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

Study commissioned by H2 Mobility

André Sternberg, Christoph Hank und Christopher Hebling

Fraunhofer Institute for Solar Energy Systems ISE

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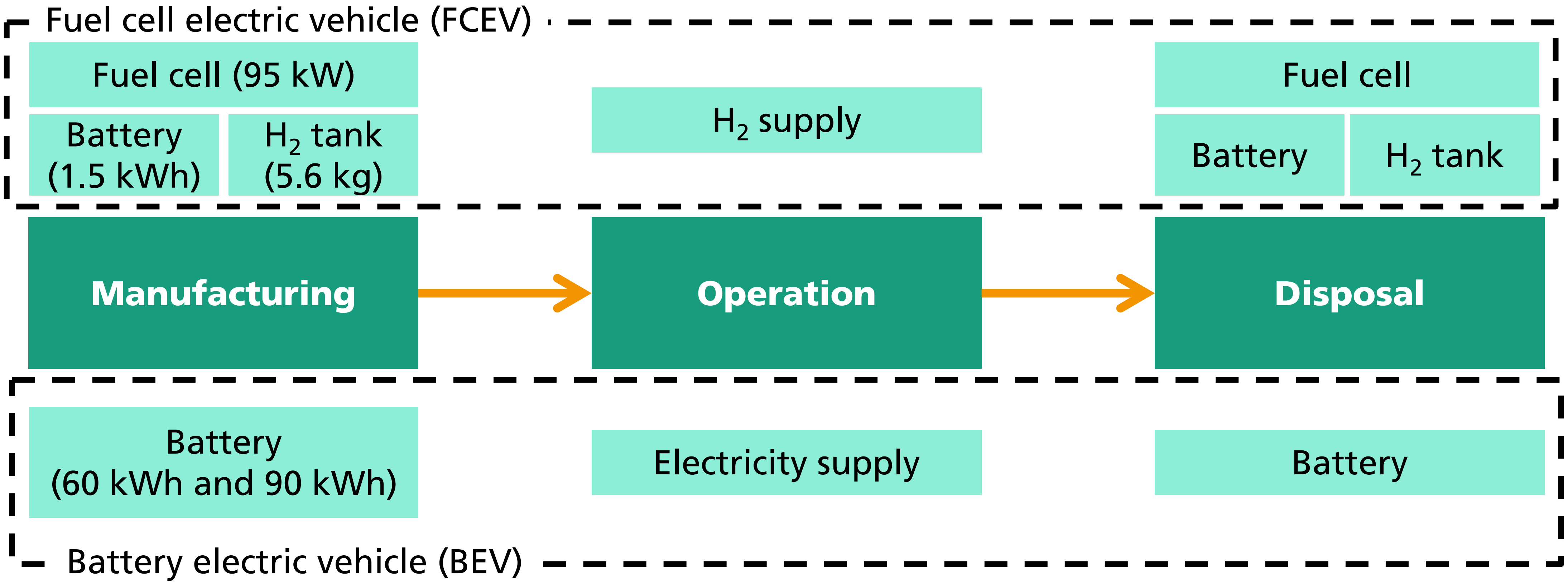
Life cycle analyzed for battery electric vehicle and fuel cell electric vehicle

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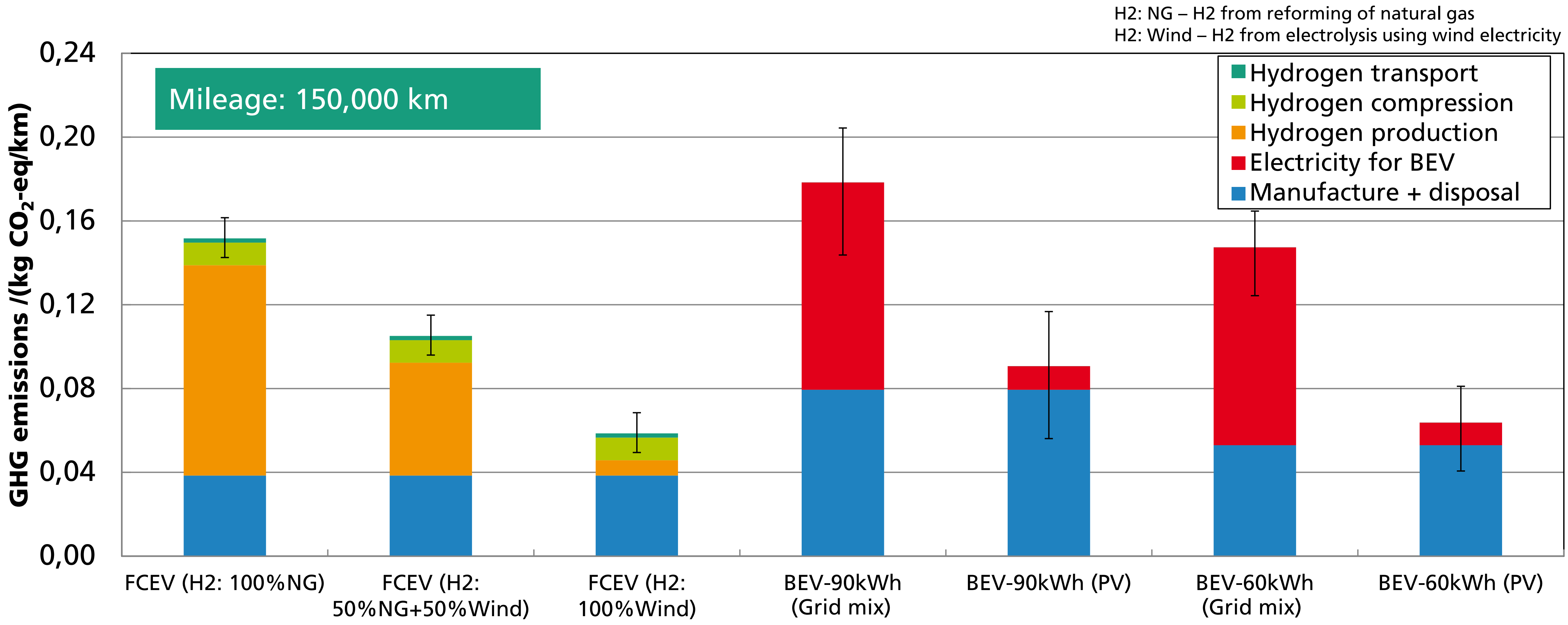
GHG emissions of vehicle operation for 2020-2030 (including manufacture + disposal of battery, fuel cell und H_2 tank)



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

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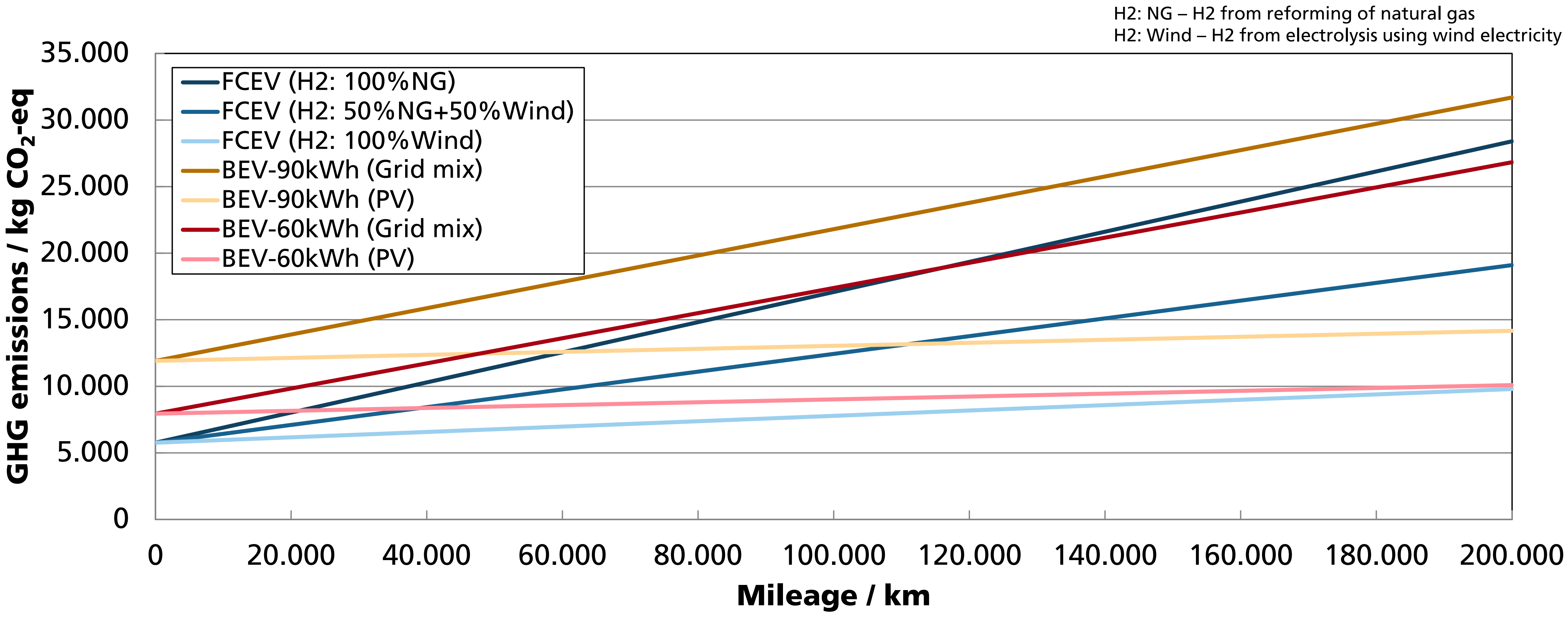
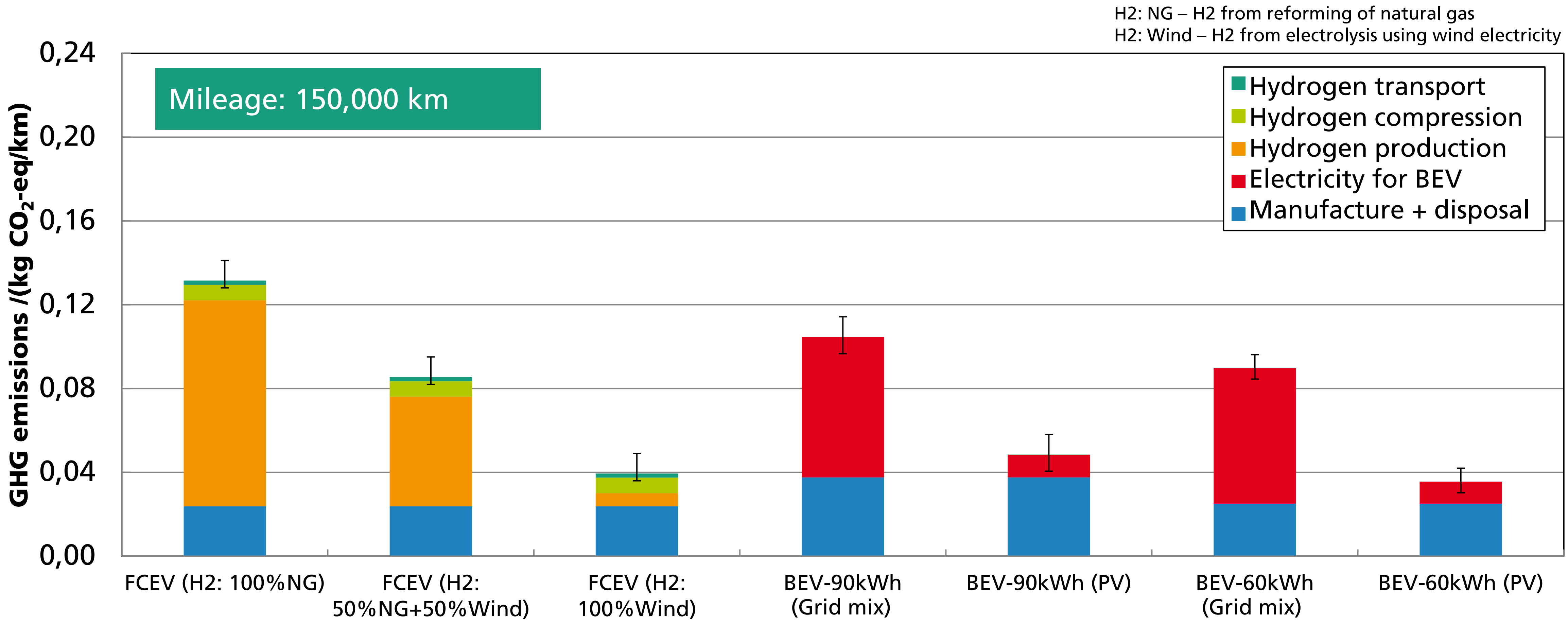
GHG emissions of vehicle operation for 2020-2030 (including manufacture + disposal of battery, fuel cell und H_2 tank)



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

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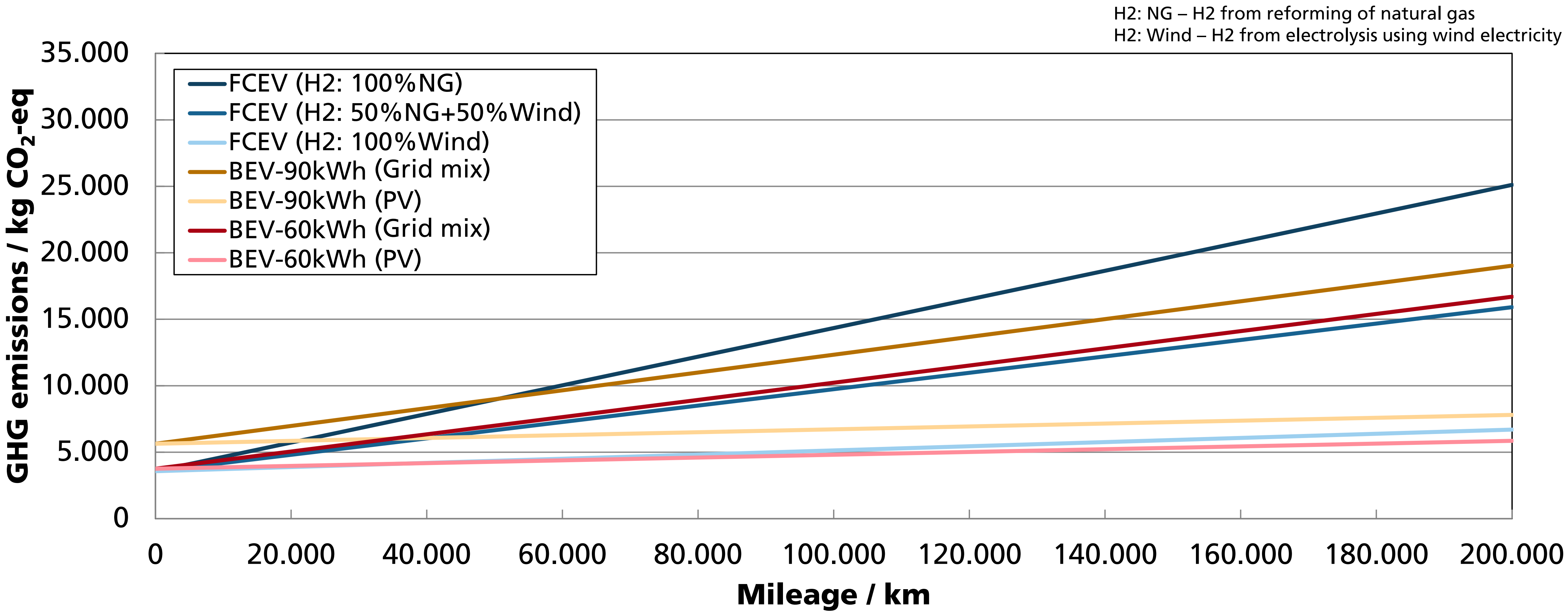
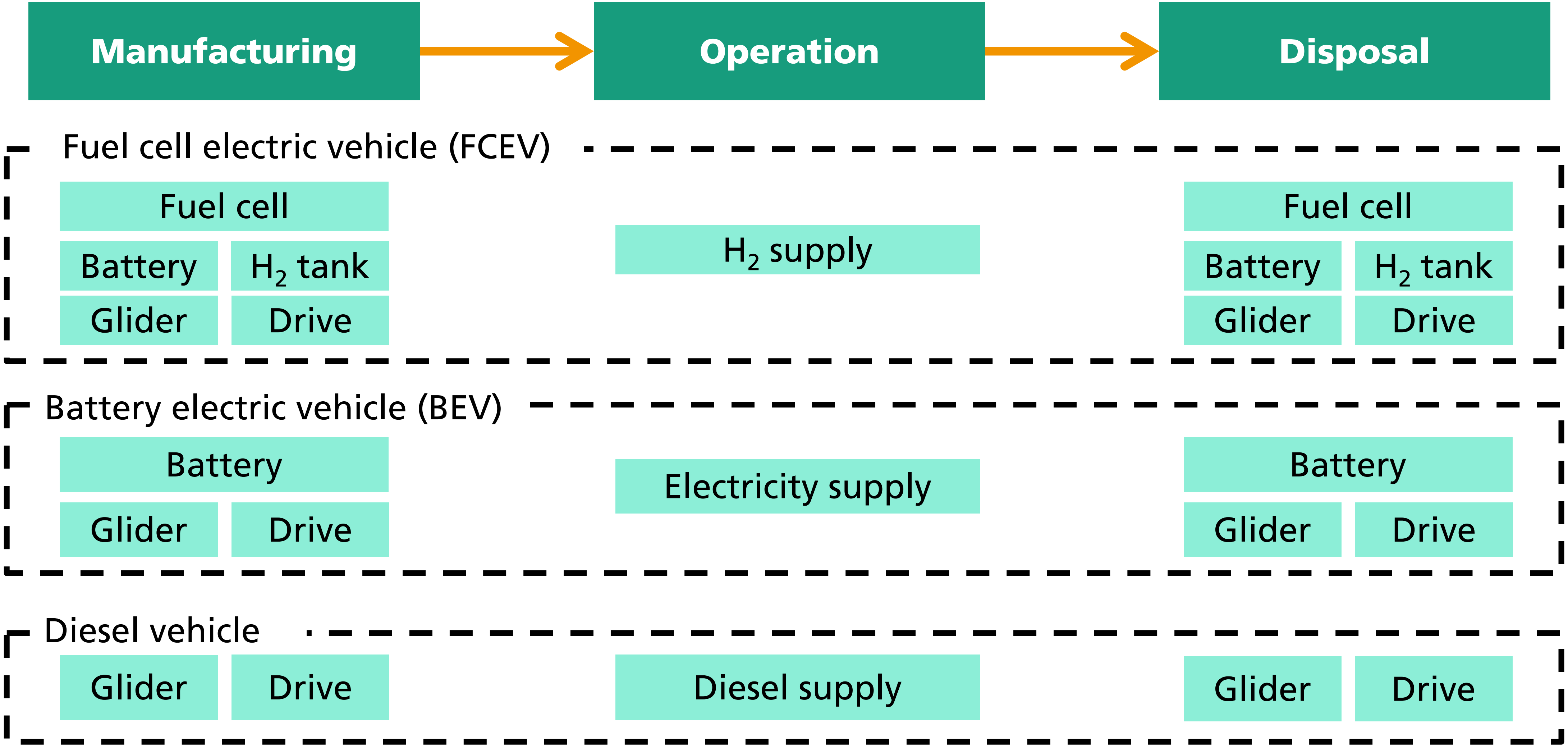
GHG emissions of vehicle operation for 2030-2040 (including manufacture + disposal of battery, fuel cell und H_2 tank)



See appendix for data basis

Comparison with diesel vehicle (100% fossil fuel)

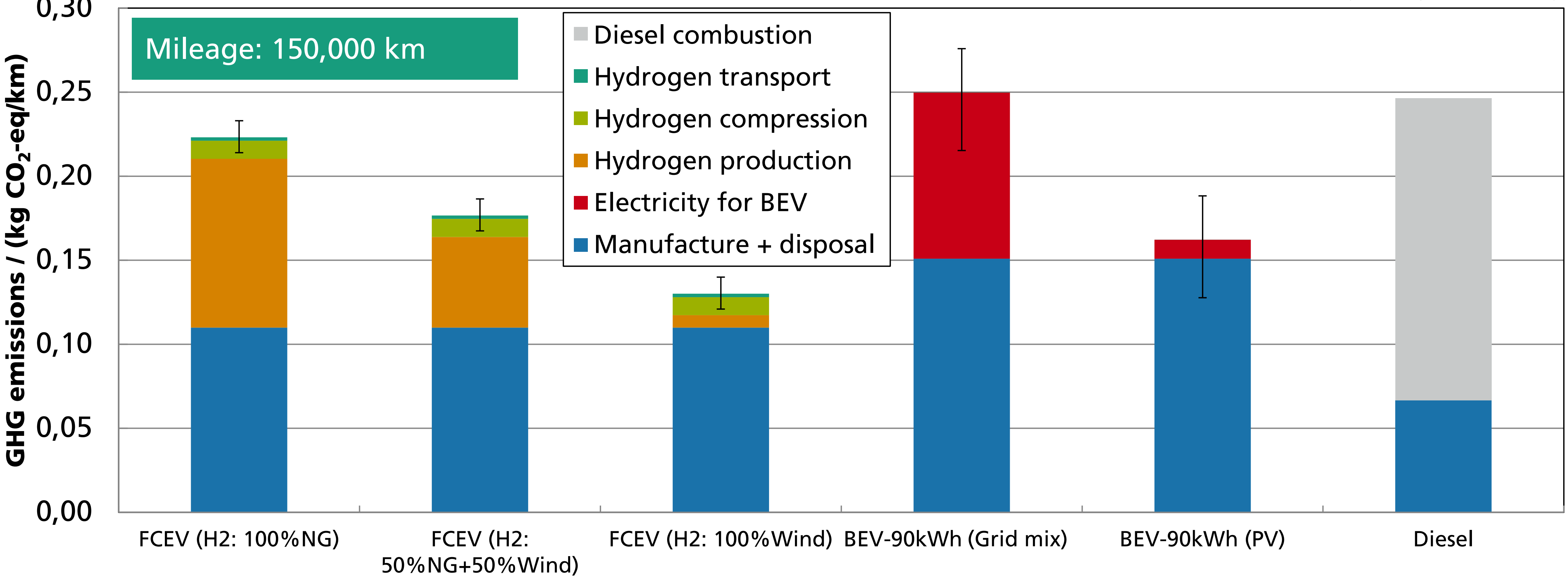


Time horizon: vehicle operation for 2020-2030

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

Glider and drive taken additionally into account, compared to slide 3.

See appendix for data basis

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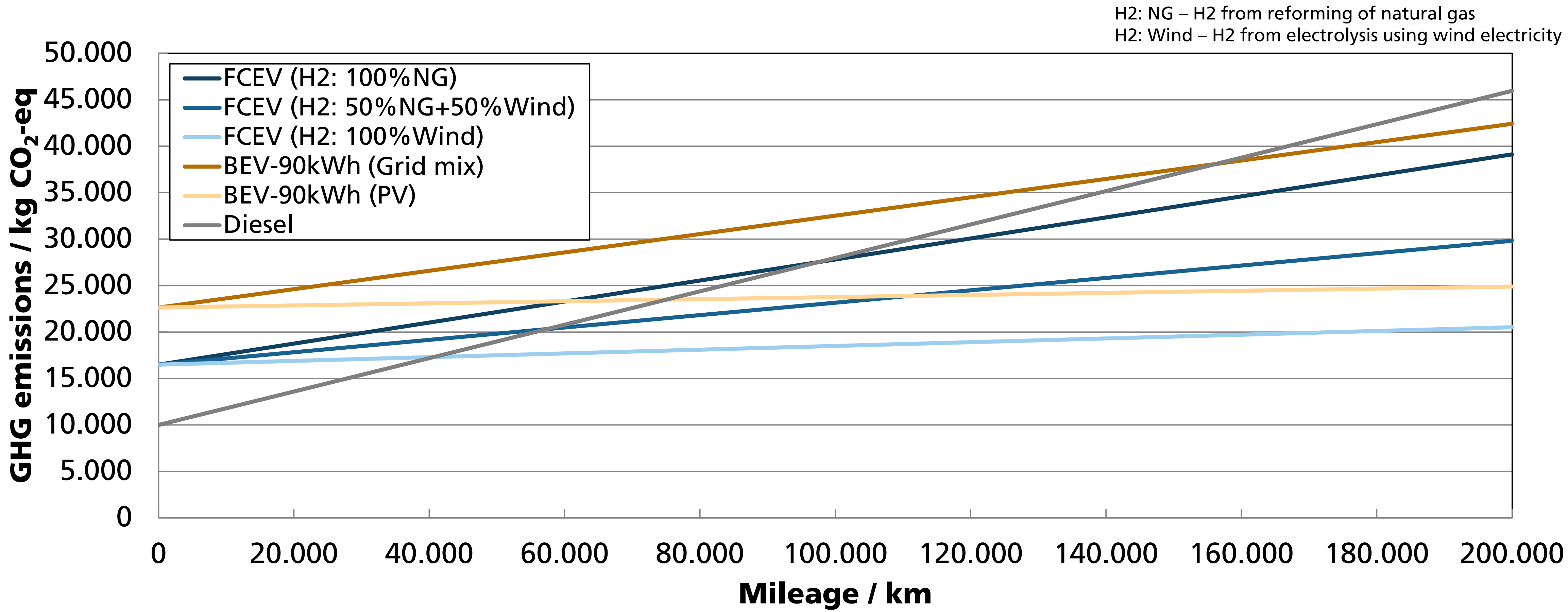
GHG emissions of vehicle operation for 2020-2030
Comparison with diesel vehicle (100% fossil fuel)



Glider and drive taken additionally into account, compared to slide 4.

See appendix for data basis

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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 for 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 generated with wind power ➔ 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 vehicles 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 were 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

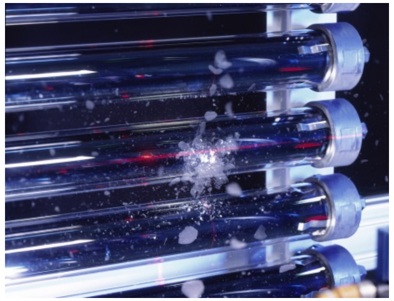
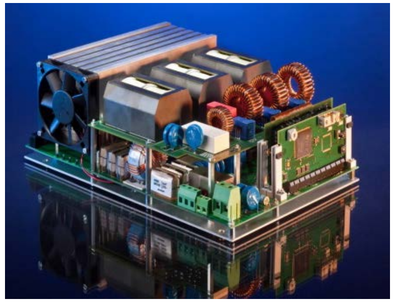
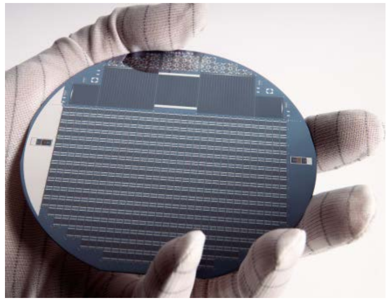
- Ellingsen, Majeau-Bettez, Singh, Srivastava, Valøen und Strømman,
  Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack
  Journal of Industrial Ecology, 18, 2014, 113-124
  - Department of Energy and Process Engineering, Norwegian University of Science and Technology
- Agora Verkehrswende (2019)
  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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André Sternberg

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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

- Fuel cell electric vehicle (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
- Battery electric vehicle (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)

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, Value for "Solar PV – utility")
  - Wind: 11 g CO_2-eq/kWh (IPCC AR5 WGII Annex III, Value 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 gaseous H_2: diesel demand = 0,35 l/km; net H_2 capacity = 1000 kg

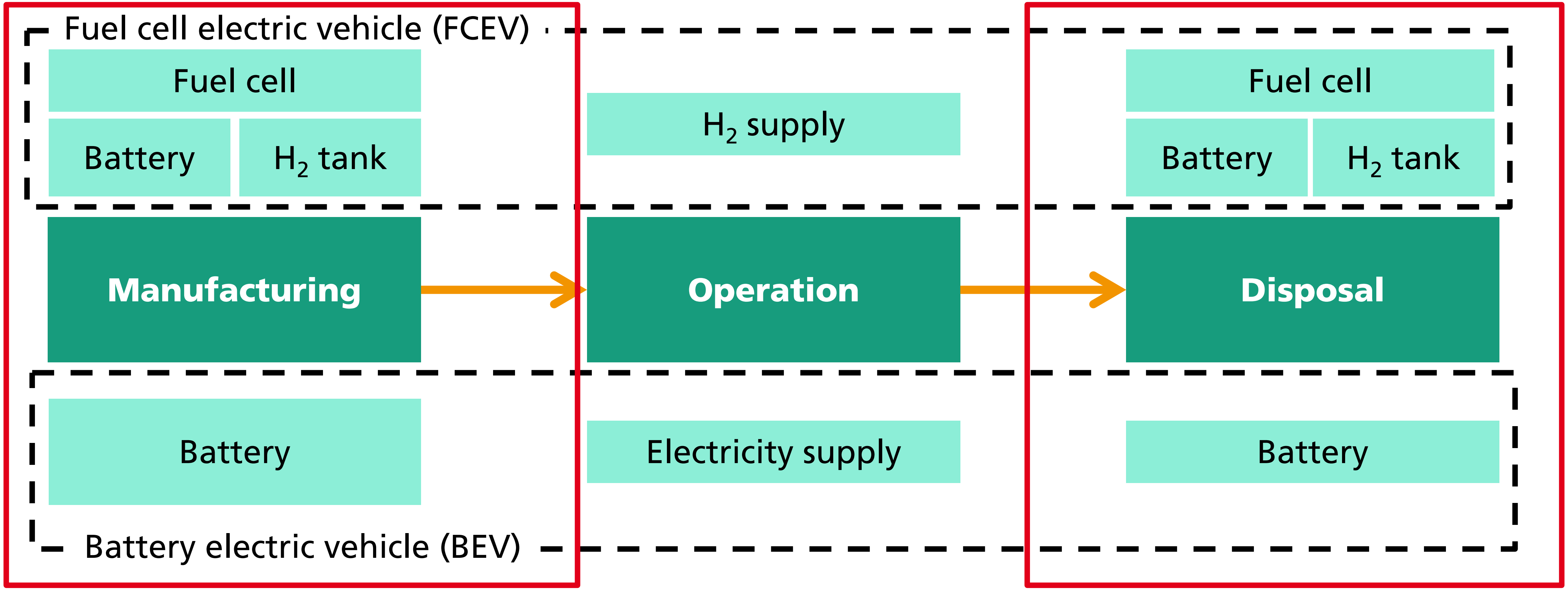
Diesel vehicle: Definition of vehicle weight and consumption

- Reference: Hyundai Tucson 1.6 CRDi (100 kW)
  - Curb weight: 1,683-1,810 kg
  - Consumption based on NEDC[1]: 4.4 l/100km
  - CO_2 emissions based on NEDC[1]: 117 g/km
  - CO_2-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



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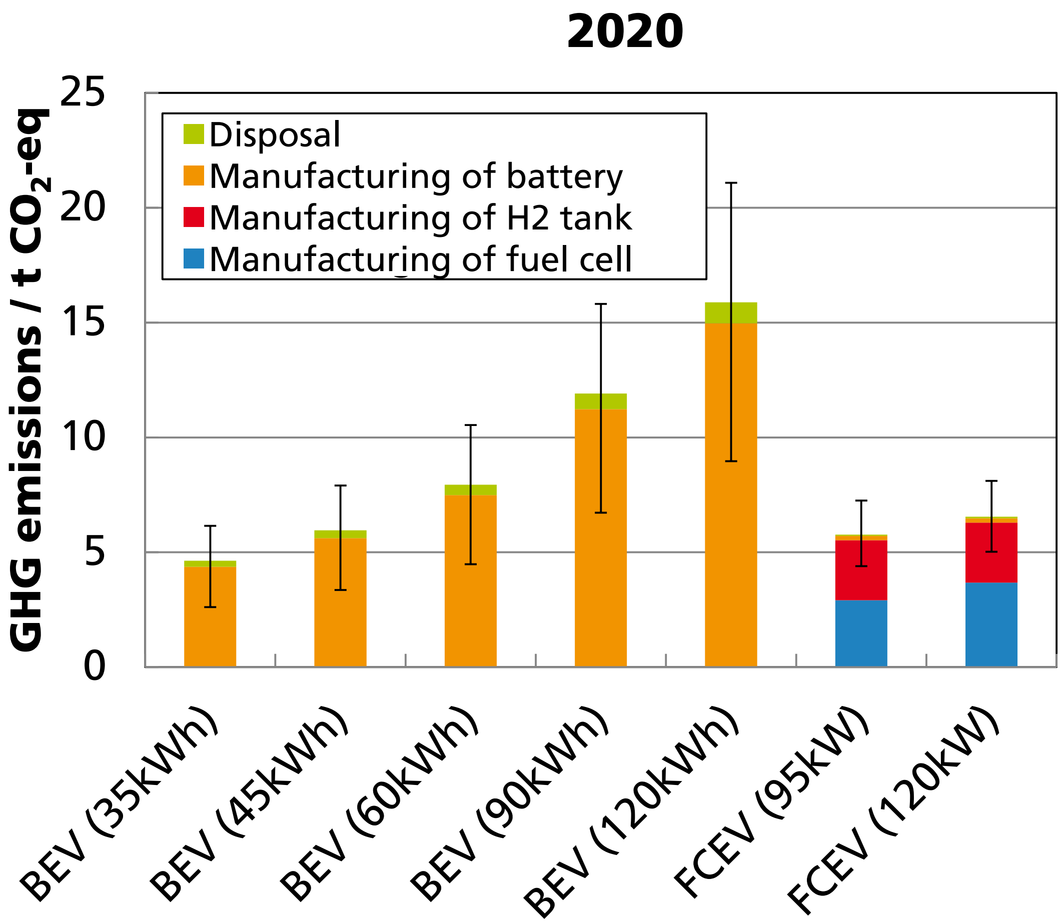
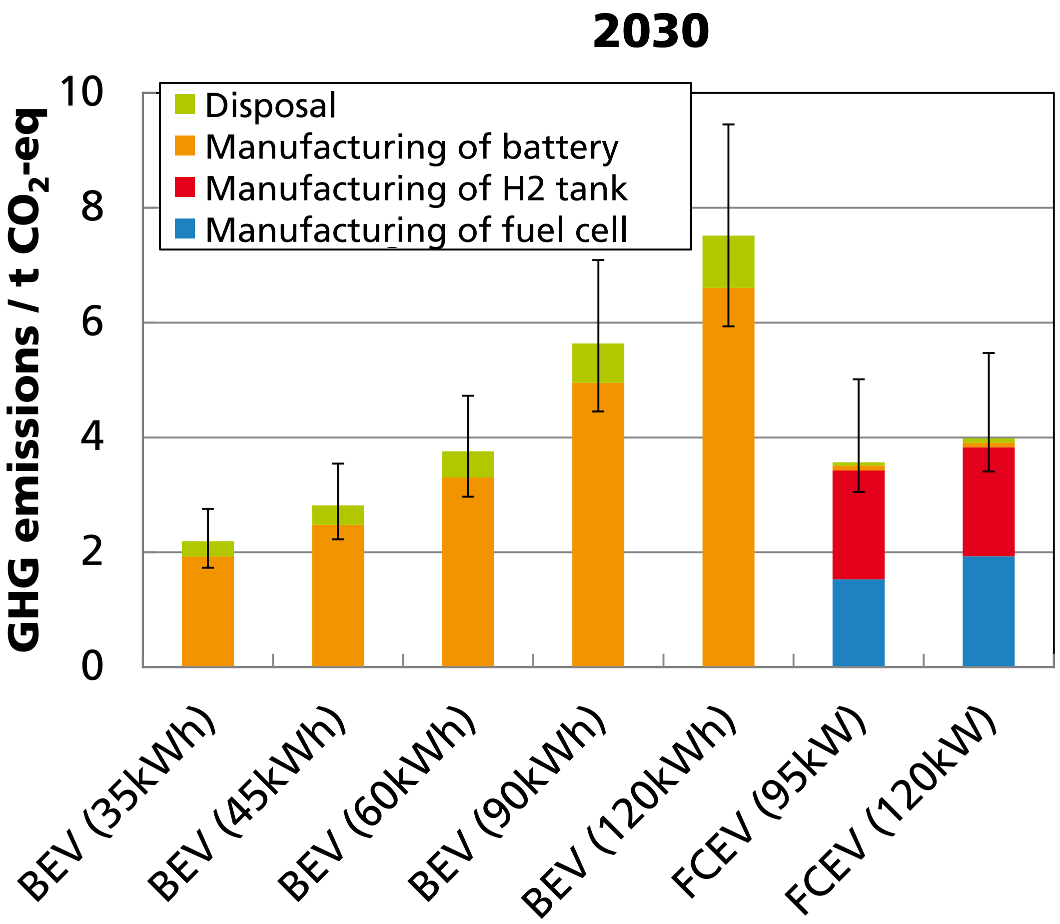
Manufacturing + disposal: greenhouse gas emissions

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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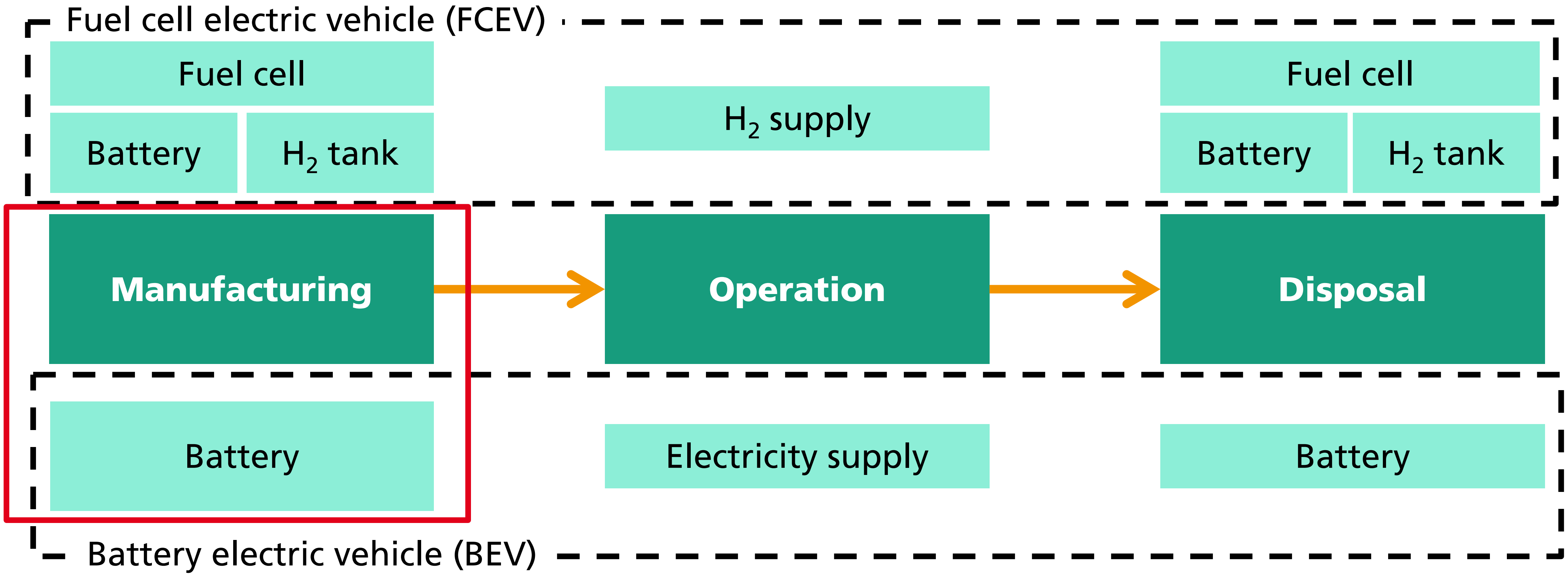

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Most important assumptions for battery

	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

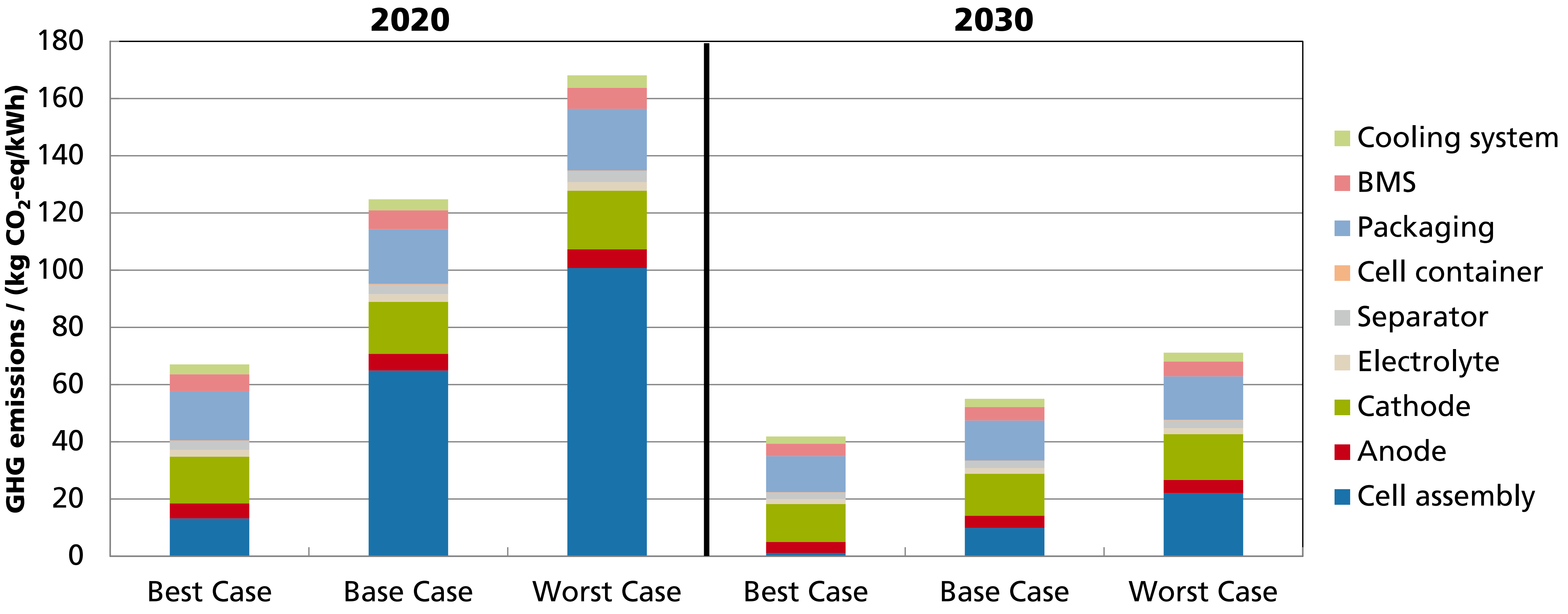
N – nickel
C – cobalt
M - manganese

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
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 electricity manufacturing	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

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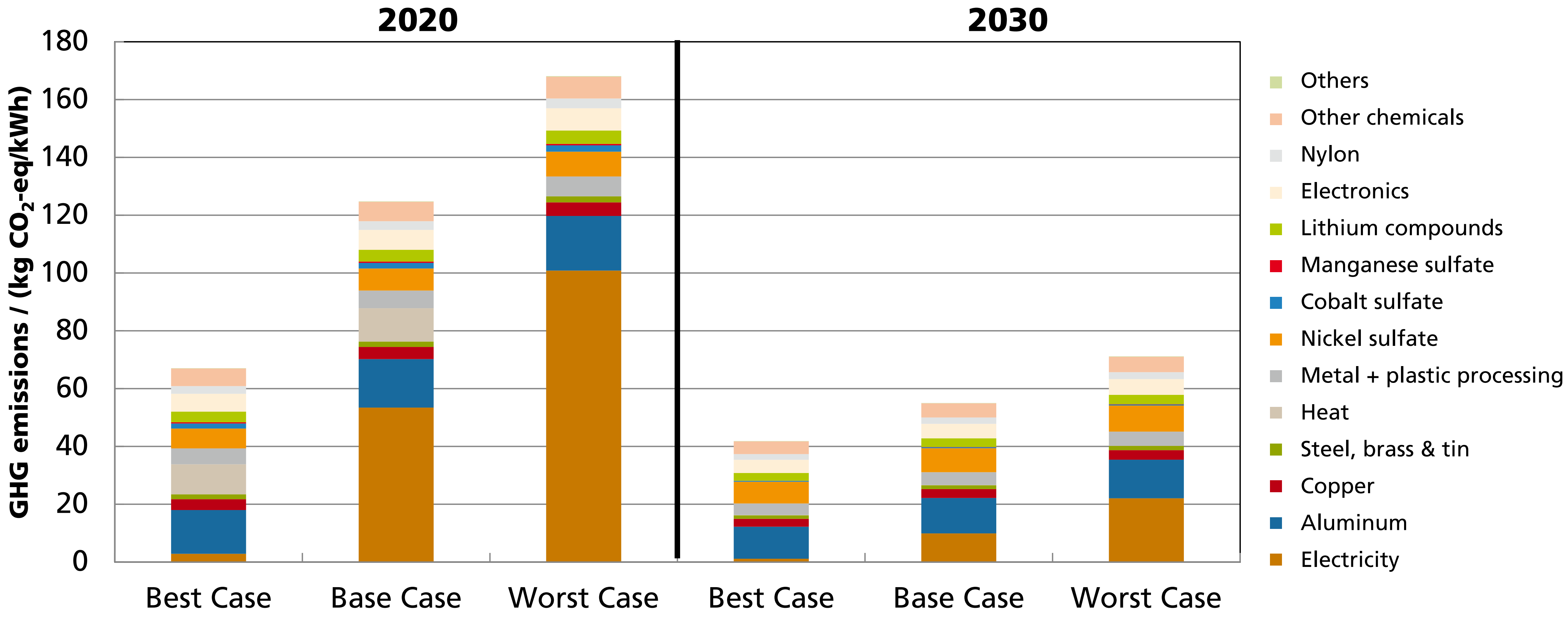
Manufacturing of batteries: GHG emissions in more detail



	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 electricity manufacturing	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

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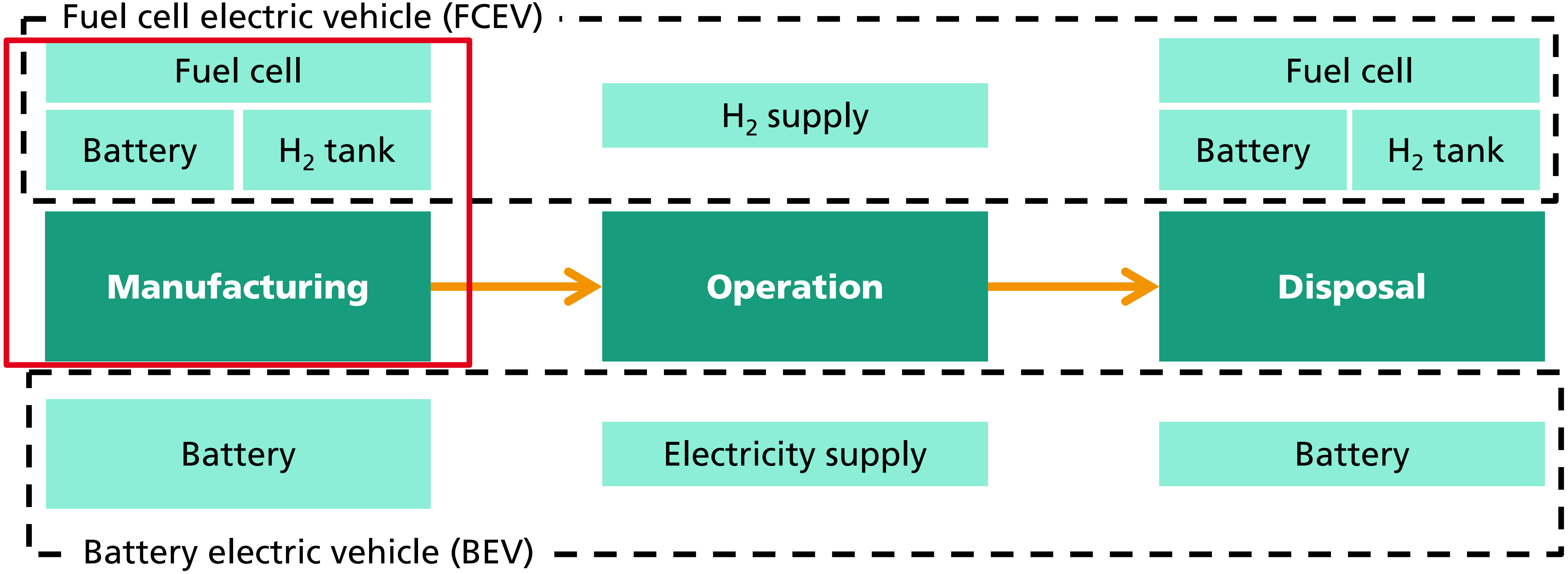
Life cycle analyzed for battery electric vehicle and fuel cell electric vehicle

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



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Most important assumptions for fuel cell

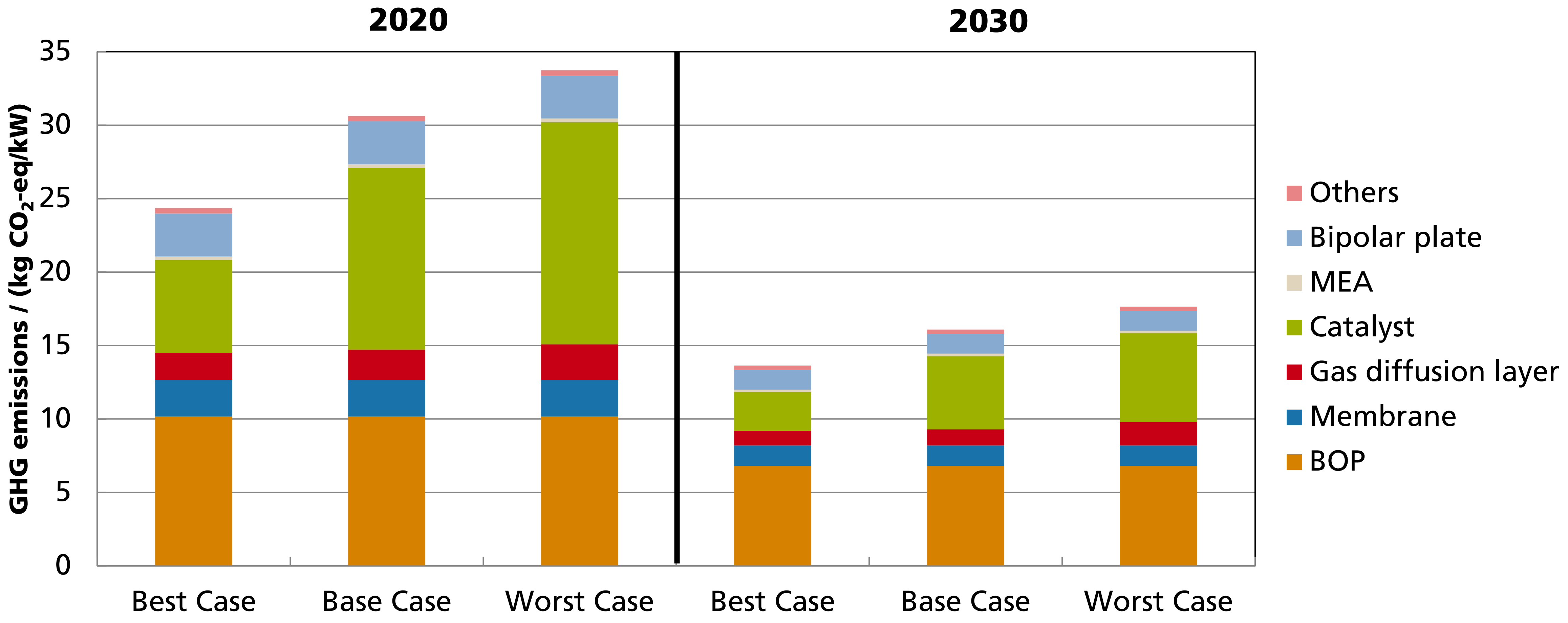
	2020	2030
Platinum loading [1]	0.4 mg/cm²	0.2 mg/cm²
Power density [1]	1060 mW/m²	1310 mW/m²
Platinum demand [1]	0.43 g/kW	0.165 g/kW

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

MEA – Membrane electrode assembly
BOP – Balance of plant

Manufacturing of fuel cells: GHG emissions



2020 Best Case	2020 Base Case	2020 Worst Case	2030 Best Case	2030 Base Case	2030 Worst Case	
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

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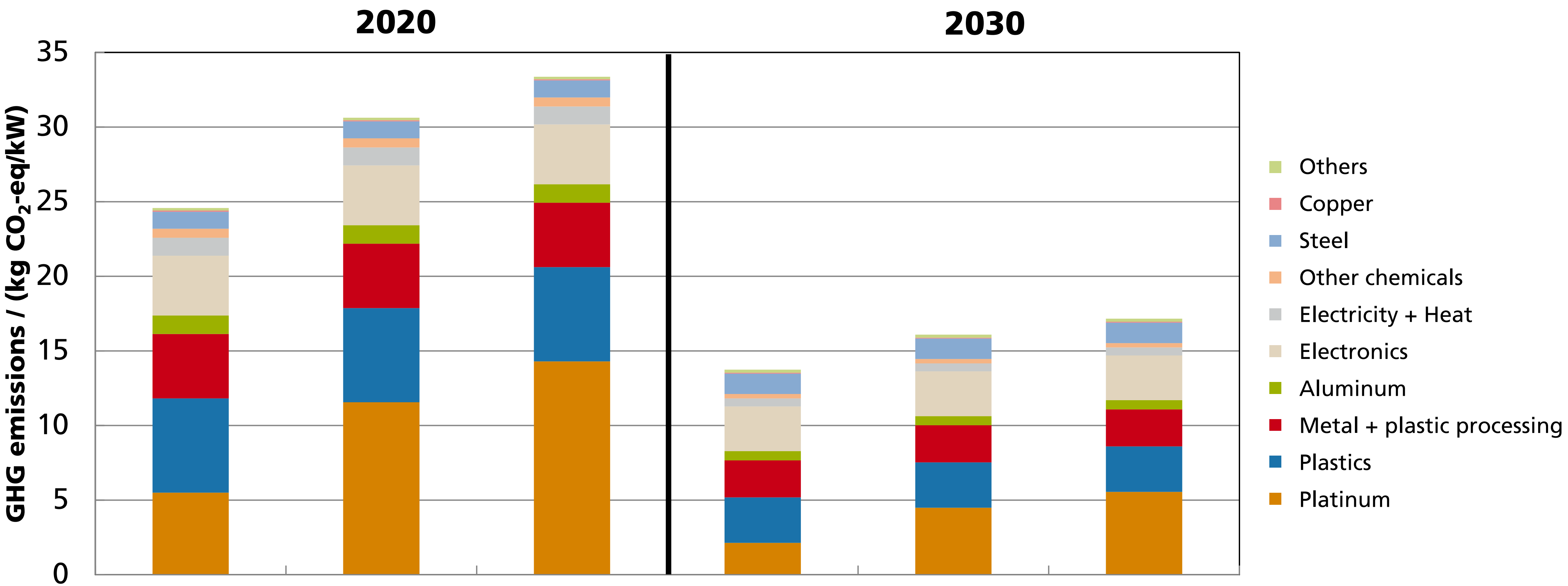
Manufacturing of fuel cells: GHG emissions



	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
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

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

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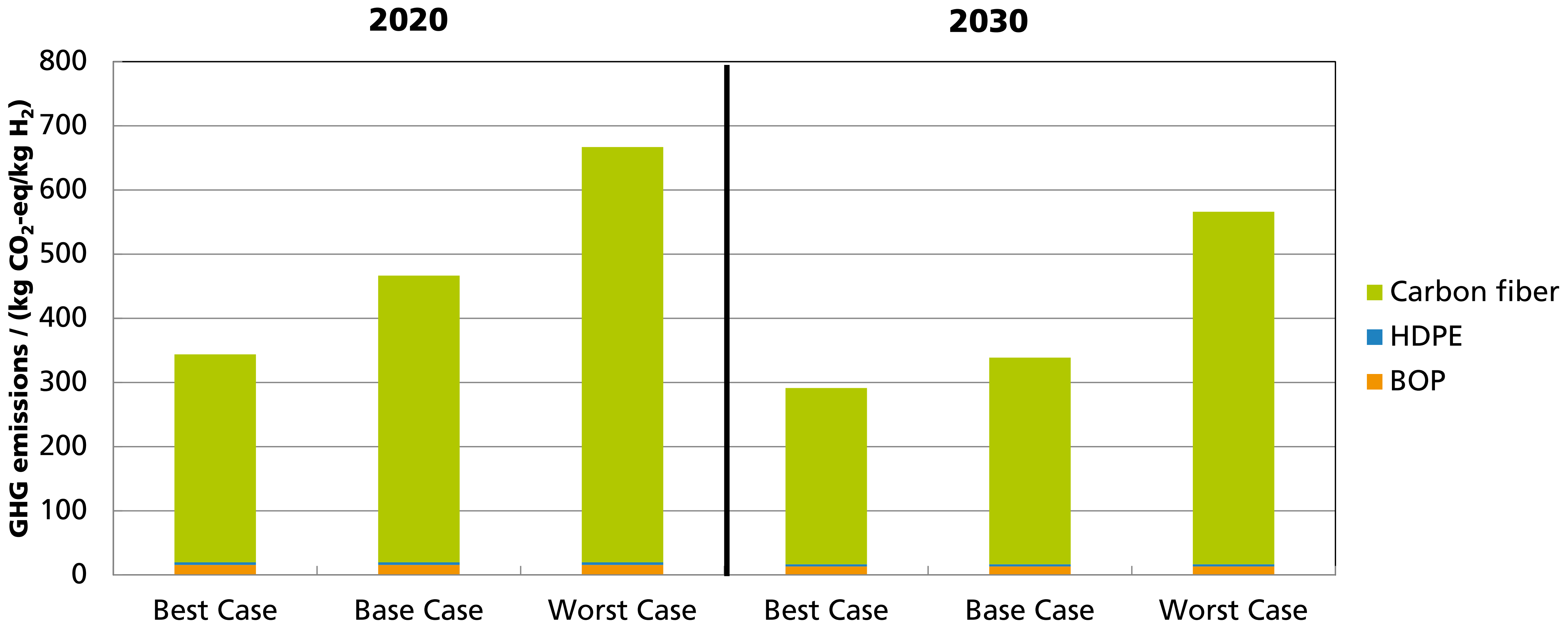
Manufacturing of hydrogen tank: GHG emissions



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 for carbon fiber

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: Base Case -10%	[Agora Verkehrswende, 2019]	Own assumption: Base Case +10%
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 electricity	[Agora Verkehrswende, 2019] grid mix of manufacturing countries	[Agora Verkehrswende, 2019] grid mix China	[IPCC] PV electricity	[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: Base Case -10%	[Miotti et al., 2017]	Own assumption: Base Case +10%	Own assumption: Base Case -10%	[Miotti et al., 2017]	Own assumption: Base Case +10%
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/

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