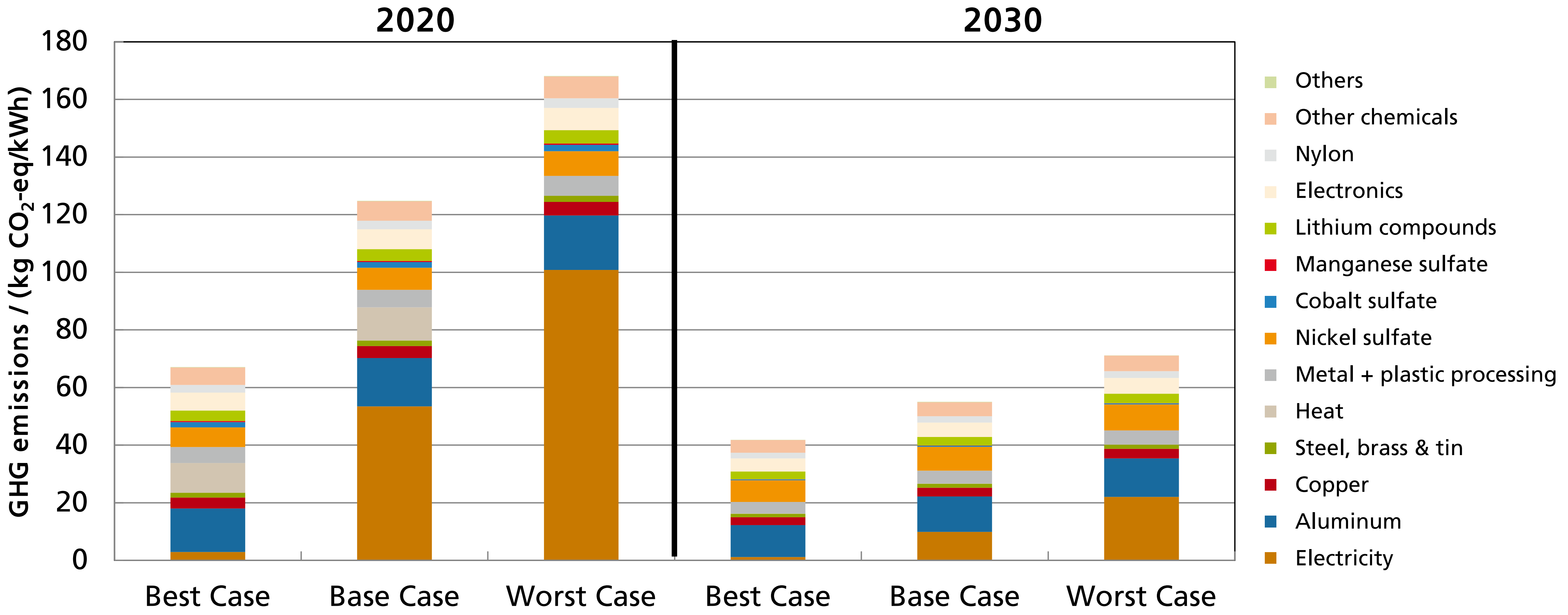
Manufacturing of batteries: GHG emissions

BMS – battery management system



2020 Best Case	2020 Base Case	2020 Worst Case	2030 Best Case	2030 Base Case	2030 Worst Case	
9.0 kWh/kg	9.0 kWh/kg	11.0 kWh/kg	5.0 kWh/kg	5.5 kWh/kg	6.0 kWh/kg	Electricity for cell production
5.6 kWh/kg	5.6 kWh/kg	-	-	-	-	Heat for cell production
48 g CO_2-eq/kWh	805 g CO_2-eq/kWh	1106 g CO_2-eq/kWh	48 g CO_2-eq/kWh	335 g CO_2-eq/kWh	620 g CO_2-eq/kWh	GHG emissions electricity
150 Wh/kg	135 Wh/kg	120 Wh/kg	205 Wh/kg	185 Wh/kg	170 Wh/kg	Energy density battery pack

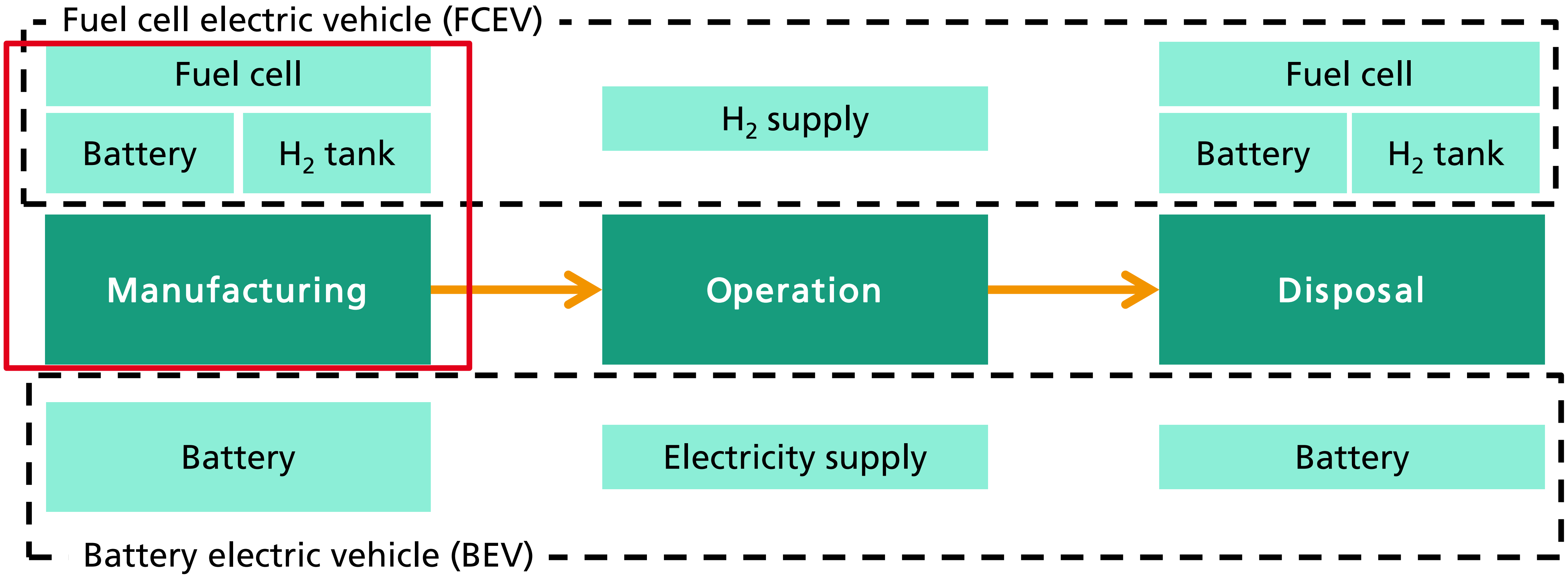
Manufacturing of batteries: GHG emissions in more detail



	2020 Best Case	2020 Base Case	2020 Worst Case	2030 Best Case	2030 Base Case	2030 Worst Case
Electricity for cell production	9.0 kWh/kg	9.0 kWh/kg	11.0 kWh/kg	5.0 kWh/kg	5.5 kWh/kg	6.0 kWh/kg
Heat for cell production	5.6 kWh/kg	5.6 kWh/kg	-	-	-	-
GHG emissions electricity	48 g CO_2-eq/kWh	805 g CO_2-eq/kWh	1106 g CO_2-eq/kWh	48 g CO_2-eq/kWh	335 g CO_2-eq/kWh	620 g CO_2-eq/kWh
Energy density battery pack	150 Wh/kg	135 Wh/kg	120 Wh/kg	205 Wh/kg	185 Wh/kg	170 Wh/kg

Life cycle analyzed for battery electric vehicle and fuel cell electric vehicle

GHG emissions of vehicle operation for 2020-2030 and 2030-2040



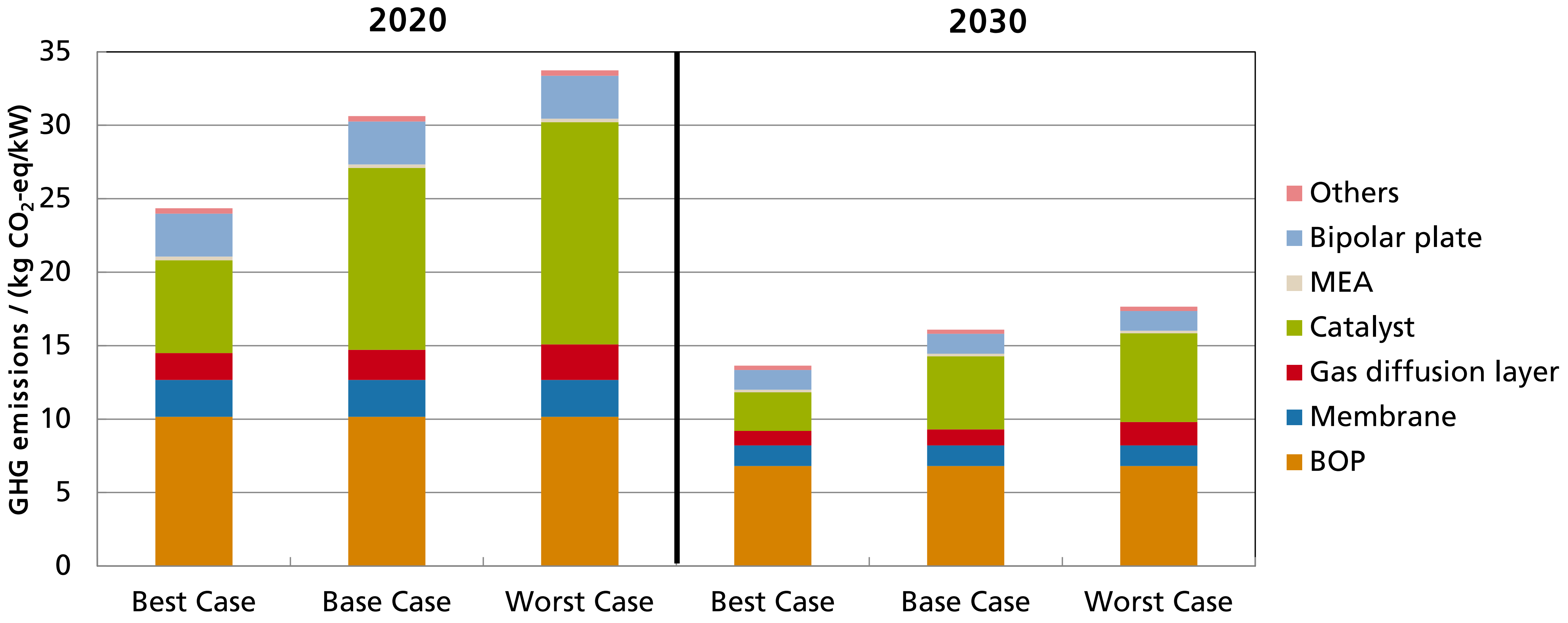
Most important assumptions for fuel cell

	2020	2030
Platinum loading [1]	0.4 mg/cm²	0.2 mg/cm²
Power density [1]	1060 mW/m²	1310 mW/m²
Platinum demand [1]	0.43 g/kW	0.165 g/kW

Fuel cell was modeled in LCA-Software Umberto LCA+
using database ecoinvent 3.5
Data for manufacturing of fuel cell is based on [1]

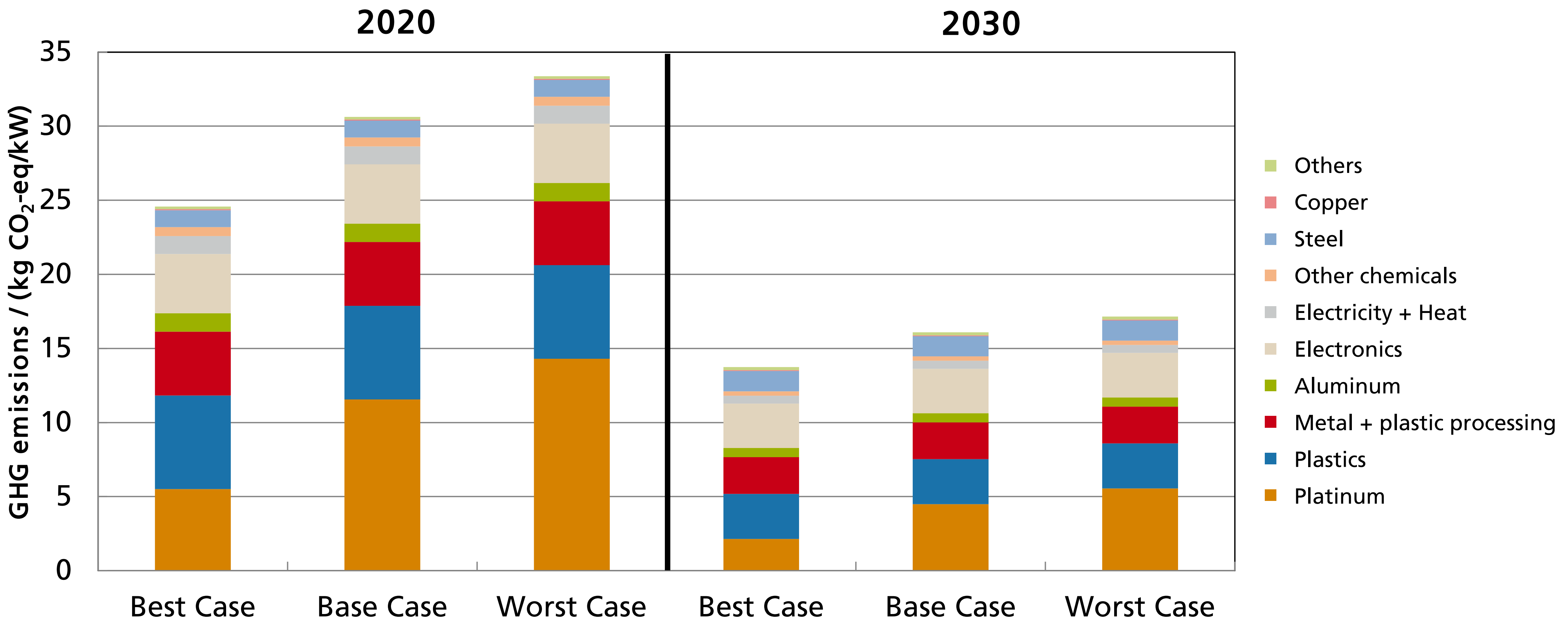
[1] Miotti et al., 2017

Manufacturing of fuel cells: GHG emissions



0.38 g/kW	0.43 g/kW	0.47 g/kW	0.15 g/kW	0.165 g/kW	0.18 g/kW	Platinum demand
14 t CO_2-eq/kg	27 t CO_2-eq/kg	30 t CO_2-eq/kg	14 t CO_2-eq/kg	27 t CO_2-eq/kg	30 t CO_2-eq/kg	GHG emissions platinum
20 kg CO_2/kg	27.6 kg CO_2/kg	39 kg CO_2/kg	20 kg CO_2/kg	23.5 kg CO_2/kg	39 kg CO_2/kg	GHG emissions carbon fiber

Manufacturing of fuel cells: GHG emissions



	2020 Best Case	2020 Base Case	2020 Worst Case	2030 Best Case	2030 Base Case	2030 Worst Case
Platinum demand	0.38 g/kW	0.43 g/kW	0.47 g/kW	0.15 g/kW	0.165 g/kW	0.18 g/kW
GHG emissions platinum	14 t CO_2-eq/kg	27 t CO_2-eq/kg	30 t CO_2-eq/kg	14 t CO_2-eq/kg	27 t CO_2-eq/kg	30 t CO_2-eq/kg
GHG emissions carbon fiber	20 kg CO_2/kg	27.6 kg CO_2/kg	39 kg CO_2/kg	20 kg CO_2/kg	23.5 kg CO_2/kg	39 kg CO_2/kg

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Most important assumptions for hydrogen tank

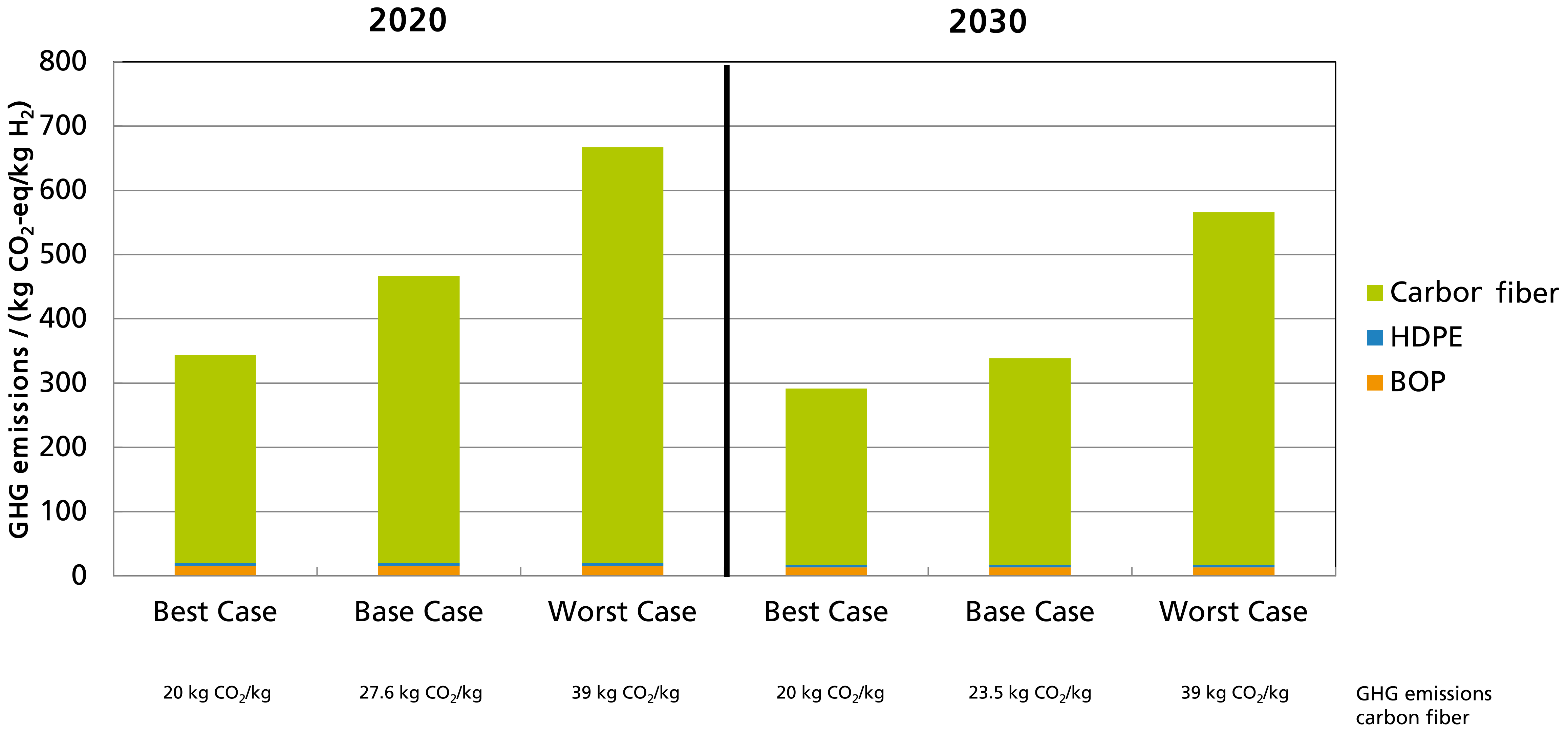
	2020	2030
Tank type	Typ IV (700 bar); 2 tank system	
Size	5.6 kg H_2	
Material demand		15% lower compared to 2020 [1]

Hydrogen tank was modeled in LCA-Software Umberto LCA+ using database ecoinvent 3.5
Data for manufacturing of hydrogen tank is based on „Argonne National Lab, ANL-10/24 Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications"

[1] Miotti et al., 2017

BOP – Balance of plant

Manufacturing of hydrogen tank: GHG emissions



References for manufacturing scenarios of battery

	2020			2030		
	Best Case	Base Case	Worst Case	Best Case	Base Case	Worst Case
Electricity demand for cell production	9.0 kWh/kg	9.0 kWh/kg	11.0 kWh/kg	5.0 kWh/kg	5.5 kWh/kg	6.0 kWh/kg
Heat demand for cell production	5.6 kWh/kg	5.6 kWh/kg	-	-	-	-
Reference for electricity and heat demand	[Peters et al., 2018]	[Peters et al., 2018]	[Agora Verkehrswende, 2019]	Own assumption: -10% from Base Case	[Agora Verkehrswende, 2019]	Own assumption: +10% from Base Case
GHG emissions electricity	48 g CO_2-eq/kWh	805 g CO_2-eq/kWh	1106 g CO_2-eq/kWh	48 g CO_2-eq/kWh	335 g CO_2-eq/kWh	620 g CO_2-eq/kWh
Reference for GHG emissions electricity	[IPCC] PV Strom	[Agora Verkehrswende, 2019] grid mix of manufacturing countries	[Agora Verkehrswende, 2019] grid mix China	[IPCC] PV Strom	[Agora Verkehrswende, 2019] grid mix EU, 2030	Forecast grid mix China, 2030
Energy density battery pack [1]	150 Wh/kg	135 Wh/kg	120 Wh/kg	205 Wh/kg	185 Wh/kg	170 Wh/kg

[1] see next slide

Energy density for battery packs

	2020			2030		
	Best Case	Base Case	Worst Case	Best Case	Base Case	Worst Case
Energy density Battery cell[1]	250 Wh/kg	225 Wh/kg	200 Wh/kg	340 Wh/kg	310 Wh/kg	280 Wh/kg
Energy density Battery pack[2]	150 Wh/kg	135 Wh/kg	120 Wh/kg	205 Wh/kg	185 Wh/kg	170 Wh/kg

[1] Roadmap „Batterieproduktionsmittel 2030-Update 2018" for pouch cells
[2] Assumption: cell is responsible for 60% of total weight of battery pack (Ellingsen et al., 2014)

References for manufacturing scenarios of fuel cell and H_2 tank

	2020			2030		
	Best Case	Base Case	Worst Case	Best Case	Base Case	Worst Case
Platinum demand	0.38 g/kW	0.43 g/kW	0.47 g/kW	0.15 g/kW	0.165 g/kW	0.18 g/kW
Reference for platinum demand	Own assumption: -10% from Base Case	[Miotti et al., 2017]	Own assumption: +10% from Base Case	Own assumption: -10% from Base Case	[Miotti et al., 2017]	Own assumption: +10% from Base Case
GHG emissions platinum	14 t CO_2-eq/kg	27 t CO_2-eq/kg	30 t CO_2-eq/kg	14 t CO_2-eq/kg	27 t CO_2-eq/kg	30 t CO_2-eq/kg
Reference for GHG emissions platinum	[ecoinvent 3.5] Platinum from Russia	[ecoinvent 3.5] Global Platinum mix, about 20% Russia + 80% South Africa	[ecoinvent 3.5] Platinum from South Africa	[ecoinvent 3.5] Platinum from Russia	[ecoinvent 3.5] Global Platinum mix, about 20% Russia + 80% South Africa	[ecoinvent 3.5] Platinum from South Africa
GHG emissions carbon fiber	20 kg CO_2/kg	27.6 kg CO_2/kg	39 kg CO_2/kg	20 kg CO_2/kg	23.5 kg CO_2/kg	39 kg CO_2/kg
Reference for GHG emissions carbon fiber	[Miotti et al., 2017]	Own calculation based on documentation of Eco Impact Calculators GHG electricity: 805 g CO_2-eq/kWh	[Eco Impact Calculator] http://ecocalculator.eucia.eu/	[Miotti et al., 2017]	Own calculation based on documentation of Eco Impact Calculators GHG electricity: 335 g CO_2-eq/kWh	[Eco Impact Calculator] http://ecocalculator.eucia.eu/