Science for a moving society

FVV
Science for a moving society

H2-ICEV
Environmental Impact Assessment and Economic Analysis
based on **FVV Fuels Studies IV / IV b**
"Transformation of mobility to the GHG neutral post fossil age"

ERTRAC H2 ICE - Research Workshop
Brussels | 20 October 2022

Dr.-Ing. Ulrich Kramer,	Ford-Werke GmbH
Dr. rer. pol. David Bothe,	Frontier Economics Ltd.
Dr. Christoph Gatzen,	Frontier Economics Ltd.
André Pfannenschmidt,	Frontier Economics Ltd.
Carolin Baum,	Frontier Economics Ltd.
Fabian Schrogl,	Frontier Economics Ltd.
Osama Mahmood,	Frontier Economics Ltd.

AiF Member

frontier economics

Presented results are based on the FVV fuel study IV and the forthcoming FVV Fuel Study IVb

Future fuels
FVV Fuel study IV

Forthcoming

Transformation of mobility to the GHG neutral post fossil age
FVV Fuel study IVb

Analysis of 42 different single fuel / powertrain combinations regarding GHG emissions and costs

Published Oct. 2021

https://www.fvv-net.de/fileadmin/Downloads/Publikationen/FVV__Future_Fuels__StudyIV_The_Transformation_of_Mobility__H1269_2021-10__EN.pdf

Dr.-Ing. Ulrich Kramer
(Ford-Werke GmbH)
Dr. rer. pol. David Bothe
Dr. Christoph Gatzen
André Pfannenschmidt
Carolin Baum
Fabian Schrogl
Osama Mahmood
(alle Frontier Economics Ltd.)

\+ >45 Counsellors

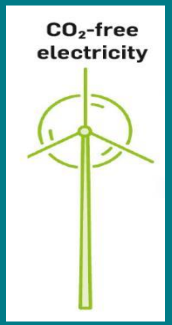
Content

Approach: FVV Fuels Study IV

Hypothetical "**Single Technology Scenarios**", all assumed to achieve carbon neutrality in 2050

PHOTO YEAR 2050 + REFERENCE RAMP-UP (2020 → 2050)

42 Single Tech. Scenarios for Carbon Neutral Mobility in EU27+UK **in 2050 …** supplied solely by wind/solar energy



2x Energy Sourcing: Domestic vs. Global

Domestic

International

6 fuel types

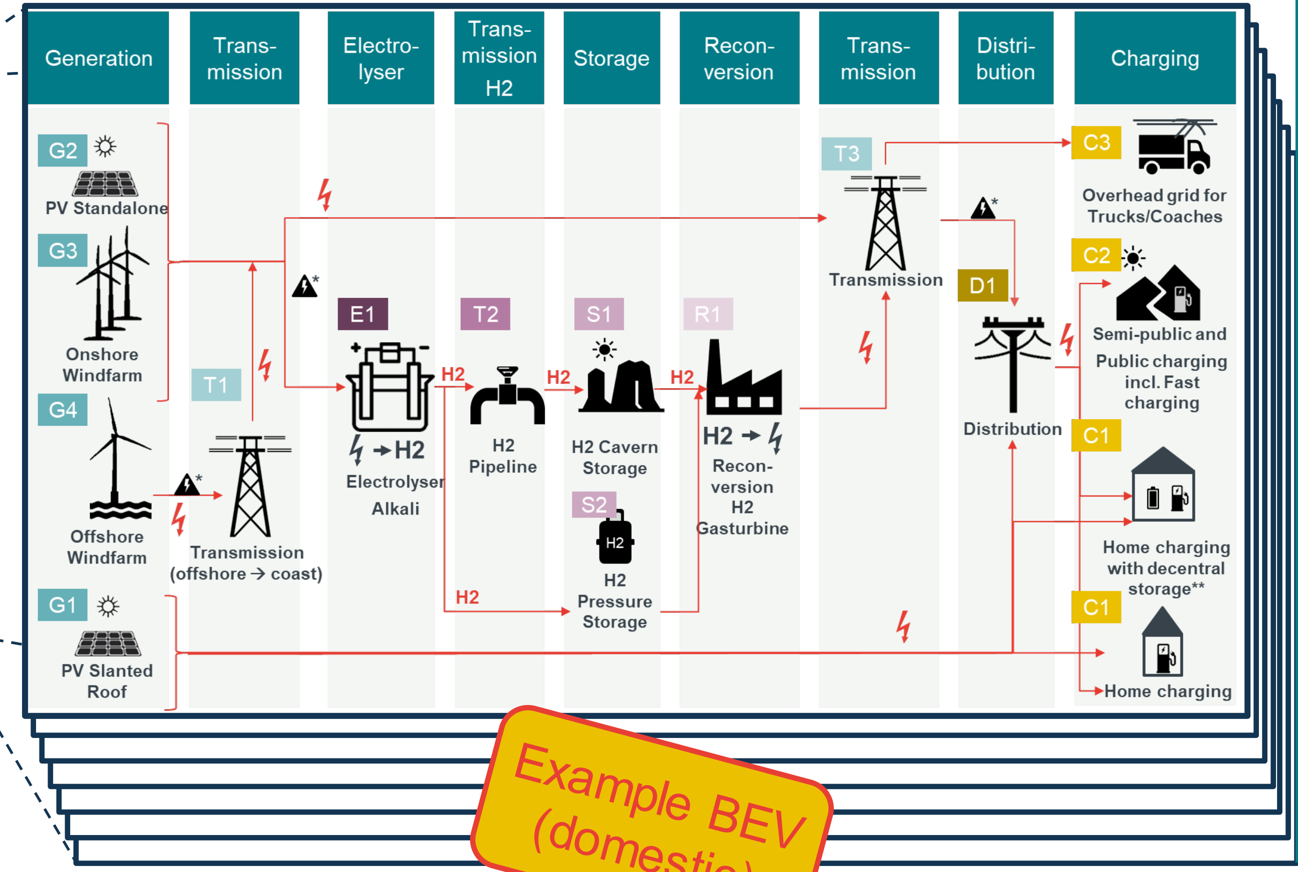
7 powertrains

- 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).



Example BEV (domestic)

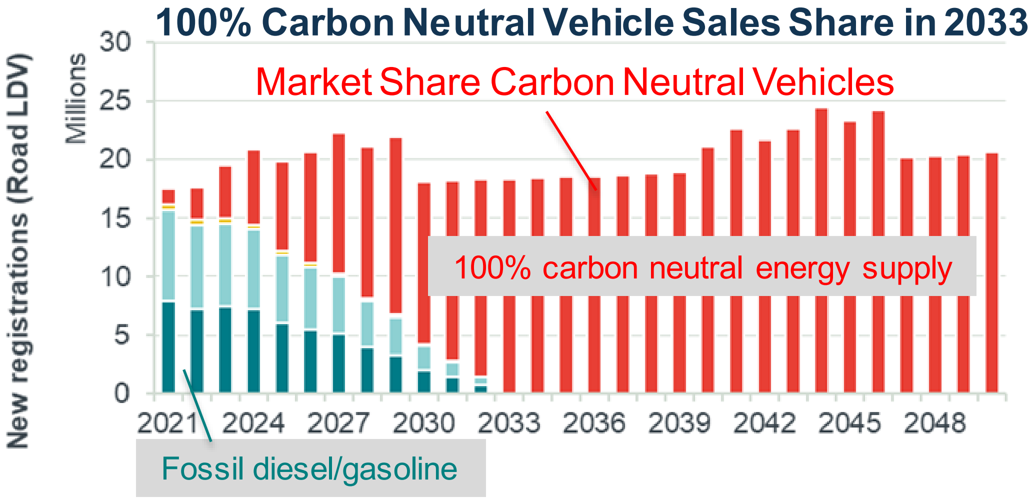
Photo year 2050, Comparison of:

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

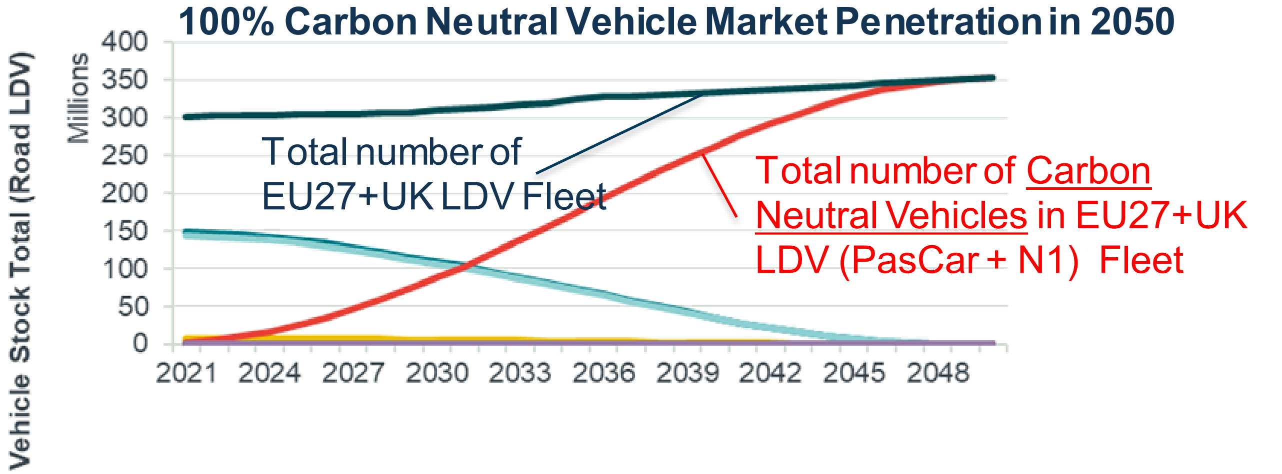
FVV Fuels Study IV – Theoretical **Reference Ramp-Up**

REFERENCE RAMP-UP: ONLY LIMITED BY VEHICLE FLEET EXCHANGE RATE

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 !)**
- **Realistic ramp-ups with further bottlenecks → FVV Fuels Study IVb**

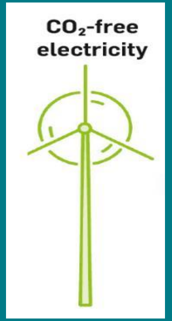
- **Target "carbon neutrality 2050" requires 100% carbon neutral vehicles in 2050**
- **Assumption:** **All new vehicles exclusively operated with renewable energy !**

Changes FVV Fuels Study IVb

Realistically max. achievable ramp-up speed:
Single Technology Scenarios
+ GHG Optimised Mixed Technology Scenario

SINGLE TECHNOLOGY & MIXED SCENARIOS WITH REALISTIC RAMP-UPS

19 realistic ramp-ups for Carbon Neutral Mobility in EU27+UK ~~in 2050~~ **asap** supplied solely by wind/solar energy



2x Energy Sourcing:
Domestic BEV vs. Global

Domestic | International

~~6~~ 5+1 fuel pathways

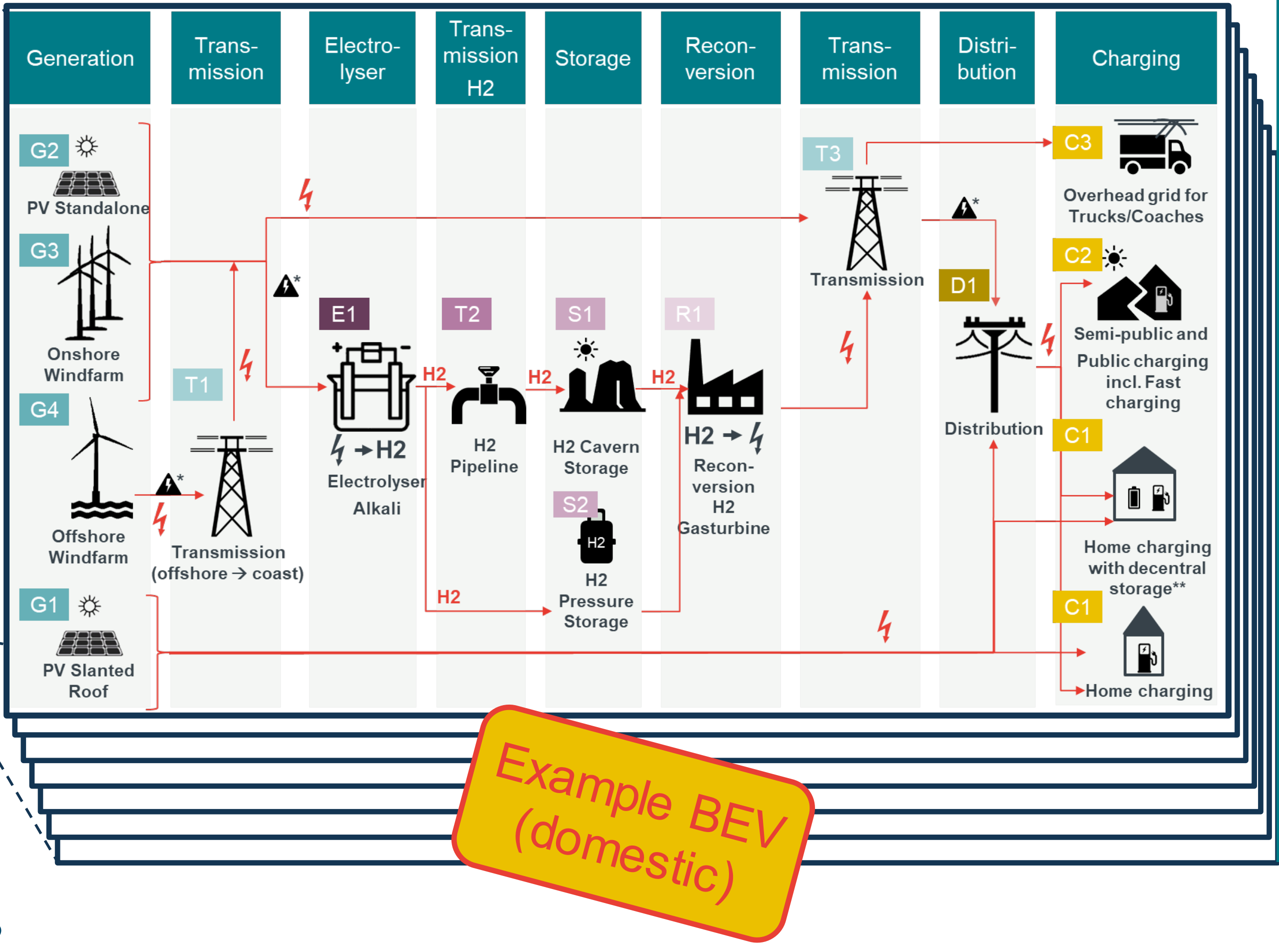
~~7~~ 7 powertrains

~~3~~ 1 vehicle efficiency scenario

- Electric (BEV)
- e-H_2 (ICEV, FCEV)
- e-FT (ICEV)
- e-CH_4 (ICEV)
- e-MTG ~~MeOH~~ (ICEV)
- e-MTG/FT PHEV ~~e-DME~~

- ~~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 environmental impacts (land use,…)~~

Content

- Approach and General Assumptions (Fuels Study IV & IVb)
- Energy Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Economic Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Cumulated Green House Gas
  - Reference Scenario (Fuels Study IV: Theoretical Reference Ramp-Up)
  - Single Technology Scenarios (Fuels Study IVb: Realistic Ramp-Ups)
  - Minimum GHG - Mixed Technology Scenario (Fuels Study IVb: Realistic Ramp-Ups)
  - Sensitivity Analysis (Fuels Study IVb: Realistic Ramp-Ups)
- Summary and Conclusions

Photo Year 2050 – Energy Analysis

WELL-TO-WHEEL (WTW) ENERGY DEMAND 2050

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

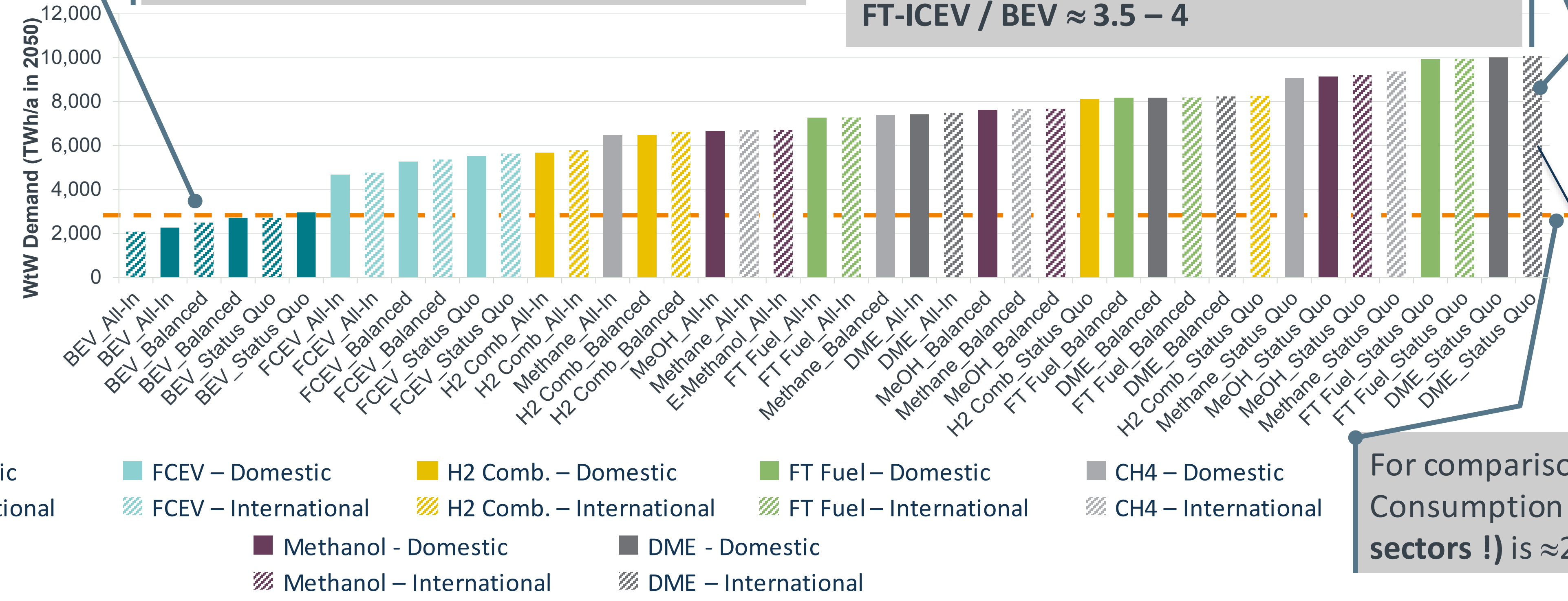
Higher WtW energy demands for ICEV. Factors: WtW energy demands

H2-ICEV / BEV ≈ 2.5 – 3

FT-ICEV / BEV ≈ 3.5 – 4

Road segment only

Well-to-Wheel Energy Demand 2050 / TWh



Solid bar: domestic energy sourcing

Dashed bar: global energy sourcing

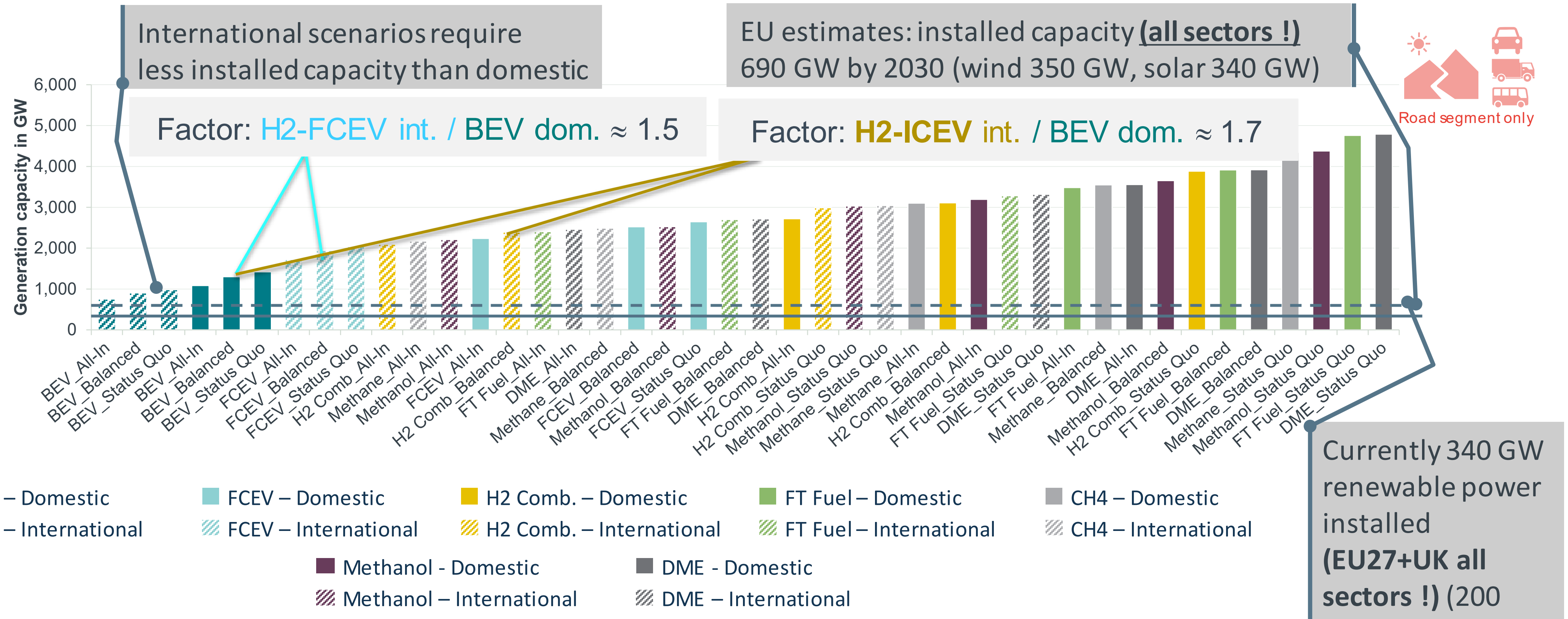
For comparison: Electricity Consumption EU-28 **(all sectors !)** is ≈2.900 TWh p.a.

- WTW Energy Demand (all pathways) 2050: 2,000…10,000 TWh/a
- WTW Energy Demand **H2-ICEV** 2050: 4,900… 8,000 TWh/a

Photo Year 2050 – Energy Analysis

INSTALLED POWER GENERATION CAPACITIES 2050

Installed Power Generation Capacities 2050 / GW

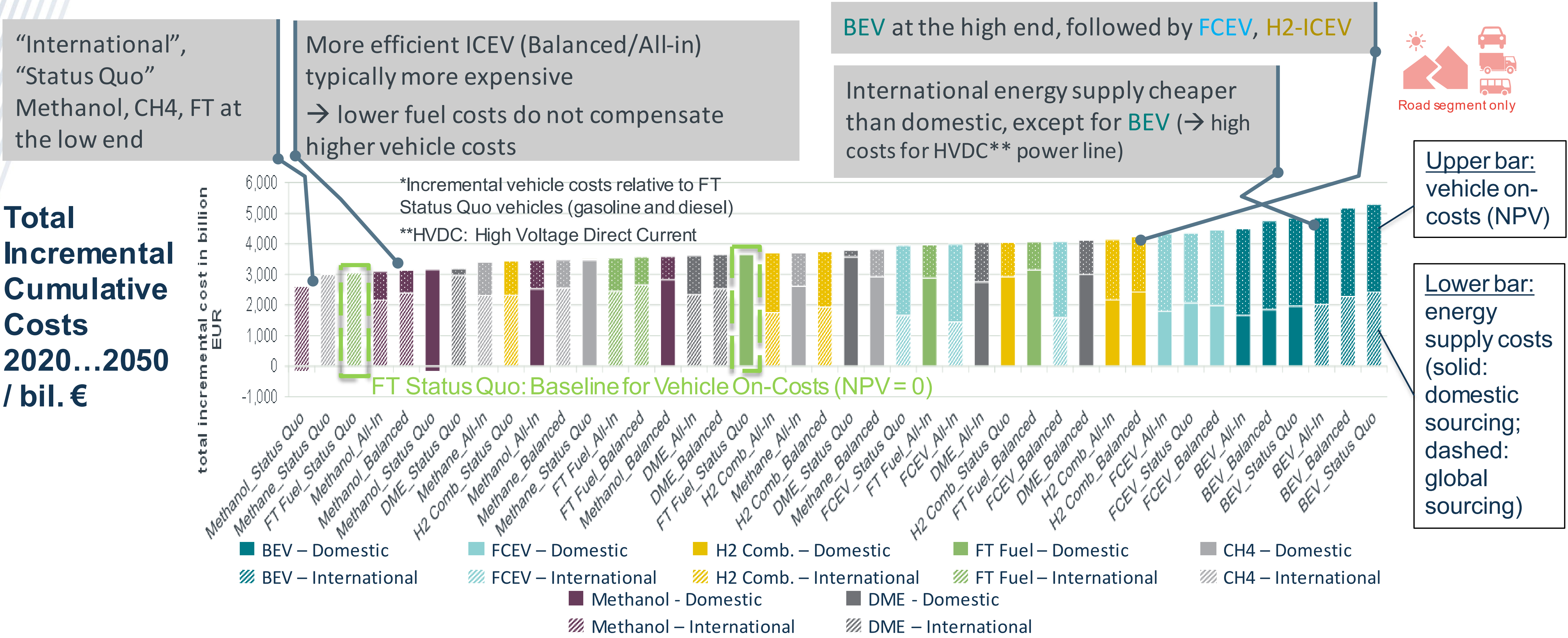


- **Not Energy Demand**, but **Installed Capacities matter** (environmental impact & cost)
- Installed capacity driven by total WtW demand and by achievable full-load-hours (location)
- Installed Power Generation Capacities 2050: 750…4,800 GW (H2-ICEV: 2,000 … 3,800 GW)

Content

Photo Year 2050 – Economic Analysis

INCREMENTAL* COSTS RELATIVE TO FOSSIL GASOLINE / DIESEL ICEV MOBILITY



- Incremental* Costs (NPV***) across all scenarios: 2,600 … 5,300 bil. €
- **H2-ICEV:** lower total costs than BEV & FCEV, but higher costs than "Hydrocarbon E-Fuels"

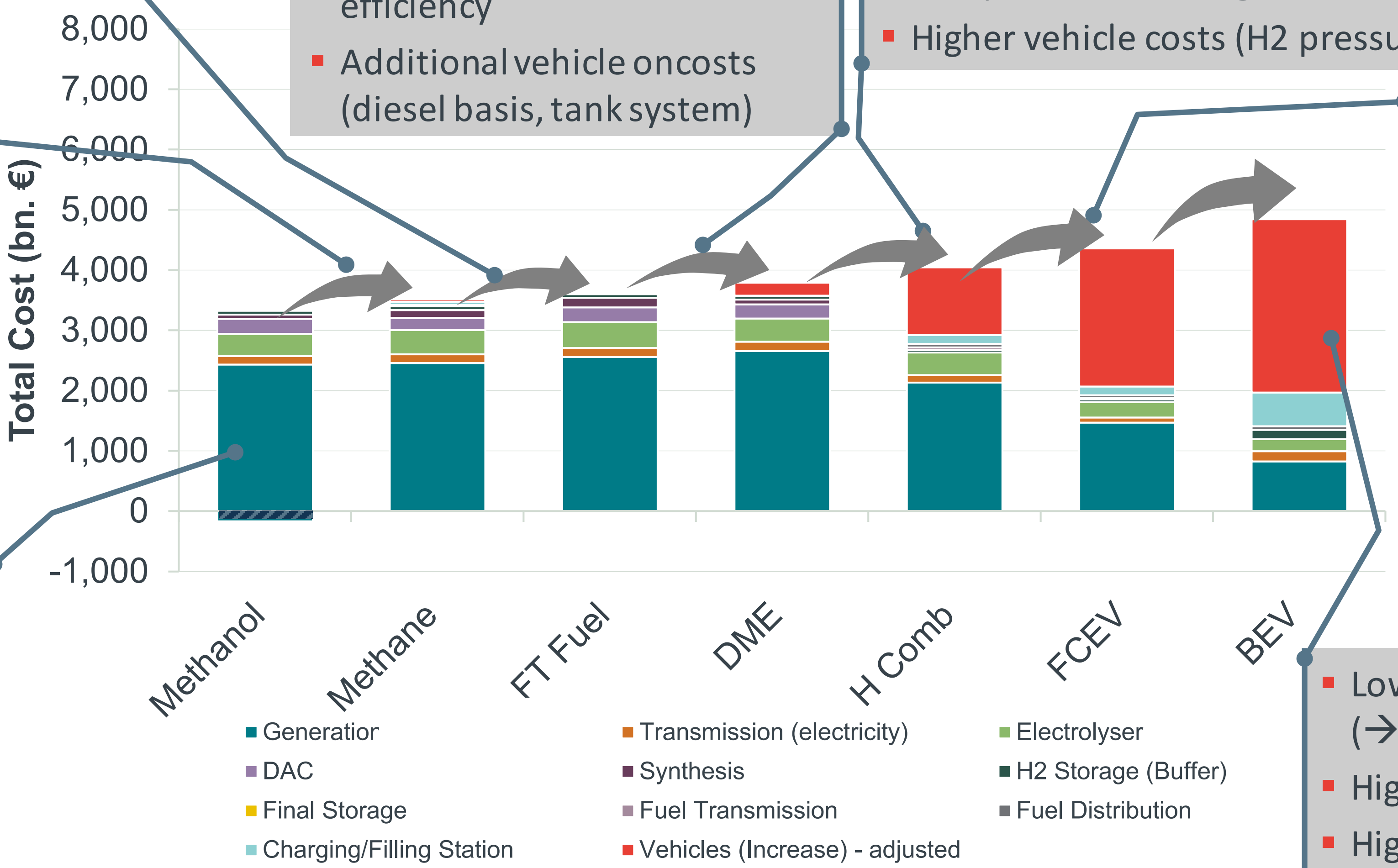
***NPV: Net Present Value

Photo Year 2050 – Economic Analysis

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 oncosts (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

- Dominated by wind & solar power generation costs, followed by electrolyser and DAC costs
- Negative vehicle oncosts vs. FT diesel/gasoline

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

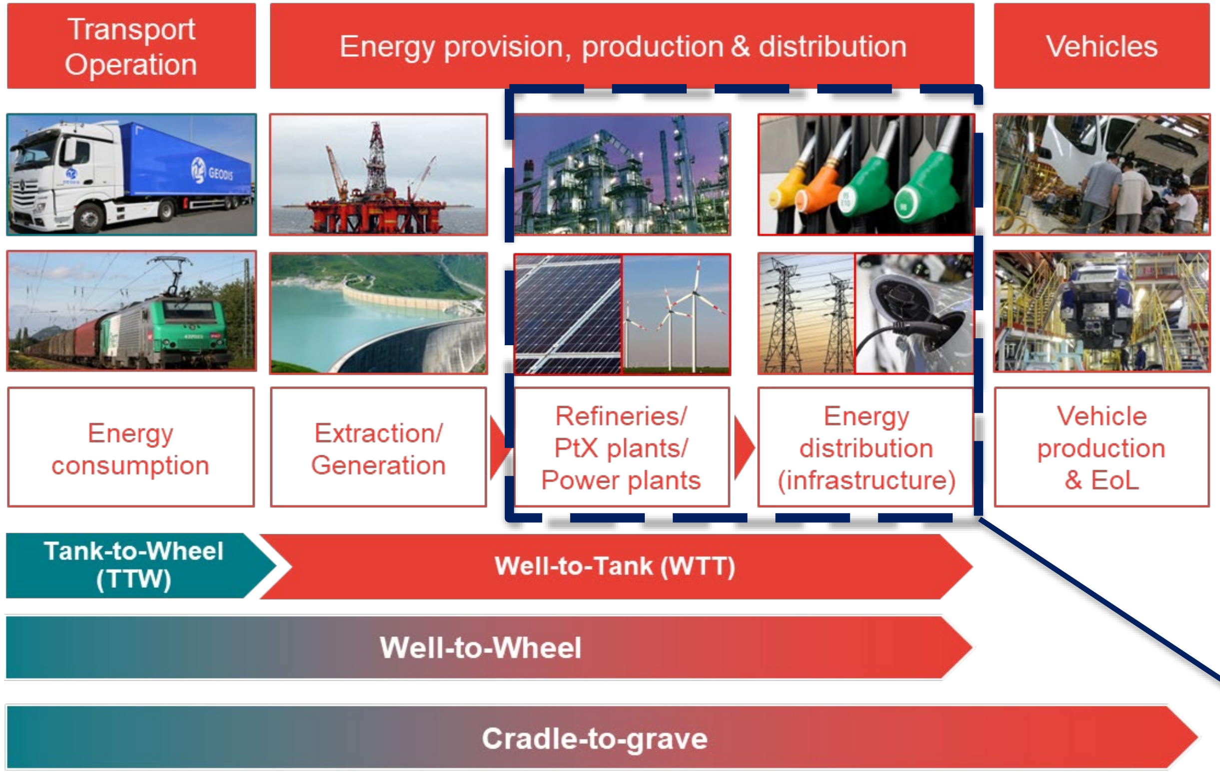
- **H2-ICEV:** oncosts driven by vehicle tank system (700 bar)

Content

- Approach and General Assumptions (Fuels Study IV & IVb)
- Energy Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Economic Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Cumulated Green House Gas
    - Reference Scenario (Fuels Study IV: Theoretical Reference Ramp-Up)
    - Single Technology Scenarios (Fuels Study IVb: Realistic Ramp-Ups)
    - Minimum GHG - Mixed Technology Scenario (Fuels Study IVb: Realistic Ramp-Ups)
    - Sensitivity Analysis (Fuels Study IVb: Realistic Ramp-Ups)
- Summary and Conclusions

FVV Fuels Study IV / IVb - Cradle-to-Grave (C2G) Analysis Approach

SEPERATE REPORT OF GHG FOR ENERGY INFRASTRUCTURE INSTALLATION



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

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

Total environmental impacts per year

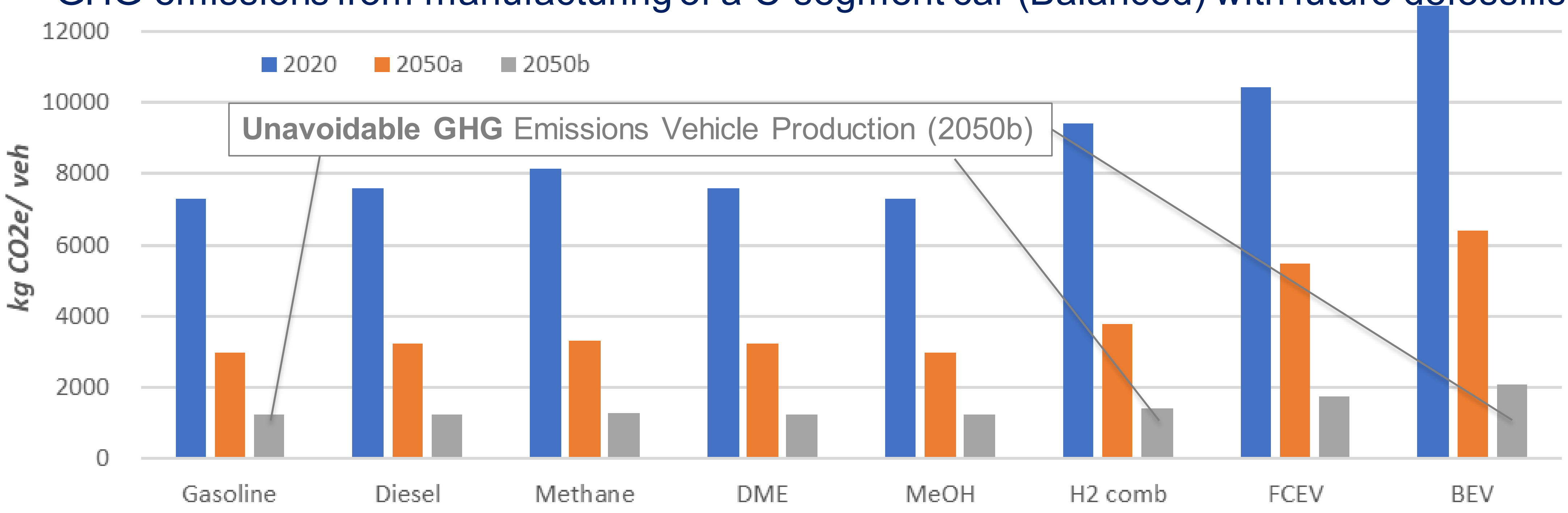
Environmental impacts vehicle operation + Environmental impacts FSC build-up + Environmental impacts vehicle production & disposal = **Total environmental impacts**

→ GHG emissions are accounted **in the year they occur**, **not depreciated over lifetime** (and then added to the WtT emissions)

FVV Fuels Study IV (Theoretical Reference Ramp-Up)

FUTURE DEFOSSILISATION OF THE BACKGROUND SYSTEM – VEHICLE PRODUCTION

GHG emissions from manufacturing of a C-segment car (Balanced) with future defossilisation



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

→ Overall differences between drivetrain concepts remain unchanged.

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

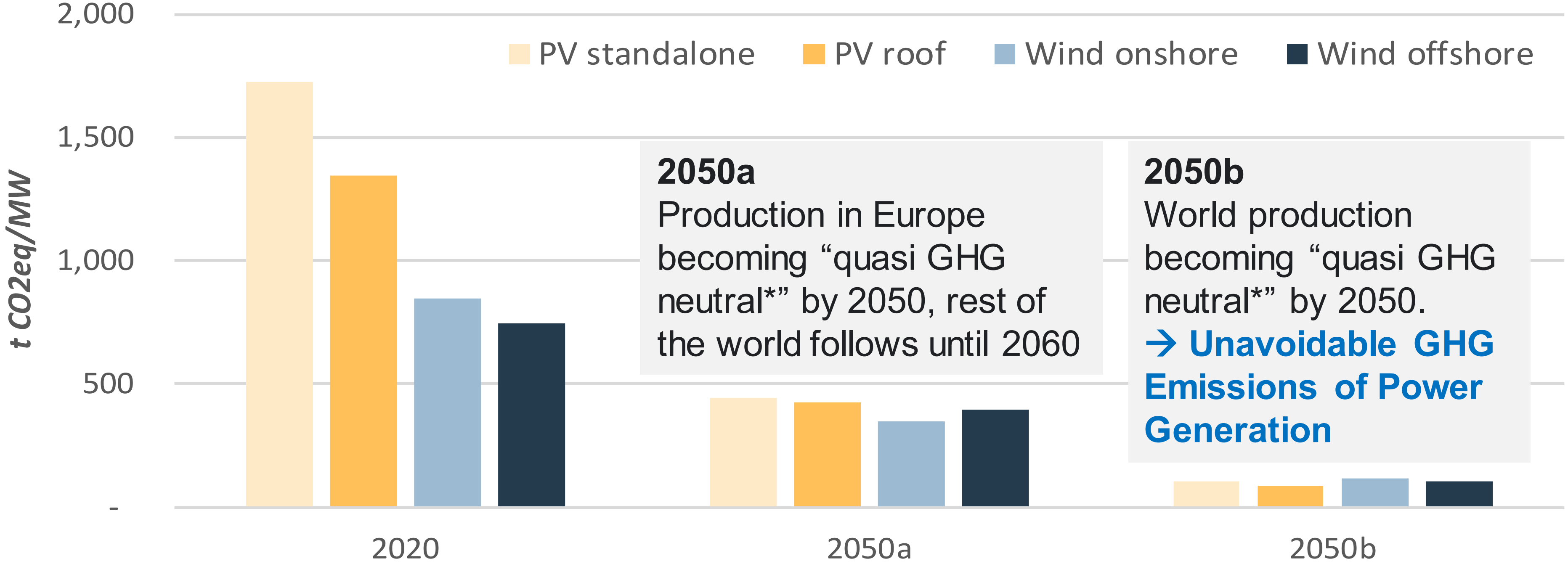
2050b
World production becoming "quasi GHG neutral*" by 2050

* only unavoidable GHG emissions left

FVV Fuels Study IV (Theoretical Reference Ramp-Up)

FUTURE DEFOSSILISATION OF THE BACKGROUND SYSTEM – ENERGY SYSTEM

GHG emissions from building-up solar and wind power plants



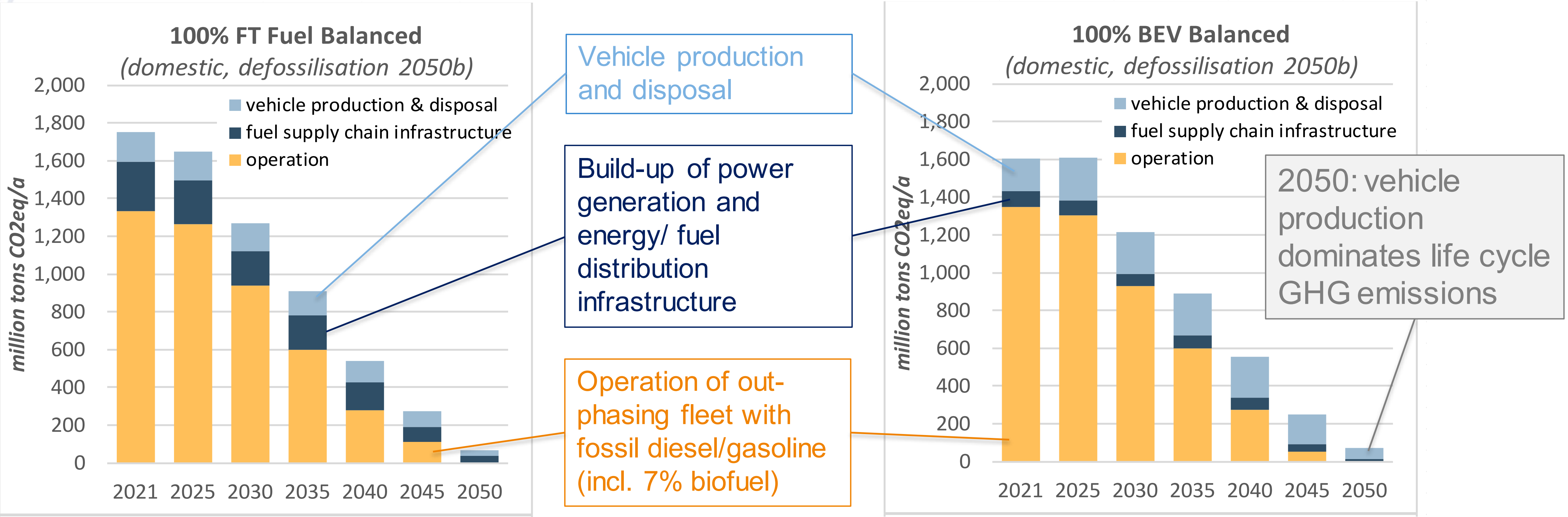
[1] In case of a complete worldwide defossilisation, unavoidable GHG emissions per MW of installed capacity are similar for PV and wind power plants. Reasons for the weaker specific GHG reduction for wind power plants are the lower process energy demand, the higher concrete proportion and that the assumed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

→ **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 building up solar and wind power plants material supply and production processes.

FVV Fuels Study IV (Theoretical Reference Ramp-Up)

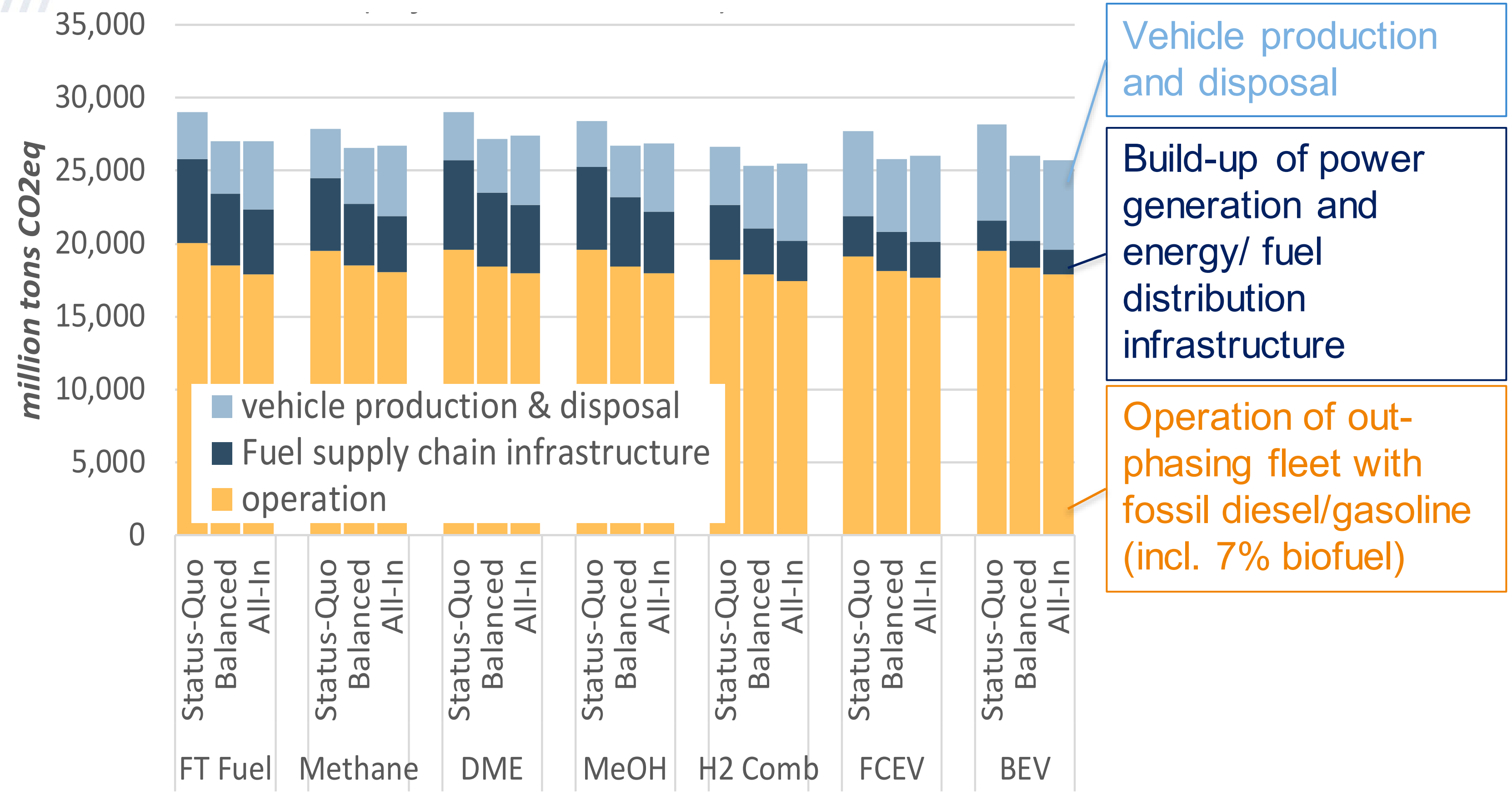
ANNUAL GHG EMISSIONS IN 100% SCENARIOS WITH IDENTICAL RAMP-UP SPEED



- 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 (**55-60%** of the cumulative GHG emissions are emitted **before 2030**)

FVV Fuels Study IV (Theoretical Reference Ramp-Up)

CUMULATIVE GHG EMISSIONS (2020 – 2050) - SINGLE TECHNOLOGY PATHS



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 single technology 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 absolutely essential for reducing cumulative GHG emissions and thus global warming impact!

Content

Fuels Study IV b - General Assumptions

TECHNOLOGIES, RAMP-UP BOTTLENECKS

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

- Assessment of **fastest achievable, realistic ramp-ups**, limited by technical bottlenecks* only
- Fair share of other sectors and other areas than EU taken into account

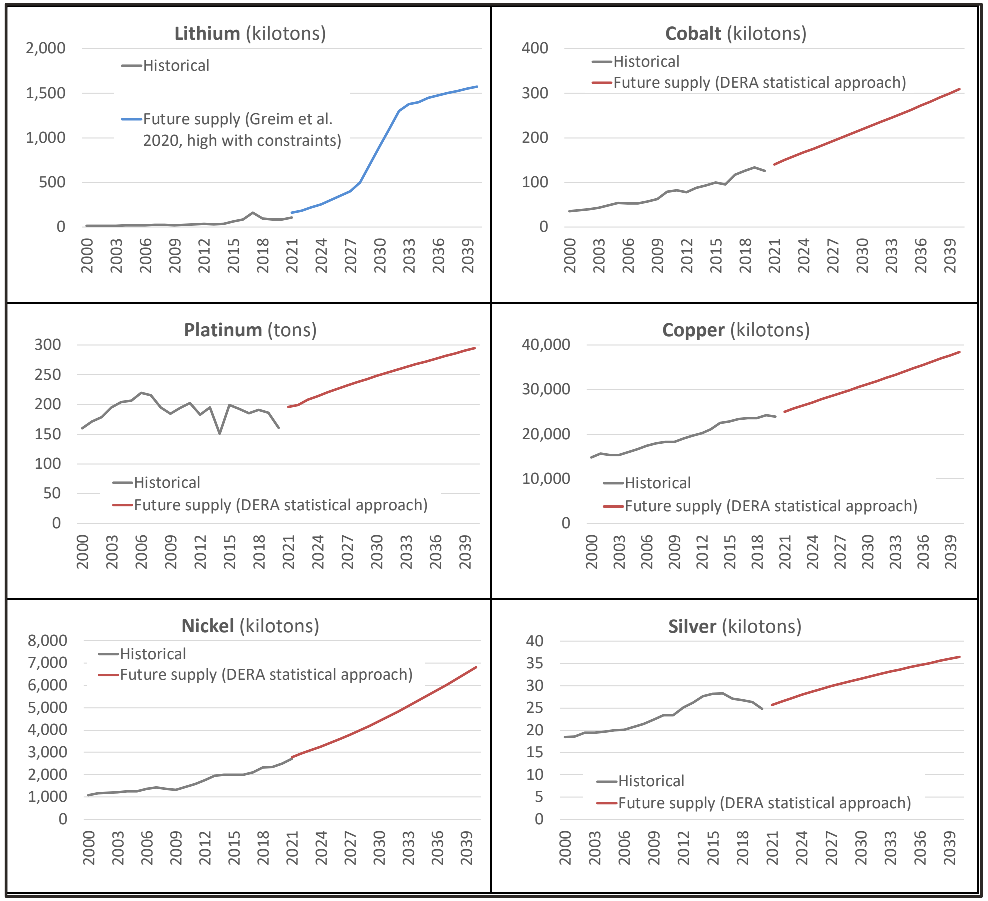
Technology	Scope	2020-2029	2030-2039	2040-2049
BEV (Battery Electric Vehicles) (Long Haul > 7.5t: Catenary HDV)	Domestic	Power transm. grid, catenary lines, cobalt, battery prod., wallboxes	Power transm. grid, catenary lines, cobalt, battery prod., wallboxes	Power transm. grid, cobalt
	International	Sea power cable, catenary lines, cobalt, power transmission grid	Sea power cable, catenary lines, cobalt, power transmission grid	Cobalt , power transm. grid
FT (Fischer Tropsch)	International	FT synthesis, nickel, electrolysis	FT synthesis, nickel, electrolysis	
MtG (Methanol-to-Gasoline, **only LDV** (Passenger Cars+ N1)	International	Electrolysis, **renewable electr. generation**, MtG synthesis	Electrolysis, **renewable electricity generation**	
Synthetic Methane	International	Methanation, CH_4 import pipelines, electrolysis	Methanation, electrolysis	
H2 Comb. (Hydrogen Combustion)	International	H_2 import pipeline, electrolysis	H_2 import pipeline, electrolysis	H_2 import pipeline
FCEV (Fuel Cell Electric Vehicles)	International	H_2 import pipeline, platinum, battery production,	H_2 import pipeline, platinum	Platinum
PHEV (Plug-In Hybrid Electric Vehicles): BEV + FT	Dom. (BEV-share)	FT synthesis, battery prod., electrolysis, wallboxes	FT synthesis	
	Int. (BEV+E-Fuels)	FT synth., sea power cable, batt. prod., electrolysis, wallboxes	FT synthesis, sea power cable	
PHEV (Plug-In Hybrid Electric Vehicles): BEV + MtG (**only LDV**)	Dom. (BEV-share)	Wallboxes, public chargers, electrolysis	Wallboxes, public chargers	
	Int. (BEV+E-Fuels)	Sea power cable, wallboxes, public chargers	Sea power cable, wallboxes, public chargers	

Single Technology Scenarios – Tech. Bottlenecks* - Model Assumptions

… e.g. for primary** material supply

Max. material supply determined with the help of DERA ***

***Sources: DERA (Deutsche Rohstoff Agentur), Greim et al. 2020

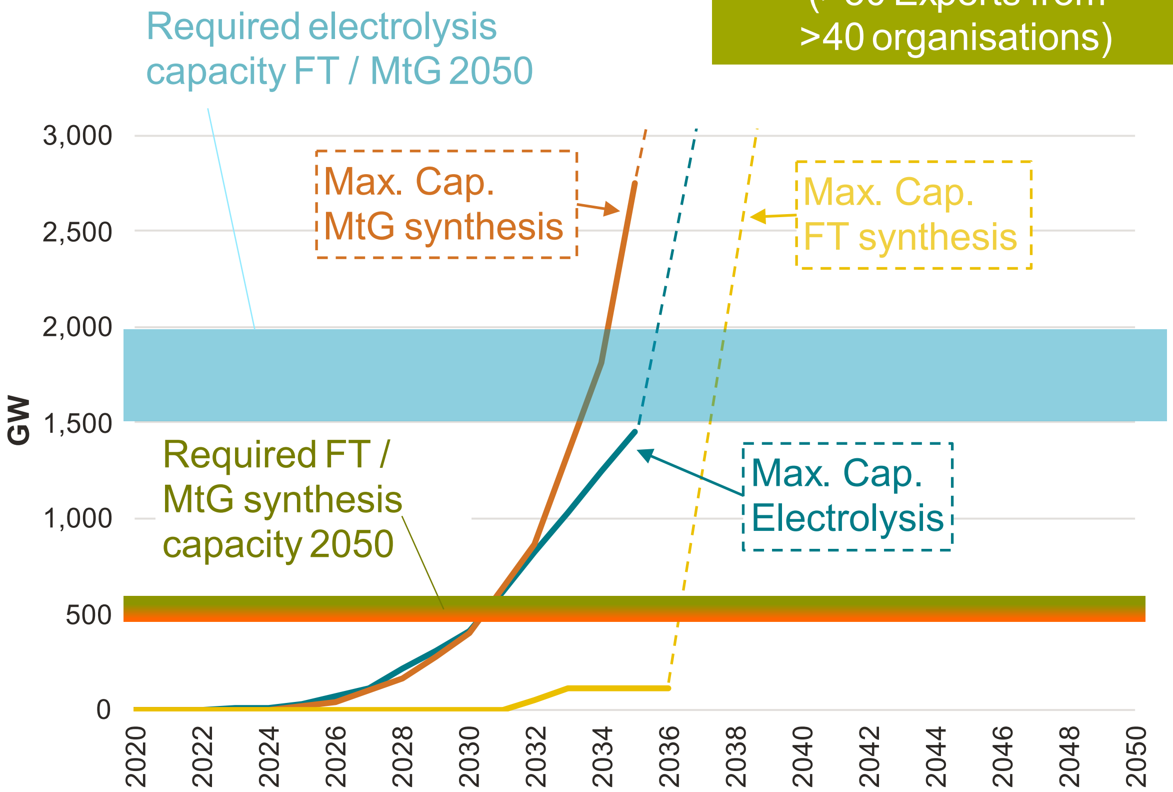


**Recycling assumptions:

- 90 % collection rate
- Material specific recycling rates: 55 … 90 %

… e.g. for ramp-up of capacities

Determined in 7 Working Groups (>50 Experts from >40 organisations)



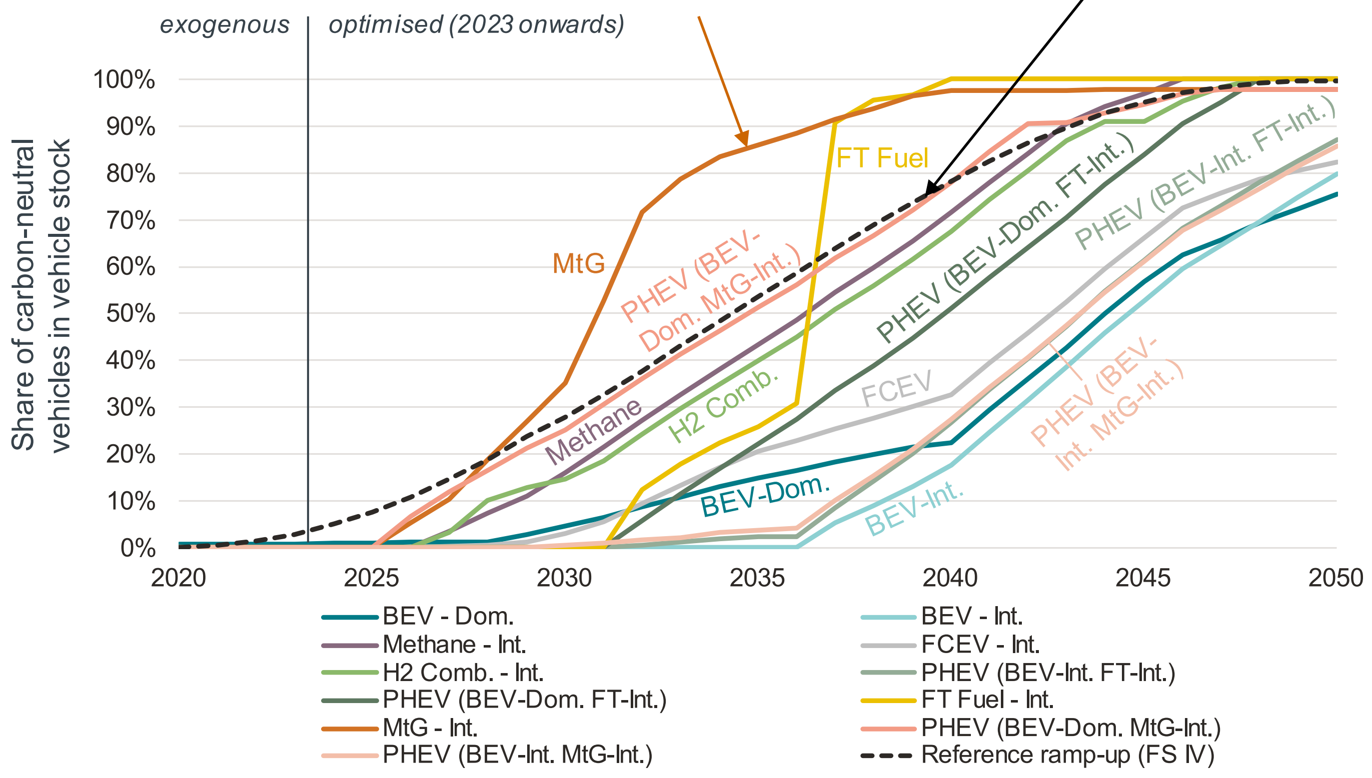
*Focus solely on "**technical bottlenecks**", assuming **ideal regulatory and financial ramp-up conditions**
("COVID 19 vaccine development" scenario)

Single Technology Scenarios - GHG-neutral vehicle ramp-up

SHARE OF CARBON-NEUTRAL VEHICLES IN STOCK

MtG just reaches 98 % carbon-neutral vehicle share, since only applied for LDV (PasCar + N1), which are 98 % of EU fleet (no simulation of MtG in HDV)

Reference Ramp-up FVV FS IV (just limited by vehicle fleet exchange rate, GHG neutrality assumed for 2050)



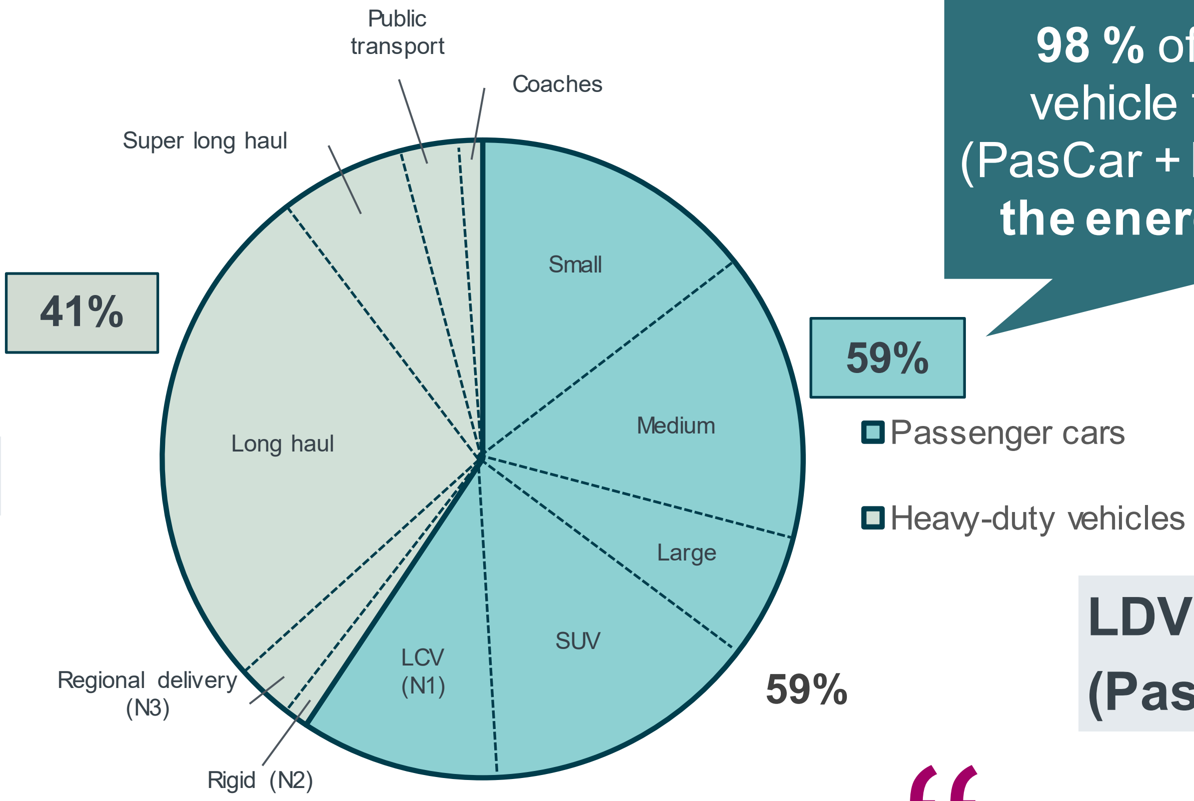
- Slower ramp-up than reference scenario for nearly all **single technology scenarios (without “drop-in capability”)**
- Ramp-up with drop-in capable e-fuels (MtG, FT) in the existing legacy fleet can exceed reference ramp-up (MtG in ≈2027, FT in ≈2036)
- Some „single technology scenarios“ (as e.g., BEV, FCEV) will not reach carbon-neutral vehicle share (100 % defossilisation) until 2050, because of bottlenecks (e.g., BEV or FCEV)

Single Technology Scenario FT Fuel – Energy Share LDV / HDV

TTW ENERGY DEMAND BY SEGMENT

2 % of the European vehicle fleet are **Heavy Duty Vehicles**, using **41 % of the energy** (FT pathway)

98 % of the European vehicle fleet are **LDVs** (PasCar + N1) using **59 % of the energy** (FT pathway)



HDV (Heavy Duty)

LDV (Passenger Cars + N1)

HDV: Low "CO2-CAPEX", high "CO2-OPEX"

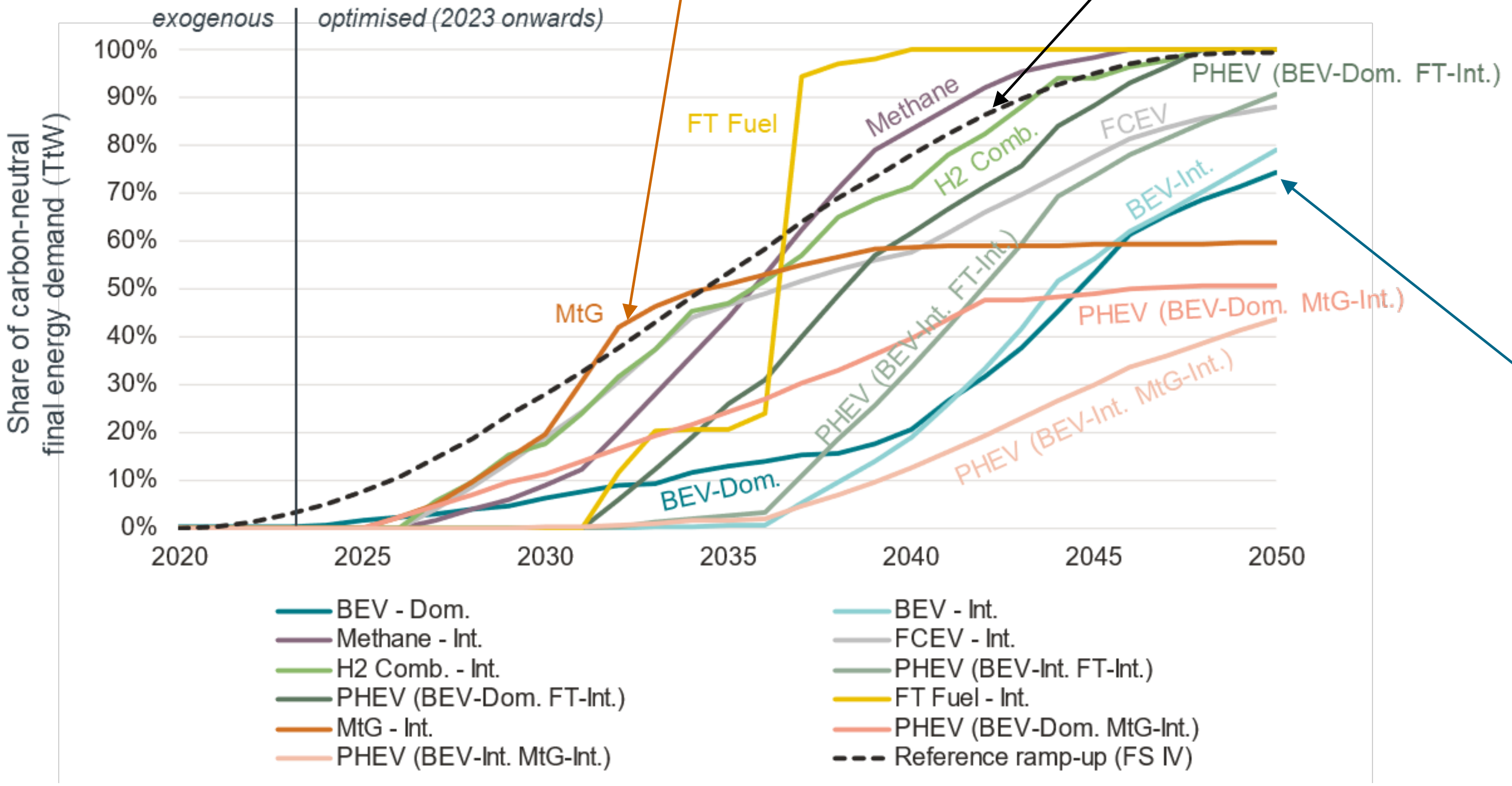
LDV: High "CO2-CAPEX", low "CO2-OPEX"

Single Technology Scenarios - GHG-neutral TtW energy demand

SHARE OF CARBON-NEUTRAL TTW ENERGY USAGE

MtG just reaches 59 % "energy" defossilisation rate, since only applied for LDV (PasCar + N1), which consume 59 % of EU transport energy

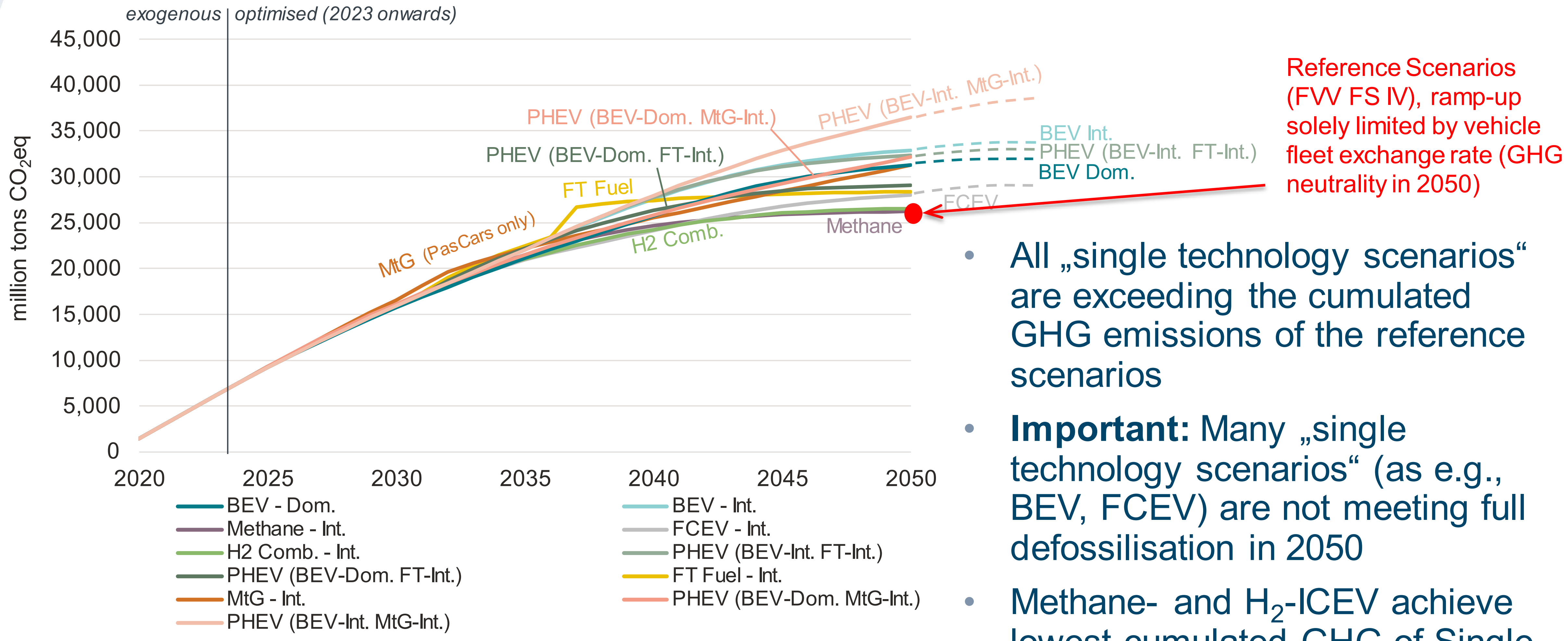
Reference Ramp-up FVV FS IV (just limited by vehicle fleet exchange rate, GHG neutrality in 2050)



- Energy-wise „single technology scenario BEV (domestic energy sourcing)" just meets ≈76 % energy defossilisation rate

Single Technology Scenarios - Cumulated Green House Gas

CUMULATED GHG: SINGLE TECHNOLOGY SCENARIOS, 2020-2050



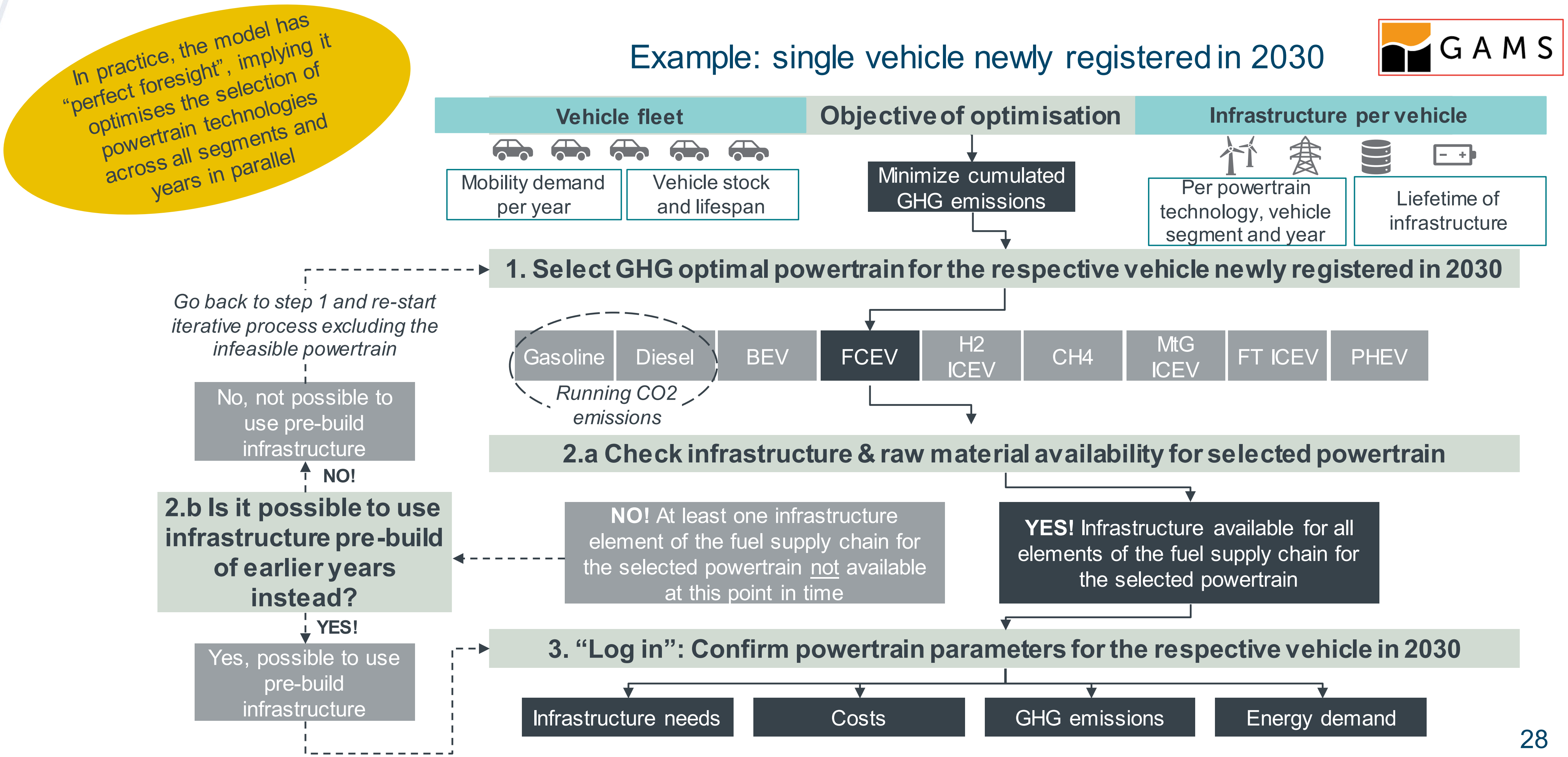
- All „single technology scenarios“ are exceeding the cumulated GHG emissions of the reference scenarios
- **Important:** Many „single technology scenarios“ (as e.g., BEV, FCEV) are not meeting full defossilisation in 2050
- Methane- and H_2-ICEV achieve lowest cumulated GHG of Single Technology Scenarios

Content

- Approach and General Assumptions (Fuels Study IV & IVb)
- Energy Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Economic Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Cumulated Green House Gas
    - Reference Scenario (Fuels Study IV: Theoretical Reference Ramp-Up)
    - Single Technology Scenarios (Fuels Study IVb: Realistic Ramp-Ups)
    - Minimum GHG - Mixed Technology Scenario (Fuels Study IVb: Realistic Ramp-Ups)
    - Sensitivity Analysis (Fuels Study IVb: Realistic Ramp-Ups)
- Summary and Conclusions

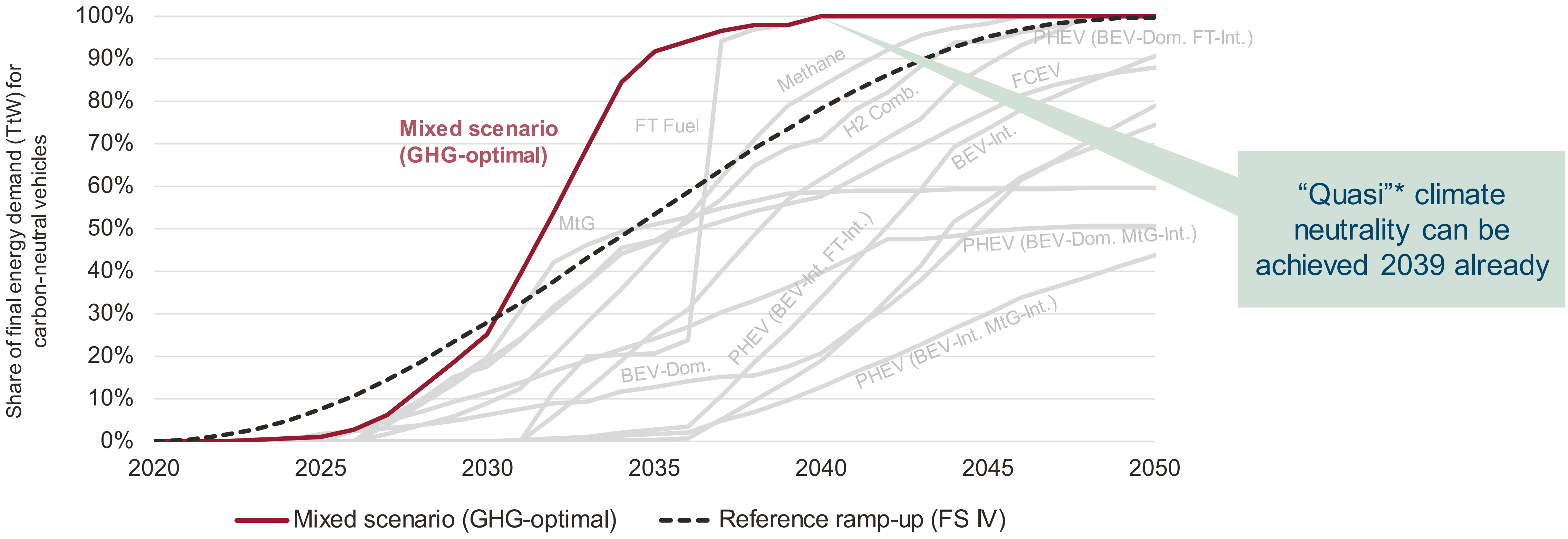
Minimum GHG - Mixed Technology Scenario

GHG MINIMISATION - SIMPLIFIED MODEL DECISION MAKING PROCESS



Minimum GHG - Mixed Technology Scenario

SHARE OF CARBON-NEUTRAL TTW ENERGY USAGE

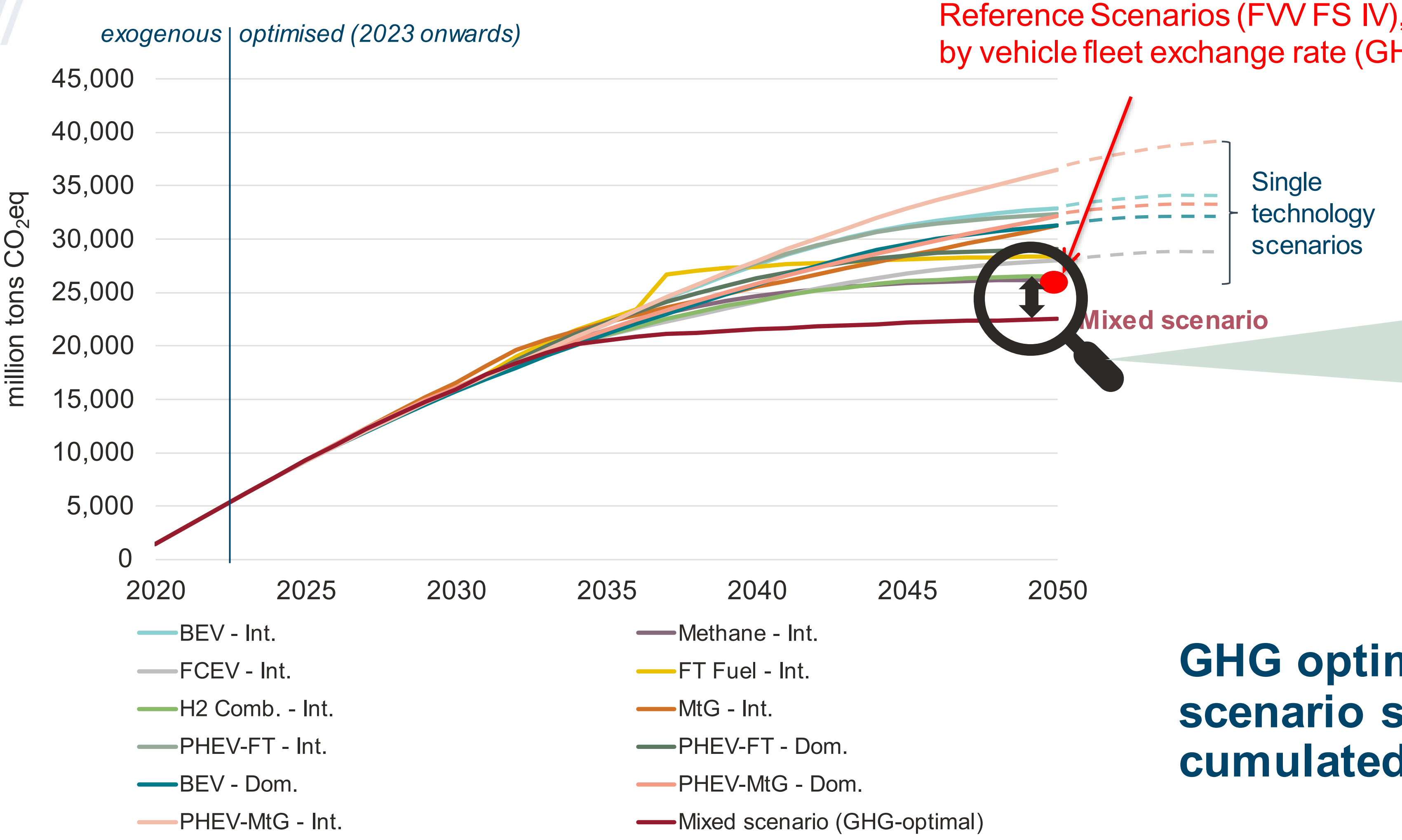


- GHG optimized mixed technology scenario can significantly increase share of carbon-neutral TtW energy use (vs. single technology scenarios)

* „quasi" means: only unavoidable GHG emissions left

Minimum GHG - Mixed Technology Scenario

CUMULATED GHG: GHG OPT. MIXED TECHNOLOGY SCENARIO, 2020-2050



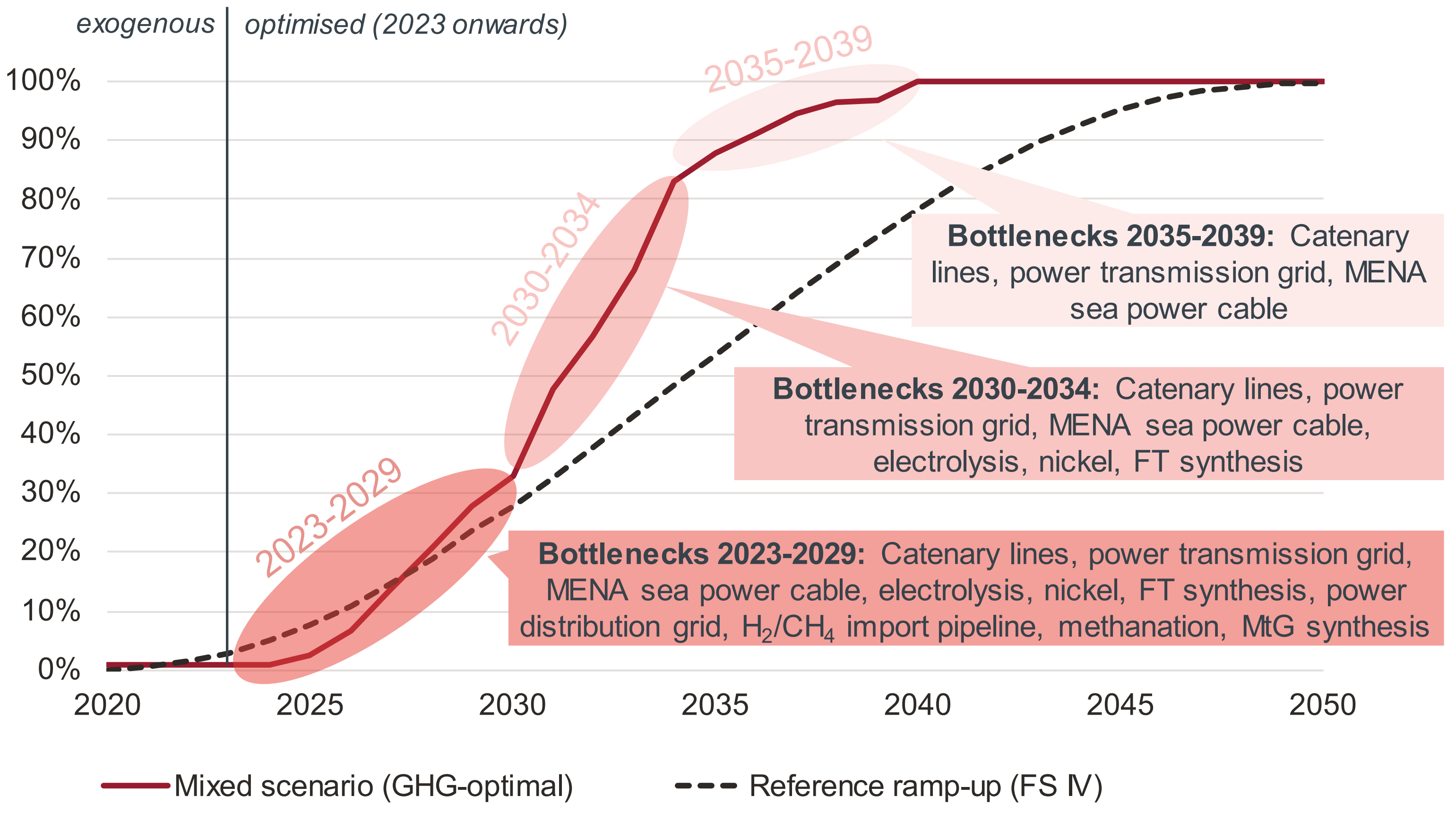
Cumulated GHG emissions until 2050 ≈3,700 Mt CO_2eq lower than best full defossilised single technology scenario (CH_4), equivalent to app. 5 years of total German GHG emissions

GHG optimized mixed technology scenario significantly reduces cumulated GHG in 2050

*** „quasi“ means: only unavoidable GHG emissions left**

Minimum GHG - Mixed Technology Scenario

MAIN TECHNICAL BOTTLENECKS RESTRICTING THE RAMP-UP

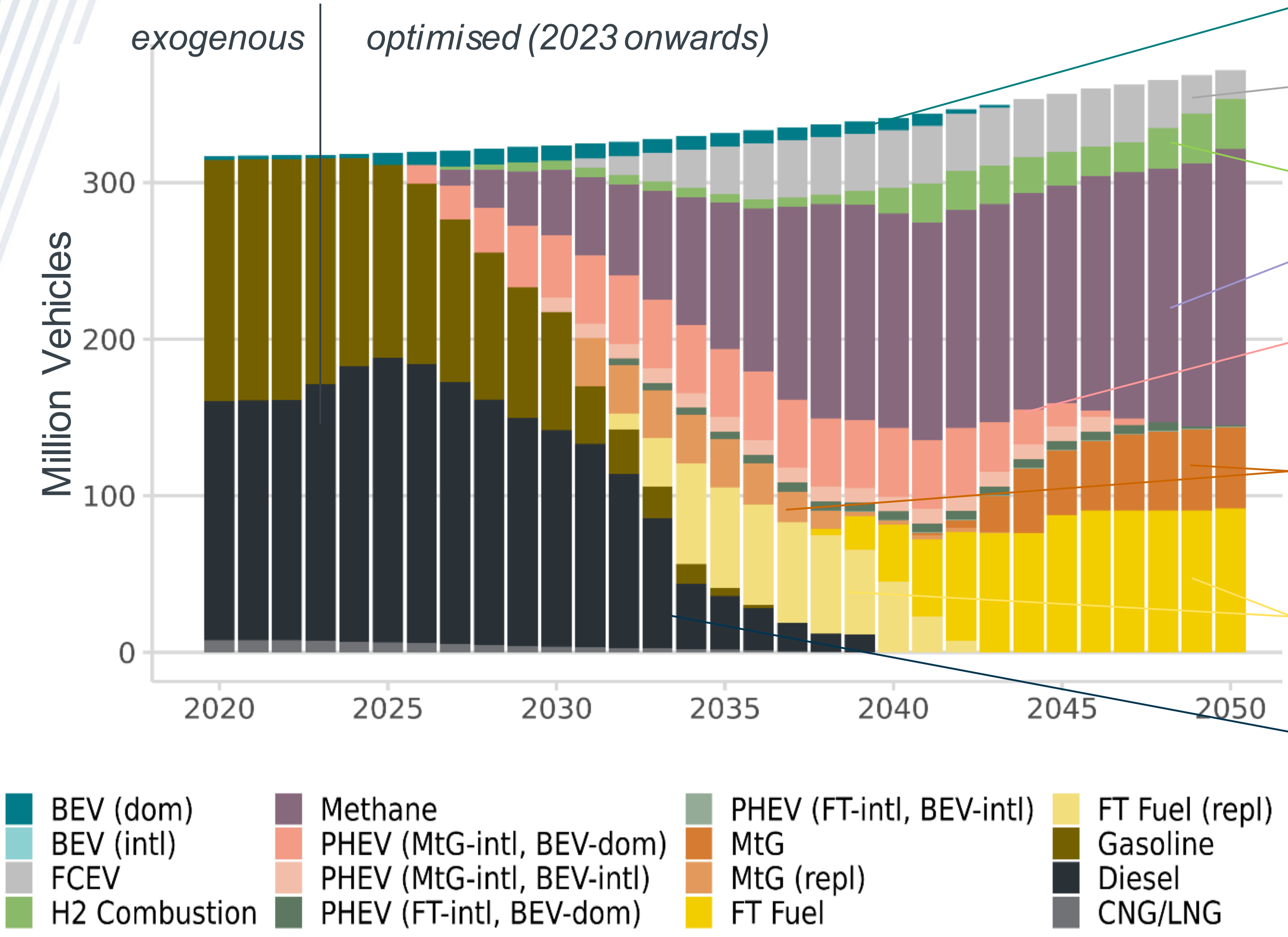


Main ramp-up bottlenecks of GHG opt. mixed scenario:

- … 2034:
  - electric supply network
  - electrolysis
  - e-fuel synthesis
  - nickel
- … 2039:
  - electric supply network
- … after 2039:
  - no restrictions

Minimum GHG - Mixed Technology Scenario

FLEET DEVELOPMENT (VEHICLE STOCK) – LDV (PASCAR + N1)



BEV phase out in 2042

H2-FCEV introduced in 2031, share in 2050 ≈ 5% (declining)

H2-ICEV introduced in 2027, share in 2050 ≈ 8 % (rising)

Methane introduced in 2027, share in 2050 ≈ 50% (rising)

MtG PHEV introduced in 2026, phase out 2047

MtG introduced in 2031 (use in existing fleet), new MtG ICEV from 2039, share of MtG ICEV in 2050 ≈ 10% (rising)

FT introduced in 2032 (use in existing fleet), new FT ICEV from 2039, share of FT vehicles in 2050 ≈ 25% (rising)

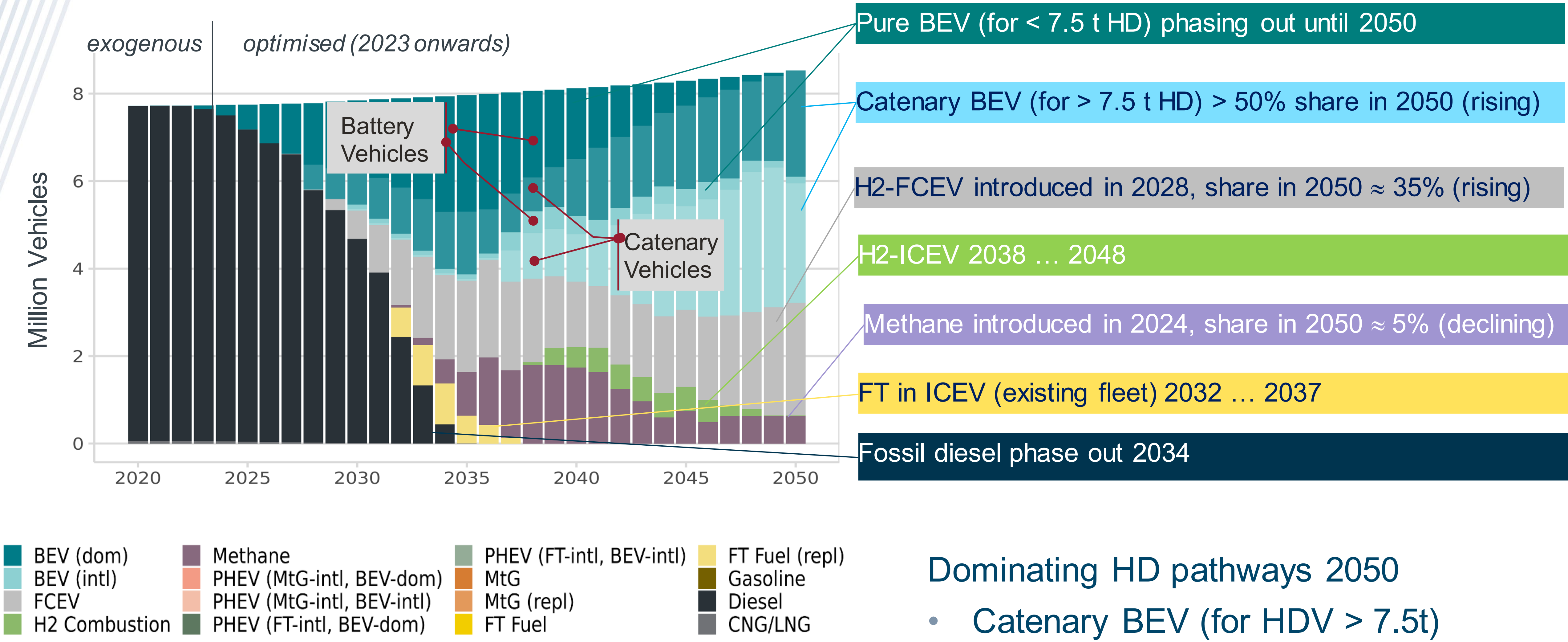
Fossil gasoline phase out 2036, fossil diesel 2039

Dominating LDV (PasCar+N1) pathways 2050

- Methane-ICEV
- FT- & MTG-ICEV
- H2-ICEV

Minimum GHG - Mixed Technology Scenario

FLEET DEVELOPMENT (**VEHICLE STOCK**) – **HEAVY DUTY**



Dominating HD pathways 2050

- Catenary BEV (for HDV > 7.5t)
- H2-FCEV (for HDV < 7.5t)

Content

- Approach and General Assumptions (Fuels Study IV & IVb)
- Energy Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Economic Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Cumulated Green House Gas
  - Reference Scenario (Fuels Study IV: Theoretical Reference Ramp-Up)
  - Single Technology Scenarios (Fuels Study IVb: Realistic Ramp-Ups)
  - Minimum GHG - Mixed Technology Scenario (Fuels Study IVb: Realistic Ramp-Ups)
  - Sensitivity Analysis (Fuels Study IVb: Realistic Ramp-Ups)
- Summary and Conclusions

Sensitivity Analysis - Robustness of results

Name	Description	Drivetrains allowed for new vehicle registrations
Sensitivities 1: Relaxed technical bottleneck assumptions		
Sensitivity 1a	No catenary line restriction	All
Sensitivity 1b	No catenary line / transmission grid restriction	All
Sensitivities 2: Reduced number of (GHG-neutral) technology pathways		
Sensitivity 2a	ICE ban from 2035	BEV, FCEV and **H_2 ICEV** from 2035; e-fuel usage in existing vehicle fleet
Sensitivity 2b	Strict ICE ban from 2035 (no H_2 ICEV)	BEV and FCEV from 2035; e-fuel usage in existing vehicle fleet
Sensitivity 2c	Only long-run technologies	BEV, FCEV, FT and MtG from 2023
Sensitivity 2d	Powertrains currently in high demand	BEV, FT, MtG and PHEV from 2023
Sensitivity 2e	No catenary system and no BEV for heavy duty segment	**LDV (PasCar + N1) :** All **Heavy duty vehicles**: FCEV, H_2 Comb., FT Fuel, Methane

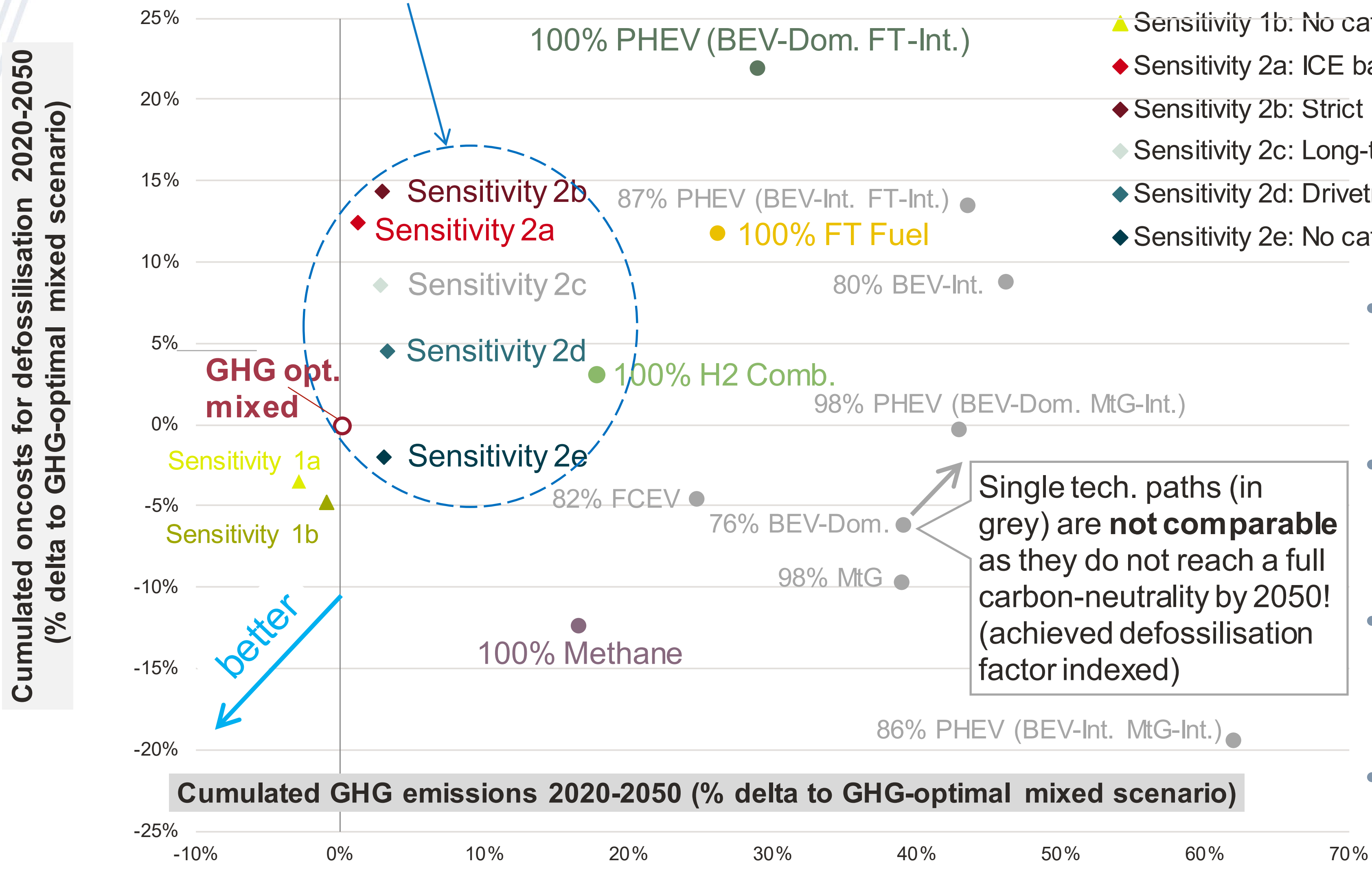
Test impact of BEV infrastructure bottlenecks

"Fit for 55" scenarios w/ bans of ICEV

BUT, with considerable **e-fuel usage in legacy fleet** → realistic under current regulatory framework?

Sensitivity Analysis - Cumulated GHG & costs (vs. GHG-opt. mixed scenario)

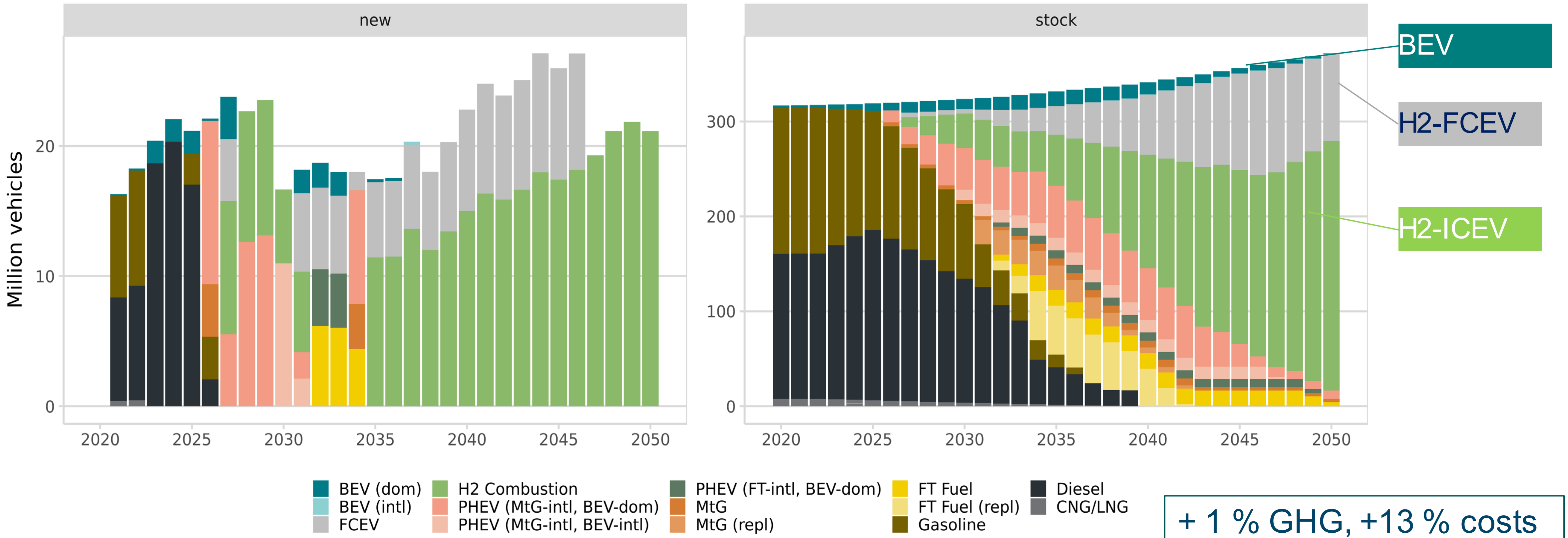
All sensitivity analyses scenarios allow for significant e-fuel usage for the existing fleet and achieve 100% defossilisation rate in 2050!



- **Single Tech. BEV (dom.)**: +39 % GHG until 2050, **only 76 %** defossilization rate
- **Single Tech. H2-ICEV (int.)**: +18 % GHG, +3% costs, 100 % defossilization rate
- **(2a) ICE Ban 2035 (H2-ICE still allowed)** and **e-fuels for fleet**: +1 % GHG, +13 % costs
- **(2e) No (catanery) BEV for HDV** and **e-fuels for fleet**: +3 % GHG, -2 % costs

Sensitivity Analysis 2a - **ICE ban** 2035 (**H2-ICE allowed,** e-fuels in fleet)

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **LDV (PASCAR + N1) ONLY**

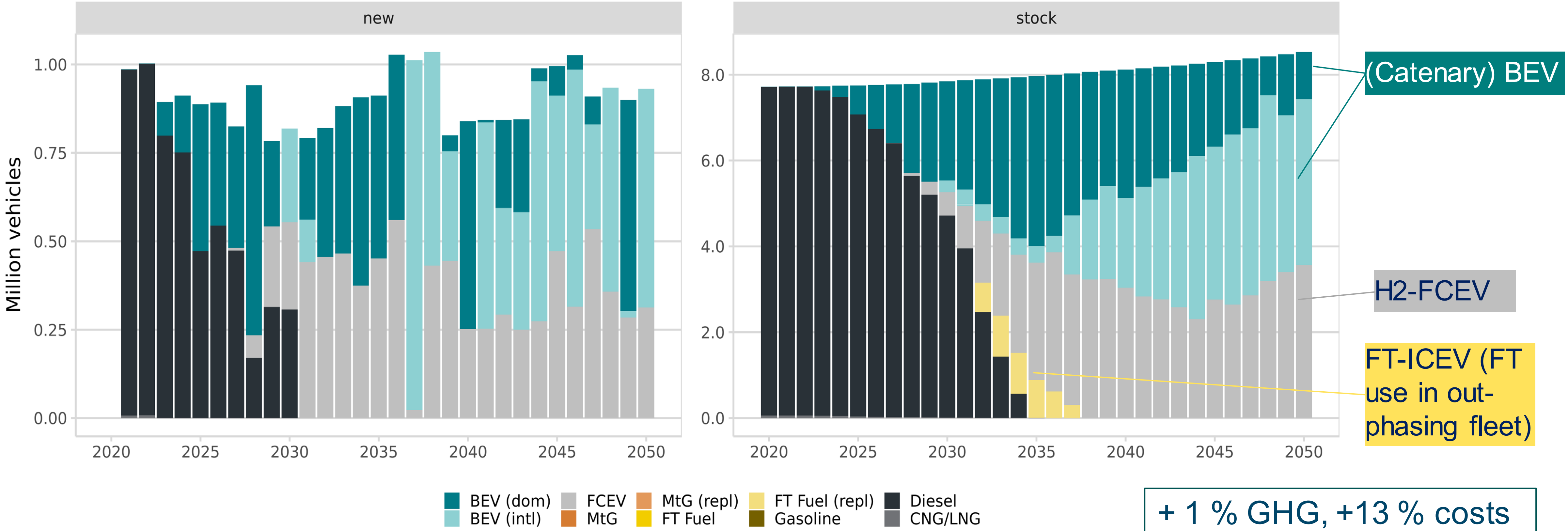


+ 1 % GHG, +13 % costs

- Min. GHG mainly achieved with H2-ICE as dominating pathway for LDVs (PasCar+N1) in 2050
- New LDV (PasCar+N1) registrations in 2050: exclusively H2-ICEV

Sensitivity Analysis 2a - **ICE ban** 2035 (**H2-ICE allowed,** e-fuels in fleet)

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **HEAVY DUTY ONLY**

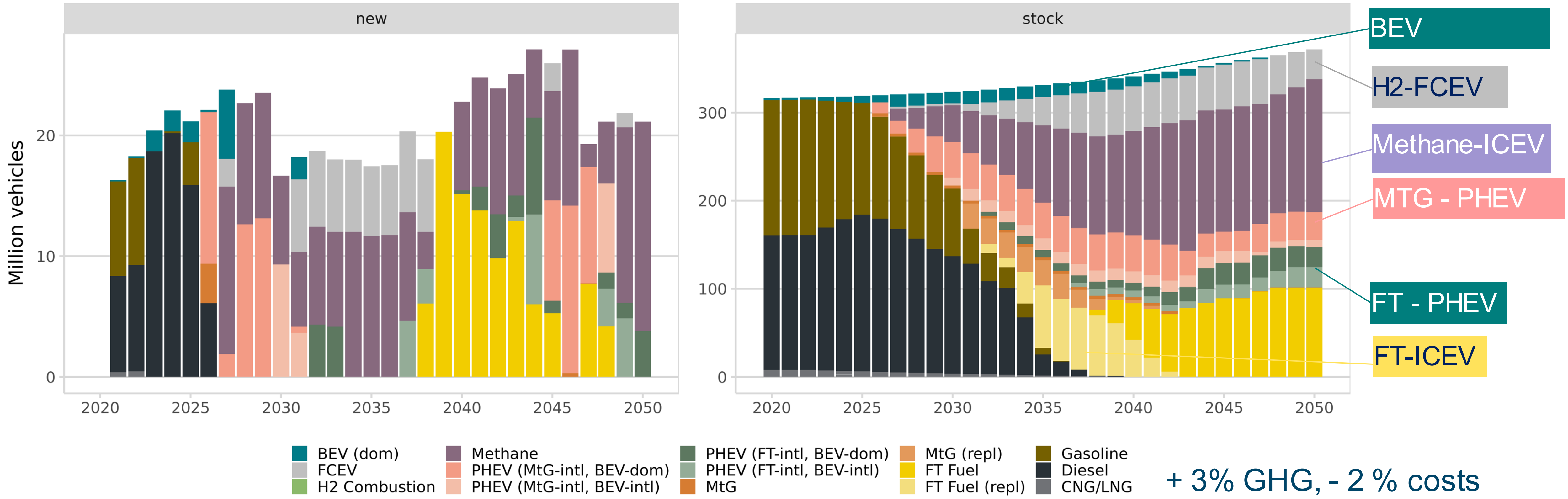


+ 1 % GHG, +13 % costs

- Min. GHG for HDV achieved with “Catenary BEV” (Lang Haul) and FCEV (Delivery Truck)
- H2-ICEV does not occur (→ reason: significantly higher mileage and energy consumption per HDV than per LDV)

Sensitivity Analysis 2e – **No (catenary) BEV for HDV**; all paths for PC

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **LDV (PASCAR + N1) ONLY**

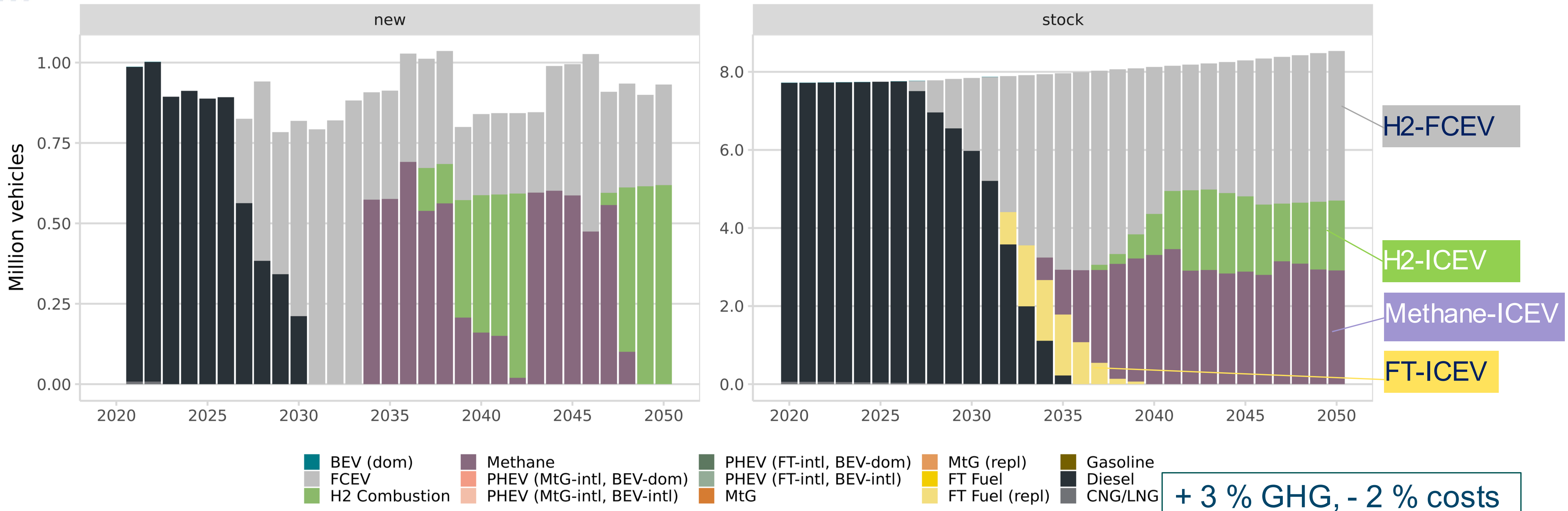


+ 3% GHG, - 2 % costs

- LDVs (PasCar+N1) 2050: bunch of technologies in 2050, but **NO H2-ICEV:**
- H2-FCEV, Methane-ICEV, MtG-PHEV, FT-ICEV, FT-PHEV

Sensitivity Analysis 2e – **No (catenary) BEV for HDV**; all paths for PC

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **HEAVY DUTY ONLY**



+ 3 % GHG, - 2 % costs

- HDVs 2050: Min. GHG achieved with H2-FCEV, H2-ICE and Methane-ICEV
- H2-ICEV rising in 2050, since lower C2G GHG for H2-ICEV than for H2-FCEV in 2050 (before: limited H2-infrastructure leads to (more efficient) H2-FCEV preference)

Content

- Approach and General Assumptions (Fuels Study IV & IVb)
- Energy Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Economic Analysis (Fuels Study IV: Theoretical Reference Ramp-Up)
- Cumulated Green House Gas
  - Reference Scenario (Fuels Study IV: Theoretical Reference Ramp-Up)
  - Single Technology Scenarios (Fuels Study IVb: Realistic Ramp-Ups)
  - Minimum GHG - Mixed Technology Scenario (Fuels Study IVb: Realistic Ramp-Ups)
  - Sensitivity Analysis (Fuels Study IVb: Realistic Ramp-Ups)
- Summary and Conclusions

Summary and Conclusions (Energy, Cost)

- **Factors of required installed power generation capacity 2050:**
  - **H2-FCEV international / BEV domestic ≈ 1.5**
  - **H2-ICEV international / BEV domestic ≈ 1.7**

- **Carbon Neutral Transportation in 2050 is affordable:** 17% … 34% of annual GDP EU27+UK 2020 (15,600 bil. €)

- International energy sourcing is cheaper than domestic for ICEV 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. €)
- **Lowest costs** (NPV) **are for ICEV (+ e-fuels) with continued 2020 vehicle technology**
  - 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.
  - **H2-ICEV:** lower total costs than BEV & FCEV, but higher costs than “Hydrocarbon E-Fuels”
  - **H2-ICEV:** oncosts driven by vehicle tank system (700 bar)

* „quasi“ GHG neutrality: only unavoidable GHG emissions left

Summary and Conclusions (Cumulated GHG Emissions)

- **Ramp-up speed** of fully sustainable technology pathways is
  THE decisive factor for minimising the global warming impact of the transport sector
- **A mix of carbon neutral pathways** can speed up the transition to GHG neutrality significantly compared to single technology scenarios. Under **ideal regulatory and financial conditions, a GHG optimized mixed scenario can reach GHG neutrality* by 2039.**
  - **LDV: H2-ICEV** share in 2050 ≈ 8 % (rising), amended by: Methane-ICEV, FT-ICEV, MTG-ICEV
  - **HDV: H2-ICEV** as interims pathway (2038 … 2048); **HDV 2050** dominated by Catenary BEV + H2-FCEV
- **Many single technology scenarios cannot achieve GHG neutrality* by 2050** (e.g., BEV limited to 76% defossilisation rate, mainly by ramp-up of the electric supply network)
- **Single technology scenarios** (without e-fuel usage in the for existing fleet) yield to considerably higher cumulated GHG in 2050 (e.g., BEV: +39 % → further GHG emissions after 2050 until 100% defossilisation rate achieved)
- **Single tech. scenario H2-ICEV can achieve GHG neutrality* by 2050** (+18% GHG, +1% costs)
- **(2a) "Fit for 55 Scenario"** (+ e-fuels in legacy fleet, H2-ICE allowed after 2035) (+1 % GHG, +13 % costs): **H2-ICEV** dominates LDV; Catenary BEV + H2-FCEV for HDV
- **(2e) "Catenary BEV & BEV excluded for HDV"** (+ e-fuels in legacy fleet) (+3 % GHG, -2% costs): **HDV 2050: H2-ICEV** rising, amended by H2-FCEV+ Methane-ICEV; **LDV 2050: No H2-ICEV**

* „quasi" GHG neutrality: only unavoidable GHG emissions left

Acknowledgement

»TRANSFORMATION OF MOBILITY TO THE GHG NEUTRAL POST FOSSIL AGE - FVV FUEL STUDY IV B« (FVV PROJECT NUMBER 1452)

This report is the scientific result of a research project undertaken by the FVV eV and performed by **Frontier Economics Ltd.** under the direction of **Dr. David Bothe**.

The FVV would like to **Dr. David Bothe** and his scientific research assistants **Dr. Christoph Gatzen, André Pfannenschmidt, Carolin Baum, Fabian Schrogl** and **Osama Mahmood** for the implementation of the project. The project was conducted by an expert group led by **Dr. Ulrich Kramer** (Ford-Werke GmbH). We gratefully acknowledge the support received from the project coordination and from all members of the project user committee.

In particular, we would like to thank the research team of **ifeu GmbH - Frank Dünnebeil, Dr. Monika Dittrich** and **Axel Liebich** - for the provision of qualified green house gas data, as well as the assessment of raw material ramp-up potential, and **Siyamend Al Barazi** of **Deutsche Rohstoffagentur (DERA)** for considerably supporting the assessment of achievable primary material supply ramp-ups.

The research project was self-financed (FVV funding no. 1452) by the FVV eV.

Science for a moving society

FVV eV

Lyoner Strasse 18 | 60528 Frankfurt / Main | Germany

+ 49 69 6603 1345 | info@fvv-net.de

www.fvv-net.de/en

Supported by BMWK – Federal Ministry for Economic Affairs and Climate Action

Member of AiF – Federation of Industrial Research Associations

Member of FKM – Mechanical Engineering Research Federation | managed by VDMA

Certified by Stifterverband | Promoting Education, Science & Innovation

AiF Member