FVV

Research Association for Combustion Engines

www.fvv-net.de/en

FVV FUEL STUDY IV

Transformation of Mobility to the GHG Neutral Post Fossil Age
Most efficient pathways to carbon neutral mobility in 2050

FVV, 30 Dec. 2021

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Content

APPROACH AND GENERAL ASSUMPTIONS

WTW* GHG** Emissions of European Mobility Today

Dominated by fossil energy carriers

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

Enrichment of atmosphere with fossil carbon

Fossil C from Coal

Fossil C from NG

Fossil C from Oil

EU27+UK Mobility

(incl. inner European aviation, rail and navigation → dominated by road mobility)

Mainly Fossil Electrical Power (Basis: Coal, Natural Gas) — BEV

Mainly Fossil Hydrogen (Basis: Natural Gas) — FCEV

Mainly Fossil Fuel Diesel / Gasoline / CNG / LPG — ICEV

→ System Boundary of FVV Fuels Study IV

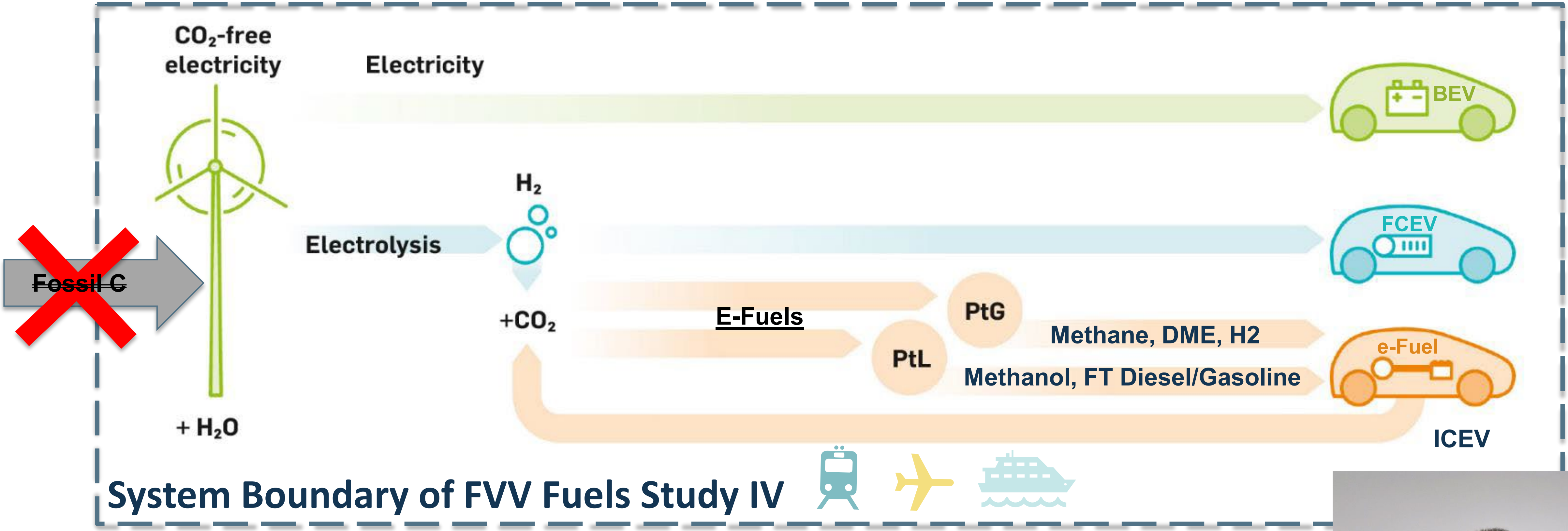
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle
ICEV: Internal Combustion Engine Vehicle

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

WTW* Carbon Neutral European Mobility in 2050

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

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



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

Closed carbon circuit → no enrichment of fossil C in atmosphere

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

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 …

2x Energy Sourcing: Domestic vs. Global

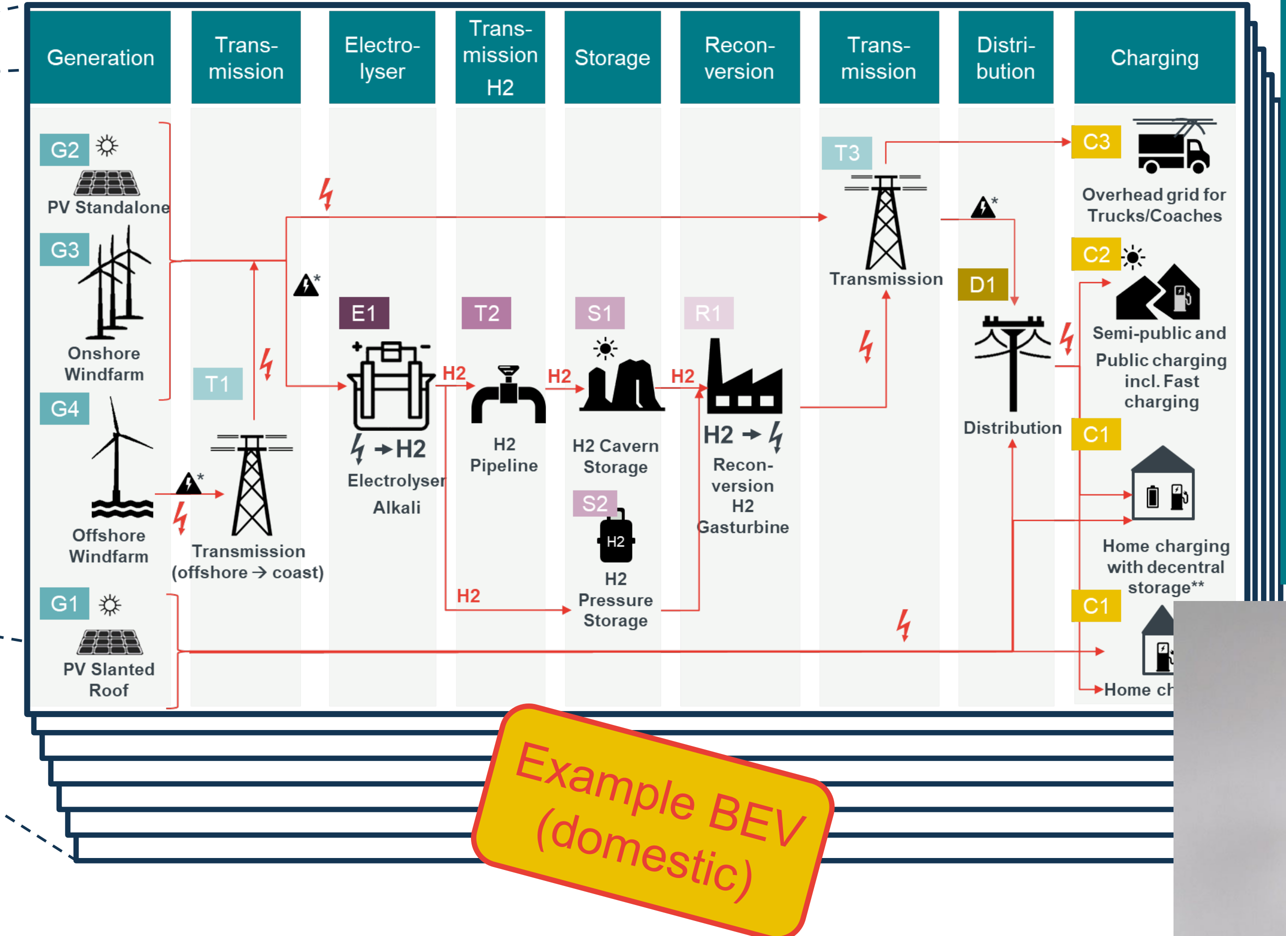
6 fuel types
7 drivetrains

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

3 vehicle efficiency scenarios

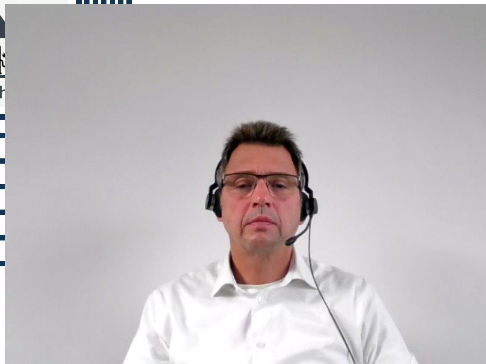
- Status Quo
- Balanced
- All-In

… 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:

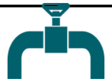
- Energy demand
- Power generation capacity
- Societal costs
- Cumulative GHG emissions
- Other environ-mental impacts (land use,…)



International Energy Sourcing Scenario

Assumptions: import options

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		X
100% Hydrogen		X
100% FT Fuel		
100% Methane		 (LNG)
100% DME		
100% Methanol		

Ammonia Route excluded

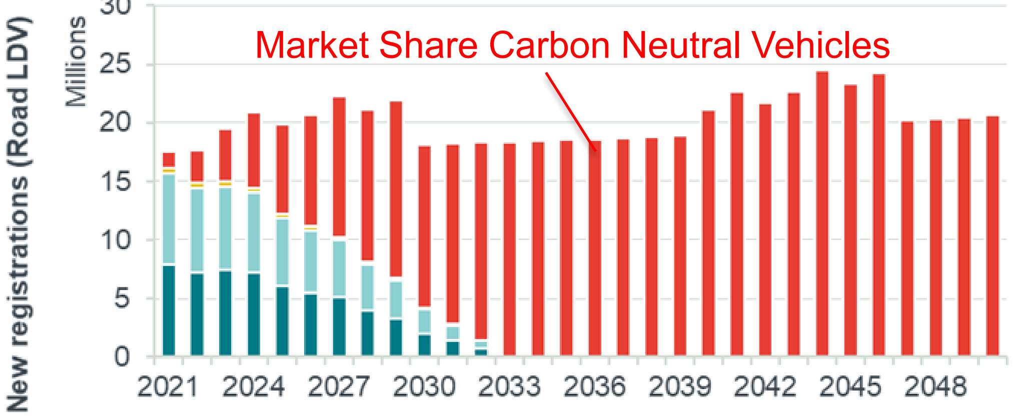
- **70% of the final fuel/energy are imported (30% still produced in Europe)**
- **Imports are equally split between far-off premium locations (such as Patagonia) and closer good locations (such as Morocco) *(except of BEV and H2 → 100% of imports from MENA → 70% of total energy imported from MENA)***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

Fleet development (ramp-up) determined by vehicle lifetime

Example PasCar/LDV

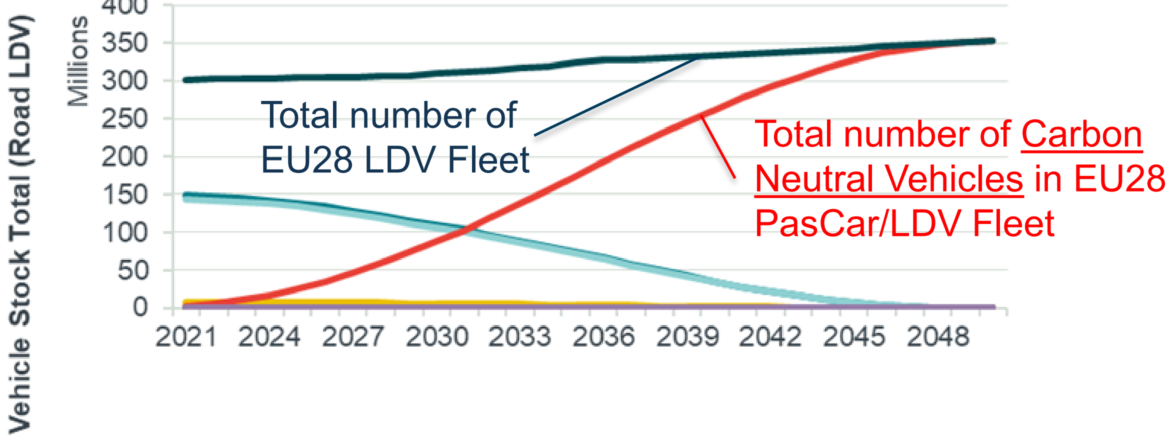
Sales Share

100% Carbon Neutral Vehicle Sales Share in 2033



Market Penetration

100% Carbon Neutral Vehicle Market Penetration in 2050



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

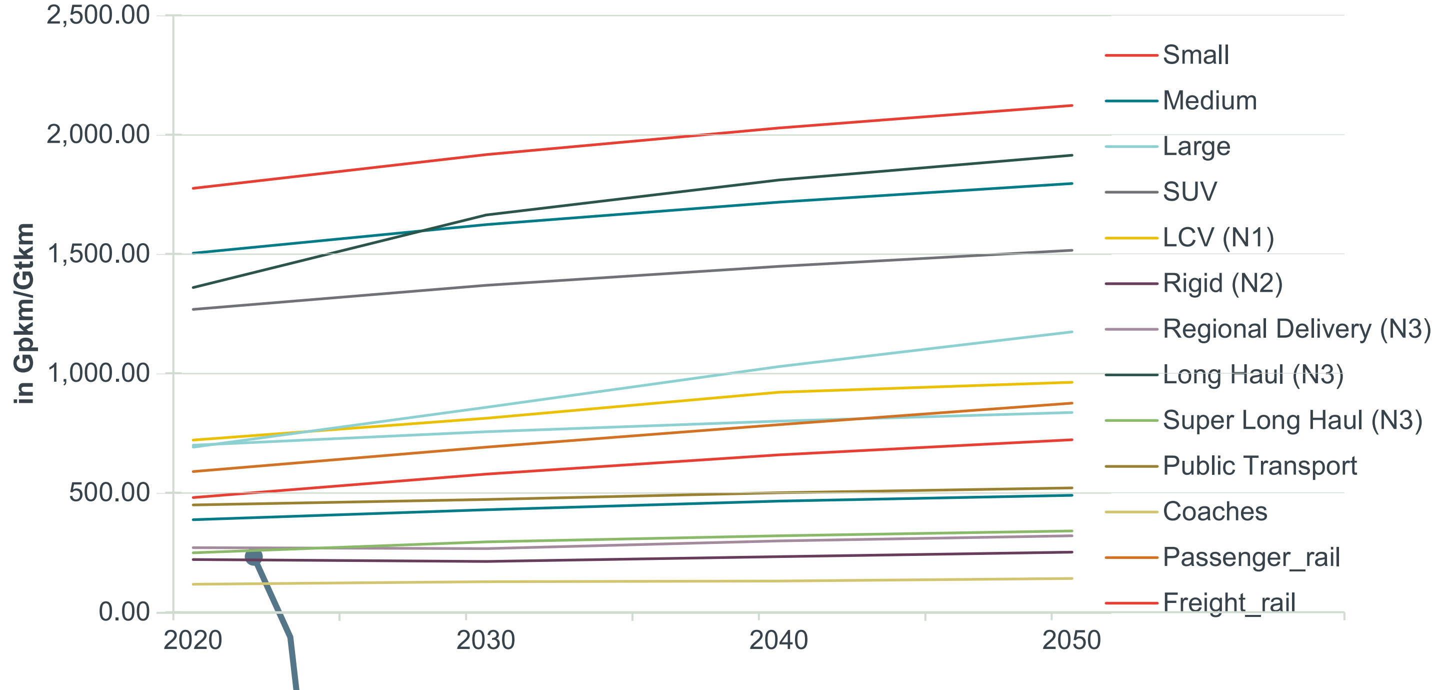
- Theoretical ramp-up gradient, determined by fleet exchange rate.
- Same gradient for all pathways (also for drop-in FT fuel !)
- Further bottlenecks need to be defined in a follow-up study .

- **Target "carbon neutrality 2050" requires 100% carbon neutral vehicles in 2050**
- **<u>Assumption:</u> All new vehicles exclusively operated with renewable energy !**

ENERGY ANALYSIS

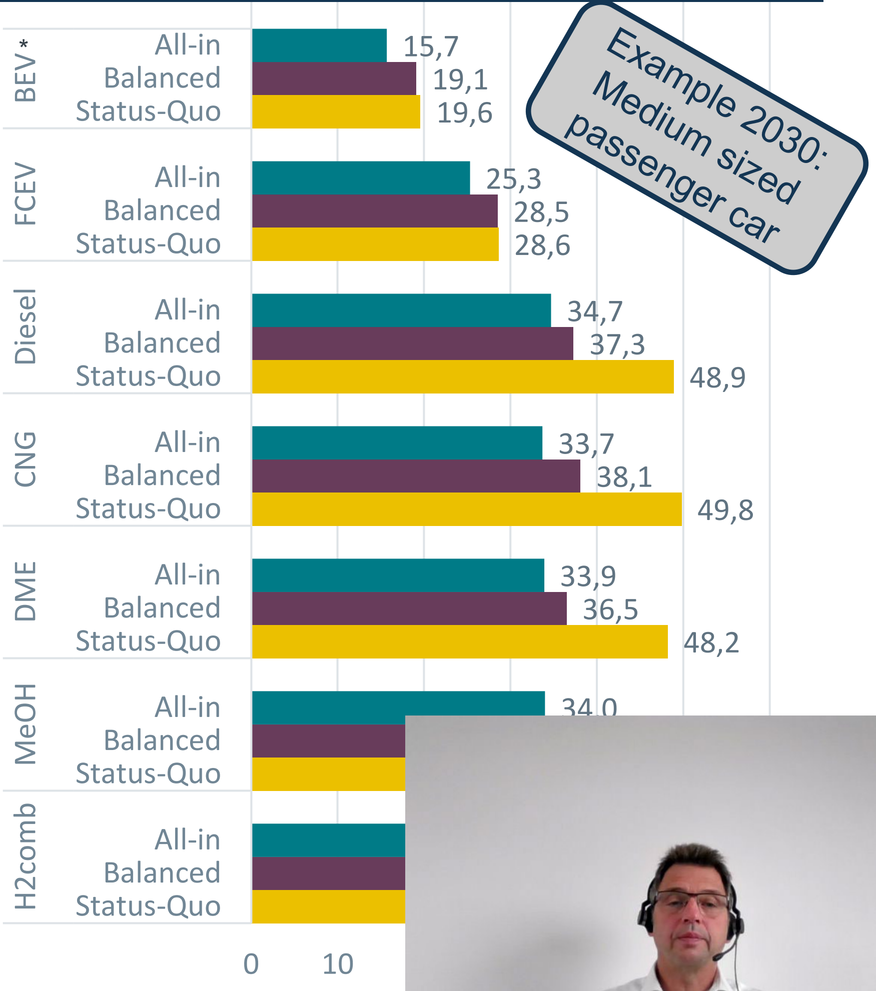
Energy demand is calculated based on fleet, mobility demand and fuel consumption (bottom-up approach)

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

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

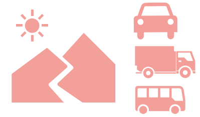
Calculation based on modelling whole fuel chains (isolated for transport sector)

The **lowest WtW demand** occurs in **all BEV scenarios** followed by FCEV: **WtW Energy demand H2-FCEV ≈ 2 x BEV**

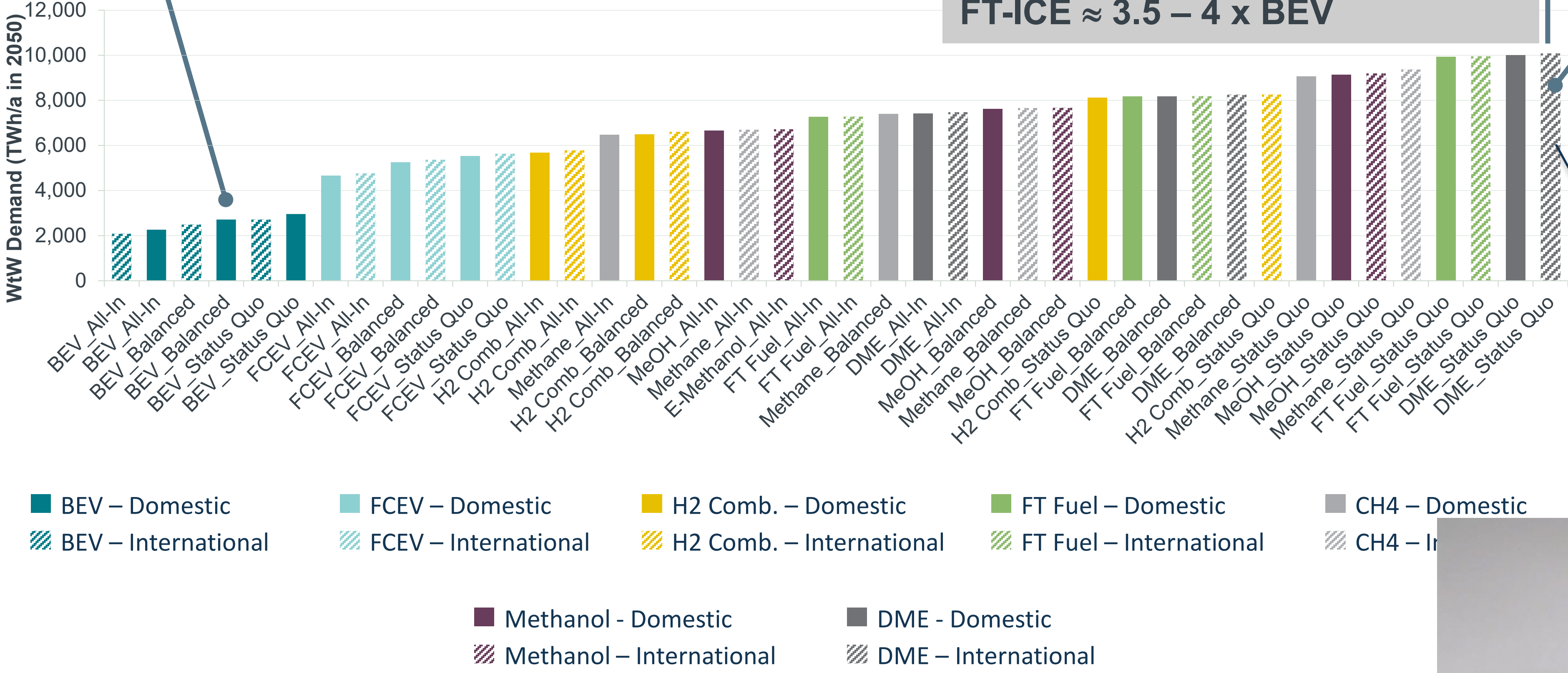
Higher WtW energy demands for ICEV:

H2-ICE ≈ 2.5 – 3 x BEV

FT-ICE ≈ 3.5 – 4 x BEV

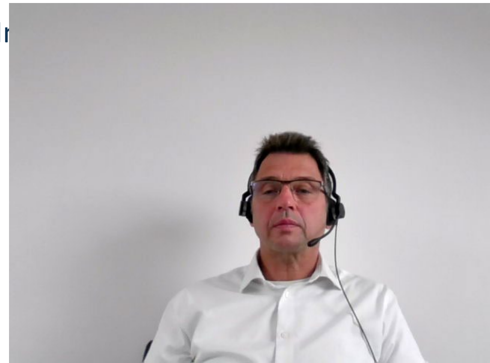


Well-to-Wheel Energy Demand 2050 / TWh



Solid bar: domestic energy sourcing

Dashed bar: global energy sourcing



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

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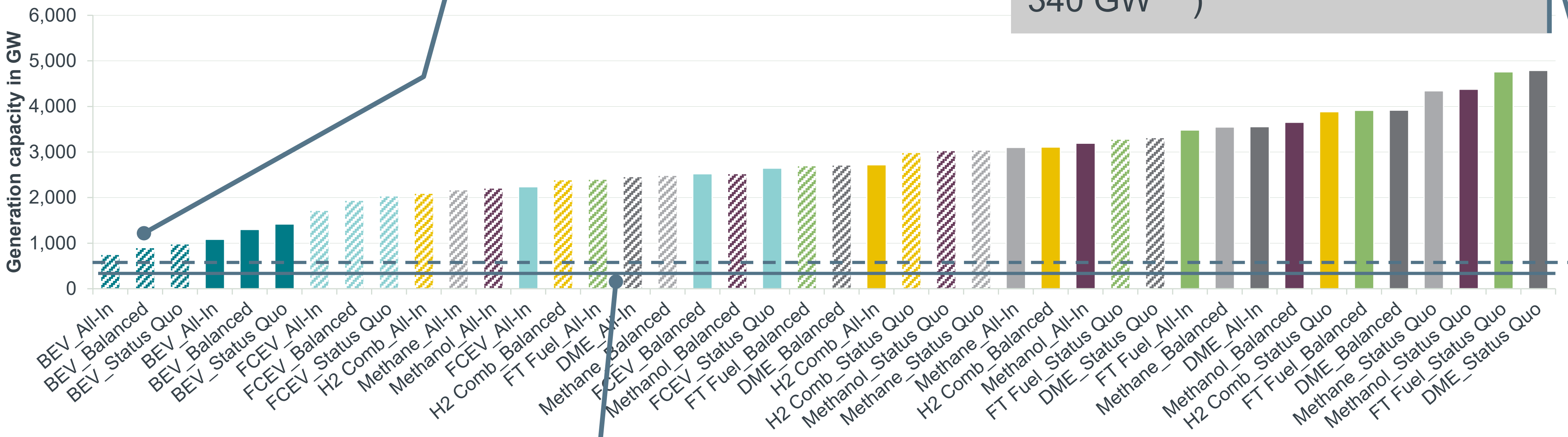
Installed capacity driven by total WtW demand, but also by achievable full-load-hours (location)

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



BEV – Domestic
BEV – International
FCEV – Domestic
FCEV – International
H2 Comb. – Domestic
H2 Comb. – International
FT Fuel – Domestic
FT Fuel – International
CH4 – Domestic
CH4 – In
Methanol - Domestic
Methanol – International
DME - Domestic
DME – International

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_St
** 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-20

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

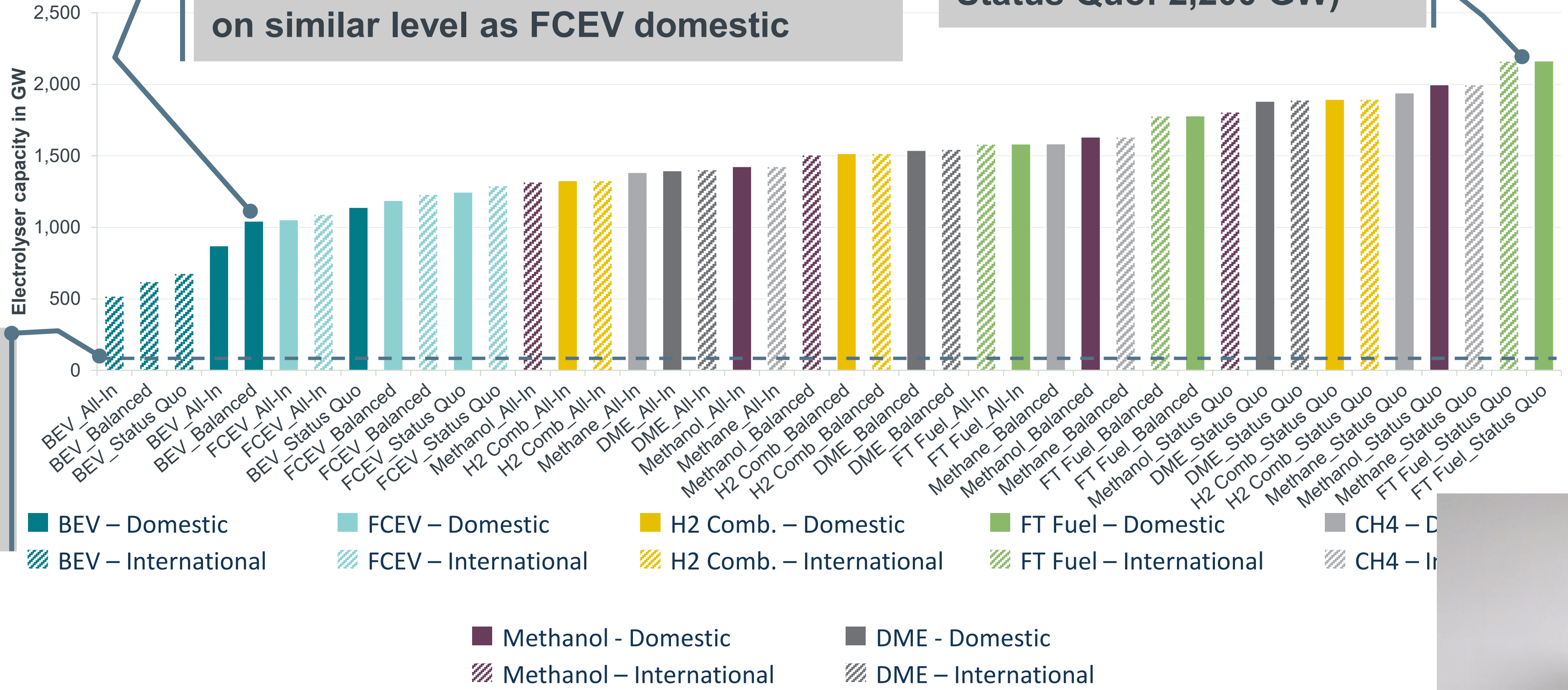
Road segment only

Lowest electrolyser capacities are required in **BEV and FCEV** scenarios.

BEV "domestic, balanced" ≈ 1,000 GW on similar level as FCEV domestic

Highest electrolyser capacities are required for **FT Fuel (All-in 1,600 GW, Status Quo: 2,200 GW)**

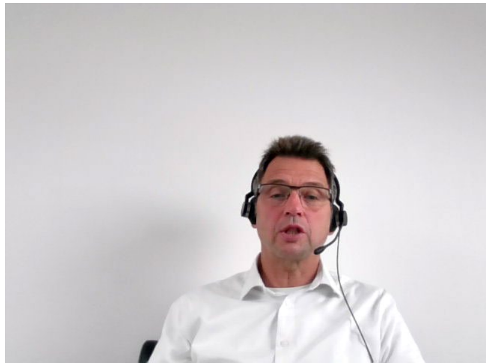
Installed Electrolysis Capacities 2050 / GW



EU plans a total capacity of **40 GW by 2030 for <u>all sectors!</u>**

* 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 & RAW MATERIAL DEMAND



Environmental impacts analysis

Cradle-to-Grave (C2G) analysis approach

Energy provision, production & distribution | Transport Operation | Infrastructure and vehicles

Extraction/ Generation → Refineries/ Power plants/ PtX plants → Energy distribution | Energy consumption | Infrastructure | Vehicles (incl. EoL)

Well-to-Tank (WTT) → Tank-to-Wheel (TTW)

Well-to-Wheel

Cradle-to-grave

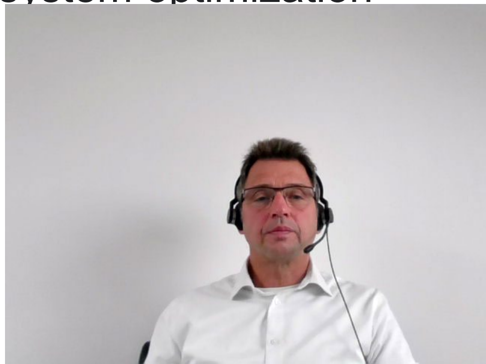
Environmental databases

- 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

Cradle-to-grave (C2G) approach is different from usual Vehicle Life Cycle Analysis (LCA)
→ GHG emissions of building-up the power supply and energy distribution infrastructure separately accounted in the year they occur, and NOT depreciated over lifetime as part of the WTT emissions → allows system optimization

Total environmental impacts per year

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

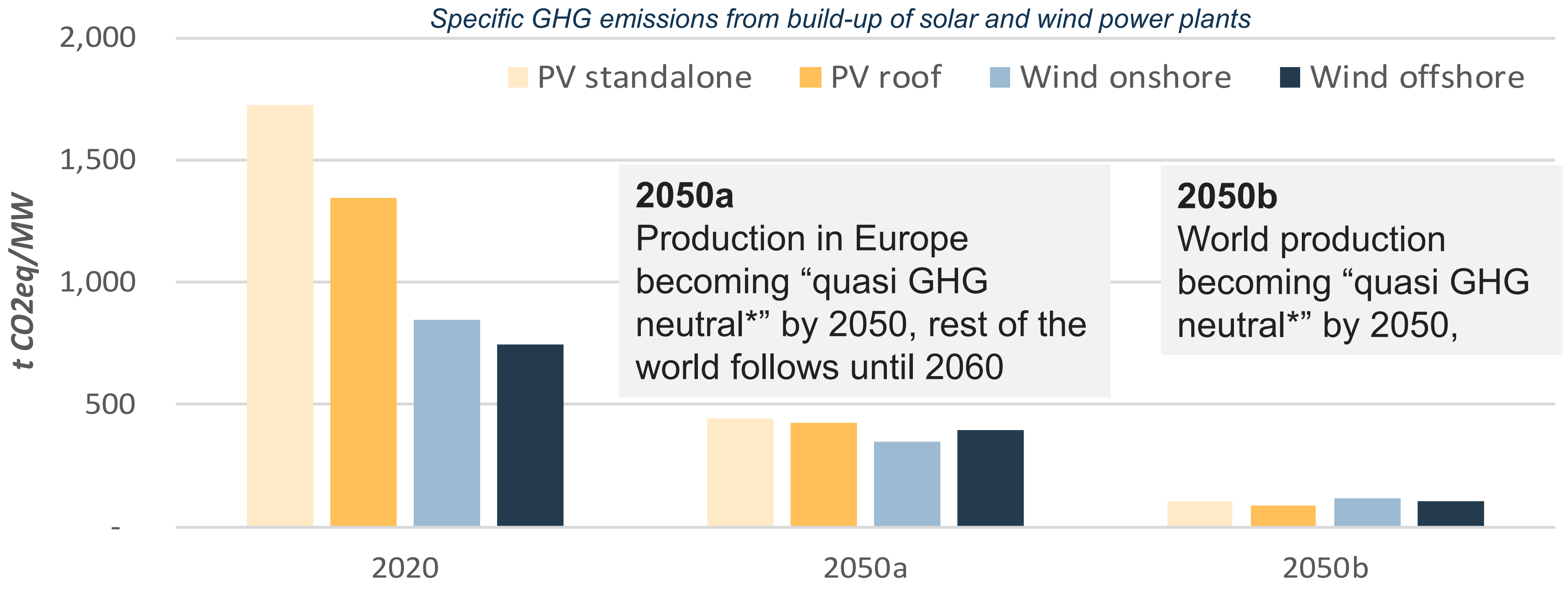


Environmental impacts analysis

Specific GHG emissions from build-up of wind and solar power plants

→ **Future defossilisation of the background system** (materials and energy emission factors) → **strong future decrease in GHG emissions of power supply infrastructure**

→ With increasing defossilisation of material supply and production processes, specific GHG emissions of PV and wind power plant installation will decrease significantly.[1]



[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.

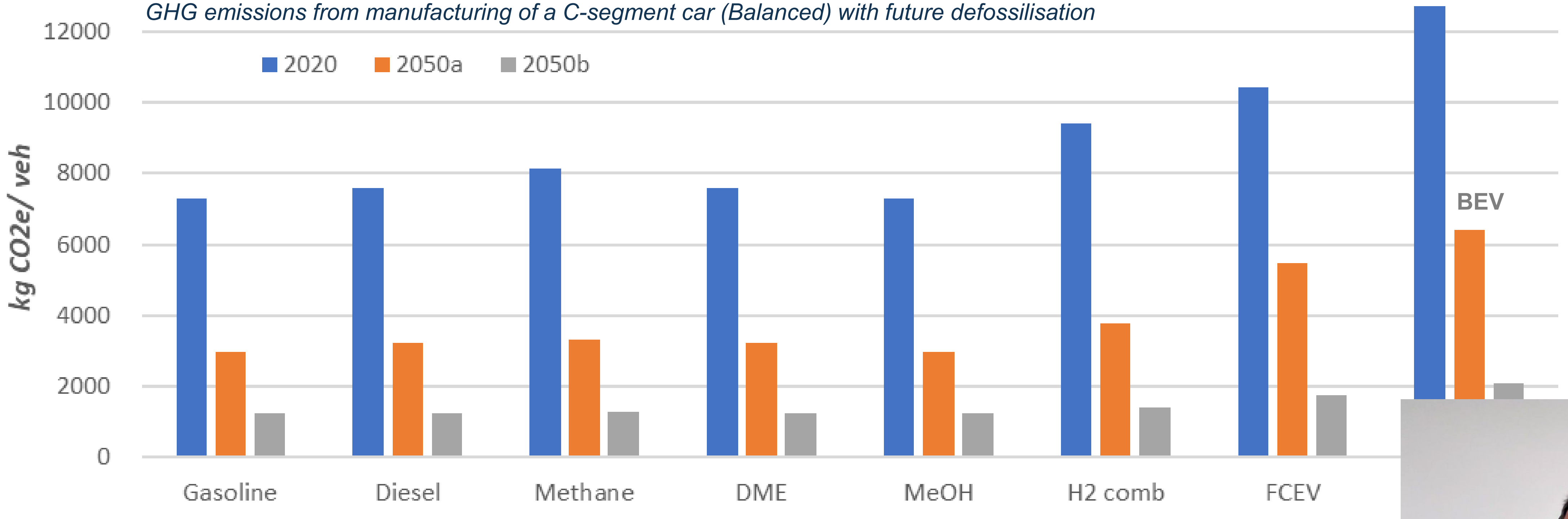
* only unavoidable GHG emissions left

Environmental impacts analysis

Specific GHG emissions from vehicle production with future defossilisaton

→ **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.



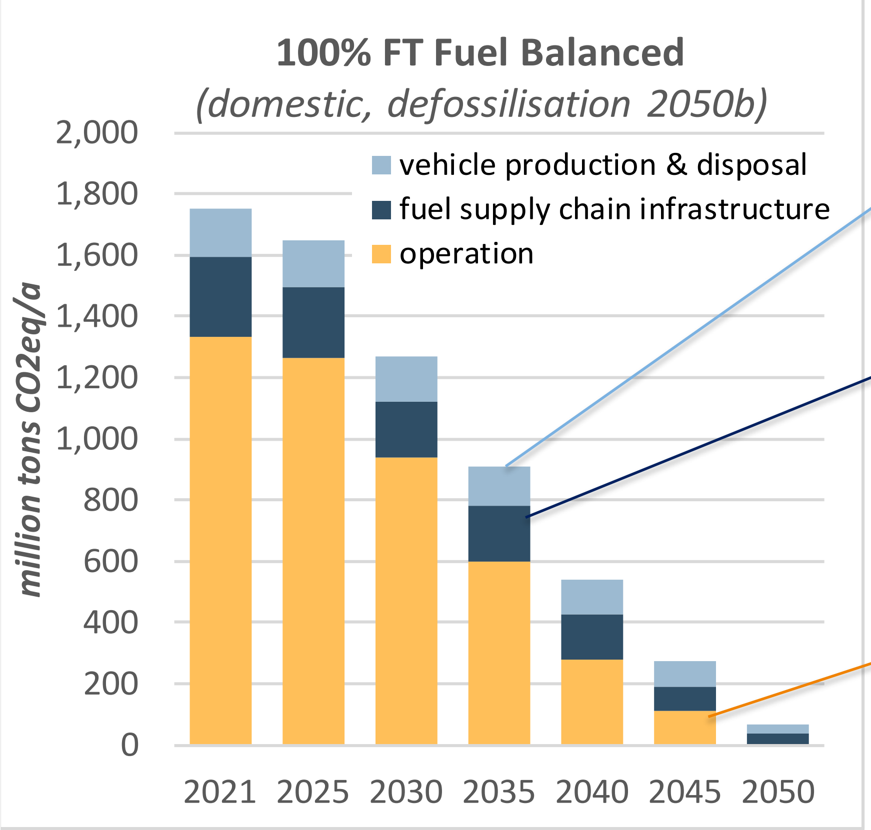
2050a
Production in Europe becoming "quasi GHG neutral*" by 2050, rest of the world follows by 2060

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

* only unavoidable GHG emissions left

Environmental impacts analysis

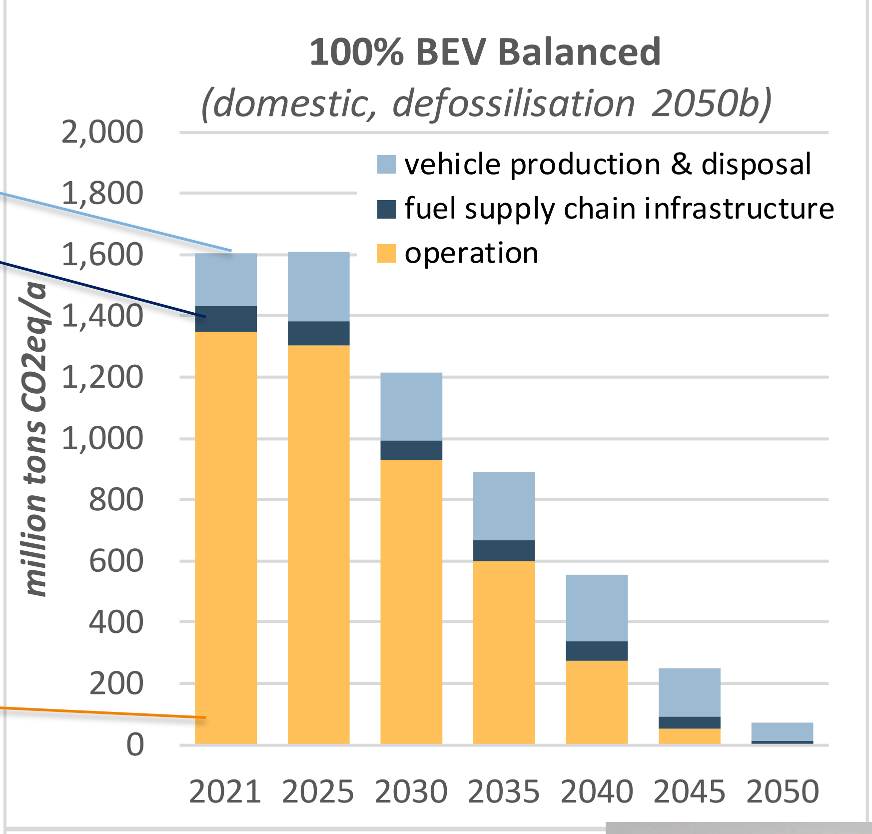
Annual GHG emissions in 100% scenarios with identical ramp-up speeds



Vehicle production and disposal

Build-up of power generation and energy/ fuel distribution infrastructure

Operation of out-phasing fleet with fossil diesel/gasoline (incl. 7% biofuel)



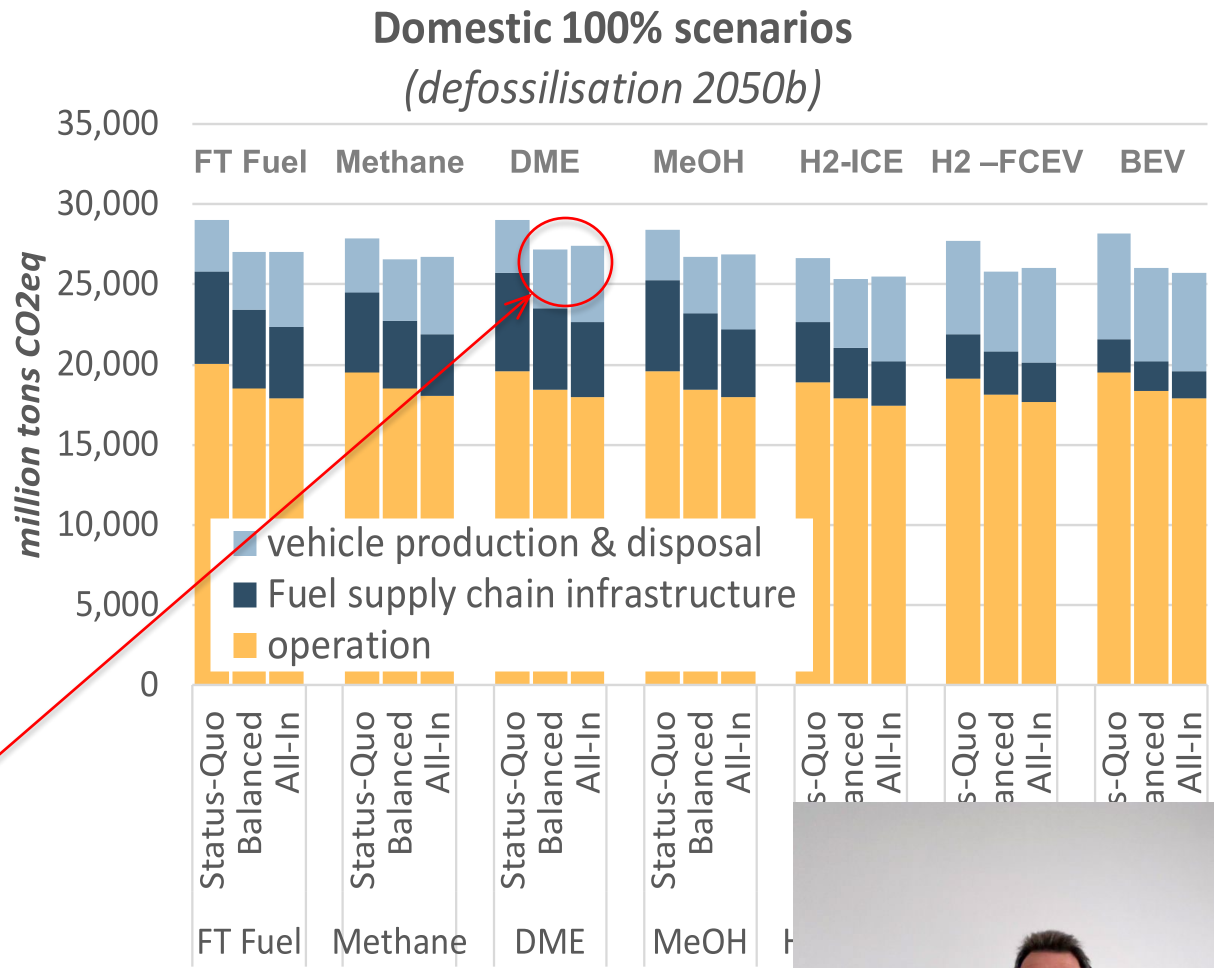
- **Vehicle operation of out-phasing fleet with fossil fuels dominate annual GHG for all pathways**
- **Emissions until 2030 dominate "GHG backpack 2050" by 55..60%**
- **Quick reduction of fossil energy use in the next decade is absolutely essential**

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

Environmental impacts analysis

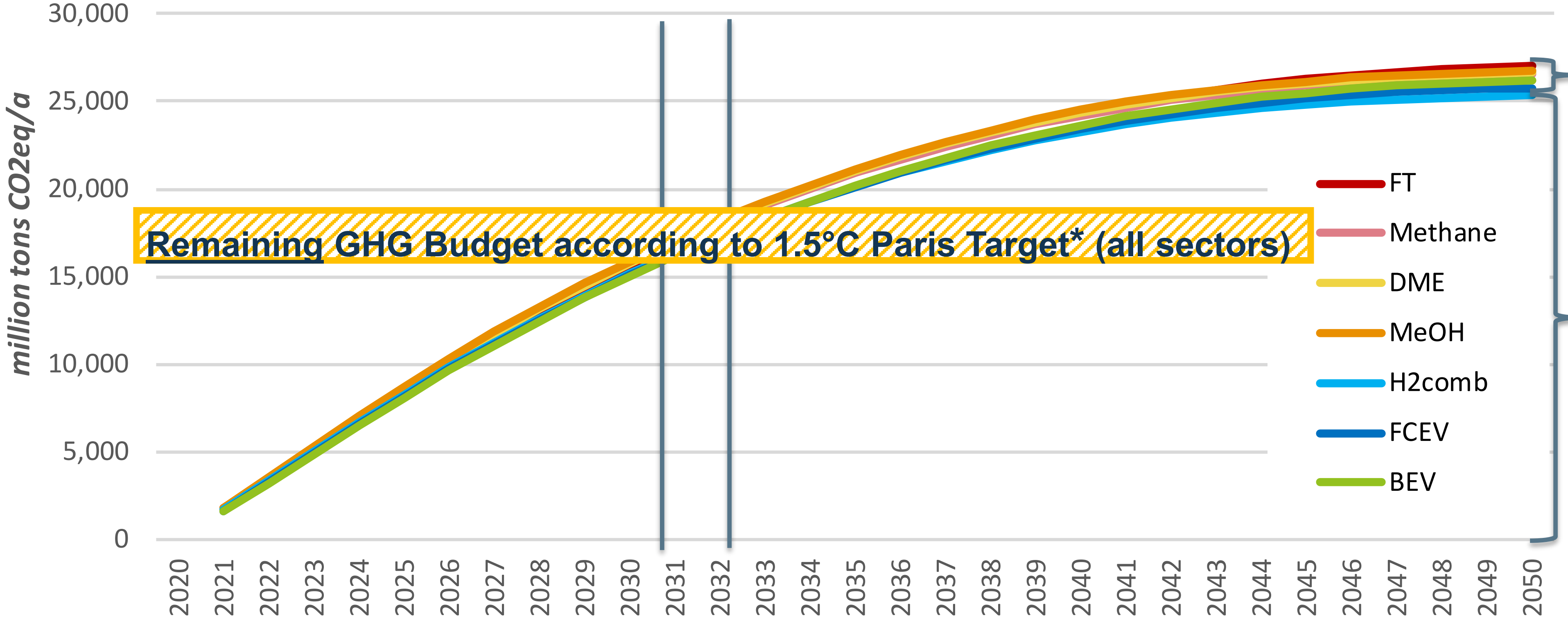
Cumulative GHG emissions with identical ramp-up speed of all 100% pathways

- **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.**
- **Vehicle production/disposal + building-up the sustainable infrastructure** contribute with **≈ 30%**
- GHG savings of improved vehicle fuel efficiencies do not generally compensate increased GHG emissions during vehicle production → **improving vehicle efficiency can lead to increased total GHG**



Environmental impacts analysis

Comparison: Cumulative GHG emissions with remaining GHG budget

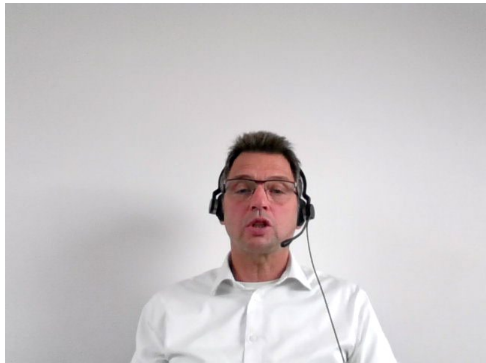


Cumulative bandwidth of future fuel / powertrain propulsion pathways

GHG emissions dominated by emissions of out-phasing fleet operated by fossil fuel

- No significant differences in cumulative GHG between pathways
- **With assumed ramp-up**** (determined by fleet exchange rate) **Paris 1.5°C GHG target* for all sectors will be exceeded soon (2031/32) just by transport related GHG** (**28% fossil energy replaced in transport incl. vehicle & energy system production by 2030)
- **Fast action required** for a quick reduction of fossil fuel use in the existing vehicle fleet

* **1.5°C 50^{th} … 67^{th} TCRE European share according to population share (6.5%)** for EU27+UK road transport (C2G basis: including build-up of fuel/energy supply infrastructure + vehicle production/disposal)

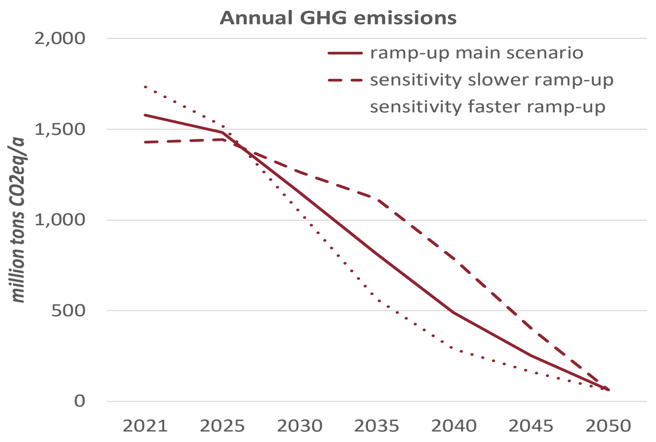


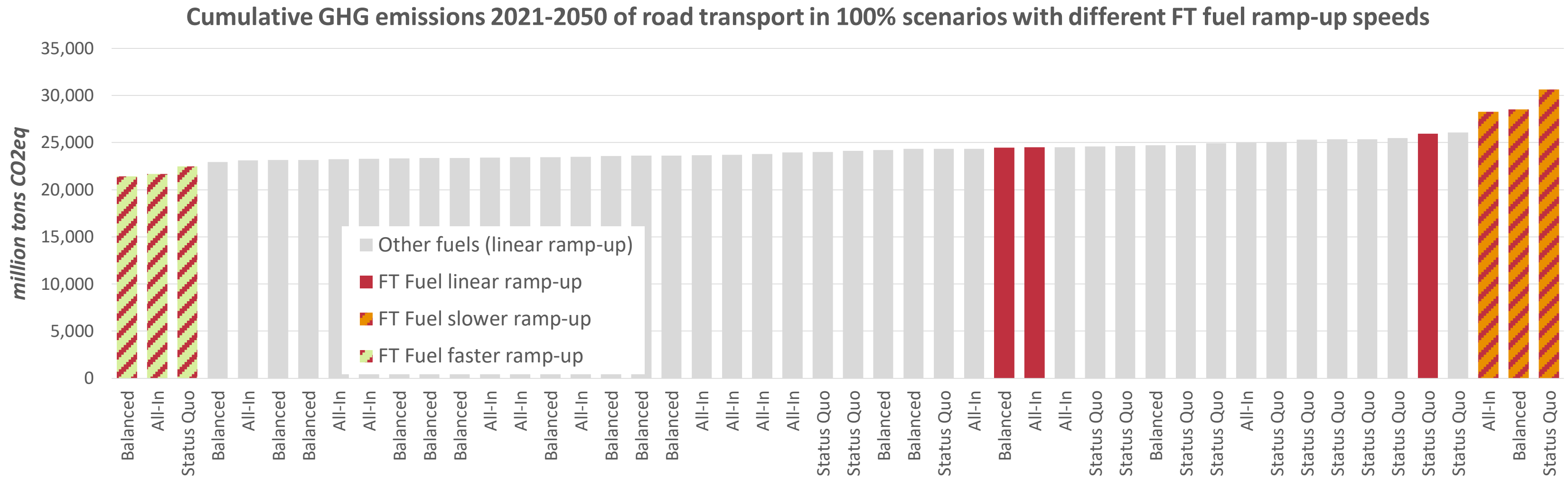
Environmental impacts analysis

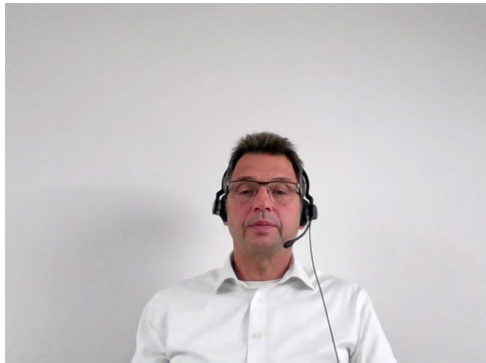
Sensitivity analysis of ramp-up speed (example: Fischer-Tropsch pathway)

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

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

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

Acidification:

- 20 … - 45% for ICEV

- 5 … - 45 % for FCEV

+ 10 … - 20 % for BEV

Eutrophication:

- 60 … - 70% for ICEV

- 70 … - 80 % for FCEV

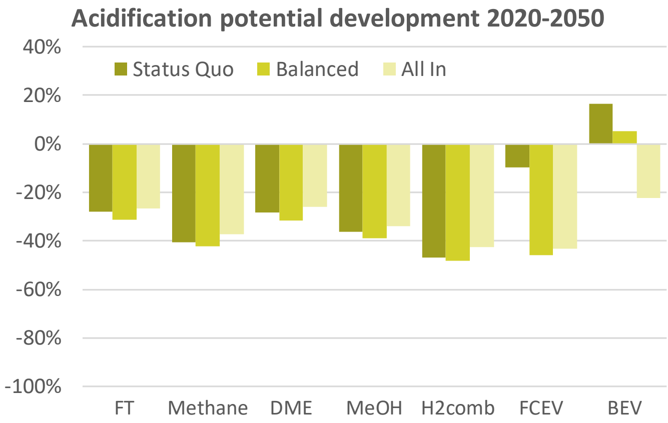
- 70 … - 75 % for BEV

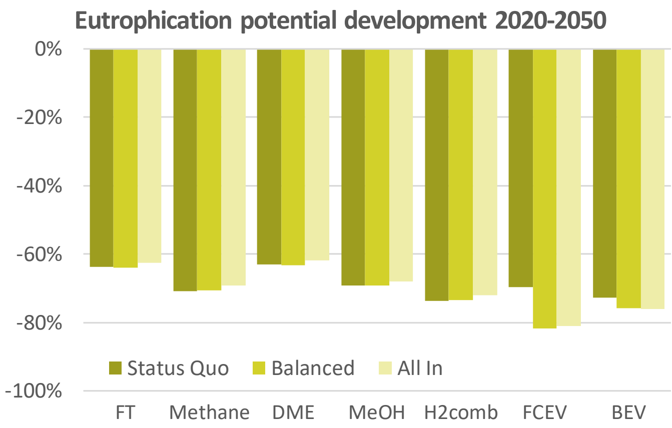
PM Formation :

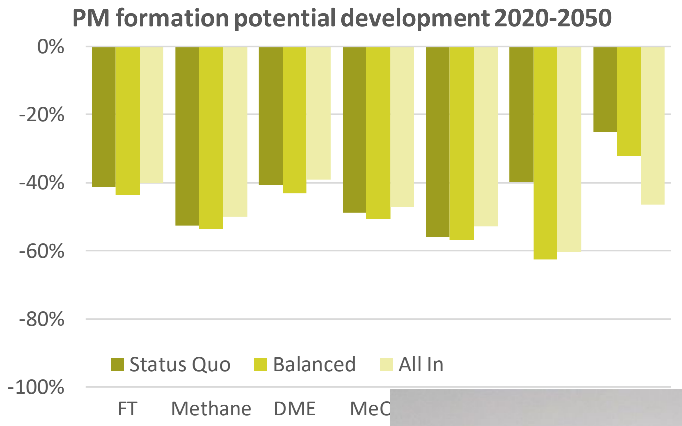
- 40 … - 55 % for ICEV

- 40 … - 60 % for FCEV

- 20 … - 45 % for BEV

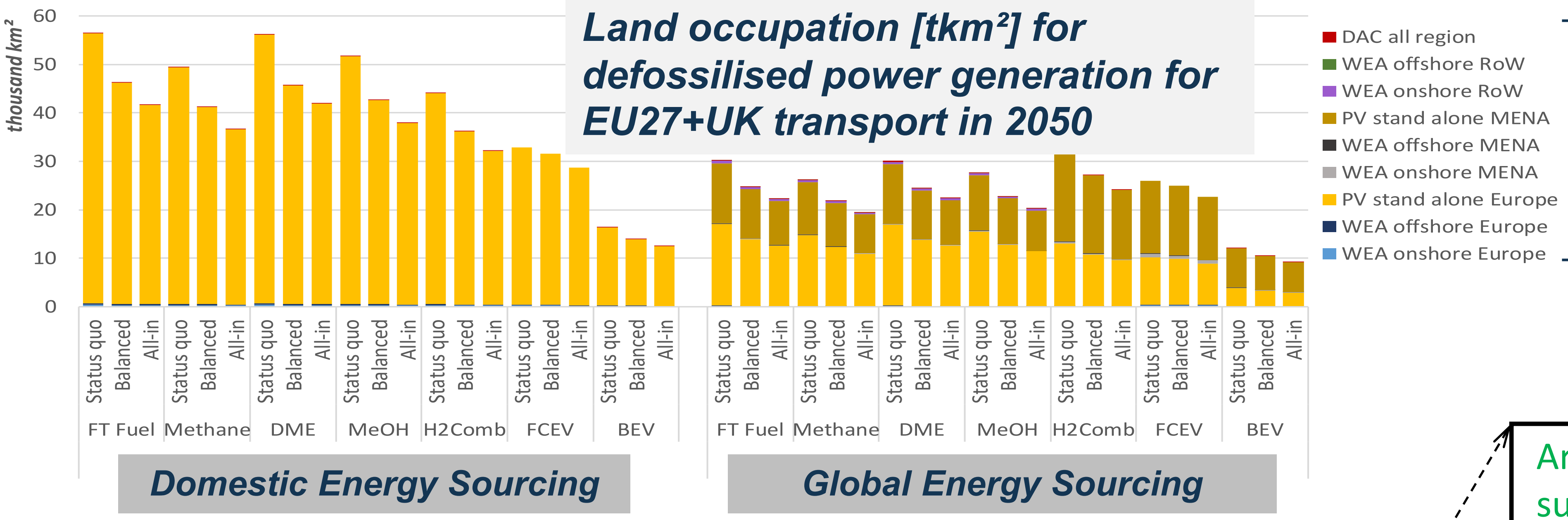






Environmental impacts analysis

Land use is no ecological bottleneck for any investigated pathway



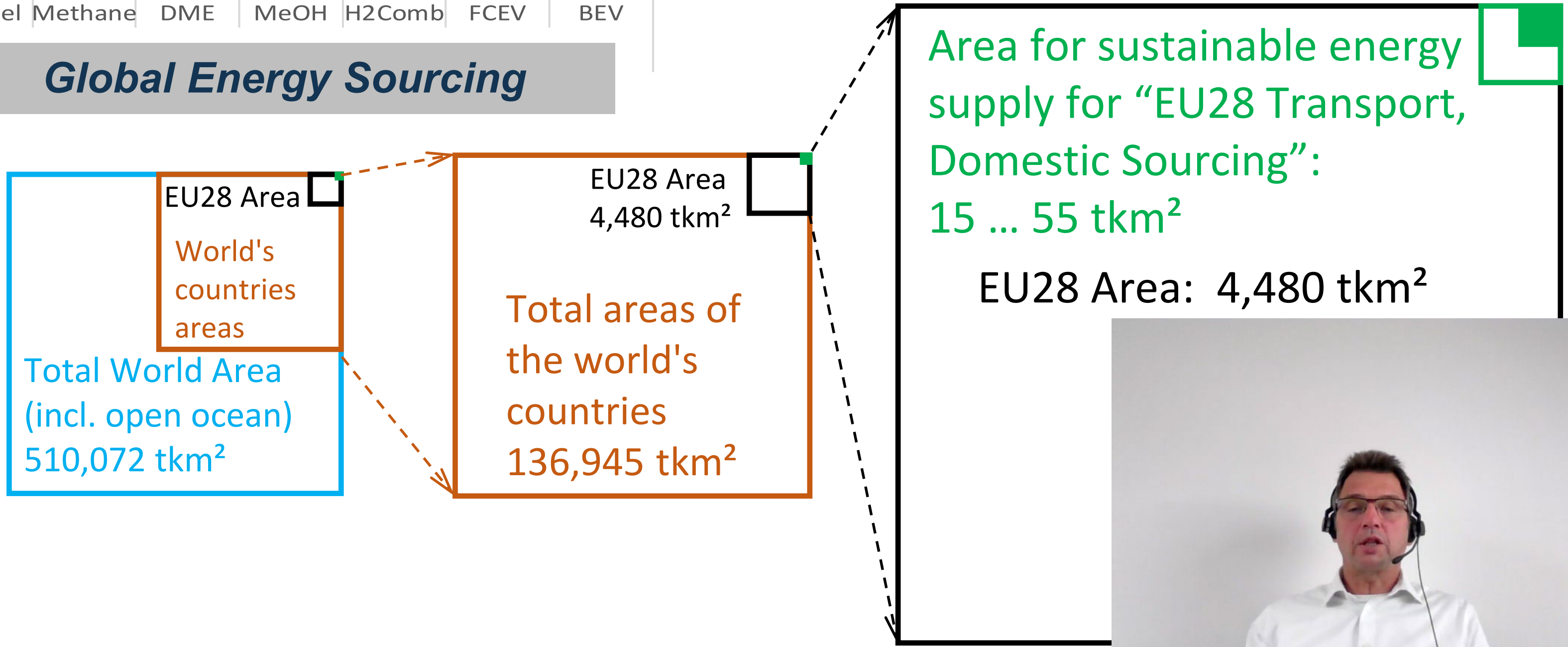
→ **Ecologically relevant land use change → amount of area covered** (cannot be used for other applications)

→ Land use is determined by sustainable 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 (all pathways)**



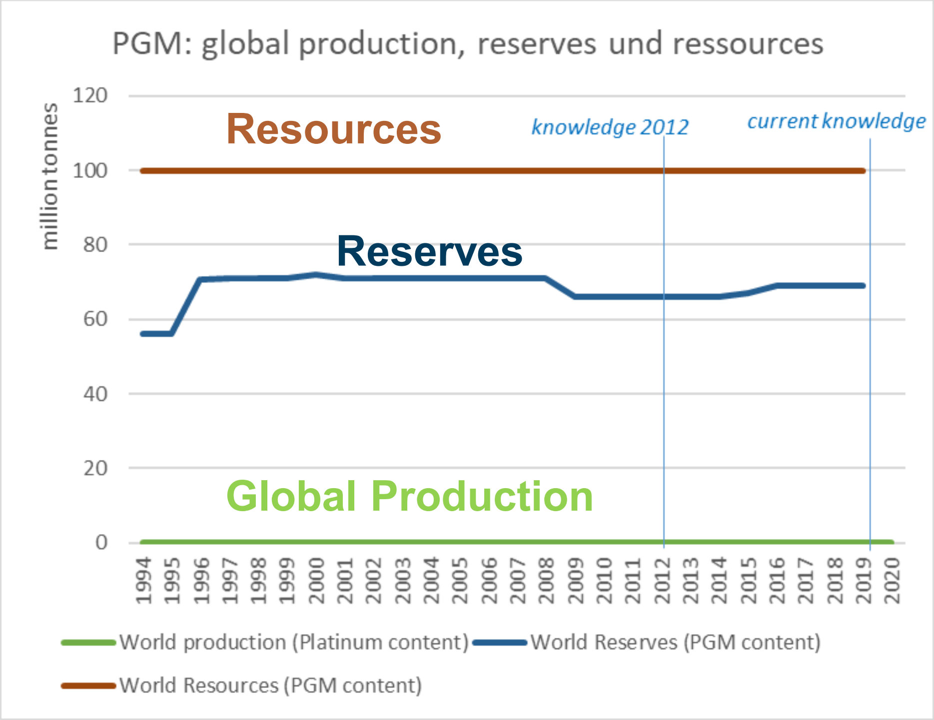
Critical raw materials

Global Resources and Reserves: Definition and Dynamics

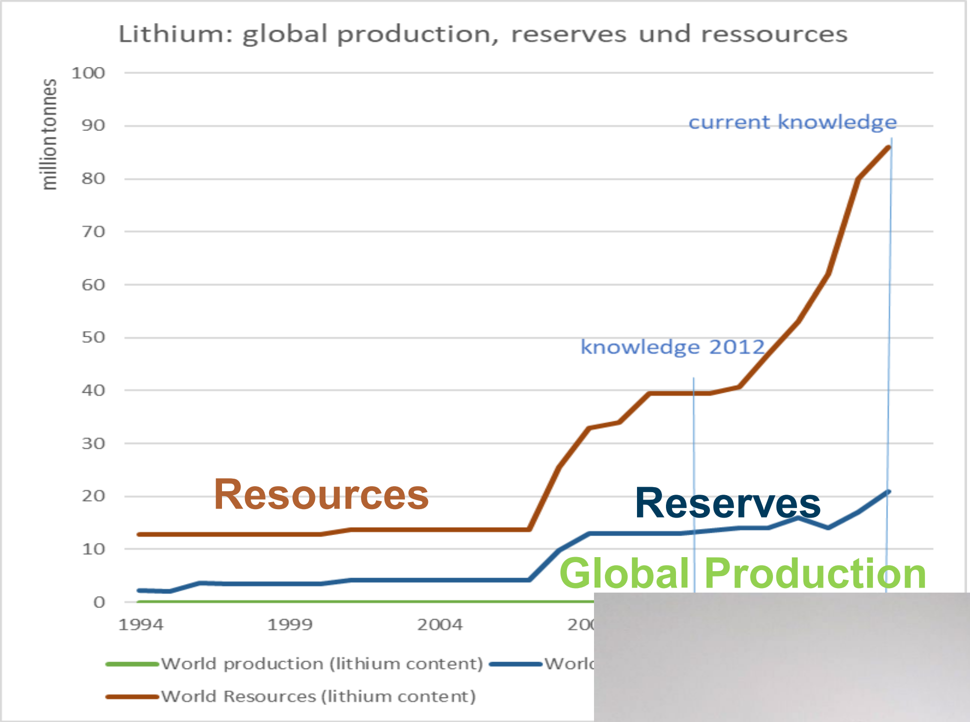
- **<u>Resources</u>**: material with **reasonable prospects for eventual economic extraction**
- Well explored reserves (e.g. Pt) → no significant change over time.
- Recently demanded reserves (e.g. Li) → dynamic increase.

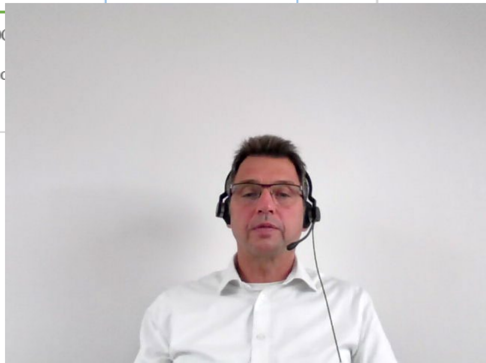
- **<u>Reserves</u>**: **<u>part of the resources</u>** known to be **economically feasible for extraction.**
- Reserves increase with increasing prices

PGM



Lithium

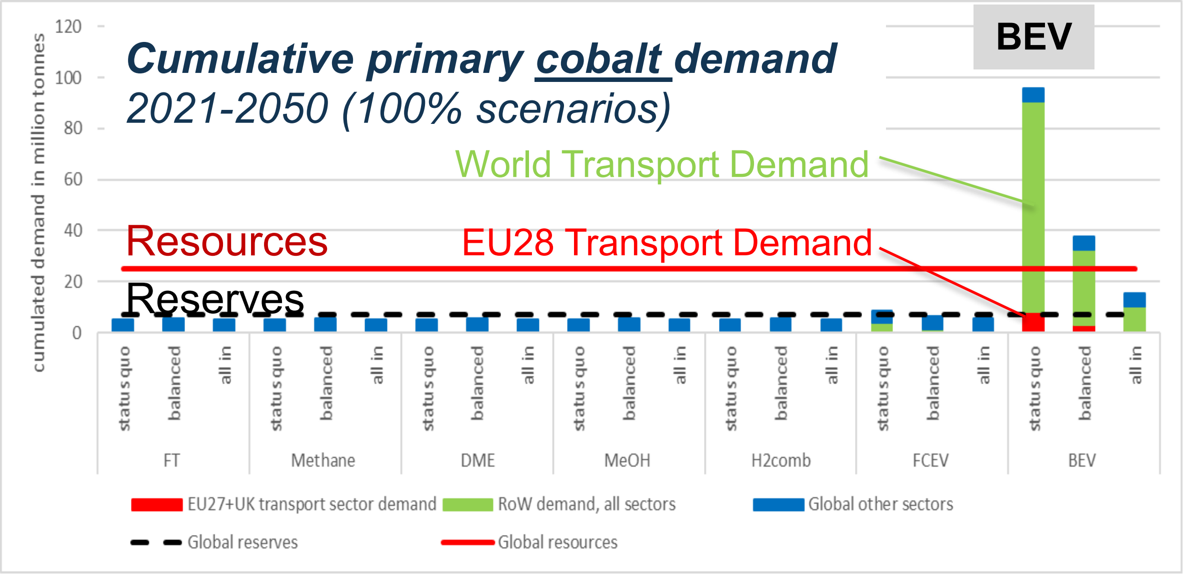


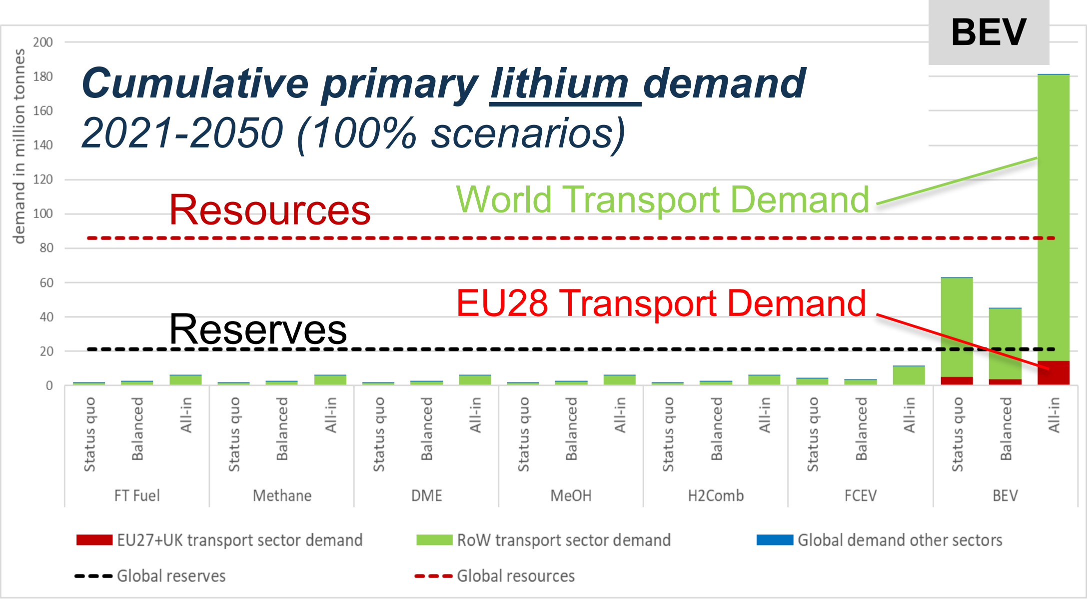


Critical raw materials for BEV (100% scenarios, worldwide demand)

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

- **Cobalt and lithium** reserves: sufficient to **fulfil cumulative <u>EU28 mobility demand</u> with 100% BEV**
- **<u>Worldwide BEV ramp-up</u> → material bottlenecks expected** (with assumed battery configurations)[1]



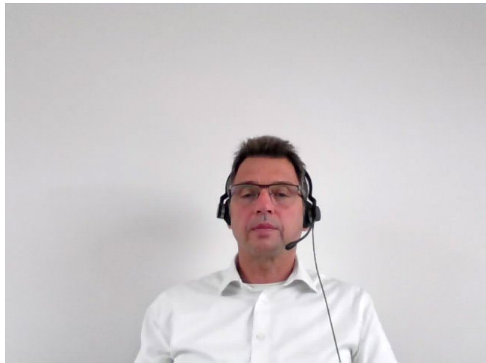


Reduction measures: global Co and Li demand:

- Mix of battery technologies (e.g. LFP, SIB)
- Reduction of battery size, worldwide motorisation

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

[1] *300-500km vehicle range, Li-Ion NMC as state-of-the-art battery technology on EU market, Economic catch-up of all countries and same per-capita-vehicle sales by 2050 as in EU*



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

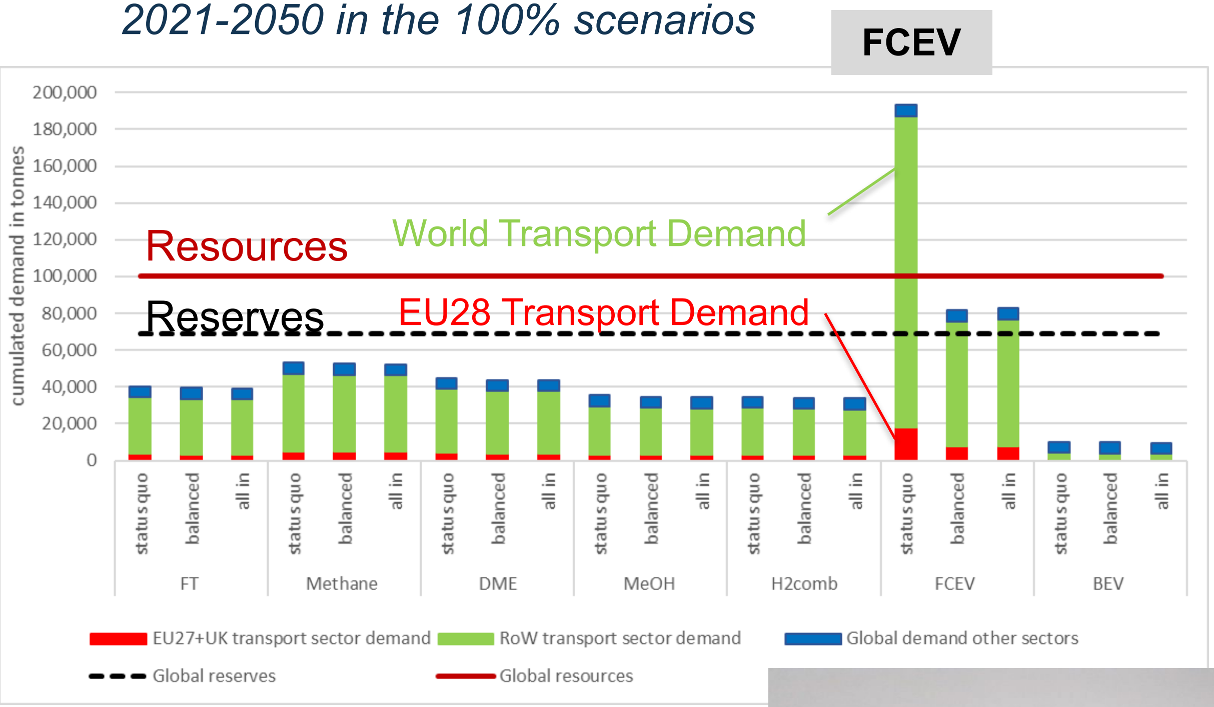
Platinum group metals (PGM) → bottleneck for worldwide FCEV

→ Current PGM reserves are sufficient to fulfil European cumulative demand for primary PGM for the mobility sector until 2050 in all 100% scenarios.

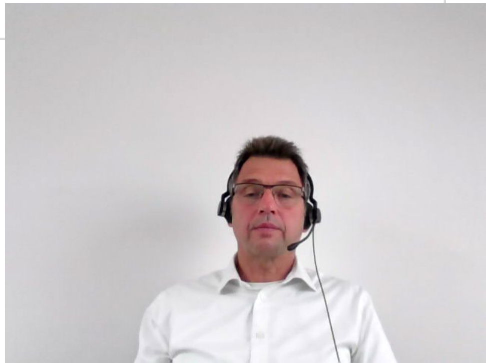
→ **For 100% FCEV pathways, a platinum bottleneck arises at global scale.** Demand would widely use up (Balanced, All-In) or clearly exceed (Status-quo) global platinum resources.

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

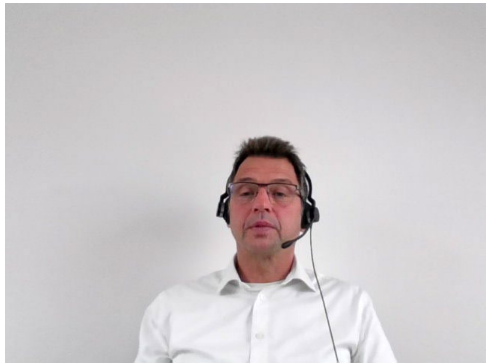
Cumulative primary PGM demand
2021-2050 in the 100% scenarios



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



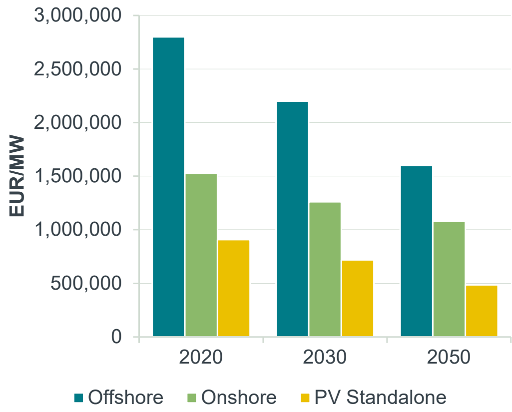
RESULTS ECONOMIC ANALYSIS

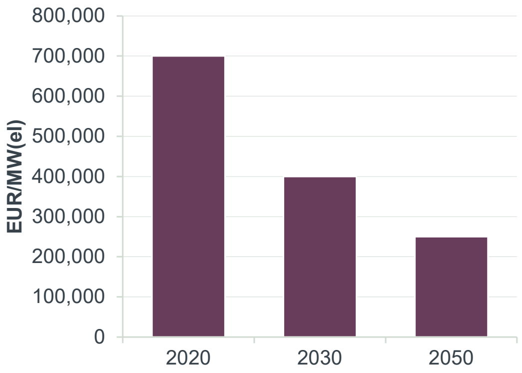


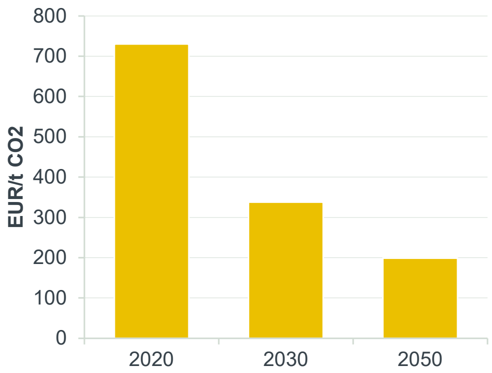
Costs are calculated based on required investment across the whole value chain, including energy/fuel infrastructure …

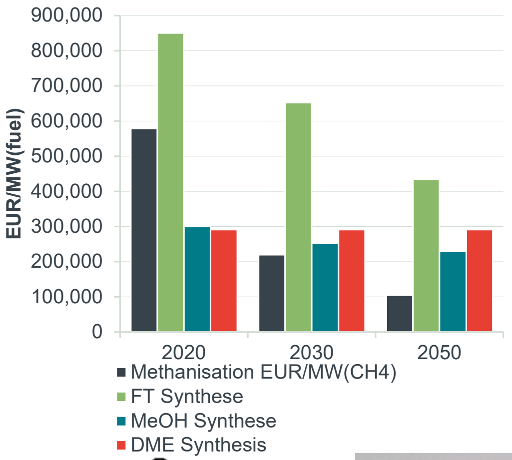
Economic approach	• Total economic costs (i.e. no taxes, margins, …) based on CAPEX and OPEX
	  • Energy losses are directly taken into account (no energy price assumptions required)
	• Calculation of NPV* in €2020 based on 6% real social discount rate
	  • Sensitivity analysis based on 0% discount rate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

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

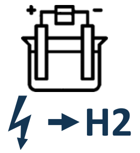




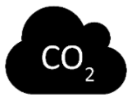




Offshore Windfarm **Onshore Windfarm** **PV Standalone**

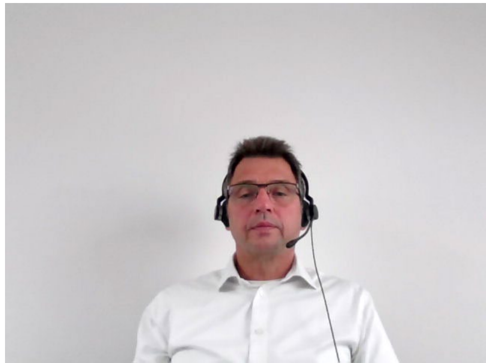


Electrolyser



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

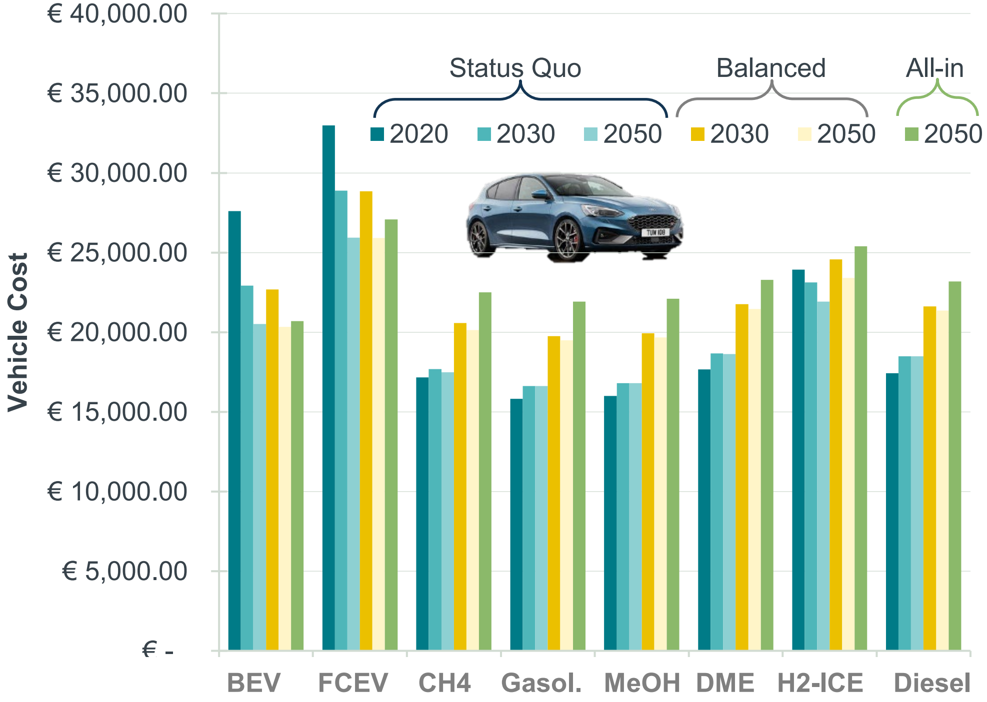
Vehicle costs are estimated following a building-block approach

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 (hybridization, light weight construction, etc.)

Example: FCEV

Example: Costs Medium passenger car



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

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

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

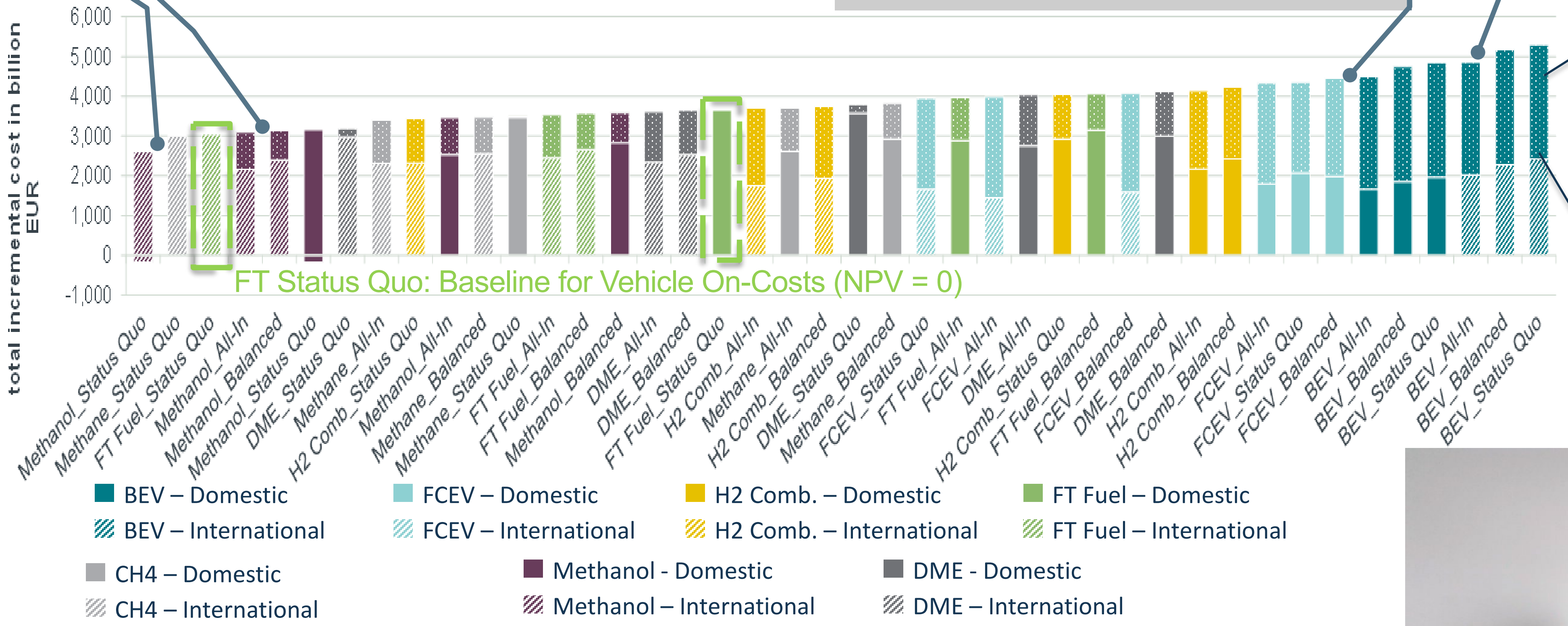
For ICEV “Balanced/All-in” typically more expensive → lower fuel costs (→ better vehicle efficiency) do not compensate higher vehicle costs

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 / billion €



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

Technology Cost Walk – Costs traced back to main drivers

Balanced scenario

Cumulative Total Costs 2020…2050 / billion €

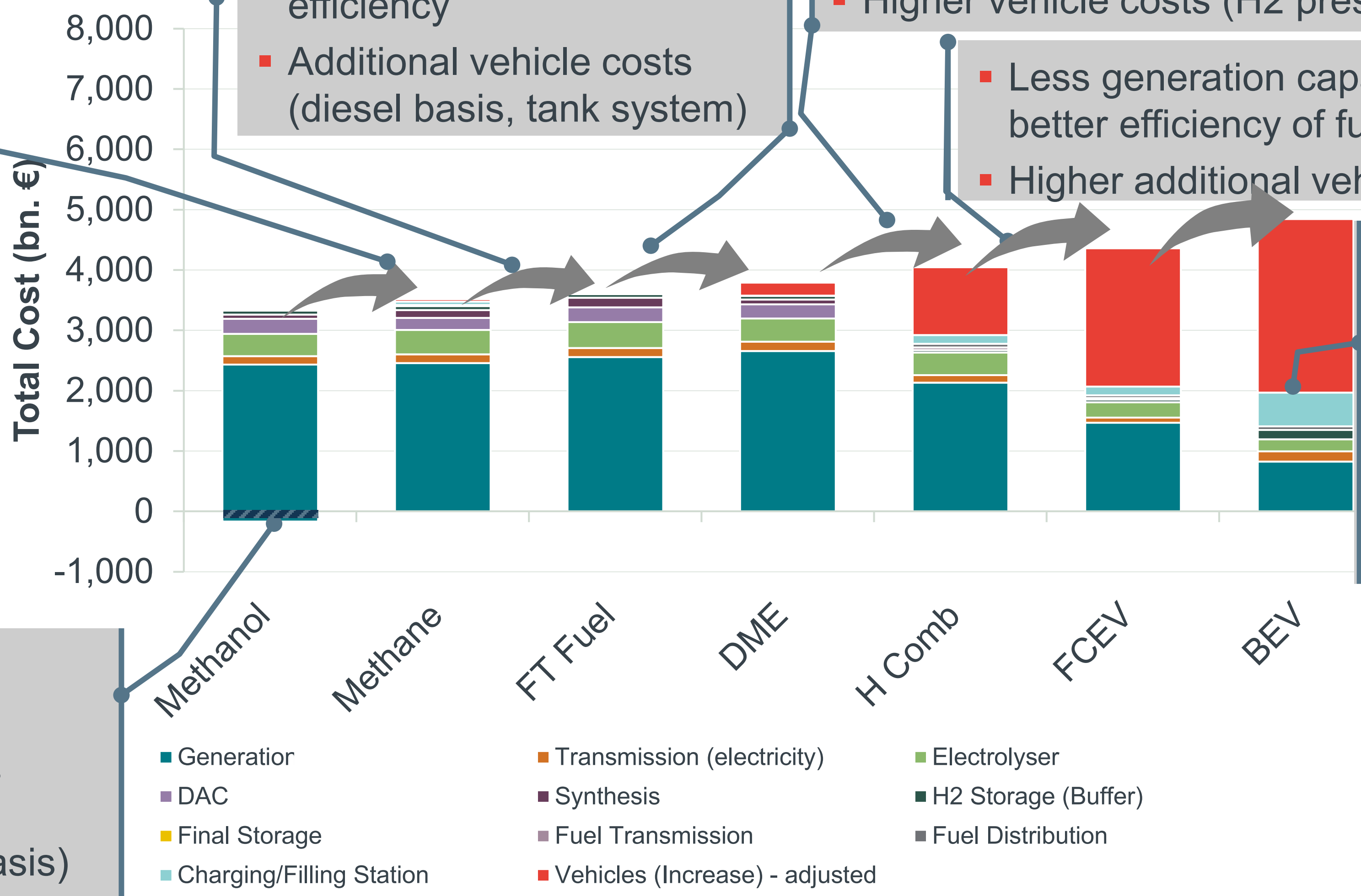
Lower synthesis efficiency

- 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



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

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

SUMMARY AND CONCLUSIONS

Summary

Key Findings (1) – Energy Demand and Installed Capacity

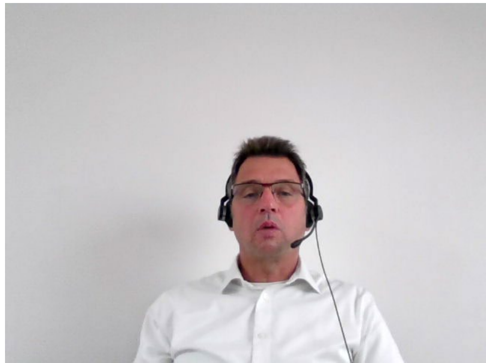
→ **Driver for environmental impacts and costs → installed power generation capacities** (not the WtW energy demand)

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

- Sensible demand for **2050 Transport only ≈ 1,000 GW … 3,000 GW**
- For comparison: **installation plan EU (<u>all sectors</u>): 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). **<u>Sensible</u> capacity ranges (2050) <u>solely for mobility</u>:**

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



Summary

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

→ Total costs (NPV): 2,600 … 5,300 bn € over 30 years → 17% … 34% of annual GDP 2020 (15,600 bn €)

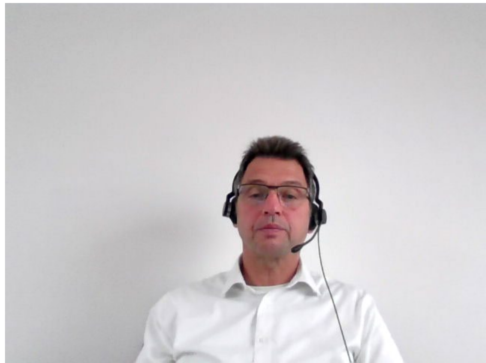
→ International energy sourcing is cheaper than domestic for ICE and FCEV (→ higher full load hours in sweet spots), except for BEV (→ expensive installation of HVDC power line)

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

- 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 bn €, FT-diesel/gasoline-ICE: ~3,000 bn €, H2-ICE ~3,500 bn €.
- **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.**
- Neither hybridisation, nor light weight measures are paying off.



* 300 – 500km passenger car/LDV range

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

Summary

Key Findings (3) – 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 total cumulative GHG emissions**

→ With assumed identical ramp-ups (determined by vehicle fleet exchange rate) → bandwidth of cumulative GHG emissions between all fuel/PT pathways is comparable (14% range)

→ **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**
- **Will require 43-51% of total** (assumed European) **GHG budget for 1.75°C target******

→ **Carbon neutral drop-in fuels** → option for faster introduction of GHG neutral energy to road transport

→ **Challenge: ramp-up of sustainable energy supply** → follow-up study

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

**Fuel Supply Chain
**** 50% Probability

Summary + Conclusions

Key Findings (4) – 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 Life Cycle 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:
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