Science for a
moving society

Transformation of mobility to the GHG neutral post fossil age
FVV Fuel Study IV b

Project No. 1452

Würzburg | 06 October 2022

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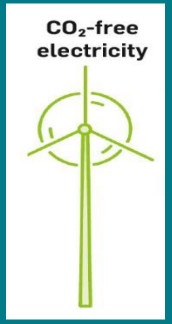
Content

Review: FVV Fuels Study IV

Hypothetical 100% scenarios (single technology scenarios, all achieving carbon neutrality in 2050)

OVERVIEW OF 42 INVESTIGATED 100% SCENARIOS IN FS IV

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



2x Energy Sourcing: Domestic vs. Global

6 fuel types

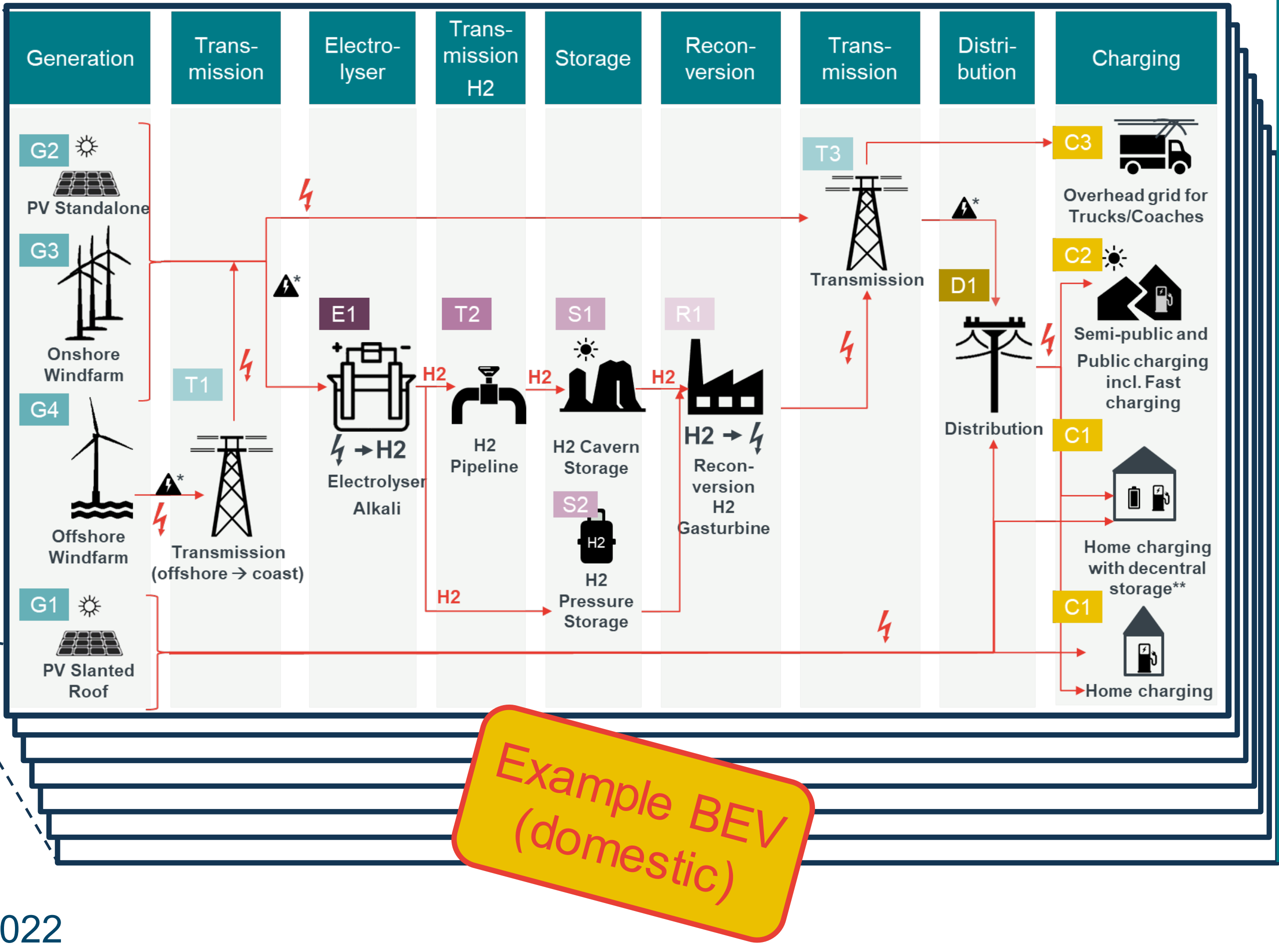
7 powertrains

- 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).



Comparison of:

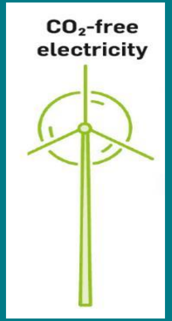
- Energy demand
- Power generation capacity
- Total Costs
- Cumulative GHG emissions
- Other environ-mental impacts (land use,…)

Review: FVV Fuels Study IV

Formerly called **"100% Scenarios"** are called **"Single Technology Scenarios"** now, since not all technology pathways can achieve GHG neutrality until 2050!

CHANGES IN FVV FS IV B: "SINGLE TECHNOLOGY SCENARIOS"

Realistic Ramp-up Scenarios for Carbon Neutral Mobility in EU27+UK ~~in 2050~~ asap supplied solely by wind/solar energy



2x Energy Sourcing: Domestic BEV vs. Global

~~6~~ 5 fuel types

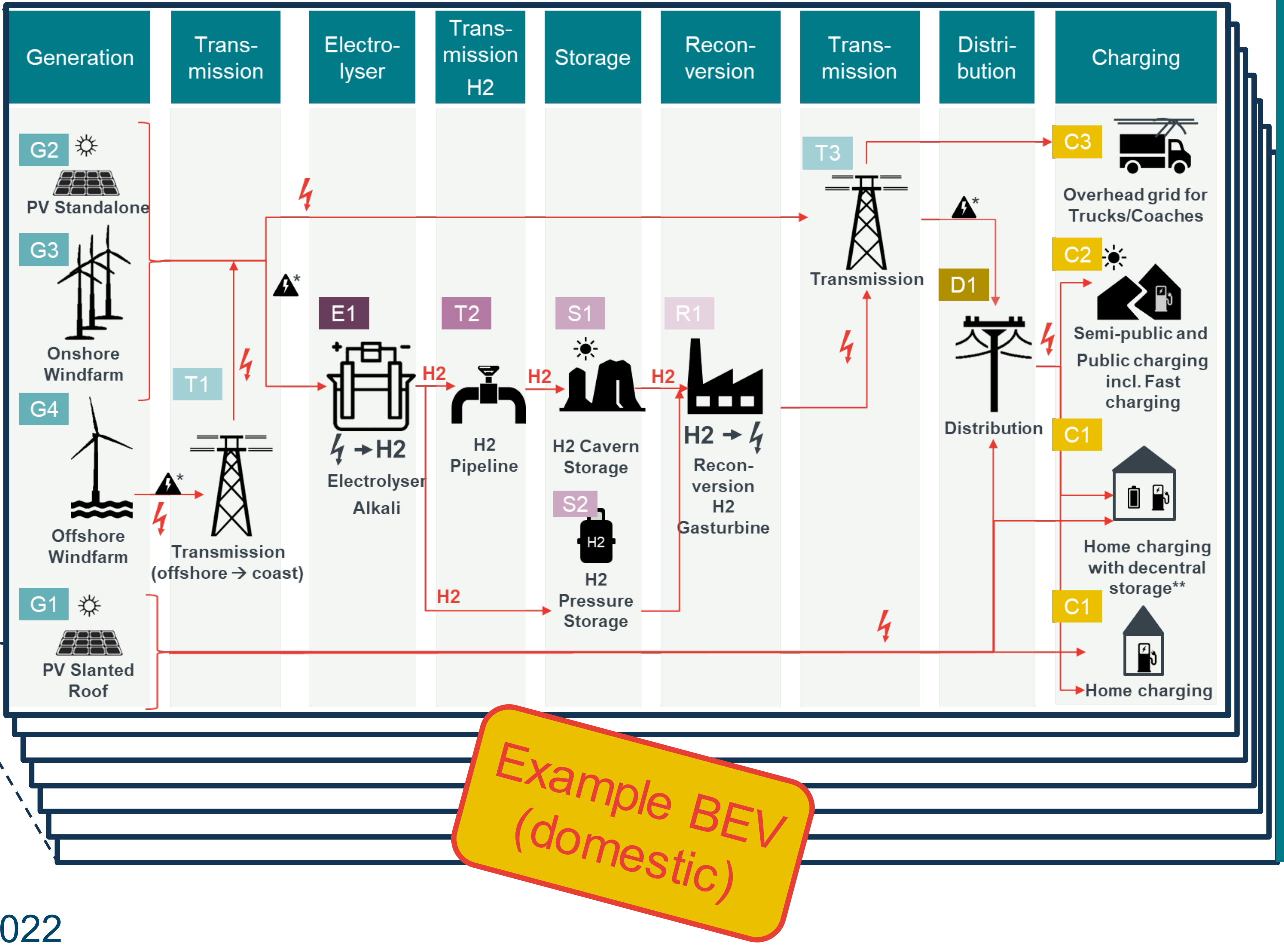
~~7~~ 7 powertrains

~~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).



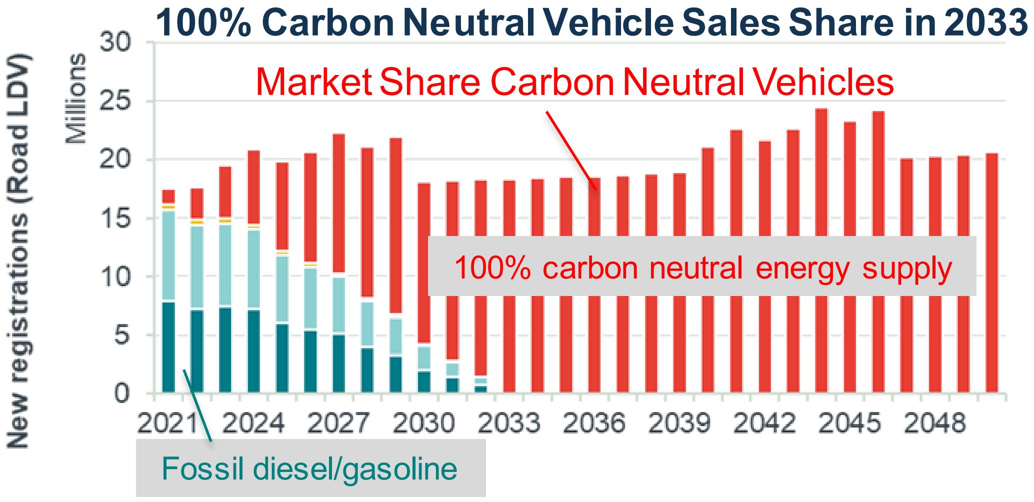
Comparison of:

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

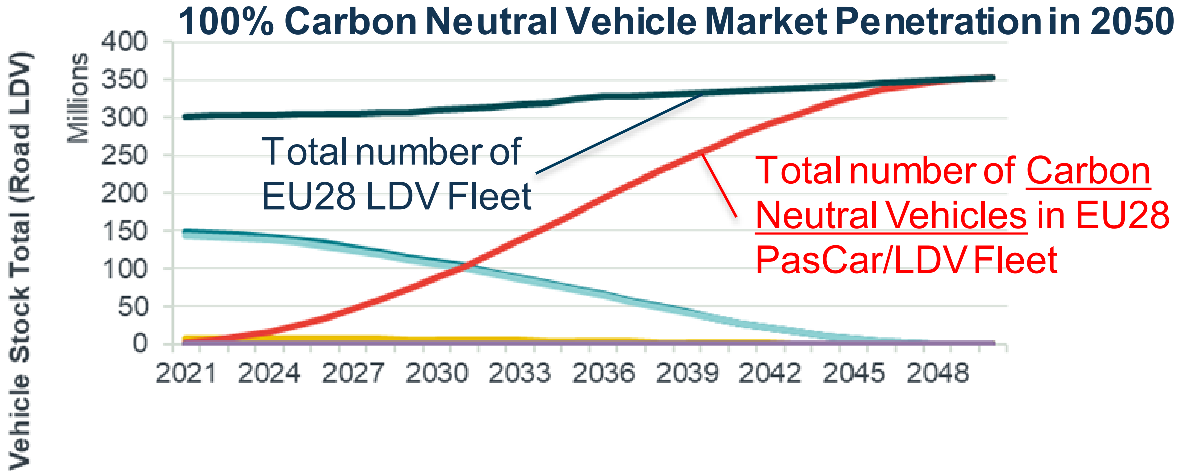
Review: FVV Fuels Study IV

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

Sales Share



Market Penetration



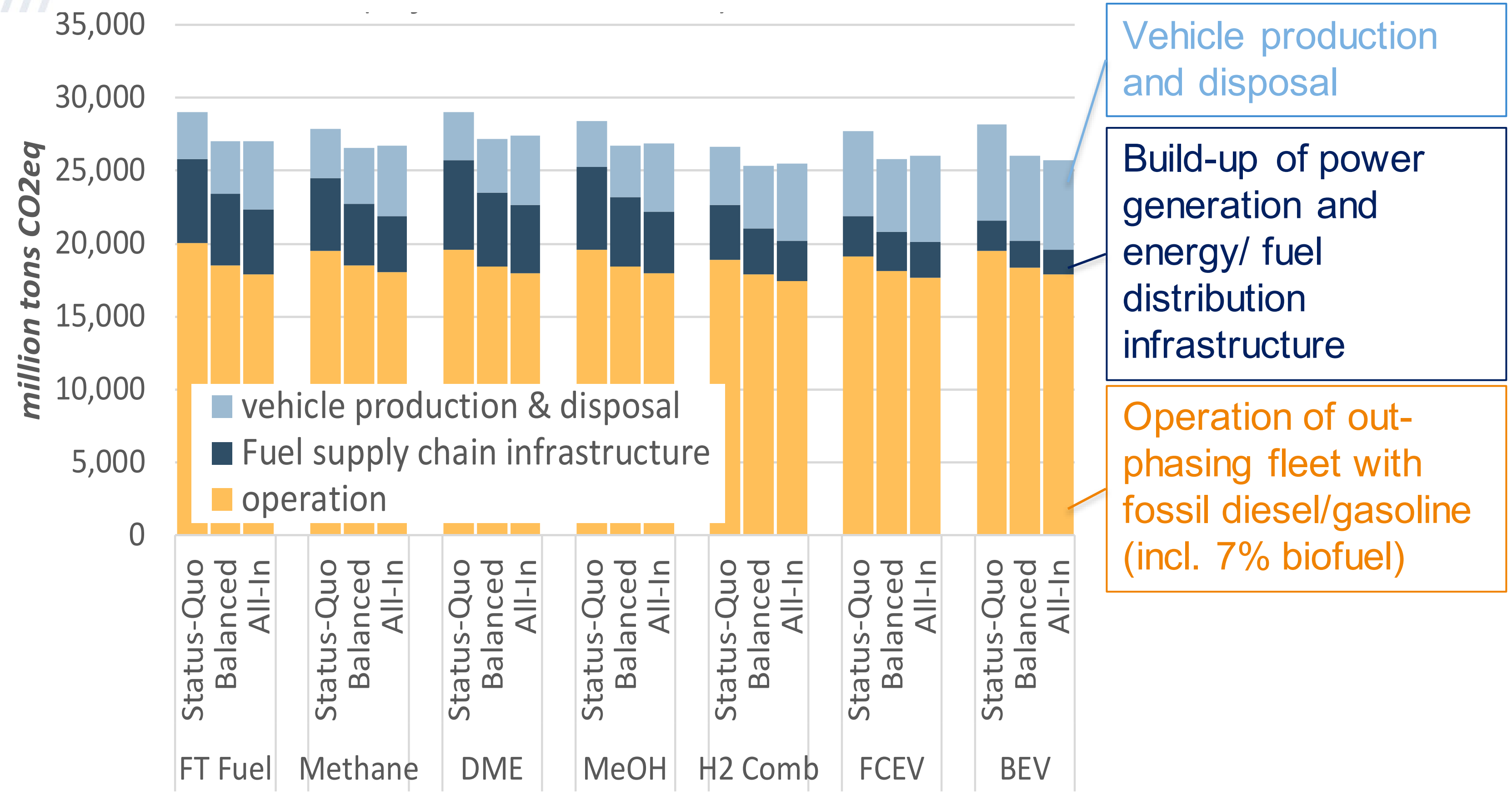
- Vehicles of out-phasing fleet, operated with fossil diesel
- Vehicles of out-phasing fleet, operated with fossil gasoline
- New carbon neutral vehicles, operated with defossilized fuel/energy
- Total number of vehicles (fleet stock)

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

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

Review: FVV Fuels Study IV – 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 essential for reducing cumulative GHG emissions!

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Approach and General Assumptions: Fuels Study IV b

TECHNOLOGIES & RAMP-UP

*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

Technology pathways	Energy sourcing – fuel supply chain sites	Technological progress scenario
1 BEV (Battery Electric Vehicles) (Long Haul > 7.5t: Catenary HDV)	Domestic / International	Balanced Scenario
2 PHEV (Plug-In Hybrid Electric Vehicles) 4 PHEV sub-options: BEV Dom. + FT Int., BEV Int. +FT Int., BEV Dom. + MtG Int. (only PasCars), BEV Int. +MtG Int. (only PasCars)	Domestic (electric mode) / International (BEV, E-Fuel)	
3 e-FT ICEV (Fischer Tropsch)	International	
4 e-MtG ICEV (Methanol-to-Gasoline, only Passenger Cars)		
5 e-CH4 ICEV (Synthetic Methane)		
6 e-H2 ICEV (Hydrogen Combustion)		
7 e-H2 FCEV (Fuel Cell Electric Vehicles)		

Vehicles exclusively operating with combustion engine (3–6)

- 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

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Single Technology Scenarios – Bottlenecks Overview

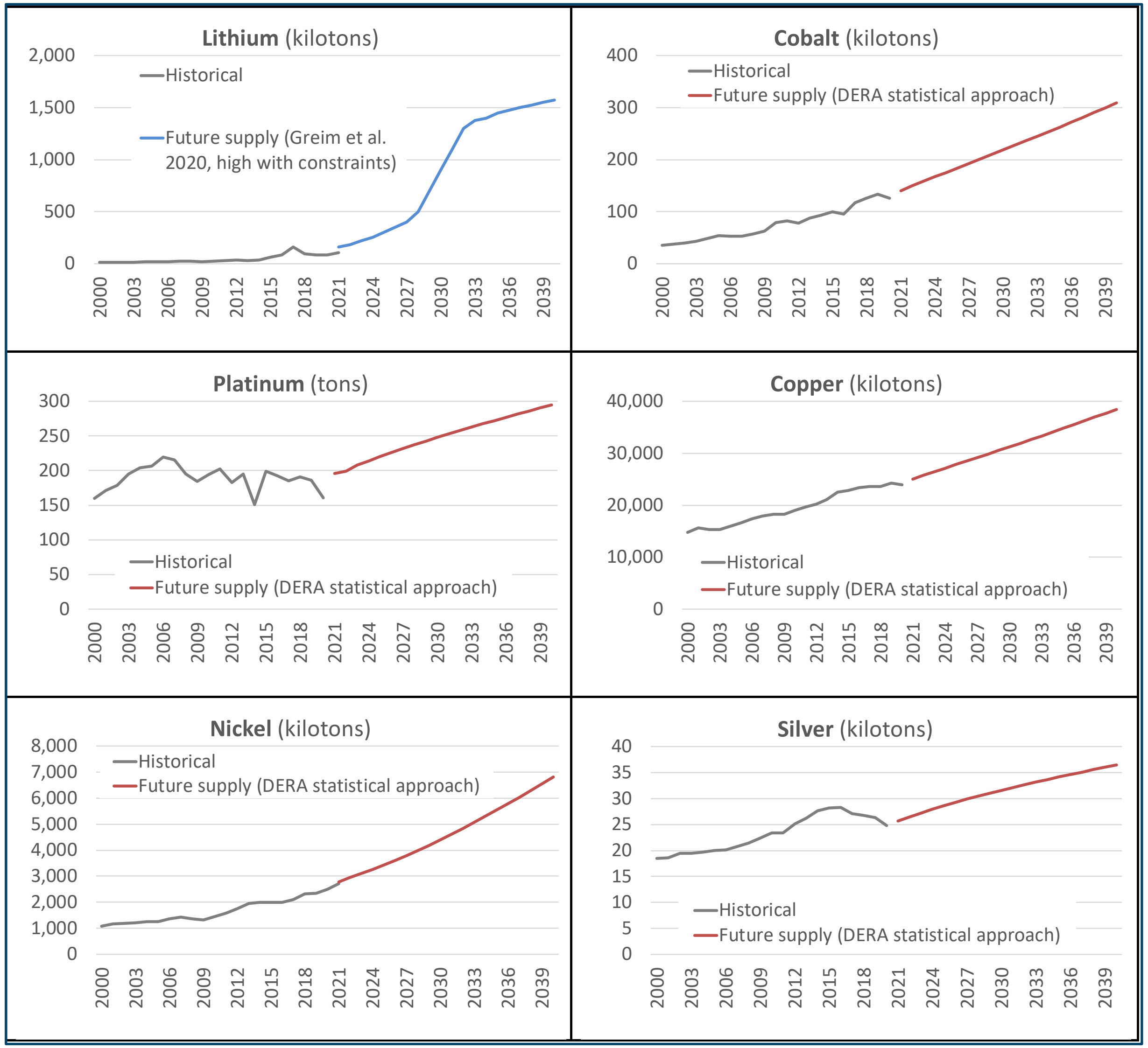
Single Technology Scenario	Technical Bottlenecks 2020-2029	Technical Bottlenecks 2030-2039	Technical Bottlenecks 2040-2049
BEV – Dom.	Power transmission grid, catenary lines, cobalt, battery production, wallboxes	Power transmission grid, catenary lines, cobalt, battery production, wallboxes	Power transmission grid, cobalt
BEV – Int.	Sea power cable, catenary lines, cobalt, power transmission grid	Sea power cable, catenary lines, cobalt, power transmission grid	Cobalt , power transmission grid
Methane – Int.	Methanation, CH_4 import pipelines, electrolysis	Methanation, electrolysis	
FCEV – Int.	H_2 import pipeline, platinum, battery production,	H_2 import pipeline, platinum	Platinum
H_2 Comb. – Int.	H_2 import pipeline, electrolysis	H_2 import pipeline, electrolysis	H_2 import pipeline
FT Fuel – Int.	FT synthesis, nickel, electrolysis	FT synthesis, nickel, electrolysis	
MtG – Int.	Electrolysis, renewable electricity generation, MtG synthesis	Electrolysis, renewable electricity generation	
PHEV (BEV-Dom. FT-Int.)	FT synthesis, battery production, electrolysis, wallboxes	FT synthesis	
PHEV (BEV-Int. FT-Int.)	FT synthesis, sea power cable, battery production, electrolysis, wallboxes	FT synthesis, sea power cable	
PHEV (BEV-Dom. MtG-Int.)	Wallboxes, public chargers, electrolysis	Wallboxes, public chargers	
PHEV (BEV-Int. MtG-Int.)	Sea power cable, wallboxes, public chargers	Sea power cable, wallboxes, public chargers	

- Main **technical** bottlenecks restricting ramp-up of GHG-neutral **single technology pathways**
- Sustainable power generation (wind / solar) is no technical bottleneck at any time for any of the scenarios
- BEV (domestic energy supply) still restricted by electrical power transmission grid extension and cobalt supply until 2050

see also: Table #2, Report

Single Technology Scenarios – Bottlenecks - Model Assumptions

MAXIMUM AVAILABLE PRIMARY MATERIAL SUPPLY



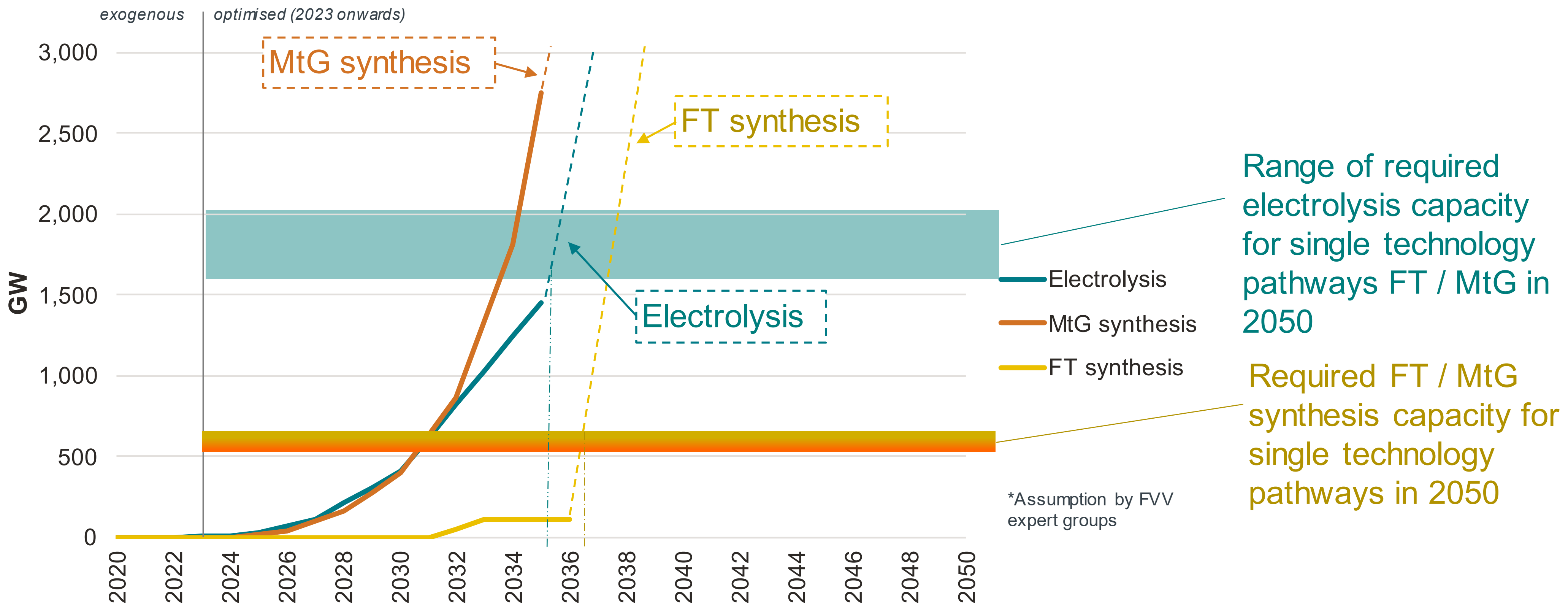
Sources: DERA, Greim et al. 2020

- Fastest possible ramp-up of material supply determined with the help of DERA (Deutsche Rohstoff Agentur)

- Detailed analysis of:
  - Lithium
  - Cobalt
  - Platinum
  - Copper
  - Nickel
  - Silver

Single Technology Scenarios – Bottlenecks - Model Assumptions

MAX. AVAILABLE ELECTROLYSIS AND SYNTHESIS CAPACITY (EU28 ROAD)

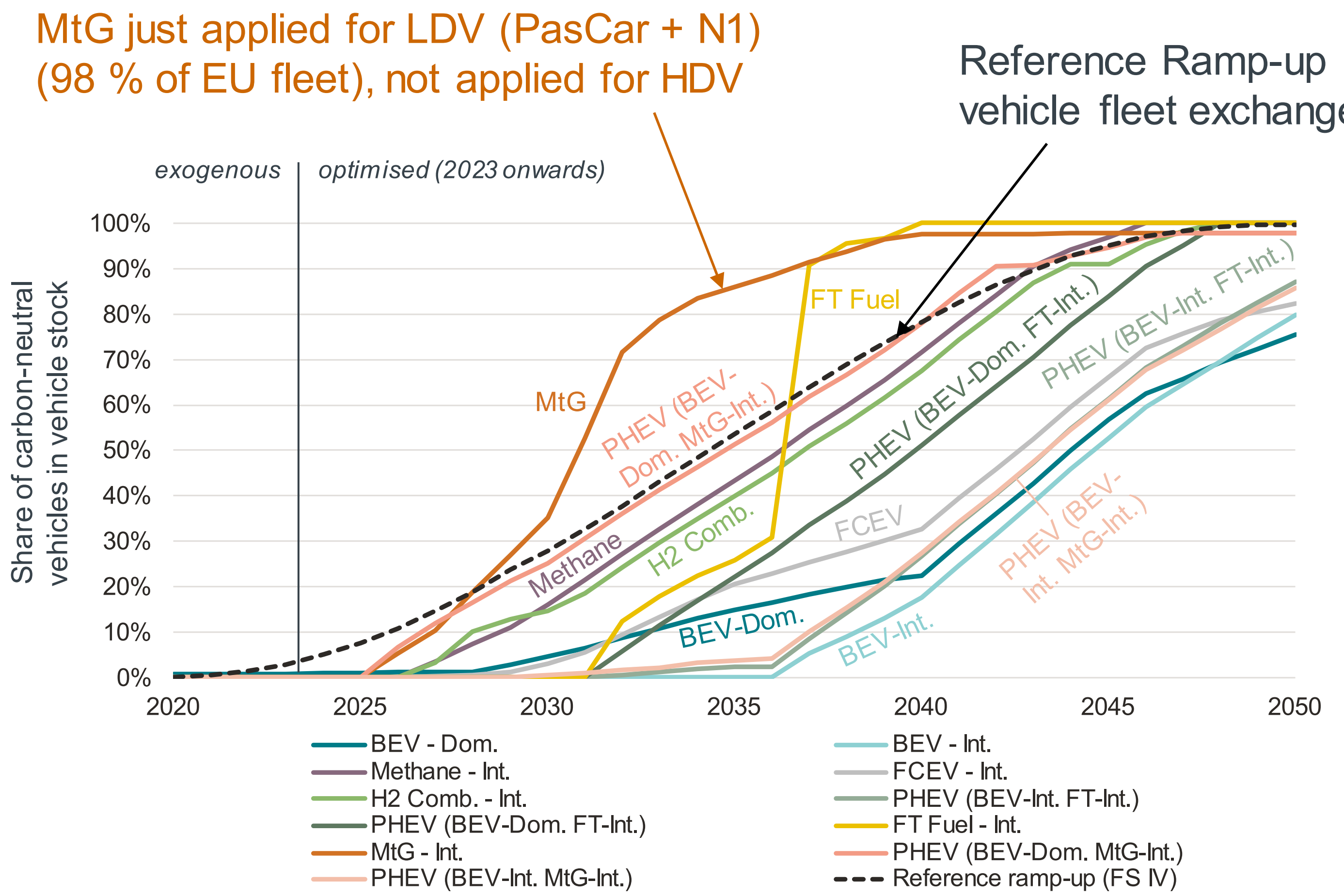


- Not limited by electrolysis and synthesis ramp-up: MtG after 2035; FT after 2037
- MtG synthesis delivers high volume output significantly faster than FT (5 … 6 years earlier), because MtG does not require RWGS** optimisation and integration

**RWGS: Reverse Water Gas Shift Reaction

Single Technology Scenarios - GHG-neutral vehicle ramp-up

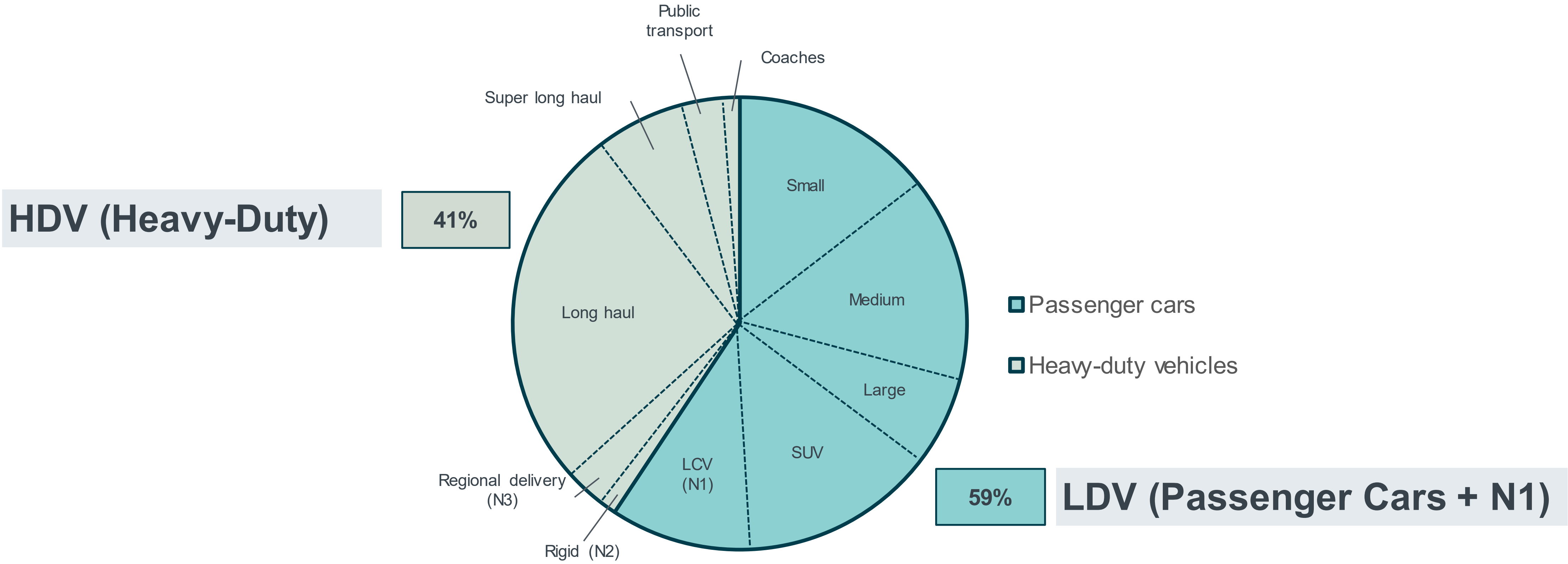
SHARE OF CARBON-NEUTRAL VEHICLES IN STOCK



- 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) are not meeting 100 % “carbon-neutral vehicles” in 2050

Single Technology Scenario (FT Fuel)

TTW ENERGY DEMAND BY SEGMENT



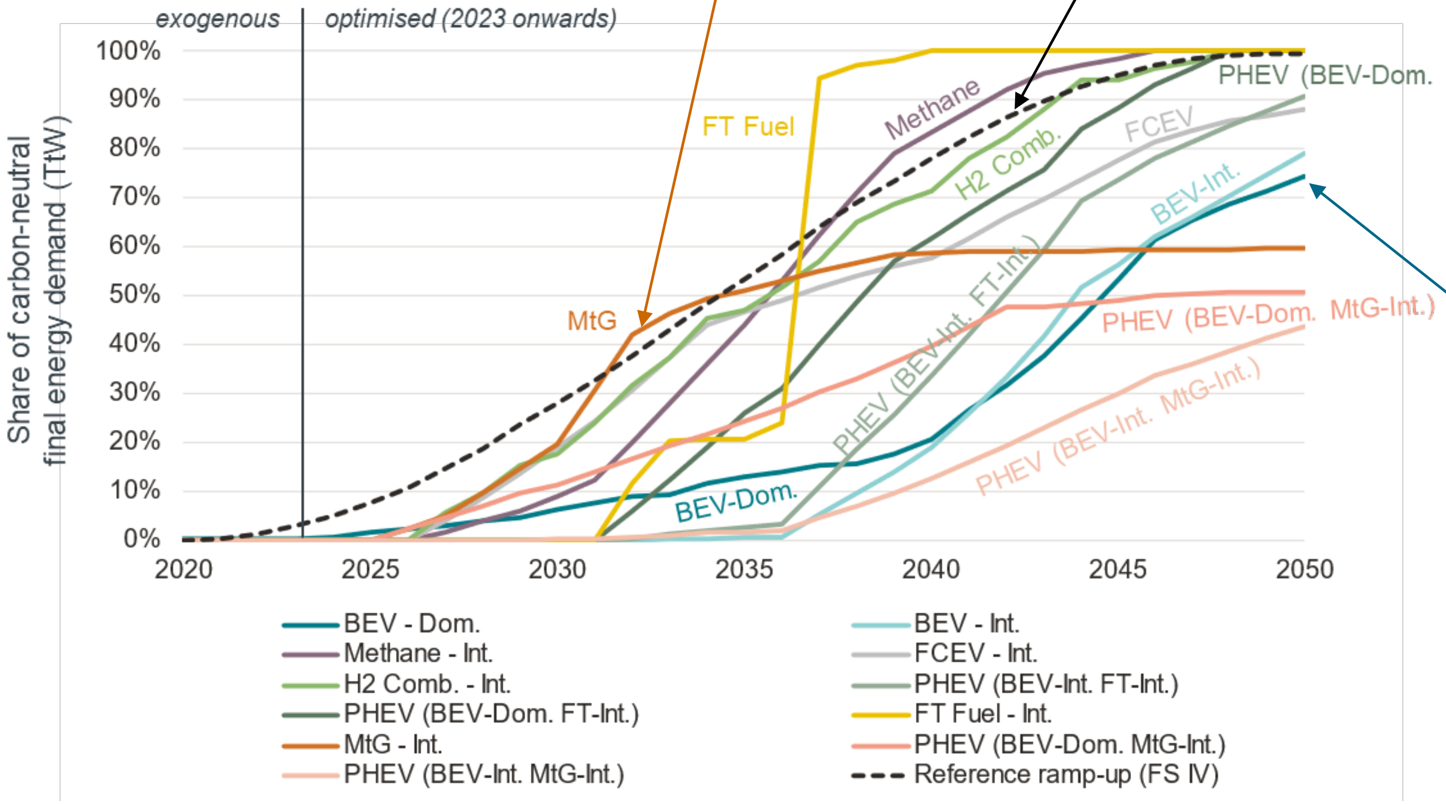
- 98 % of the European vehicle fleet are LDV (Passenger Cars + N1) using 59 % of the energy
- 2 % of the European vehicle fleet are Heavy-Duty Vehicles, using 41 % of the energy

Single Technology Scenarios - GHG-neutral TtW energy demand

SHARE OF CARBON-NEUTRAL TTW ENERGY USAGE

MtG just applied for LDV (PasCar + N1) (98 % of EU fleet), not applied for HDV

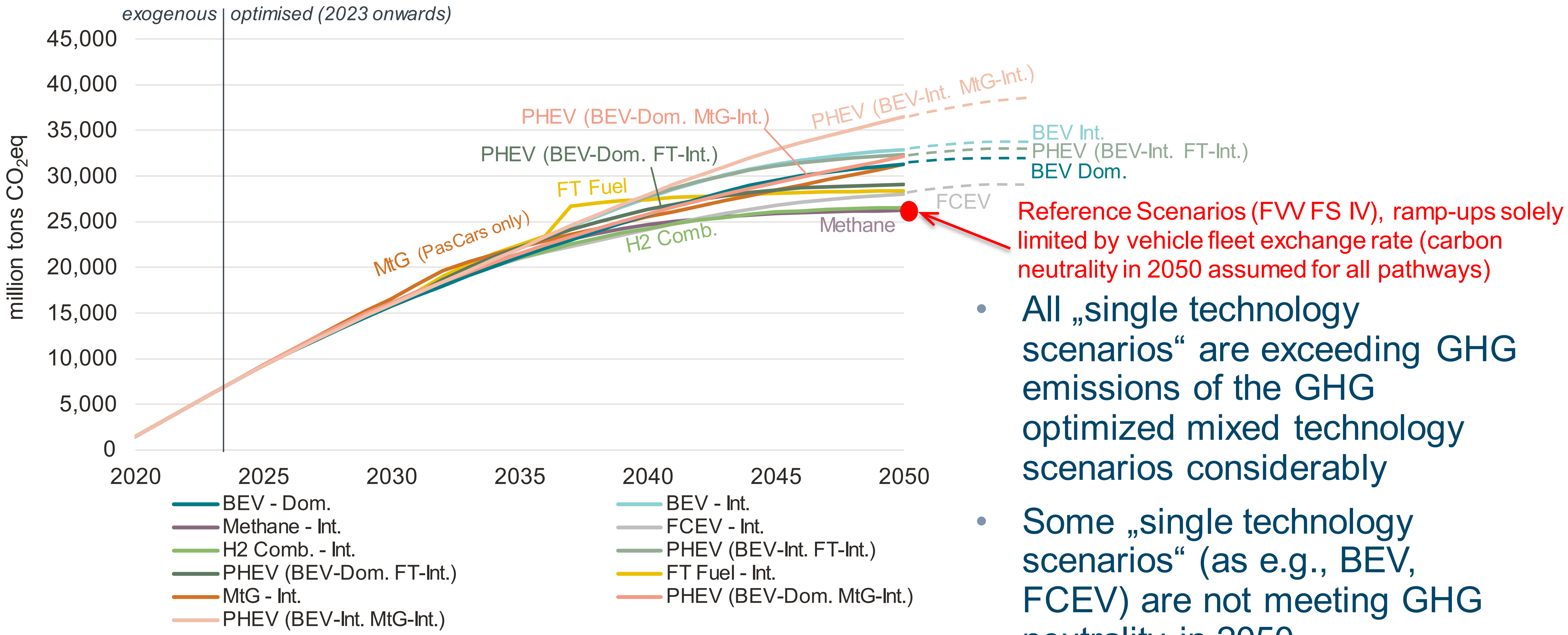
Reference Ramp-up FVV FS IV (just limited by vehicle fleet exchange rate, GHG neutrality in 2050)



- Energy-wise MtG just slightly exceeds reference ramp-up, since only applied LDVs (Passenger Cars +N1) (98% of fleet with just 41% of energy consumption)
- Energy-wise „single technology scenario BEV (domestic energy sourcing)“ just meets ≈76 % defossilisation rate

Single Technology Scenarios - Cumulated Green House Gas

CUMULATED GHG: SINGLE TECHNOLOGY SCENARIOS, 2020-2050

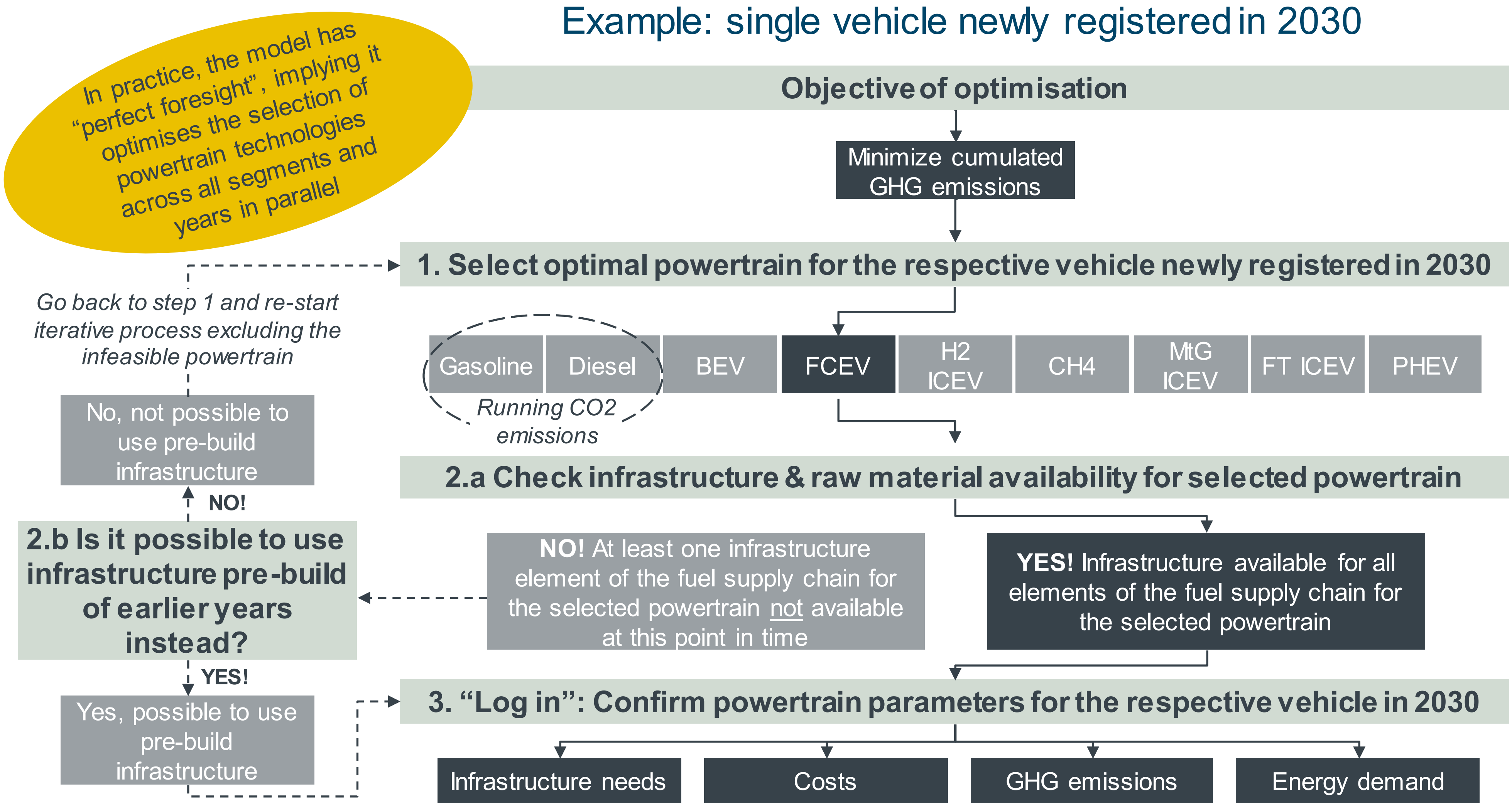


- All „single technology scenarios“ are exceeding GHG emissions of the GHG optimized mixed technology scenarios considerably
- Some „single technology scenarios“ (as e.g., BEV, FCEV) are not meeting GHG neutrality in 2050

Content

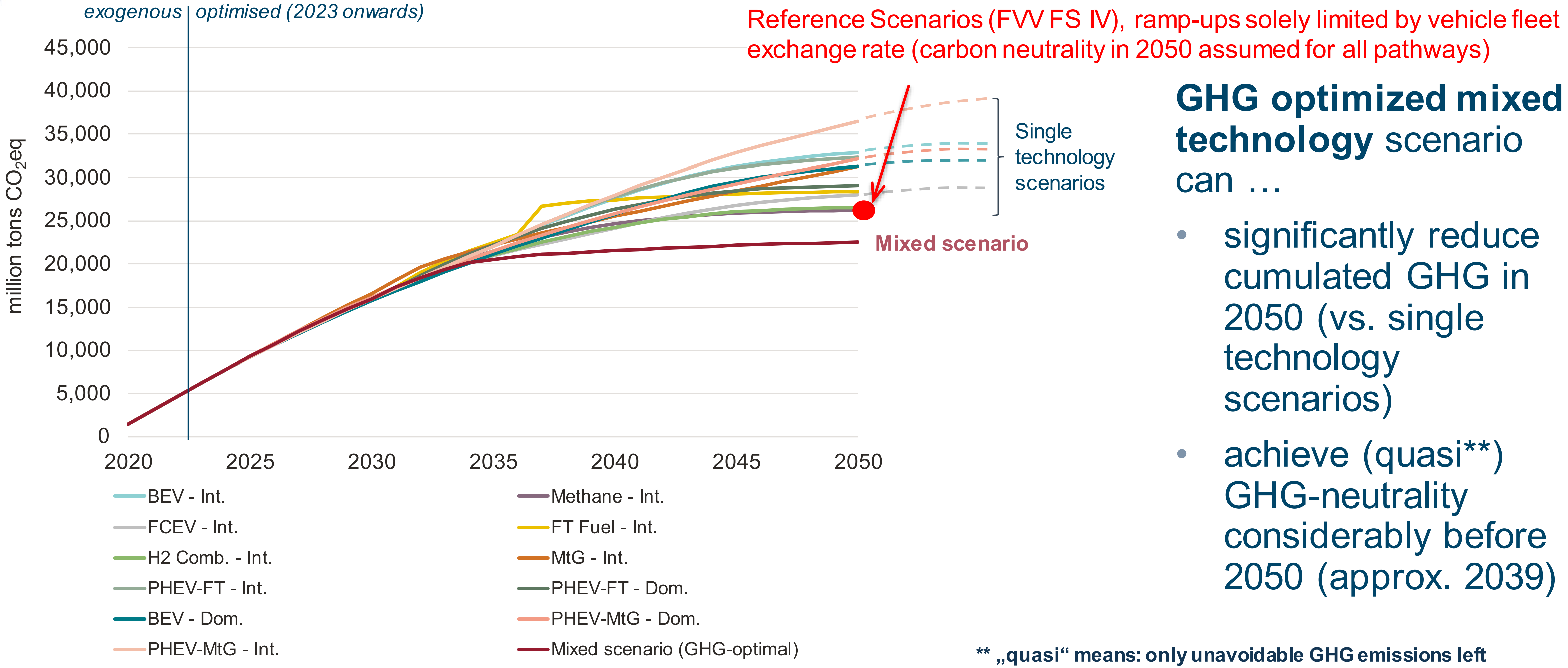
Minimum GHG - Mixed Technology Scenario

GHG MINIMISATION - SIMPLIFIED MODEL DECISION MAKING PROCESS



Minimum GHG - Mixed Technology Scenario

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



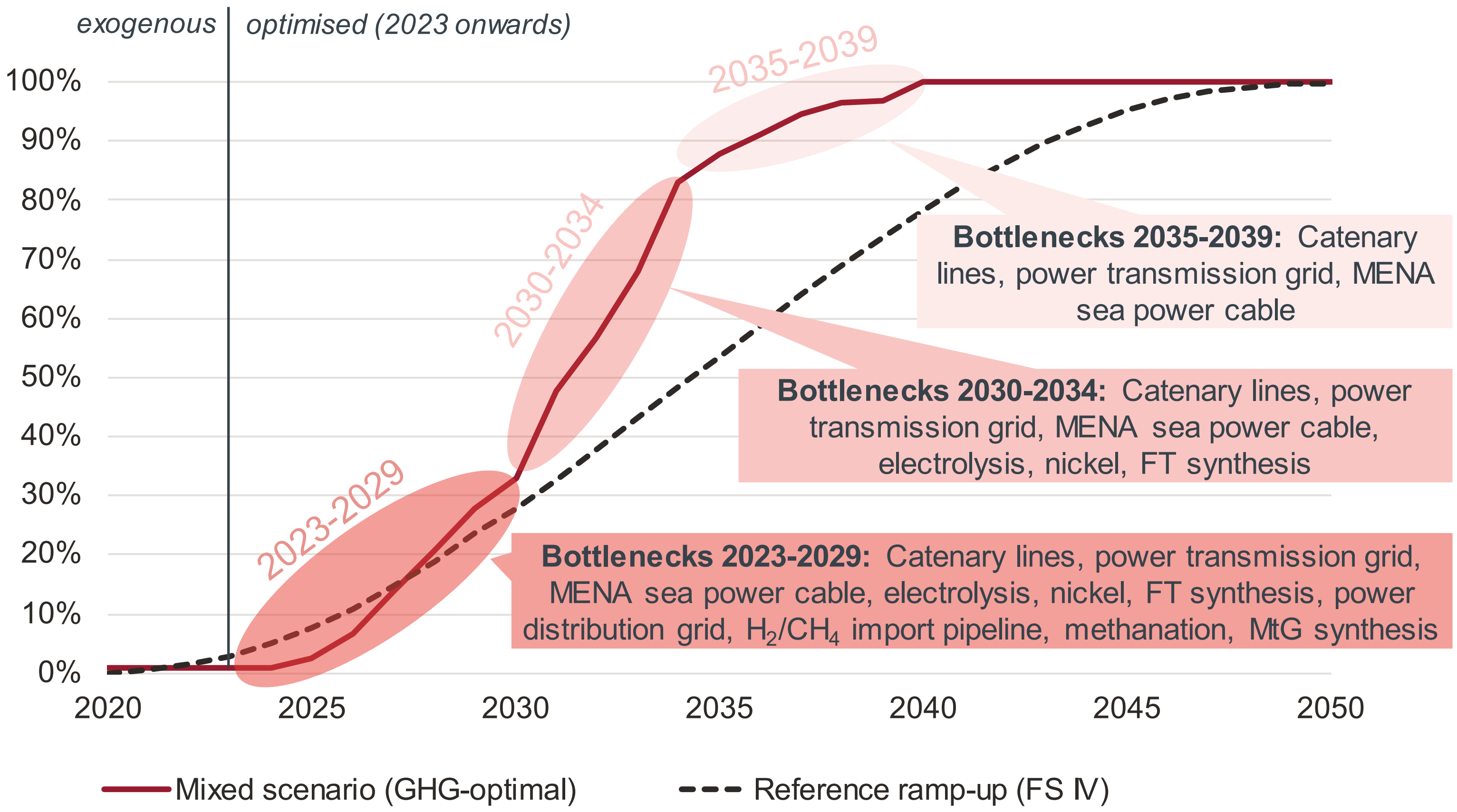
GHG optimized mixed technology scenario can …

- significantly reduce cumulated GHG in 2050 (vs. single technology scenarios)
- achieve (quasi**) GHG-neutrality considerably before 2050 (approx. 2039)

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

Minimum GHG - Mixed Technology Scenario

MAIN TECHNICAL BOTTLENECKS RESTRICTING THE RAMP-UP

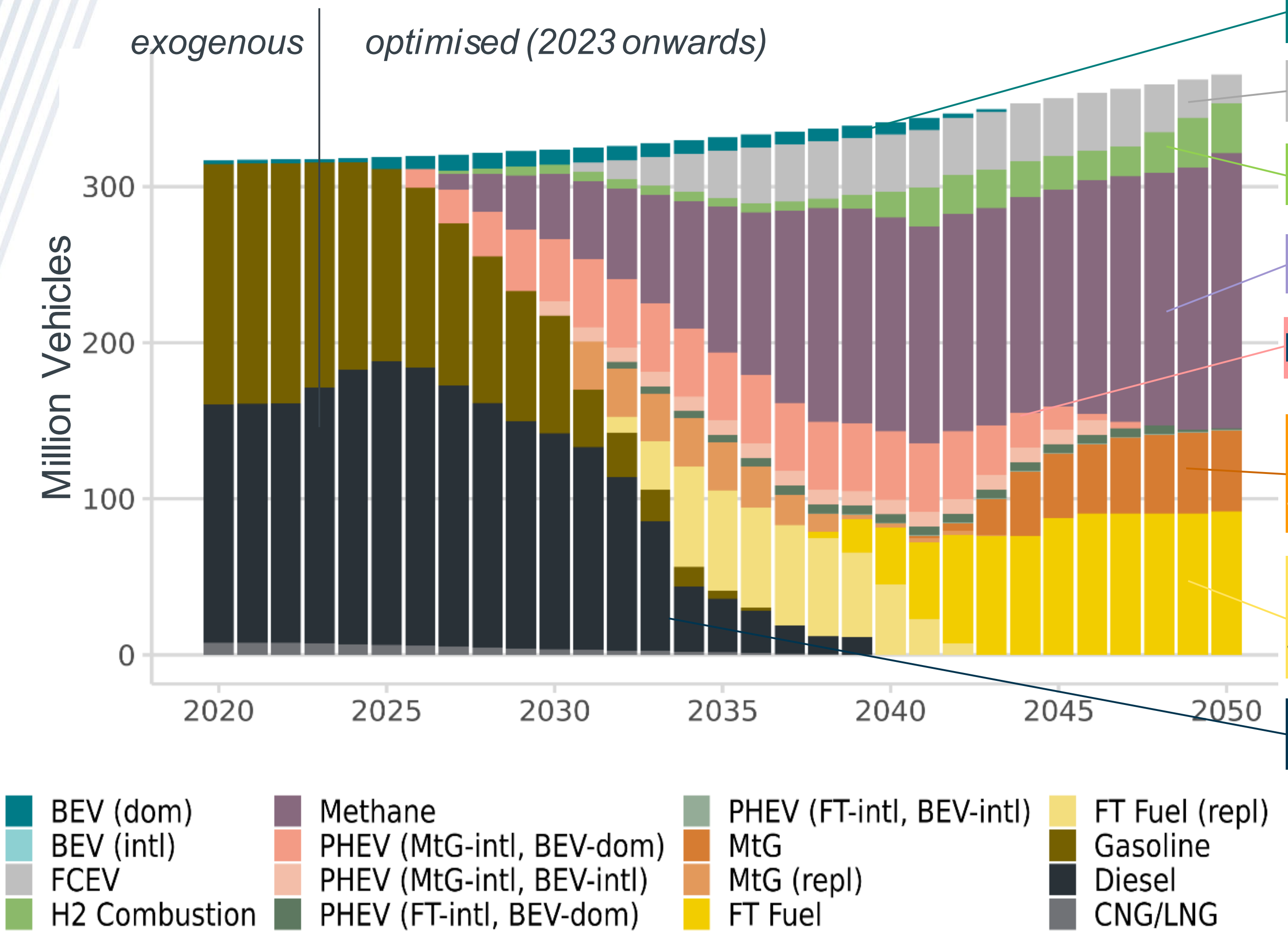


Main ramp-up bottlenecks of GHG opt. mixed scenario:

- … 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**) – **PASSENGER CARS**



BEV phase out in 2042

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

H2-ICE 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 ICEV (existing fleet) introduced in 2031,
Share of MtG vehicles in 2050 ≈ 10% (rising)

FT in ICEV (existing fleet) introduced in 2032,
Share of FT vehicles in 2050 ≈ 25% (rising)

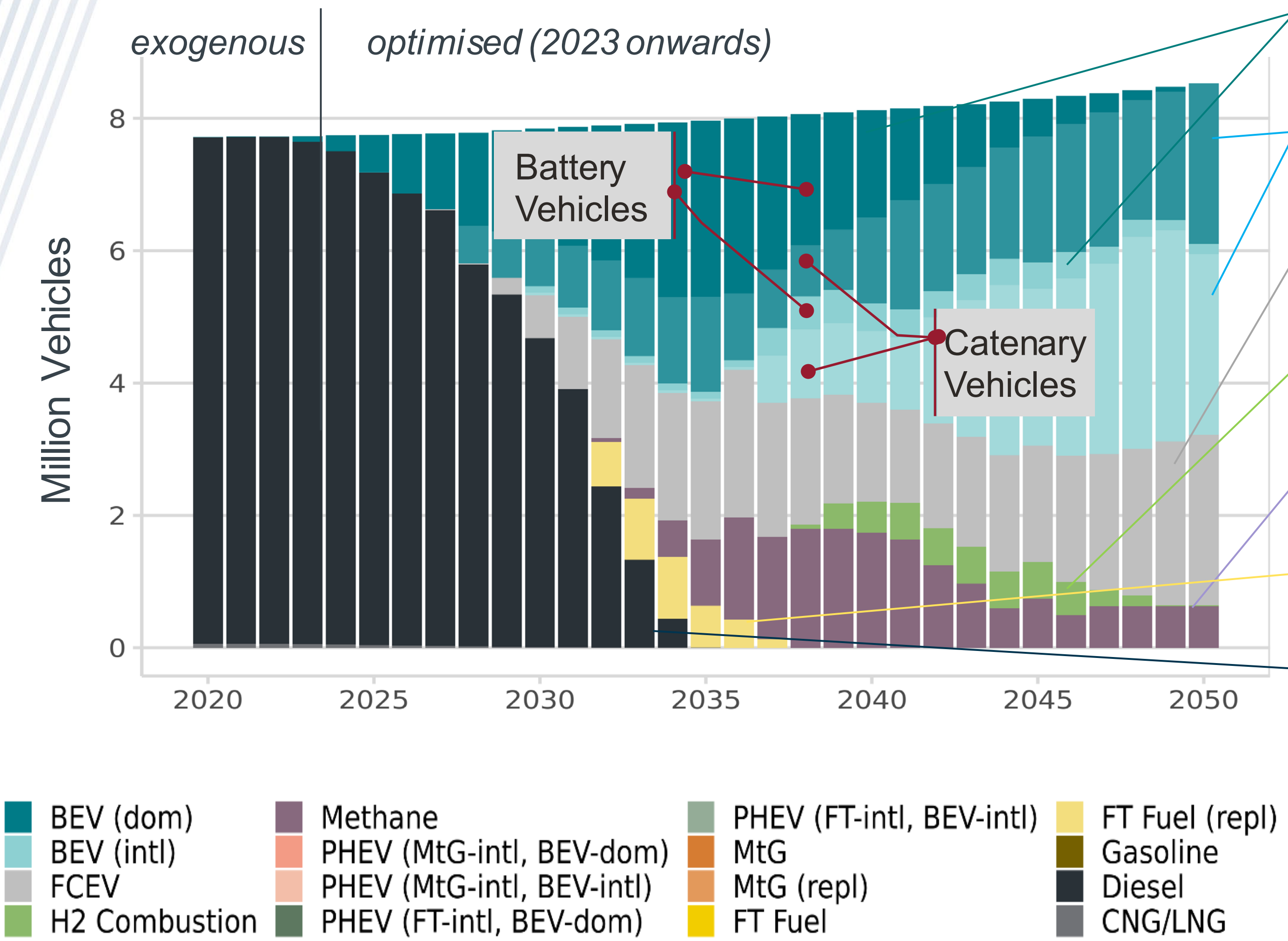
Fossil gasoline phase out 2036, fossil diesel 2039

Dominating PasCar/LDV pathways 2050

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

Minimum GHG - Mixed Technology Scenario

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



Pure BEV (for < 7.5 t HD) phasing out in 2050

Catenary BEV (for > 7.5 t HD) > 50% share in 2050 (rising)

H2-FCEV introduced in 2028, share in 2050 ≈ 35% (rising)

H2-ICE 2038 … 2048

Methane introduced in 2024, share in 2050 ≈ 5% (declining)

FT in ICEV (existing fleet) 2032 … 2037

Fossil diesel phase out 2034

Dominating HD pathways 2050

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

Content

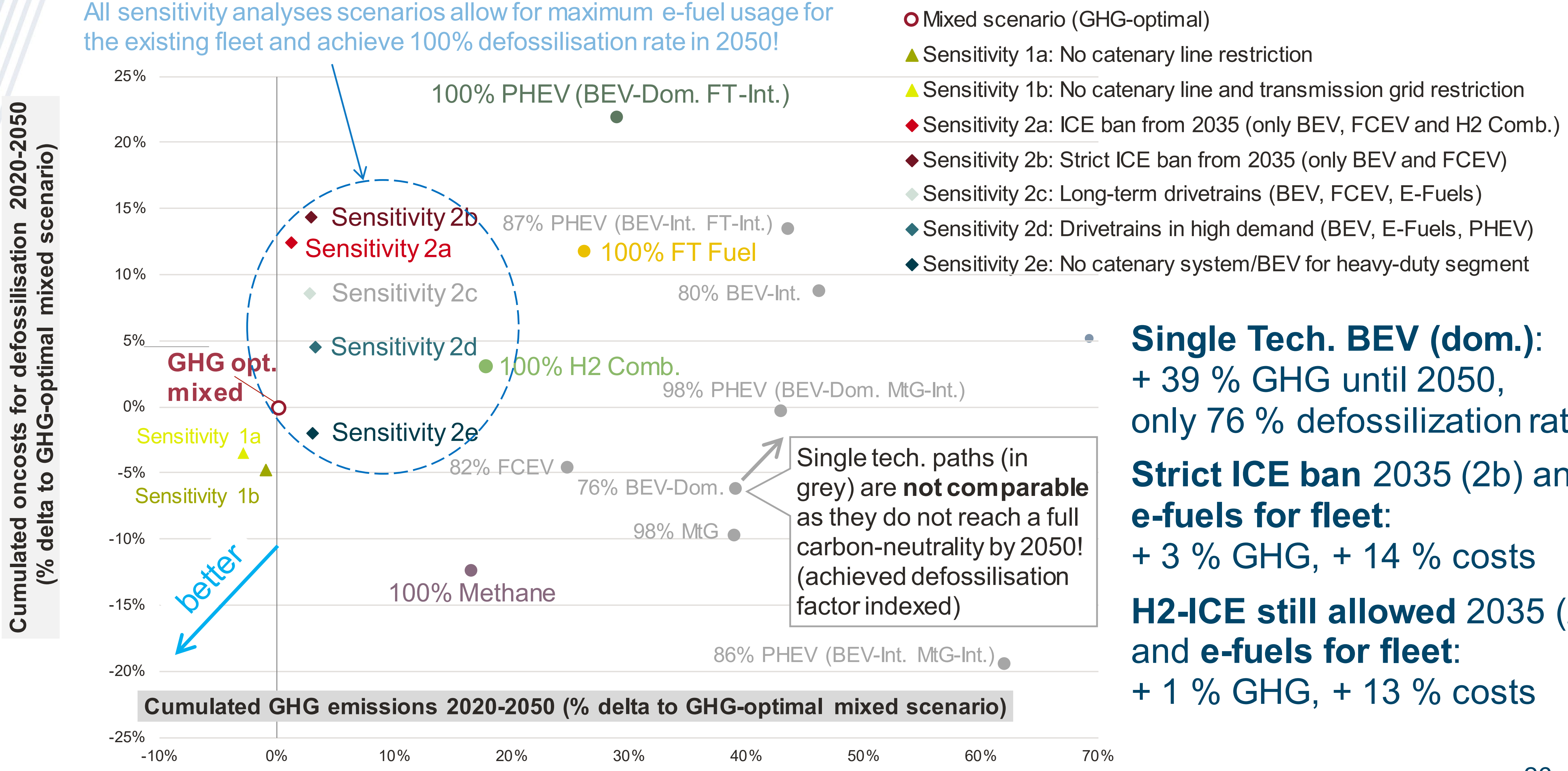
Sensitivity Analysis - Approach

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 and transmission grid restriction	All
Sensitivities 2: Reduced number of (GHG-neutral) technology pathways		
Sensitivity 2a	ICE ban from 2035	BEV, FCEV and H_2 Comb. from 2035; e-fuel usage in existing vehicle legacy fleet
Sensitivity 2b	Strict ICE ban from 2035	BEV and FCEV from 2035; e-fuel usage in existing vehicle legacy fleet
Sensitivity 2c	Only long-run technologies	BEV, FCEV, FT Fuel and MtG from 2023
Sensitivity 2d	Focus on powertrains currently in high demand	BEV, FT Fuel, MtG and PHEV from 2023
Sensitivity 2e	No catenary system/BEV for heavy-duty segment	**Passenger cars:** All **Heavy-duty vehicles**: FCEV, H_2 Comb., FT Fuel, Methane

„Fit for 55“ + e-fuels for legacy fleet

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

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



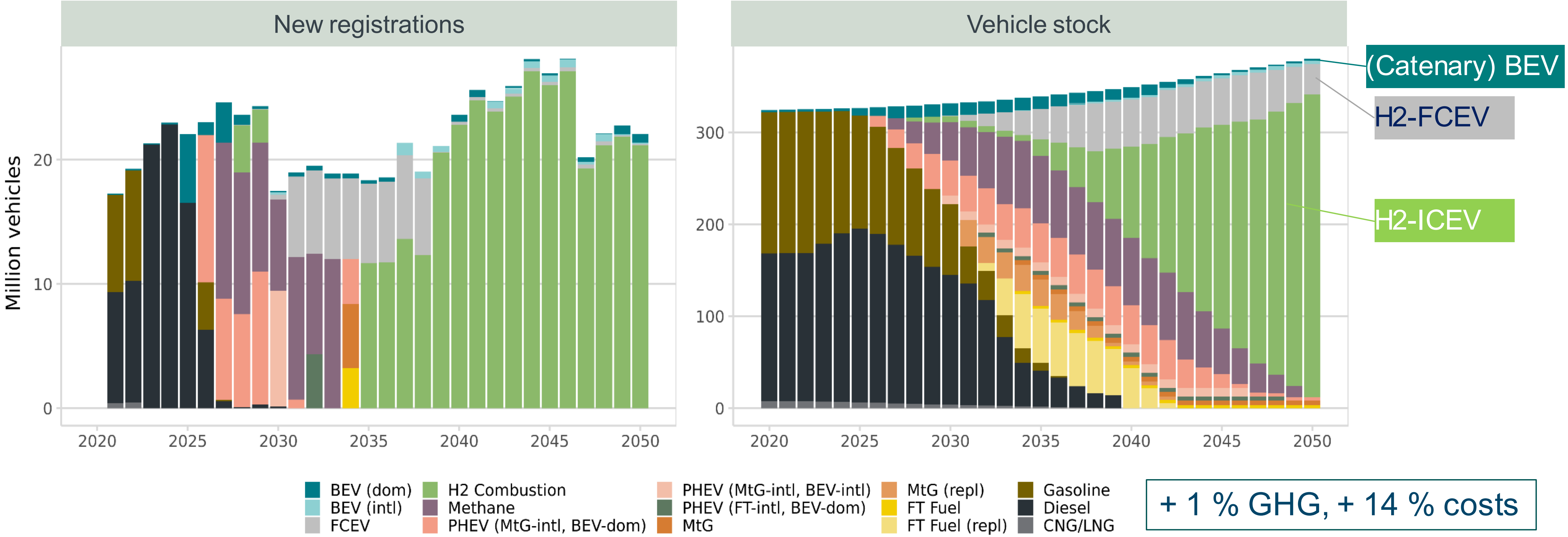
Single Tech. BEV (dom.):
+ 39 % GHG until 2050,
only 76 % defossilization rate

Strict ICE ban 2035 (2b) and **e-fuels for fleet**:
+ 3 % GHG, + 14 % costs

H2-ICE still allowed 2035 (2a) and **e-fuels for fleet**:
+ 1 % GHG, + 13 % costs

Sensitivity Analysis 2a - **ICE ban** from 2035 (**H2-ICE allowed**)

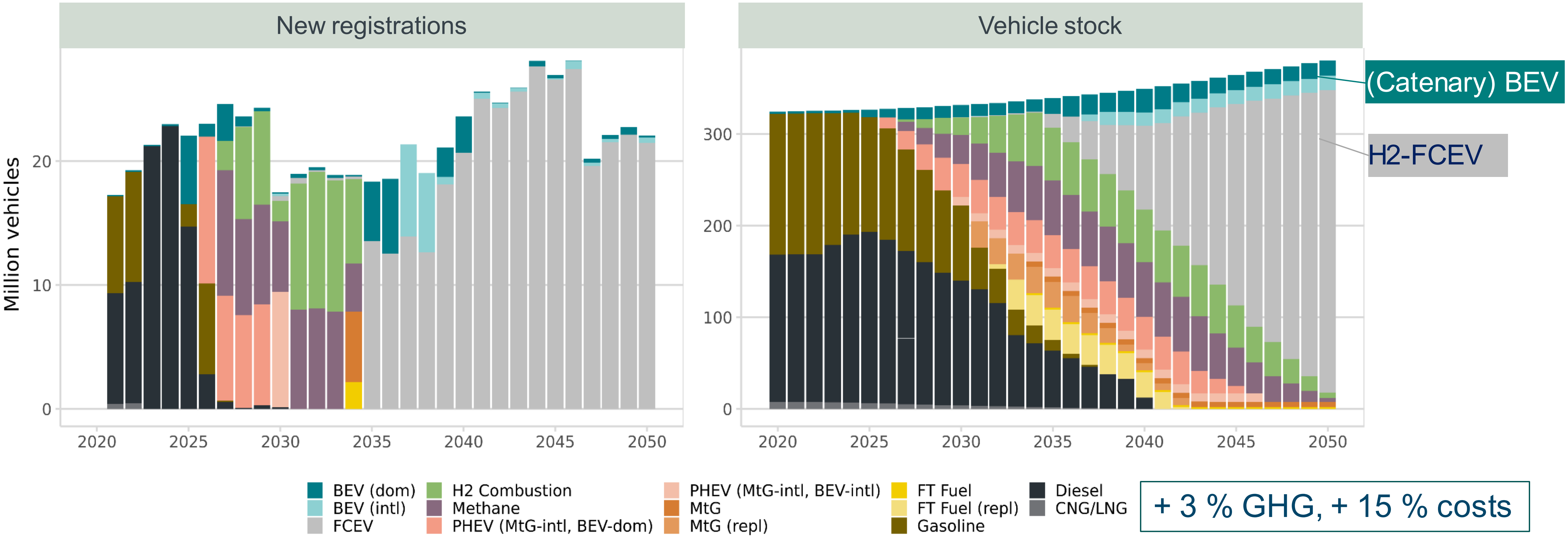
NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **ALL VEHICLE SEGMENTS COMBINED**



- Min. GHG achieved with H2-ICE as dominating pathway (for PasCars) by 2050
- (Catenary) BEV dominate 2050 HDV share. FCEV for both, PasCar and HDV.

Sensitivity Analysis 2b – **Strict ICE ban** from 2035 (**H2-ICE also banned**)

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **ALL VEHICLE SEGMENTS COMBINED**



+ 3 % GHG, + 15 % costs

- Min. GHG achieved with H2-FCEV as dominating pathway (for PasCar) by 2050
- Approx. 50/50 share of (Catenary) BEV and H2-FCEV for by 2050

Content

Summary and Conclusions

- **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** (energy forms and powertrains) can speed up the transition to GHG neutrality significantly compared to single technology scenarios. Under **ideal regulatory and financial conditions, a mixed scenario can reach GHG neutrality* by 2039.**
- **Some single technology scenarios cannot achieve GHG neutrality* by 2050** (e.g., "BEV only" limited to 76% defossilisation rate, mainly by ramp-up of the electric supply network),
- **Some single technology scenarios** yield to considerably higher cumulated GHG in 2050 (e.g., "BEV only": +39 % → further GHG emissions after 2050 until 100% defossilisation achieved)
- **Mixed min. GHG scenario**; dominating **PasCar** pathways 2050: Methane-ICEV, FT-ICEV, MTG-ICEV, H2-ICEV
- **Mixed min. GHG scenario**; dominating **HDV** pathways 2050: "Catenary BEV", H2-FCEV
- In a **"Fit for 55** (incl. max e-fuel usage in legacy fleet)" with **"H2-ICE still allowed** after 2035"
  → H2-ICE + H2-FCEV for PasCar, Catenary BEV + H2-FCEV for HDV
- In a "**Fit for 55** (incl. max e-fuel usage in legacy fleet)" with **"strict ICE ban** in 2035"
  → H2-FCEV for PasCar, Catenary BEV + H2-FCEV for HDV

*** „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)

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Backup

Approach and General Assumptions: Fuels Study IV b

SCHEMATIC OVERVIEW ON MODEL INPUTS AND OUTPUTS

Inputs

Vehicle fleet

- Mobility demand per year
- Vehicle stock and lifespan

Infrastructure requirements

- Per powertrain technology, vehicle segment and year
- Liefetime of infrastructure

GHG emissions and raw materials

- Per powertrain, vehicle segment and year
- Initial, running and disposal emissions

CAPEX and OPEX

- Specific investment and operating costs per year

Technical bottlenecks

- **Infrastructure and raw marerial availability per year**

Model

Linear optimisation model, solved in GAMS

GAMS

Optimisation objective:

Minimisation of cumulated GHG emissions of the EU27+UK road transport sector until 2050

…under **constrains:**

- **Technical bottlenecks restricting the use of (GHG-neutral) powertrains**: (e.g., infrastructure, raw material restrictions)
- **The (GHG-neutral) powertrain(s) available in the modelling setup** : Restrictions to a certain number of powertrains available

Outputs

Optimised pathway

- Share of powertrain technology (per vehicle segment and year)
- **Ramp-up speed**
- **Binding technical bottleneck constraints per year**

Additional information

- Infractructure and raw metarial requirements (per powertrain technology, vehicle segment and year)
- **Specific investment and operating costs** (per powertrain technologie, vehicle segment and year)
- **GHG emissions** (per powertrain technology, vehicle segment and year)
- **Tank-to-wheel and well-to-wheel energy demand** (per powertrain technology, vehicle segment and year)

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

- Minimisation of GHG with ramp-up restrictions
- Fair share of other sectors and other areas than EU taken into account

Approach and General Assumptions: Fuels Study IV b

SCHEMATIC OVERVIEW OF MODELLING SETUP

Starting point: "100% scenarios" (single powertrain technology scenarios) from FS IV in relation to the road segment

- Updated **vehicle Ramp-up** and **fuel demand**
- Updated choice of **technology pathways** (New powertrains: **PHEV and MtG**)
- Focus on **"International Energy Sourcing"** ("Domestic Energy Sourcing" additionally for BEV and PHEV)
- Focus on **"Balanced" scenario**

Model input: Per-vehicle infrastructure requirements

Building on the assumptions of FS IV, we determine requirements of the different vehicle segments and powertrain technologies on a per-vehicle basis

Modelling input: Associated raw material demand, GHG emissions and cost

Associated raw material requirements, GHG emissions and costs of the different vehicle segments and powertrain technologies on a per-vehicle basis

Modelling input: Technical bottleneck analysis

Ramp-up of required infrastructure and raw material availability under ideal legal and financial conditions for all technology pathways considered

Model-based optimisation (target: Minimising cumulated GHG emissions until 2050)

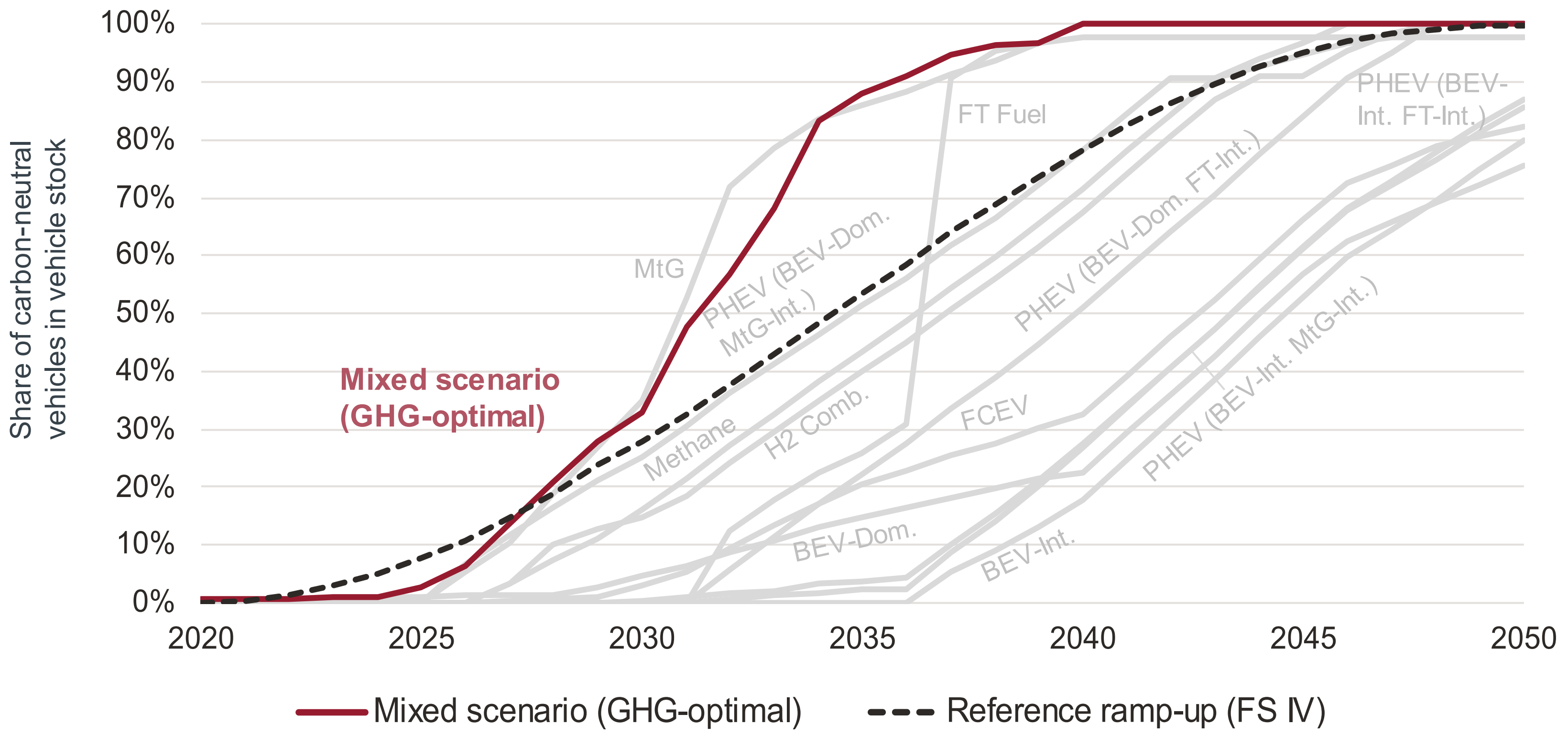
GAMS

Output 1: **Optimised single technology scenarios incl. technical bottlenecks**

Output 2: **Optimised mixed scenario – optimal combination of powertrains across vehicle segments, incl. technical bottlenecks**

Minimum GHG - Mixed Technology Scenario

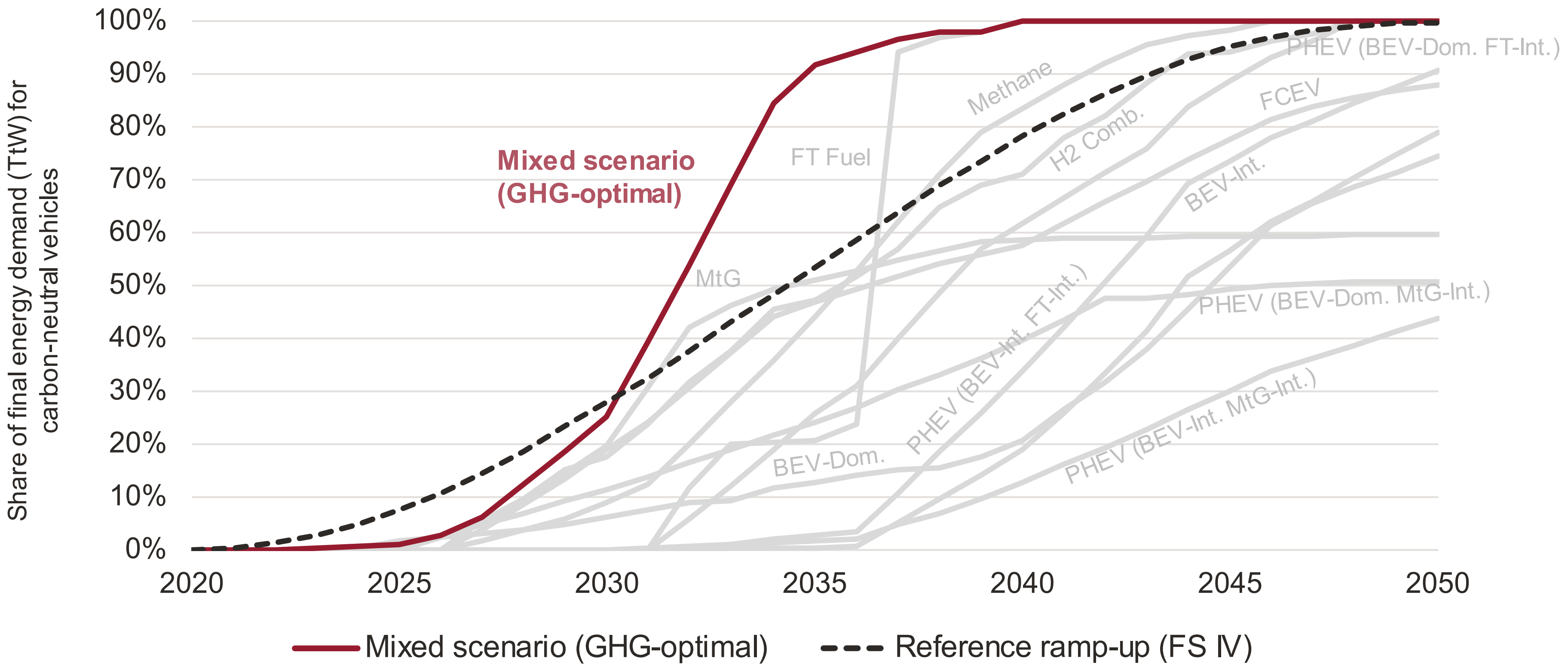
SHARE OF CARBON-NEUTRAL VEHICLES IN STOCK



GHG optimized mixed technology scenario can significantly increase Share of carbon-neutral vehicles (vs. single technology scenarios)

Minimum GHG - Mixed Technology Scenario

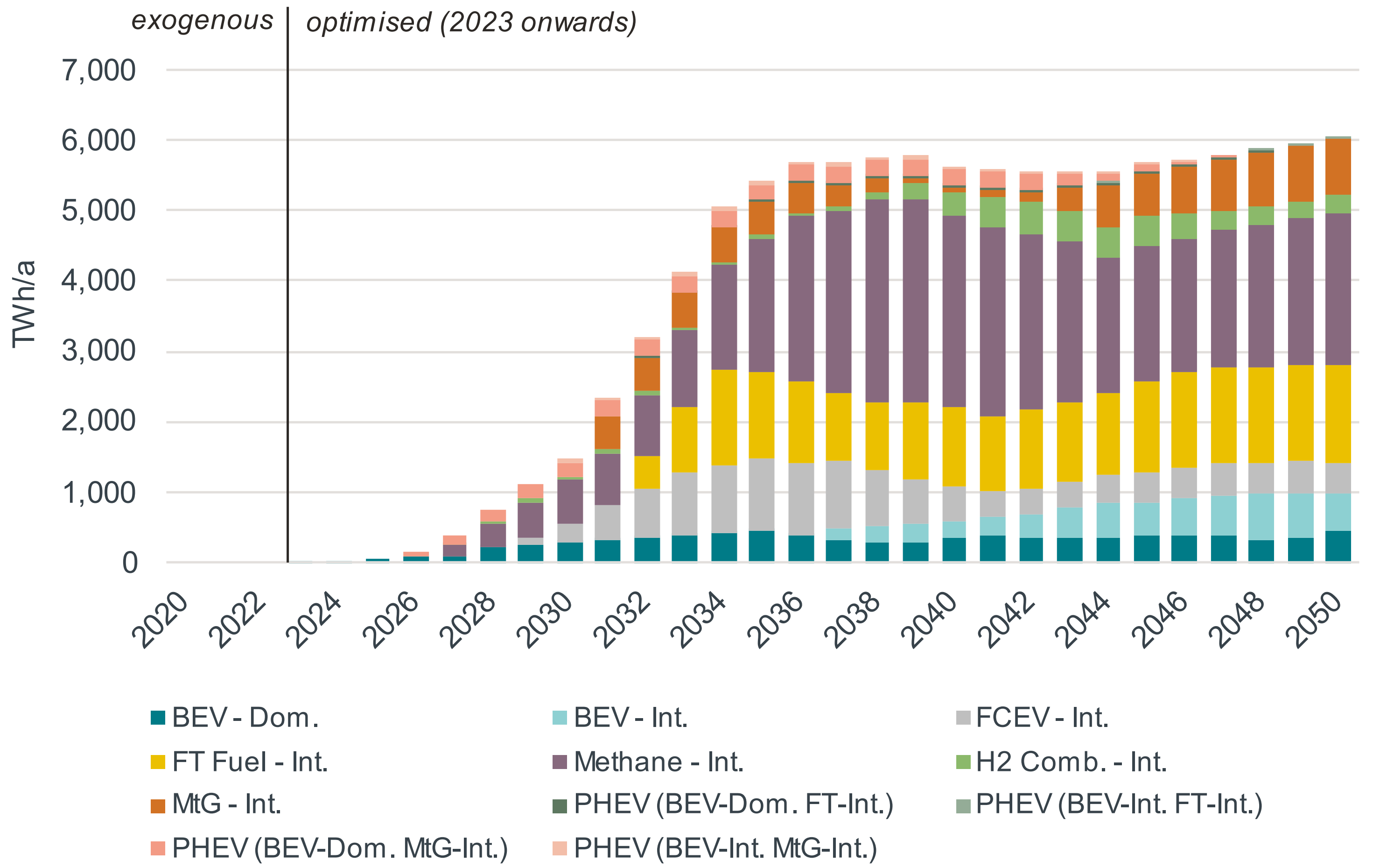
SHARE OF CARBON-NEUTRAL TTW ENERGY USAGE



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

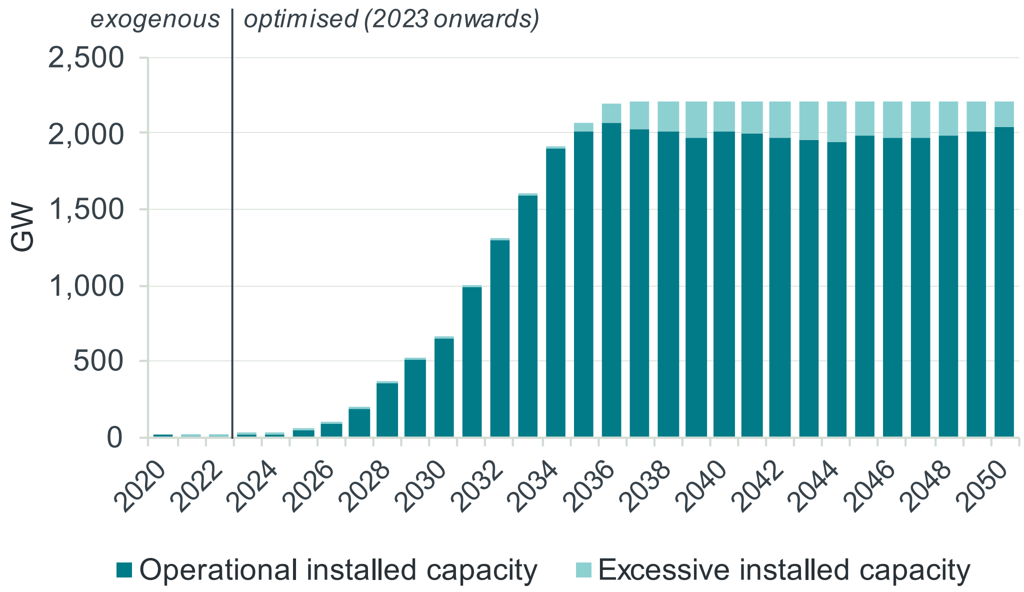
Minimum GHG - Mixed Technology Scenario

PRIMARY RENEWABLE ENERGY DEMAND (WTW) BY POWERTRAIN OVER TIME



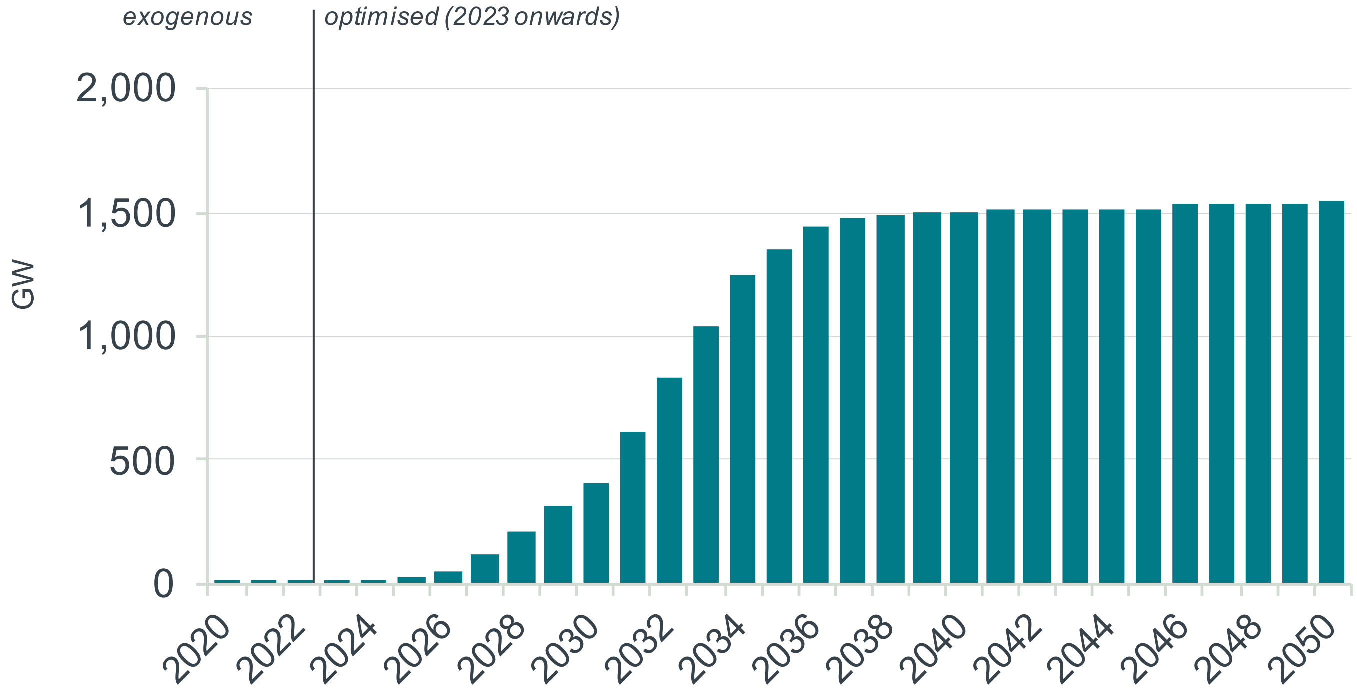
Minimum GHG - Mixed Technology Scenario

INSTALLED RENEWABLE ELECTRICITY GENERATION CAPACITY OVER TIME



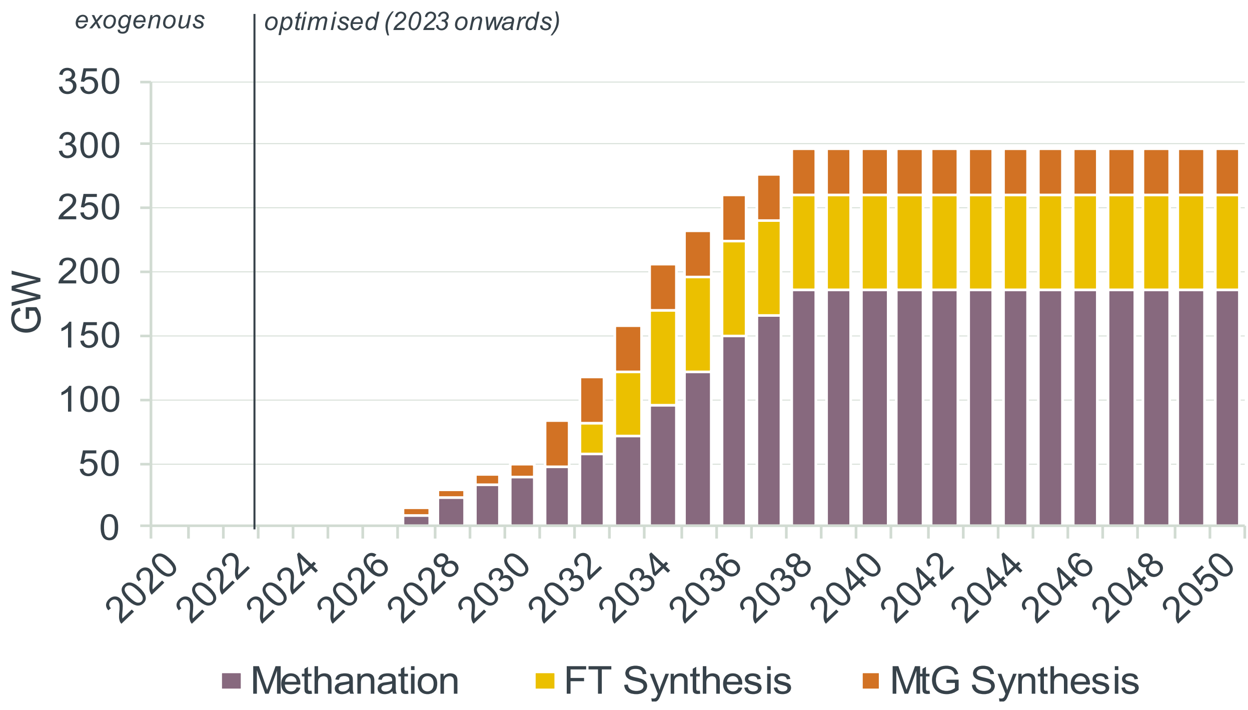
Minimum GHG - Mixed Technology Scenario

INSTALLED ELECTROLYSIS CAPACITY OVER TIME



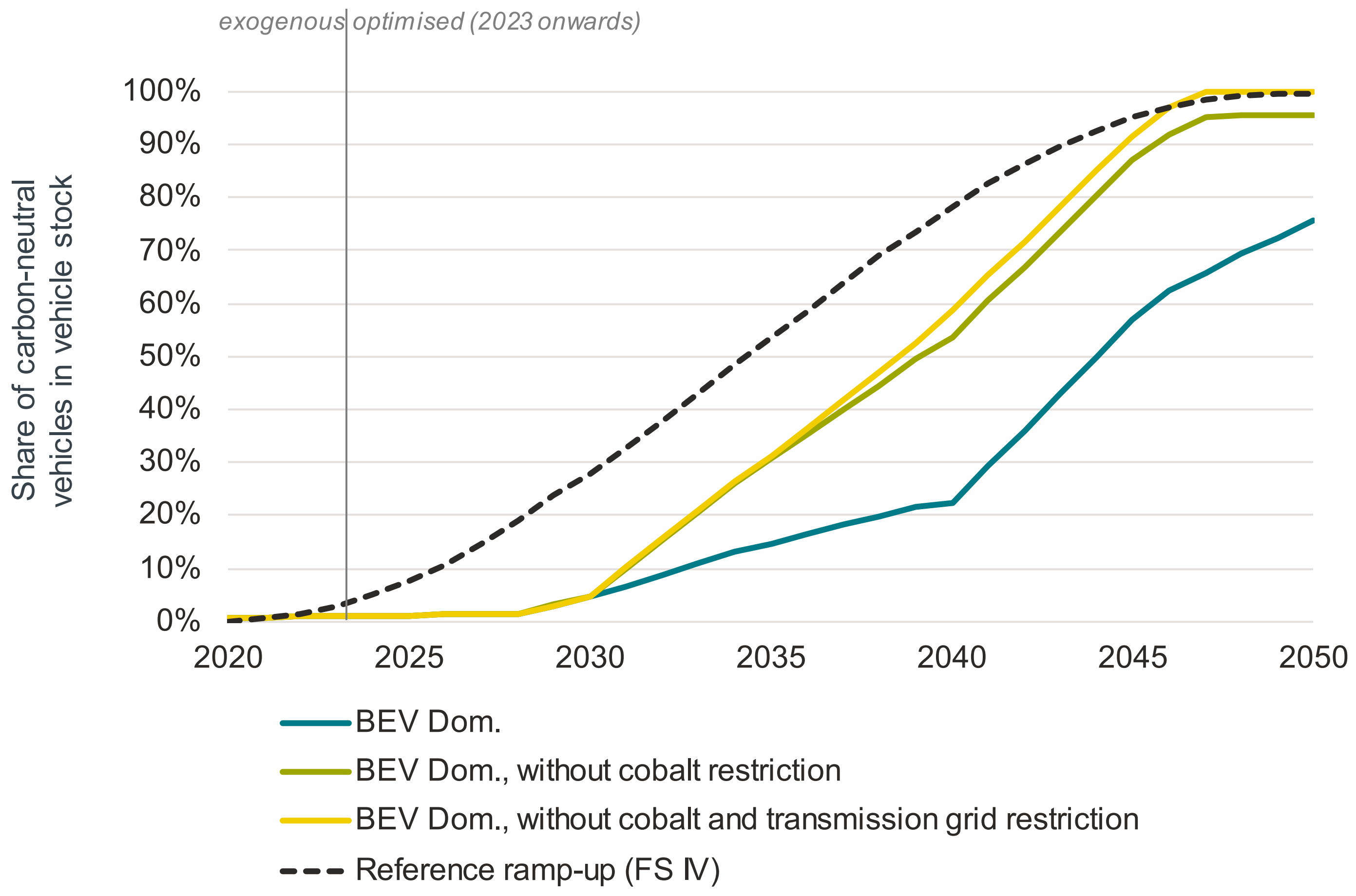
Minimum GHG - Mixed Technology Scenario

INSTALLED SYNTHESIS CAPACITY OVER TIME



Sensitivity Analysis 1, Single Technology BEV: Carbon Neutral Vehicle Share

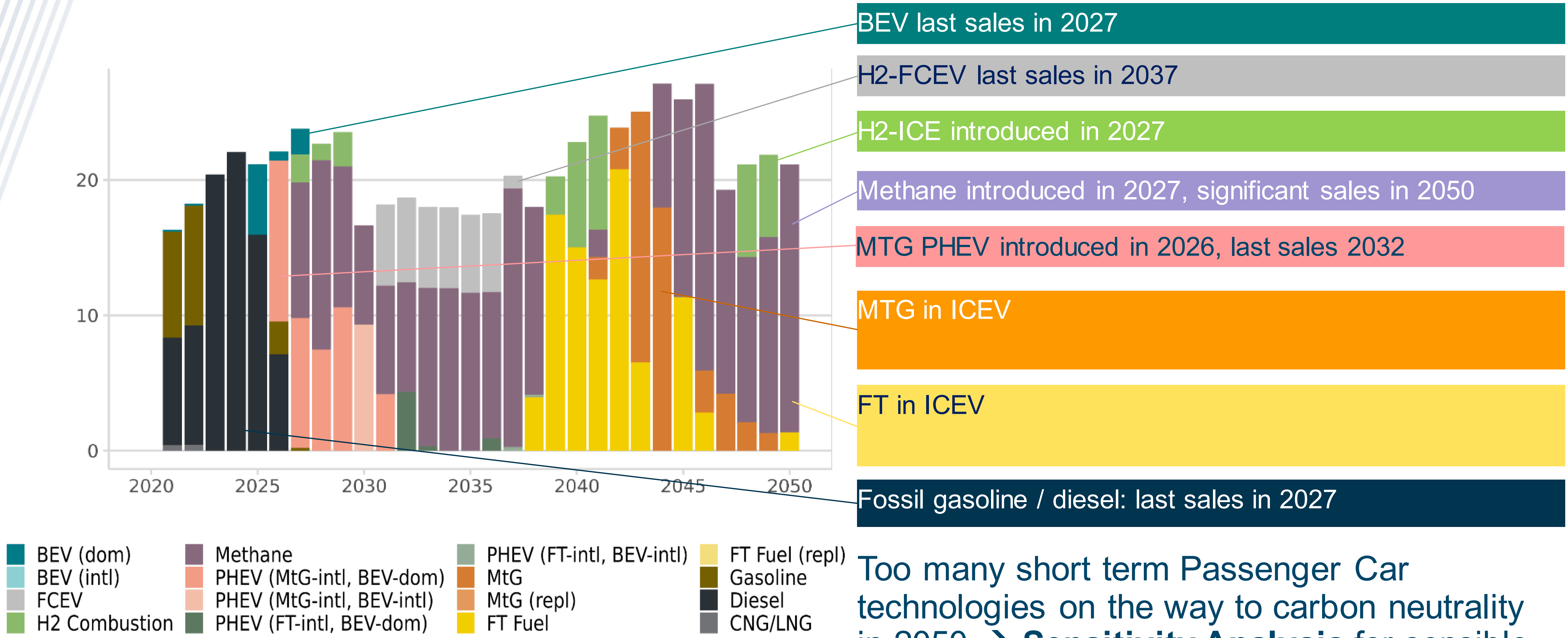
UNRESTRICTED COBALT AND POWER TRANSMISSION GRID AVAILABILITY



- Without cobalt restriction: accelerated BEV ramp-up, not achieving carbon neutrality in 2050
- Without cobalt & grid restriction: Single Tech. BEV ramp-up still below reference ramp-up

Minimum GHG - Mixed Technology Scenario

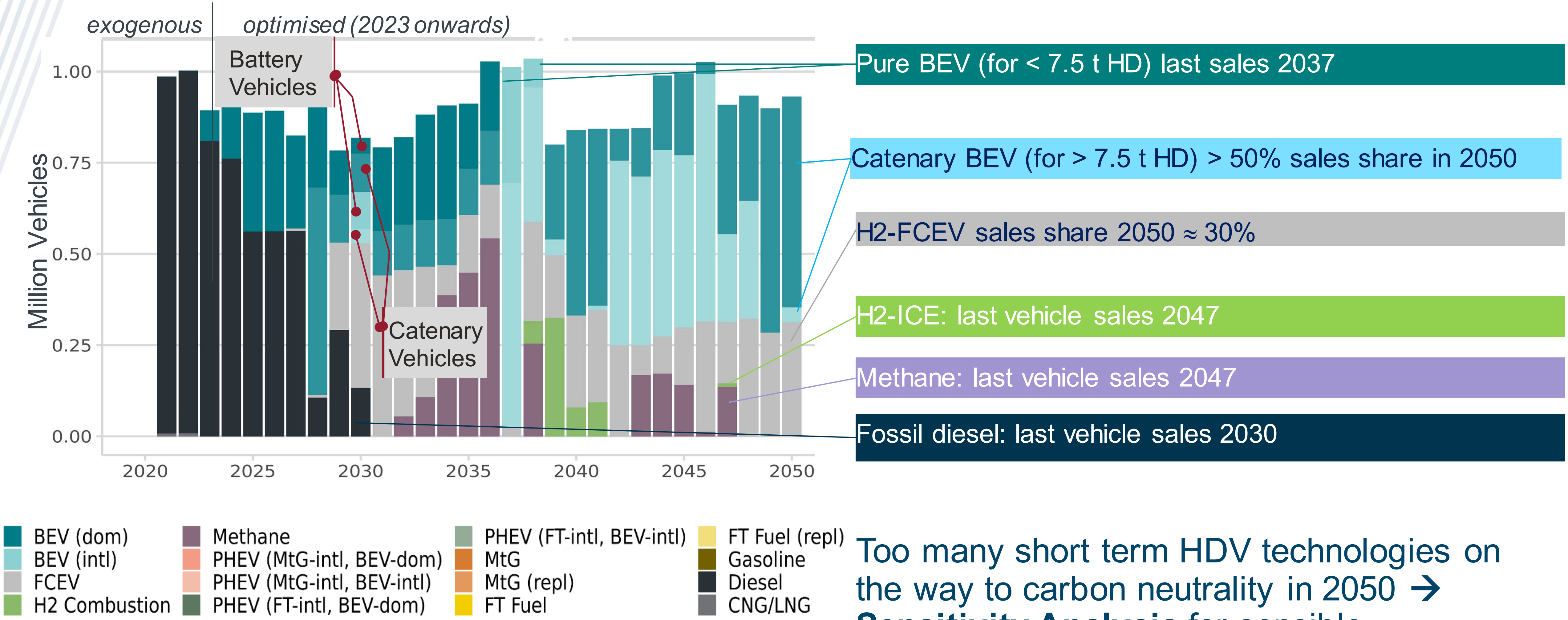
FLEET DEVELOPMENT (**NEW REGISTRATIONS**) – PASSENGER CARS



Too many short term Passenger Car technologies on the way to carbon neutrality in 2050 → **Sensitivity Analysis** for sensible technology reduction

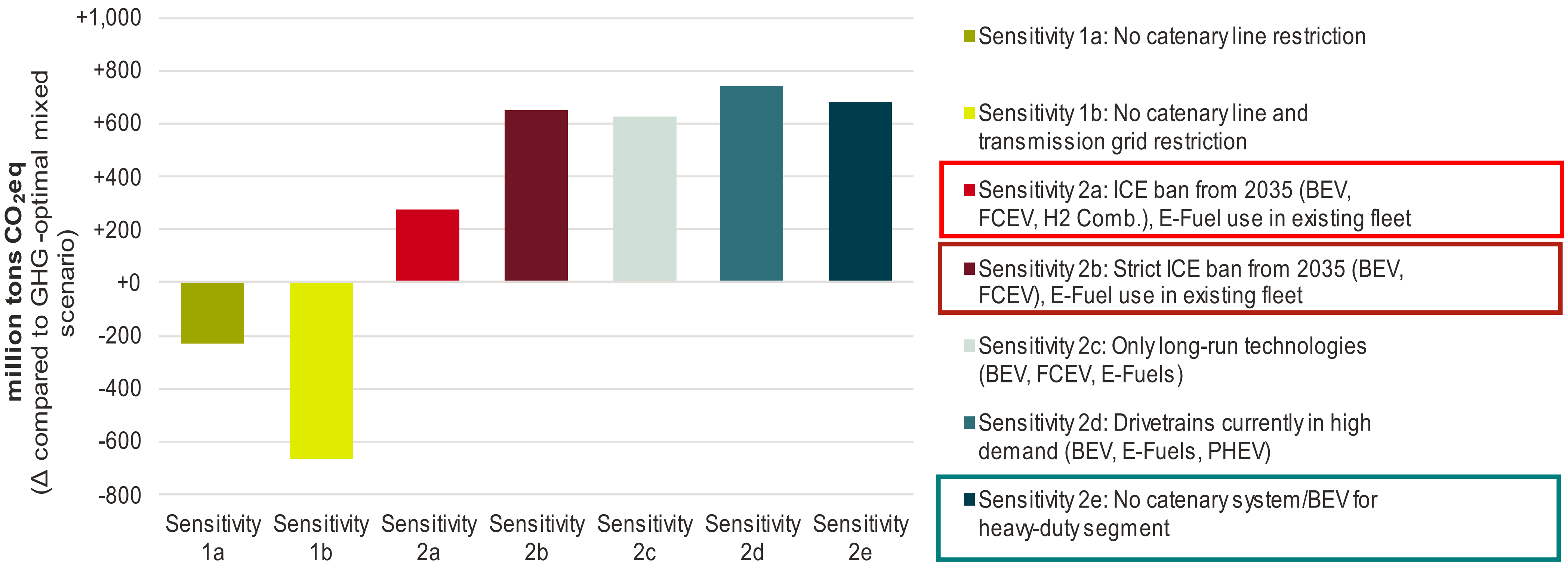
Minimum GHG - Mixed Technology Scenario

FLEET DEVELOPMENT (**NEW REGISTRATIONS**) – HEAVY DUTY



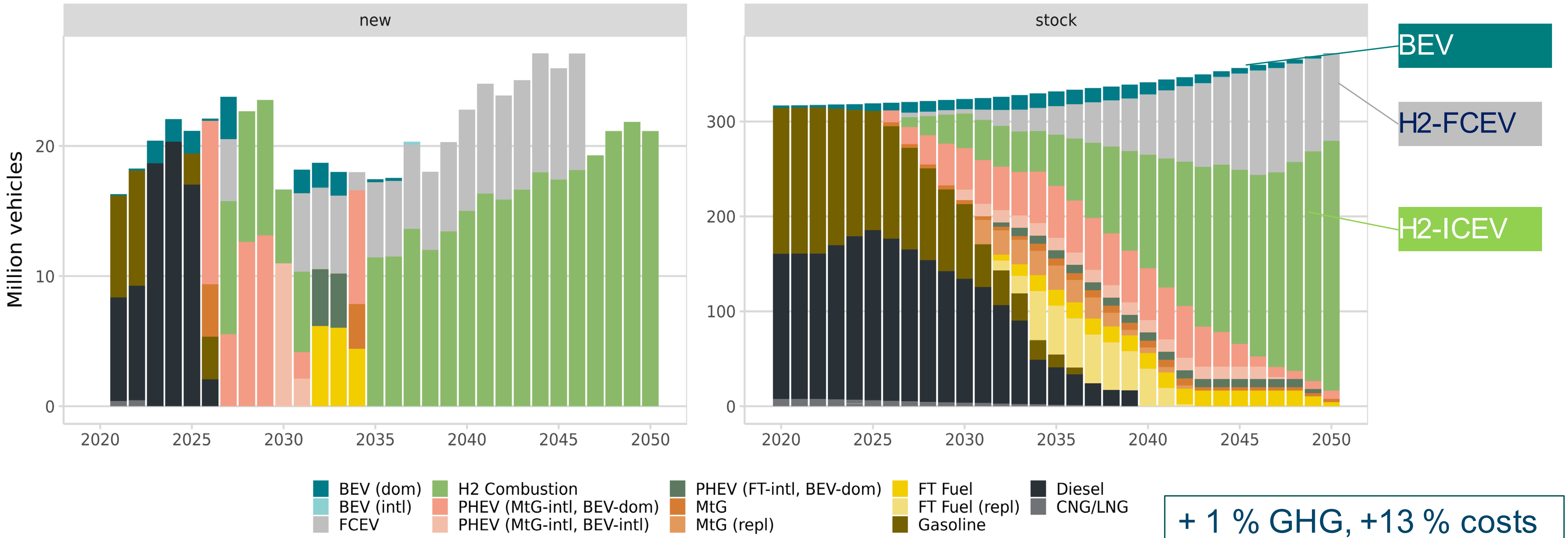
Too many short term HDV technologies on the way to carbon neutrality in 2050 → **Sensitivity Analysis** for sensible technology reduction

Sensitivity Analysis - Cumulated GHG vs. GHG-optimal mixed scenario



Sensitivity Analysis 2a - **ICE ban** from 2035 (**H2-ICE allowed**)

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **PASSENGER CARS ONLY**

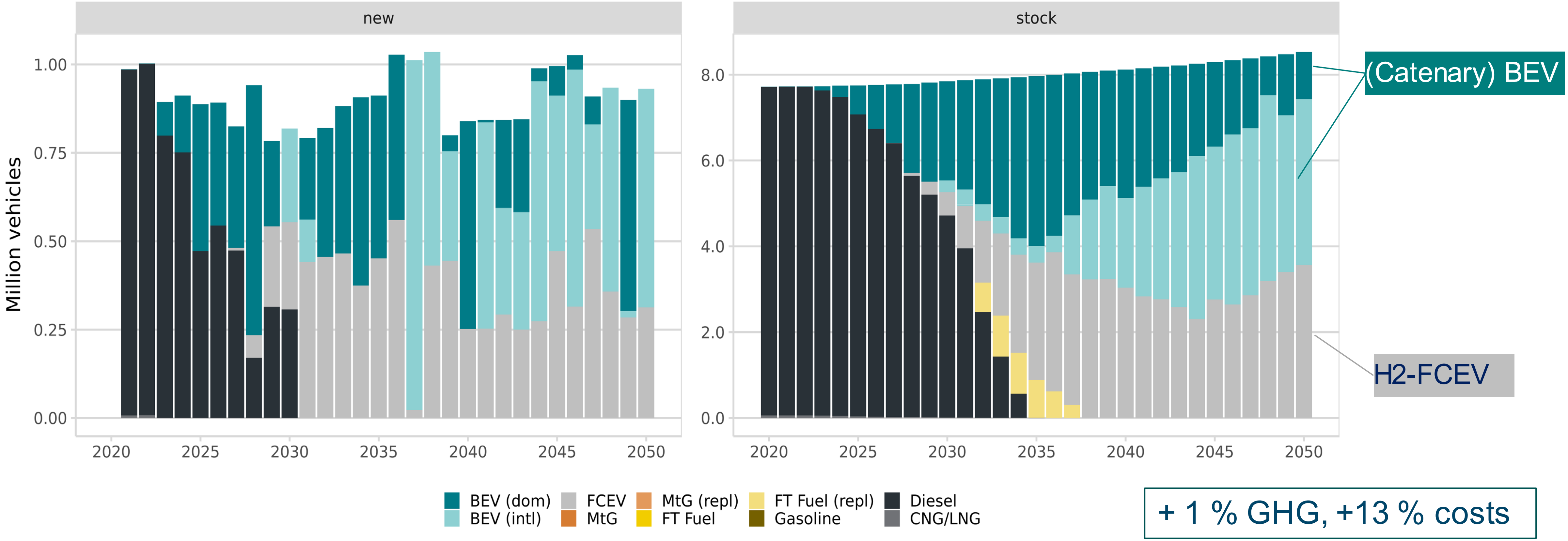


+ 1 % GHG, +13 % costs

- Min. GHG mainly achieved with H2-ICE as dominating pathway for PasCars in 2050
- Smaller share of PasCar FCEV in 2050

Sensitivity Analysis 2a - **ICE ban** from 2035 (**H2-ICE allowed**)

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

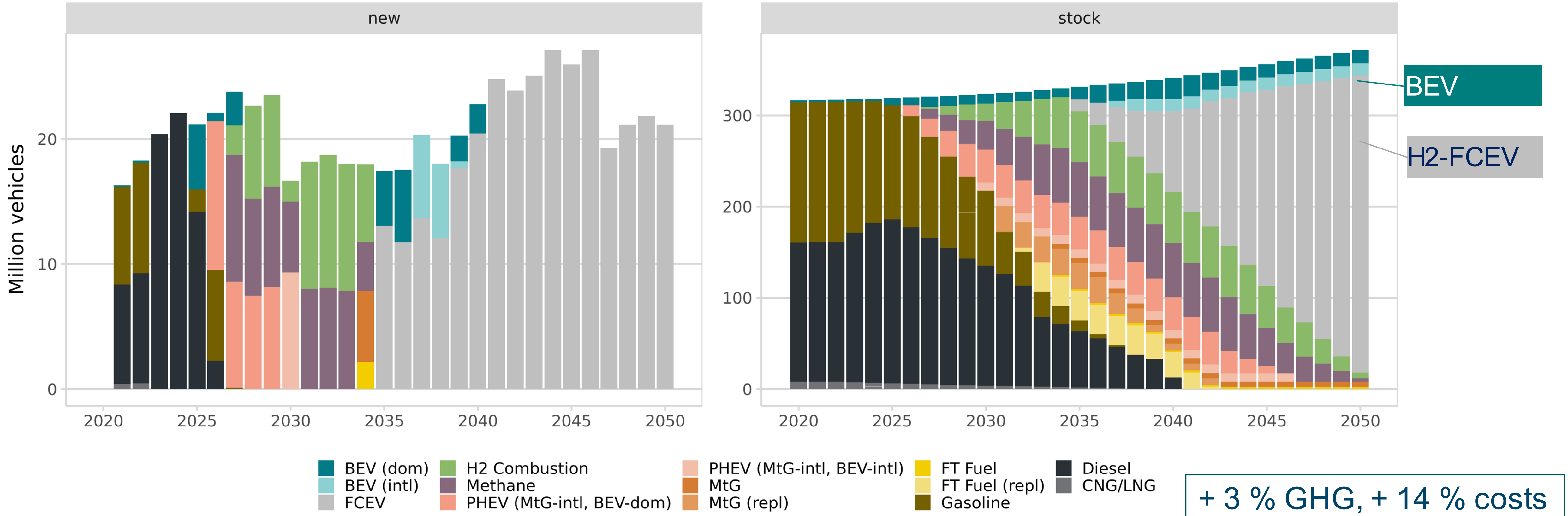


+ 1 % GHG, +13 % costs

- Min. GHG for HDV achieved with (Catenary) BEV and FCEV

Sensitivity Analysis 2b – **Strict ICE ban** from 2035 (**H2-ICE also banned)**

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **PASSENGER CARS ONLY**

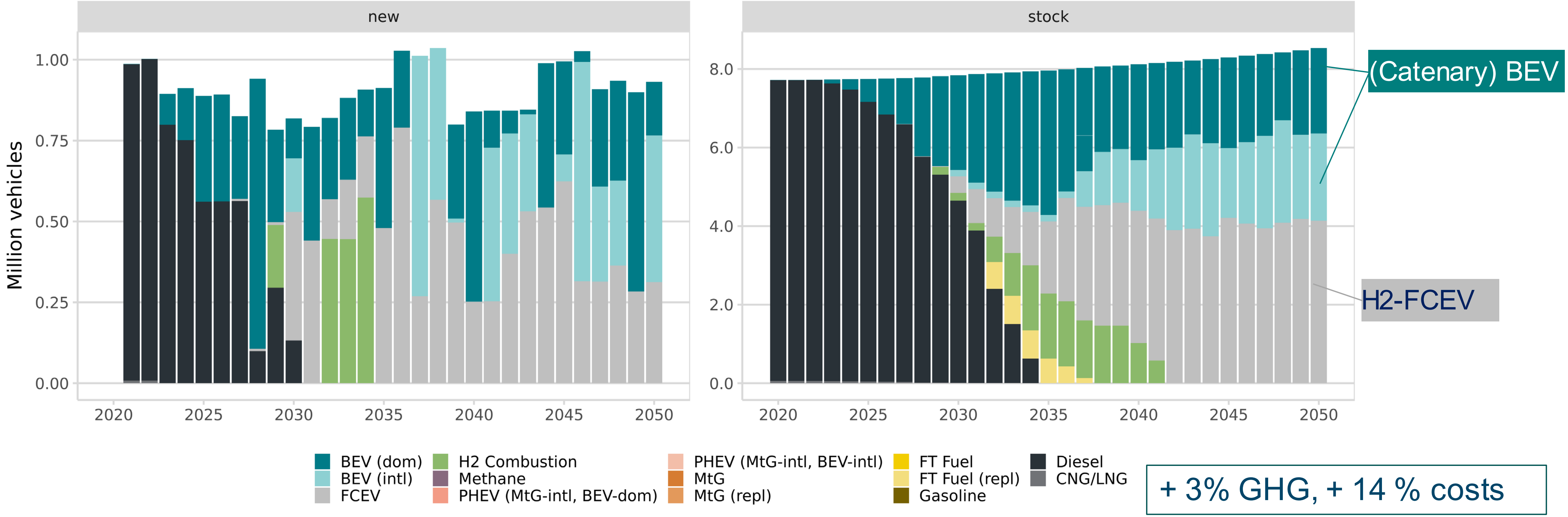


+ 3 % GHG, + 14 % costs

- Min. GHG achieved with H2-FCEV as dominating pathway by 2050
- Small share of BEV (outphasing) for PasCar 2050

Sensitivity Analysis 2b – **Strict ICE ban** from 2035 (**H2-ICE also banned)**

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

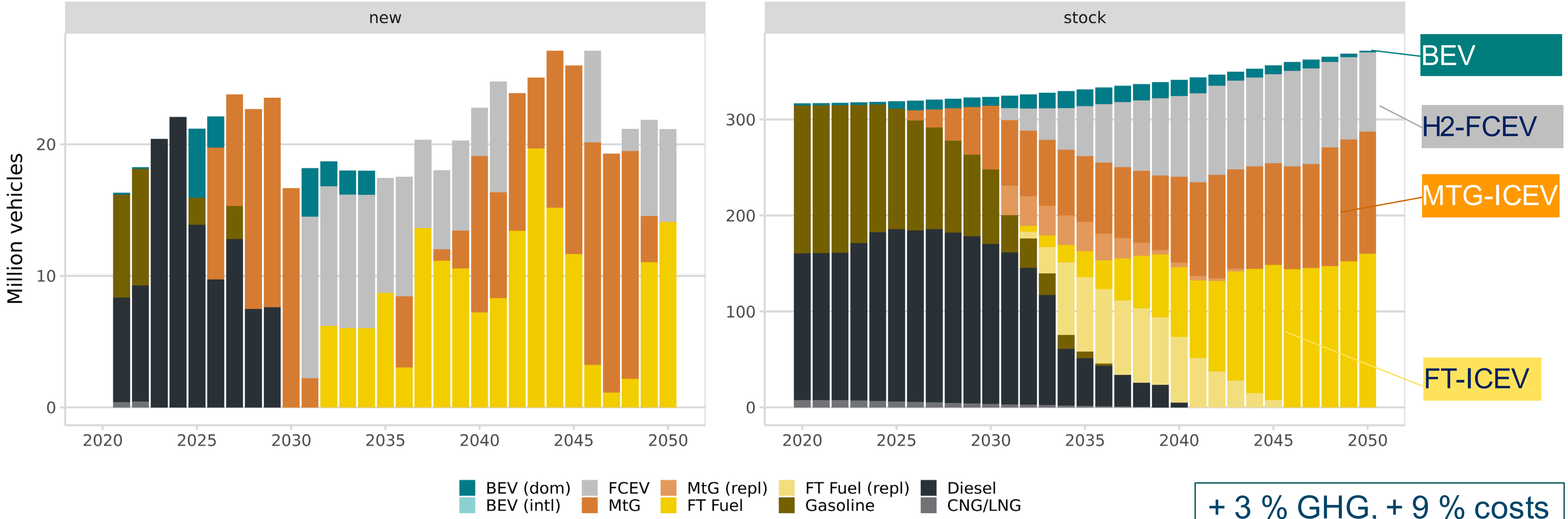


+ 3% GHG, + 14 % costs

- HDV: Min. GHG achieved with H2-FCEV and (Catenary) BEV by 2050

Sensitivity Analysis 2c – Long-run technologies (BEV, FCEV, FT, MtG)

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **PASSENGER CARS ONLY**

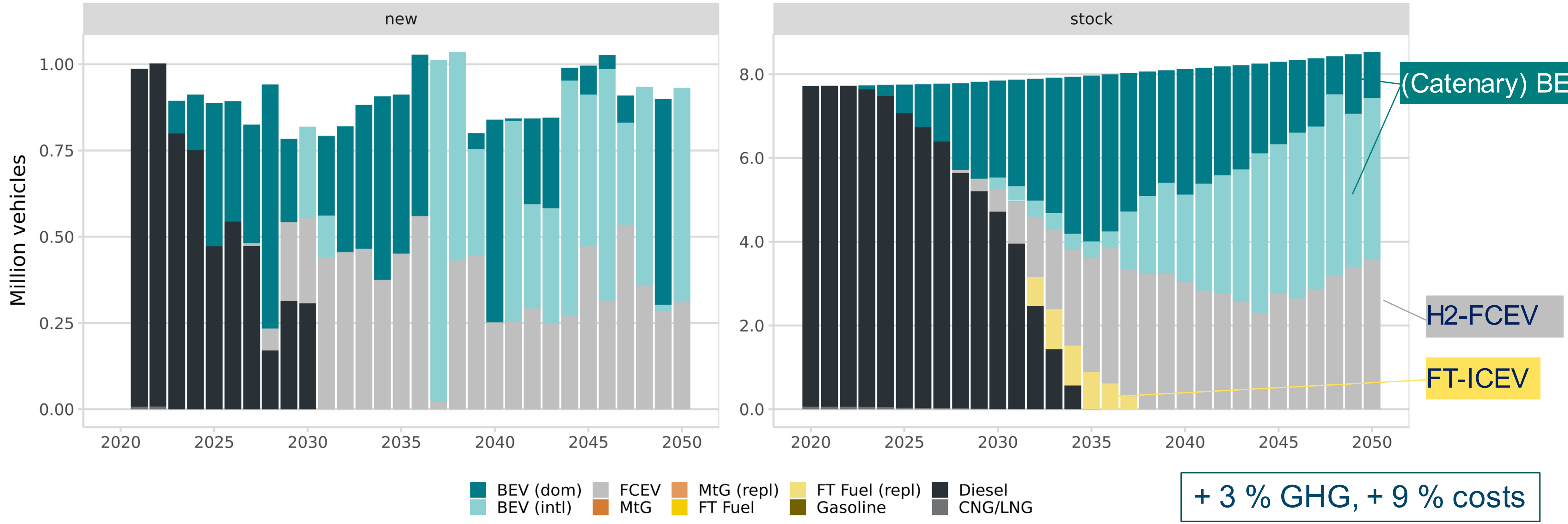


+ 3 % GHG, + 9 % costs

- Dominating PasCar pathways 2050: H2-FCEV, MtG, FT
- BEV phasing out in 2050

Sensitivity Analysis 2c – Long-run technologies (BEV, FCEV, FT, MtG)

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

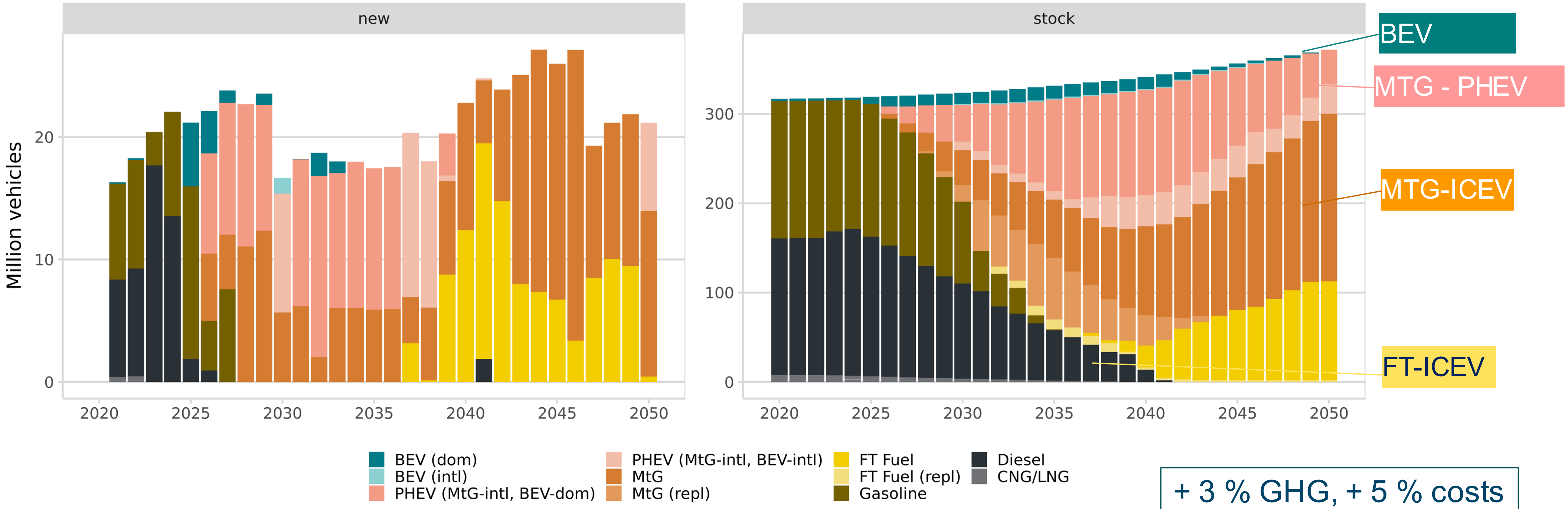


+ 3 % GHG, + 9 % costs

- HDVs 2050: Min. GHG achieved with H2-FCEV, and (Catenary) BEV

Sensitivity Analysis 2d – Highly demanded PT today (BEV, PHEV, FT, MtG)

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **PASSENGER CARS ONLY**

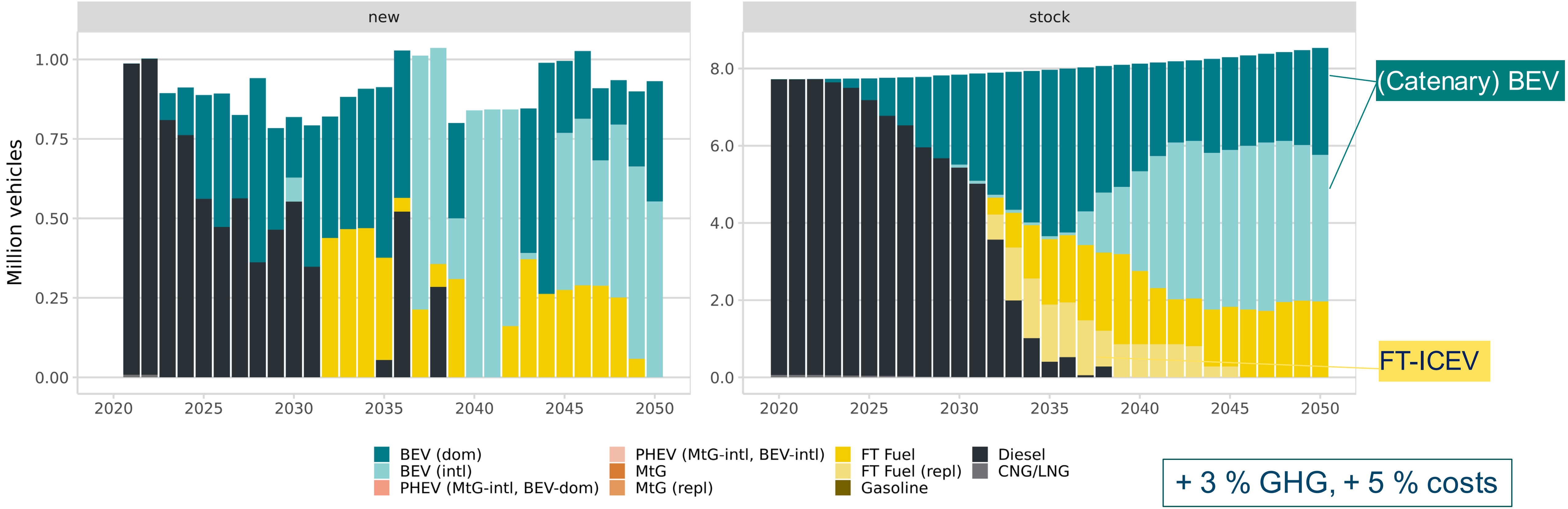


+ 3 % GHG, + 5 % costs

- HDVs 2050: Min. GHG achieved with MtG-ICEV, FT-ICEV, MtG-PHEV
- BEV phasing out by 2050

Sensitivity Analysis 2d – Highly demanded PT today (BEV, PHEV, FT, MtG)

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

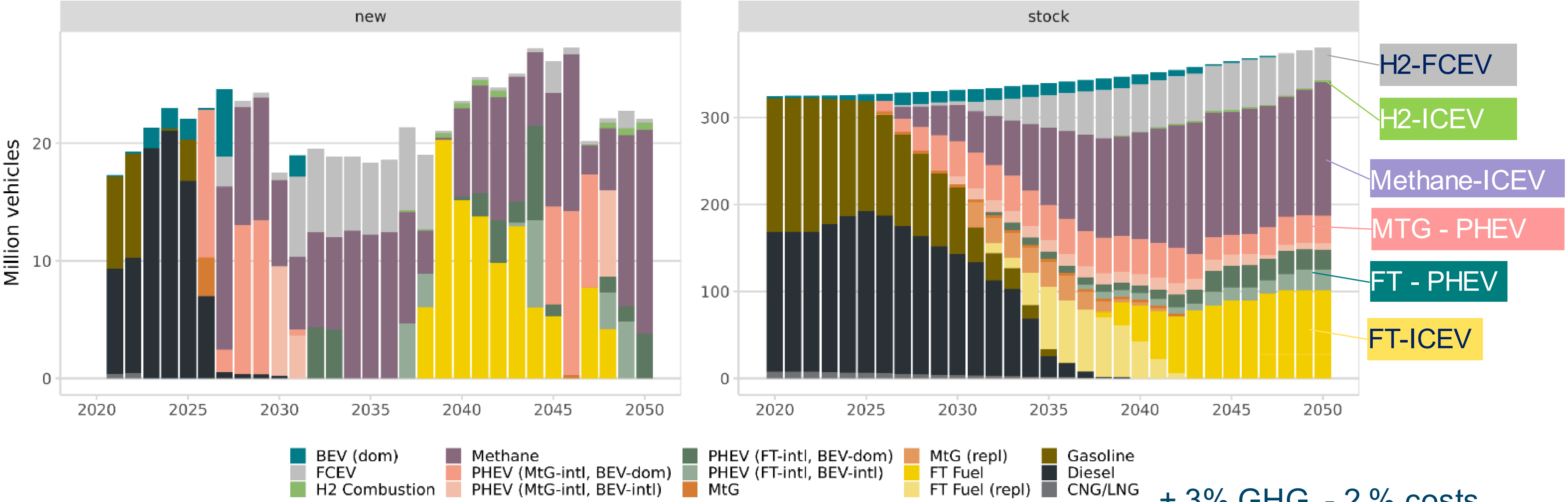


+ 3 % GHG, + 5 % costs

- HDVs 2050: Min. GHG achieved with (Catenary) BEV and FT-ICEV

Sensitivity Analysis 2e – No catenary system/BEV for heavy-duty

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **ALL VEHICLE SEGMENTS COMBINED**

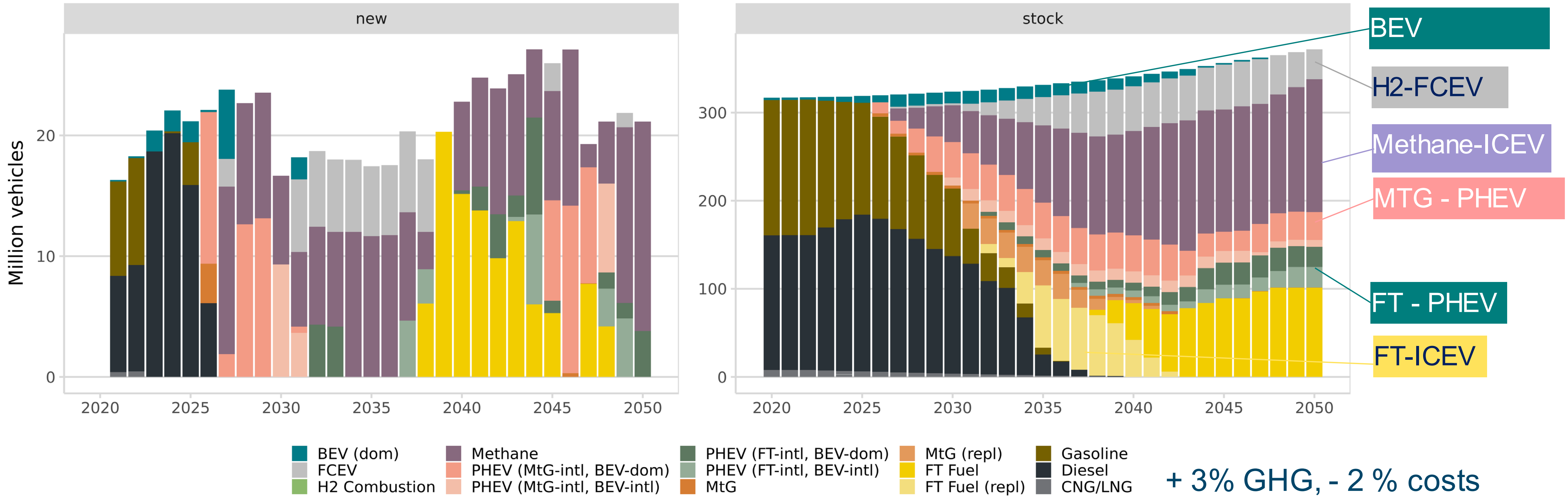


+ 3% GHG, - 2 % costs

- Min. GHG achieved with Methane ICEV, FT ICEV & FT-MTG-PHEV rising by 2050
- Detailed effect on HDVs? → next slide

Sensitivity Analysis 2e – No catenary system/BEV for heavy-duty

NEW VEHICLE REGISTRATIONS (LEFT) AND VEHICLE STOCK (RIGHT) BY POWERTRAIN, **PASSENGER CARS ONLY**

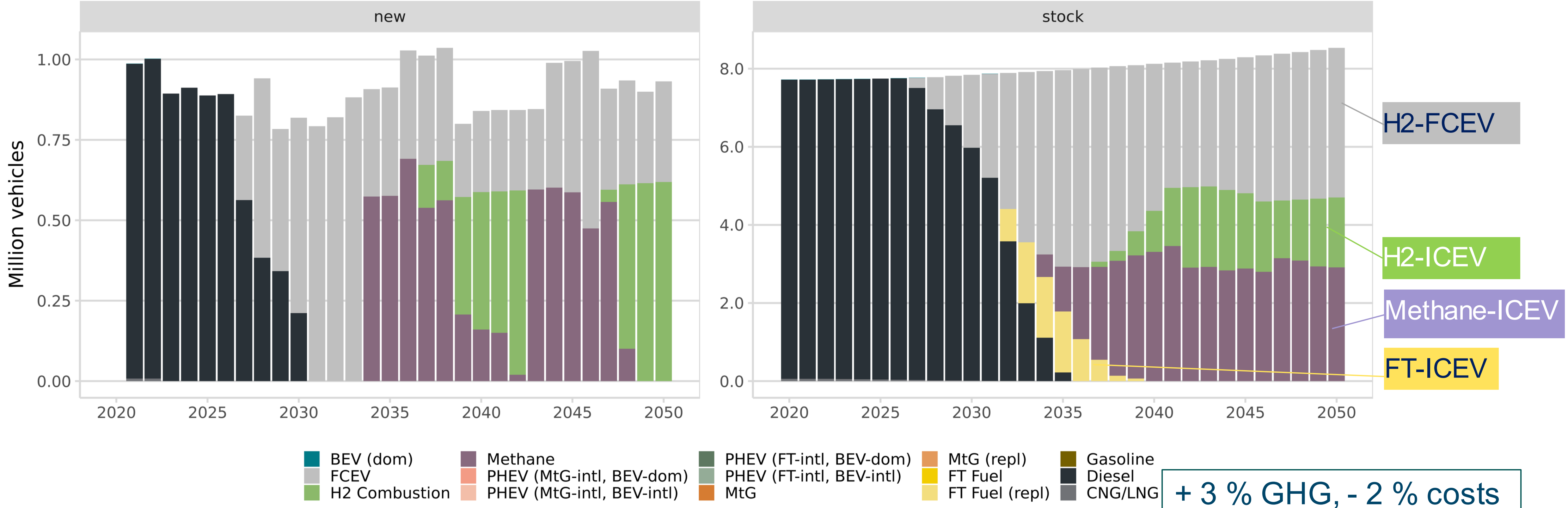


+ 3% GHG, - 2 % costs

- PasCars / LDV 2050: bunch of technologies in 2050:
- H2-FCEV, Methane-ICEV, MtG-PHEV, FT-ICEV, FT-PHEV

Sensitivity Analysis 2e – No catenary system/BEV for heavy-duty

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

FVV Fuels Study IV - Simulation Basis – Road & Other Transport Sectors

BOTTOM-UP APPROACH (FLEET COMPOSITION) FOR ROAD TRANSPORT

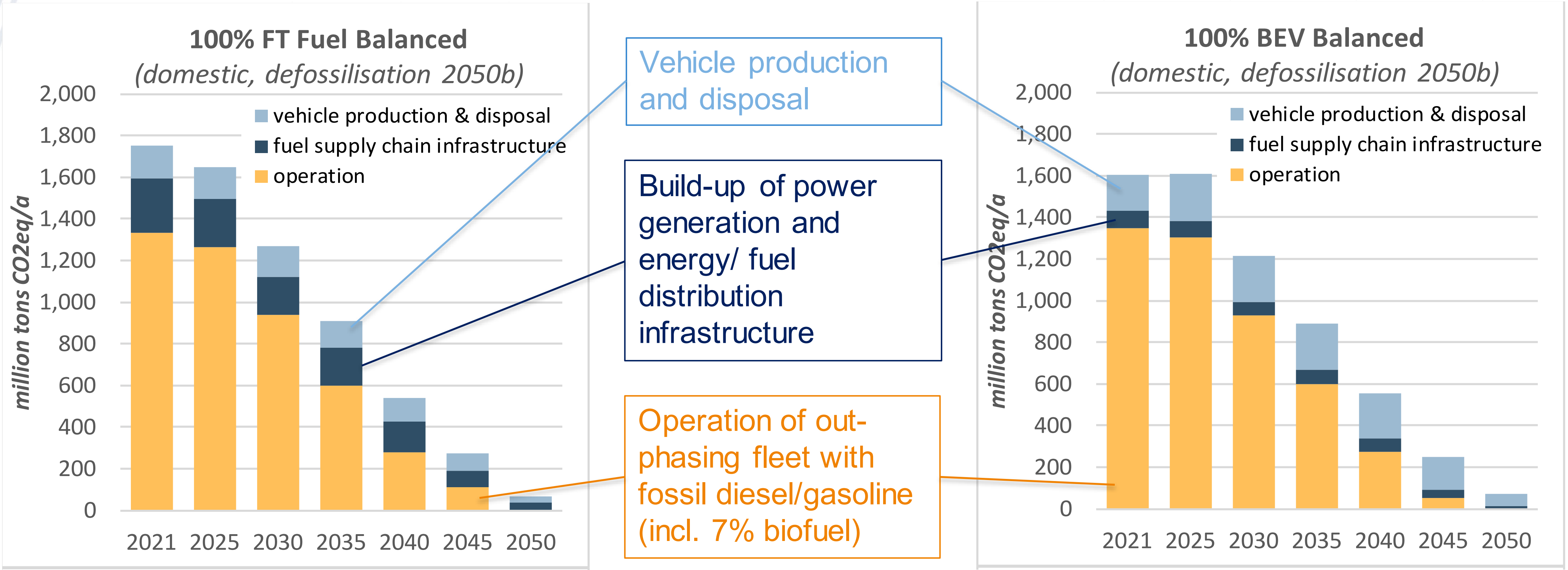
Example BEV

Technology Pathways – 100% **Electric** Scenario			
	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 ✓
	Bus	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**

FVV FS IV: Environmental impacts analysis

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

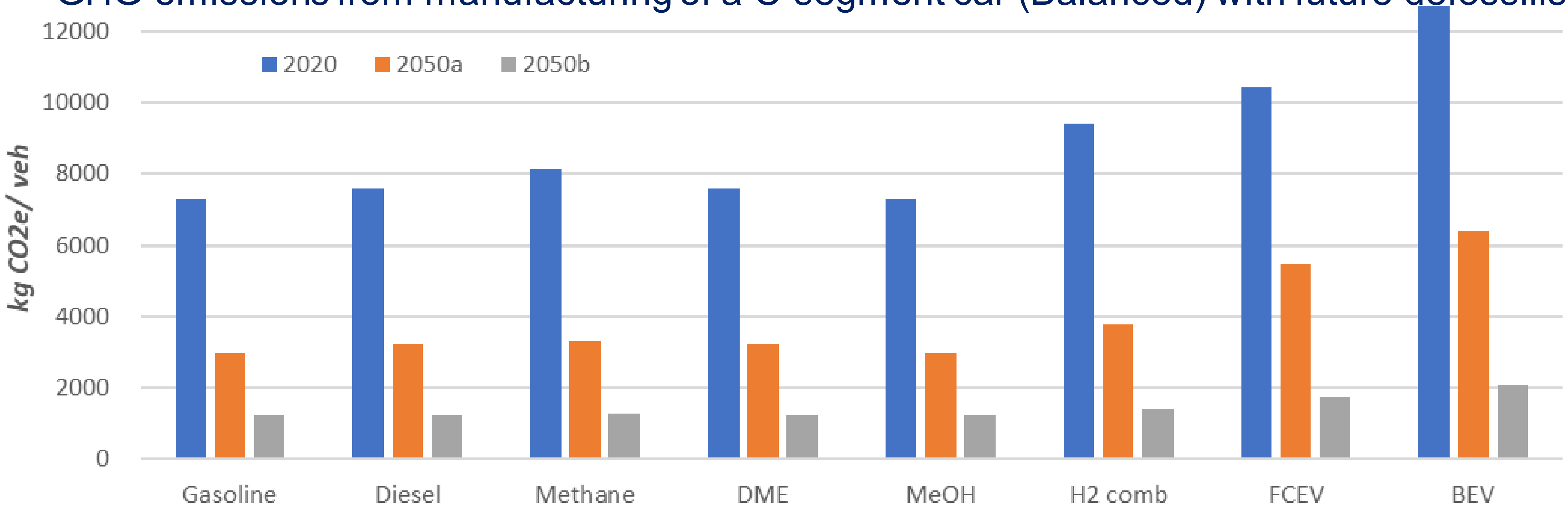


- Annual GHG emissions in the year 2050 are in all fuel pathways 95-97% lower than in 2020*
- Vehicle operation of out-phasing fleet with **fossil fuels dominates annual GHG emissions until ≈ 2040** for all pathways

FVV FS IV: Environmental impacts analysis

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.

* only unavoidable GHG emissions left

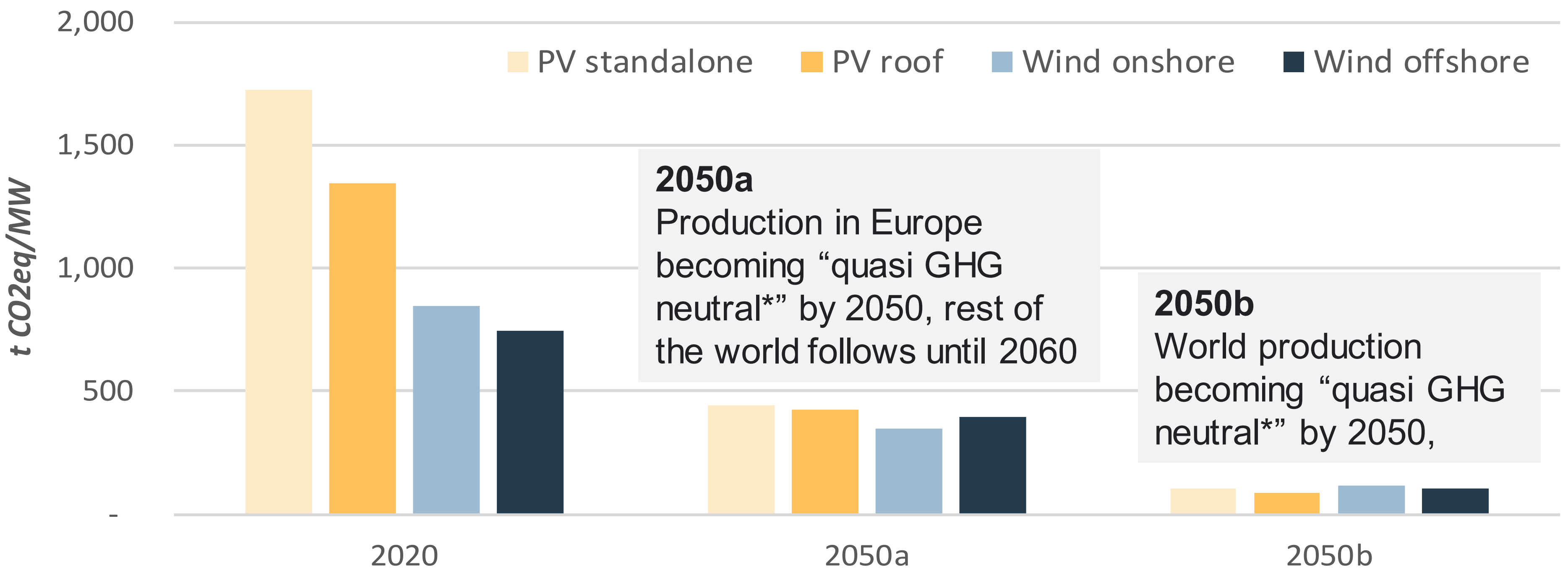
2050a
Production in Europe becoming “quasi GHG neutral*” by 2050, rest of the world follows until 2060

2050b
World production becoming “quasi GHG neutral*” by 2050

FVV FS IV: Environmental impacts analysis

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.