FVV

Research Association for
Combustion Engines

www.fvv-net.de/en

FVV FUEL STUDY IV

Sensible pathways to defossilised European mobility in 2050 on a cradle-to-grave basis

Sinnvolle Pfade zur Erreichung defossilisierter europäischer Mobilität in 2050 nach einem Cradle-to-Grave Ansatz

International Vienna Motor Symposium

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AiF Member

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→ Summary and Conclusions

APPROACH AND GENERAL ASSUMPTIONS

Overview of 42 Investigated 100% Scenarios

Simulation of the complete energy system for each energy/fuel pathway

Hypothetical 100% scenarios

42 Scenarios (100%) for Carbon Neutral Mobility in EU27+UK **in 2050 …** supplied solely by wind/solar energy

CO2-free electricity

2x Energy Sourcing:

Domestic vs. Global

Domestic | International

6 fuel types

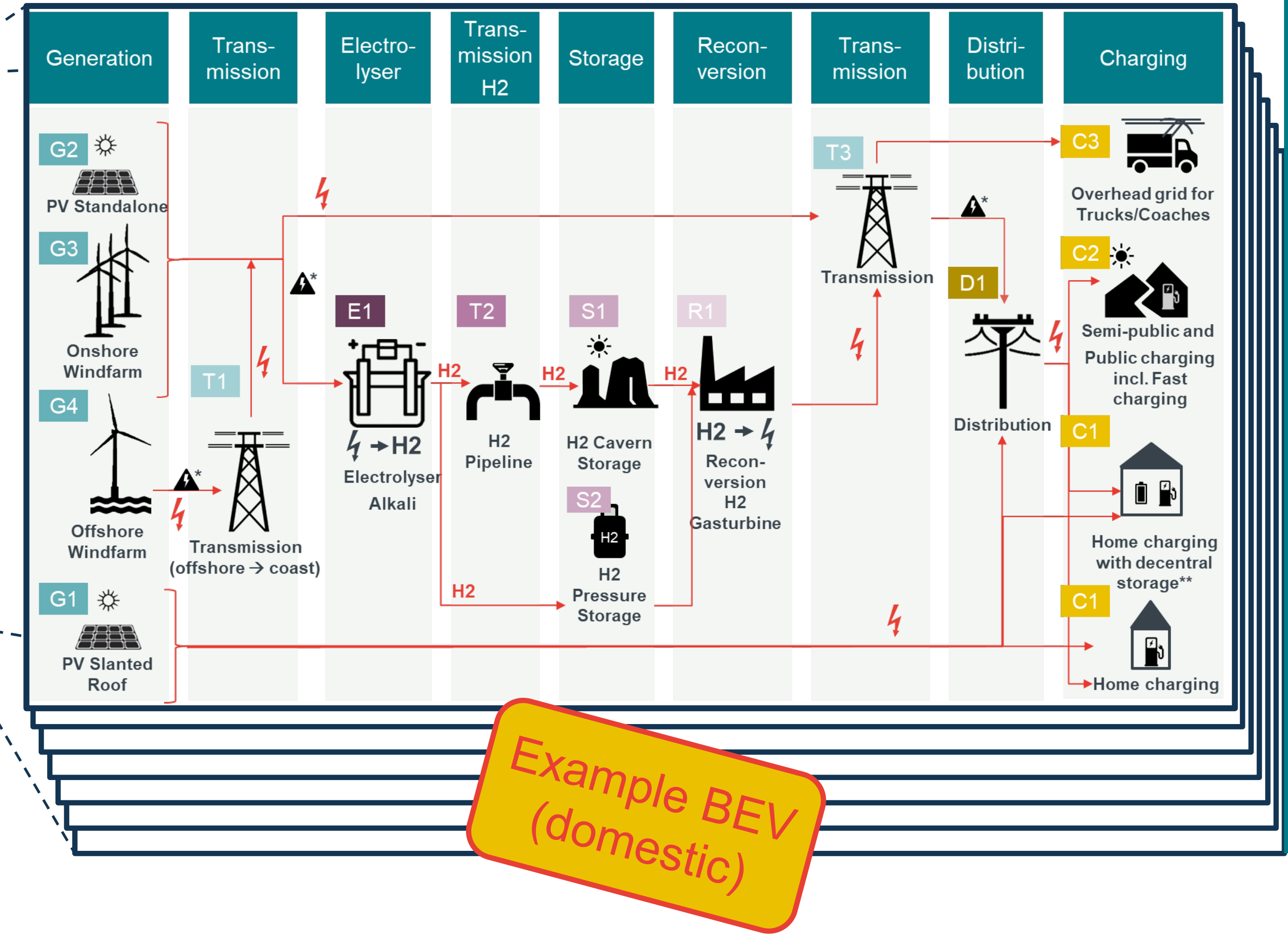
7 drivetrains

- Electric (BEV)
- e-H_2 (ICEV, FCEV)
- e-FT (ICEV)
- e-CH_4 (ICEV)
- e-MeOH (ICEV)
- e-DME (ICEV)

3 vehicle efficiency scenarios

- **Status Quo**
- **Balanced**
- **All-In**

… each taking the whole fuel supply chain into account. (C2G basis: vehicle operation/build/disposal, build-up of sustainable power generation and energy distribution).



Comparison of:

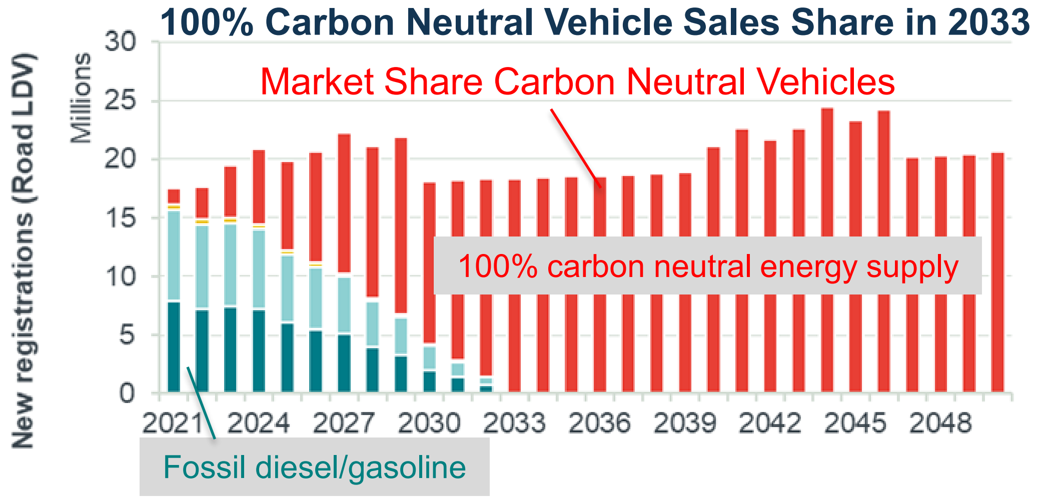
- Energy demand
- Power generation capacity
- Total Costs
- Cumulative GHG emissions
- Other environ-mental impacts (land use,…)

Fleet development (ramp-up) determined by vehicle lifetime

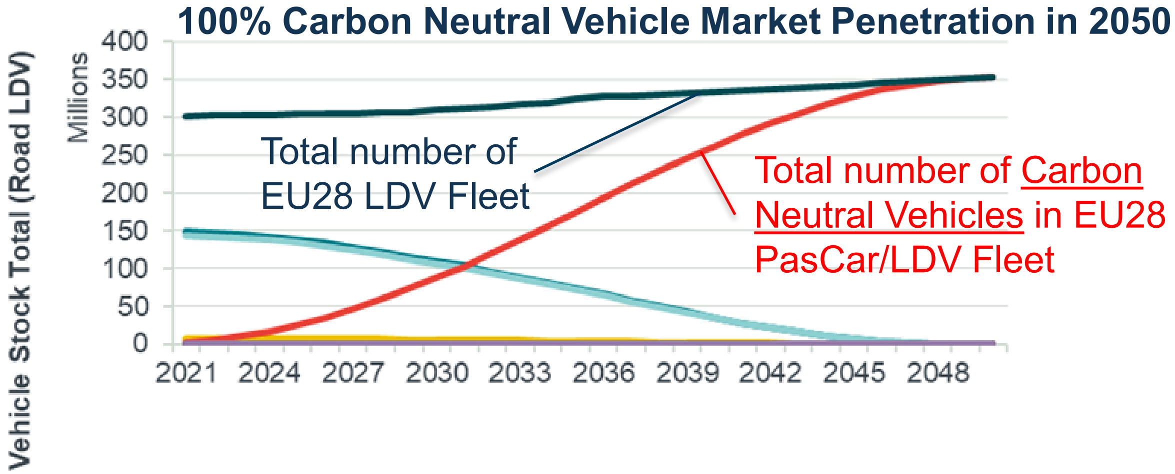
”Reference Ramp-Up”: ramp-up limited by vehicle fleet exchange rate

Example PasCar/LDV

Sales Share



Market Penetration



- Vehicles of out-phasing fleet, operated with fossil diesel
- Vehicles of out-phasing fleet, operated with fossil gasoline
- New carbon neutral vehicles, operated with defossilized fuel/energy
- Total number of vehicles (fleet stock)

- Theoretical ramp-up gradient, determined by fleet exchange rate.
- Same gradient for all pathways (also for drop-in FT fuel !)
- Further bottlenecks → follow-up study (FVV Fuels Study IV b).

- **Target “carbon neutrality 2050” requires 100% carbon neutral vehicles in 2050**
- **Assumption: All new vehicles exclusively operated with renewable energy !**

ENERGY ANALYSIS

Well-to-Wheel Energy Demand 2050 (2,000…10,000 TWh/a)

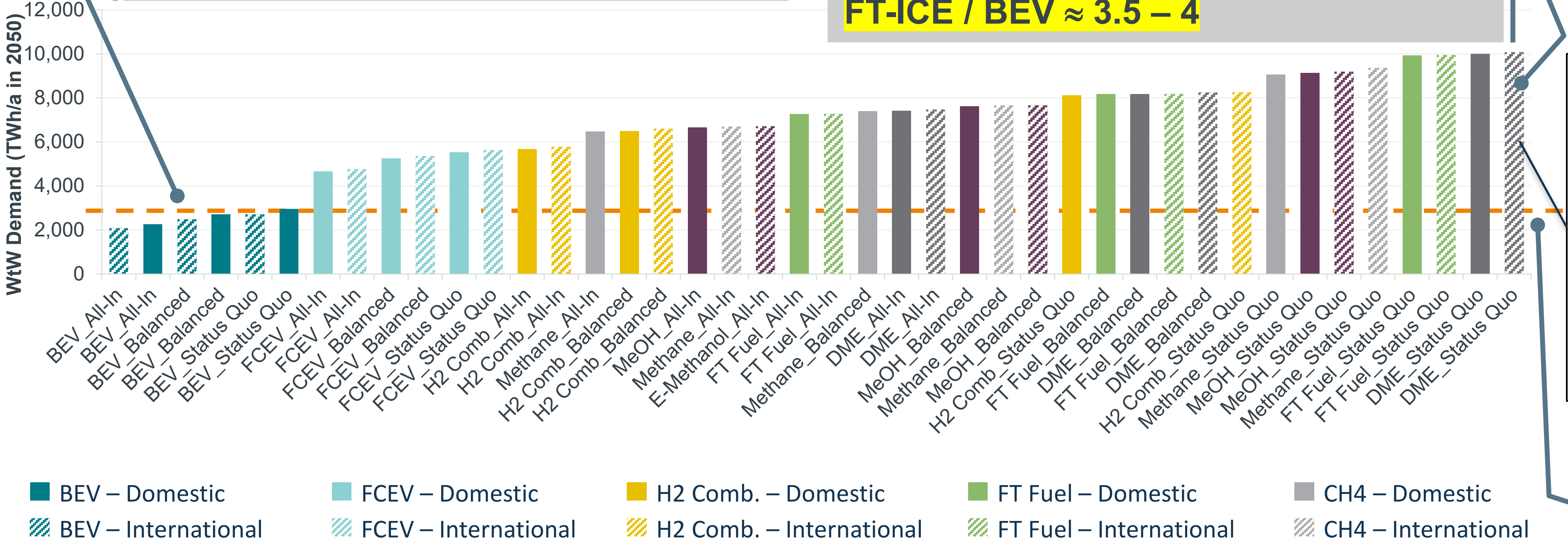
Calculation based on modelling whole fuel chains (isolated for transport sector)

Lowest WtW energy demand for BEV followed by FCEV. **Factor: WtW energy demand H2-FCEV / BEV ≈ 2**

Higher WtW energy demands for ICEV. Factors: WtW energy demands
H2-ICE / BEV ≈ 2.5 – 3
FT-ICE / BEV ≈ 3.5 – 4

Road segment only

Well-to-Wheel Energy Demand 2050 / TWh



Solid bar: domestic energy sourcing

Dashed bar: global energy sourcing

For comparison: Electricity Consumption EU-28 **(all sectors !)** is approx. 2.900 TWh p.a.

Environmental impact & costs → **not Energy Demand, but Installed Capacities matter** → highly depend on geographic location **(≈ 750…4,800 GW)**

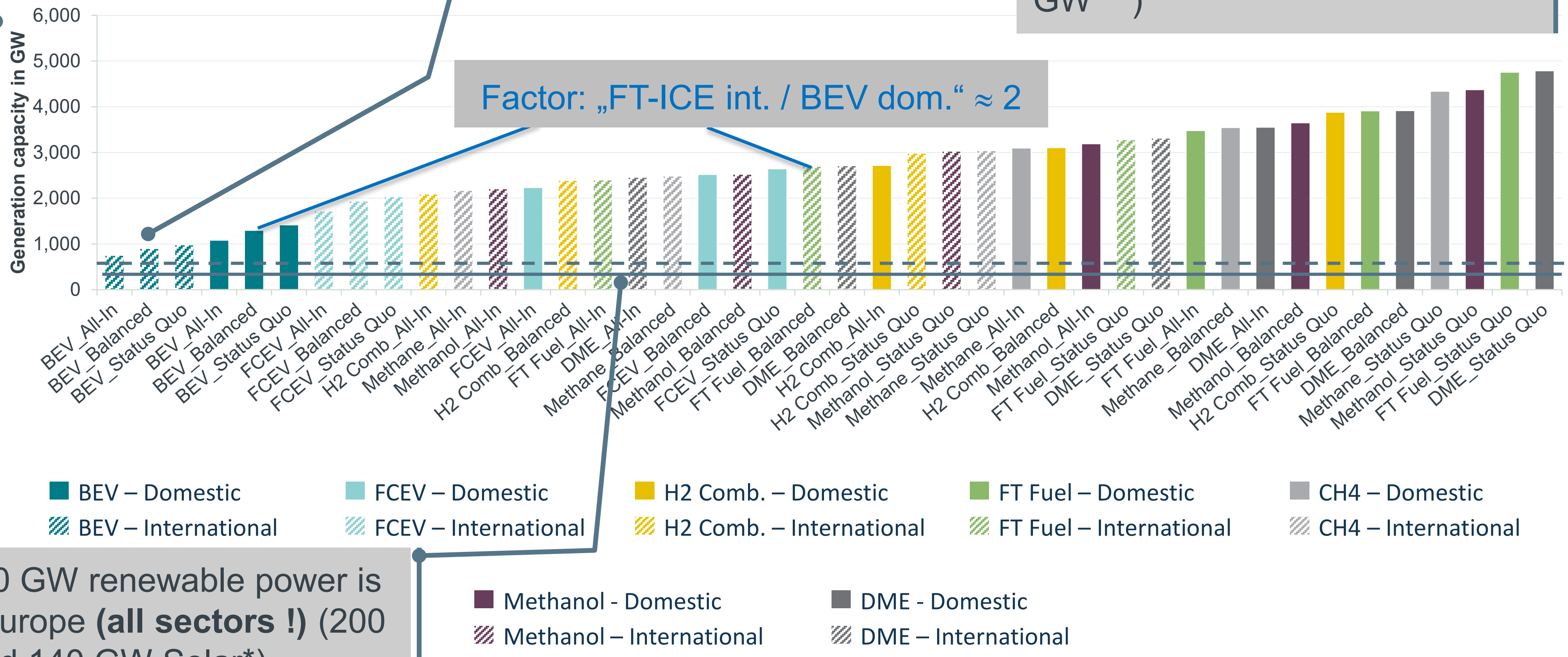
Installed capacity driven by total WtW demand and by achievable full-load-hours (location)

International scenarios require less installed capacity than domestic

EU estimates: installed capacity **(all sectors !)** 690 GW by 2030 (wind 350 GW**, solar 340 GW***)

Road segment only

Installed Power Generation Capacities 2050 / GW



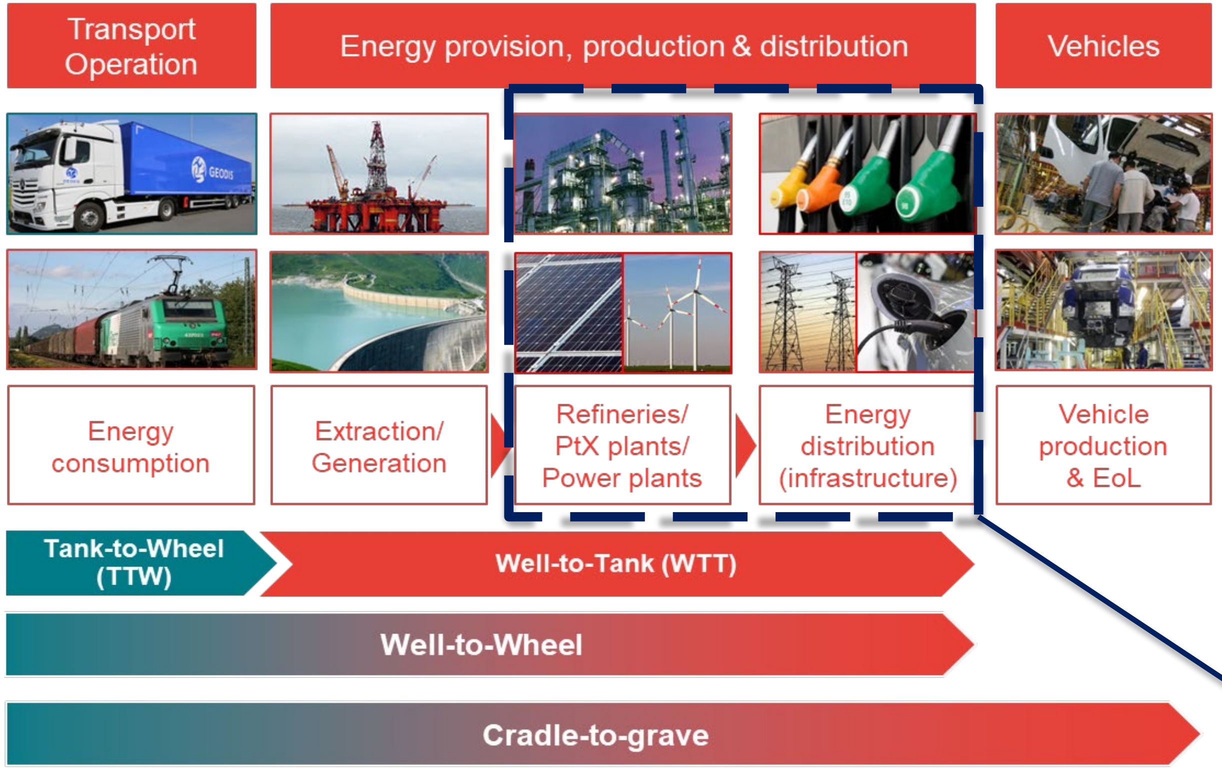
Currently 340 GW renewable power is installed in Europe **(all sectors !)** (200 GW Wind and 140 GW Solar*)

*Irena (2020) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf
** https://ec.europa.eu/info/research-and-innovation/research-area/energy-research-and-innovation/wind-energy_en#:~:text=The%20EU%20currently%20has%20the,to%2024%25%20of%20electricity%20demand
*** https://www.solarpowereurope.org/national-energy-and-climate-plans-a-solar-powered-energy-system-by-2030/

ENVIRONMENTAL IMPACTS – GREEN HOUSE GAS

Environmental impacts analysis

Cradle-to-Grave (C2G) analysis approach



Separate disclosure of **building-up** the power generation and energy/ fuel distribution infrastructure

Total environmental impacts per year

Environmental impacts vehicle operation + Environmental impacts FSC build-up + Environmental impacts vehicle production & disposal = **Total environmental impacts**

→ Emissions are accounted **in the year they occur**, not depreciated over lifetime

Environmental databases and studies

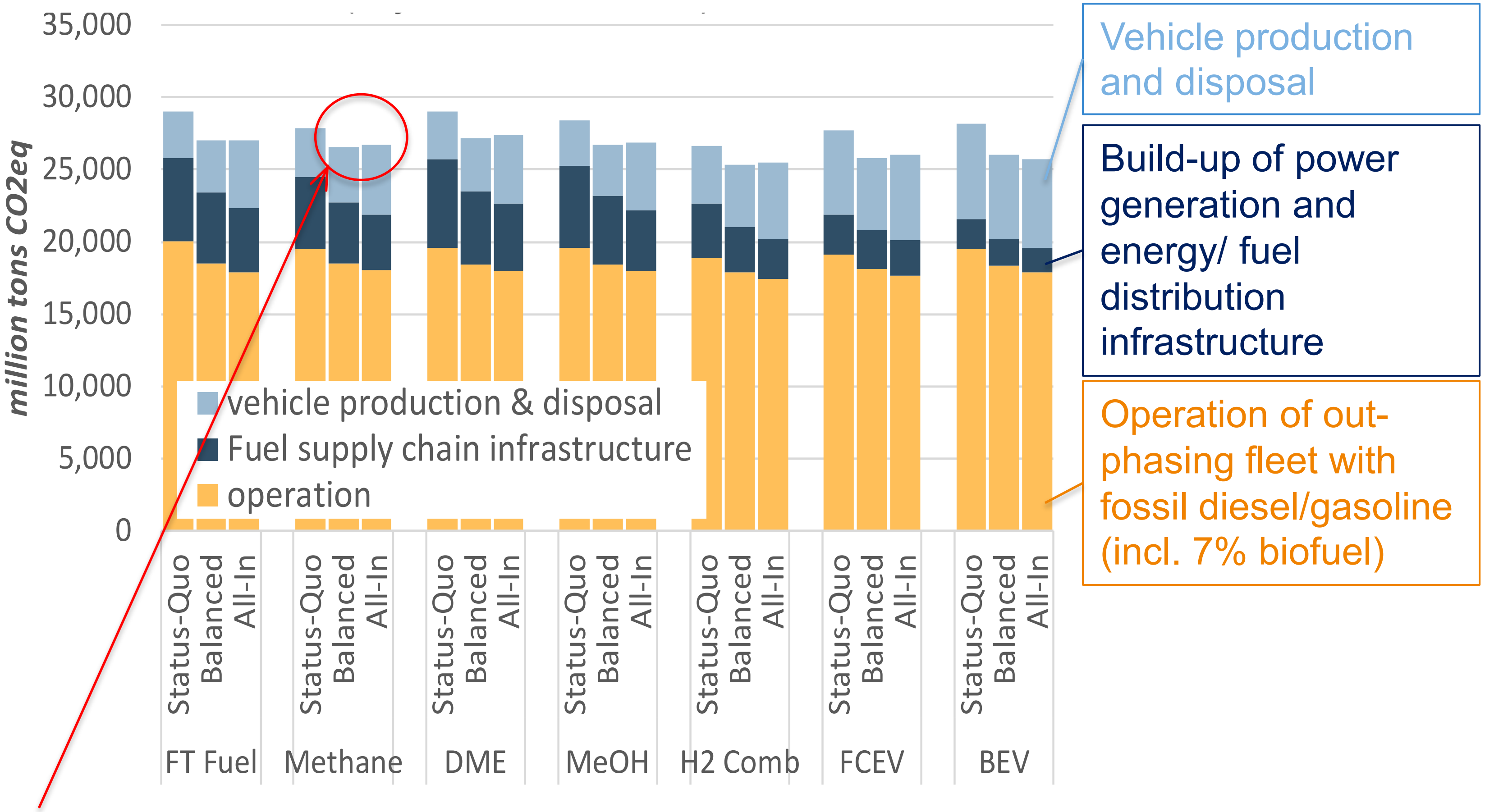
- LCA databases and models: e.g. EcoInvent, Umberto, eLCAr
- Emission factor databases: HBEFA 4.1, TREMOD
- ifeu scientific studies: e.g. SYSEET, RESCUE
- Scientific literature research

Cradle-to-grave (C2G) approach

includes GHG emissions of
- fossil fuels consumption (wtw)
- building-up defossilised energy supply and distribution infrastructure
- vehicle production and disposal

Environmental impacts analysis

Cumulative GHG emissions (2020 – 2050) with identical ramp-up for all 100% pathways



- Improved vehicle efficiency reduces GHG of vehicle operation, but is over-compensated by increased GHG of vehicle production → **Improving vehicle efficiency can lead to increased total GHG**.

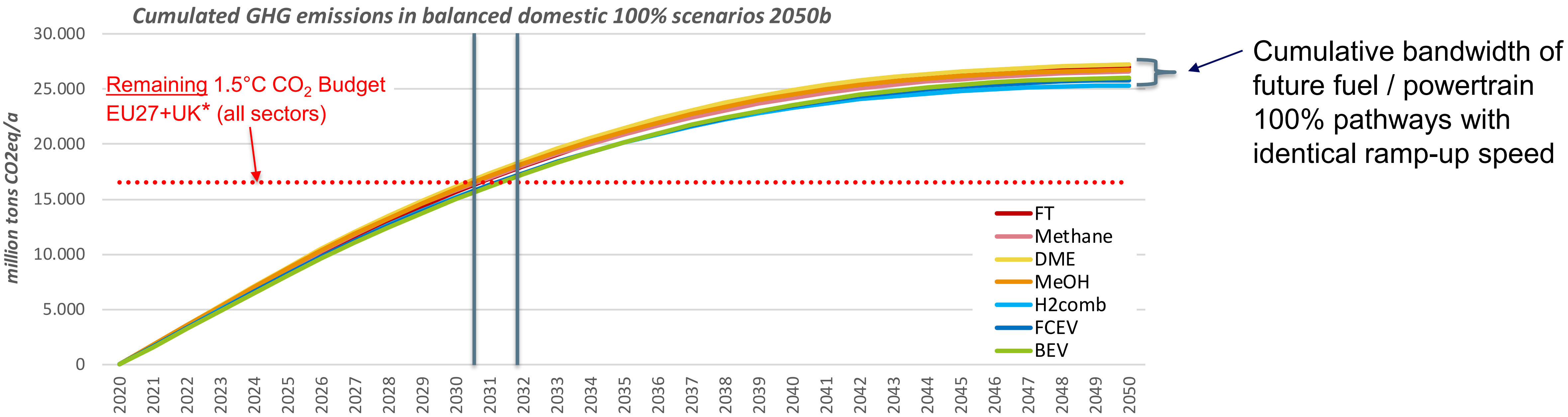
Global warming is determined by cumulative GHG emissions:

- **Vehicle operation** of out-phasing fleet with fossil fuels dominates cumulative GHG emissions with ≈ **70%** in all 100% scenarios.
- ≈ **30%** of cumulative GHG emissions are from **vehicle production/disposal** and **building up the complete renewable energy infrastructure** in all 100% scenarios
- **55-60%** of the cumulative GHG emissions are emitted before **2030**

→ Fast replacement of fossil fuels for vehicle operation is essential for reducing cumulative GHG emissions!

Environmental impacts analysis

Comparison of cumulative GHG emissions with remaining CO_2 budget



- No significant differences in cumulative GHG between pathways (with identical ramp-up determined by fleet exchange rate)
- EU27+UK's **1.5°C CO_2 budget* for all sectors will be exceeded soon (2031/32) just by transport** with assumed ramp-up speed**
  (**28% fossil energy replaced in transport incl. vehicle & energy system production by 2030)
- **Fast action required for a quick reduction of fossil fuel use, also in the existing vehicle fleet**

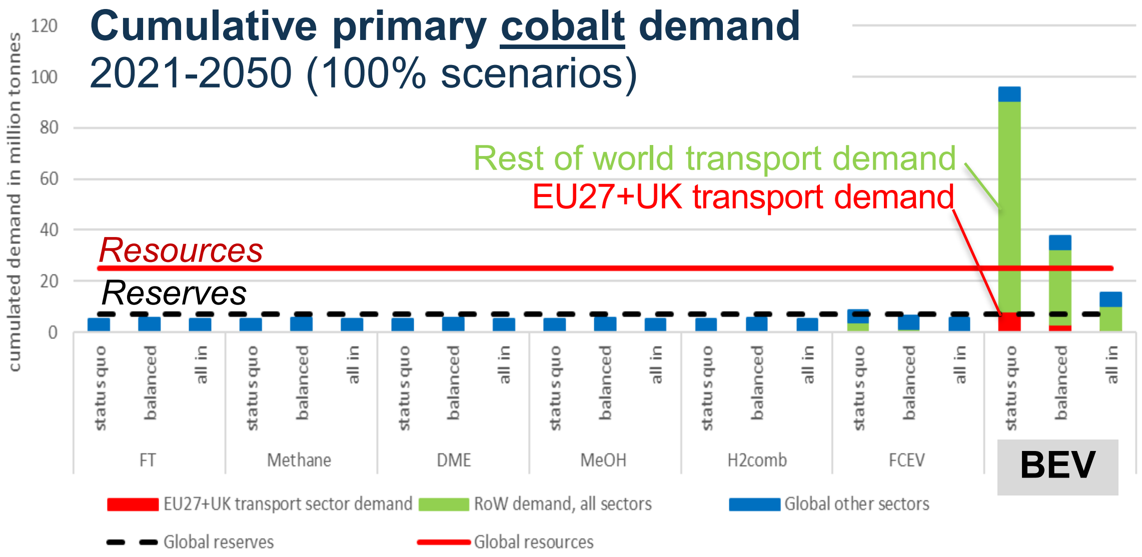
* **1.5°C 67th TCRE European share according to population share (6.5%)** for EU27+UK; cumulative GHG from transport on C2G basis: including build-up of FSC infrastructure + vehicle production/disposal)

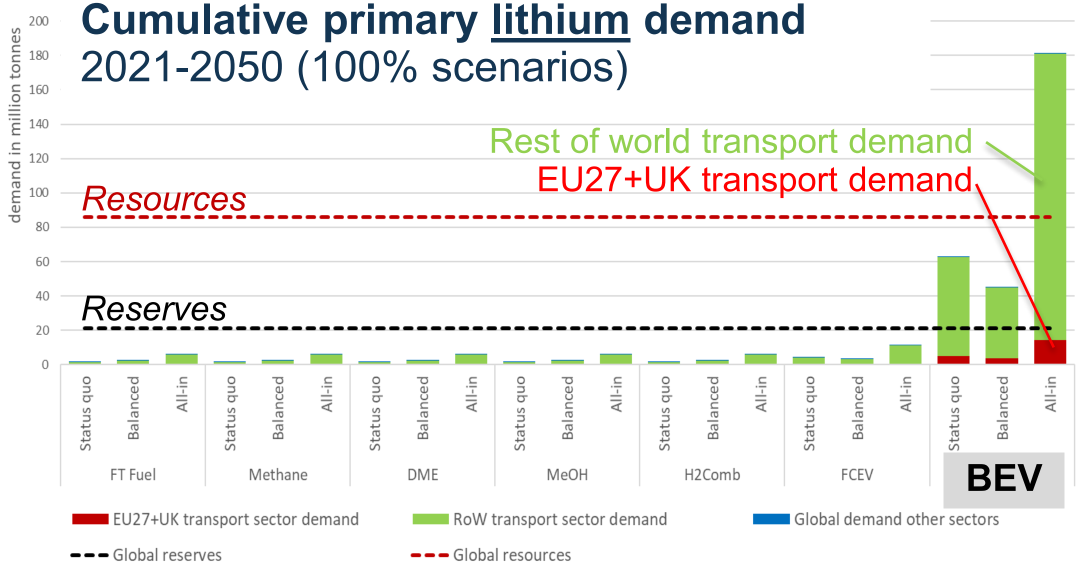
RAW MATERIAL DEMAND

Critical raw materials for BEV (100% scenarios, worldwide demand)

Cobalt and **Lithium** can become a bottleneck in 100% BEV Scenarios

- **Cobalt & lithium** reserves: sufficient to **fulfil cumulative <u>EU27+UK mobility demand</u> for 100% BEV[1]**
- **<u>Worldwide BEV ramp-up</u> could lead to** (temporary*) **material bottlenecks for 100% BEV[1]**
  - *Lower global Co/Li demand likely (weaker global motorisation increase; battery mix with reduced Co/Li demand (LFP, SIB, ..);
  - *Co/Li resources and reserves increased dynamically in recent years → future increase of primary material supply expected





[1]with assumed battery configurations and extrapolated worldwide motorisation (economic catch-up to EU):
- *300-500km vehicle range, Li-Ion NMC as state-of-the-art battery technology on the EU market*
- *Economic catch-up of all countries and same per-capita-vehicle sales by 2050 as in EU (~300 million new vehicles/year worldwide in 2050)*

[1] Assumptions	Status Quo	Balanced	All-In
Battery type	NMC 622	NMC 811	NMC 811 solid state
Energy density (system level)	150 Wh/kg	200 Wh/kg	300 Wh/kg

Critical raw materials for FCEV (100% scenarios, worldwide demand)

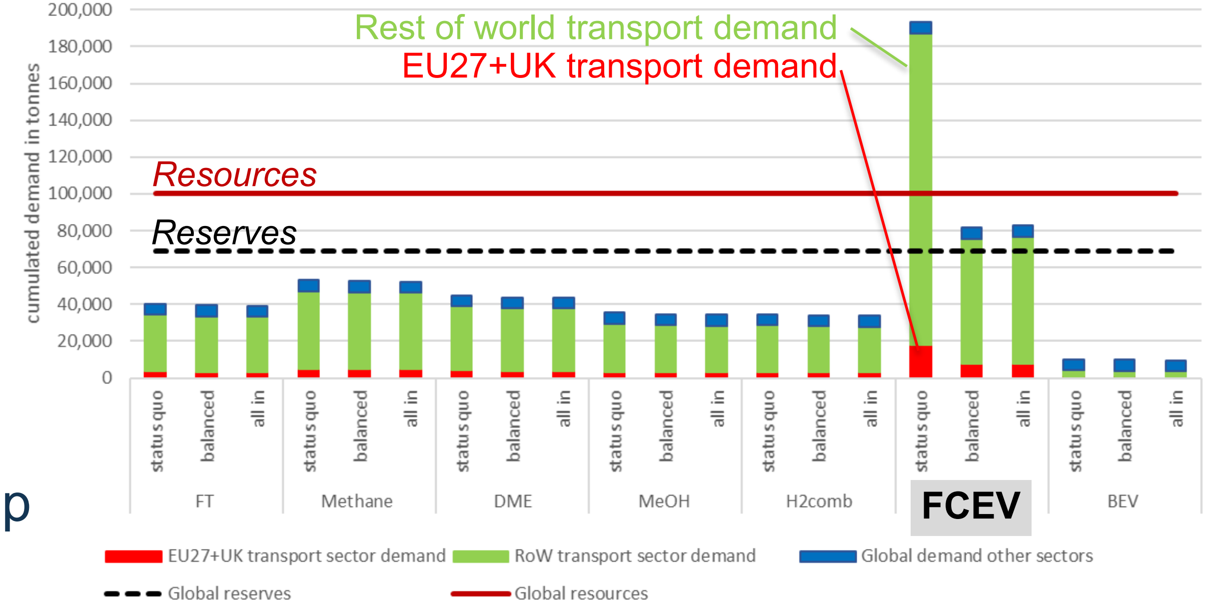
Platinum group metals (PGM) → bottleneck for worldwide FCEV

→ Current PGM reserves are sufficient to fulfil European cumulative demand for primary PGM for transport in all 100% scenarios.

→ **For 100% FCEV pathways, a platinum bottleneck arises at global scale.**

→ Weaker worldwide increase of vehicle sales and further exploration activities (including deep mining) could enable 100% FCEV worldwide.

Cumulative primary PGM demand
2021-2050 in the 100% scenarios



* PGM: Platinum Group Metals (i.e. Platinum, Rhodium, Palladium)

→ **Further materials** required in the fuel supply chain (copper, silver, nickel,…) **could cause (temporary) bottlenecks in all fuel pathways**. Proactive demand & supply strategies can prevent bottlenecks.

RESULTS ECONOMIC ANALYSIS

Main results: Incremental* Costs (NPV**) across all scenarios (2,600 … 5,300 bil. €)

“International”, “Status Quo” Methanol, CH4, FT at the low end

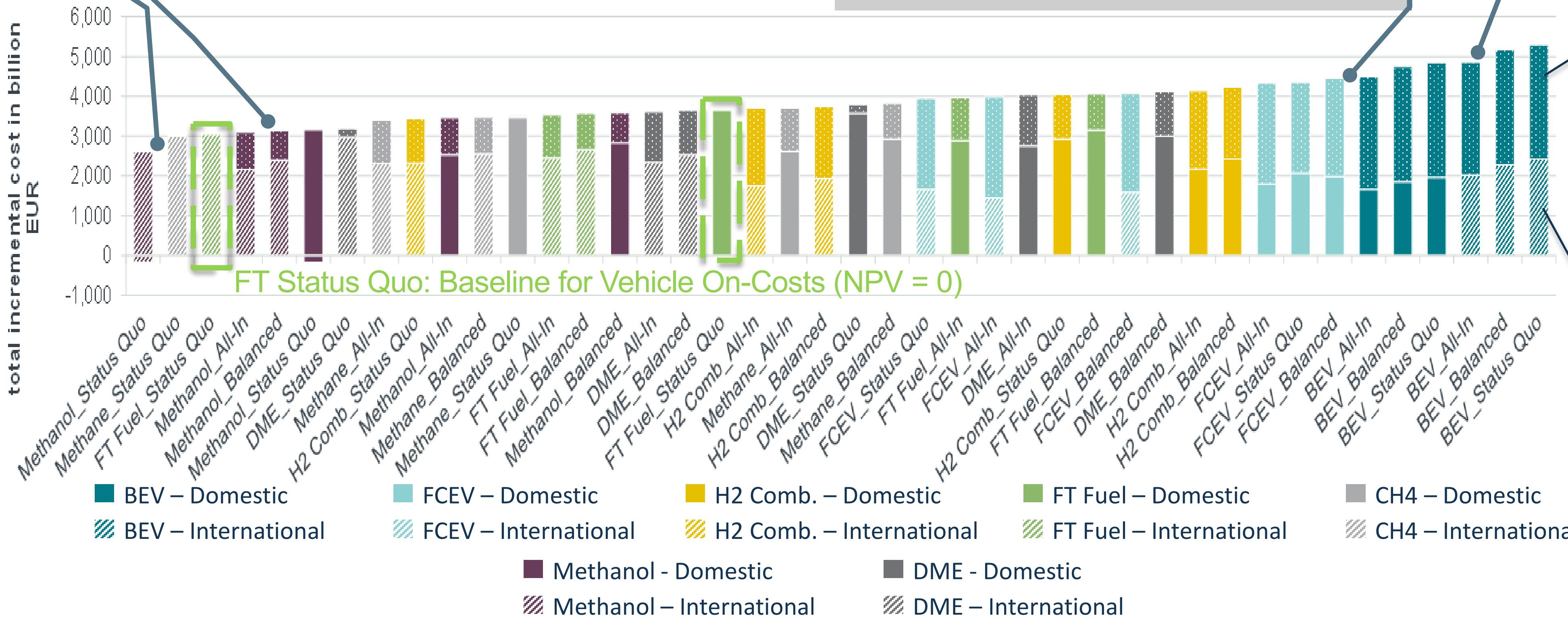
More efficient ICEV (Balanced/All-in) typically more expensive
→ lower fuel costs do not compensate higher vehicle costs

BEV at the high end, followed by FCEV

International cheaper than domestic scenarios, except for BEV (→ high costs for HVDC*** power line)

Road segment only

Total Incremental Cumulative Costs 2020…2050 / bil. €



Upper bar: vehicle on-costs (NPV)

Lower bar: energy supply costs (solid: domestic sourcing; dashed: global sourcing)

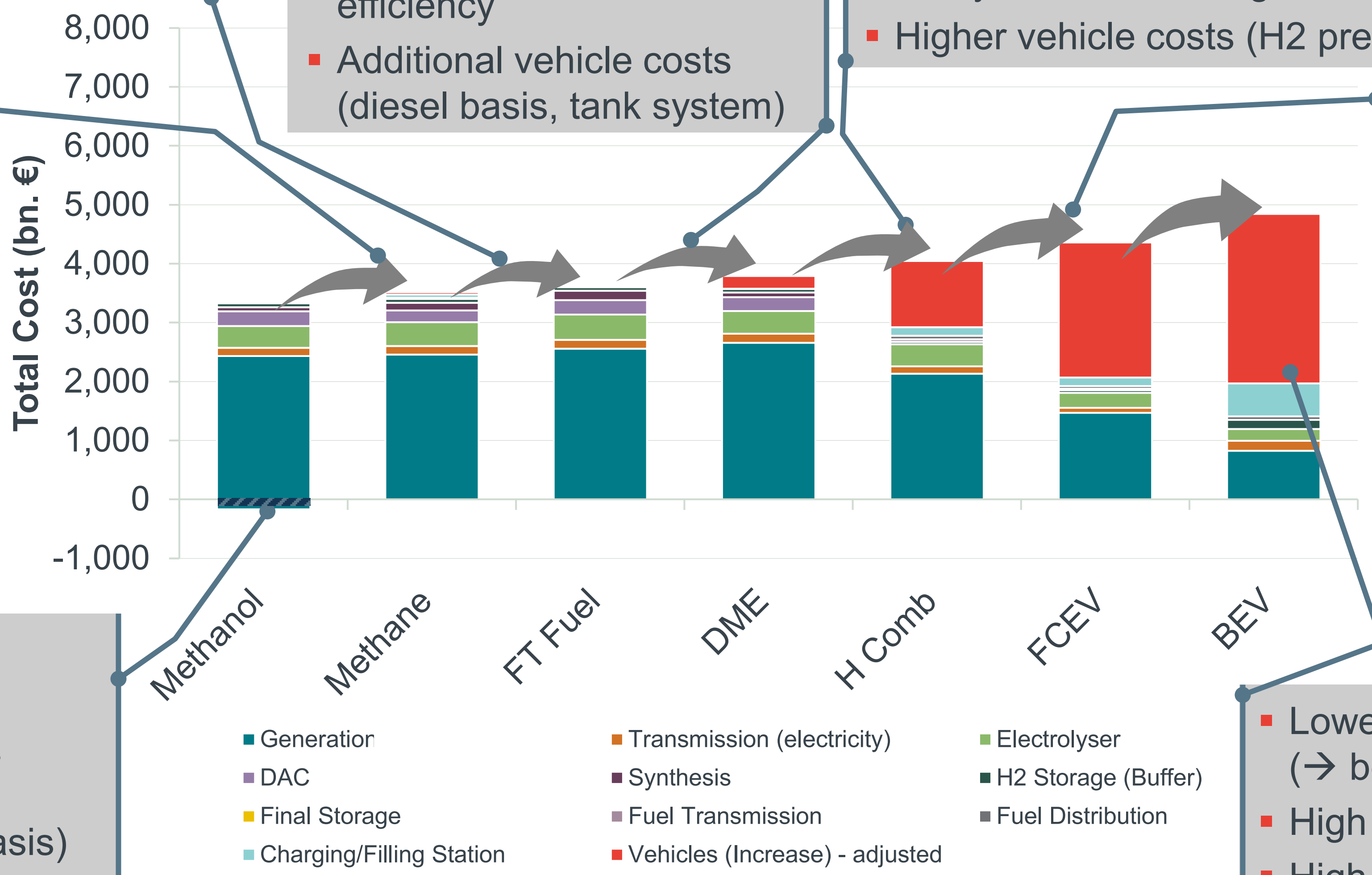
*Incremental vehicle costs relative to **FT Status Quo** vehicles (gasoline and diesel)

**NPV: Net Present Value ***HVDC: High Voltage Direct Current

Technology Cost Walk – Costs traced back to main drivers

Status Quo domestic scenario

Cumulative Total Costs 2020…2050 / billion €



Lower synthesis efficiency

- More complex fuelling infrastructure
- Higher vehicle costs (pressure tanks)

- Comparable synthesis efficiency
- Additional vehicle costs (diesel basis, tank system)

- No synthesis → less generation capacity required
- Higher vehicle costs (H2 pressure tanks)

- Less generation capacity required, due to better efficiency of fuel cell vs. ICE
- Higher additional vehicle costs by fuel cell

- High synthesis efficiency
- Low vehicle costs (negative vs. FT diesel/gasoline basis)

- Lowest generation capacity (→ best WTW efficiency)
- High additional vehicle costs
- High costs for charging infrastructure

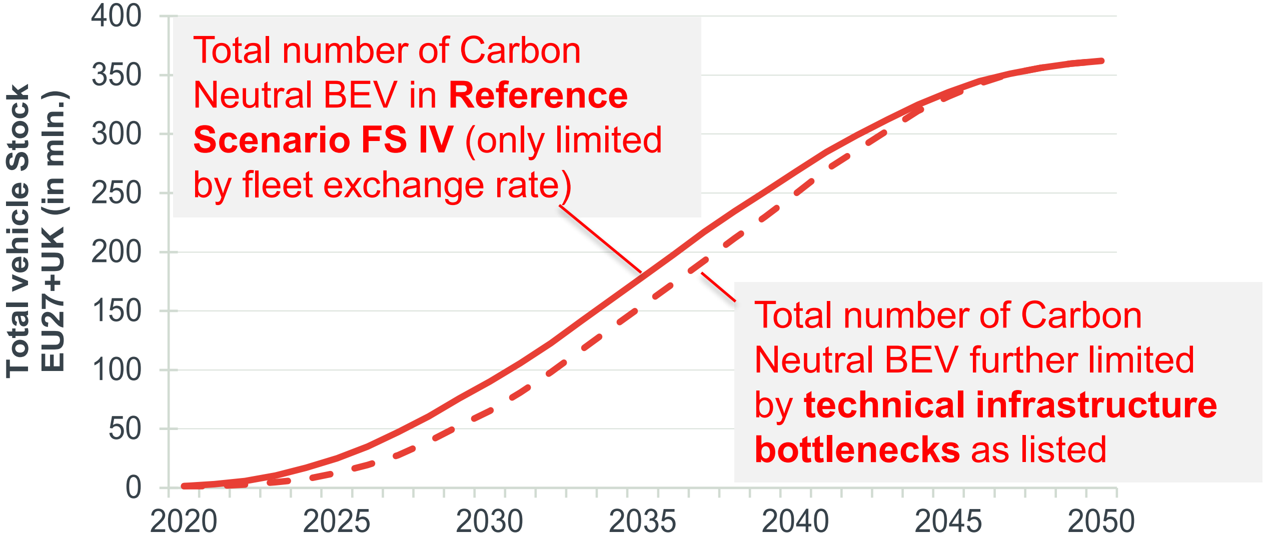
OUTLOOK - ACHIEVABLE RAMP-UPS

Outlook: achievable ramp-ups - effect of "technical (!)" bottlenecks

Technically achievable ramp-ups slow down 100% sustainable BEV penetration

Example: 100% BEV (preliminary)

Carbon Neutral PasCar/LDV Market Penetration "reference scenario" vs. "further technical bottlenecks"



Focus solely on "**technical bottlenecks**", assuming **ideal financial and legal ramp-up conditions** (similar to "COVID 19 vaccine development" → accelerated (from usually 10 years) to 1 year

Technical bottleneck *		Comment
Wind/PV capacity	✓	No binding bottleneck expected
Power grid extension	?	Short/medium term bottleneck expected, e.g. power grid extension on transmission level
Electrolysis (required for energy storage)	?	Bottleneck expected until 2023/2024
Charging infrastructure	?	Bottleneck for fast/public charging expected until ≈2025
Battery manufacturing	✓	No binding bottleneck expected
… further bottlenecks	tbd.	*E.g. critical materials*

- → **Fuel Study IV:** only 1 ramp-up bottleneck applied: "vehicle fleet exchange rate"
- → **Follow-up Fuel Study IVb**: considers **all potential technical bottlenecks → more realistic cumulative GHG emissions**
- → **100% BEV example:** infrastructure ramp-up bottlenecks are likely to further slow down GHG avoidance
- → Further bottlenecks (e.g., materials) will be considered in FS IVb. **Final (mixed) scenarios** → FVV Autumn Conference 2022.

** Listed bottlenecks serve as examples for elements considered in FS IVb; further bottlenecks (not listed here) are considered in Fuel Study IVb; vehicle fleet development from FS IV serves as reference scenario (limited solely by fleet exchange rate)*

SUMMARY AND CONCLUSIONS

Summary

Key Findings (1) – Environmental Impacts - GHG Emissions

→ **Cumulative GHG emissions** (C2G: 2021 – 2050) are dominated by **vehicle operation** with fossil fuels* of the out-phasing legacy fleet by ≈ **70%.**

→ Ramp-up of **renewable energy/fuel supply chain infrastructure** + **vehicle production/disposal** contribute ≈ **30% to cumulative GHG emissions**

→ **Ramp-up speed of sustainable pathways is "the crucial factor" to reduce cumulative GHG emissions**

→ With the assumed identical ramp-ups **EU27+UK transport GHG emissions** (C2G incl. FSC**) **will exceed total** (assumed European) **GHG budget for Paris 1.5°C target*** in 2031-32**

→ **Carbon neutral drop-in fuels** could be an option for faster introduction of GHG neutral energy to road transport. **Challenge: ramp-up of sustainable energy supply** → follow-up study (FVV Fuels Study IV b)

* Fossil fuels already blended with 7% biofuel share
*** 67% Probability

**Fuel Supply Chain

Summary

Key Findings (2) – Total Incremental Costs (NPV)

→ **Carbon Neutral Transportation in 2050 is affordable →** Total costs (NPV): 2,600 … 5,300 bil. € over 30 years → 17% … 34% of annual GDP 2020 (15,600 bil. €) → ≈ 1% of GDP per year over 30 years

→ International energy sourcing is cheaper than domestic for ICE and FCEV (→ higher full load hours in sweet spots), except for BEV (→ expensive installation of HVDC power line)

→ **Highest costs** (NPV) **for BEV** (4,500 … 5,300 bil. €) followed by FCEV (3,900 … 4,500 bil. €)

- Vehicle costs are dominating total costs
- BEV costs are determined by range* and battery costs** assumptions

→ **Lowest costs** (NPV) **are for ICEV with continued 2020 vehicle technology** ("Status Quo" pathway: without hybridization or light-weight measures)

- Methanol ICE: ~2,600 billion €, FT-diesel/gasoline-ICE: ~3,000 billion €, H2-ICE ~3,500 billion €.
- It is more cost efficient to build additional power generation and energy/fuel distribution infrastructure, than to maximise efficiency measures (at high cost) on vehicle level.
- While hybridization reduces cumulative GHG emissions, light-weight measures can increase them.

* 300 – 500km passenger car/LDV range

** Specific battery system costs: 160 €/kWh for 2020, 120 €/kWh for 2030, 80 €/kWh for 2050

Summary + Conclusions

Key Findings (3) – Other Environmental Impacts / Material Demand + Conclusions

→ Land use, eutrophication, PM formation and acidification are no bottlenecks

→ **Temporary Li and Co bottlenecks** are expected in **a worldwide 100% BEV ramp-up**

→ **Pt bottlenecks** are expected **in a worldwide 100% FCEV ramp-up**

Conclusions:

→ **Paris climate targets require defossilisation measures for the existing vehicle fleet** (e.g. drop-in e-fuels)

→ **A mix of carbon neutral technology pathways is likely to be the fastest and thus most efficient way to minimize cumulative GHG emissions** (e.g. BEV with domestically sourced energy and drop-in e-fuels with internationally sourced energy)

→ Increasing vehicle efficiency is not always leading minimum GHG emissions and lowest total incremental costs → **Efficient GHG avoidance policy requires a "Technology Neutral" approach for efficient overall GHG reduction at lowest costs.**

→ If sector targets are set, they need to be well aligned with the life cycle approach

Expression of Gratitude

We would especially like to thank the many colleagues from Frontier Economics, ifeu and the FVV working group "Fuels" who supported this study.

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Complete Study - Download:
https://www.fvv-net.de/en/media/news/detail/energy-transition-of-transport-valid-insights-can-only-be-obtained-by-simulations-of-the-entire-ene/

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BACKUP

Approach: FVV Fuels Study IV

Significant extension of FVV III scope

	Basis FVV study # III (2018)	***Step 1*** Long term vision with autarchy	***Step 2*** Glidepath implications	***Step 3*** Global fuel trade implications	***Step 4*** Close to cost- / GHG-optimal solution
Assumptions	▪ 100% CO_2 free world (2050+) ▪ 100% technology scenarios ▪ WtW ▪ Automotive only (1 vehicle) ▪ Focus Germany	✚ Vehicle life (Cradle-to-Grave) & energy provision ✚ All transport sectors ✚ Focus on Europe	✚ Glidepath today → 100% GHG free world 2050+ ✚ Energy sourced in Europe	→ Energy sourced worldwide	✚ Approximately three mixed technology scenarios with fastest CO_2 reduction at minimum cost (trade-off)
Results	▪ Primary energy demand 2050 ▪ Mobility / investment costs 2050	✚ Land use 2050 ✚ Demand vs. availability of critical rare materials ✚ Further critical environmental impacts ✚ Unavoidable GHG →	✚ All snapshots of 2050 now as glidepath from today until 2050 as f(t) → 1 ramp-up gradient only (determined by vehicle fleet exchange rate) ✚ ~~Bottlenecks in timeline (vehicle fleet exchange rate, PtX plant development, renewable electricity availability)~~ GHG emissions as f(t); Cumulative GHG 2050		✚ Minimise mobility / investment costs with mixed technologies scenarios Minimise C2G GHG emissions as fast as possible with mixed technologies scenarios
Goal:		Covered in FVV Fuels Study IV			**Meaningful Route → Follow-Up Study "FVV Fuels Study IVb"**

Current scope of the analysis

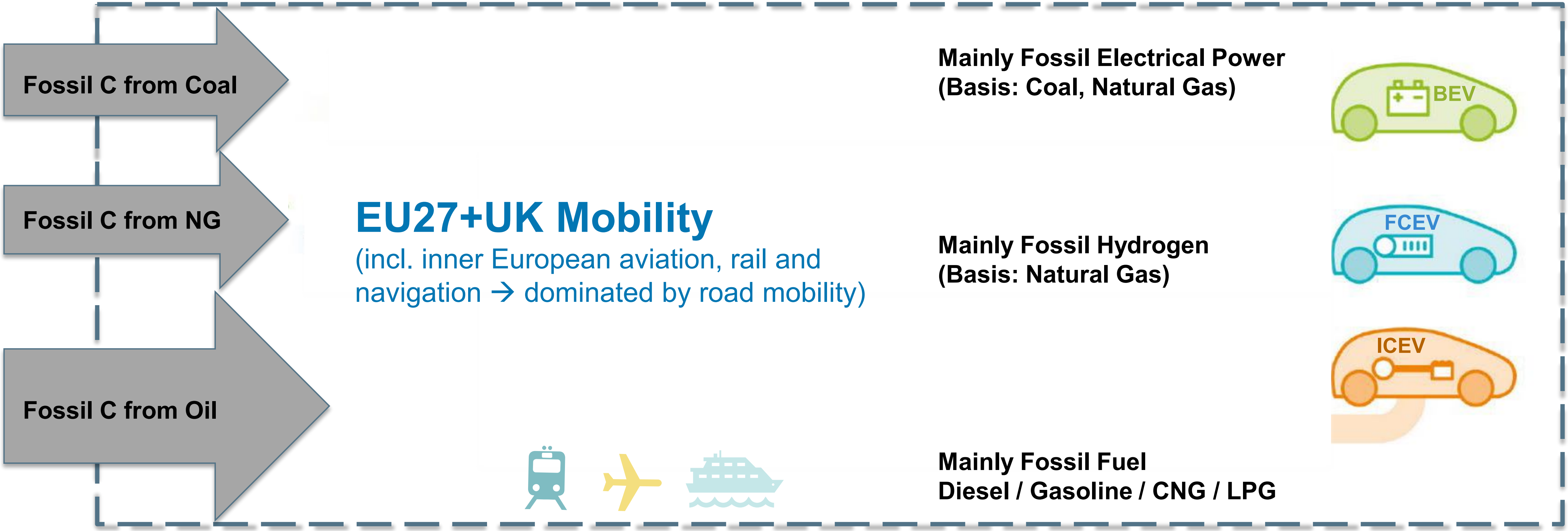
Report Out in 11/2021

FVV Fuels Study IV Results

WTW* GHG** Emissions of European Mobility Today

Dominated by fossil energy carriers

Enrichment of atmosphere with fossil carbon



→ System Boundary of FVV Fuels Study IV

* WTW: Well-To-Wheel

** GHG: Green House Gas

BEV: Battery Electric Vehicle

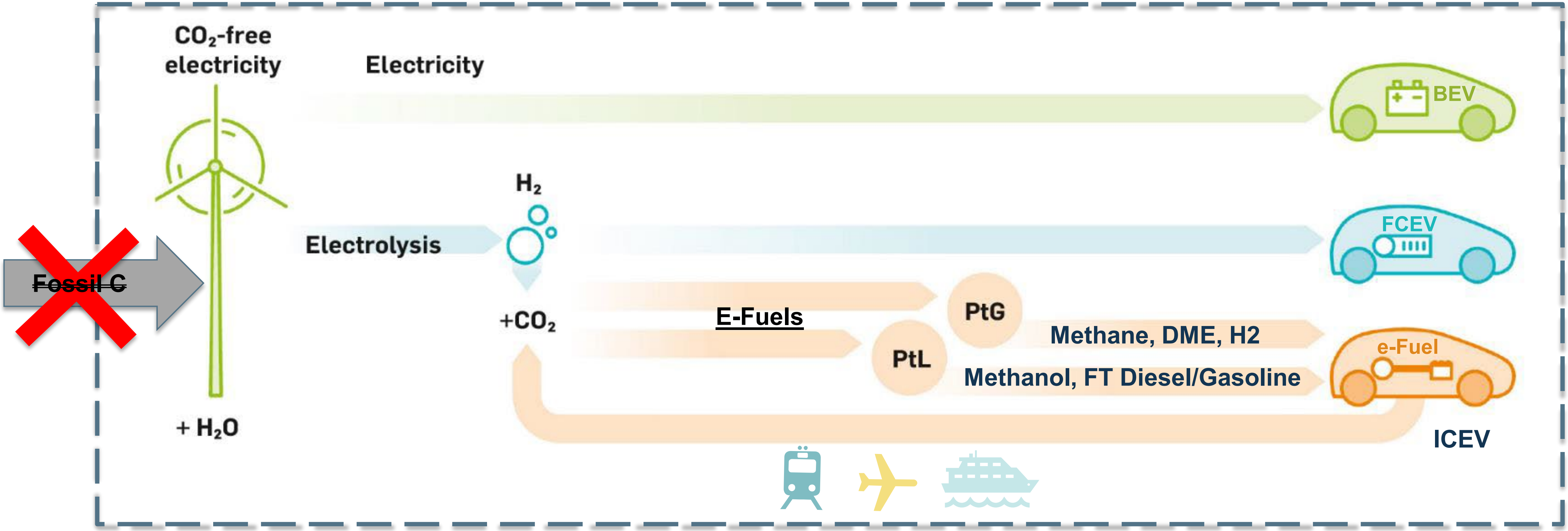
FCEV: Fuel Cell Electric Vehicle

ICEV: Internal Combustion Engine Vehicle

No Fossil Carbon Enrichment in System Boundaries of FVV Fuels Study IV

WTW* Carbon Neutral European Mobility in 2050

100% Scenarios for GHG neutral (carbon neutral) mobility on a WtW* basis (photo year 2050)**



All future propulsion pathways operated by carbon neutral electricity (solar / wind).

Closed carbon circuit → no enrichment of fossil C in atmosphere

* WTW: Well-To-Wheel
** GHG: Green House Gas

BEV:	Battery Electric Vehicle
FCEV:	Fuel Cell Electric Vehicle
ICEV:	Internal Combustion Engine Vehicle

Simulation Basis – Road Transport / Other Transport Sectors

Bottom-Up Approach (Fleet Composition) for Road Transport

Example BEV

Technology Pathways – 100% **Electric** Scenario			
Road	Passenger	Small	BEV ✓
		Medium	BEV ✓
		Large	BEV ✓
		SUV	BEV ✓
		LCV	BEV ✓
	Freight	< 7.5 t Rigid	BEV ✓
		< 16 t Regional	Grid Bound ✓
		< 40 t Long Haul	Grid Bound ✓
		> 40 t Super Long Haul	Grid Bound ✓
	Buses	Public Transport	BEV ✓
		Coach	Grid Bound ✓
Rail		Passenger	100% Electrification ✓
		Freight	100% Electrification ✓
Aviation			FT Kerosene
Shipping			FT Fuel

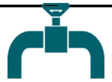
- **Detailed bottom-up simulation approach for road transport, based on fleet composition**
- **High level approach (energy based) for other transport modes**

International Energy Sourcing Scenario

Assumptions: import options

International

The most economically viable import option is chosen for each fuel and location !

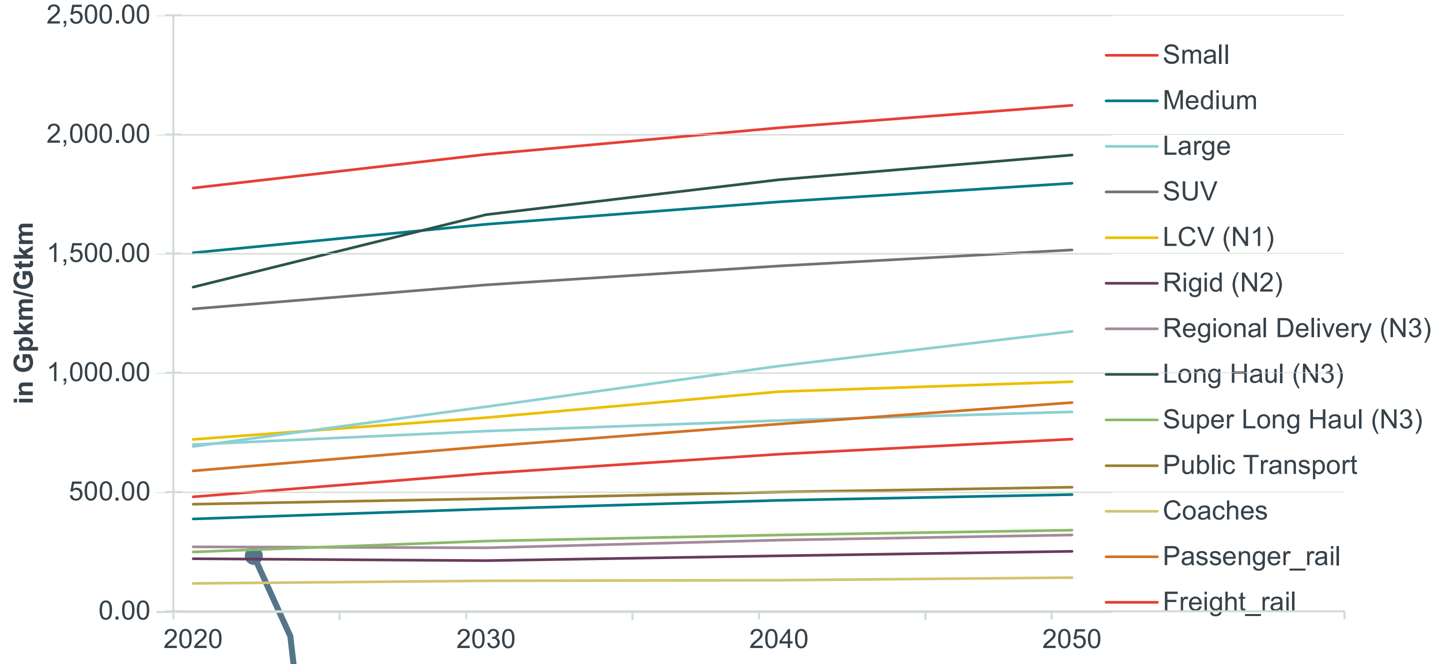
	„Nearby“ good location (e. g. MENA)	**Far-off premium location (e.g. Patagonia)**
100% Electric		✕
100% Hydrogen		✕
100% FT Fuel		
100% Methane		 (LNG)
100% DME		
100% Methanol		

Ammonia Route excluded

- **70% of the final fuel are imported (30% produced in Europe)**
- **Imports are equally split between far-off premium locations (such as Patagonia) and closer good locations (such as Morocco)** ***(except of BEV and H2 → 100% of imports = 70% of fuel imported from MENA)***
- **We assume that the final fuel is imported wherever feasible**

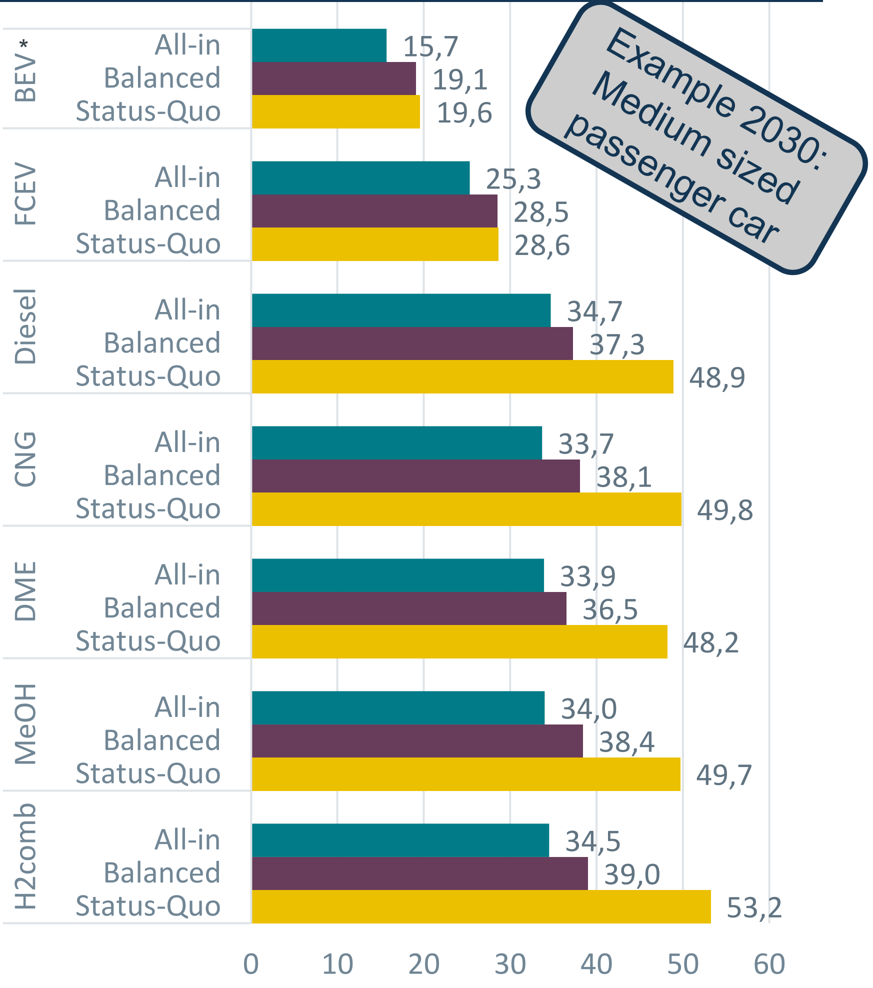
Energy demand is calculated based on fleet, mobility demand and fuel consumption (bottom-up approach)

Mobility demand (Gpkm / Gtkm) per segment as starting point



Mobility demand assumptions based on
EU Reference Scenarios (EU Commission, 2016)

Consumption per vehicle (kWh/100km)



*Including AC/heating and charging losses

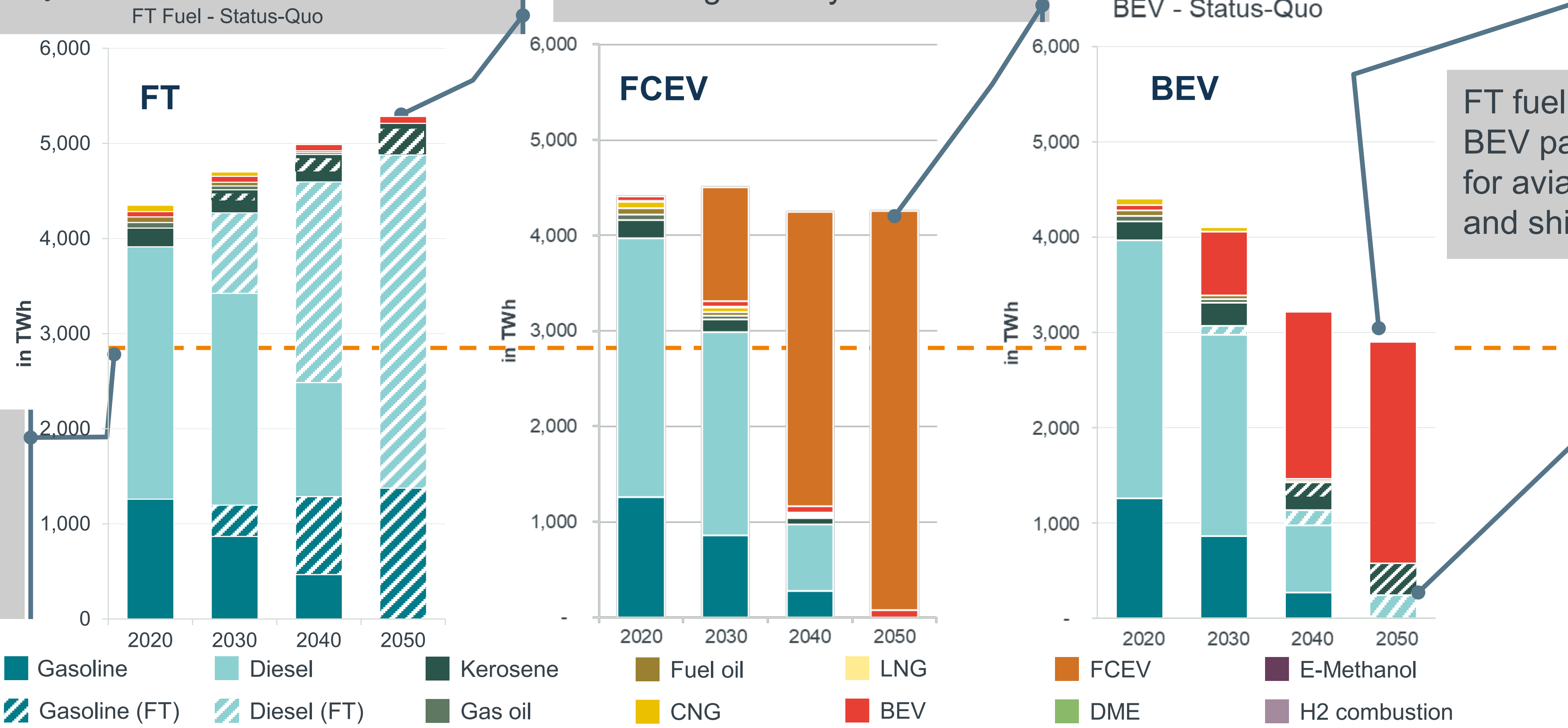
Total annual Fuel Demands (TtW, all sectors) show different trends over time depending on technology

Growing demand in **FT-ICE „Status quo“** scenario (c/o 2020 vehicle efficiency) due to increasing mobility demand …

Improved efficiency of FCEV and H2 FSC* outweighs increasing mobility demand

Reduced WTW energy demand with BEV due to increased efficiency

Tank-to-Wheel Energy Demand 2050 / TWh



FT fuel use in BEV pathway for aviation and shipping

For comparison: Electricity Consumption EU-28 is approx. **2.900 TWh p.a.**

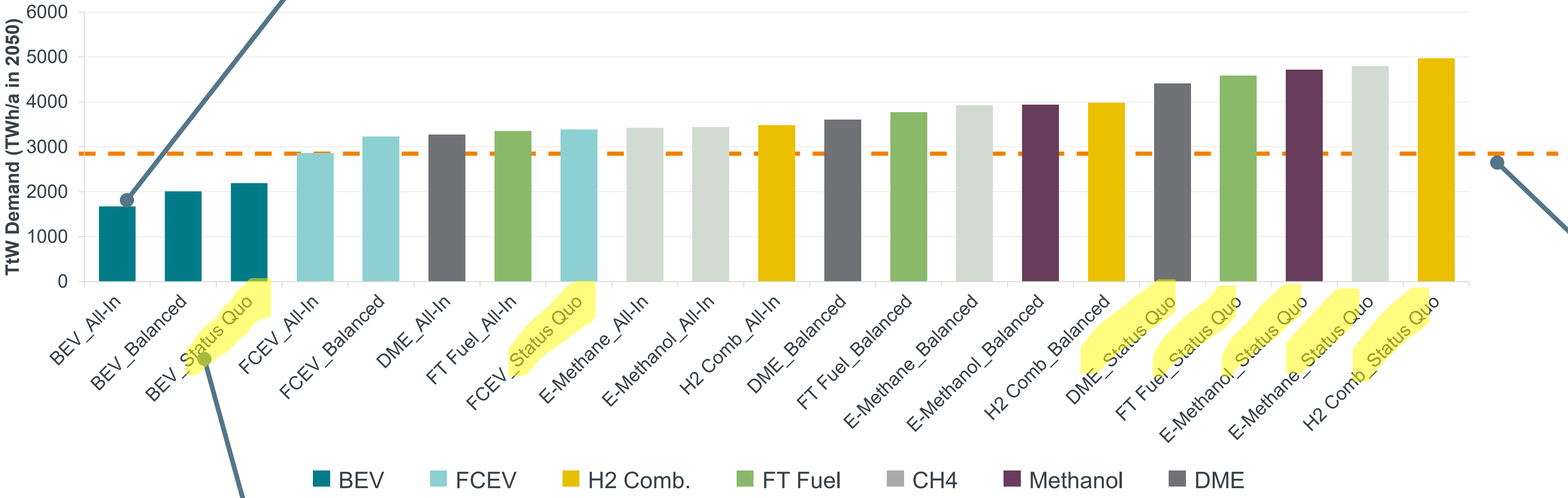
*FSC: Fuel Supply Chain

Tank-to-Wheel Energy Demand 2050 in **Road Segment** across all scenarios driven by efficiency of end applications **(~ 2,000 – 5,000 TWh/a)**

All-in Scenarios with lowest TtW fuel/energy consumption

Road segment only

Tank-to-Wheel Energy Demand 2050 / TWh



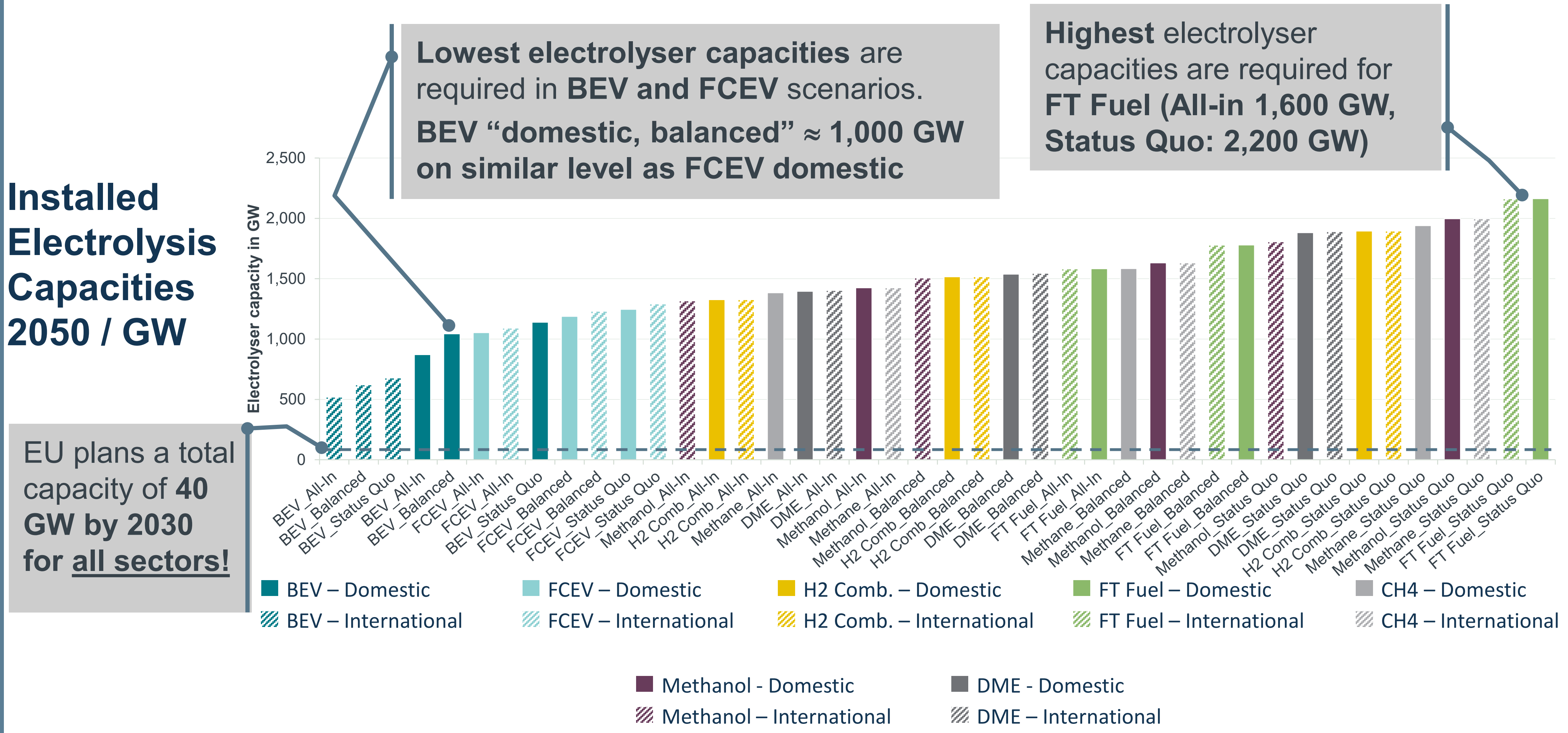
Comparison of Status Quo bars shows **three „groups“ of efficiency**: **BEV > FCEV > ICEV**

For comparison: Electricity Consumption EU-28 (<u>all sectors !</u>) is approx. **2.900 TWh p.a.**

Substantial **electrolysis capacity (500…2,200 GW)** required until 2050 for **all pathways** – urgent action required to reach capacities.

Road segment only

Installed Electrolysis Capacities 2050 / GW



* Note for BEV Scenarios: Relatively high capacities required due to low FLH and high losses due to re-conversion (Gas to Power). Only 8% (2%) of final demand (TtW) runs through H2 storage in domestic (international) scenario.

Environmental impacts analysis

Modelling approach

Vehicle configurations

Vehicle characteristics (motor size, battery technology, empty weight, specific fuel demand …) per drive concept for each vehicle size class in three different technology scenarios (status quo, balanced, all in)

Fuel supply chain infrastructure configuration

Technical characteristics of fuel supply infrastructure for 6 fuel supply chains: power generation, energy conversion & fuel production, distribution and charging

Environmental databases

- Specific environmental impacts of material supply and production processes
- LCA databases and models: e.g. EcoInvent, Umberto, eLCAr
- Emission factor databases: HBEFA 4.1, TREMOD
- ifeu scientific studies: e.g. SYSEET, RESCUE
- Scientific literature research

Specific environmental impacts

vehicle production & disposal

- 250 vehicle-size-drive concept combinations for all 3 scenarios
- Impacts for 2020, 2050a & 2050b

vehicle operation

- GHG factors fossil fuels
- Euro 6d TTW factors
- PM emissions from abrasion

installation of FSC infrastructure

- ~70 types of infrastructure
- >1000 parameter settings
- Impacts for 2020, 2050a % 2050b

Vehicle fleet 2020-2050

- New registrations & stock
- Vehicle disposals

Vehicle operation 2020-2050

- Final energy demand by fuel
- Vehicle mileage & non-road transport demand

Fuel infrastructure 2030 + 2050

- Generation capacity wind & PV
- Energy conversion / fuel production capacity
- Fuel transmission, distribution, charging

working steps in environmental analyses

Total environmental impacts per year

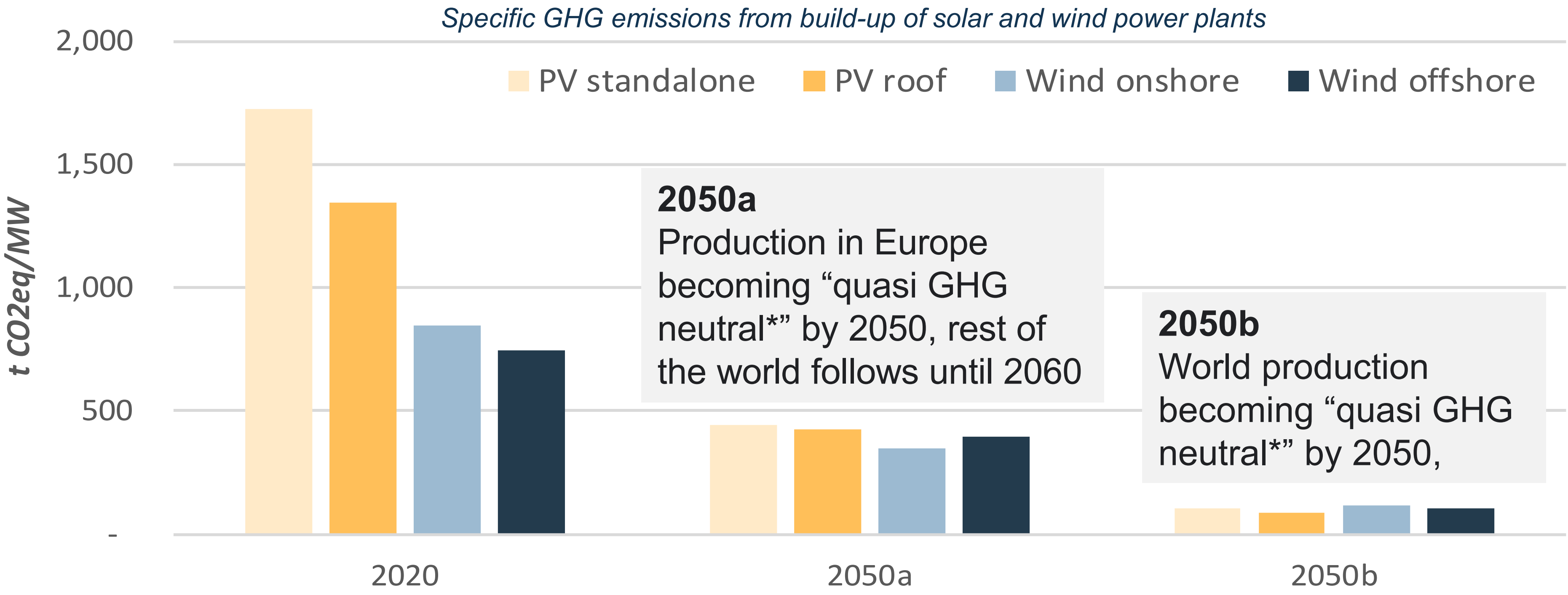
Environmental impacts vehicle production & disposal + Environmental impacts vehicle operation + Environmental impacts FSC construction = **Total environmental impacts**

Environmental impacts analysis

Future defossilisation of the background system – build-up of FSC infrastructure

→ **Future defossilisation of the background system:** Besides fossil-free energy carriers all production processes (materials and energy supply) are defossilised in the future.

→ **Strong future decrease in GHG emissions of building-up power supply infrastructure**, e.g. specific GHG emissions of PV and wind power plant installation will decrease significantly[1] with increasing defossilisation of material supply and production processes.



[1] In case of a complete worldwide defossilisation, unavoidable GHG emissions per MW of installed capacity are similar for PV and wind power plants. Reasons for the weaker specific GHG reduction for wind power plants are the lower process energy demand, the higher concrete proportion and that the assumed increasing size class of new wind turbines is accompanied by a higher specific material demand per MW.

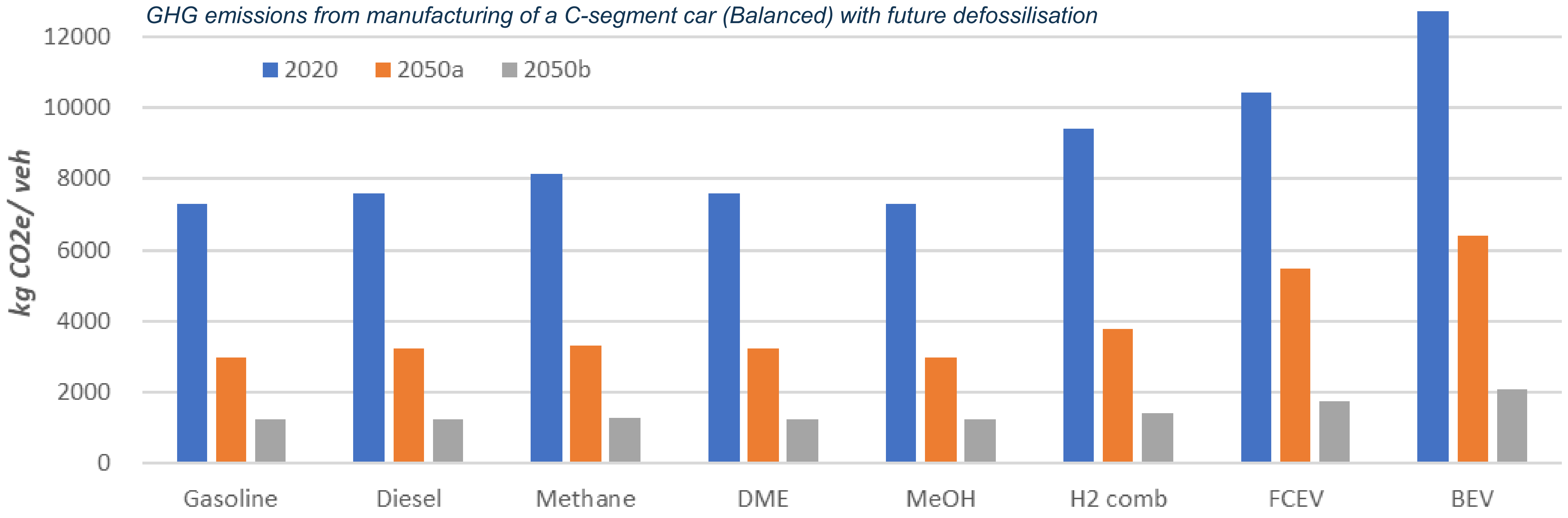
* only unavoidable GHG emissions left

Environmental impacts analysis

Future defossilisation of the background system – Vehicle production

→ **Future defossilisation of the background system** (materials and energy emission factors) leads to a **strong future decrease of manufacturing GHG emissions for all drivetrains**.

→ Overall differences between drivetrain concepts remain unchanged.



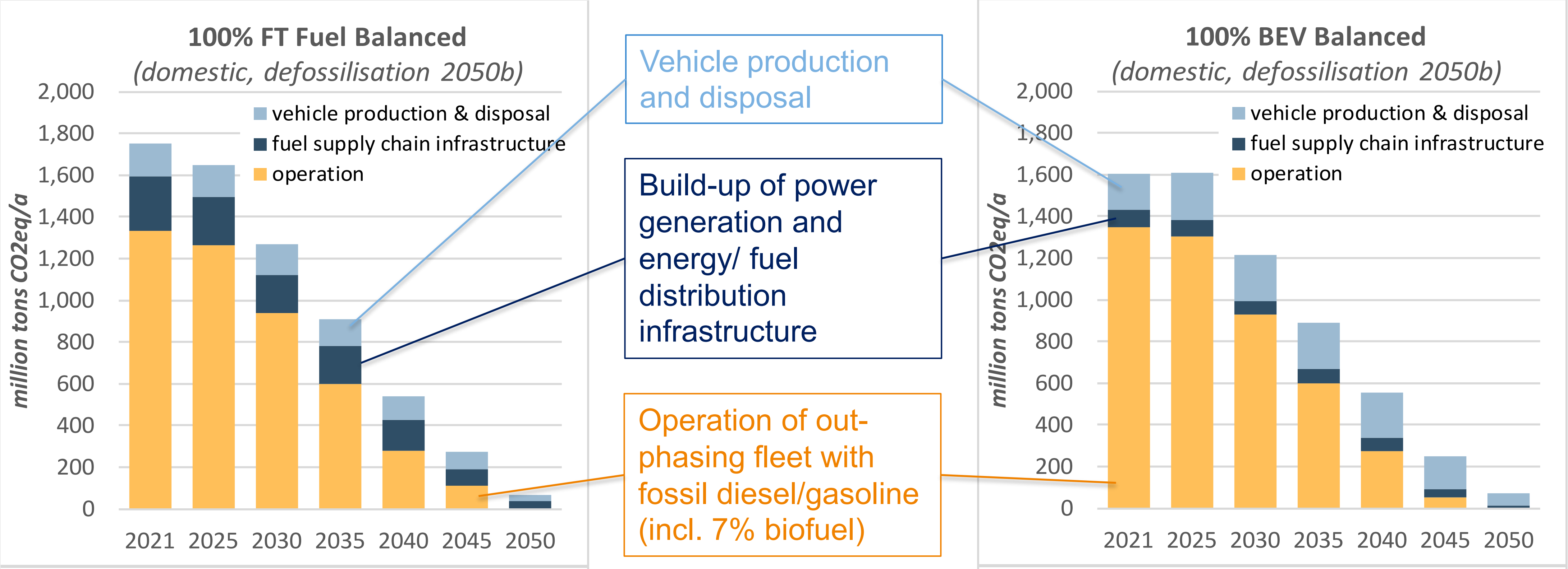
2050a
Production in Europe becoming "quasi GHG neutral*" by 2050, rest of the world follows until 2060

2050b
World production becoming "quasi GHG neutral*" by 2050

* only unavoidable GHG emissions left

Environmental impacts analysis

Annual GHG emissions in 100% scenarios with identical ramp-up speeds



- Annual GHG emissions in the year 2050 are in all fuel pathways 95-97% lower than in 2020*
- Vehicle operation of out-phasing fleet with **fossil fuels dominates annual GHG emissions until ≈ 2040** for all pathways

** Only unavoidable GHG emissions remain in 2050, primarily processes in the background system (e.g. concrete use for wind turbine foundations, methane slip).*

Environmental impacts analysis

Annual GHG emissions in 100% scenarios with identical ramp-up speeds

→ Objective of 100% backcasting scenarios: complete defossilisation of the transport sector by 2050

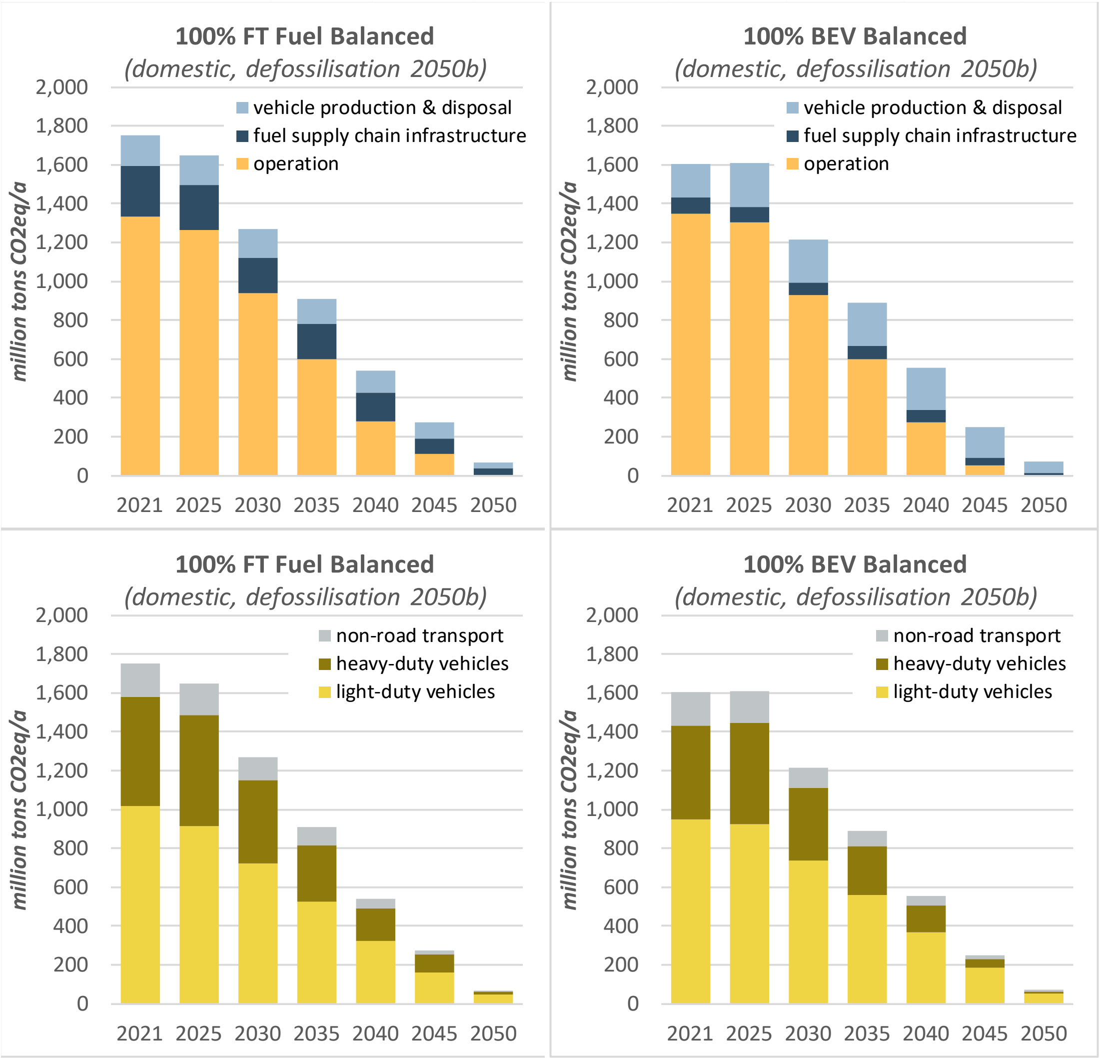
→ **Annual GHG emissions** in 2050 are in all fuel pathways 95-97% lower than in 2020*

→ GHG contributions of different processes

- **Vehicle operation w/ fossil fuels dominates annual GHG emissions in all pathways even in 2040/2045.**
- Contributions of vehicle production and build-up of FSC infrastructure depend on fuel/energy pathway.

→ GHG contributions from vehicle categories

- **Light-duty vehicles with largest contributions**: ~ 60% in 2021; 66-75% in 2050.
- Heavy-duty vehicles: 16-35%.
- Non-road transport: 5-10%.



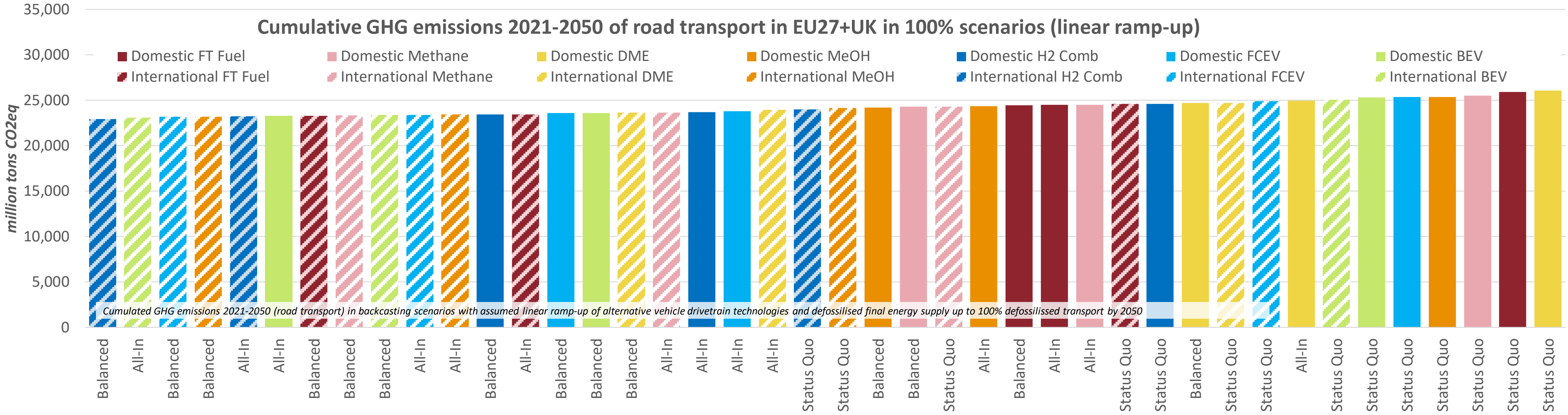
** Only unavoidable GHG emissions remain in 2050, primarily processes in the background system (e.g. concrete use for wind turbine foundations, methane slip).*

Environmental impacts analysis

Bandwidth of cumulative GHG emissions in road transport with **identical ramp-up**

→ **14% bandwidth of cumulative GHG emissions in road transport between 100% scenarios,** with assumed identical ramp-up* and (*determined by vehicle fleet exchange rate)

→ **Assessment of real cumulative GHG avoidance potential of fuel/drivetrain pathways requires thorough analysis of feasible ramp-up speeds** (→ determination of bottlenecks in ramp-ups)



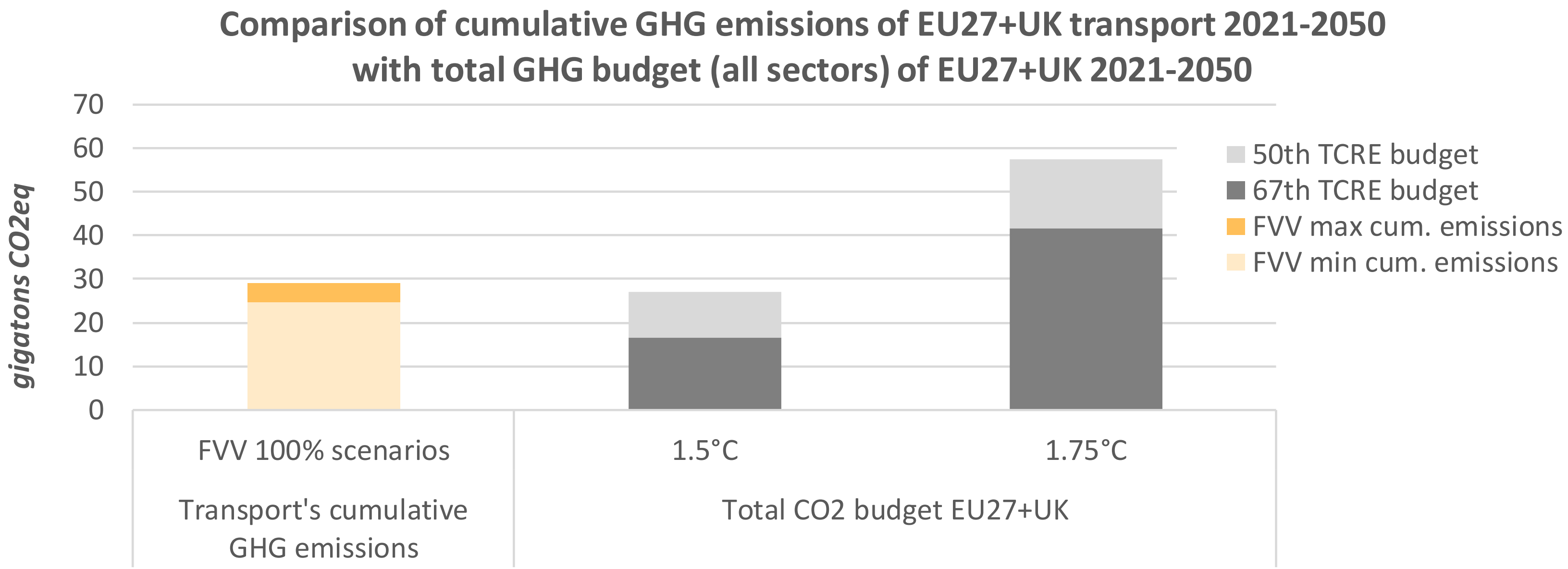
Environmental impacts analysis

Comparison: Cumulative GHG emissions with remaining CO_2 budget

	1.5 °C (50-67th TCRE)	1.75 °C (50-67th TCRE)
Global CO_2 budget (1.1.2018)[1]	420-580 Gt	800-1040 Gt
EU27+UK CO_2 budget 2021-2050[2]	16-27 Gt	42-57 Gt

[1] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

[2] *based on global population share of EU27+UK (6.6%) and GHG emissions 2018-2020: 11.2 Gt*



Additional Warming since 2006–2015 [°C]*(1)	Approximate Warming since 1850–1900 [°C]*(1)	Remaining Carbon Budget (Excluding Additional Earth System Feedbacks*(5)) [$GtCO_2$ from 1.1.2018]*(2)		
		Percentiles of TCRE *(3)		
		33rd	50th	67th
0.3		290	160	80
0.4		530	350	230
0.5		770	530	380
0.53	~1.5°C	840	580	420
0.6		1010	710	530
0.63		1080	770	570
0.7		1240	900	680
0.78		1440	1040	800
0.8		1480	1080	830
0.9		1720	1260	980
1		1960	1450	1130
1.03	~2°C	2030	1500	1170
1.1		2200	1630	1280
1.13		2270	1690	1320
1.2		2440	1820	1430

1.5°C 67th TCRE: EU27+UK transport only (C2G*) will exceed total EU27+UK budget in 2031-32.

1.75°C 50th TCRE: EU27+UK transport (C2G*) will require 43-51% of total EU27+UK budget.

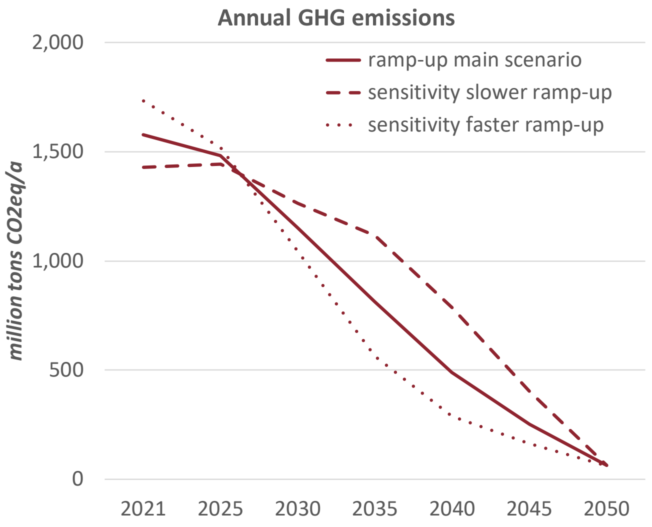
**C2G = including build-up of fuel supply chain infrastructure & vehicle production/disposals*

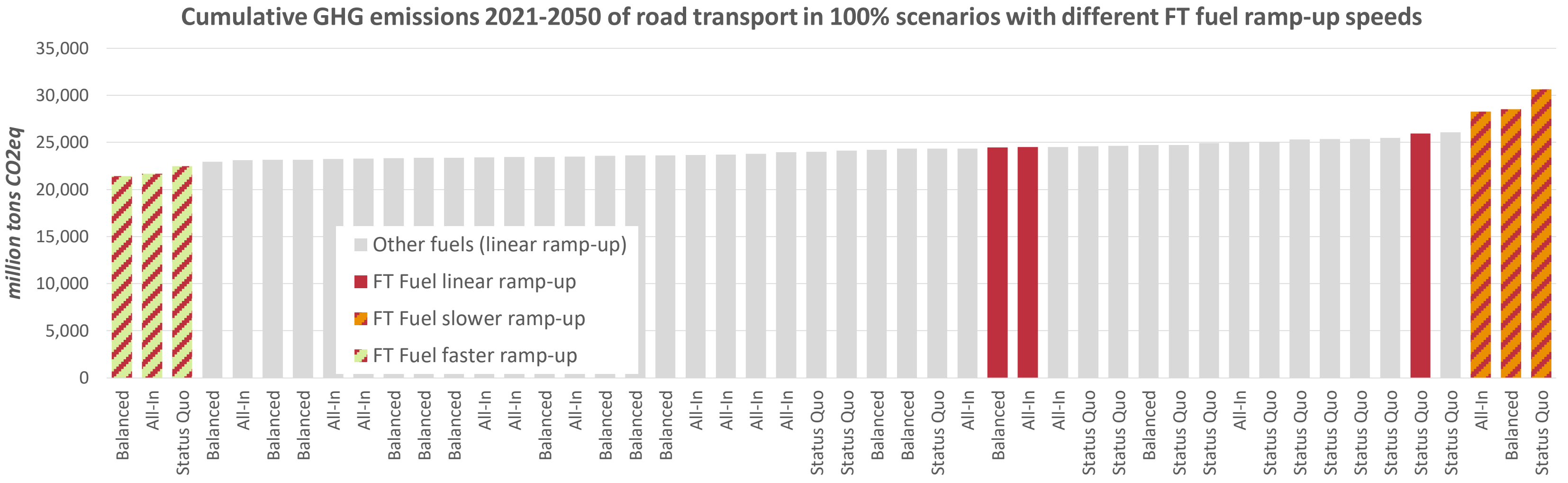
Environmental impacts analysis

Sensitivity analysis of ramp-up speed (example: Fischer-Tropsch pathway)

- **Realistically reachable ramp-up speed can differ considerably** between the fuel/drivetrain pathways → **further bottleneck identification in follow-up study (FVV IV b)**
- Sensitivity analysis (FT share 2030 ± 20%) → **impact of ramp-up speed on cumulative GHG emissions higher** than differences between fuel/drivetrain pathways (with assumed identical ramp-up)
- **Achievable ramp-up speed of carbon neutral pathways is the decisive factor** for fast GHG reduction

Sensitivity:	**Linear ramp-up**	**Slower ramp-up**	**Faster ramp-up**
FT fuel share 2030	28%	8%	48%
Cumulative GHG compared to linear	-	+15-18%	-12-13%





Environmental impacts analysis

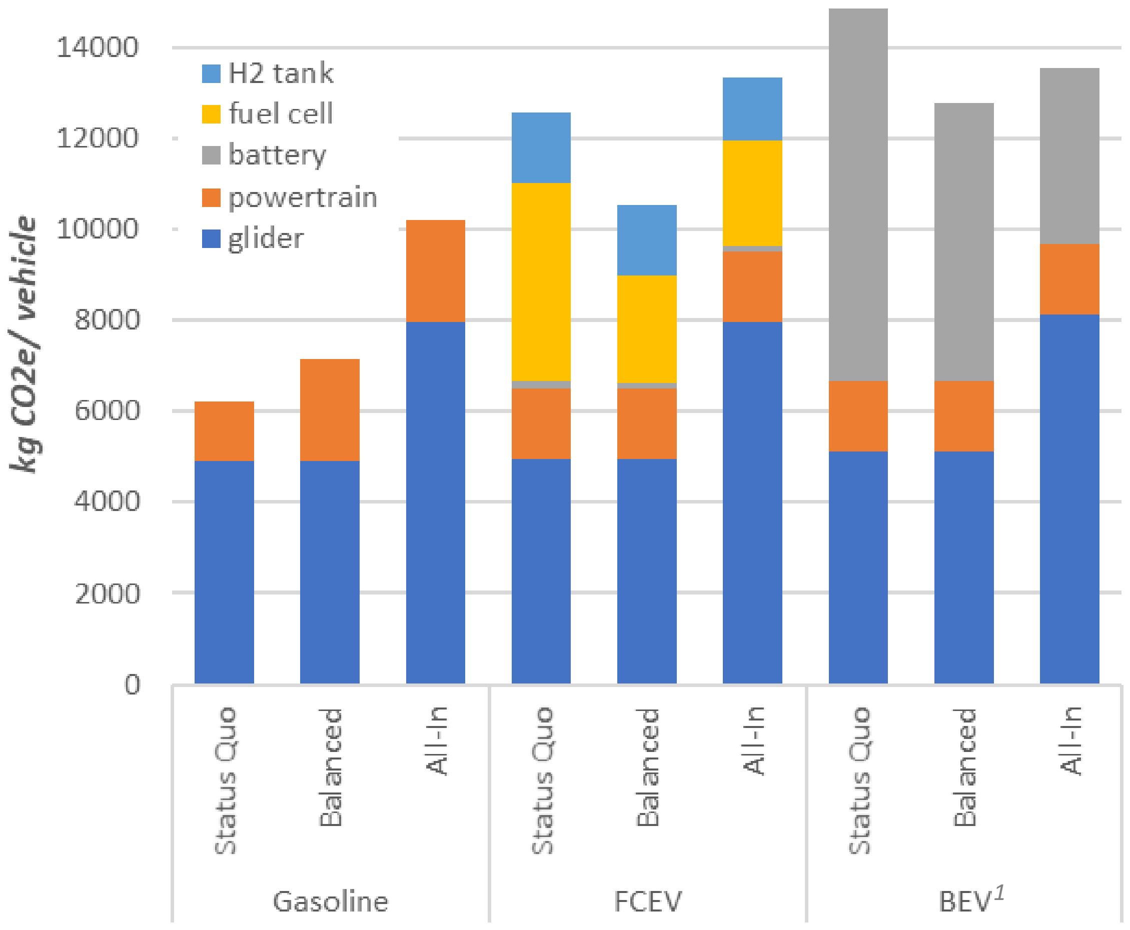
Cumulative GHG emissions from vehicle production

→ In general, fuel cell as well as electric cars have higher GHG emissions from vehicle manufacturing than the gasoline cars.

→ Impact of technology levels:

- **ICEV**: Higher technology levels (hybridisation, aluminium lightweighting) increase GHG emissions from vehicle manufacturing.
- **FCEV**: lower platinum loading and smaller H_2 tanks reduce GHG emissions from manufacturing - (partly) balancing out additional emissions from lightweighting
- **BEV**: Battery production[1] dominates GHG from vehicle production. Battery improvements (energy density, required capacity) lead to reduced GHG emissions from manufacturing even with additional aluminium lightweighting.

GHG emissions from manufacturing of selected C-segment cars in 2020



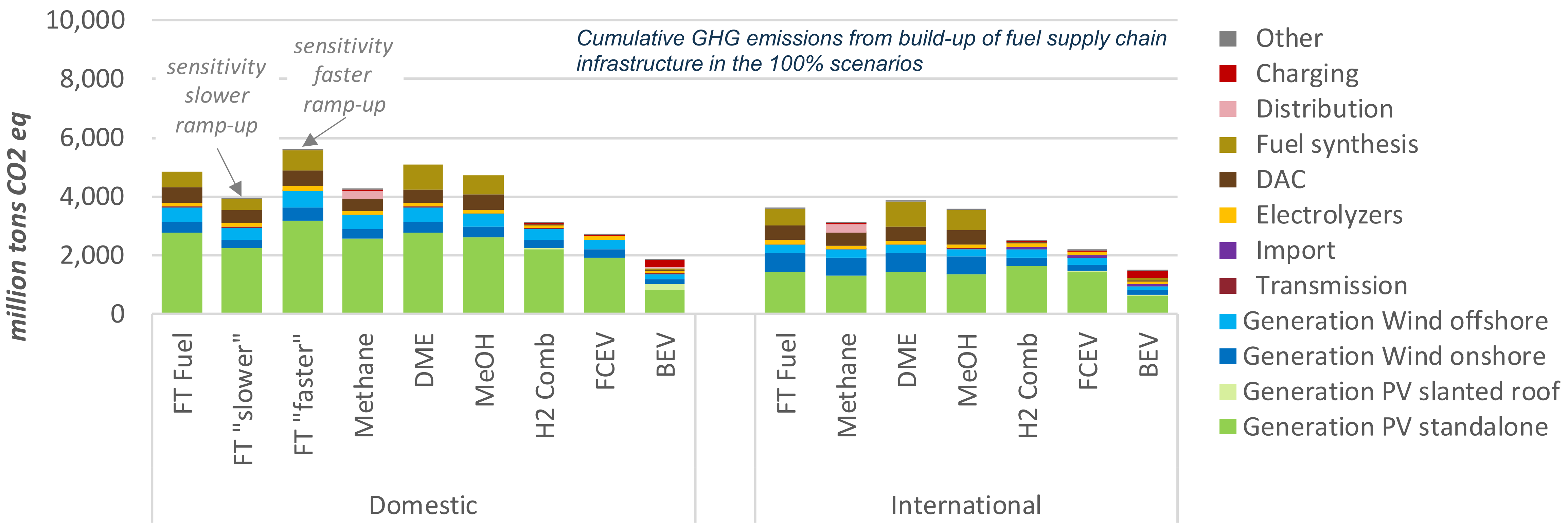
[1] 500km operating range according to the FVV focus group assumptions.

Environmental impacts analysis

Cumulative GHG emissions from build-up of fuel supply chain infrastructure

→ Build-up of energy/fuel supply chain (FSC) infrastructure contributes 5-20% to total cumulative GHG emissions (lowest contribution in BEV) in the 100% scenarios

→ Build-up of renewable power generation dominates GHG emissions of FSC infrastructure

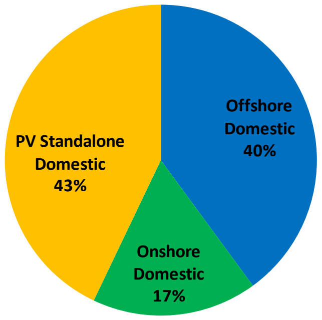


Environmental impacts analysis

Cumulative GHG emissions from build-up of fuel supply chain infrastructure

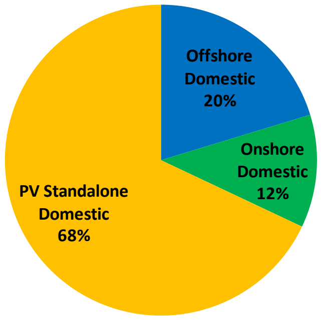
Domestic Scenario

Power generation 2050



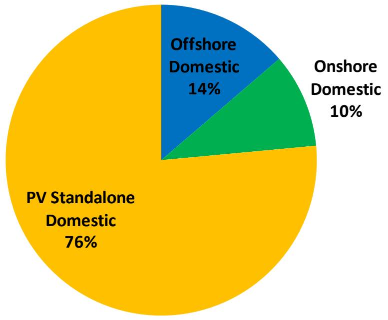
Different Full Load Hours cause shift:
PV: 1300 h/a
Onshore: 3000 h/a
Offshore: 4200 h/a

Installed Capacity 2050



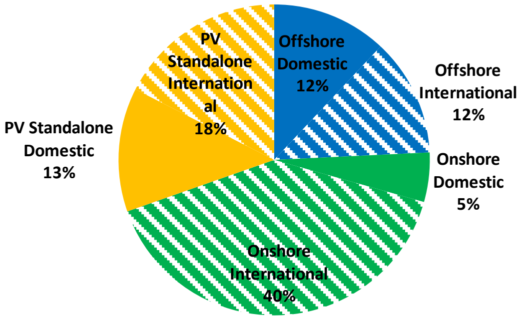
Higher GHG intensities for PV during non/partly defossilized ramp-up

GHG cumulated



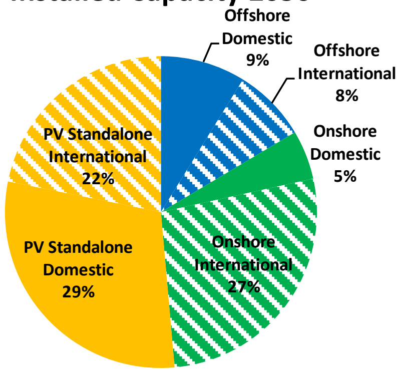
International Scenario

Power generation 2050

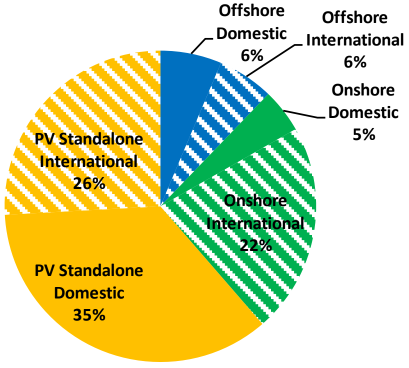


PV: 2400 h/a
Onshore: 4500 h/a
Offshore: 5000 h/a

Installed Capacity 2050



GHG cumulated



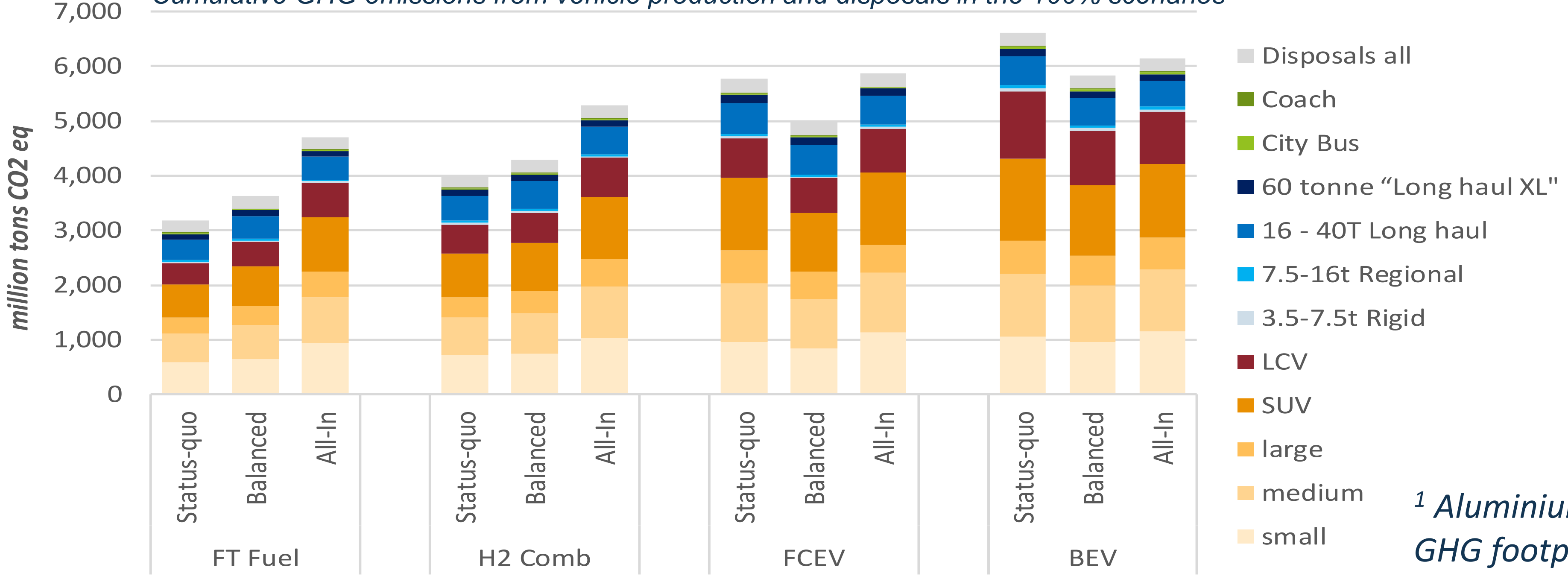
Environmental impacts analysis

Cumulative GHG emissions 2021-2050 from vehicle production and disposals

→ Vehicle production and disposals contribute 11-24% to total cumulative GHG emissions

- FCEV and BEV scenarios with higher GHG emissions from vehicle production than ICEV scenarios
- Additional technical vehicle efficiency improvements (hybridisation, aluminium light weighting) increase GHG footprint from vehicle production for ICEV[1]
- Improving batteries (energy density) decreases GHG footprint from BEV production

Cumulative GHG emissions from vehicle production and disposals in the 100% scenarios



[1] Aluminium light weighting increases GHG footprint for all powertrains.

Environmental impacts analysis

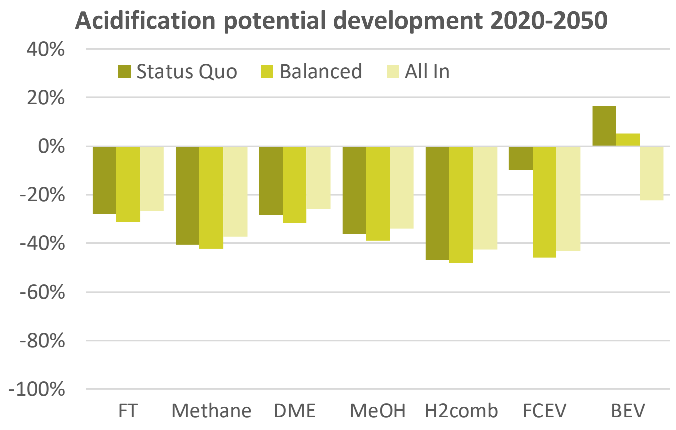
No risk of Acidification, Eutrophication and PM Formation for any pathway

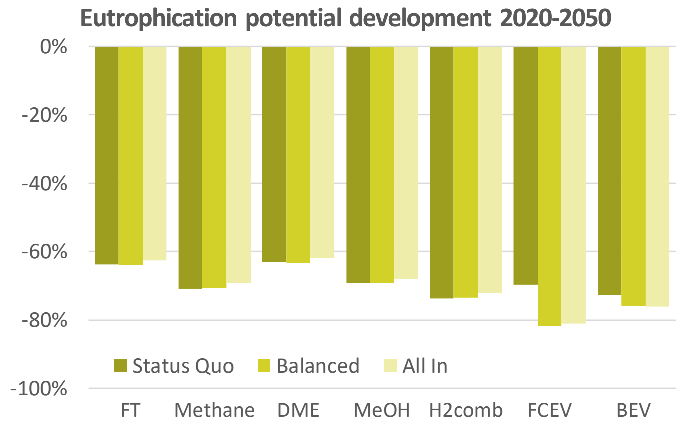
Further analysed environmental impacts as **acidification, eutrophication & PM formation do not show general ecological risks** for any of the investigated defossilisation pathways.

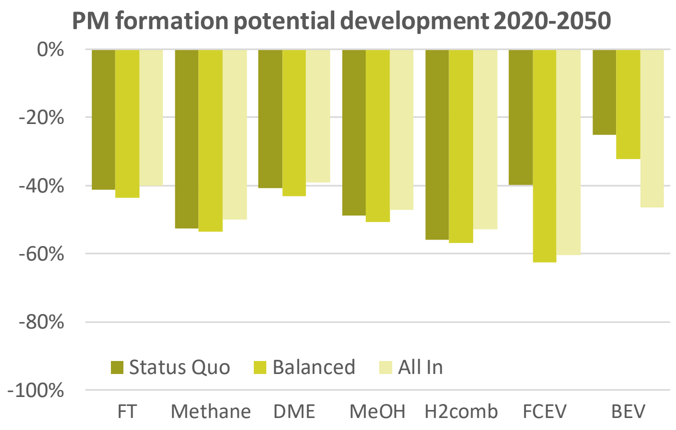
Acidification:
- 25 … - 45% for ICEV
- 10 … - 45% for FCEV
+ 15 … - 20% for BEV

Eutrophication:
- 60 … - 75% for ICEV
- 70 … - 80% for FCEV
- 70 … - 75% for BEV

PM Formation :
- 40 … - 55% for ICEV
- 40 … - 60% for FCEV
- 25 … - 45% for BEV

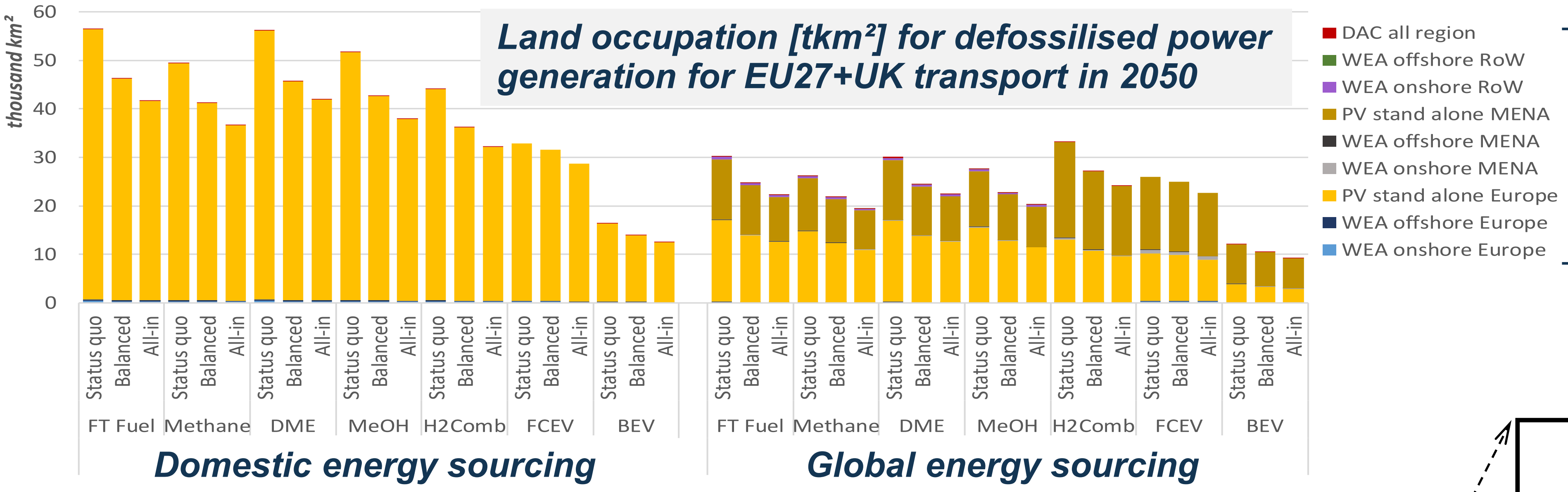






Environmental impacts analysis

Land use is no ecological bottleneck for any investigated pathway



→ **Ecologically relevant land use change → amount of area covered** (which cannot be used for other applications)

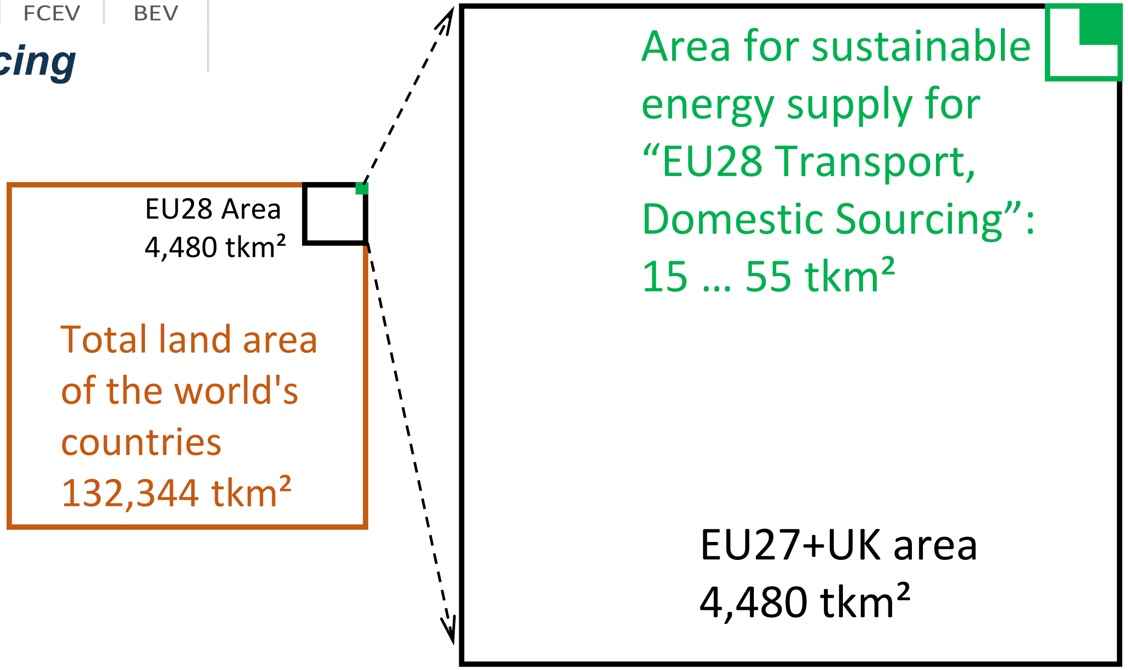
→ Land use is determined by renewable power generation (solar/wind)

→ 15 … 55 tkm² for domestic sourcing

→ 10 … 30 tkm² for global sourcing

→ **Land use is no ecological bottleneck for defossilised transportation in all pathways***

**However, installation of renewable power generation capacities should avoid environmentally sensitive areas in order to minimize land use related environmental impacts.*



Critical raw materials

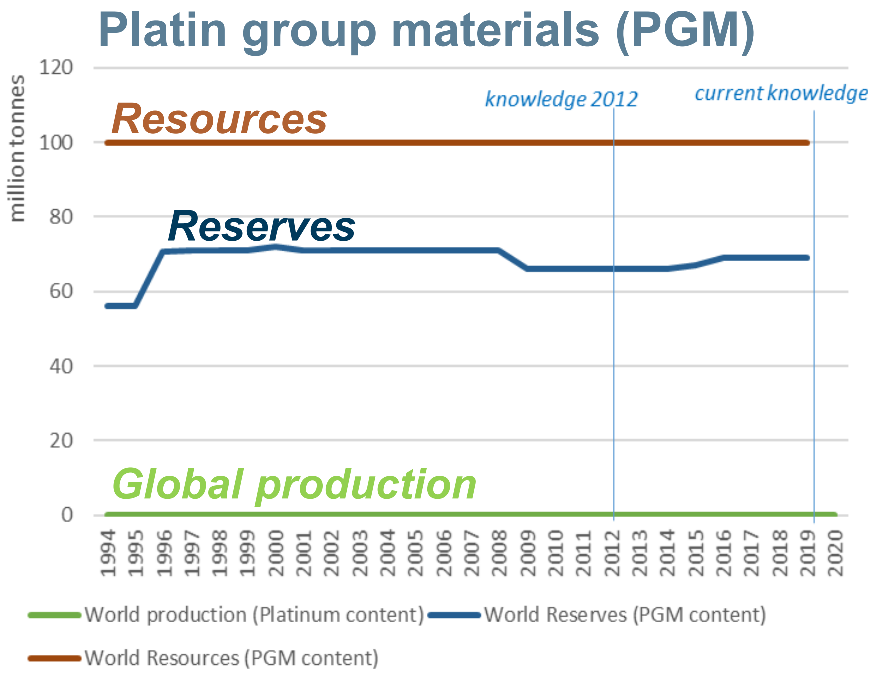
Global Resources and Reserves: Definition and Dynamics

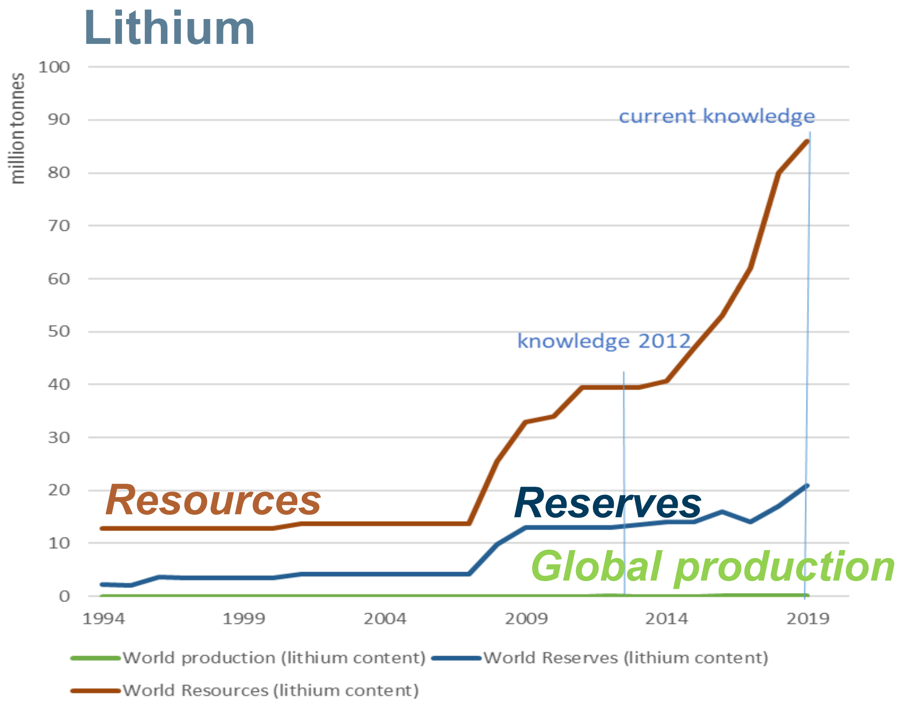
Resources: global material quantity with **reasonable prospects for eventual economic extraction**

- Well explored resources (e.g. Pt) do not change significantly.
- Recently demanded raw materials (e.g. Li)
  → Active exploration activities = dynamic increase.

Reserves: **part of the resources** known to be **economically feasible for extraction.**

- Reserves increase with increasing prices (e.g. higher global demand).



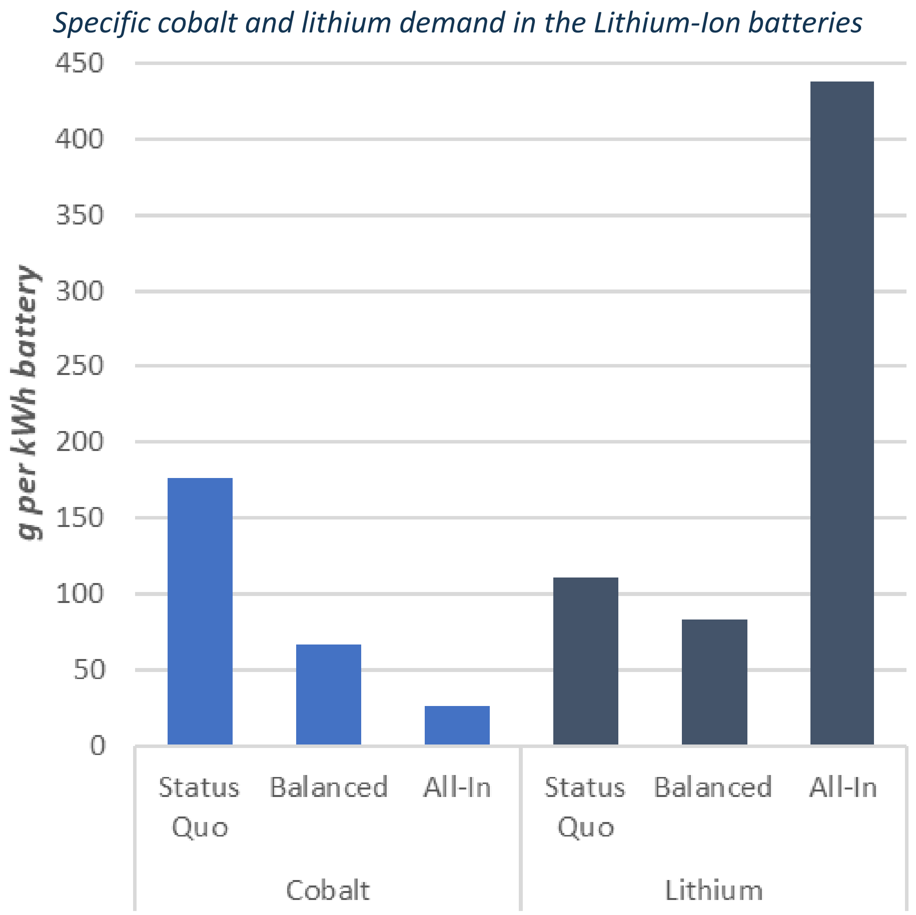


Critical raw materials
Cobalt and lithium: Specific demand

→ In this study, we consider Li-Ion NMC as state-of-the-art battery technology on the EU market.

	Status Quo	Balanced	All-In
Battery type	NMC 622	NMC 811	Solid-state NMC 811
Energy density (system level)	150 Wh/kg	200 Wh/kg	300 Wh/kg

→ **Cobalt and lithium are key materials for electric mobility with battery Li-Ion NMC technologies.**[1]



[1]*Alternative battery technologies with lower specific demands of cobalt and lithium (e.g. lithium iron phosphate batteries, sodium-ion batteries), which could gain more relevance in future, are covered in an additional simplified sensitivity analysis of global raw material demands in the study.*

Critical raw materials

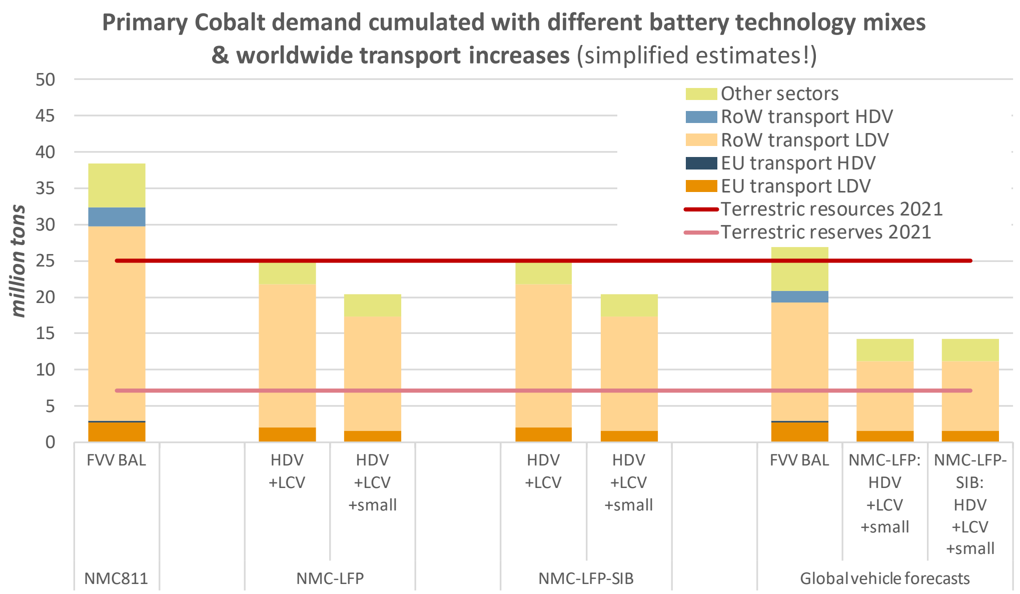
Reduction potentials for cobalt and lithium demand (sensitivity analysis)

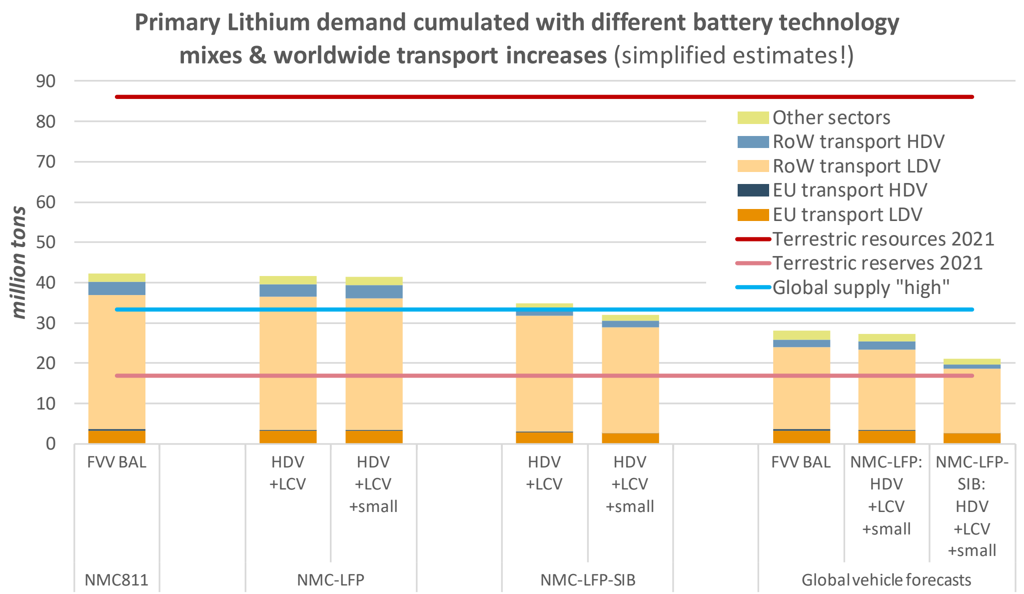
→ Extrapolated global cobalt and lithium demand in 100% BEV scenarios is on the upper end. Lower future global cobalt and lithium demand is possible:

- Mix of different battery technologies, including with less/no Co and Li (e.g. LFP, SIB)
- Weaker increase of required global battery capacities (worldwide motorisation forecasts)

→ Cobalt and lithium resources and reserves have developed very dynamically in the last few years. A considerable future increase of primary material supply can be expected.

→ How likely are temporary bottlenecks in worldwide 100% BEV scenarios? (→ cost effects?)



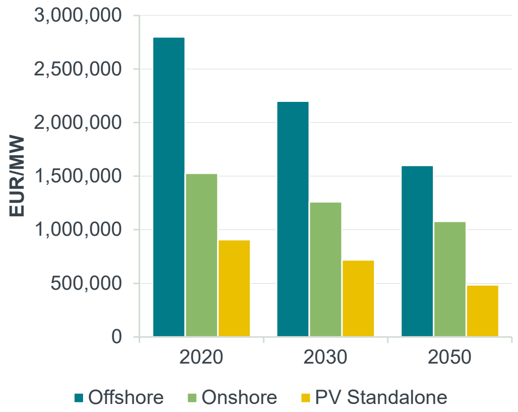


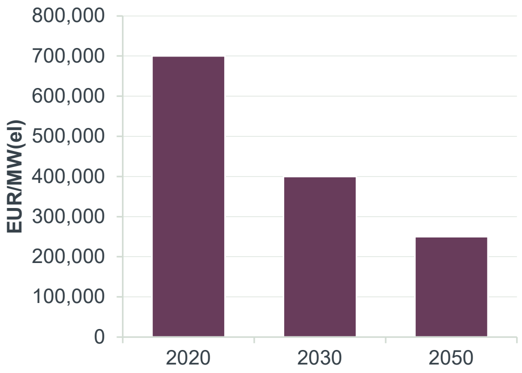
Costs are calculated based on required investment across the whole value chain, including energy/fuel infrastructure …

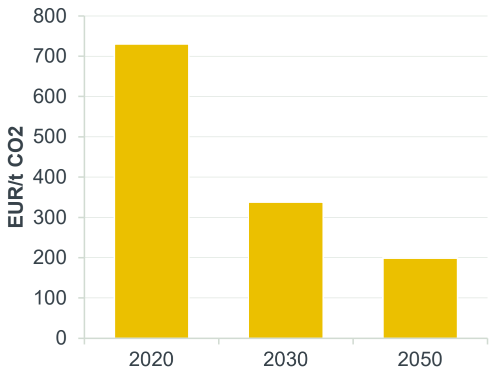
Economic approach

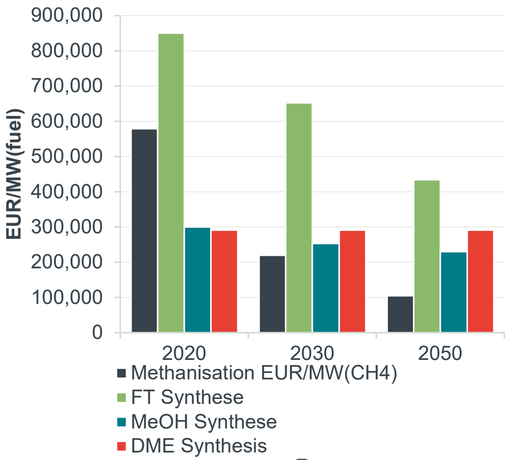
- Total economic costs (i.e. no taxes, margins, …) based on CAPEX and OPEX
  - Energy losses are directly taken into account (no energy price assumptions required)
- Calculation of NPV* in €2020 based on 6% real social discount rate
  - Sensitivity analysis based on 0% discount rate showed no changes to key findings

Costs of fuel supply in a 100% renewable system are dominated by CAPEX, e.g. for

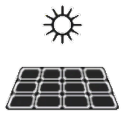




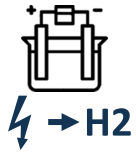




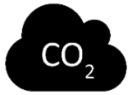




Offshore Windfarm **Onshore Windfarm** **PV Standalone**



Electrolyser



DAC

Synthesis

***NPV: Net Present Value:** Difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project. NPV is the result of calculations used to find today's value of a future stream of payments

Infrastructure costs* are lowest for 100% H2 international FCEV scenarios followed by domestic BEV scenarios

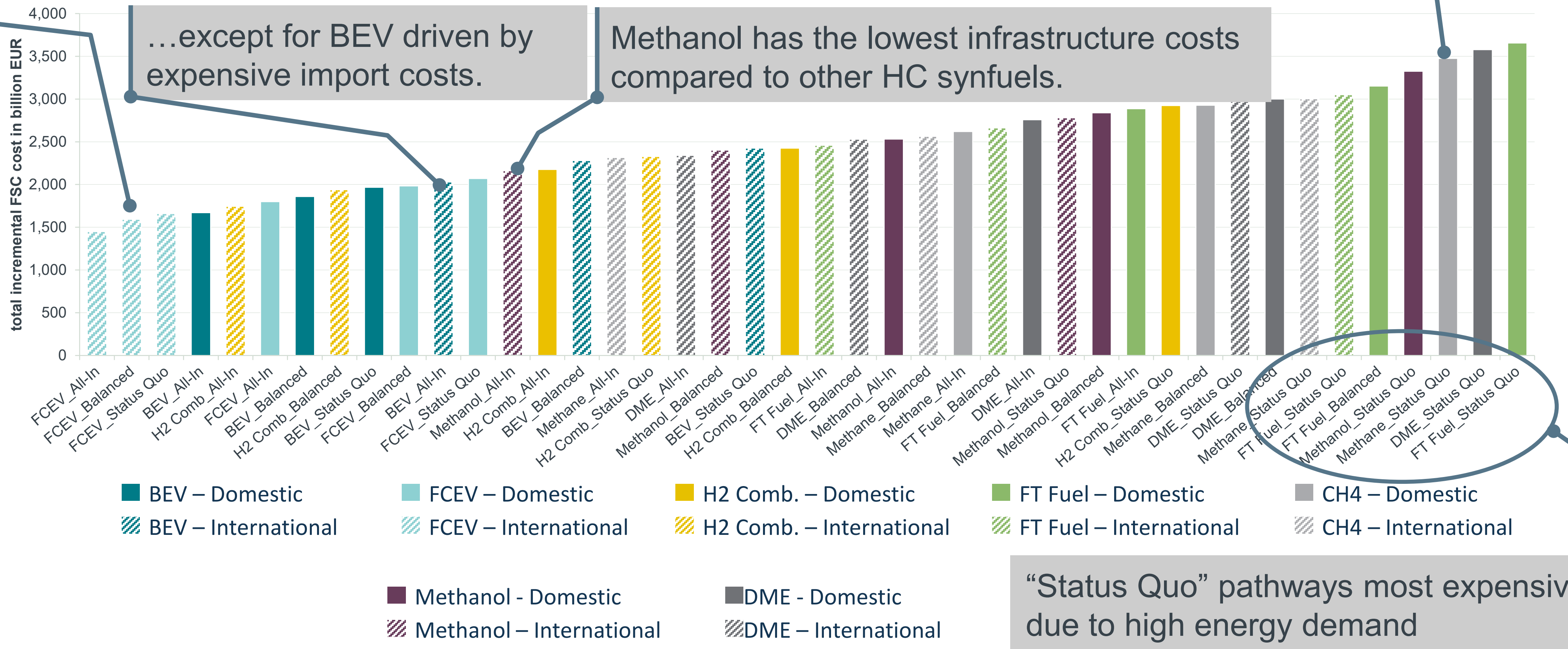
International scenarios usually cheaper due to lower capacity requirements in international scenarios because of higher full load hours abroad …

Highest infrastructure (incl. power generation) costs for **domestic synfuels** (e.g. FT Fuel, DME, Methane and Methanol) for **Status Quo** scenario.

…except for BEV driven by expensive import costs.

Methanol has the lowest infrastructure costs compared to other HC synfuels.

Total Energy/Fuel Supply Infrastructure Costs 2050 / bil. €



"Status Quo" pathways most expensive due to high energy demand

* Costs are in 2020 values – NPV, assumption of WACC of 6%

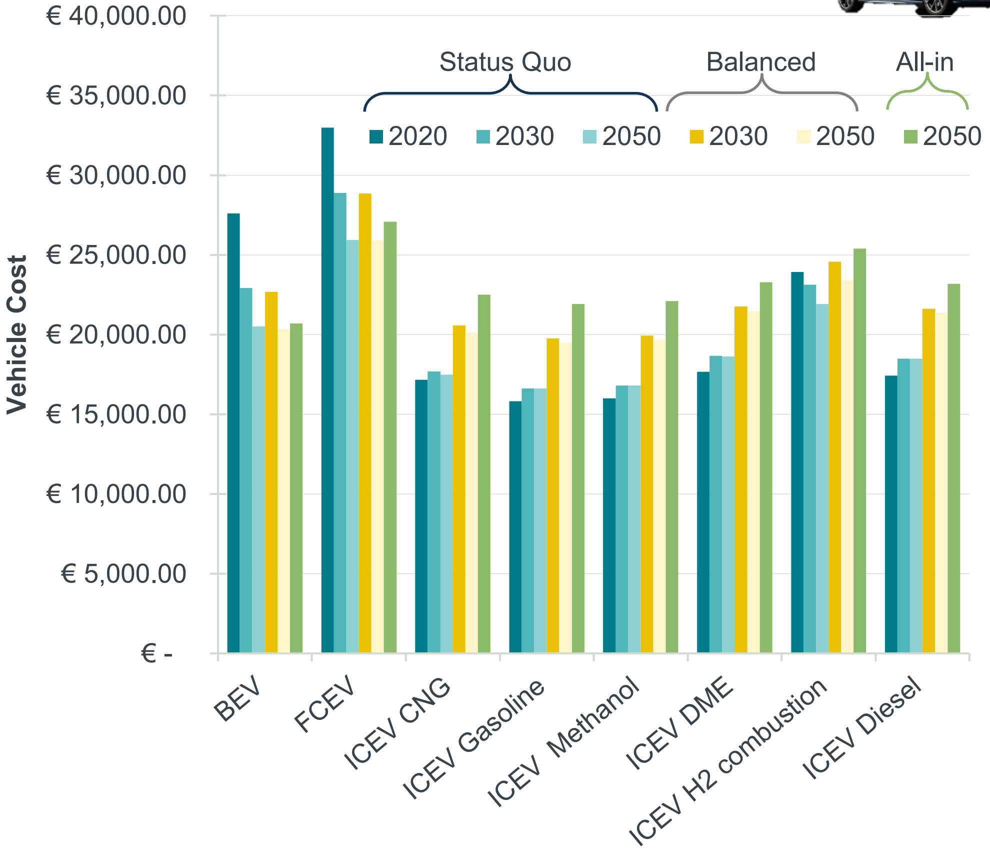
Vehicle costs are estimated following a building-block approach

Approach to vehicle costs

Current vehicle costs as starting point	List-price - VAT - Retail margin
Correction for changes in components	- Engine / gearbox + Electric drivetrain + Fuel cell + battery + H2 tank
Assumption on future cost development	Significant cost reductions for "new" components over time (learning curve effects); Cost increases for ICEV (because of emission standards)
Assumption on efficiency scenarios	Cost premiums/savings for new components added (hybridiztion, light weight construction, etc.)

Example: FCEV

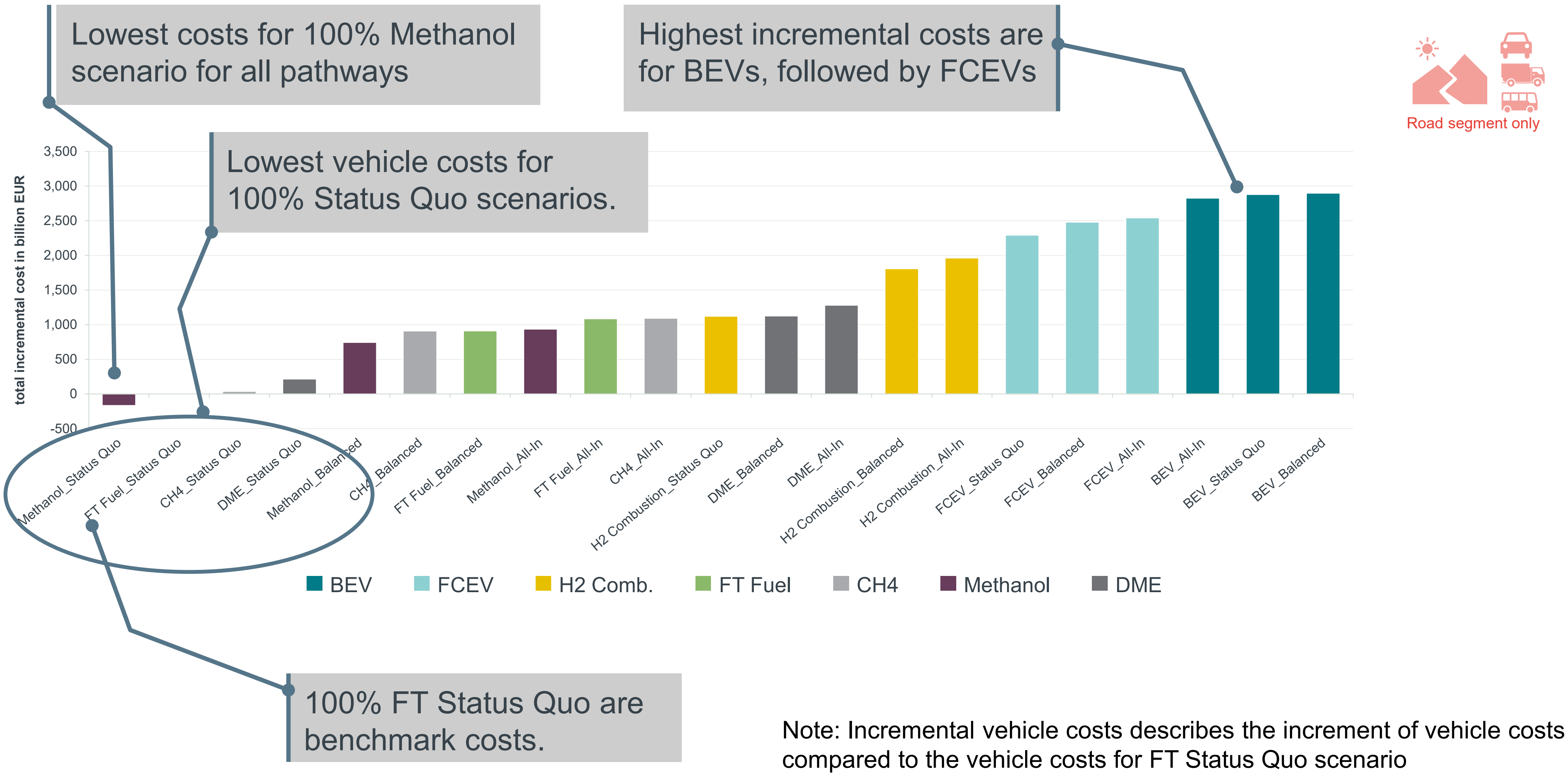
Example: Costs Medium passenger car



Cost assumptions have been coordinated by Frontier Economics strictly following compliance rules.

Focus on **incremental vehicle costs** compared to FT Status Quo Vehicles to compare drivetrain options

Total Incremental Cumulative Vehicle Costs 2020…2050 / bil. €



Note: Incremental vehicle costs describes the increment of vehicle costs compared to the vehicle costs for FT Status Quo scenario

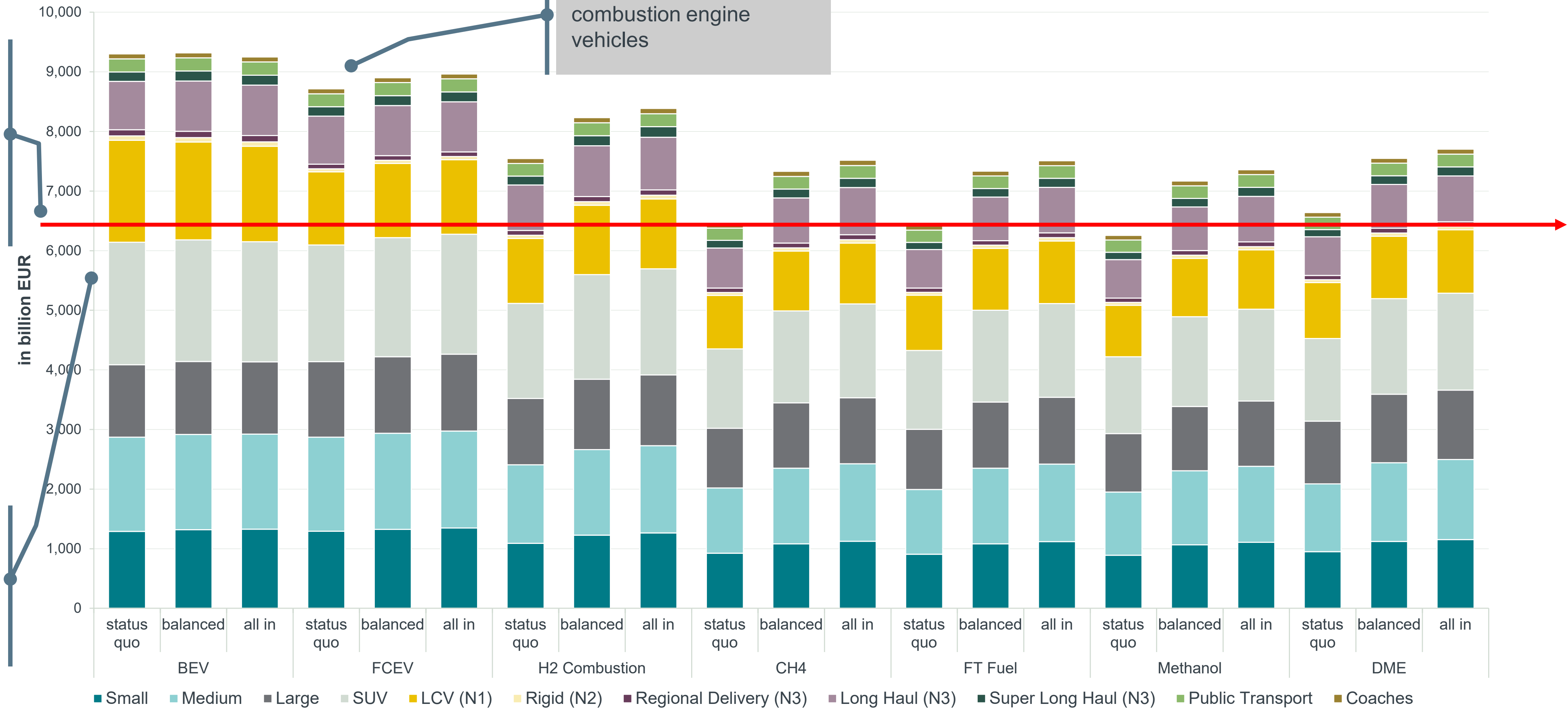
* Costs are in 2020 values – NPV, assumption of WACC of 6%

Based on modelled fleet total vehicle costs (2020 to 2050) can be derived

Cost for vehicles exceed infrastructure costs by factor 2-6, we therefore focus on „incremental“ costs compared to diesel/perrol ICEV (Status Quo)

LDVs constitute the bulk of vehicle costs (>80%) because of large fleet share

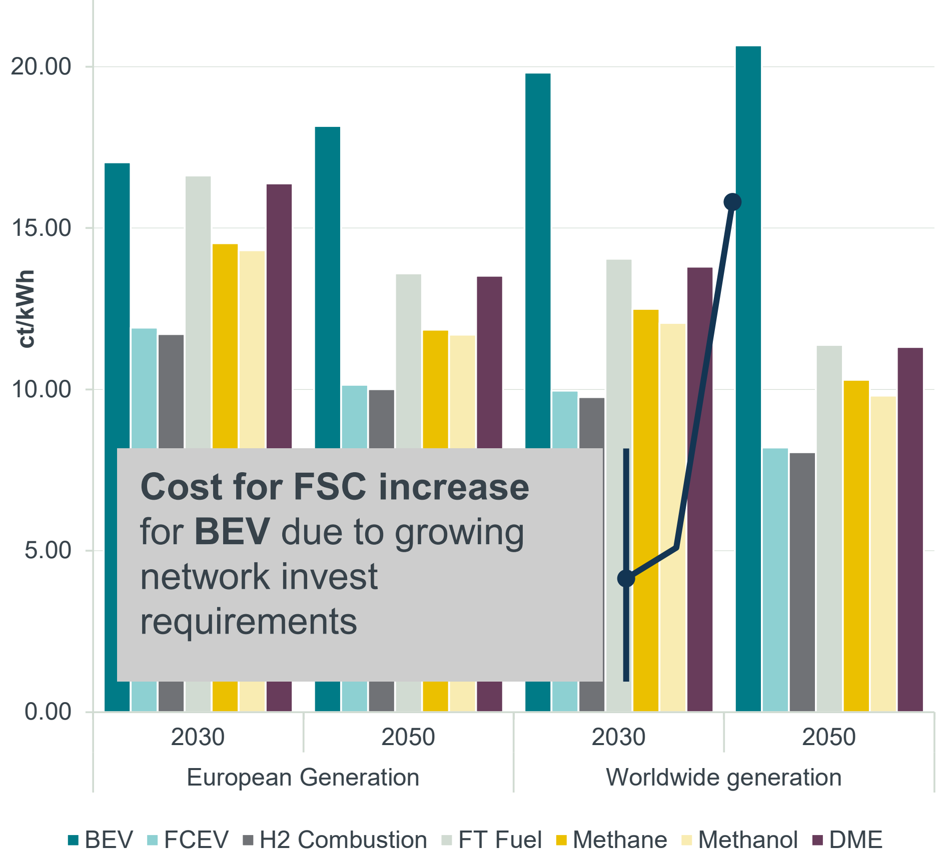
LDVs‘ costs für BEV / FCEV significantly exceed costs for combustion engine vehicles



* discounted in 2020 Euros.

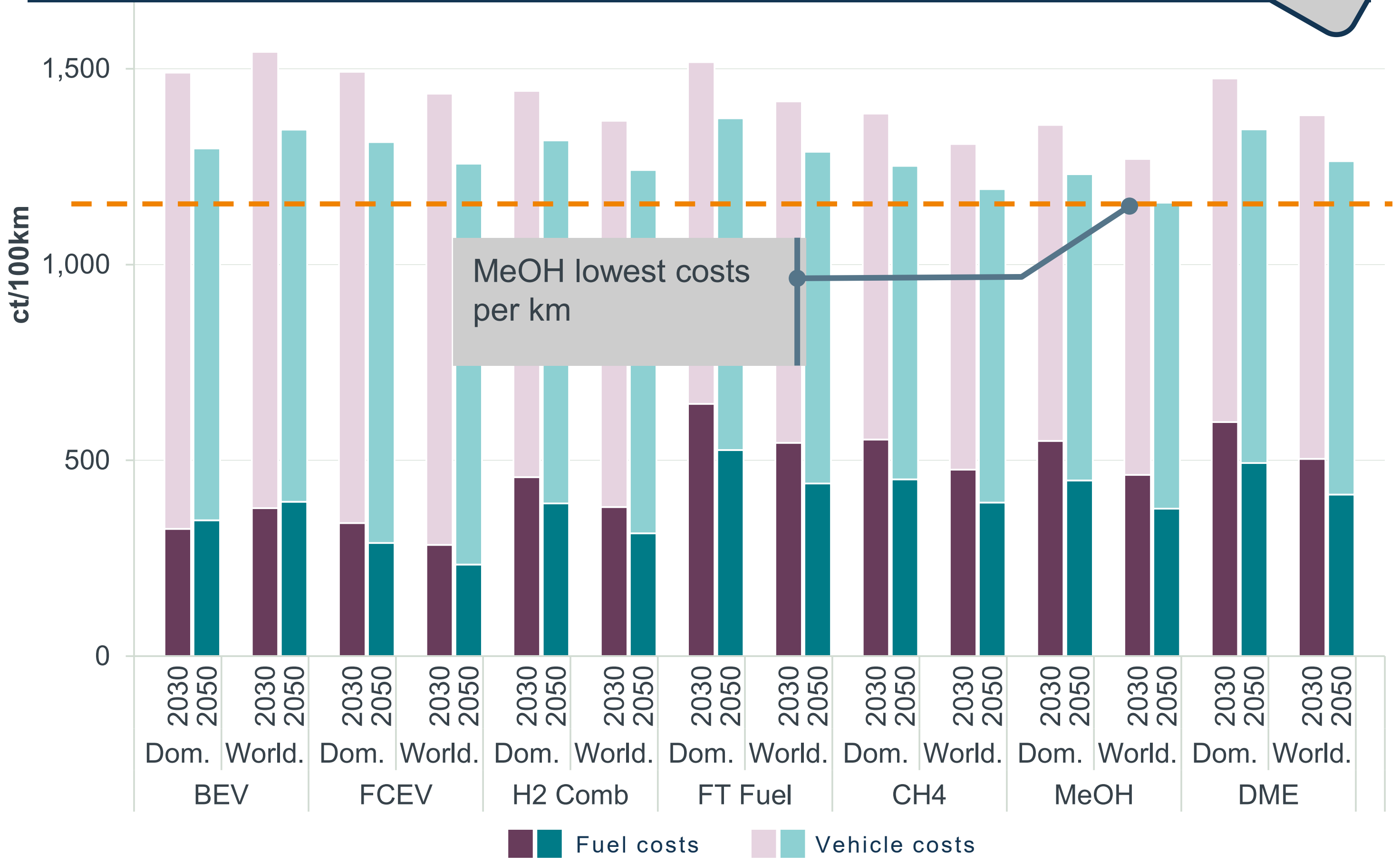
Total costs allow derivation of mobility costs*, but figures have to be interpreted carefully

est. Fuel-Costs per kWh (based on annuitised CAPEX for new infr.)



est. Mobility Costs per 100km (only vehicle and fuel costs)

Balanced scenario



*"Mobility costs based on i) est. fuel costs based on annuitized CAPEX and OPEX for new infrastructure and ii) vehicle costs.

Summary

Key Findings (4) – Energy Demand and Installed Capacity

→ **Driver for environmental impacts and costs → installed power generation capacities** (not WtW energy demand)

→ **International energy scouring requires less power generation capacity than domestic**:

- Sensible demand **solely for 2050 Transport ≈ 1,000 GW … 3,000 GW**
- For comparison: **installation plan EU (all sectors): 690 GW in** 2030
- **Factor power generation capacities „FT-ICE int. / BEV dom.“ ≈ 2**

→ Electrolysers are key technology for all pathways (also BEV → seasonal energy buffering). Sensible capacity ranges (2050) solely for mobility:

- ≈ **1,000 GW** (BEV Balanced, dom.) **… ≈ 1,700 GW** (FT-ICE Balanced int./dom.)
- For comparison: **installation plan EU: 40 GW in 2030 (for all sectors)**