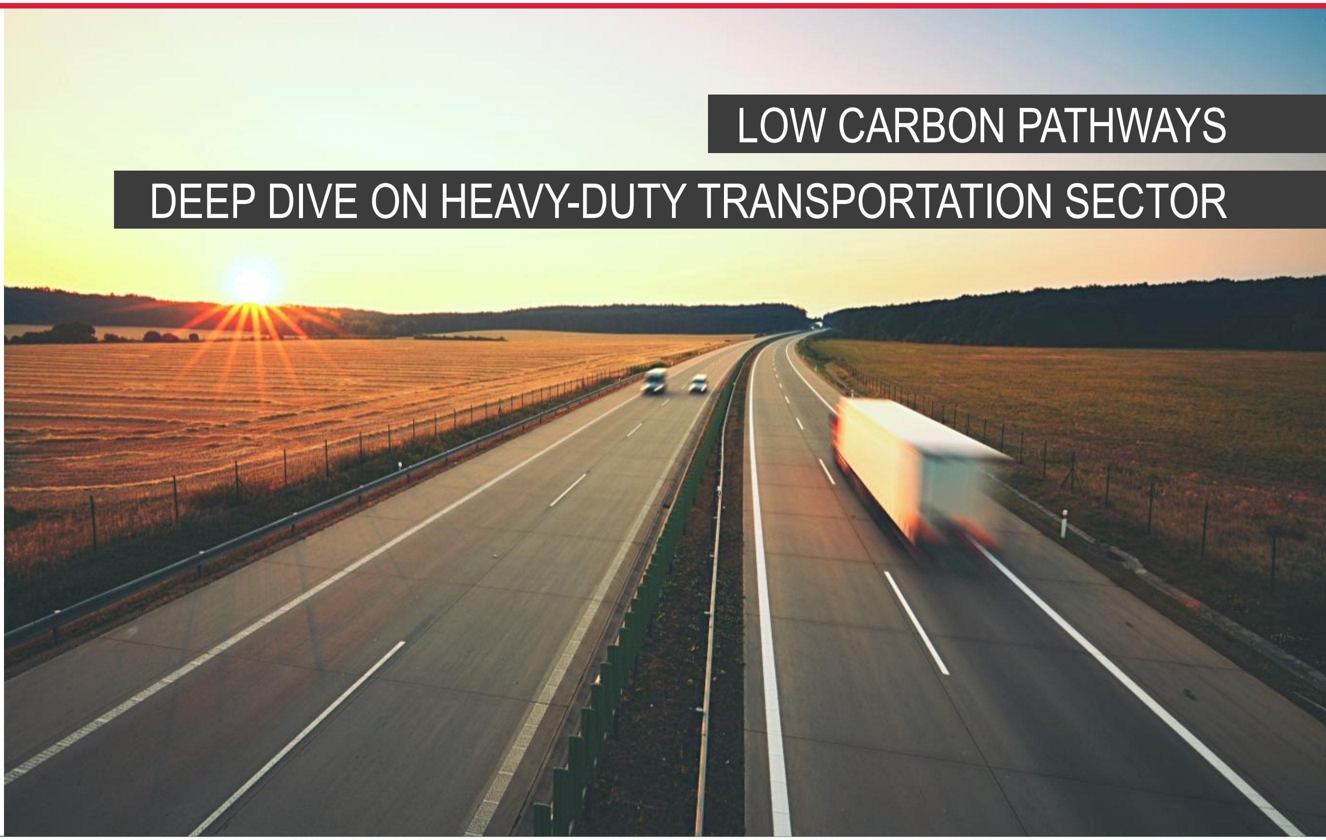
Revised final meeting presentation

Prepared for

Concawe



LOW CARBON PATHWAYS

DEEP DIVE ON HEAVY-DUTY TRANSPORTATION SECTOR

Aachen, 28th of June 2019
FEV Consulting GmbH

Agenda

- Executive summary
- Framework and long-term scenarios for HD on-road transportation
- Technology options towards 2050
- Future pathways towards clean on-road transportation
- Reduced GHG emissions with holistic technology strategies
- CO_2 abatement costs for selected reference trucks
- TCO performance of underlying reference trucks
- Life-cycle analysis for HD trucks

CO_2 emission reduction of heavy-duty trucks by 80% requires serious actions of authorities, operators, OEMs and energy companies

EXECUTIVE SUMMARY

- FEV's analysis of low carbon pathways in the EU transportation sector shows that **CO_2 reduction targets of 80%** and above (vs. 1990) **can be achieved**; high efforts of regulatory bodies, logistics companies, OEMs, energy producers and providers are required
- **Authorities** should involve all key stakeholders and (jointly) **define long-term boundary conditions** driving infrastructural investments and technology decisions (e.g. well-to-wheel vs. tank-to-wheel; CO_2 based taxation; standards for e-fuel / blends)
- **Logistics companies, operators** and **technology providers** should enable efficient solutions of transportation resulting in **increased utilization of trucks**; a holistic approach is the baseline to counteract implications of growing freight demand throughout 2050
- **OEMs** should develop and implement **efficient glider and powertrain technologies**: aerodynamics, weight and rolling resistance reduction and automation on glider side; efficient ICEs (incl. hybridization), battery electric and fuel cell solutions on powertrain side
- The **energy sector** should invest into **scaling up production** of electricity, gaseous and liquid fuels from **renewables** as well as into the underlying infrastructure; this incudes not only the **electric grid** but also a **roll-out of hydrogen fueling stations**
- The **scenario analyses 2050** leads to three **common key findings** for the European transportation sector:
  - To achieve the ambitious 80% CO_2 reduction target, a **combination of discussed technology options** is required; additionally, a **high share of energy carriers from renewables** (including gaseous and liquid fuels) is key
  - The strong **interdependency of stakeholders** requires an **aligned strategy** enabling the required shift of the industry
  - The path towards **"near zero" CO_2 emissions** is linked to significant **investments** for all stakeholders

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*: CO_2 reduction based on a Well-to-Wheel balance; **: TCO = Total Cost of Ownership; ***: LCA = Life Cycle Analysis
Source: FEV

High market shares of electric and hydrogen powered vehicles, combined with fuels from renewables lead to CO_2 target achievement

EXECUTIVE SUMMARY

- FEV has analyzed **four different scenarios** assessing low carbon pathways in the EU transportation sector
- **Current Policies Scenario**, 7% CO_2 emission reduction* (2050 vs. 1990); announced policies until today are carried forward until 2050; no further tightening is considered
  - Energy demand 2050 is reduced by 13% and mostly covered by liquid fuels from fossils (80%); renewables play a minor role
- **Balanced Energy Carriers Scenario**, 80% CO_2 emission reduction* (2050 vs. 1990); electrification for heavy-duty vehicles occurs for selected use-cases, efficiency measures will be introduced at the current pace and fuels from renewables ensure to reach the ambition
  - Energy demand shrinks by ~25%, driven by a wide roll-out of efficient gliders and powertrains; ~70% of energy demand will be covered by gaseous (mostly hydrogen) and liquid fuels from renewables; Diesel-type fuels from fossils account for ~20%
- **Accelerated Transformation Scenario**, 80% CO_2 emission reduction* (2050 vs. 1990); developments in automation and battery technology happen quicker: higher energy densities and charging power come at lower cost, the infrastructure is built-up rapidly
  - Energy demand shrinks by ~37%, driven by the high penetration of efficient electric powertrains; ~50% of energy demand will be provided by gaseous and liquid fuels from renewables; Diesel-type fuels from fossils account for ~23%
- **Approaching Zero Scenario**, 95% CO_2 emission reduction* (2050 vs. 1990); the industry develops corresponding to the balanced energy carriers scenario but to achieve the target an even stronger focus on e-fuels is assumed
  - Energy demand shrinks by ~25% as in the Balanced Energy Carriers Scenario; ~90% of energy demand will be provided by gaseous and liquid fuels from renewables; Diesel-type fuels from fossils account for only ~5%
- The **LCA** (focus: powertrain) shows that “usage” accounts for 90% or more of the CO_2 footprint for conventional or fuel cell electric powertrains; the “usage” share for BEVs is lower due to the battery (high CO_2 impact of production); values range between ~70-80%

*: Defined targets and mentioned CO_2 emission reduction performance is based on an extended tank-to-wheel balance; details for the well-to-wheel analysis are shown in the report
Source: FEV

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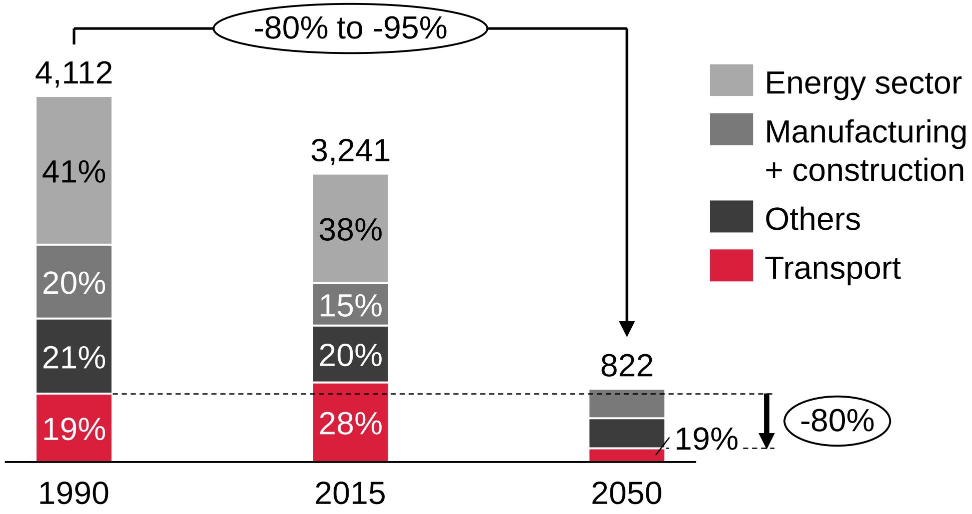
The EU aims to cut the greenhouse gas emissions by at least 80% by 2050 compared to 1990; transport sector emissions are to be cut accordingly

EUROPEAN COMMISSION GREENHOUSE GAS REDUCTION AMBITIONS FOR 2050

CO_2 emissions in the EU in million tons



Overall 20% reduction compared to 1990

*In Transportation increase by **17%***

- It is the ambition of the EU to cut the total anthropogenic greenhouse gas emissions by at least 80% by 2050 compared to 1990
- The energy sector needs to go down to zero net emissions by 2050
  - Therefore we consider additional energy to be produced from renewable sources
- The transport sector needs to cut its greenhouse gas emissions by 80% by 2050, compared to 1990
- Main focus of the project is to understand the potentials to achieve the defined CO_2 reduction targets for the HD CV sector, assuming evolutions in
  - **Usage** (future of transport and logistics)
  - **Electrification** (opportunities to electrify the CV segment)
  - **Efficiency** (opportunities to increase the efficiency of vehicles, incl. powertrain)
  - **Energy carriers** (opportunities of blends, e-fuels, etc.)

Source: European Commission, FEV

The provisional regulation, on which the Parliament and the Council agreed on, is largely based on the last proposal from the Council

AGREED REGULATION

	Provisional agreement
Proposal's date	19th February 2019
Scope / metric	As highlighted in shown slides (subject to revision in 2022)
Regulation target	2025: 15% CO_2 lower emissions than 2019 baseline 2030: 30% CO_2 lower emissions than 2019 baseline (subject to revision in 2022)
Penalties	2025: 4,250 €/g_{CO2} /tkm 2030: 6,800 €/g_{CO2} /tkm
ZLEVs' definition and incentives	■ ZEV: < 1 g_{CO2} /km (fixed across sub-groups) ■ LEV: < half the sub-group's reference emissions in g_{CO2} /km (varying across sub-groups) ■ Accounting system: – Until 2024: Super-credits system **(bonus only),** – 2025+: benchmark system **(bonus only, no malus)** starting from a minimum quota ■ Directly impacting the final CO_2/tkm amount for each manufacturer, up to 3% reduction ■ Vehicles included: all CV >3.5 tons, **incl. vocational, excl. buses, coaches;** unregulated categories can account for maximum 1.5% (included in the overall maximum of 3%) ■ Benchmark quotas: – 2025: 2% of newly registered heavy-duty trucks – 2030: to be discussed in 2022
Miscellaneous	■ Post-2030 targets to be proposed during 2022 revision ■ Data will be obtained also through on-board devices, which monitor the actual fuel and energy consumption of heavy-duty vehicles ■ Up 2-tonnes additional weight allowance for zero-emissions and alternative fuels trucks ■ Between 2025 and 2029, a banking system is used to account for credits and debts

- The agreement must be firstly approved by the Environment Committee of the European Parliament, and then voted together with the Council
- The formal adoption by the European Council is likely to happen by the end of May

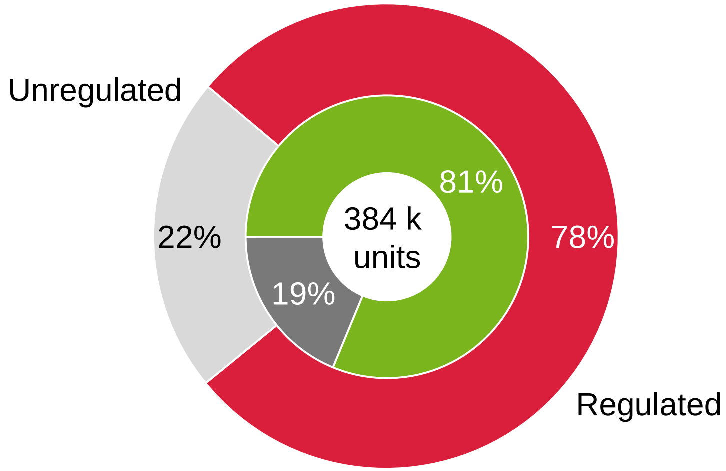
ZLEV: Zero- and Low- Emissions Vehicles
Source: EU, FEV

The actual regulation proposals are taking into account only the main categories of Medium- and Heavy-Commercial Vehicles (MHCV)

Vehicle group	Axle configuration	Chassis	GVW	Included in CO_2 Regulation
0	4x2	Rigid	>3.5, <7.5	Not included*
1		Rigid (or tractor)	7.5 – 10	
2		Rigid (or tractor)	>10, 12	
3		Rigid (or tractor)	>12, 16	
4	4x2	Rigid	>16	Included
5		Tractor	>16	
6	4x4	Rigid	7.5 - 16	Not included*
7		Rigid	>16	
8		Tractor	>16	
9	6x2	Rigid	All	Included
10		Tractor	All	
11	6x4	Rigid	All	Not included*
12		Tractor	All	
13	6x6	Rigid	All	
14		Tractor	All	
15	8x2	Rigid	All	
16	8x4	Rigid	All	
17	8x6, 8x8	Rigid	All	

*Subject to revision in 2022
Source: ICCT, EU, FEV

2018 MHCV sales in EU



- All vehicles that are not intended for the delivery of goods are exempted from the regulation:
  - Buses and coaches are excluded
  - Vocational vehicles are excluded
- Manufacturers have to define if a truck is intended for vocational operations or freight transportation*
- Only trucks presenting a 6x2 axle configuration, independently from the GVW (Gross Vehicle Weight), and a 4x2 axle configuration, exceeding 16 tons, are included in the CO_2 emission regulation
- These groups account for approx. 70% of CO_2 emissions from all heavy-duty vehicles in Europe

🟩 Heavy Commercial Vehicles (>16 tons) ⬛ Medium Commercial Vehicles (<16 tons)

In that project FEV looks into the heavy-duty on-road segment and distinguishes long haul and regional haul applications

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MARKET OVERVIEW

Share of heavy-duty use-cases

Regional haul	~ 40% of vehicle sales
Long haul	~ 60% of vehicle sales

Stock

~ 4,100,000 vehicles in 2018

Sales

~ 300,000 vehicles per year

Key facts

Average distance travelled per year	~ 85,000 km
Average age of vehicles in stock	~ 11 years

Source: FEV

Three exemplary long haul use-cases require different trucks and are in operation with different kind of goods and purposes

EXEMPLARY LONG HAUL USE-CASES

Truck	VOLVO FM450	Scania R730	Iveco Stralis 460
Layout	4x2, sleeper cab	6x2, sleeper cab	4x2, sleeper cab
Engine	10.8-liter, 332 kW	16-liter, 537 kW	12.9-liter, 338 kW
Weight	33,000 kg	40,000 kg	33,000 kg
Use-case	GeoDis transports palletized goods for Procter&Gamble in Europe. An exemplary trip is 1,400 km from Euskirchen, Germany to Rome, Italy. The typical payload is 22 ton. On this trip, the truck travels 90% of the time on motorways. The trip is typically performed at two days.	O'Toole is a refrigerated transport company in Ireland. They offer international seafood logistics services. For instance, from their facility located in Dublin Port, they supply major markets in Western Europe, including Milan, Barcelona, Madrid, Hamburg. The trips have different distances between 500 km and 2,500 km. Most of the trips take multiple days.	i-FAST Automotive Logistics is part of the FIAT Group and also distributes Maserati vehicles within Italy and Europe. The trucks typically travel from the production site in Italy to the distribution centers, e.g. in Tychy, Poland. This trip length is 1,300 km long and is typically performed in two days. One trip typically is fully loaded and the other only partially loaded.

Weight refers to the maximum permissible weight of the truck.
Source: FEV; Pictures courtesy of OEMs Volvo, Scania and Iveco

Three exemplary regional haul use-cases are performed with different trucks and in different environments

EXEMPLARY REGIONAL HAUL USE-CASES

			
Truck	Mercedes-Benz Actros 2536L	DAF XF 440 FT	Mercedes-Benz Actros 1842 LS
Layout	6x2, day cab	4x2, day cab	4x2, sleeper cab
Engine	10.6-liter, 265 kW	10.8-liter, 320 kW	12.8-liter, 310 kW
Weight	26,000 kg	33,000 kg	40,000 kg
Use-case	REWE distributes goods from their logistics centers to their stores. For the store in Aachen the trucks travel between Cologne and Aachen, with an average distance of 250 km per day – never more than 400 km. Loading and un-loading is highly time consuming. On one way it is mostly loaded and on one way the utilization is comparably low.	The inner-city distribution of goods in Albert Heijn supermarkets in Amsterdam is carried out partly by GeoDis logistics company. The route is a 90 km roundtrip. It can be done multiple times at a day. Major part of the roundtrip is made in heavily congested conditions. The payload varies during the roundtrip, with typical payloads at 15 t, 9 t and 3 t.	Samskip supplied more than 80,000 bricks from the Netherlands to Scotland for the construction of a new college in Alloa. The bricks were produced in the Netherlands, transported 150 km on-road to Rotterdam, then shipped to Grangemouth in Scotland. From there, the transport went for the last 20 km to the construction site. The examples shows the wide range of mission profiles the trucks accomplish.

Weight refers to the maximum permissible weight of the tractor-trailer combination.
Source: FEV; Pictures courtesy of OEMs MB and DAF

FEV, together with Concawe, defined four different scenarios for 2050; these are the baseline for the analysis

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SET-UP OF FOUR SCENARIOS 2050 FOR THE ANALYSIS

	Name	Description
Scenario 1	Current policies	The policies announced until today are carried forward until 2050 and no further tightening is considered. Technology application and electrification is only introduced as necessary. Considered policies include CO_2 fleet targets, RED II, fuel quality directive, etc.
Scenario 2	Balanced energy carriers	The ambition of 80% CO_2 emission reduction until 2050 compared to 1990 is met and in that time, the world evolves around the tracks we expect currently: Electrification is a hype for light vehicles but for heavy-duty vehicles only a limited number of use-cases is beneficial, efficiency measures will be introduced at the current pace and fuels from renewables ensure to reach the ambition.
Scenario 3	Accelerated transformation	Achieving 80% of CO_2 emission reduction until 2050 compared to 1990 while developments in automated driving and battery technology happen quicker than expected: higher energy densities and charging power come at lower cost and the infrastructure is built-up more rapidly and broader than in the balanced energy carriers scenario – which includes overhead catenary lines.
Scenario 4	Approaching zero	In this scenario the industry develops corresponding to the balanced energy carriers scenario but fulfills an even more challenging ambition of a reduction of CO_2 emissions by 95% in 2050 compared to 1990 from trucks. This can be achieved by scaling fuels from renewables further.

Source: FEV; Concawe

FEV further detailed the scenarios; assumptions are key for expected market penetrations, TCO analysis results and overall findings

DETAILS FOR DEVELOPED SCENARIOS 2050 (1/2)

	Current policies				Balanced energy carriers				Accelerated transformation				Approaching zero			
	2018	2320	2040	2050	2018	2030	2040	2050	2018	2030	2040	2050	2018	2030	2040	2050
Standard diesel price at the pump in €/l	1.20	1.30	1.50	1.70	1.20	1.30	1.50	1.70	1.20	1.35	1.60	2.35	1.20	1.30	1.50	1.70
Diesel from renewables price at the pump in €/l	1.70	1.70	1.60	1.55	1.70	1.30	1.30	1.30	1.70	1.70	1.60	1.55	1.70	1.30	1.30	1.30
Hydrogen price at the pump in €/kg	9.50	8.00	7.50	7.00	9.50	7.00	4.50	3.50	9.50	7.50	6.00	5.00	9.50	7.00	4.50	3.50
Electricity price at household rate in €/kWh	0.20	0.21	0.21	0.21	0.20	0.21	0.21	0.21	0.20	0.21	0.21	0.21	0.20	0.21	0.21	0.21
Electricity price at industry rate in €/kWh	0.11	0.12	0.12	0.12	0.11	0.12	0.12	0.12	0.11	0.12	0.12	0.12	0.11	0.12	0.12	0.12
Electricity price at a slow charger in €/kWh	0.40	0.40	0.30	0.25	0.40	0.35	0.28	0.25	0.40	0.30	0.23	0.15	0.40	0.35	0.28	0.25
Electricity price at a rapid charger in €/kWh	0.90	0.80	0.70	0.60	0.90	0.75	0.40	0.35	0.90	0.70	0.35	0.30	0.90	0.75	0.40	0.35

Source: Worldbank, IEA, OECD, EEA, Eurostat, FEV

FEV further detailed the scenarios; assumptions are key for expected market penetrations, TCO analysis results and overall findings

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DETAILS FOR DEVELOPED SCENARIOS 2050 (2/2)

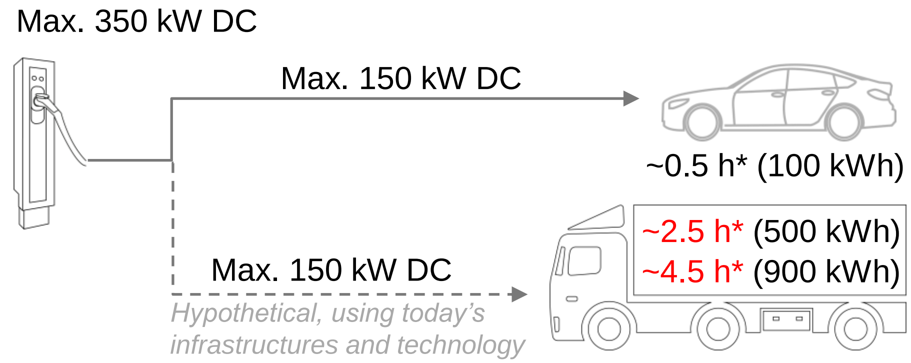
	Current policies	Balanced energy carriers	Accelerated transformation	Approaching zero
	2018 2030 2040 2050	2018 2030 2040 2050	2018 2030 2040 2050	2018 2030 2040 2050
CO_2 emission reduction ambition	None	80% in 2050 compared to 1990	80% in 2050 compared to 1990	95% in 2050 compared to 1990
Freight transport demand, billion ton-km	2018: 5,380; 2050: 7,311; Total Increase = 36%; $CAGR_{2018\text{-}2050}$ ~1%			
Usage of trucks (key points only)	Similar as today: minor utilization increase, minor shift to rail, few automated trucks	Minor shift to road by automated trucks, minor shift from HD to MD/LD, increase in utilization	Some shift to road by automated trucks, some shift from HD to MD/LD, increase in utilization	Shift towards road by automated trucks, minor shift from HD to MD/LD, increase in utilization
E-charging infrastructure availability	Limited dedicated public charging points; mainly charging at depots	Dedicated charging points on main freight arteries in Europe; new specific CV standard (350-500 kW charging power)	High power alongside motorways (>500 kW) and other roads (350-500 kW); Electrified road systems available on main arteries	Dedicated charging points on main freight arteries in Europe; new specific CV standard (350-500 kW charging power)
Hydrogen infrastructure availability	No dedicated public truck refueling pumps; mainly refueling at depot	Dedicated public truck refueling pumps, ~2045 also liquefied hydrogen	No dedicated public truck refueling pumps; mainly refueling at depot	Dedicated public truck refueling pumps, ~2045 also liquefied hydrogen

Source: FEV

In accelerated scenarios FEV expects high power charging points (>500 kW) to be located along highways

CHARGING INFRASTRUCTURE AVAILABILITY

Main charging technological issue



Max. 350 kW DC

Max. 150 kW DC

~0.5 h* (100 kWh)

~2.5 h* (500 kWh)

~4.5 h* (900 kWh)

Max. 150 kW DC

Hypothetical, using today's infrastructures and technology

- New technology and charging standards are needed in order to support the ramp-up of battery electric trucks (>500 kW DC)
- A higher charging power will lead to an extremely high peak-power demand at the station, considering that more trucks will be charging at the same time i.e. at resting areas along motorways

*Time estimations refer to a 10 to 80% charge

Source: ACEA, FEV

Current situation

- Today, as battery electric trucks are a niche segment, no dedicated charging points exist for such vehicles

Infrastructures' usage consideration

- Due to the different usage, commercial vehicles cannot be compared to passenger cars when it comes to charging habits
- Commercial vehicles will charge most of the time at the depot, with a significantly lower electricity price
- Dedicated public charging points for trucks have to be rolled out, along main arteries, in order to support the uptake of such vehicles

Regulatory measures for battery electric trucks

- Last European regulation proposal sets a "super-credit system" until 2025 and a benchmark of 2% starting from 2025, in order to push for ZLEV adoption
- Although mentioned, no specific measures have been included in the regulation to push the roll-out of charging infrastructures

As of today, light duty vehicle H_2 stations do not support heavy-duty vehicles; still, stations supporting both classes can be built

H_2 FUEL STATION ENGINEERING STANDARDS

SAE J2601-1

- Fueling protocol for gaseous hydrogen powered light duty vehicles
- Provides the protocol and process limits for hydrogen fueling of light duty vehicles
- A table based protocol and a formula-based protocol is used for different temperature and pressure levels
- 35 MPa and 70 MPa pressure levels and tank sizes from 1.2 kg to 10 kg are supported

SAE J2601-2

MD HD

- Fueling protocol for gaseous hydrogen powered heavy-duty vehicles
- Provides performance requirements for hydrogen dispersing systems used for fueling 35 MPa heavy-duty hydrogen transit buses and vehicles
- Suitable for vehicles with more than 10 kg hydrogen charging capacity
- Heavy-duty vehicle hydrogen charging stations must either support fueling of light duty vehicles or prevent them from fueling with electrical or mechanical barriers
- Standard is mainly aimed at transit buses and might be updated in the future as the market for heavy-duty vehicles further develops

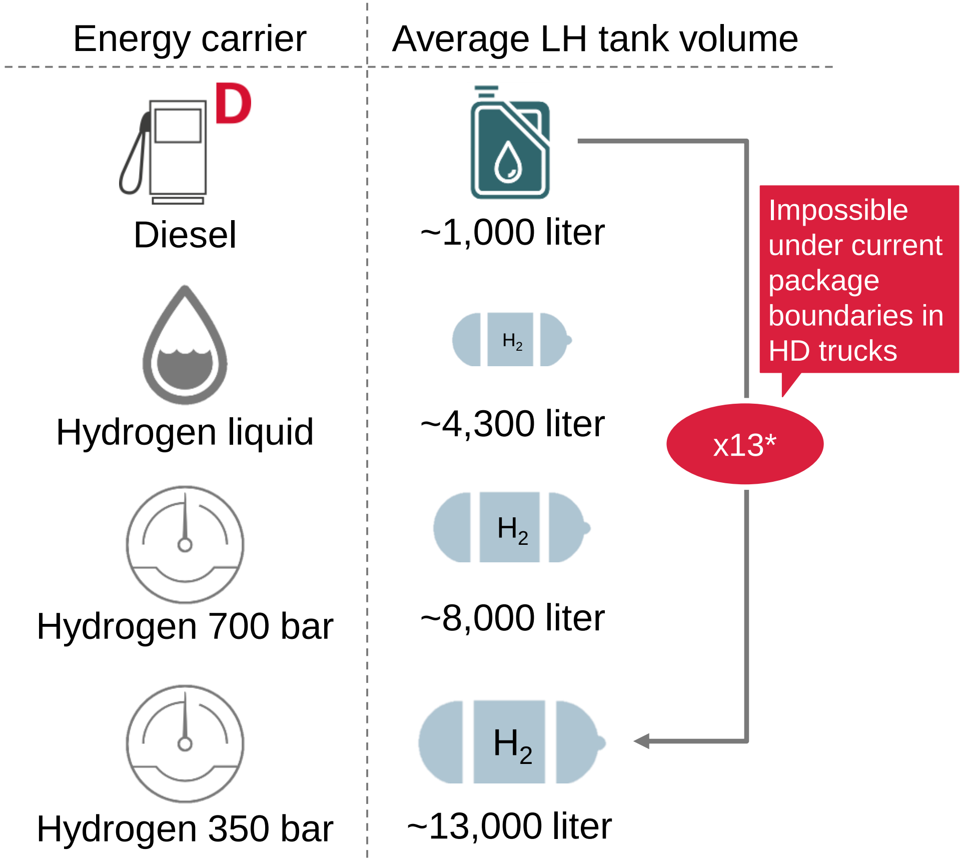
H_2 fueling stations for light duty vehicles are not necessarily compatible with heavy-duty vehicles as the standard fueling protocol only supports tanks sizes up to 10 kg, but stations serving both vehicle classes can be designed / are expected to be rolled-out

Source: SAE, FEV

Next to the discussed standards for light and heavy-duty H_2 stations, also the pressure level plays an important role for the roll-out of H_2 trucks

HYDROGEN TRUCK INFRASTRUCTURE

Hydrogen volumetric density issue



Energy carrier	Average LH tank volume
Diesel	~1,000 liter
Hydrogen liquid	~4,300 liter
Hydrogen 700 bar	~8,000 liter
Hydrogen 350 bar	~13,000 liter

Impossible under current package boundaries in HD trucks

*In order to have the same amount of energy in the tank

Source: FEV

Current situation

- There are almost no vehicles running on hydrogen in Europe: just a few passenger cars and almost no trucks
- In the same way, the H_2 fueling infrastructures is (as of today) limited and engineered to support just cars

Infrastructures' usage consideration

- Heavy-duty vehicles for long-haul applications need a range autonomy of at least 800 km
- Considering current state-of-the-art engine's efficiency, the only acceptable hydrogen storage solutions are
  - Gas, compressed at 700 bar for RH and LH, or
  - Liquid, cooled at -253 °C for LH

Regulatory measures for H_2 trucks

- Last European regulation proposal sets a "super-credit system" until 2025 and a benchmark of 2% starting from 2025, in order to push for ZLEV adoption
- Although mentioned, no specific measures have been included in the regulation to push the roll out of H_2 fueling infrastructures

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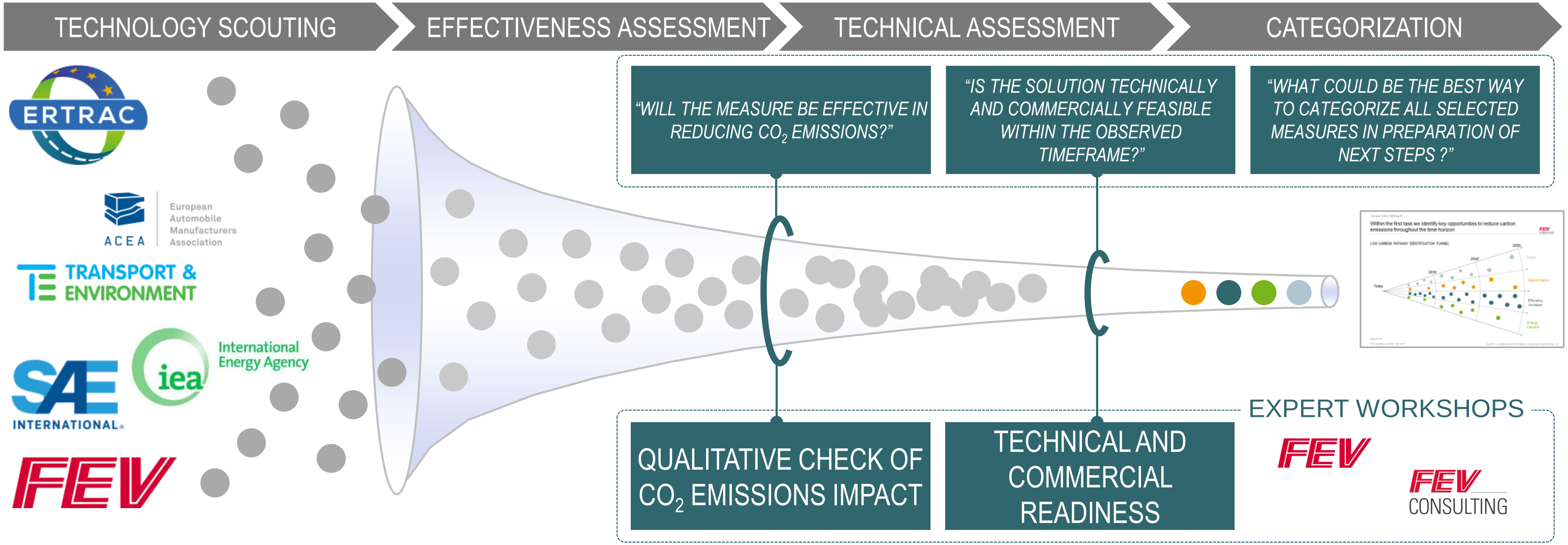
FEV has followed a structured approach together with internal experts to identify the most suitable technologies for future HD trucks

FEV TECHNOLOGY SELECTION PROCESS



TECHNOLOGY SCOUTING | EFFECTIVENESS ASSESSMENT | TECHNICAL ASSESSMENT | CATEGORIZATION

"WILL THE MEASURE BE EFFECTIVE IN REDUCING CO_2 EMISSIONS?"

"IS THE SOLUTION TECHNICALLY AND COMMERCIALLY FEASIBLE WITHIN THE OBSERVED TIMEFRAME?"

"WHAT COULD BE THE BEST WAY TO CATEGORIZE ALL SELECTED MEASURES IN PREPARATION OF NEXT STEPS ?"

QUALITATIVE CHECK OF CO_2 EMISSIONS IMPACT

TECHNICAL AND COMMERCIAL READINESS

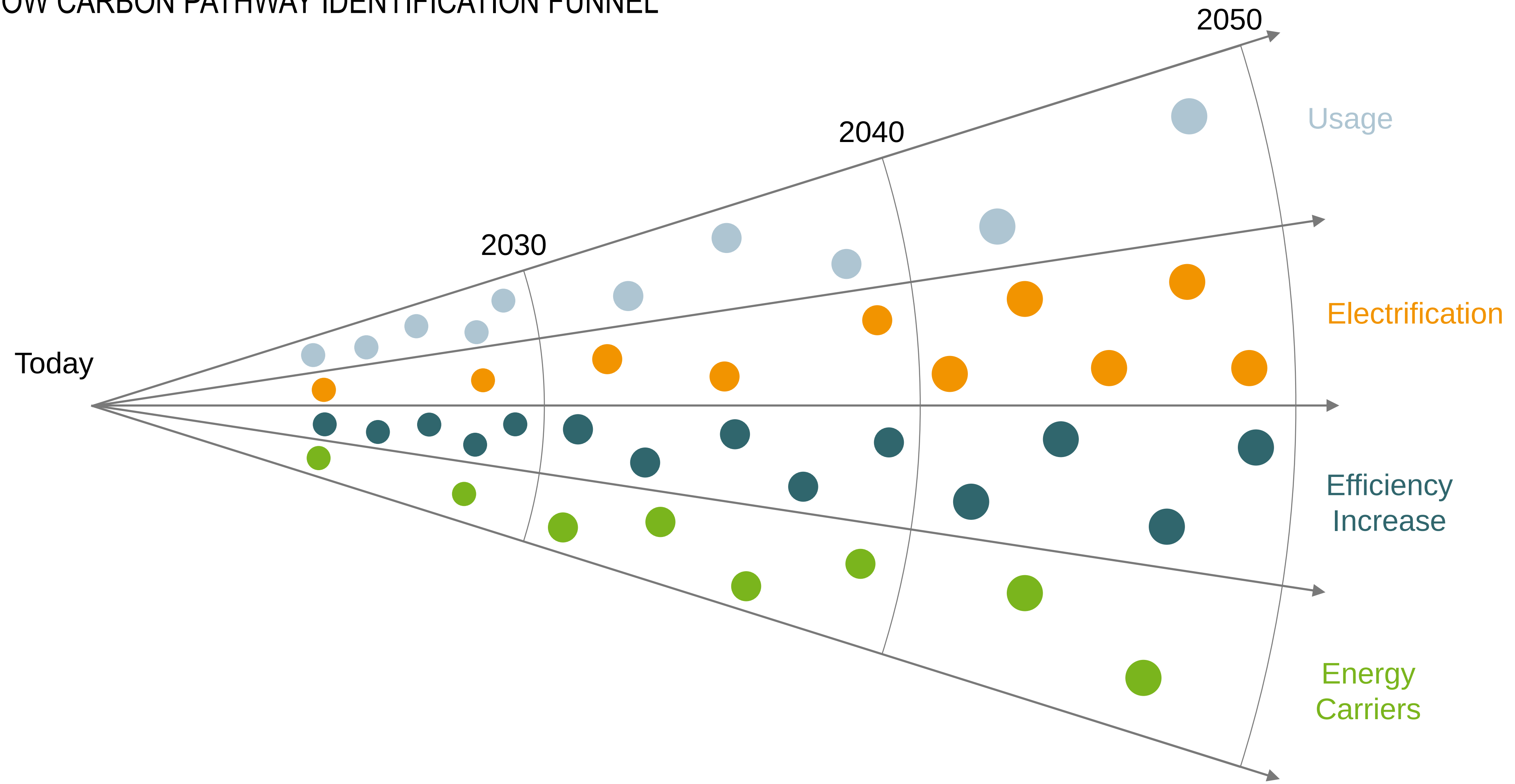
EXPERT WORKSHOPS

- Through workshops and scouting, assessment of a wide list of measures that could be relevant for HD vehicles in the future
- Qualitative assessment of emissions impact, considering actual trends and forecasts, on a fleet level
- Technical and commercial assessment of technologies regarding application HD commercial vehicles
- Allocation of chosen technologies into groups, categories and timeframes

Source: FEV

Within the first task we identify key opportunities to reduce carbon emissions throughout the time horizon

LOW CARBON PATHWAY IDENTIFICATION FUNNEL



Source: FEV

In total, FEV has selected 42 technologies within the key areas “usage”, “electrification”, “efficiency increase” and “energy carriers”

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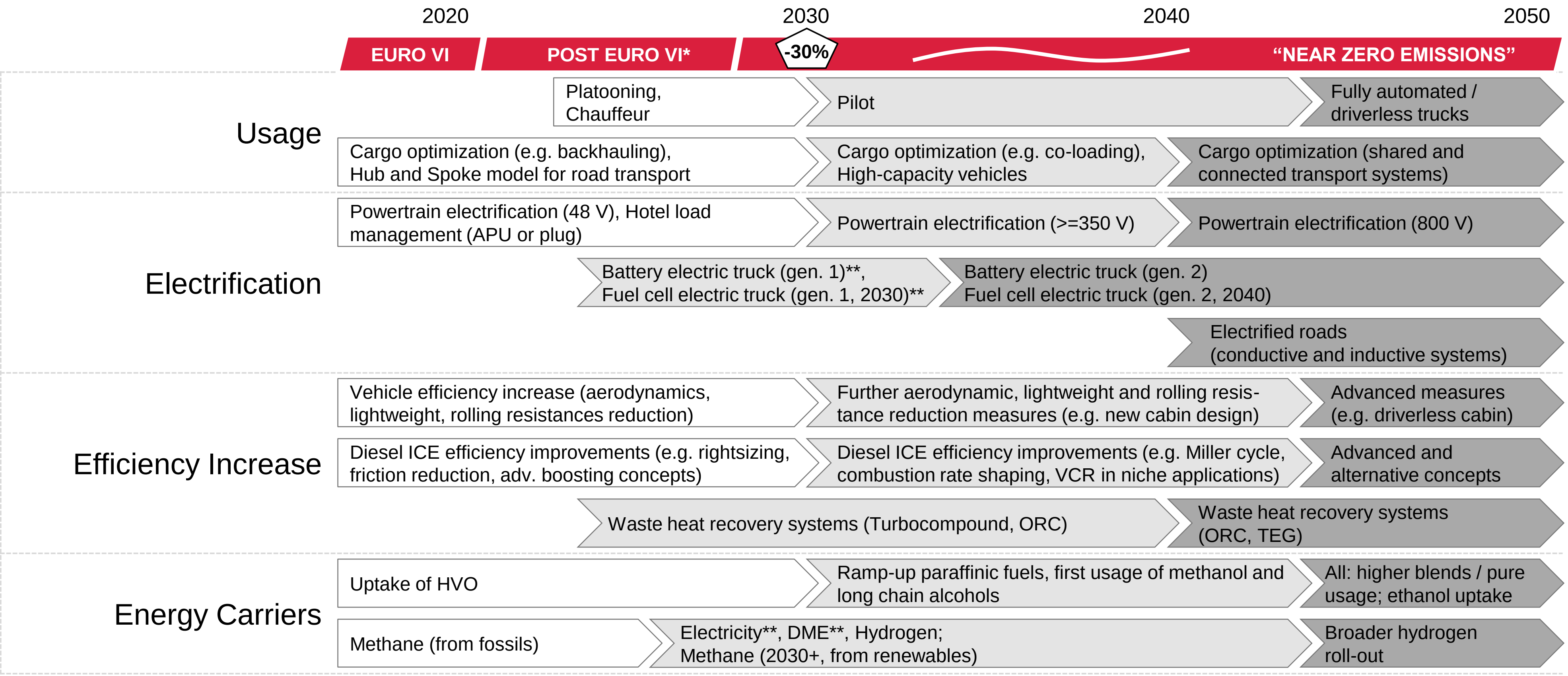
OVERVIEW OF IDENTIFIED TECHNOLOGIES

Technology area	2020-2030	2030-2040	2040-2050
Usage	Platooning Chauffeur Driver behavior optimization Cargo optimization (step 1) Hub and Spoke model	Pilot High-capacity vehicles Cargo optimization (step 2)	Fully automated / driverless trucks Cargo optimization (step 3)
Electrification	Powertrain electrification (step 1) Hotel load management	Powertrain electrification (step 2) Battery electric truck (gen. 1) Fuel cell truck (gen. 1)	Powertrain electrification (step 3) Battery electric truck (gen. 2) Fuel cell truck (gen. 2) Conductive road systems Inductive road systems
Efficiency Increase	Demand controlled auxiliaries Lightweight measures (step 1) Aerodynamic measures (step 1) Rolling resistance reduction measures (step 1) ICE’s internal efficiency improvements (step 1)	Lightweight measures (step 2) Aerodynamic measures (step 2) Rolling resistance reduction measures (step 2) ICE’s internal efficiency improvements (step 2) Waste heat recovery systems	Lightweight measures (step 3) Aerodynamic measures (step 3) Rolling resistance reduction measures (step 3) ICE’s internal efficiency improvements (step 3)
Energy carriers	Methane Paraffinic fuels	Methanol Hydrogen DME Electricity	Long chain alcohols Ethanol

Source: FEV

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul

OVERVIEW ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



2020 2030 2040 2050

EURO VI | POST EURO VI* | -30% | "NEAR ZERO EMISSIONS"

Usage

- Platooning, Chauffeur → Pilot → Fully automated / driverless trucks
- Cargo optimization (e.g. backhauling), Hub and Spoke model for road transport → Cargo optimization (e.g. co-loading), High-capacity vehicles → Cargo optimization (shared and connected transport systems)

Electrification

- Powertrain electrification (48 V), Hotel load management (APU or plug) → Powertrain electrification (>=350 V) → Powertrain electrification (800 V)
- Battery electric truck (gen. 1)**, Fuel cell electric truck (gen. 1, 2030)** → Battery electric truck (gen. 2) Fuel cell electric truck (gen. 2, 2040)
- Electrified roads (conductive and inductive systems)

Efficiency Increase

- Vehicle efficiency increase (aerodynamics, lightweight, rolling resistances reduction) → Further aerodynamic, lightweight and rolling resistance reduction measures (e.g. new cabin design) → Advanced measures (e.g. driverless cabin)
- Diesel ICE efficiency improvements (e.g. rightsizing, friction reduction, adv. boosting concepts) → Diesel ICE efficiency improvements (e.g. Miller cycle, combustion rate shaping, VCR in niche applications) → Advanced and alternative concepts
- Waste heat recovery systems (Turbocompound, ORC) → Waste heat recovery systems (ORC, TEG)

Energy Carriers

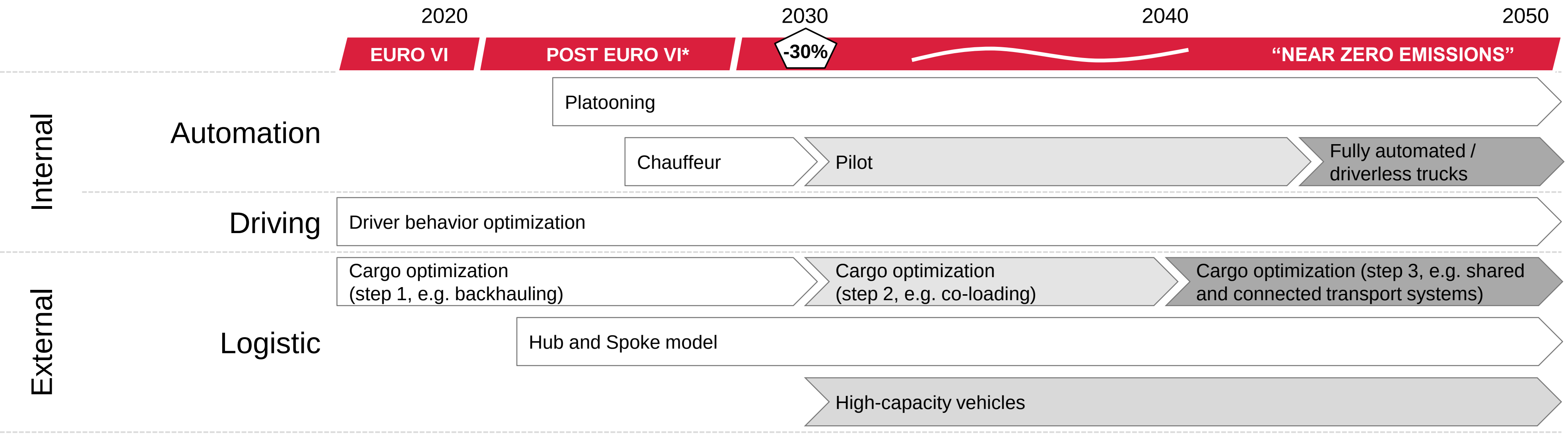
- Uptake of HVO → Ramp-up paraffinic fuels, first usage of methanol and long chain alcohols → All: higher blends / pure usage; ethanol uptake
- Methane (from fossils) → Electricity**, DME**, Hydrogen; Methane (2030+, from renewables) → Broader hydrogen roll-out

* FEV scenario; **In dedicated use-cases only
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Usage

USAGE – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



2020 2030 2040 2050

EURO VI | POST EURO VI* | -30% | "NEAR ZERO EMISSIONS"

Internal

Automation
- Platooning
- Chauffeur → Pilot → Fully automated / driverless trucks

Driving
- Driver behavior optimization

External

Logistic
- Cargo optimization (step 1, e.g. backhauling) → Cargo optimization (step 2, e.g. co-loading) → Cargo optimization (step 3, e.g. shared and connected transport systems)
- Hub and Spoke model
- High-capacity vehicles

* FEV scenario
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Electrification

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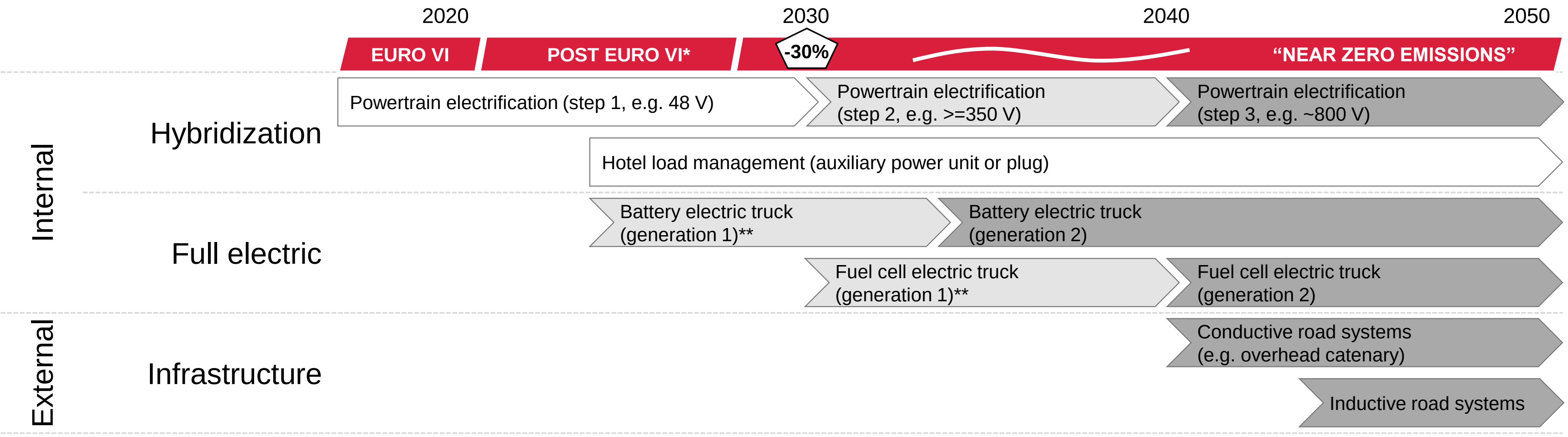
ELECTRIFICATION – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



2020 2030 2040 2050

EURO VI | **POST EURO VI*** | **-30%** | **“NEAR ZERO EMISSIONS”**

Internal

Hybridization

- Powertrain electrification (step 1, e.g. 48 V)
- Powertrain electrification (step 2, e.g. >=350 V)
- Powertrain electrification (step 3, e.g. ~800 V)
- Hotel load management (auxiliary power unit or plug)

Full electric

- Battery electric truck (generation 1)**
- Battery electric truck (generation 2)
- Fuel cell electric truck (generation 1)**
- Fuel cell electric truck (generation 2)

External

Infrastructure

- Conductive road systems (e.g. overhead catenary)
- Inductive road systems

* FEV scenario; ** In dedicated use-cases only
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Efficiency increase

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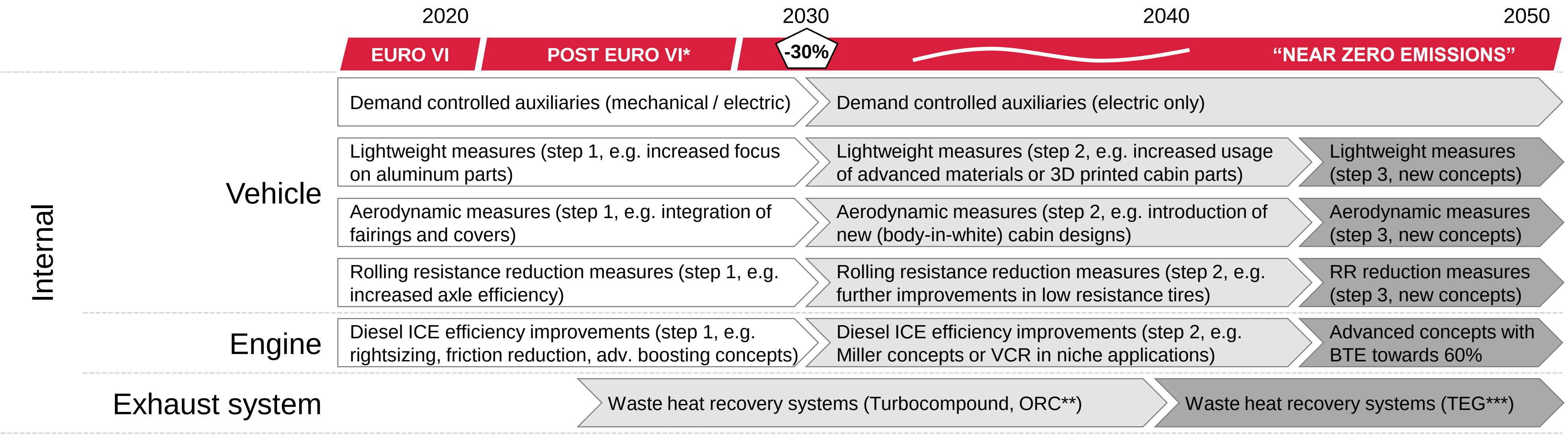
HD

EFFICIENCY INCREASE – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



Demand controlled auxiliaries (mechanical / electric)

Demand controlled auxiliaries (electric only)

Lightweight measures (step 1, e.g. increased focus on aluminum parts)

Lightweight measures (step 2, e.g. increased usage of advanced materials or 3D printed cabin parts)

Lightweight measures (step 3, new concepts)

Aerodynamic measures (step 1, e.g. integration of fairings and covers)

Aerodynamic measures (step 2, e.g. introduction of new (body-in-white) cabin designs)

Aerodynamic measures (step 3, new concepts)

Rolling resistance reduction measures (step 1, e.g. increased axle efficiency)

Rolling resistance reduction measures (step 2, e.g. further improvements in low resistance tires)

RR reduction measures (step 3, new concepts)

Diesel ICE efficiency improvements (step 1, e.g. rightsizing, friction reduction, adv. boosting concepts)

Diesel ICE efficiency improvements (step 2, e.g. Miller concepts or VCR in niche applications)

Advanced concepts with BTE towards 60%

Waste heat recovery systems (Turbocompound, ORC**)

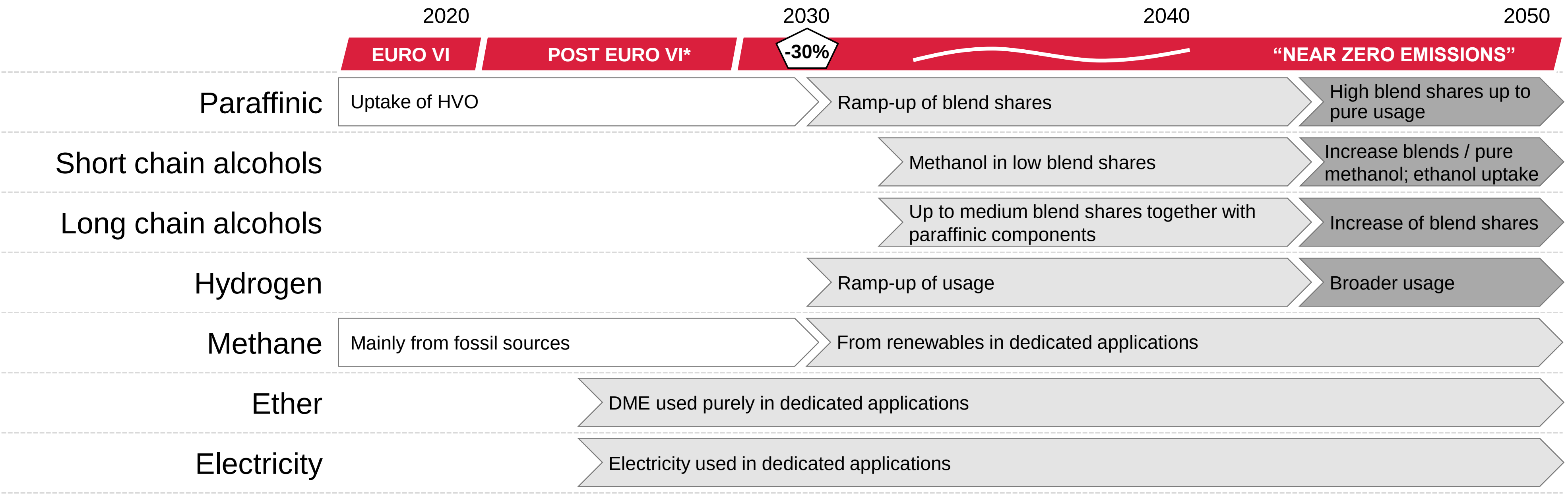
Waste heat recovery systems (TEG***)

* FEV scenario; ** ORC: Organic Rankine Cycle; *** TEG: Thermo-Electric Generator;
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Energy carriers

ENERGY CARRIERS – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



2020 | 2030 | 2040 | 2050

EURO VI | POST EURO VI* | -30% | "NEAR ZERO EMISSIONS"

Paraffinic: Uptake of HVO → Ramp-up of blend shares → High blend shares up to pure usage

Short chain alcohols: Methanol in low blend shares → Increase blends / pure methanol; ethanol uptake

Long chain alcohols: Up to medium blend shares together with paraffinic components → Increase of blend shares

Hydrogen: Ramp-up of usage → Broader usage

Methane: Mainly from fossil sources → From renewables in dedicated applications

Ether: DME used purely in dedicated applications

Electricity: Electricity used in dedicated applications

* FEV scenario

Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Agenda

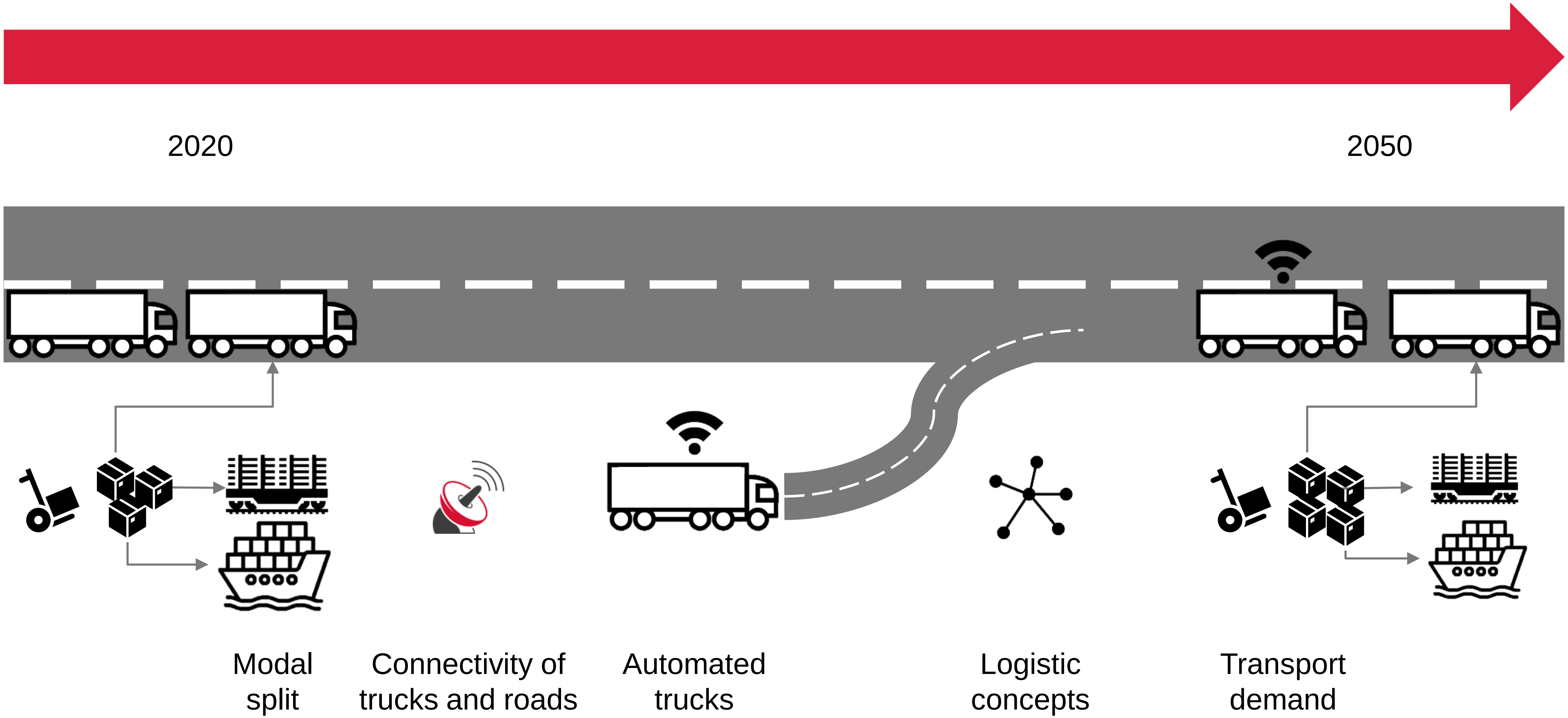
- Executive summary
- Framework and long-term scenarios for HD on-road transportation
- Technology options towards 2050
- Future pathways towards clean on-road transportation
- Reduced GHG emissions with holistic technology strategies
- CO_2 abatement costs for selected reference trucks
- TCO performance of underlying reference trucks
- Life-cycle analysis for HD trucks

Agenda

- Future pathways towards clean on-road transportation
  - Usage: Strategies for efficient goods transportation
  - Electrification: The potential of electrified and electric powertrains
  - Efficiency: Further measures on vehicle side
  - Energy carriers: Alternative fuels as a key contributor

Modal split, connectivity, automated driving, logistics concepts and an increase in freight demand are key factors on sales for heavy-duty vehicles

SALES FIGURES – OVERVIEW OF INFLUENCING FACTORS

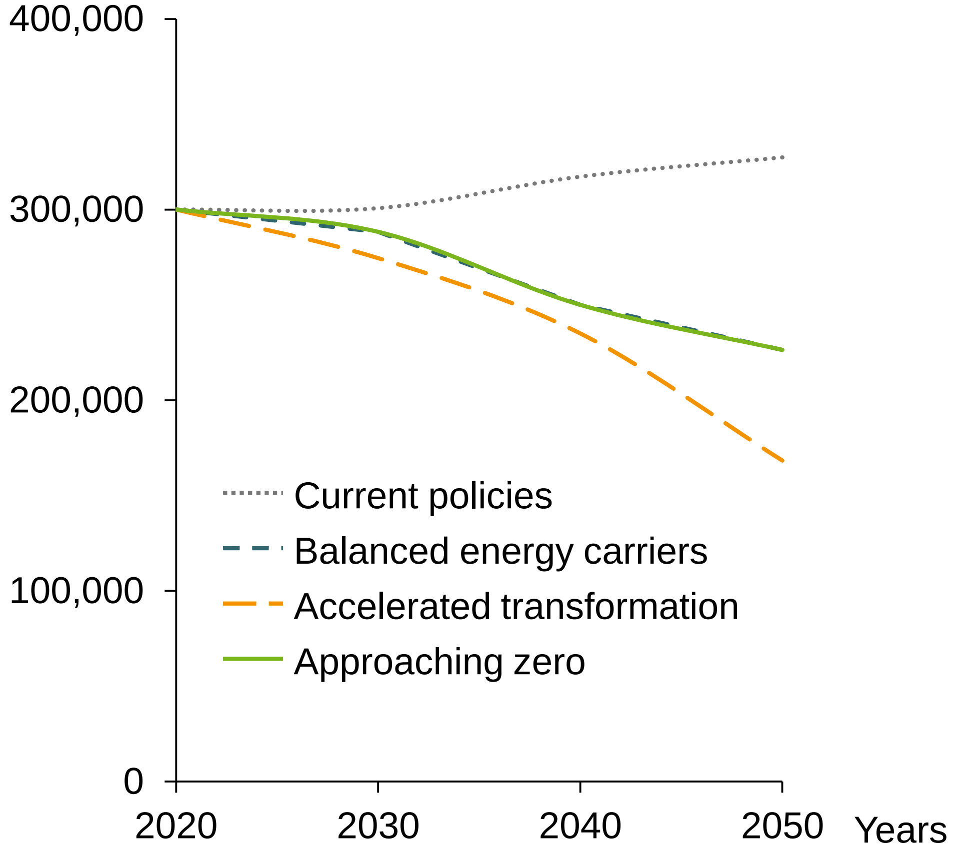


Source: FEV

Sales figures are higher in the current policies than in the other scenarios – mostly driven by fewer and later automation and less connectivity

SALES FIGURES – RESULTS IN THE DIFFERENT SCENARIOS

Number of vehicles sold per year

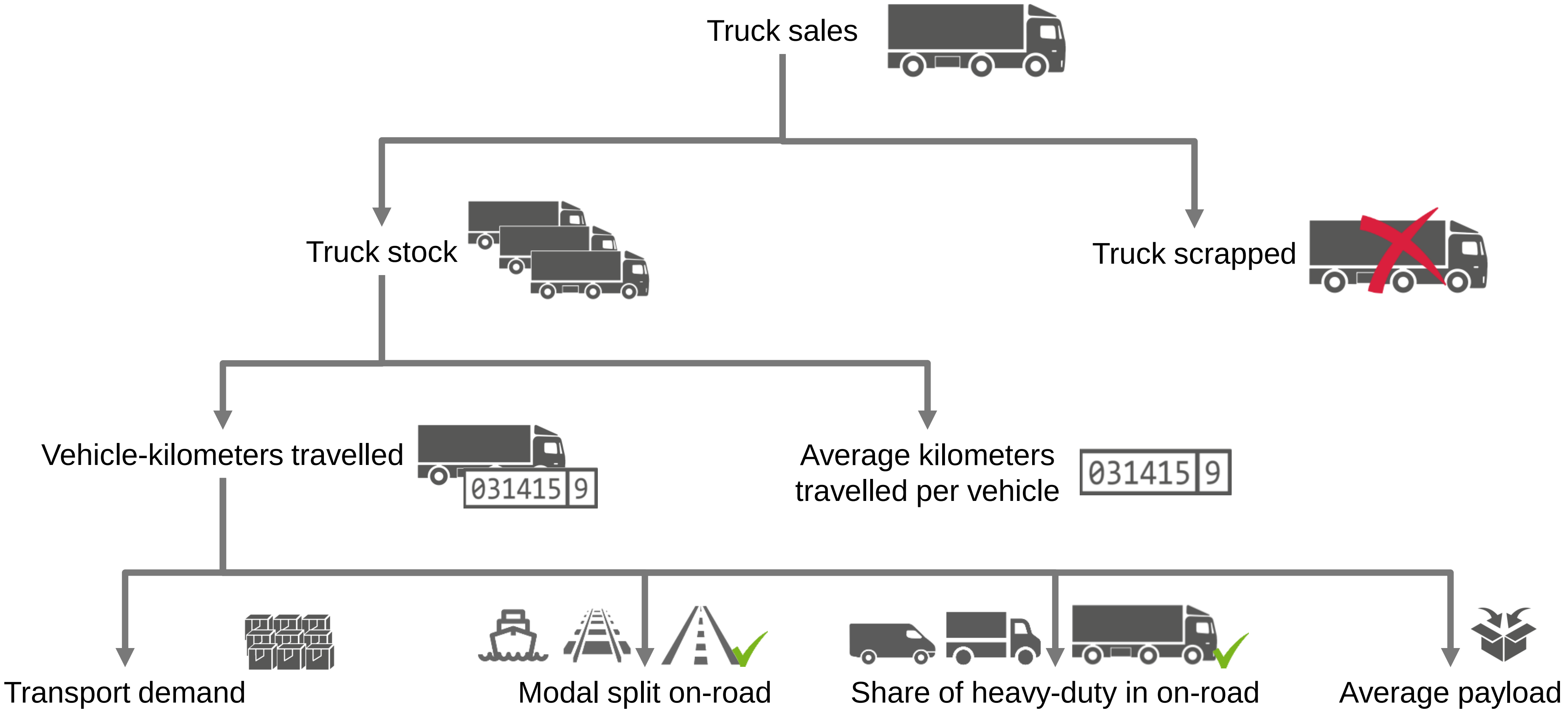


- In all scenarios, the freight demand in ton-kilometers increases at 35% between 2020 and 2050, but the scenarios offer different solutions to fulfill the freight demand
- The main drivers for this are
  - Modal split between road, rail, navigation and aviation
  - Share of heavy-duty vehicles in on-road transport
  - Average truck utilization
  - Share of automated trucks in the stock
  - Average capacity of the vehicles
- In the subsequent pages we will lay out
  - How those factors are interconnected
  - How those factors affect the number of vehicles sold per year
  - How those factors change in each scenario

Source: FEV

The truck sales depend on the transportation demand, modal split, split of on-road transportation and payload

SALES FIGURES – CONSIDERED INFLUENCING FACTORS AND THEIR RELATION



Truck sales

Truck stock

Truck scrapped

Vehicle-kilometers travelled

Average kilometers travelled per vehicle

Transport demand

Modal split on-road

Share of heavy-duty in on-road

Average payload

Source: FEV

Different parameters are necessary to define the truck sales

SALES FIGURES – EXPLANATION OF INFLUENCING FACTORS

Factor group	Comments
Truck sales	Computed considering the increase in stock size of two consecutive years and the number of vehicles scrapped in this timeframe
Truck stock	Number of vehicles in-use
Truck scrapped	Number of vehicles that are scrapped in a year – average lifetime of a truck in Europe is about 11 years
Vehicle-kilometers travelled	Depends on the ton-kilometers transport demand, trips per day, kilometers displaced per trip and average truck payload
Average kilometers travelled per vehicle per year	Approximatively 85,000 kilometers per year and vehicle are done by heavy-duty vehicles (considers the mix of vehicles in regional and long haul use-cases)

Source: FEV

The influencing parameters for the vehicle sales are transport demand, modal split, share of heavy-duty in on-road and average payload

SALES FIGURES – EXPLANATION OF INFLUENCING FACTORS

Factor group	Factor	Input and comments
Transport demand	-	35% increase in ton-kilometer transport demand between 2020 and 2050; impacted by population and GDP development
Modal split on-road	On-water transportation	70% of all ton-kilometers are covered by on-road transportation; impacted by adoption of automated trucks
	On-rail transportation	
	On-road transportation	
Share of heavy-duty in on-road	Light-duty vehicles	86% of all ton-kilometers covered by on-road transportation are handled though heavy-duty vehicles; impacted by adoption of hub and spoke model and automated trucks
	Medium-duty vehicles	
	Heavy-duty vehicles	
Average payload	Average vehicle capacity	16 tons per vehicle; impacted by adoption of high capacity vehicles and freight container modularization
	Average truck utilization	65% of the total vehicle capacity is used by heavy-duty vehicles; will change due to backhauling, co-loading and physical internet

Source: FEV

Each parameter influences in a different way the vehicle sales and the size of the stock

SALES FIGURES – IMPACT OF INFLUENCING FACTORS

		Effect on sales	Effect on stock size	Comment
Influencing parameter: "Increase of…leads to…"	Vehicle scrapped per year	↑	↓	Increased number of scrapped vehicles increases vehicle sales but shrinks the stock size
	Billion-ton-km	↑	↑	Expresses the need of freight transportation – influences mainly stock size but an increase in two consecutive years influences the sales, too
	Modal split on-road	↑	↑	Share of on-road transportation – affects the demand of on-road freight transportation but not directly the heavy-duty sector
	Share of heavy-duty vehicles	↑	↑	Share of heavy-duty vehicles with respect to other vehicle classes – affects both stock and sales size of the heavy-duty sector
	Average vehicle capacity	↓	↓	Increases vehicle capacity; the same amount of freight will be handled by a lower number of heavy-duty vehicles
	Average truck utilization	↓	↓	Increases vehicle utilization; the same amount of freight will be handled by a lower number of heavy-duty vehicles
	Annual kilometer travelled by heavy-duty	↓	↓	Increasing the annual mileage, the same amount of freight will be handled by a lower number of heavy-duty vehicles
	Share of automated trucks	↓	↓	Automation affects the annual mileage travelled by each heavy-duty truck in a positive way; hence, sales and stock shrink

Source: FEV

The evolving trend over time of the influencing parameters is different for the four considered scenario

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SALES FIGURES – TREND OF INFLUENCING FACTORS IN THE DIFFERENT SCENARIOS

	Current policies	Balanced energy carriers	Accelerated transformation	Approaching zero
Modal split on-road	-	+	++	+
Share of heavy-duty vehicles in on-road transportation	O	-	--	-
Average vehicle capacity	O	++	+	++
Truck utilization	O	+	+	+
Annual kilometer travelled non-automated truck	-	-	-	-
Annual kilometer travelled automated truck	+	+	+	+
Share of automated trucks in the stock	+	+	++	+

Source: FEV

++ Strong increase + Increase O Neutral - Decrease -- Strong decrease

High capacity vehicles result in lower fuel consumptions, emission and impact road traffic without affecting safety

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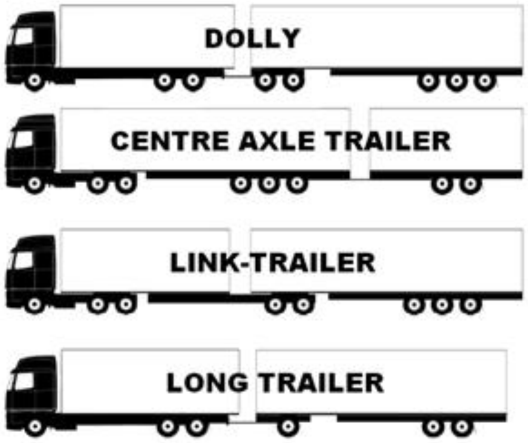
LOGISTIC CONCEPTS – HIGH CAPACITY VEHICLES

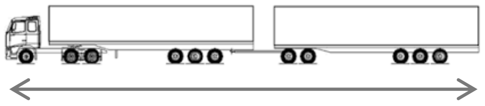
Types of high capacity vehicles



Description

- High capacity vehicles consist in a combination of one or two trailer, pulled by a traction unit
- Key advantages
  - Reduced fuel consumption: studies show up to 15% less energy per ton-km in comparison to conventional heavy-duty vehicles
  - Reduced transport costs: less vehicles are needed to transport the same amount of freight
- Key challenges
  - Local policies and infrastructures: bridges and roads not dimensioned for such vehicles

General specifications



Up to 25,25 meters long*

Max. weight of 60 tons*

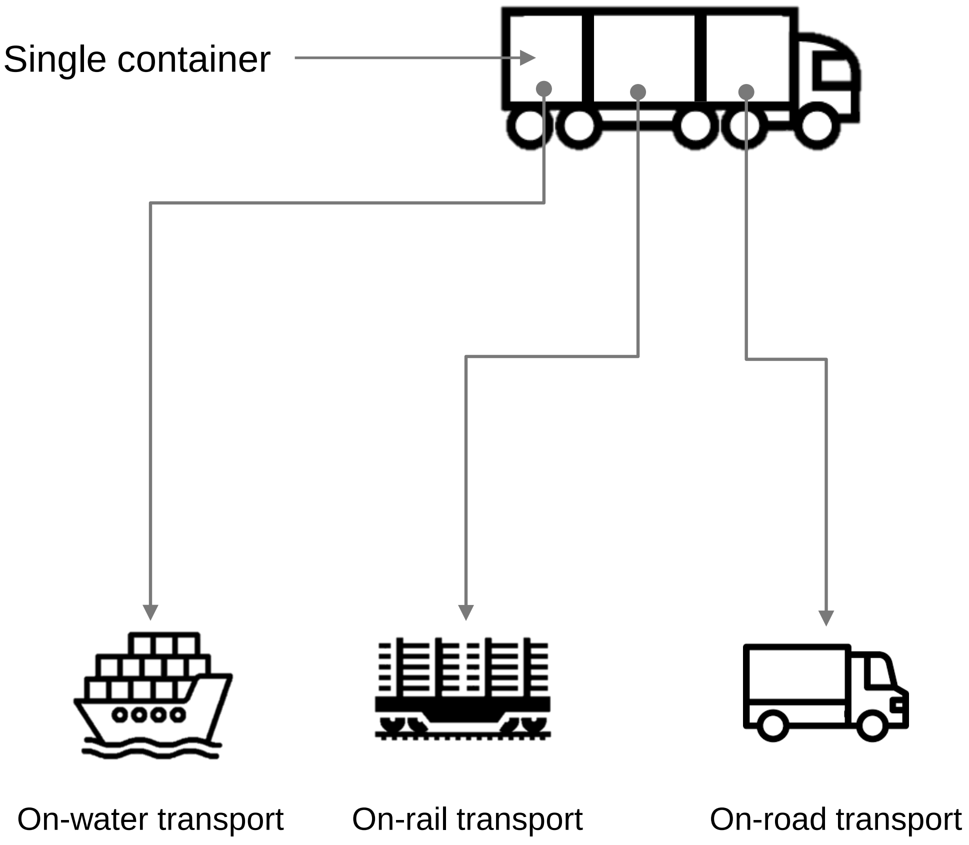
Today's situation in Europe

- Currently allowed only in northern countries i.e. Finland, Sweden, Norway, Denmark, Netherlands
- Trials are currently running in Germany and Belgium to test the effectiveness of such trucks

*Maximum permissible length and weight are locally different
Source: FEV

Freight container modularization is an advanced logistic concept that eases the process for intermodal transportation

LOGISTIC CONCEPTS – FREIGHT CONTAINER MODULARIZATION



Description

- Goods are packed into standardized containers, allowing to easily move them from one to another mean of transport
- Containers can be combined with each other, allowing adaptation depending on the goods that have to be transported and the carrier
- Freight container modularization eases the process for intermodal transportation

Requirements

- A common regulation is required in order to define a valid standard

Source: FEV

Backhauling and co-loading increase vehicle utilization through collaborations among senders and similar shipment characteristics

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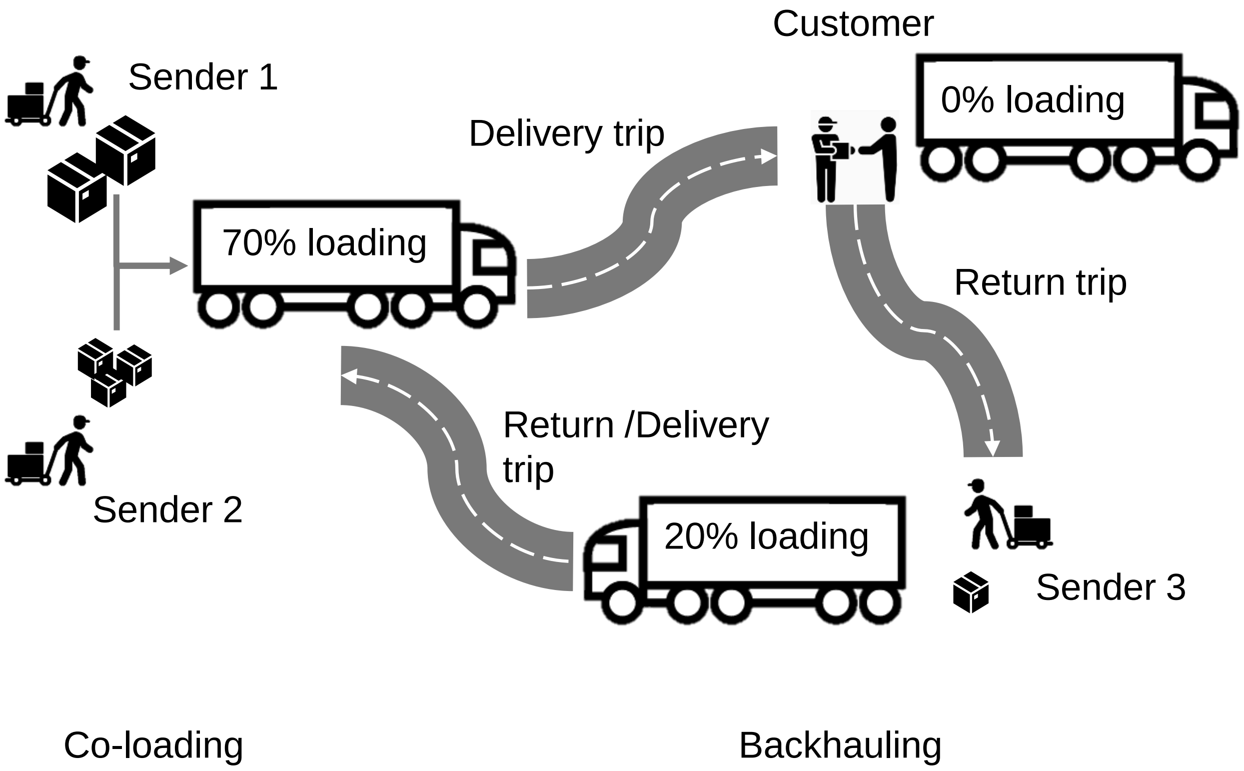
LOGISTIC CONCEPTS – BACKHAULING AND CO-LOADING

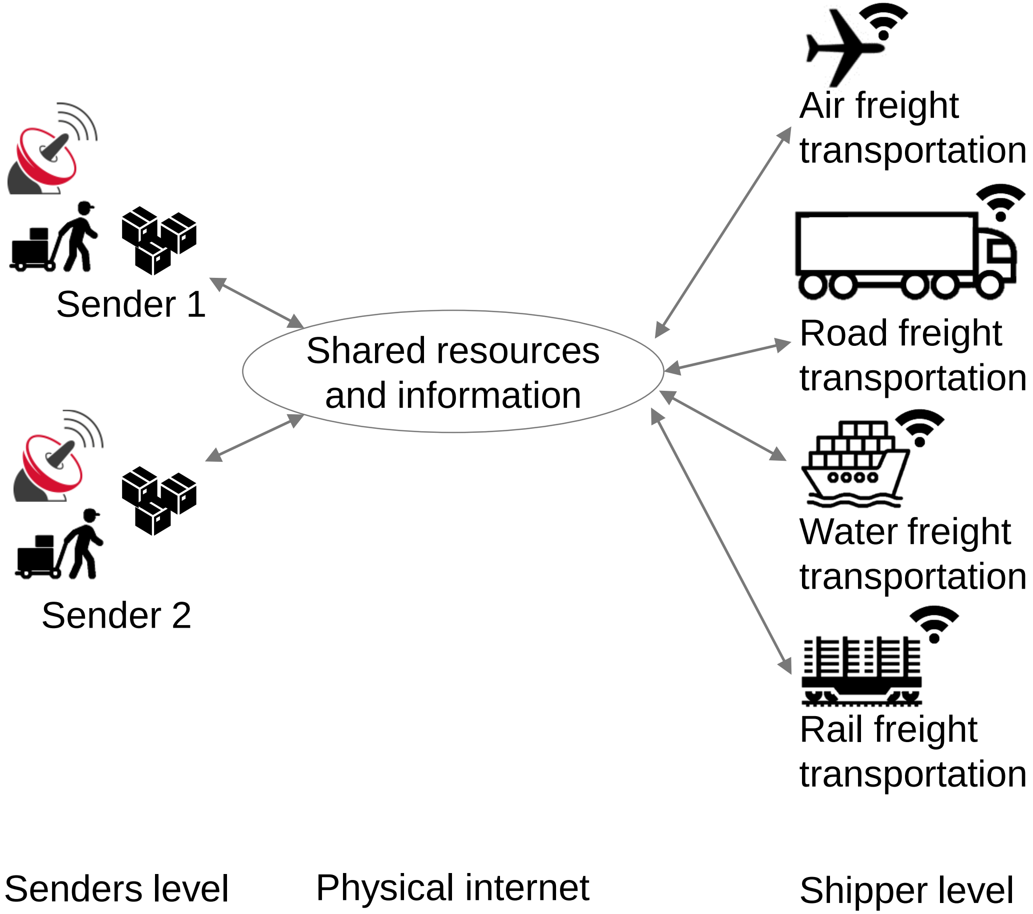


- Backhauling
  - Deigned to increase vehicle utilization: reduces the number of empty runs
  - Consists in the practice of delivering cargo in return trips
  - Requires collaboration across senders
- Co-loading
  - Designed to increase the vehicle utilization
  - Realizable through supply chain collaboration across warehousing or non-competing firm
  - Consist in bundling shipments across product categories with similar shipment characteristics

Source: IEA, FEV

The Physical Internet consists in an open, shared logistic system that can result in a 20% efficiency improvement of the entire logistic system

LOGISTIC CONCEPTS – PHYSICAL INTERNET

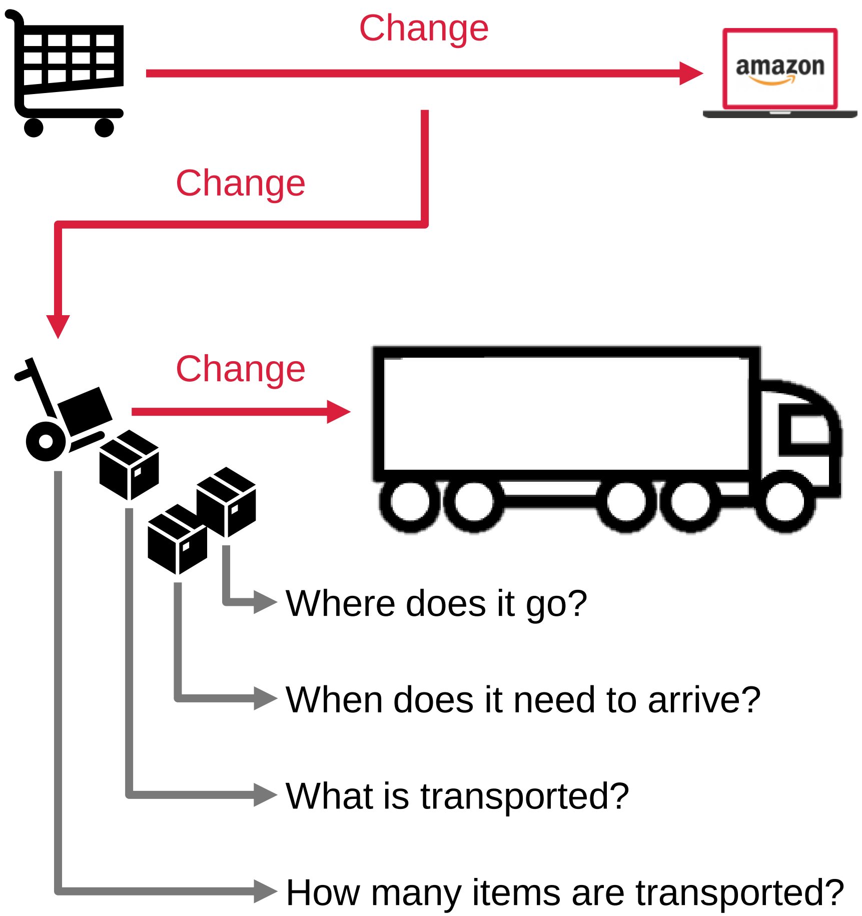


- The Physical Internet consists in an open, shared global logistic system
- Data and resources are pooled among senders: interconnectivity, high performance logistic centers, world standards protocols
- No competition on the basis of supply chain secrets:
  - Senders compete on the basis of their products, not on how well they deliver them
- Studies claim a 20% efficiency improvement of the overall logistic system

Source: IEA, FEV

The hub and spoke model is a trend to adapt the logistic to the changing customer demands and affects all vehicle classes

HUB AND SPOKE MODEL – MOTIVATION



Change

Change

Change

Where does it go?

When does it need to arrive?

What is transported?

How many items are transported?

- Changes in customer demands drive a changes of logistics
  - Increase in online shopping
  - Increase in variety of goods that need to be transported
  - Increase of demand for faster delivery
  - Increase of demand for flexibility in delivery
- One logistic concept to adapt to the expected change is the hub and spoke model where a wider market roll-out is expected both for proprietary and public warehouses
- The hub and spoke model impacts al vehicle classes in logistic with regard to trip lengths, frequencies and location

» The impact on kilometers travelled per heavy-duty vehicle needs to be analyzed

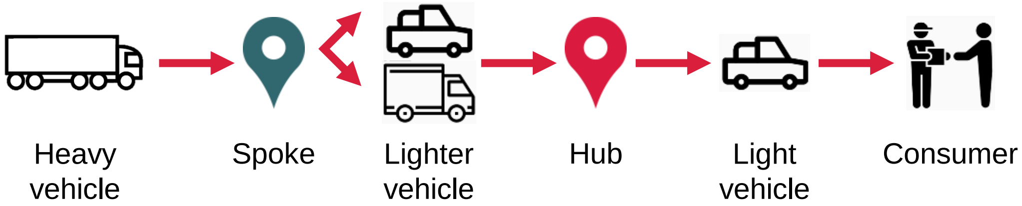
Source: FEV

Hub and spoke model can alter the logistics of 145 million people in 447 cities – easing electrification and avoiding heavy-duty traffic in the city

HUB AND SPOKE MODEL – INTRODUCTION

What is the hub and spoke model?

How does it work?



What are the main advantages?

- Ease electrification of traffic between spokes and hubs and to the customer by a shift to shorter trips
- Increased load factor of heavy-duty trucks
- Fewer heavy-duty vehicles drive into the city
- More flexible delivery in time and place

Where do we expect hubs and spokes?

- We expect a deployment of hubs and spokes based on the number of inhabitants in a city
  - All cities between 100,000 and 500,000 inhabitants are provided with hubs
  - All cities with more than 500,000 inhabitants are provided with hubs and spokes
- Logistics for 145 million people are affected by hubs and spoke
  - 385 cities in Europe have between 100,000 to 500,000 inhabitants, that increase on average by 5% during daytime, in total this affects 65 million people in Europe during daytime
  - 62 cities in Europe have more than 500,000 inhabitants, that increase on average by 15% during daytime, in total this affects 80 million people in Europe during daytime

Source: FEV

The hub and spoke model displaces only a minor share of the kilometer travelled – advantages of the hub and spoke model are in other aspects

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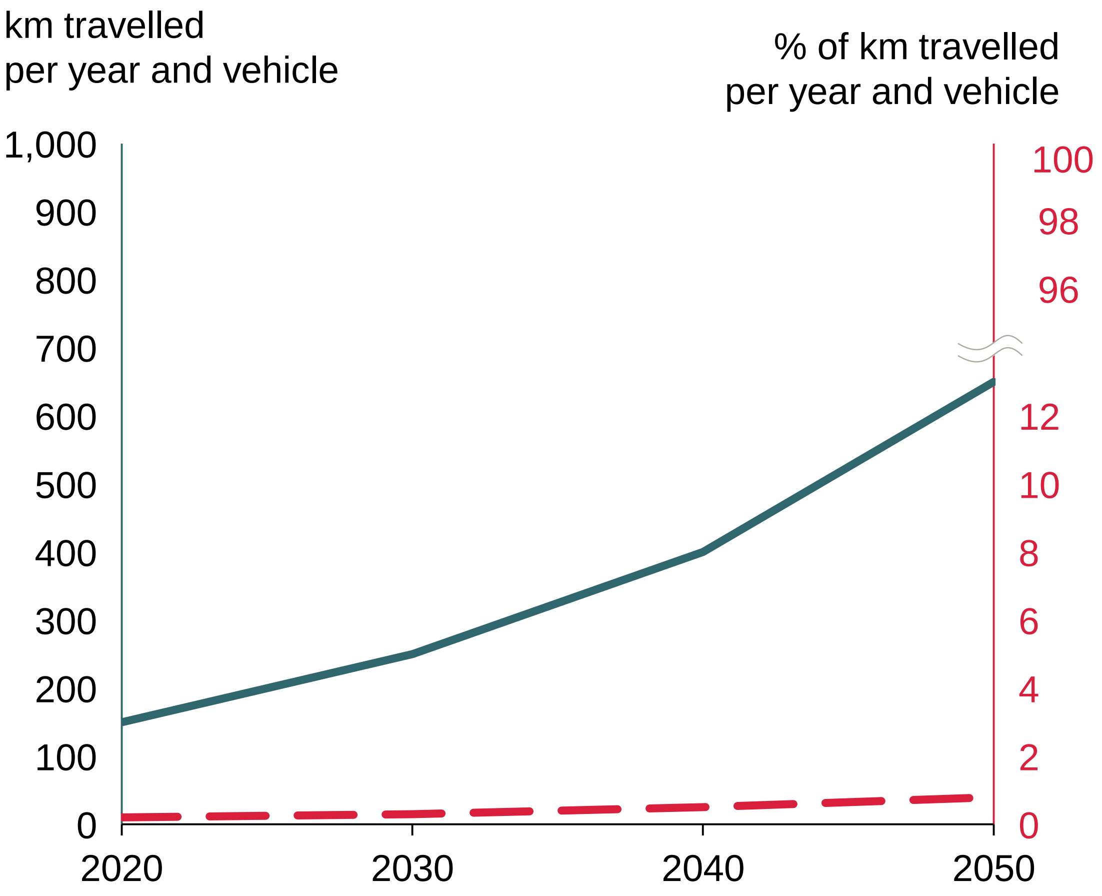
HUB AND SPOKE MODEL – RESULTS



- Only up to 650 km per year and vehicle or less than 1% of the kilometers travelled will be displaced to lighter vehicles by application of the hub and spoke model
  - Only few kilometers on a long haul trip change
  - Less than 35% of the overall freight demand are affected

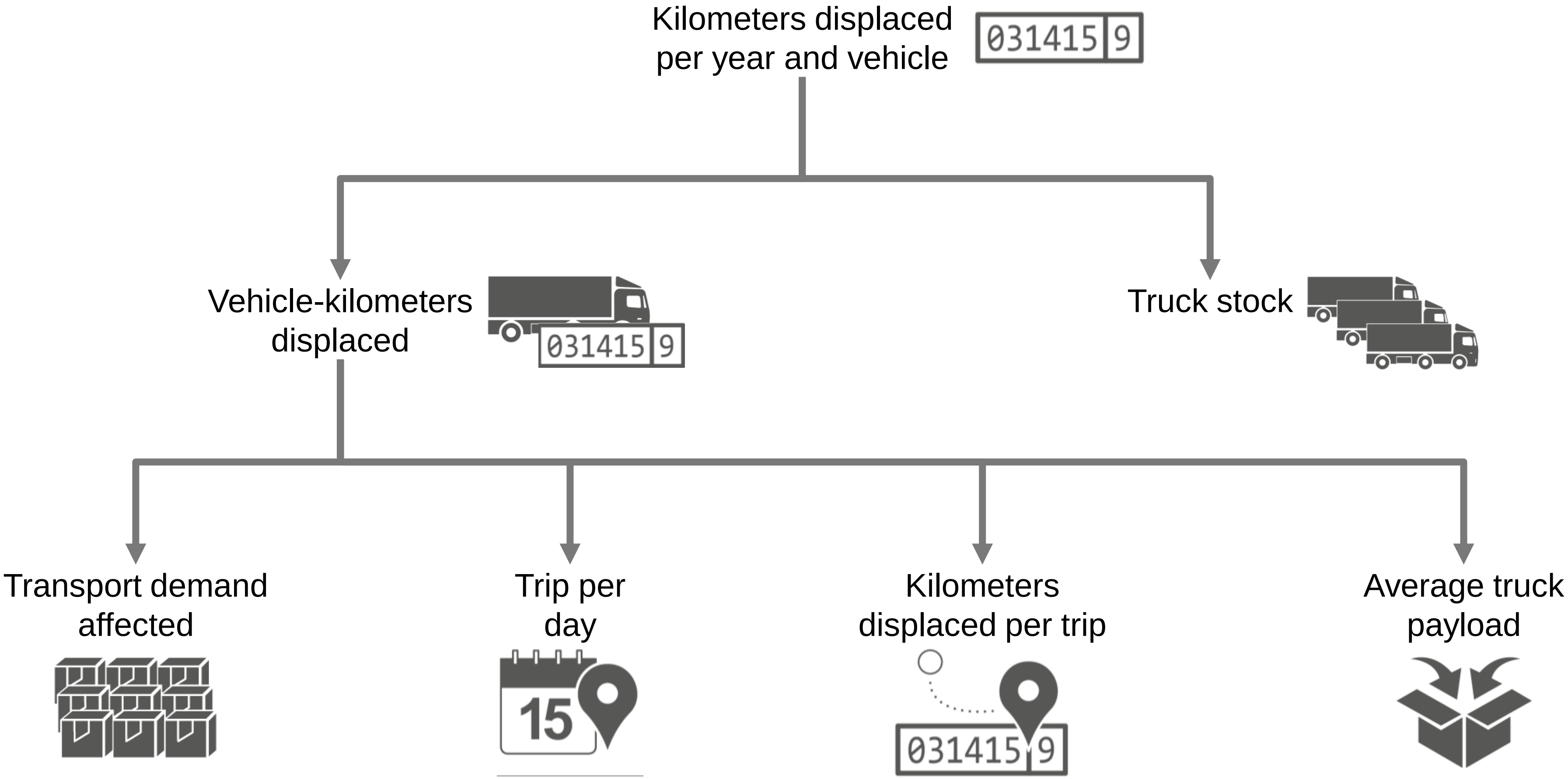
Average kilometers displaced per year and vehicle

Share of km displaced in km travelled per year and vehicle

Source: FEV

The kilometer displaced per year by hub and spoke model depends on transportation demand, trip characteristic and payload

HUB AND SPOKE MODEL – CONSIDERED INFLUENCING FACTORS AND THEIR RELATION



Kilometers displaced per year and vehicle

Vehicle-kilometers displaced

Truck stock

Transport demand affected

Trip per day

Kilometers displaced per trip

Average truck payload

Source: FEV

The kilometers displaced per year and vehicle

HUB AND SPOKE MODEL – EXPLANATION OF INFLUENCING FACTORS

Factor group	Comment
Kilometers displaced per year and vehicle	Quotient of vehicle-kilometers travelled per year and the number of trucks in stock
Vehicle-kilometers displaced	Product of the ton-kilometers transport demand, trips per day, kilometers displaced per trip and average truck payload
Truck stock	Number of heavy-duty vehicles in use

Source: FEV

Various factors influence the impact of the hub and spoke model

HUB AND SPOKE MODEL – EXPLANATION OF INFLUENCING FACTORS

Factor group	Factors	Input
Transport demand affected	Share of freight demand handled through spokes	16% in 2020, this increases to 25% for 2050 – based on the share of inhabitants living in cities with spokes
	Share of freight demand handled only through hubs	13% in 2020, this increases to 20% for 2050 – based on the share of inhabitants living in cities with only hubs
	Share of goods affected	20% in 2020, this increases to 70% for 2050 – only a share of goods is expected to be handled through hubs and spokes
Trips affected per day and vehicle	Trips affected per day and vehicle	0.6 trips per day and vehicle, which considers a mix of trips with different frequency to hubs and spokes
Kilometers displaced per trip	Kilometers displaced in a trip to a spoke	15 km per trip
	Kilometers displaced in a trip to a hub	5 km per trip
Average truck payload	Average truck payload	10 ton per vehicle

Source: FEV

An exemplary long haul trip from Alba to Cologne is 975 km long of which 12 kilometers would be displaced in a trip to a spoke

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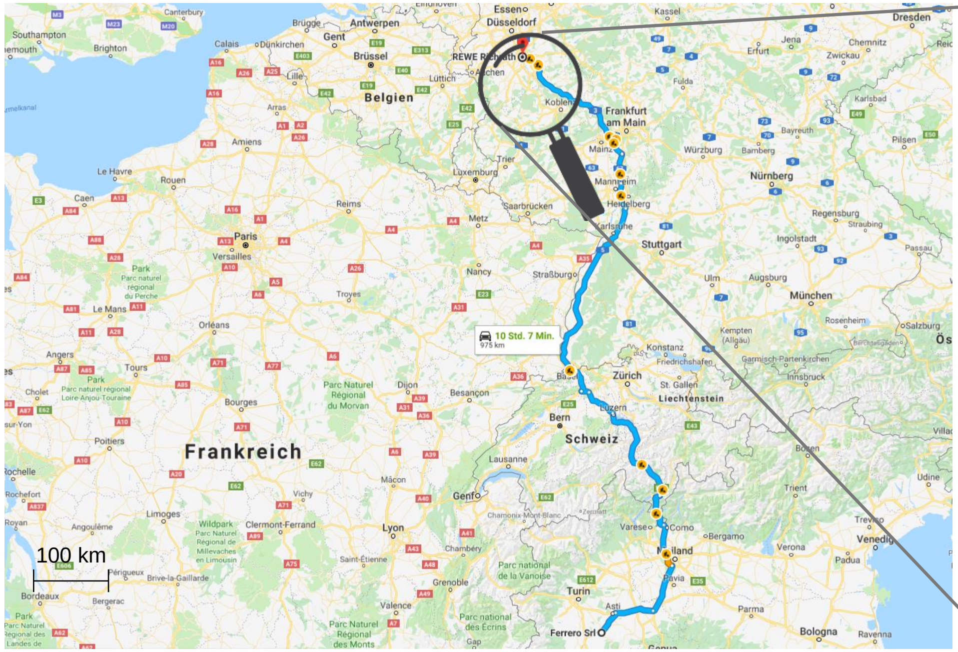
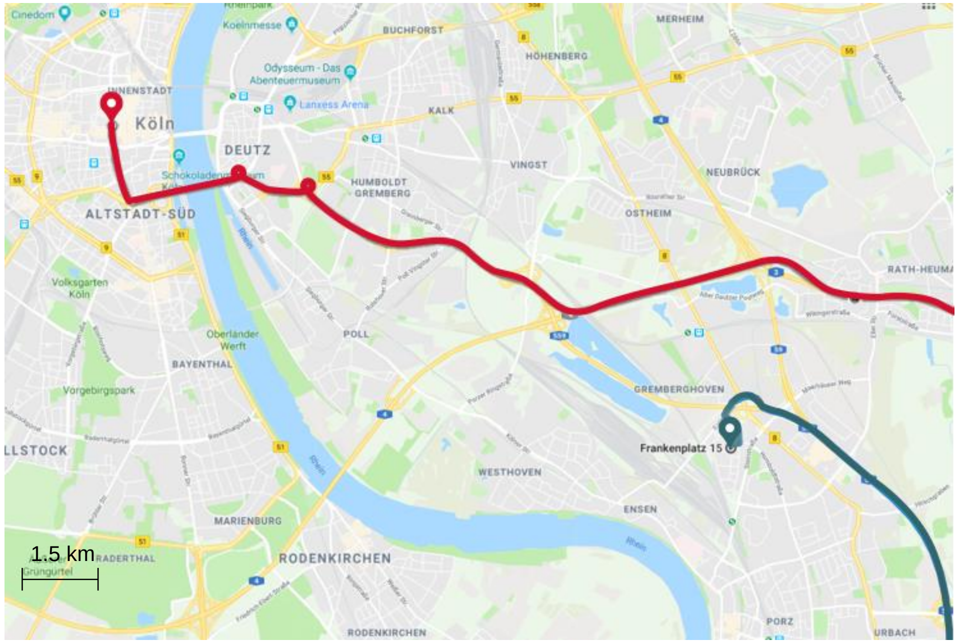
HUB AND SPOKE MODEL – EXAMPLE

Exemplary heavy-duty long haul trip



- Considering an exemplary heavy-duty route, from Alba, Italy to Cologne, Germany
- The total trip length is 975 kilometers

Impact of delivering to the spoke on the exemplary trip



🟥 Direct trip 🟦 Spoke trip

- The difference between the direct trip and the trip to the spoke is approximatively 12 kilometers

Source: Google, FEV

Agenda

- Future pathways towards clean on-road transportation
  - Usage: Strategies for efficient goods transportation
  - Electrification: The potential of electrified and electric powertrains
  - Efficiency: Further measures on vehicle side
  - Energy carriers: Alternative fuels as a key contributor

Drivers for electrification differ between the vehicle classes – for passenger cars regulation is key, while commercial vehicles are driven by TCO

EVALUATION OF MAIN DRIVERS FOR ELECTRIFICATION

Passenger car		Heavy-duty	
Regulation	🟢	Regulation	🟠
Usage profile	🔴	Usage profile	🔴
TCO	🟠	TCO	🟢

- The drivers for electrification of vehicles differs considerably between passenger cars and heavy-duty vehicles
  - Regulation drivers and usage profile are significantly different
  - Total cost of ownership is of different importance
- Less market adoption for electric heavy-duty vehicles expected than for passenger cars
  - Regulation does not focus that much on electrification as for passenger cars
  - With high weight and long distances the usage profile requires a high energy density of the energy carrier
  - In a total cost of ownership balance electric vehicles are only beneficial in limited use-cases

Driver relevance: 🟢 high relevance 🟠 medium relevance 🔴 low relevance

TCO: Total-cost-of-ownership
Source: BMW, Nikola, FEV

First units of the all-electric Mercedes-Benz eActros truck for the heavy-duty distribution sector have been rolled out to customers in 2018

BATTERY ELECTRIC TRUCKS – EXAMPLE

- Is based on the “Urban eTruck” concept for a heavy-duty electric distribution truck for urban areas which has been displayed at the IAA Commercial Vehicles show in 2016
- Ten vehicles in two variants, with a gross vehicle weight of 18 or 25 t, will be handed over in the next few weeks to customers
- Aim is to achieve series-production and economically competitive electric trucks for use in HD transport until 2021
- The drive axle is based on the ZF AVE 130
- The drive system comprises two electric motors located close to the rear-axle wheel hubs
  - Liquid-cooled 400 V induction motors,
  - 125 kW per, 485 Nm per e-motor
  - 11,000 Nm torque at wheels
- Two lithium-ion batteries with a capacity of 240 kWh
  - 11 packs: 3 are located in the frame area, 8 underneath
  - For safety, battery packs are protected by steel housings
- Combined Charging System (CCS) standard is used
- Additional weight of about 2.5 t; however, this is mitigated by EU directive 2015/719, which raises the permissible gross vehicle weight for trucks with alternative powertrains by up to 1 t

Source: Daimler, FEV

Hyundai announces to deliver the first of 1,000 fuel cell HD-trucks in Switzerland by the end of 2019

FUEL CELL ELECTRIC TRUCKS – EXAMPLE

- Beginning in 2019 and over a 5-years period, Hyundai Motor and H_2 Energy will provide 1,000 HD FC electric trucks and an adequate supply chain for renewable hydrogen, in Switzerland
- The fuel cell electric truck is being developed according to European regulations:
  - It features a new 190 kW hydrogen fuel cell system with two fuel cell systems connected in parallel
  - It is expected to deliver a single-fueling travel range of approximately 400 km (eight compactly installed hydrogen tanks, installed between the cabin and the rigid body)
  - The refueling time is expected to be ~7 minutes
- Hyundai plans to diversify its fuel cell electric commercial vehicle line:
  - Currently under development is the medium sized fuel cell electric truck (payload: 4~5 tons) which can be used in the public services domain (e.g. cleaning vehicle)

Source: Hyundai, FEV

Volvo Trucks tests a hybrid drive for trucks

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VOLVO TRUCKS

HYBRID TRUCKS – EXAMPLE

- With the Concept Truck unveiled on May 2016, Volvo has developed its first hybrid vehicle designed for long-haul applications
- Concept Truck is the result of the Swedish part of a bilateral research project involving the Swedish energy authority “Energimyndigheten” and the U.S. Department of Energy
- In addition to the improvements in aerodynamics, rolling resistance and reduced weight, the new version also features a hybrid powertrain
- In long-haul transportation, the manufacturer estimates that the hybrid powertrain will allow:
  - The shutting off of the ICE for up to 30% of driving time
  - Fuel savings between 5-10% in fuel, depending on the vehicle type, equipment and driving cycle
  - Up to 10 km of full electric mode range, enabling the vehicle to operate with zero emissions and low noise
  - Kinetic energy recovery from slopes and braking
- The new hybrid powertrain uses Volvo Trucks’ I-See program, taking data from GPS and electronic maps to analyze the driving topography and ensure the most efficient combination of power is used (predictive driving)

Source: Volvo Trucks, FEV

Scania uses a parallel hybrid electric truck for tests in Sweden on an electrified road with overhead catenary lines

HYBRID TRUCKS – EXAMPLE ON AN ELECTRIFIED ROAD

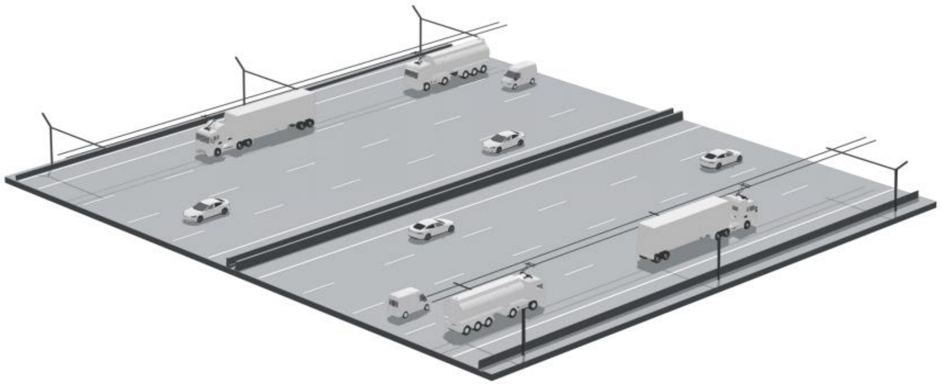
- Hybrid electric truck, combustion engine operated with fuels from renewables
- Automatic pantograph connects and disconnects to overhead electricity lines
- Outside electric highways the truck can be powered by the combustion engine or the battery
- Technologic specifications of the Scania G360 4x2

Driveline topology	Parallel hybrid
Engine displacement	9 liter
Engine rated power	270 kW
Electric motor power	130 kW
Electric motor torque	1,050 Nm
Battery capacity	5 kWh
Pure electric range	Up to 3 km
System voltage	700 V
Weight	9 t

Source: Scania, FEV

The federal state Hessia and the university of Darmstadt in Germany test electrified roads with overhead catenary lines on the German highway

ELECTRIFIED ROAD – EXAMPLE



- Construction and testing of an 10 km long electric highway between the cities Frankfurt and Darmstadt in Germany
- Federal state Hessia and university of Darmstadt lead the project with Siemens as infrastructure provider
- Two project phases
    - Phase 1 : Planning and construction of the highway until end of 2018 with Siemens AG as partner
    - Phase 2: Testing and analysis of the system from 2019 to 2022, vehicle partner to be decided
- Sensor of the truck detect the overhead lines and the pantograph connects and disconnects automatically
- Funding by the federal government € 14.6 million

Source: Hessen Mobil, FEV

For the modeling, FEV has assumed different evolutions of electrified powertrains until 2050

DEVELOPMENT TRENDS ON ELECTRIFIED POWERTRAINS

	~2025	~2035	~2045
Hybrid	■ Optimized combustion engine ■ 48V hybrid system with boosting, limited recuperation and operating point shift functionalities ■ Small e-motor and battery (~2 kWh) ■ Adoption of battery APU	■ Optimized combustion engine ■ 350 V hybrid system with recuperation, operating point shift and sailing functionalities ■ Bigger e-motor and battery (~5 kWh) ■ APU through interface to grid	■ Optimized combustion engine ■ 800 V hybrid system ■ Electric motor and battery (~15 kWh) allowing boosting as well as electric drive for very small ranges ■ APU through interface to grid
Battery electric	■ Dedicated applications with rather small ranges of < 350 km and thus battery capacities of ~500 kWh due to considerably high battery costs ■ Peak power of the electric motor and the power electronics needs to be higher than for a combustion engine to ensure a sufficient continuous power	■ Lower costs – especially for the battery – ease the adoption of battery electric powertrains and enable longer range version to be competitive ■ Two measures allow to use a smaller battery capacity for the same range – Efficiency increase of e-motor, power electronics and battery – Higher usable share of the battery capacity	■ Costs decrease further and thus improve the competitive position of battery electric powertrains ■ Both – efficiency increase in the powertrain and an increasing usable share of the battery capacity – continue to reduce the battery capacity that is necessary to cover a given range
Fuel cell electric	■ Hybrid powertrain, since it has two energy storages: H_2 tank and battery ■ FEV expects a hybrid setup where the fuel cell power matches the power of a comparable combustion engine, adding a 10-20 kWh battery ■ Introduction in applications with comparably low power since costs scale with the fuel cell power	■ Lower costs for the fuel cell stack and the hydrogen tank favor the adoption of fuel cell electric powertrains – Lower costs for the fuel cell stack enable higher power applications to become competitive ■ Efficiency increases in the fuel cell system, power electronics, e-motor and battery are expected	■ Further reduced costs and increased efficiencies promote a wider uptake of fuel cell electric powertrains ■ With the market uptake more hybrid set-ups are likely to enter the market since the optimal size of the fuel cell stack and the battery is coupled to the use-case of the vehicle

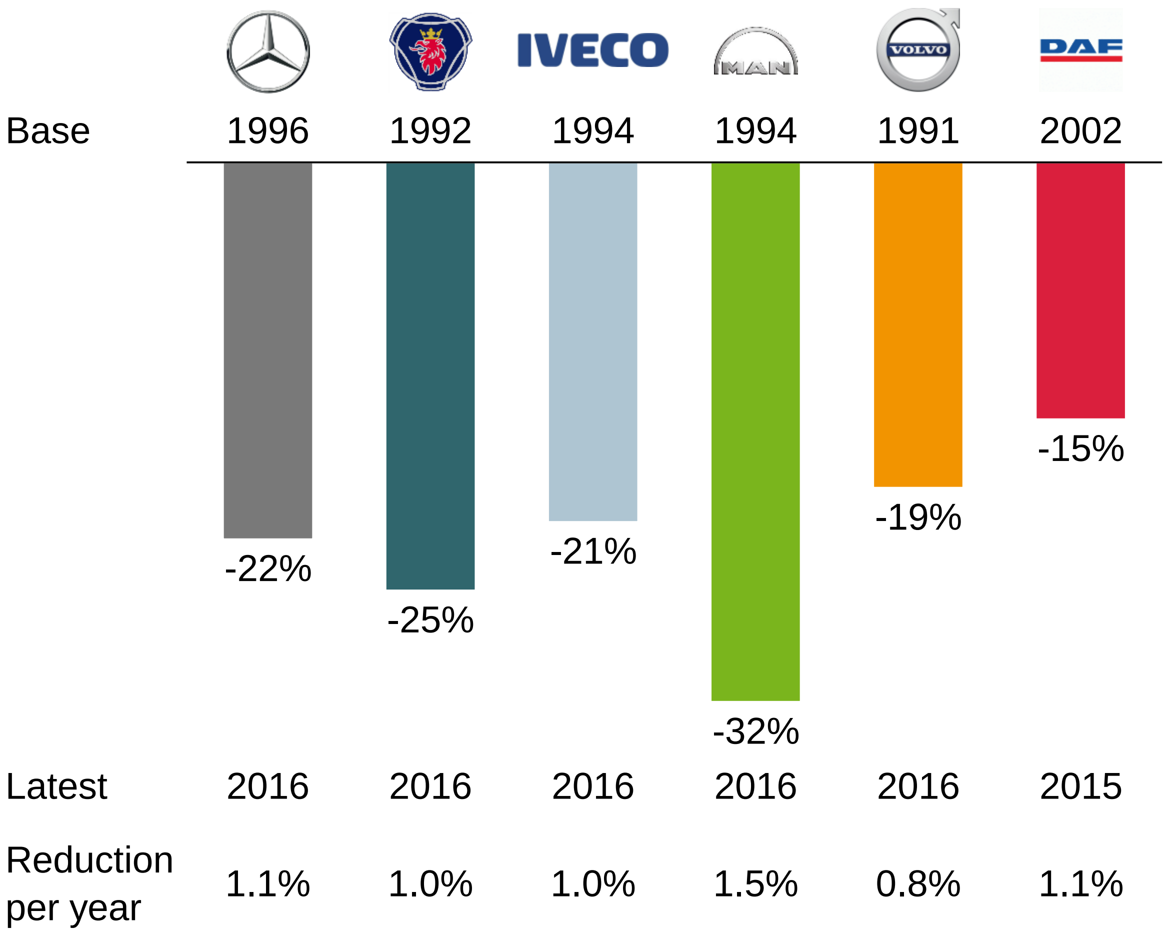
Source: FEV

Agenda

- Future pathways towards clean on-road transportation
  - Usage: Strategies for efficient goods transportation
  - Electrification: The potential of electrified and electric powertrains
  - Efficiency: Further measures on vehicle side
  - Energy carriers: Alternative fuels as a key contributor

Six vehicles of different truck OEM achieved about 1% of fuel efficiency benefit per year in a long term comparison carried out by ACEA

LONG TERM FUEL EFFICIENCY COMPARISON DEVELOPMENT FOR SELECTED OEM

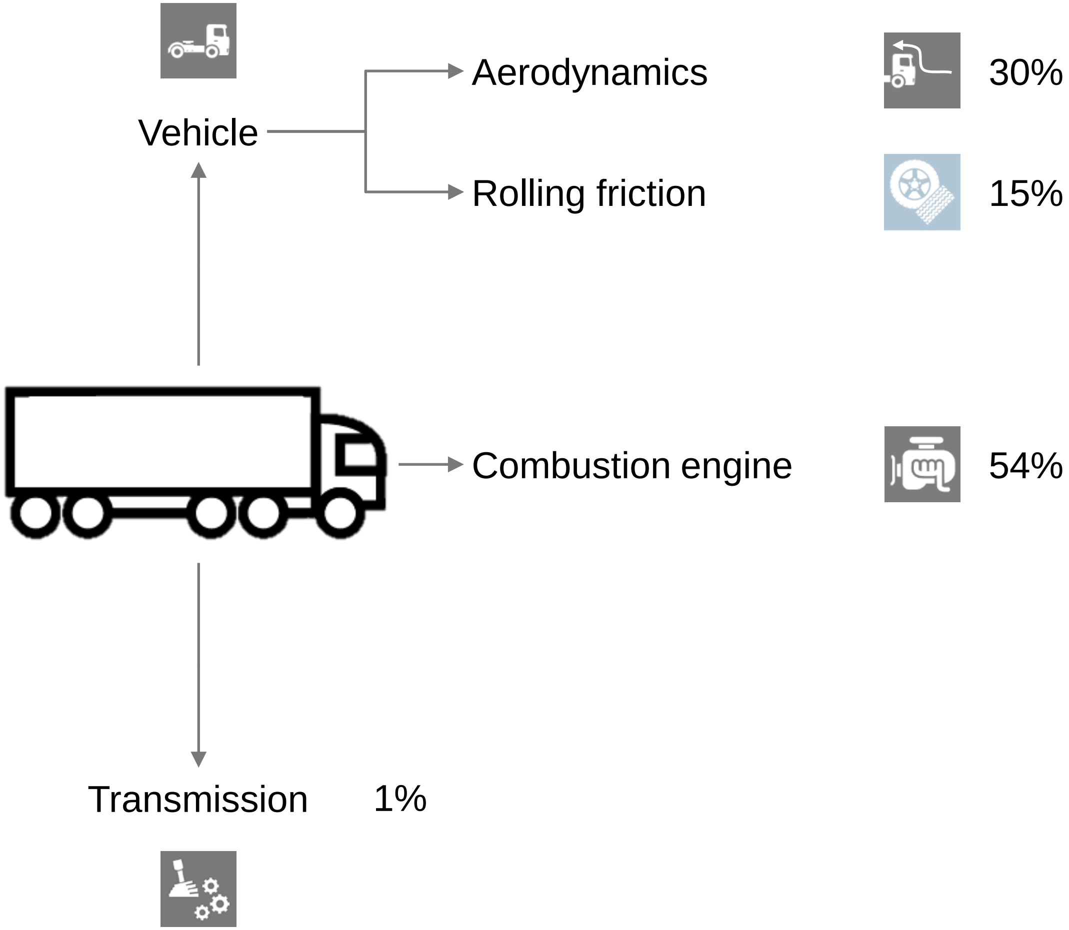


- Test were performed by independent companies with on-road measurement
- Tests were performed with the same mission profile, speed and payload, comparable vehicle configuration and representative version at the time of its introduction
- In the same time period from 1991 to 2016 the pollutant emissions were reduced from Euro I to VI by 95% for NO_x and 98% for particulate matter

Results are OEM specific and not directly comparable. Test were performed by different agencies and with different boundary conditions.
Source: ACEA, FEV

The two most important areas for efficiency improvements are aerodynamics and the combustion engine

INDICATIVE FUEL ENERGY USAGE SHARE OF A HEAVY-DUTY COMMERCIAL VEHICLE ON THE HIGHWAY



Vehicle

Aerodynamics 30%

Rolling friction 15%

Combustion engine 54%

Transmission 1%

- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, 100% of fuel energy are roughly lost at
  - 54% in the combustion engine
  - 30% in aerodynamic drag
  - 15% in rolling friction
  - 1% in transmission
- High potential in optimizing vehicle technology for the most important operation point
  - Recently many design changes optimizing vehicle aerodynamics were introduced to the market
  - Rolling friction improvements mostly come evolutionary to the market

Source: NRC, FEV

FEV estimates that future glider design will be present on the CV market for at least 10 years after introduction

REFERENCE GLIDERS AND VEHICLE TECHNOLOGY IMPROVEMENTS

	Baseline	Improved	New cabin	Cabinless
Reference / example				
Market introduction	Today	~2025	~2035	~2045
Aerodynamic measures	Today's standard	■ Improvements in aerodynamic are mostly driven by adding static metal / plastic covers and extenders to baseline's design ■ No modifications to the body-in-white	■ Completely new body-in-white for the cabin ■ Wide use of active elements, together with sensors, to optimize truck's aerodynamic according to driving conditions	■ The absence of the cabin shifts the design focus ■ Aerodynamic optimization of the truck will be realized through dedicated forms, applied to the tractor or directly to the front of trailers
Lightweight measures		■ Use of aluminum	■ Use of composites materials	■ Wider use of composites
Rolling resistance measures		■ General improvements in nowadays technology	■ Optimized control of tires' pressure, through sensing	■ Radical change in design will shift main improvement's focus, compared to prior generations
Auxiliaries		■ Electric	■ Electric	■ Radical change in design will shift main improvement's focus, compared to prior generations

Source: FEV

Up to 55% of break thermal efficiency are targeted for heavy-duty engines, steps towards this can be realized by various improvement areas

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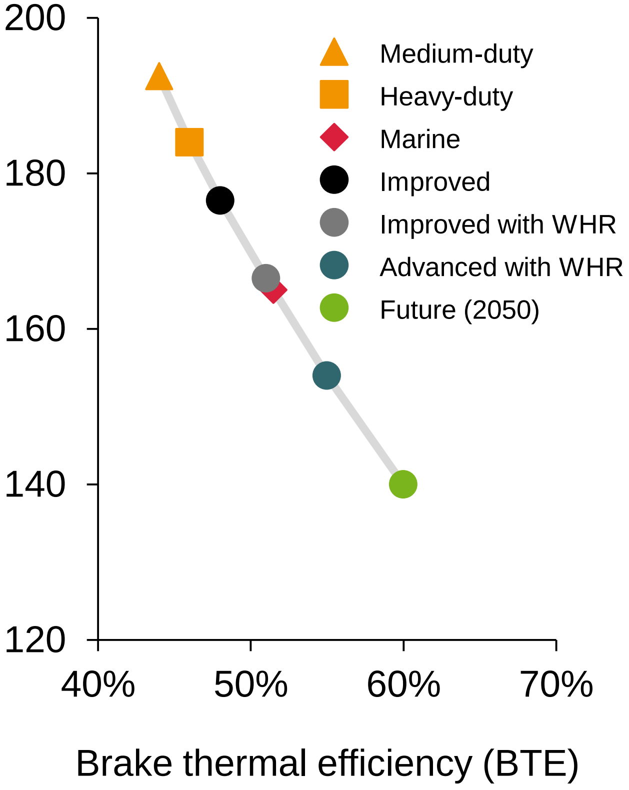
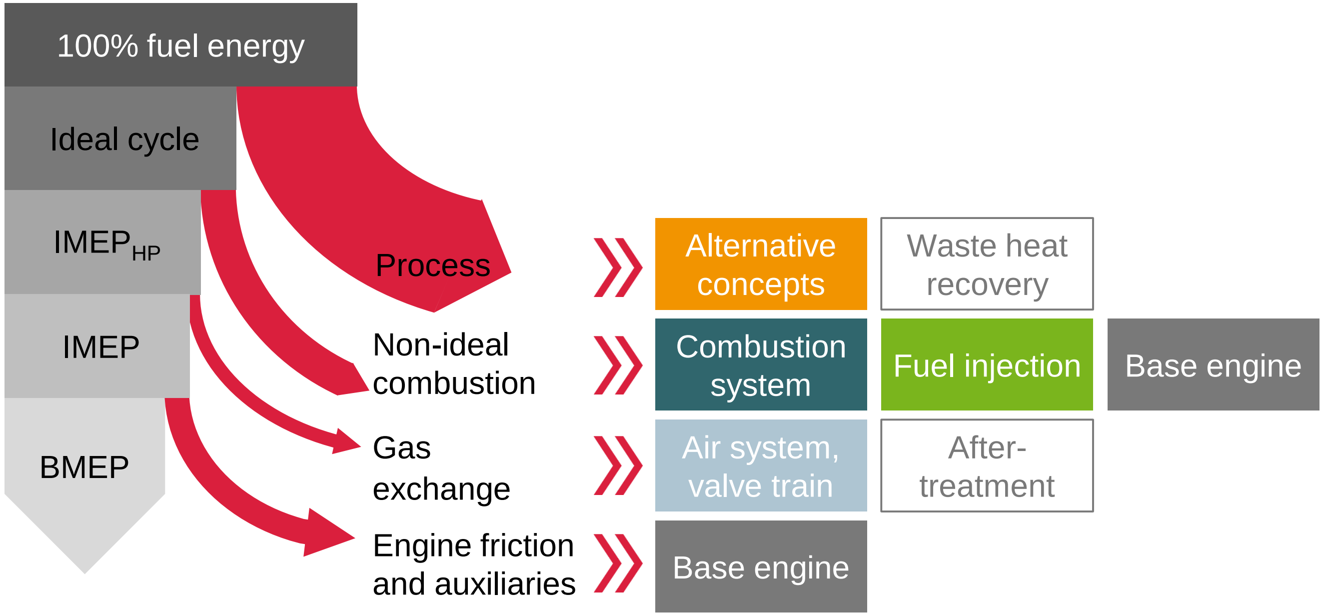
COMBUSTION ENGINE – EFFICIENCY INCREASE TARGET, LOSS SOURCES AND IMPROVEMENT AREAS

Fuel consumption in g/kWh



Schematic energy losses

Improvement areas

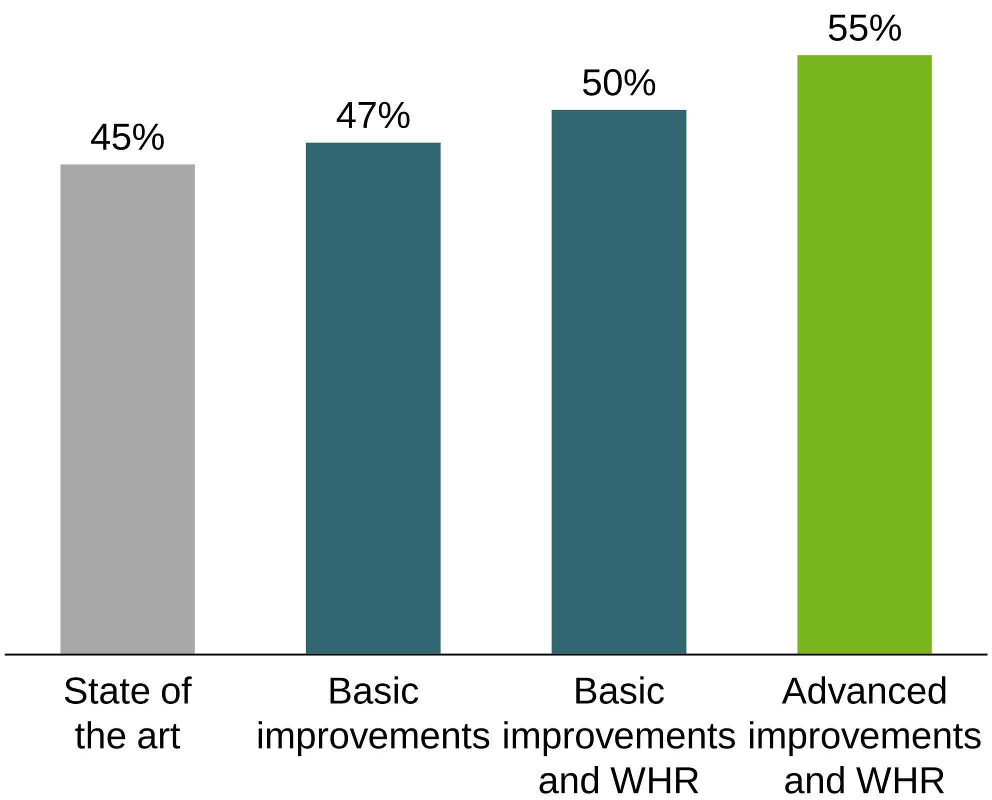


Remark: cycle average BTE values ~3-5 percentage points less for long-haul heavy-duty truck operation and up to >10% less for distribution trucks (strongly depending on cycle)
IMEP: Indicated mean effective pressure, BMEP: Break mean effective pressure, HP: high-pressure, WHR: Waste heat recovery
Source: FEV

The efficiency increase of engines is expected to happen in several steps and touching all parts of the engine

COMBUSTION ENGINES – MEASURES TO INCREASE THE EFFICIENCY

Potential brake thermal efficiency development



WHR: Waste heat recovery
Source: FEV

- The brake thermal efficiency of today's heavy-duty engines is around 45% and with highly sophisticated measures up to 55% are targeted
  - Basic improvements can gain benefits at limited costs
  - Waste heat recovery systems enable high benefits but are expensive and complex to integrate
- Measures to reach this target influence all parts of the engine: base engine, combustion system, air system, valve train and fuel injection system
- Alternative concepts as opposed piston engine and split cycle are under discussion
  - Promise high benefits
  - Yet in an early stage of development

Daimler took several measures to increase the efficiency between 1st and 2nd generation of their OM471 engine

FEV CONSULTING

COMBUSTION ENGINE – CASE EXAMPLE DAIMLER'S OM471 EVOLUTION

		OM471 1st generation	OM471 2nd generation
Bore	mm	132	132
Displacement	l	12.8	12.8
Compression ratio	-	17.3	18.3
Injection nozzle		7-hole	8-hole
Piston bowl			Stepped bowl
Max. injection pressure	bar	2300 (rail pressure 900 bar)	2700 (rail pressure 1160 bar)
Boosting system		Asymmetric turbine w/ wastegate	Asymmetric turbine w/o wastegate
Asymmetric rate (symmetric = 100%)	%	34	56
Aftertreatment		DOC, DPF, SCR, ASC	DOC,DPF, SCR, ASC
Rated speed	rpm	1800	1600
Max. torque	Nm	2500	2100 / 2200 / 2300 / 2500 / 2600
Rated power	kW	375	310 / 330 / 350 / 375 / 390
Engine-out NO_x emission			~ 50% higher compared to 1st generation
Fuel consumption			~ 3% less compared to 1st generation
Diesel exhaust fluid consumption		~ 3% of Diesel consumption	~ 5% of Diesel consumption

Source: MTZ 06/2016, Daimler Vienna Motor Symposium 2016, FEV

For the modeling, FEV has assumed different evolutions of conventional powertrains until 2050

MAIN POWERTRAINS

	~2025	~2035	~2045
Compression ignition	■ Integration of Start / Stop capacity ■ Rightsizing of the engine together with certain measures such as optimized injection system and crank train ■ Adoption of turbo compound	■ Increased injection and peak firing pressures or integration of Miller cycle and Variable Compression Ratio (VCR) ■ Adoption of organic rankine cycle	■ Further improvements ■ Adoption of advanced organic rankine cycle
Spark ignition	■ Many spark ignition engines for heavy-duty applications are based on compression ignition engines ■ Adaptions include ignition system, turbocharger, mixture preparation and engine management system	■ Base engine improvements and hybridization as for compression ignition engines (spark ignition engines are derived from them) ■ Increase of waste heat recovery systems, especially for stoichiometric combustion ■ Increase of customized cylinder heads	■ Further improvements, following the compression ignition engine trends ■ Improvements of the valvetrain as variable valve timing and lift or variable compression ratio ■ Potential for lean combustion
Hydrogen combustion	■ Adaption of existing engines ■ Basis for the adaption can be a diesel or methane combustion engine; the effort is significantly lower to adapt a methane combustion engine	■ Efficiency increases of the base engine and hybridization as expected for the compression ignition / spark ignition engines ■ Customized cylinder heads and turbo compound seem possible	■ Further efficiency increase expected, e.g. variable valve lift / timing and a variable compression ratio (VCR) ■ Upgrade of waste heat recovery systems seems possible

Source: FEV

Agenda

- Future pathways towards clean on-road transportation
  - Usage: Strategies for efficient goods transportation
  - Electrification: The potential of electrified and electric powertrains
  - Efficiency: Further measures on vehicle side
  - Energy carriers: Alternative fuels as a key contributor

Various opportunities and threats drive the market development of alternative liquid fuels

POSITIVE AND NEGATIVE DRIVERS FOR FUTURE USE OF ALTERNATIVE LIQUID FUELS

ILLUSTRATIVE

Positive drivers

Well-to-wheel regulation (if implemented)

EU fuel quality directive

EU renewable energy directive

EU Energy Roadmap

Local immission reduction

Technology push

Independence from fossil fuels and imports

Negative drivers

Tank-to-wheel regulation

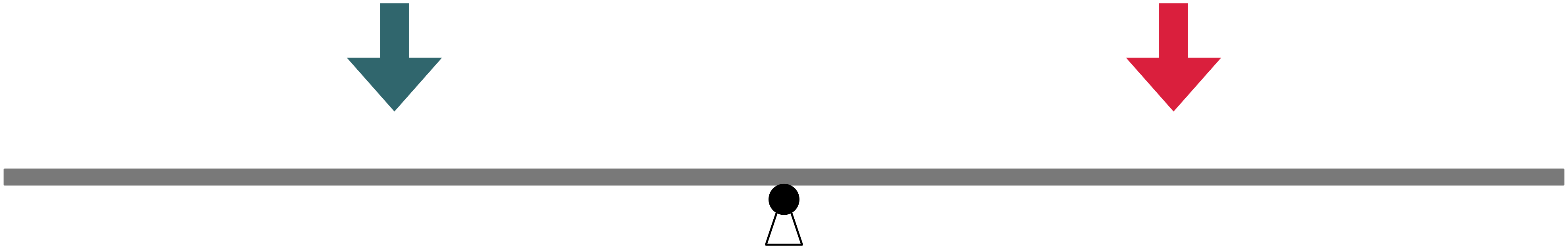
Lack of fuel norms

Production costs

Market pull

Competition with food production

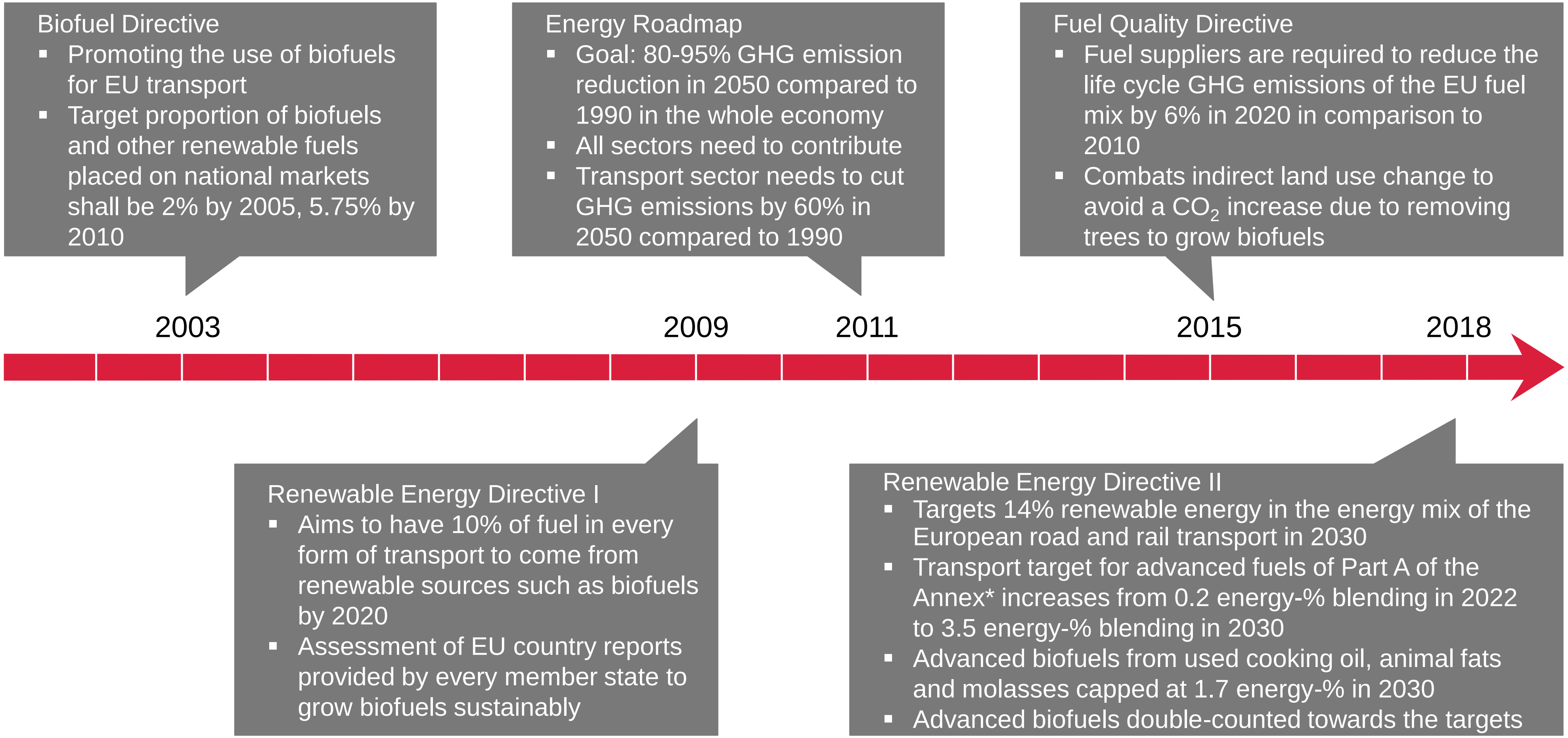
Land-use change



Source: FEV

EU directives target the reduction of GHG emissions by promoting biofuels as alternative and sustainable fuels for the European transport sector

FUEL ROADMAP OF THE EUROPEAN UNION



Biofuel Directive
- Promoting the use of biofuels for EU transport
- Target proportion of biofuels and other renewable fuels placed on national markets shall be 2% by 2005, 5.75% by 2010

Energy Roadmap
- Goal: 80-95% GHG emission reduction in 2050 compared to 1990 in the whole economy
- All sectors need to contribute
- Transport sector needs to cut GHG emissions by 60% in 2050 compared to 1990

Fuel Quality Directive
- Fuel suppliers are required to reduce the life cycle GHG emissions of the EU fuel mix by 6% in 2020 in comparison to 2010
- Combats indirect land use change to avoid a CO_2 increase due to removing trees to grow biofuels

Renewable Energy Directive I
- Aims to have 10% of fuel in every form of transport to come from renewable sources such as biofuels by 2020
- Assessment of EU country reports provided by every member state to grow biofuels sustainably

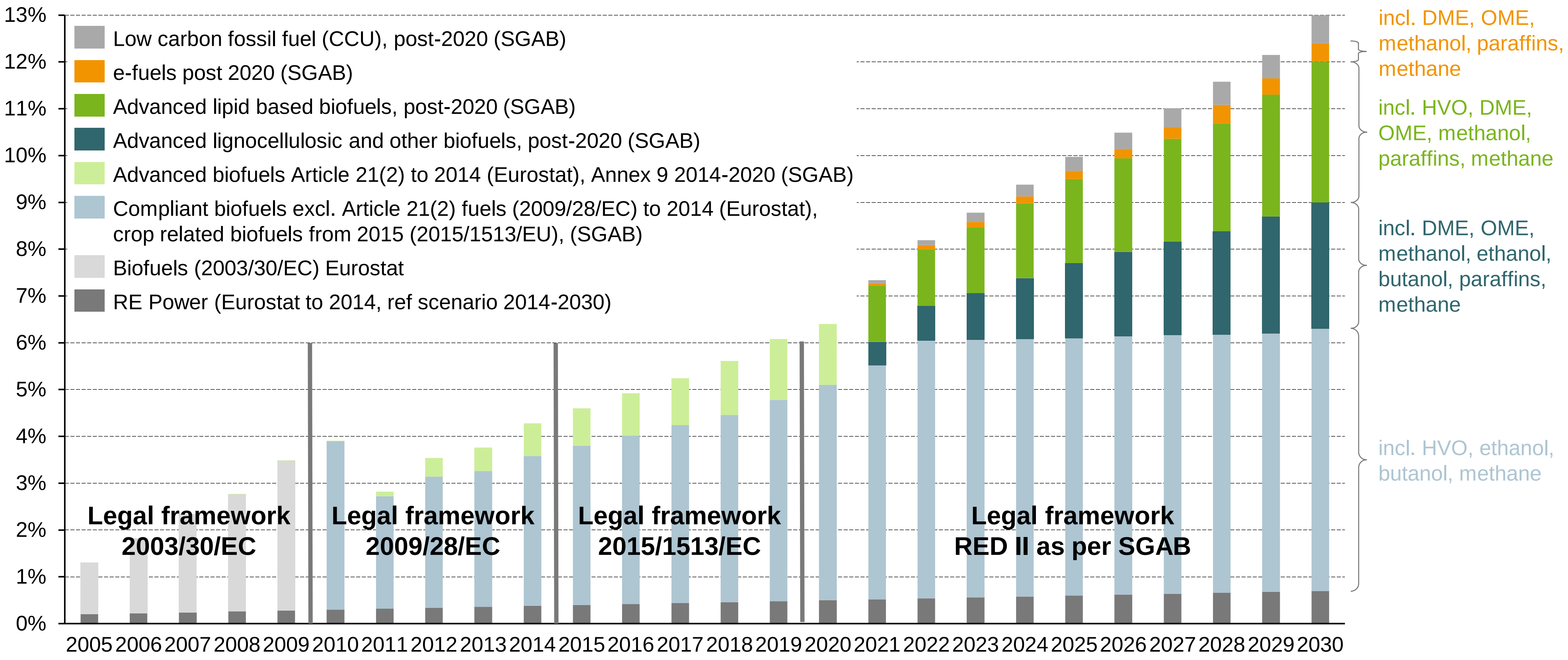
Renewable Energy Directive II
- Targets 14% renewable energy in the energy mix of the European road and rail transport in 2030
- Transport target for advanced fuels of Part A of the Annex* increases from 0.2 energy-% blending in 2022 to 3.5 energy-% blending in 2030
- Advanced biofuels from used cooking oil, animal fats and molasses capped at 1.7 energy-% in 2030
- Advanced biofuels double-counted towards the targets

*Includes fuels from non-food-based biofuels, renewable power to liquid fuels, waste-based fuels and renewable electricity used in PHEVs and BEVs

Source: European Commission Directives 2003/30/EC, 2009/28/EC, 2009/30/EC, 2015/1513, 2016/0382, FEV

Scenario of REDII reaches 13% of energy from renewables in 2030 without double counting – high impact of HVO, ethanol, butanol and methane

BIOFUELS ENERGY-SHARE IN OVERALL TRANSPORT – OUTLOOK 2030



Note: Food-crop-based fuels is assumed to level out at 19 Mtoe, which is slightly below the cap volume allowed;
The advanced lignocellulosics, and the advanced HVO both reach 10.3 Mtoe and 15.5 Mtoe;
E-fuel provides 1.7 Mtoe, whereas Low Carbon Fuels provide 2.4 Mtoe;
Source: European Commission, FEV

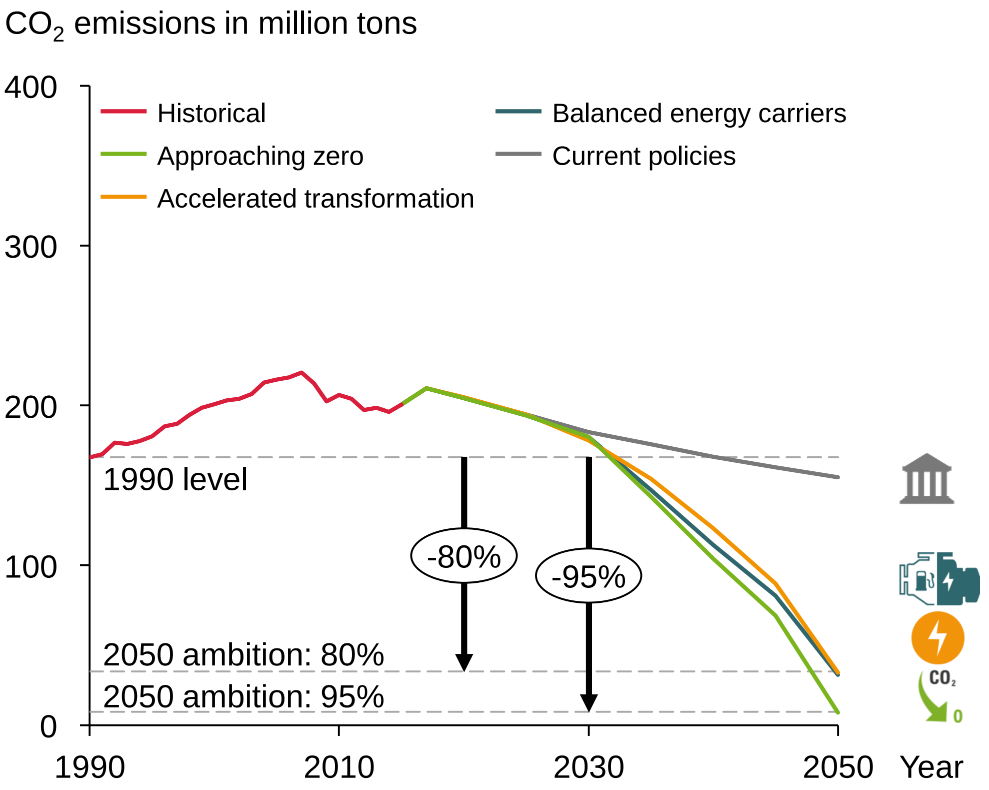
Agenda

- Executive summary
- Framework and long-term scenarios for HD on-road transportation
- Technology options towards 2050
- Future pathways towards clean on-road transportation
- Reduced GHG emissions with holistic technology strategies
- CO_2 abatement costs for selected reference trucks
- TCO performance of underlying reference trucks
- Life-cycle analysis for HD trucks

FEV analyzes pathways to achieve long-term CO_2 emission reduction ambitions for on-road transport – the following chapters detail the results

SUMMARY OF CO_2 EMISSIONS ACROSS THE SCENARIOS

Extended tank-to-wheel balance

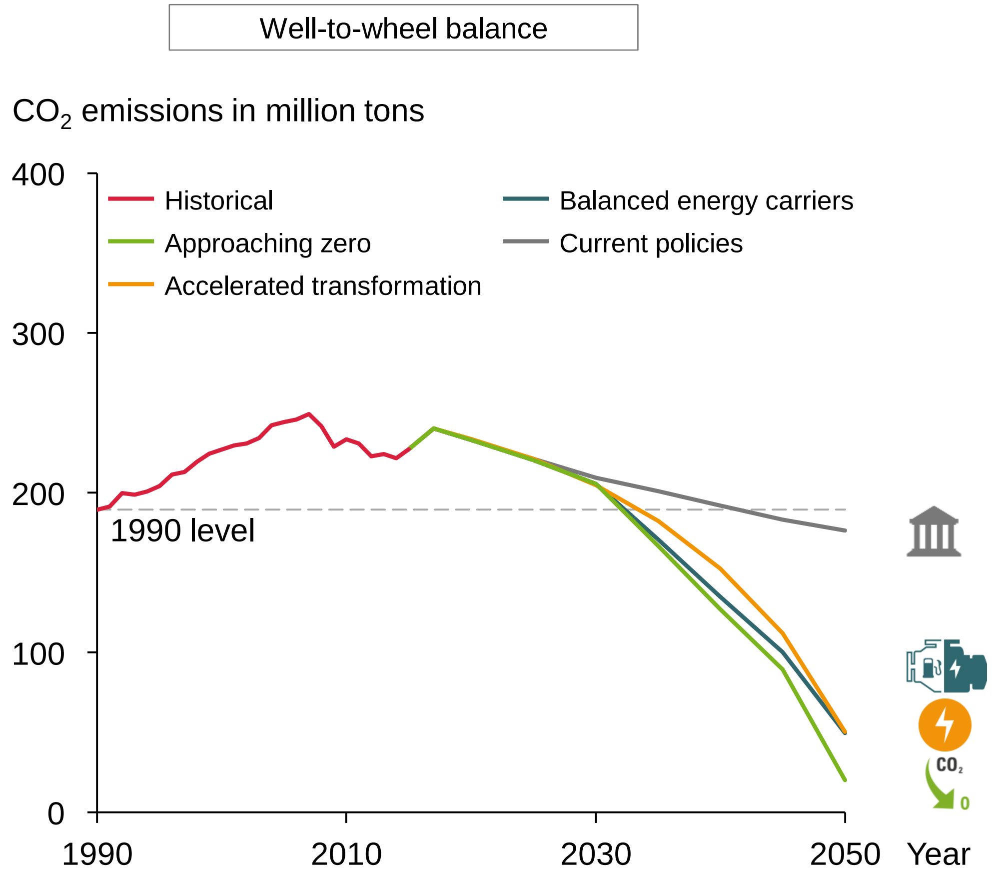


- FEV analyzes pathways towards a low carbon heavy-duty transport sector in four scenarios
  - In all scenarios the development between 2018 and 2030 is very similar since regulations are fixed; technology decisions have a low bandwidth to change
  - Most, but not all OEMs, comply with the CO_2 emission reduction regulation defined for 2030
- After 2030, the current policies scenario assumes a ~constant pace of reducing carbon emissions
- The balanced energy carriers scenario and accelerated transformation achieve their target at a similar pace, but on very different pathways
- The approaching zero scenario has the highest pace of CO_2 emission reduction and accelerates strongest between 2040 and 2050 to reach its target

The extended tank-to-wheel balance considers the CO_2 emissions created when conversing the energy carrier to kinetic energy and a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

In the well-to-wheel balance a similar picture as in the extended tank-to-wheel balance emerges

SUMMARY OF CO_2 EMISSIONS ACROSS THE SCENARIOS

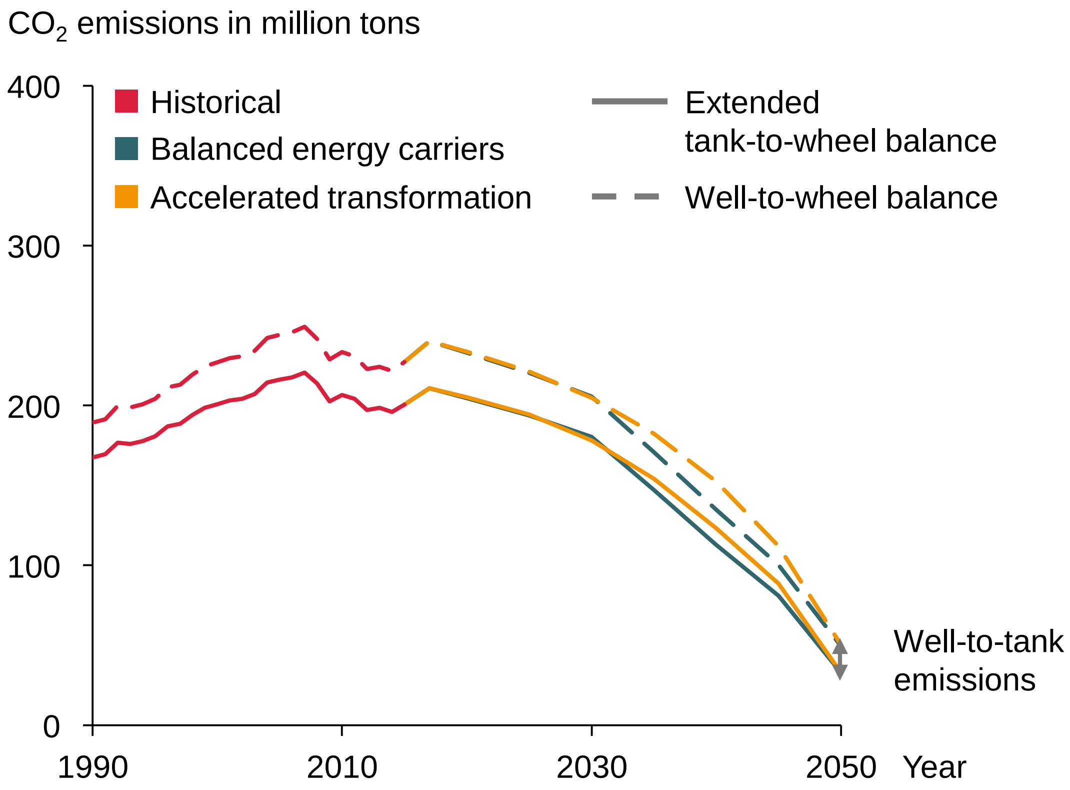


- In the well-to-wheel balance the result is similar to the results in the extended tank-to-wheel balance
  - The same assumptions apply
  - Only change is to consider the emission from well-to-tank
  - The course of the CO_2 emissions is nearly parallel to the extended tank-to-wheel balance but on a somewhat higher level

The well-to-wheel balance considers the CO_2 emissions created when producing, transporting and conversing the energy carrier to kinetic energy as well as a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

The difference between well-to-wheel and extended tank-to-wheel balance reduces over time

SUMMARY OF CO_2 EMISSIONS IN BOTH BALANCES FOR THE TWO LEAD SCENARIOS



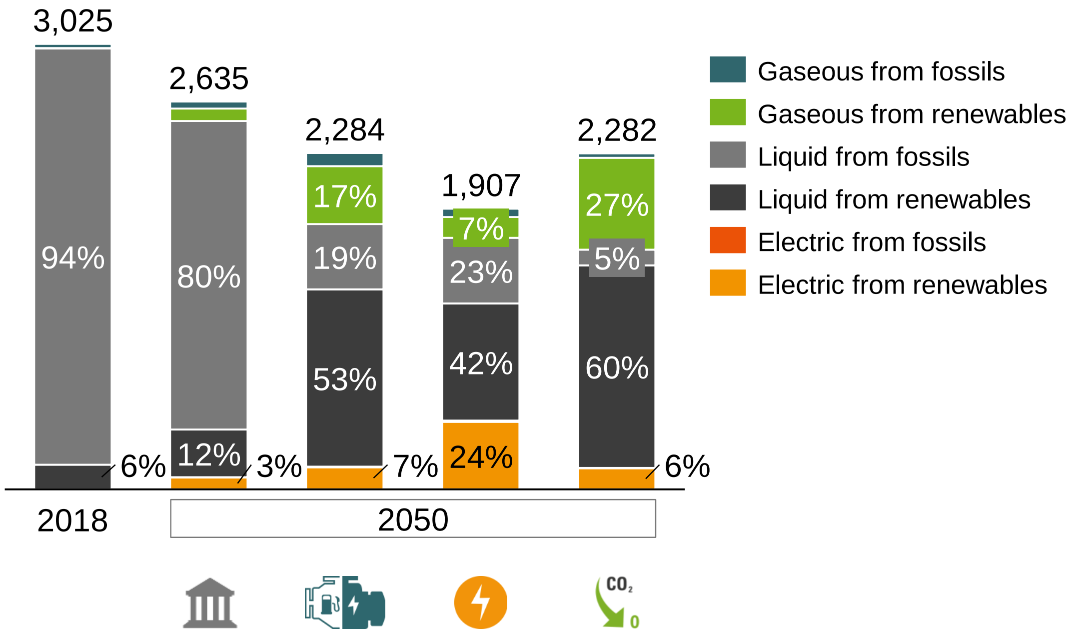
- Over time the difference between extended tank-to-wheel and well-to-wheel balance reduces
  - Due to improvements in the energy provision from well-to-tank
  - Led by fuels from power-to-x processes and electricity from renewables that nearly emit no CO_2 from well-to-tank

Source: FEV

The final energy demand develops differently in all scenarios – as well in total energy demand as in the distribution to the energy carriers

SUMMARY OF THE STOCK OF HEAVY-DUTY VEHICLES ACROSS THE SCENARIOS

Final energy demand by energy carrier in PJ



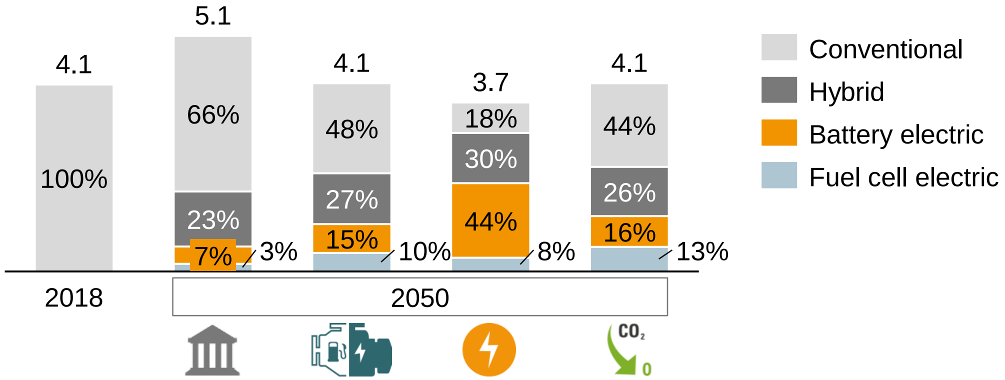
- The final energy demand develops differently between 2018 and 2050 in the four scenarios
  - The overall energy demand is lowest in the accelerated transformation scenario where also the demand for electricity is highest
  - In the current policies scenario liquids from fossils still dominate the energy demand
  - In the balanced energy carriers and approaching zero scenario the demand for liquids from renewables are the dominating category
- There is a high demand for liquid fuels from renewables in all three scenarios that achieve an ambitious CO_2 emission reduction of at least 80% in 2050 compared to 1990
  - At least 23 billion liters in the accelerated transformation scenario and up to 40 billion liters in the approaching zero scenario

Source: FEV

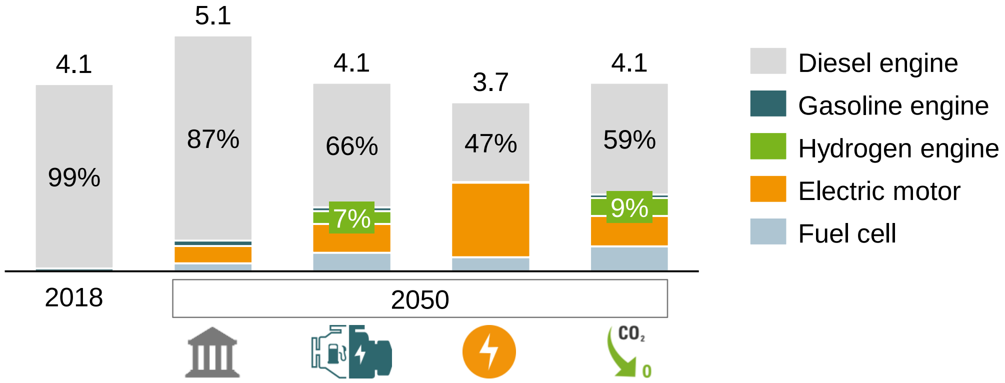
Stock sizes and distribution of the electrification level and main energy conversion system differ between the scenarios

SUMMARY OF THE STOCK OF HEAVY-DUTY VEHICLES ACROSS THE SCENARIOS

Stock of heavy-duty vehicles by electrification level



Stock of heavy-duty vehicles by main energy conversion system



Source: FEV

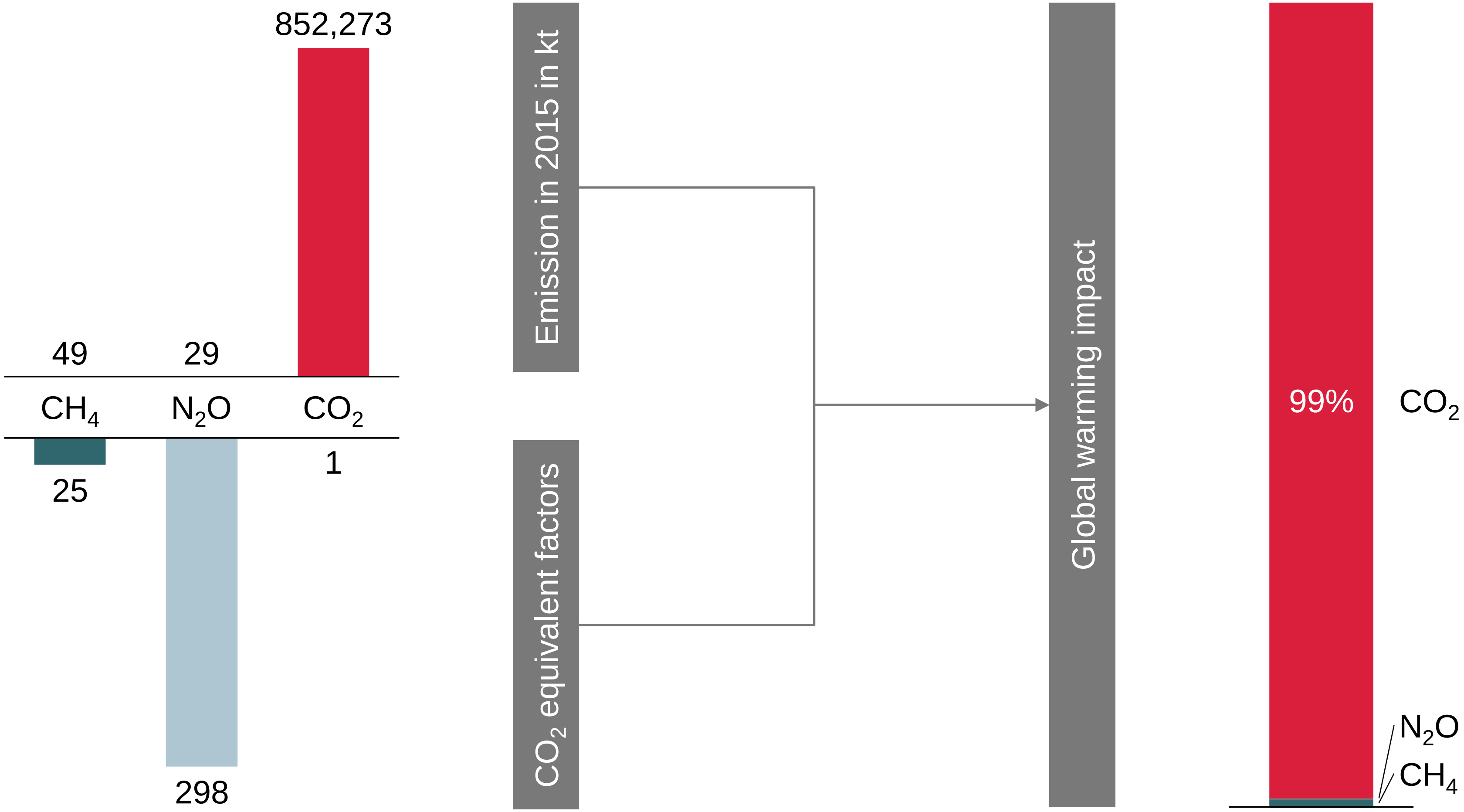
- The stock develops differently in most scenarios between 2018 and 2050
  - Only the balanced energy carriers and approaching zero scenario show similarities due to their similar presumption
  - Total stock size is highest in the current policies scenario and lowest in the accelerated transformation scenario
  - Distribution in electrification level and main energy conversion system differs
- In the accelerated transformation scenario the share of battery electric vehicles is higher than in any other scenario
- The current policies scenario stays dominated by conventional powertrains and diesel engines

Agenda

- Reduced GHG emissions with holistic technology strategies
  - Energy demand model: Key functionalities and assumptions
  - Current policies scenario
  - Balanced energy carriers scenario
  - Accelerated electrification scenario
  - Approaching zero scenario

FEV's analysis focuses on CO_2 emissions since these account for 99% of the global warming in the transport sector

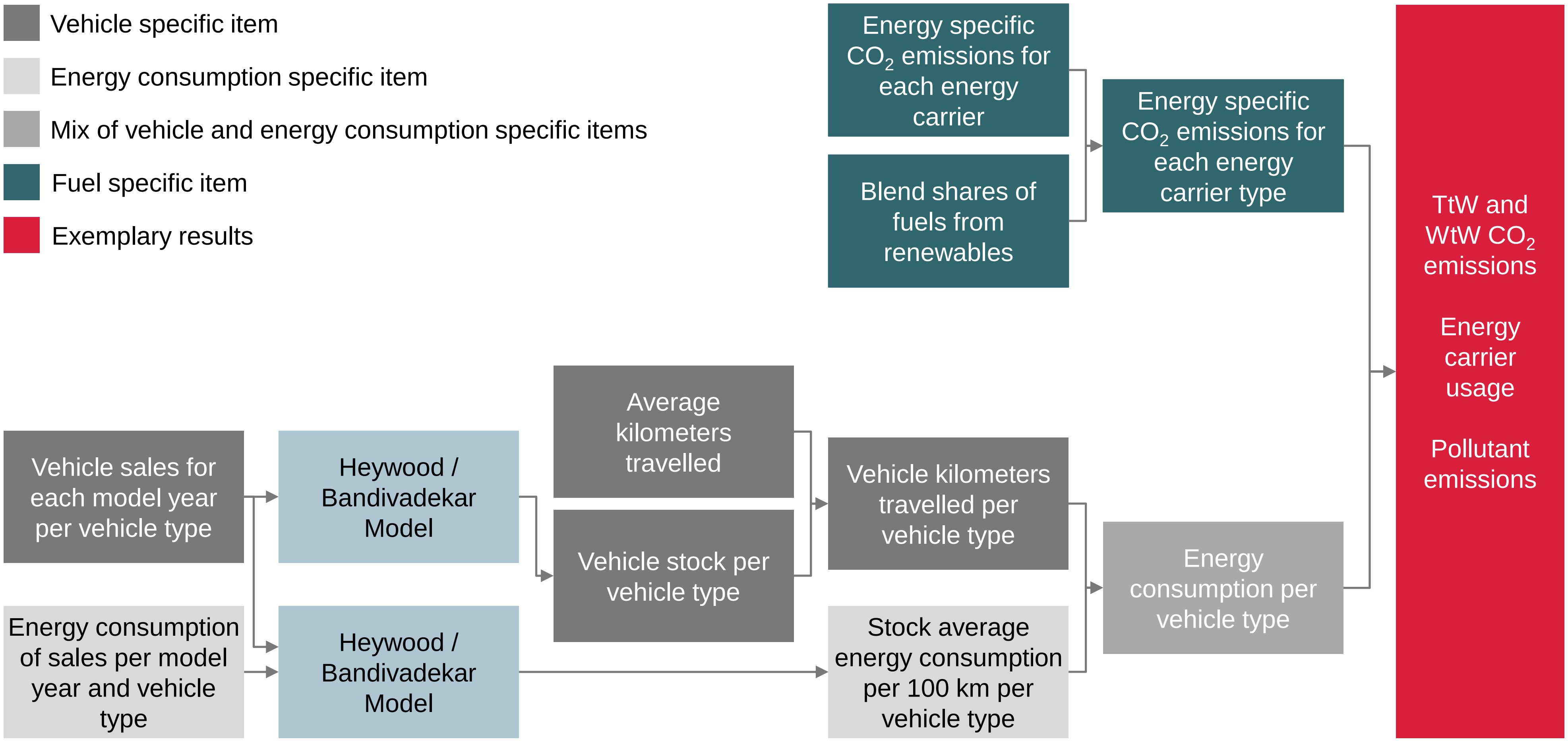
GLOBAL WARMING IMPACT OF CO_2, N_2O AND CH_4



Source: European Commission, UNFCCC, FEV

FEV calculates CO_2 emissions by integrating the vehicle stock, its energy consumption and energy carriers

APPROACH – STRUCTURE OF THE ENERGY DEMAND MODEL



■ Vehicle specific item

□ Energy consumption specific item

▨ Mix of vehicle and energy consumption specific items

🟦 Fuel specific item

🟥 Exemplary results

Source: FEV

Representative baseline heavy-duty trucks for long and regional haul are described below

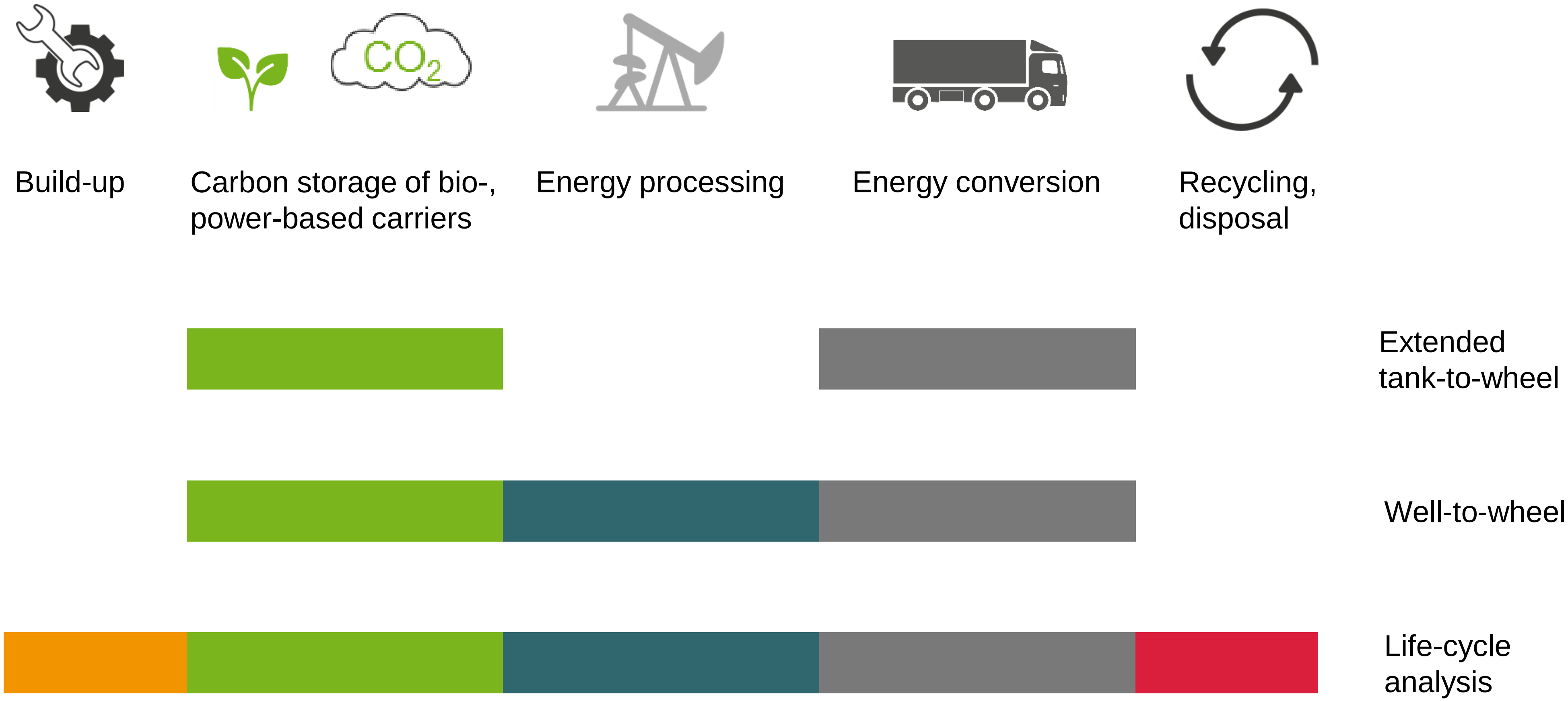
REPRESENTATIVE BASELINE HEAVY-DUTY TRUCKS FOR THE USAGE IN LONG AND REGIONAL HAUL

		Long haul	Regional haul
Model year		2018	2018
Typical GVW range in t		30-40	16-30
Powertrain type		Compression ignition	Compression ignition
Powertrain layout		6 cylinders, inline	6 cylinders, inline
Hybridization		None	None
Energy carrier		93 vol.-% diesel from fossils, 7 vol.-% FAME	93 vol.-% diesel from fossils, 7 vol.-% FAME
Displacement in Liter		12	8
Maximum power in kW		330	240
Maximum torque in Nm		2,400	1,300
Energy demand in real world drive cycle	in MJ/km	10	8
	in l/100km	27	21

Source: FEV

FEV has developed results in three different balances: extended tank-to-wheel (EU regulative approach), well-to-wheel and life-cycle analysis

SELECTED BALANCES TO ACCOUNT CO_2 EMISSIONS



Build-up

Carbon storage of bio-, power-based carriers

Energy processing

Energy conversion

Recycling, disposal

Extended tank-to-wheel

Well-to-wheel

Life-cycle analysis

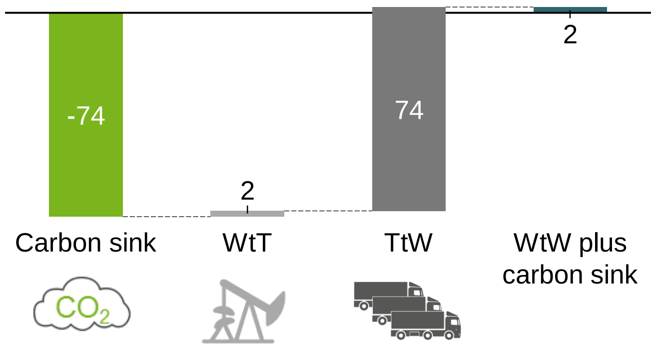
Source: FEV

In the well-to-wheel and extended tank-to-wheel balances fuels from renewables emit much fewer CO_2 than diesel from fossils

EXEMPLARY EXPLANATION OF EMISSIONS IN THE SELECTED BALANCES

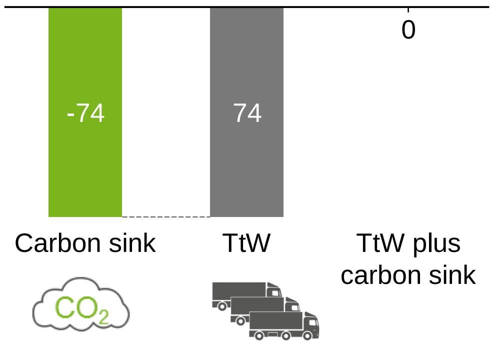
Well-to-wheel – Diesel from PtL¹⁾

In g $CO_{2\text{-eq}}$ per MJ



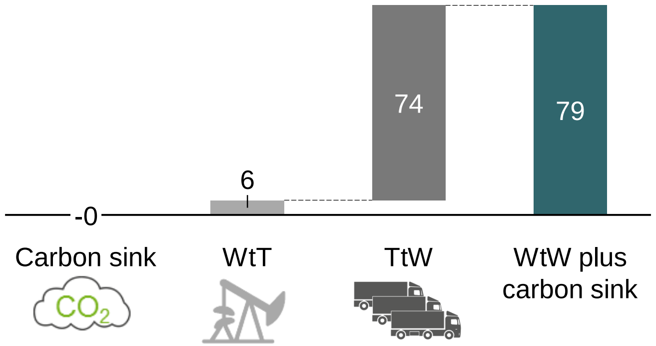
Extended tank-to-wheel – Diesel from PtL¹⁾

In g $CO_{2\text{-eq}}$ per MJ



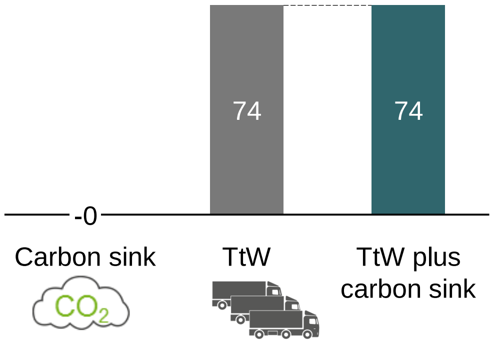
Well-to-wheel – Diesel from fossils

In g $CO_{2\text{-eq}}$ per MJ



Extended tank-to-wheel – Diesel from fossils

In g $CO_{2\text{-eq}}$ per MJ



1) PtL (Power-to-Liquid) process assessed with nearly only electricity from renewables as input; Abbreviations: WtT: Well-to-tank, TtW: Tank-to-wheel, WtW: Well-to-wheel

Source: FEV

FEV and Concawe agreed on the following well-to-wheel CO_2 emissions

FEV CONSULTING

WELL-TO-WHEEL CO_2 EMISSIONS

In g/MJ	2017	2030	2050
Methane from fossils	70	68	65
Methane from PtL		4	2
Methane from biomass	28	25	20
Diesel from fossils	81	79	77
FAME from biomass	53	48	41
Paraffinic diesel from biomass	19	17	15
Paraffinic diesel from PtL		4	2
Higher alcohols from PtL		4	2
DME from PtL		4	2

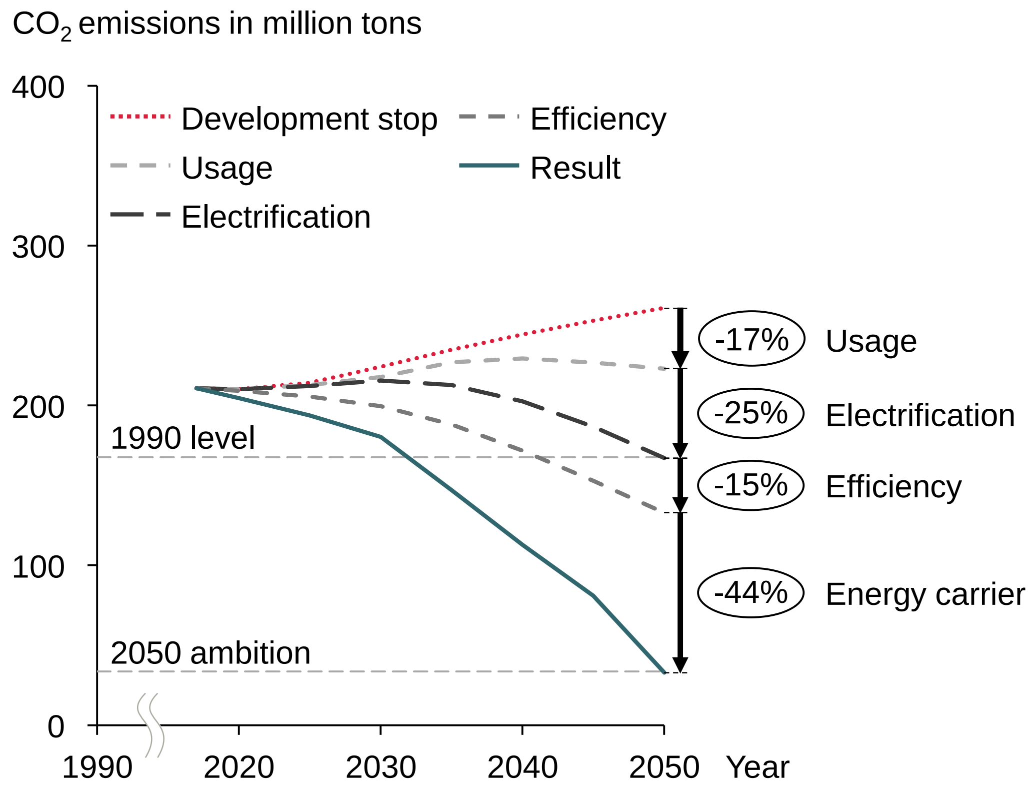
In g/MJ	2017	2030	2050
Gasoline from fossils	79	77	76
Ethanol from biomass	39	28	25
Methanol from PtL		4	2
Electricity mix	136	80	5
Hydrogen from electrolysis from renewable energy		4	2
Hydrogen from electrolysis from electricity mix	200	118	3
Hydrogen from steam methane reforming	120	90	55

Source: Concawe, European Union, FEV

The CO_2 emission reduction consist of four factors: usage, electrification, efficiency and energy carriers

HOW TO READ THE KEY RESULT CHART*

Extended tank-to-wheel balance



- **Development stop** represents the increase of CO_2 emissions driven by increased freight demands; the HD truck fleet is based on 2018 and not changed throughout 2050
- **Usage** represents the CO_2 emission mitigation by more efficient logistics and shifts away from on-road heavy-duty transport; still, the fleet remains unchanged (2018)
- **Electrification** includes the CO_2 emission mitigation by hybrid, battery and fuel cell electric vehicles; the underlying electricity production is based on 2018
- **Efficiency** comprises the CO_2 emission mitigation by more efficient powertrains and gliders that will be introduced over time
- **Energy carriers** conclude the impact of using energy carriers that emit fewer CO_2 in the respective balance; in that group, also the effect of the evolving energy sector towards 2050 is considered

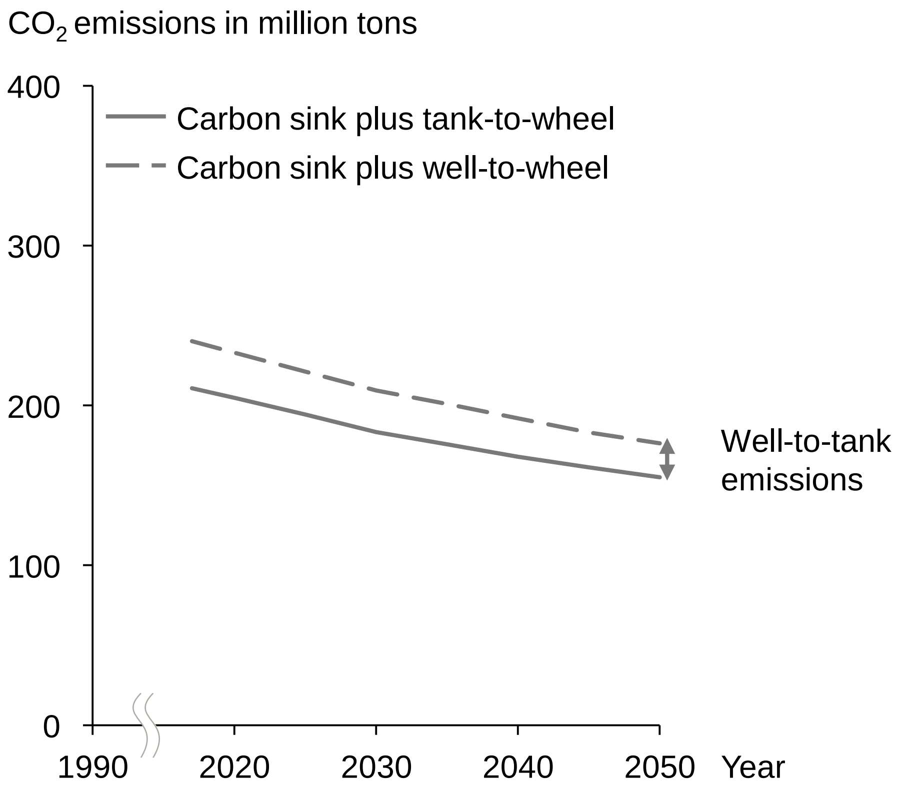
*: Graph is added to explain the different CO_2 reduction pathways; the given numbers originate from the Balanced Energy Carriers scenario
Source: FEV

Agenda

- Reduced GHG emissions with holistic technology strategies
  - Energy demand model: Key functionalities and assumptions
  - Current policies scenario
  - Balanced energy carriers scenario
  - Accelerated electrification scenario
  - Approaching zero scenario

In the current policies scenario both extended tank-to-wheel and well-to-wheel emissions reduce slowly but steadily

CO_2 EMISSION REDUCTION IN BOTH BALANCES



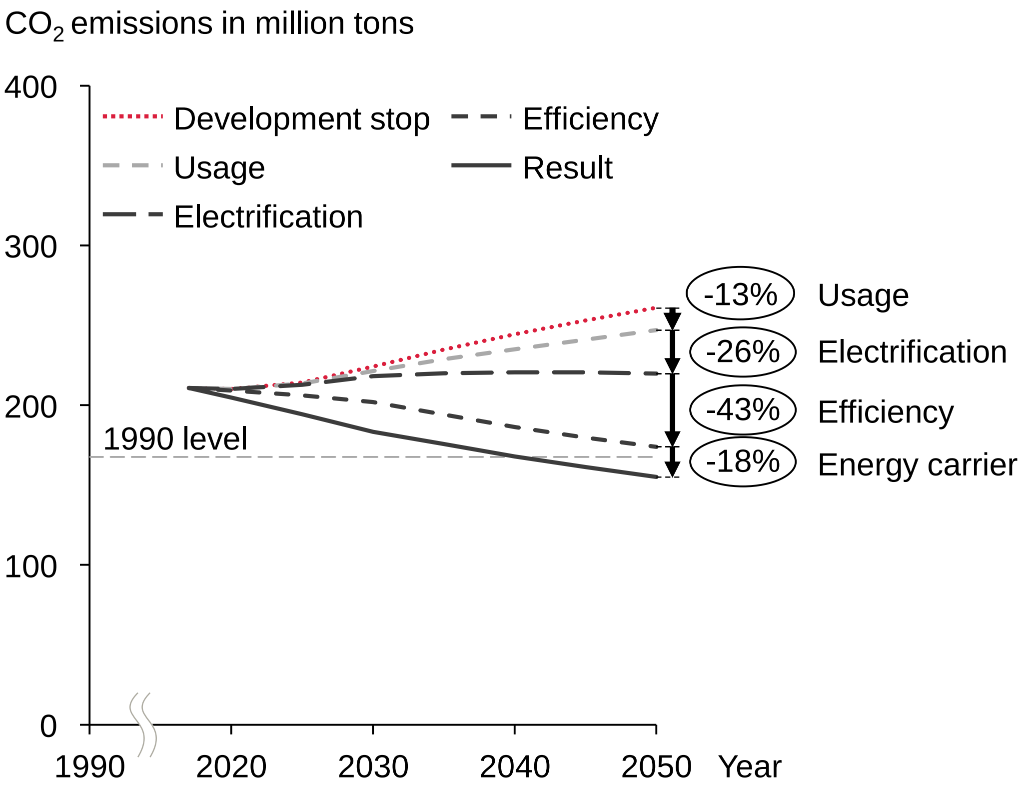
- In both the extended tank-to-wheel and the well-to-wheel balance the emissions reduce slowly but steadily
  - The reduction will be broken down to its drivers on the next pages
  - The resulting energy demand and vehicle stock will be presented at the end of the chapter
- The difference between the two balances are the emissions from well-to-tank
- The relation between the two balances is nearly constant
  - Only few changes to the energy carriers considered in this scenario
  - Few electrification as well as few fuels from biomass and power-to-x

Source: FEV

The CO_2 emission reduction in the current policies scenario is dominated by efficiency improvements of gliders and powertrains

DRIVERS OF THE CO_2 EMISSION REDUCTION IN AN EXTENDED TANK-TO-WHEEL BALANCE[1)]

Extended tank-to-wheel balance



- In the current policies scenario the CO_2 emissions can be reduced to 155 million tons per year in 2050 which is only a 7% reduction compared to 1990
- Usage contributes to the reduction by three factors
  - 1%-point of freight demand in ton-kilometer shifted away from road-transport, e.g. to rail
  - 2%-point reduction of heavy-duty vehicles in on-road transport
  - Increase of average truck utilization by 2%-point
- Electrification represents a significant number of hybrids, some battery electric and only few fuel cell electric vehicles
- Efficiency increase dominates the CO_2 emission reduction and combines the results of upgraded gliders and improved powertrains
- Energy carriers include the increased blend shares as demanded by the RED II until 2030 and no major changes afterwards due to a lack of competitiveness of other energy carriers in this scenario

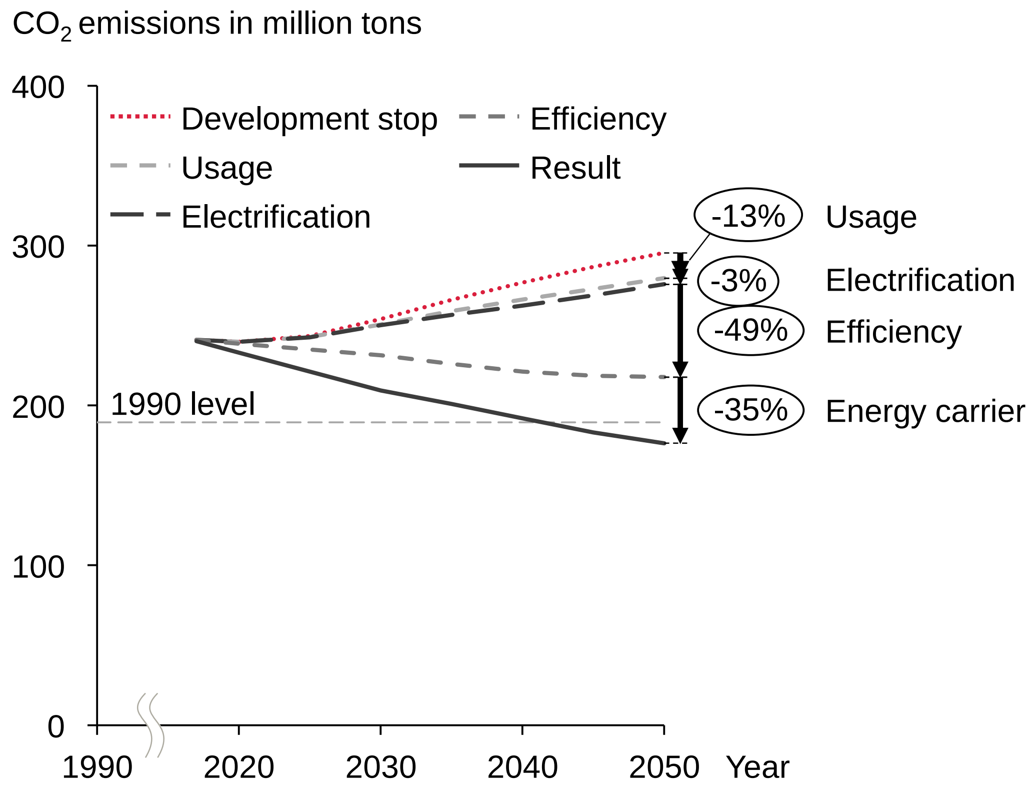
---

1) The extended tank-to-wheel balance considers the CO_2 emissions created when conversing the energy carrier to kinetic energy and a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

The CO_2 emission reduction in the current policies scenario is dominated by efficiency improvements of gliders and powertrains

DRIVERS OF THE CO_2 EMISSION REDUCTION IN A WELL-TO-WHEEL BALANCE[1)]

Well-to-wheel balance



- In the current policies scenario the CO_2 emissions can be reduced to 176 million tons per year in 2050 which equals a reduction of 7% compared to 1990
- Usage contributes to the reduction by three factors
  - 1%-point of freight demand in ton-kilometer shifted away from road-transport, e.g. to rail
  - 2%-point reduction of heavy-duty vehicles in on-road transport
  - Increase of average truck utilization by 2%-point
- Electrification leads only to a small CO_2 emission decrease since the production of hydrogen and the electricity mix of 2018 emit a high amount of CO_2 that can only be in part off-set by tank-to-wheel savings
- Efficiency increase dominates the CO_2 emission reduction and combines the results of upgraded gliders and improved powertrains
- Energy carriers reduce CO_2 emissions by the uptake of renewables, 74% of the reduction by liquid fuels, 19% by electricity and 7% by gaseous fuels

---

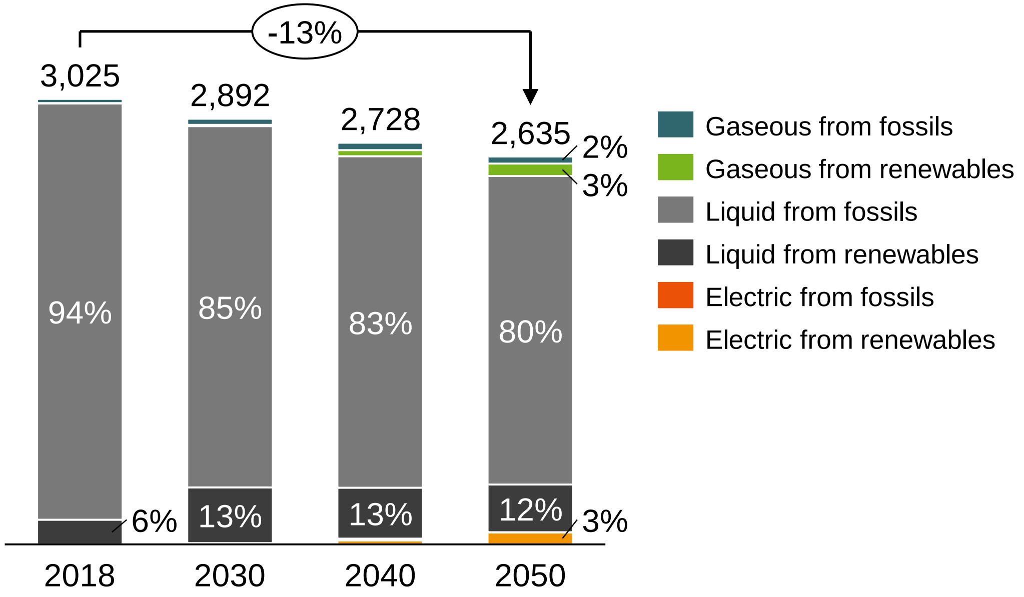
1) The well-to-wheel considers the CO_2 emissions created when producing, transporting and conversing the energy carrier to kinetic energy as well as a subtract of carbon storage that are realized during the production of the energy carrier.

Source: FEV

The final energy demand in the current policies scenario is dominated by liquid fuels from fossils – which is mostly diesel

FINAL ENERGY DEMAND

Final energy demand by energy carrier in PJ



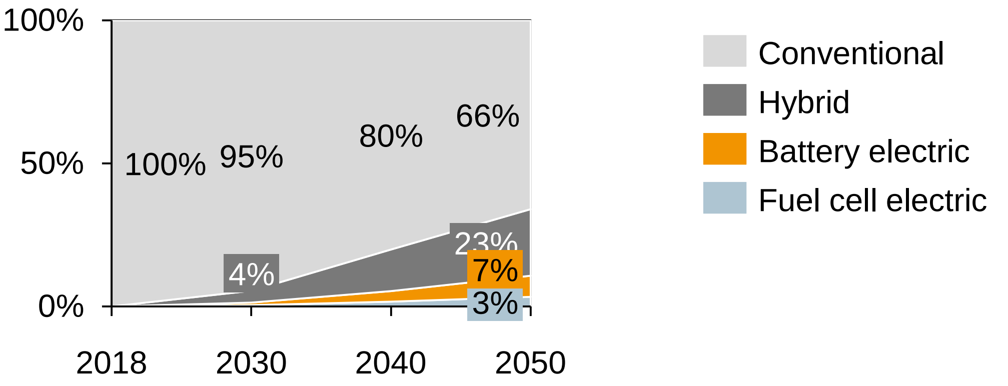
- Gaseous fuels include methane and hydrogen
  - Demand adds-up to 700 million kg of hydrogen and 1 billion kg of methane in 2050
  - Until 2050 a change to a production dominated from renewables is considered
- Liquid fuels are nearly almost diesel-type fuels, gasoline-type fuels being the remainder
  - 60 billion liters diesel from fossils demand in 2050
  - Liquid fuels from renewables include paraffins, short and long chain alcohols, the demand adds-up to 10 billion liters in 2050
  - Volumetric blend shares of liquid fuels from renewables in compliant with the RED II in 2030 and considered stable afterwards (missing policies challenge the competitiveness of fuels from renewables vs. fossil fuels)
- Electricity demand rises until 2050 up to 65 PJ per year, while electricity production needs to be dominated by renewables until then

Source: FEV

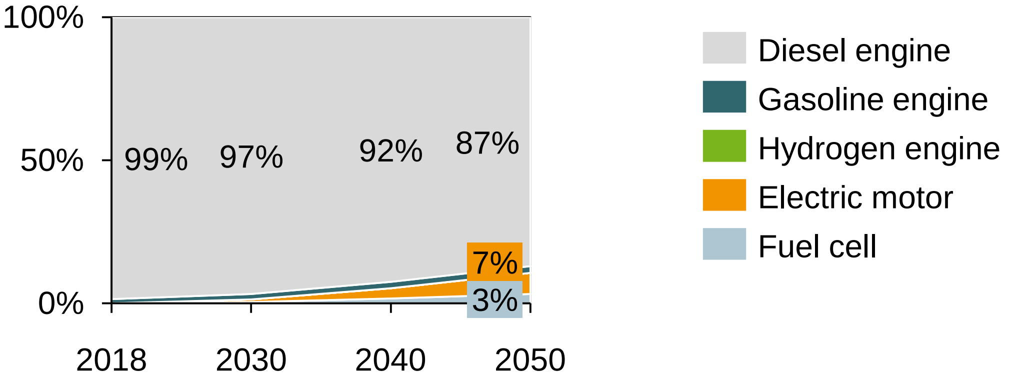
Conventional and hybrid powertrains dominate the vehicle stock in the current policies scenario

STOCK OF HEAVY-DUTY VEHICLES

Stock of heavy-duty vehicles by electrification level



Stock of heavy-duty vehicles by main energy conversion system



Source: FEV

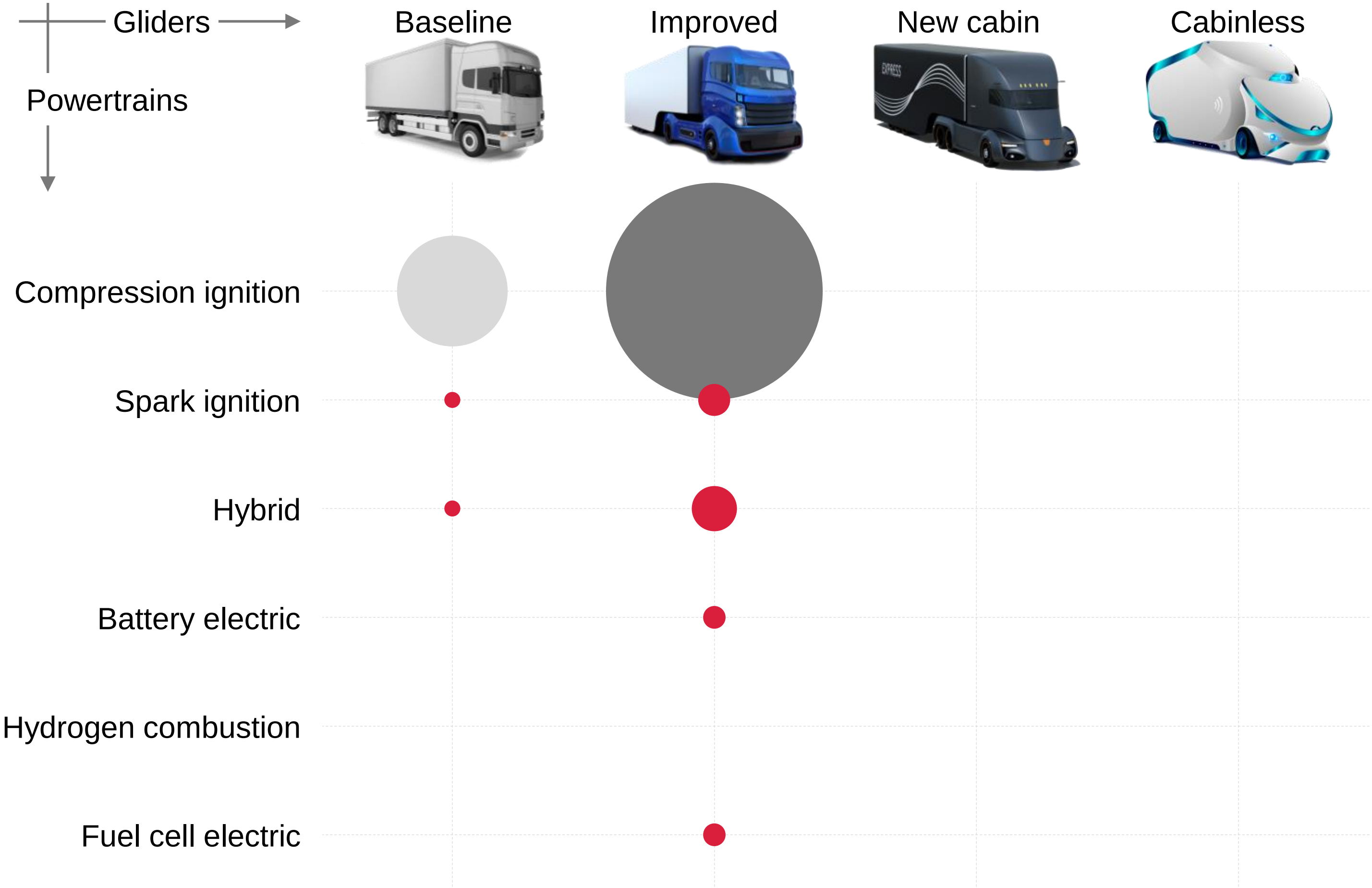
- The vehicle stock is defined by the vehicle sales and the average time a vehicle stays in the European market
  - The average age of the stock reduces throughout 2050, mainly by an increase of sales numbers
- In 2050 5.1 million vehicles are in the stock which is considerably more than the 4.1 million vehicles in 2018
- The stock of vehicles is dominated by conventional and hybrid powertrains
- Battery electric powertrains experience a slow but steady uptake
  - Introduced towards 2030 in considerable numbers to support the OEM's targets achievement
  - Post 2030, the uptake accelerates since first use-cases get favorable in total cost of ownership
- Fuel cell electric vehicles are introduced slowly to the market and play a minor role

In the 2020/2030 timeframe long haul trucks are expected to be mostly sold with a compression ignition powertrain in an improved glider

FEV CONSULTING

2020/2030 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

LH 2020/30



- The most sold vehicle has a compression ignition powertrain and an improved glider
- There is still a considerable number of sales of compression ignition powertrains in the baseline glider
- The majority of powertrains is compression ignition and the majority of gliders is the improved one
- Hybrid powertrains begin to emerge in the improved glider
- Battery electric and fuel cell powertrains are sold in low quantities in improved gliders

Source: FEV

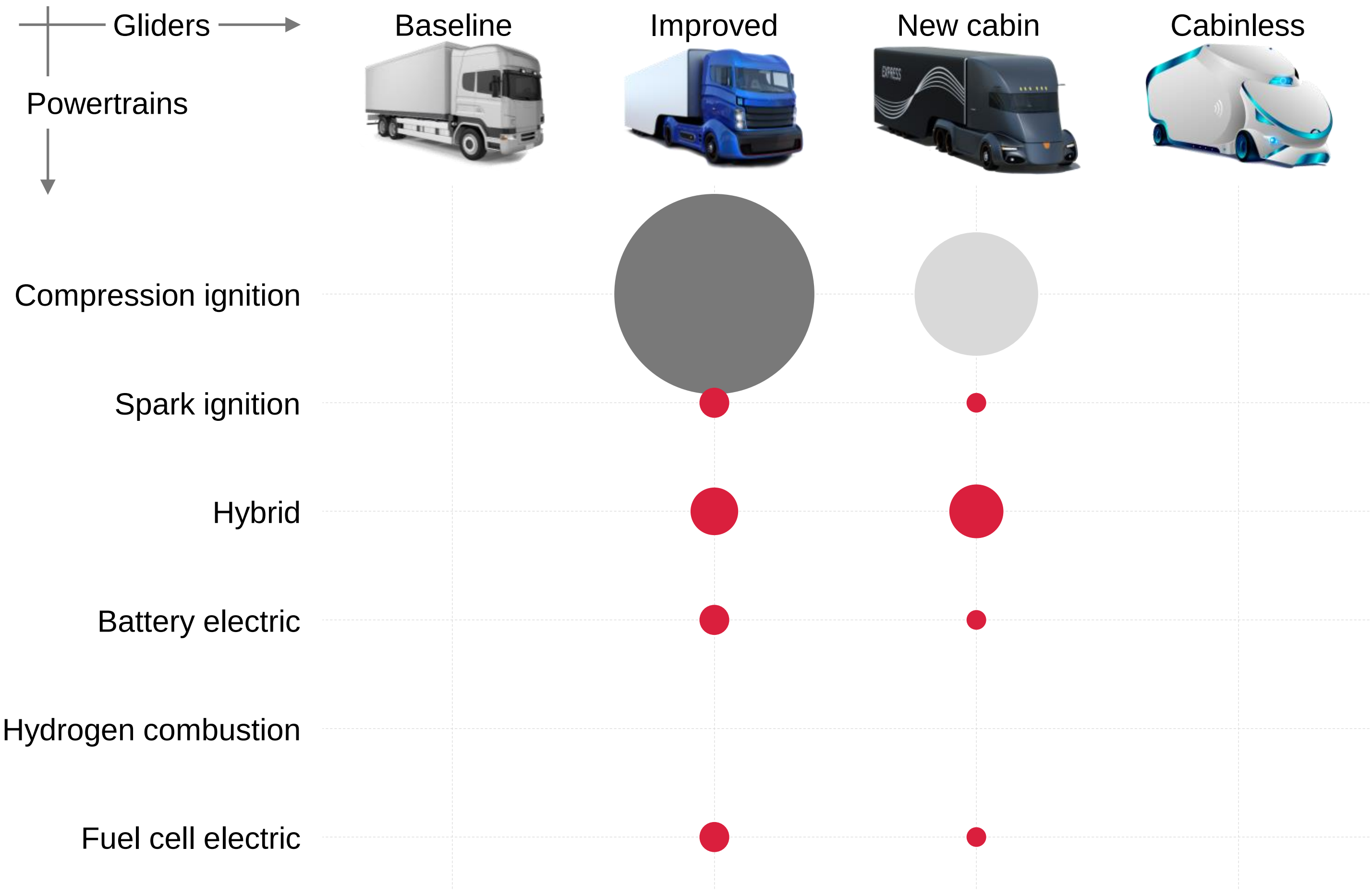
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In 2030/2040, FEV expects the majority of sales still in the compression ignition powertrain in the improved glider – yet the new cabin emerges

FEV CONSULTING

2030/2040 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

LH 2030/40



- The most sold vehicle has a compression ignition powertrain and an improved glider
- Already a considerable number of sales of compression ignition powertrains is in the new cabin glider which is new in the market
- The majority of powertrains is compression ignition, the majority of gliders is the improved one
- Hybrid powertrains are sold in the improved and new cabin glider
- Battery electric and fuel cell powertrains are sold in low quantities in improved and new cabin gliders

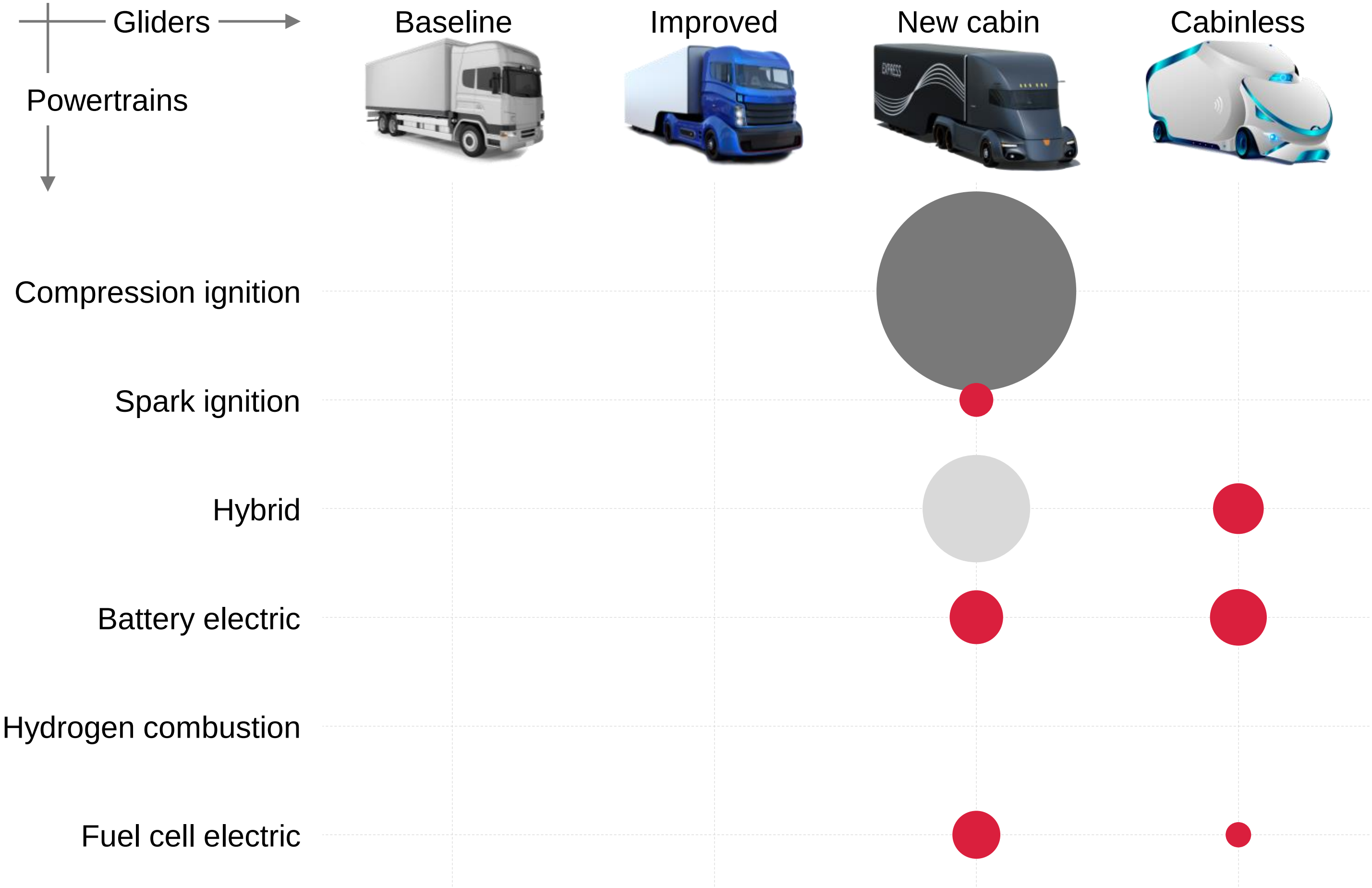
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the long run, around the 2040/2050 timeframe, the cabinless glider is introduced to the market – yet sales remain high in the new cabin design

2040/2050 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

LH | 2040/50



- The most sold vehicle has a compression ignition powertrain and a new cabin glider
- Some vehicles are expected to be sold in the cabinless glider, here with a hybrid, battery electric and fuel cell electric powertrain
- The majority of powertrains is compression ignition, the majority of gliders is the new cabin
- Hybrid powertrains exceed 15% of sales for the first time in the new cabin glider
- Sales of battery electric and fuel cell powertrains remain at a comparably low level

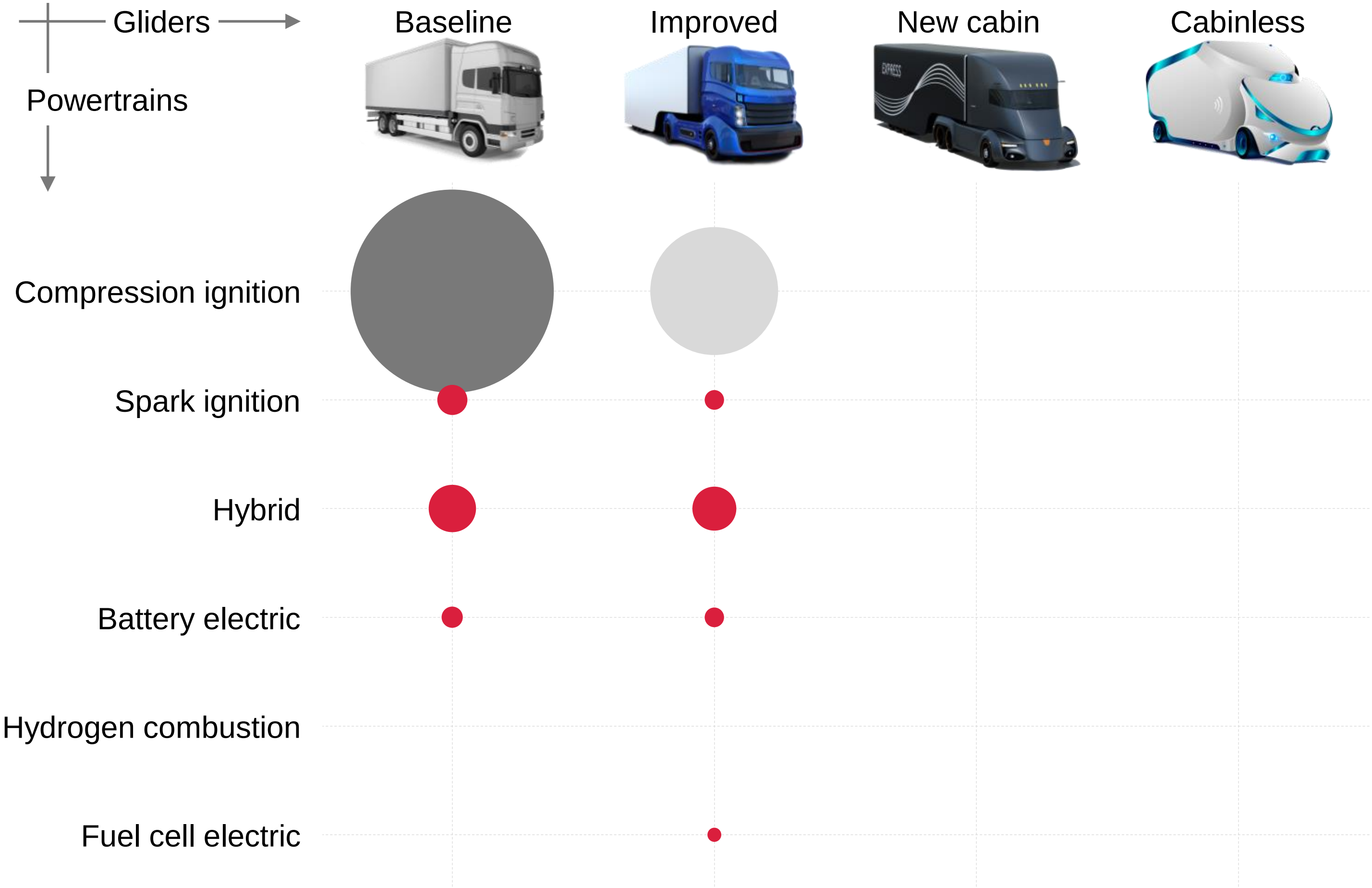
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In 2020/2030 most of regional haul sales are baseline gliders with a compression ignition powertrain – sales of improved gliders are small

2020/2030 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES

RH | 2020/30



- The most sold vehicle has a compression ignition powertrain and the baseline glider
- Some vehicles are already being sold with the compression ignition powertrain in the improved glider
- The majority of powertrains is compression ignition and the majority of gliders is the baseline one
- Hybrid powertrains begin to emerge in the baseline and improved glider
- Battery electric and fuel cell powertrains are sold in very low quantities

Source: FEV

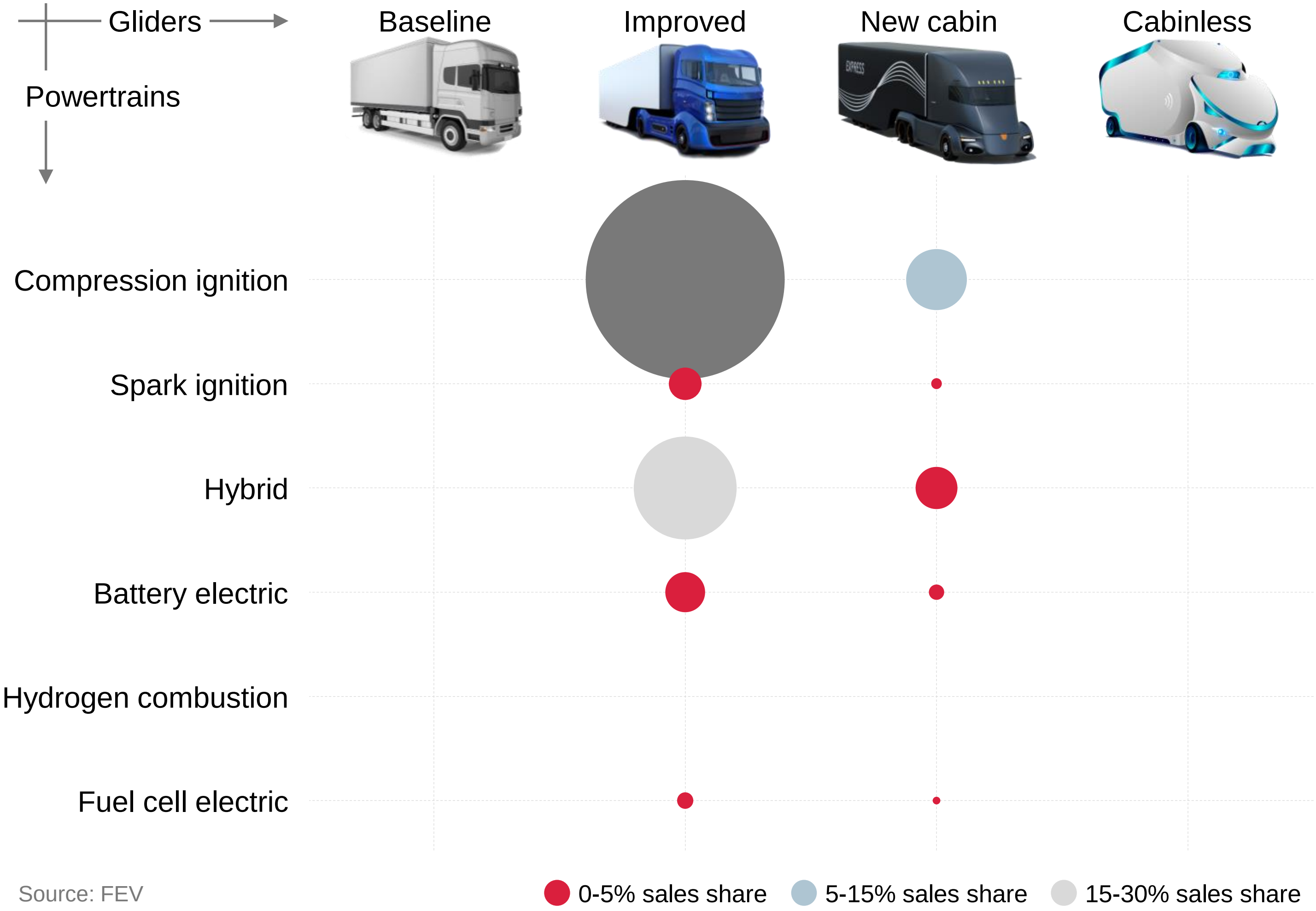
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

FEV expects sales in the 2030/2040 timeframe to remain strong for the improved glider with compression ignition powertrain

FEV CONSULTING

RH 2030/40

2030/2040 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The most sold vehicle has a compression ignition powertrain and an improved glider
- Already a considerable number of sales of compression ignition powertrains is in the new cabin glider which is new in the market
- The majority of powertrains is compression ignition, the majority of gliders is the improved one
- Hybrid powertrains are mainly sold in the improved glider
- Battery electric and fuel cell powertrains are sold in low quantities in improved and new cabin gliders

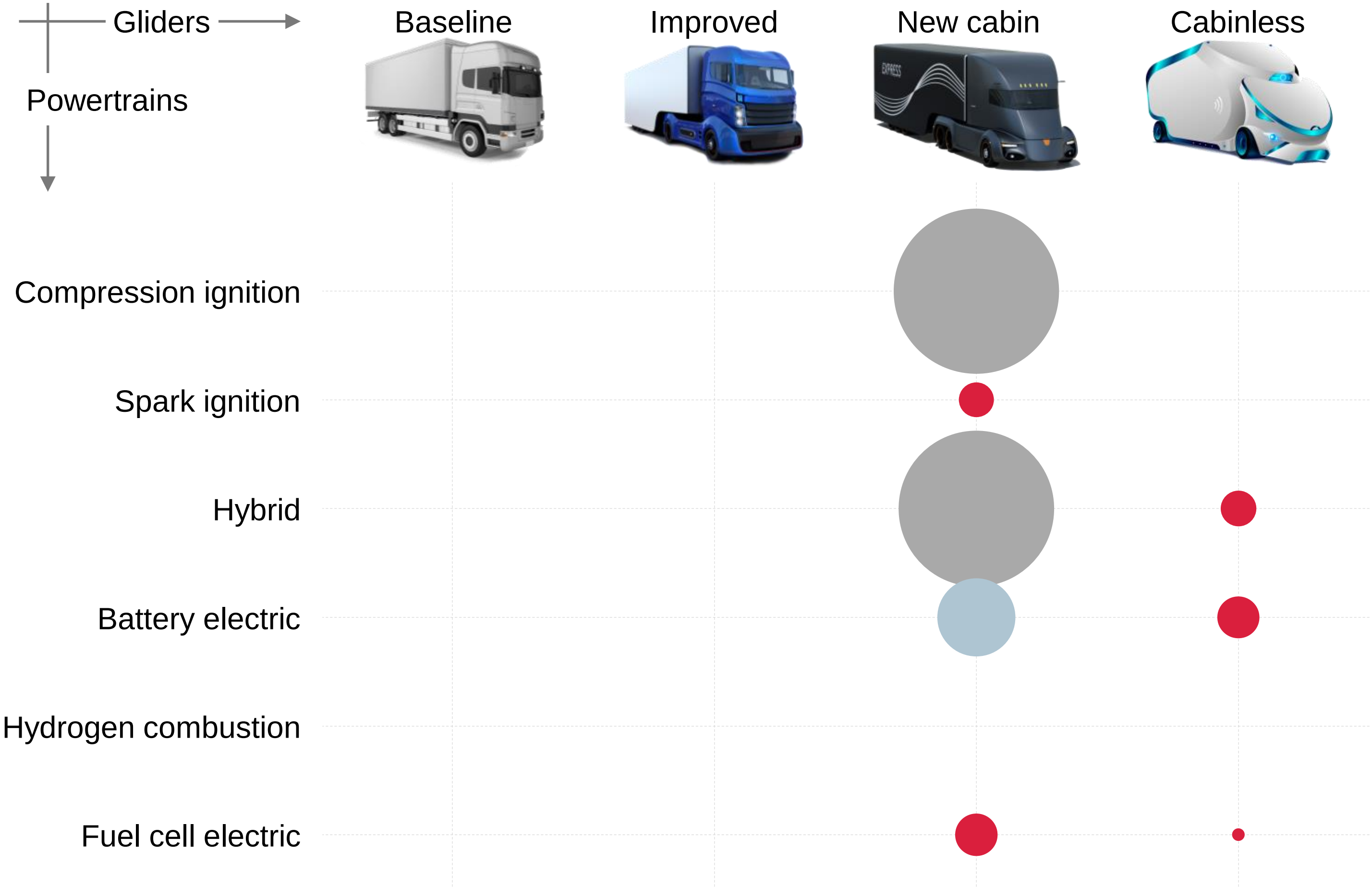
Source: FEV

In the 2040/2050 timeframe sales volume of hybrid and compression ignition powertrains are similar

FEV CONSULTING

2040/2050 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES

RH 2040/50



- Sales of compression ignition and hybrid powertrains are comparable in terms of volume
- Some vehicles are expected to be sold in the cabinless glider, here with a hybrid, battery electric and fuel cell electric powertrain
- The majority of gliders is the new cabin glider
- Sales of battery electric powertrains exceed 5% for the first time in the new cabin glider
- Sales of fuel cell powertrains remain at a comparably low level

Source: FEV

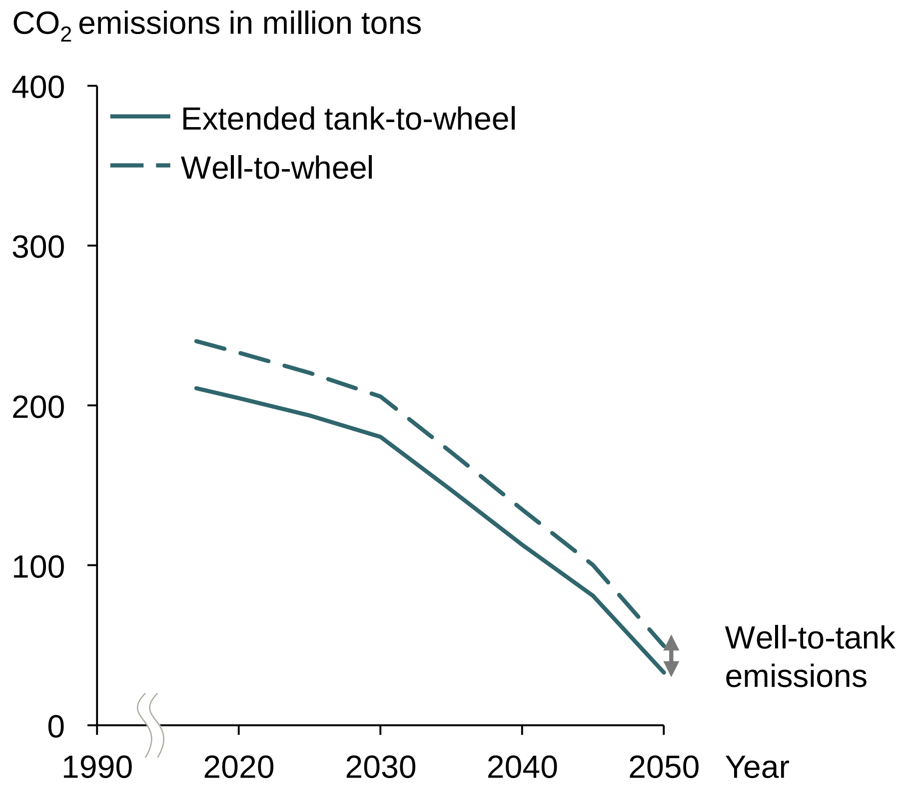
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

Agenda

- Reduced GHG emissions with holistic technology strategies
  - Energy demand model: Key functionalities and assumptions
  - Current policies scenario
  - Balanced energy carriers scenario
  - Accelerated electrification scenario
  - Approaching zero scenario

In the balanced energy carriers scenario the CO_2 emission reduction accelerated after 2030 and 2045 in both balances

CO_2 EMISSION REDUCTION IN BOTH BALANCES



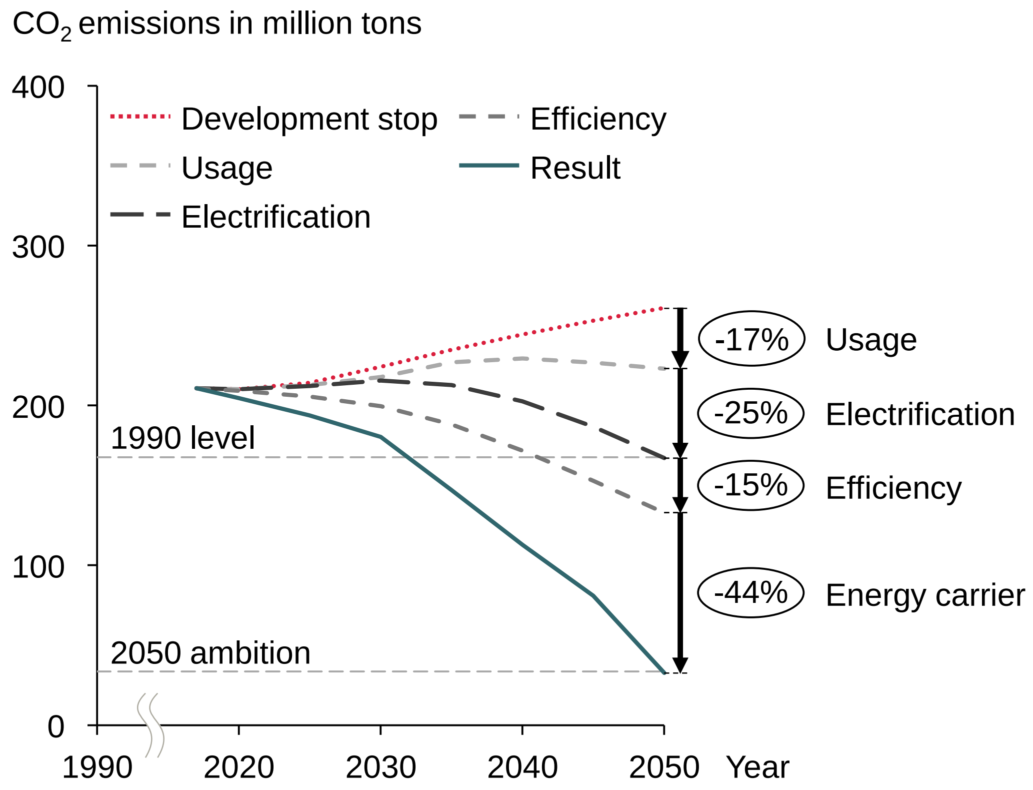
- In both the extended tank-to-wheel and the well-to-wheel balance the emissions reduce steadily and at an increasing pace after 2030 and 2045
  - The reduction will be broken down to its drivers on the next pages
  - The resulting energy demand and vehicle stock will be presented at the end of the chapter
- The difference between the two balances are the emissions from well-to-tank
- The difference between the balances reduces due to improvements in the well-to-tank emissions
  - Led by fuels from power-to-x processes and electricity from renewables that nearly emit no CO_2 from well-to-tank

Source: FEV

In the balanced energy carriers scenario energy carriers and electrification contribute the most to reduce CO_2 emissions

DRIVERS OF THE CO_2 EMISSION REDUCTION IN AN EXTENDED TANK-TO-WHEEL BALANCE1)

Extended tank-to-wheel balance



- In the balanced energy carriers scenario the CO_2 emissions can be reduced to 33 million tons per year and thus achieve the goal of a 80% reduction compared to 1990
- Usage contributes to the reduction by two factors that offset a 3%-point higher share of goods transported on-road compared to 2018
  - 5%-point reduction of the share of heavy-duty vehicles in on-road transport
  - 5%-point increase of average truck utilization
- Electrification represents a significant number of hybrids, followed by battery electric and fuel cell electric vehicles in considerable numbers
- Efficiency increase contributes to the CO_2 emission reduction by improvements of gliders and powertrains
- Energy carriers includes a blend share of renewables at 75 vol.-% in liquid and 80 mass-% in gaseous fuels

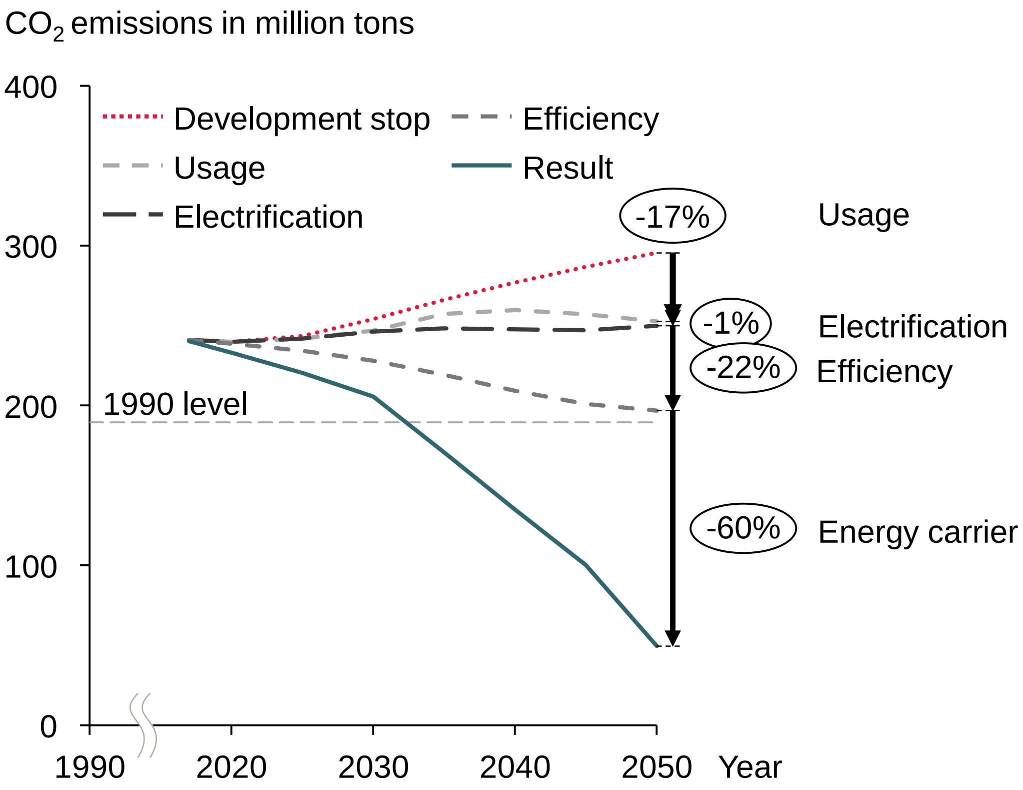
---

1) The extended tank-to-wheel balance considers the CO_2 emissions created when conversing the energy carrier to kinetic energy and a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

In the well-to-wheel balance the contribution of energy carriers is much higher and covers 60% of the total reduction

DRIVERS OF THE CO_2 EMISSION REDUCTION IN A WELL-TO-WHEEL BALANCE[1)]

Well-to-wheel balance



- In the balanced energy carriers scenario CO_2 emissions are reduced to 48 million tons in 2050 which equals a 74% reduction compared to 1990
- Usage contributes to the reduction by two factors that offset a 3%-point higher share of goods transported on-road compared to 2018
  - 5%-point reduction of the share of heavy-duty vehicles in on-road transport
  - 5%-point increase of average truck utilization
- Electrification leads only to a small CO_2 emission reduction since the production of hydrogen and the electricity mix of 2018 emit a high amount of CO_2 that can only be in part off-set by tank-to-wheel savings
- Efficiency increase contributes to the CO_2 emission reduction and combines the results of upgraded gliders and improved powertrains
- Energy reduce CO_2 emissions by the uptake of renewables, 73% of the reduction by liquid fuels, 13% by electricity and 14% by gaseous fuels

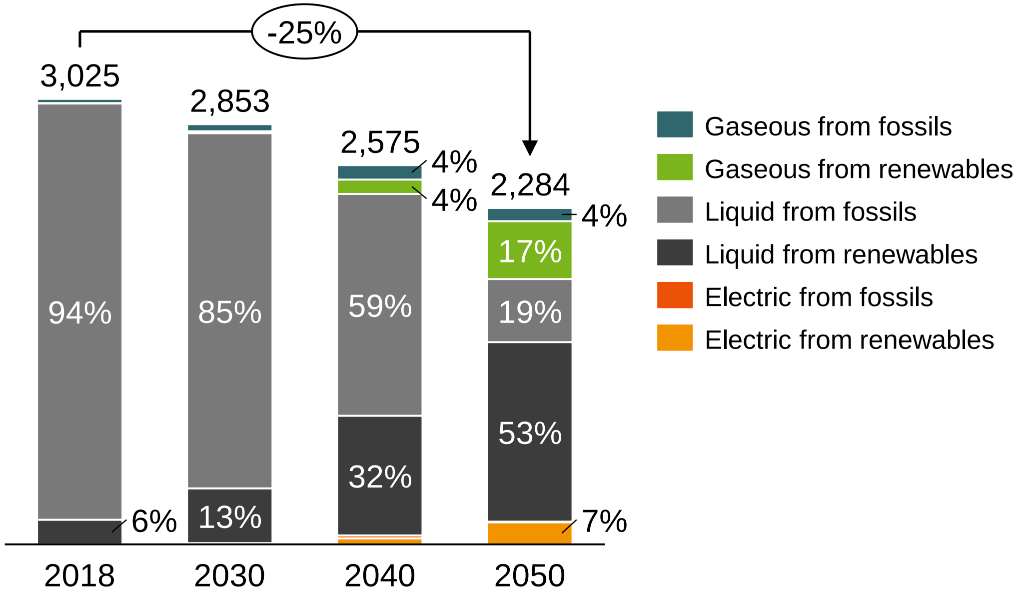
---

1) The well-to-wheel balance considers the CO_2 emissions created when producing, transporting and conversing the energy carrier to kinetic energy as well as a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

The final energy demand in the balanced energy carriers scenario in 2050 is diversified, yet liquid fuels from renewables have a high contribution

FINAL ENERGY DEMAND

Final energy demand by energy carrier in PJ



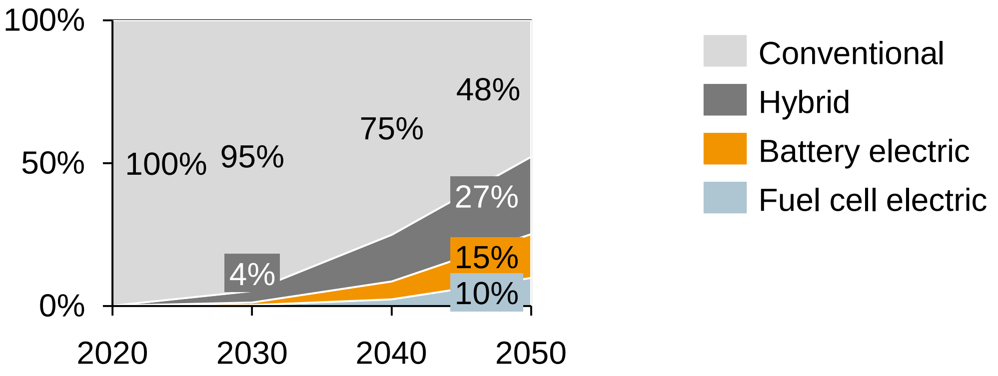
- Gaseous fuel include methane and hydrogen
  - Demand adds-up to 850 million kg of methane and about 4 billion kg of hydrogen in 2050
  - Until 2050 a change to a production dominated from renewables is considered
- Liquid fuels are dominated by fuels from renewables while almost all are diesel-type fuels, gasoline-type fuels being the remainder
  - Still 12 billion liters of diesel from fossils are demanded in 2050
  - Liquid fuels from renewables include paraffins, short and long chain alcohols and the demand adds-up to 35 billion liters in 2050
- Electricity demand rises until 2050 to 154 PJ per year
  - The production of electricity needs to be dominated by renewables by 2050 according to European targets

Source: FEV

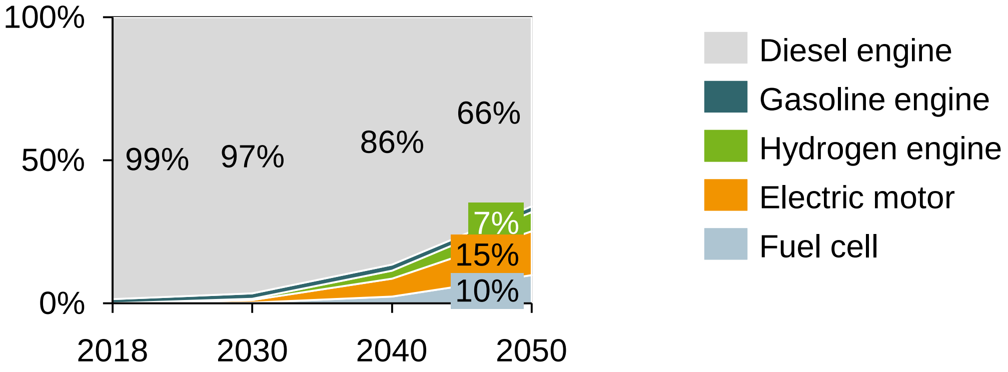
The vehicle stock is diversified in 2050 while conventional and hybrid powertrains are dominating, battery electric and fuel cell powertrains rise

STOCK OF HEAVY-DUTY VEHICLES

Stock of heavy-duty vehicles by electrification level



Stock of heavy-duty vehicles by main energy conversion system



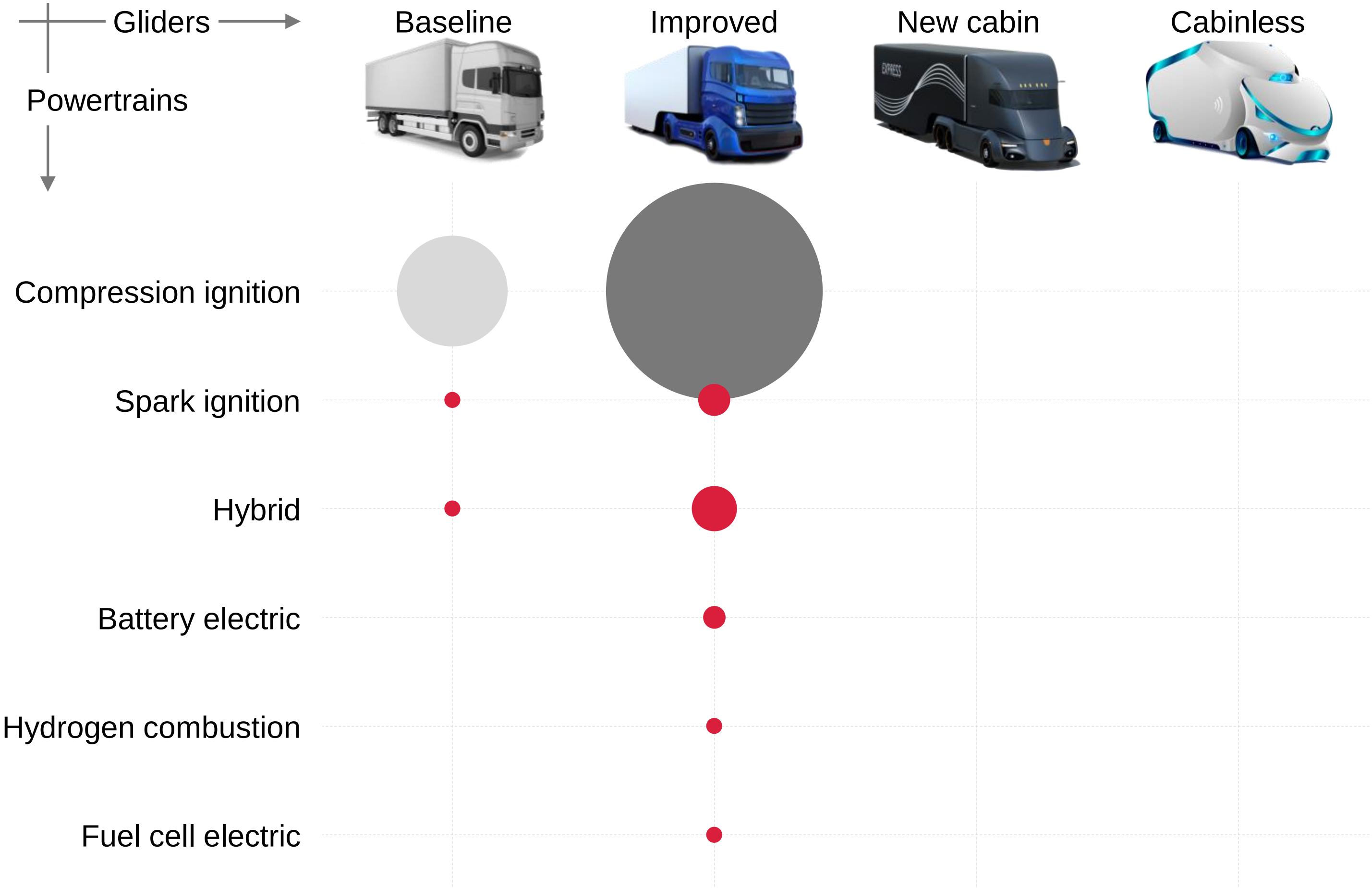
Source: FEV

- The vehicle stock is defined by the sales and the average time a vehicle stays in the European market
  - The average age of the stock is higher in 2050 than in 2018, mainly by a reduction of sales numbers due to automation
- In 2050 4.1 million vehicles are in stock which is nearly equal to 2018
- The vehicle stock is diversified in 2050, while conventional and hybrid powertrains have the highest shares
- Battery electric powertrains experience a steady uptake in the vehicle stock
  - Introduced towards 2030 in considerable numbers to ensure the OEMs meet their respective targets
  - After 2030 the uptake accelerates since more and more use-cases get favorable
- Fuel cell electric vehicles are increasingly important post 2040, final market stock share in 2050 is 10%

In the 2020/2030 timeframe long haul trucks are expected to be mostly sold with a compression ignition powertrain in an improved glider

LH 2020/30

2020/2030 TIMEFRAME – OVERVIEW OF LONG HAUL SALES



- The most sold vehicle has a compression ignition powertrain and an improved glider
- There is still a considerable number of sales of compression ignition powertrains in the baseline glider
- The majority of powertrains is compression ignition, the majority of gliders is the improved one
- Hybrid powertrains begin to emerge in the improved glider
- Battery electric, hydrogen combustion and fuel cell powertrains are sold in low quantities in improved gliders

Source: FEV

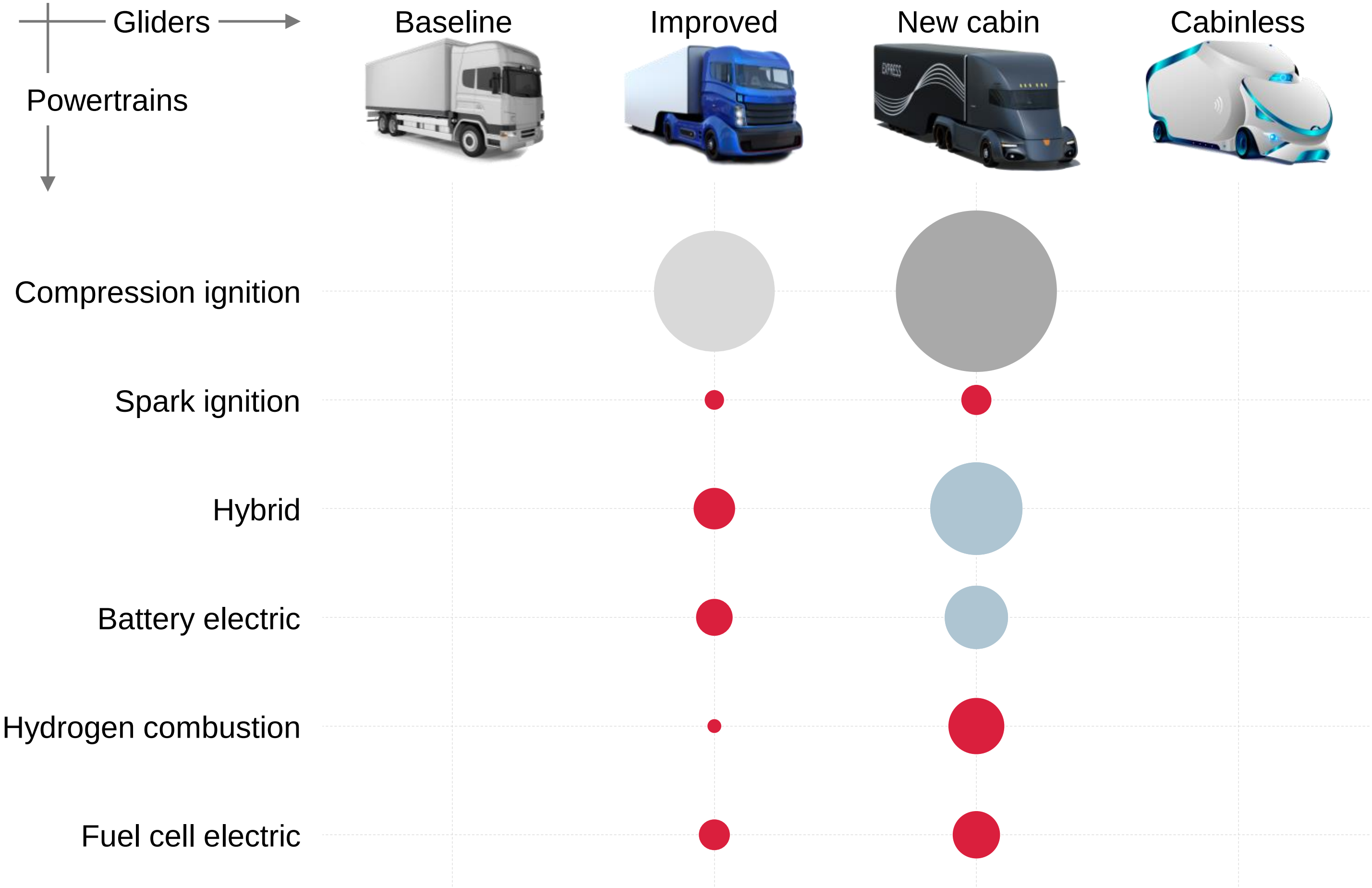
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2030/2040 timeframe the sales are divided on multiple powertrains and are shifted towards the new cabin glider

LH

2030/40

2030/2040 TIMEFRAME – OVERVIEW OF LONG HAUL SALES



- The most sold vehicle has a compression ignition powertrain and a new cabin glider
- The majority of powertrains is compression ignition, the majority of gliders is the new cabin one
- Hybrid and battery electric powertrains are sold in the improved and new cabin glider, where they already exceed 5% of market share
- Hydrogen combustion and fuel cell electric powertrains are sold in the improved and new cabin glider

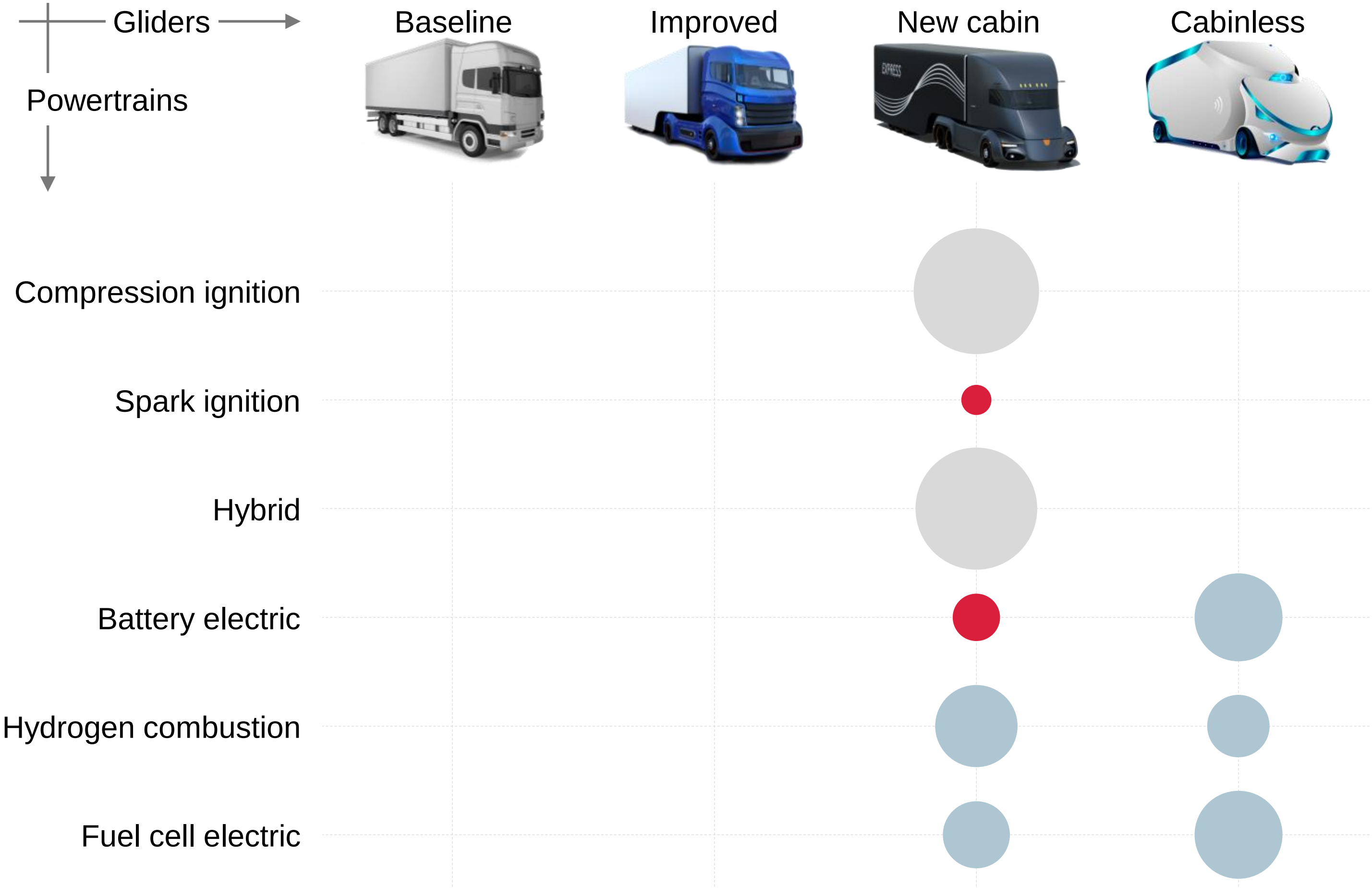
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2040/2050 timeframe zero CO_2 emission powertrains combine a relevant amount of the sales share

2040/2050 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

LH 2040/50



- Sales of compression ignition and hybrid powertrains are similar in terms of sales volume
- The majority of gliders are based on a new body-in-white cabin while cabinless gliders are introduced to the market
- In the cabinless glider only battery electric, hydrogen combustion and fuel cell electric powertrains get sold
- The zero CO_2 emission powertrains – battery electric, hydrogen combustion and fuel cell electric – combine a relevant amount of the sales share

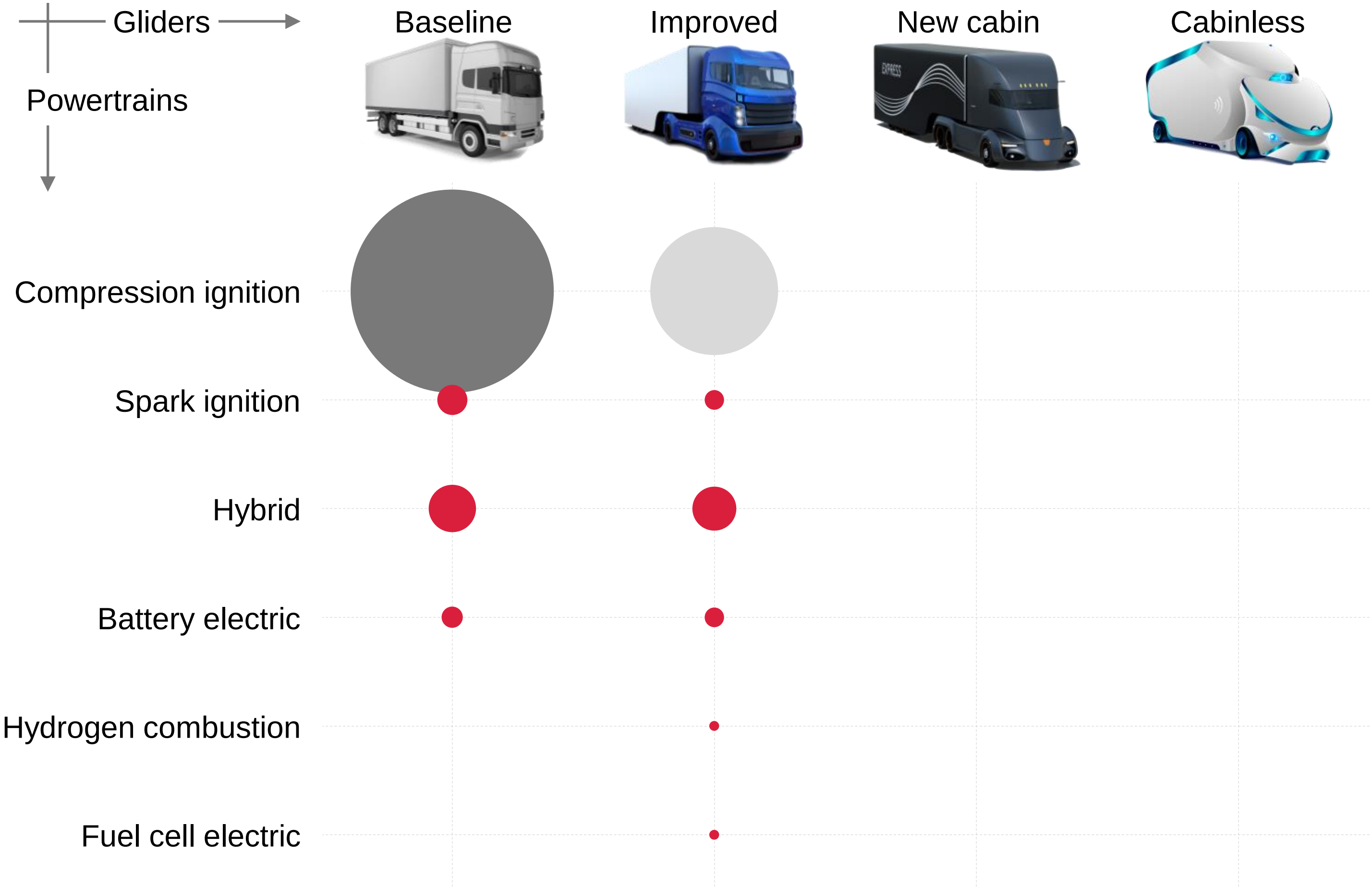
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In 2020/2030 most of regional haul sales are baseline gliders with a compression ignition powertrain –sales of improved gliders increases

RH 2020/30

2020/2030 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The most sold vehicle has a compression ignition powertrain and the baseline glider
- Some vehicles are already being sold with the compression ignition powertrain in the improved glider
- The majority of powertrains is compression ignition and the majority of gliders is the baseline one
- Hybrid powertrains begin to emerge in the baseline and improved glider
- Battery electric and fuel cell powertrains are sold in low quantities

Source: FEV

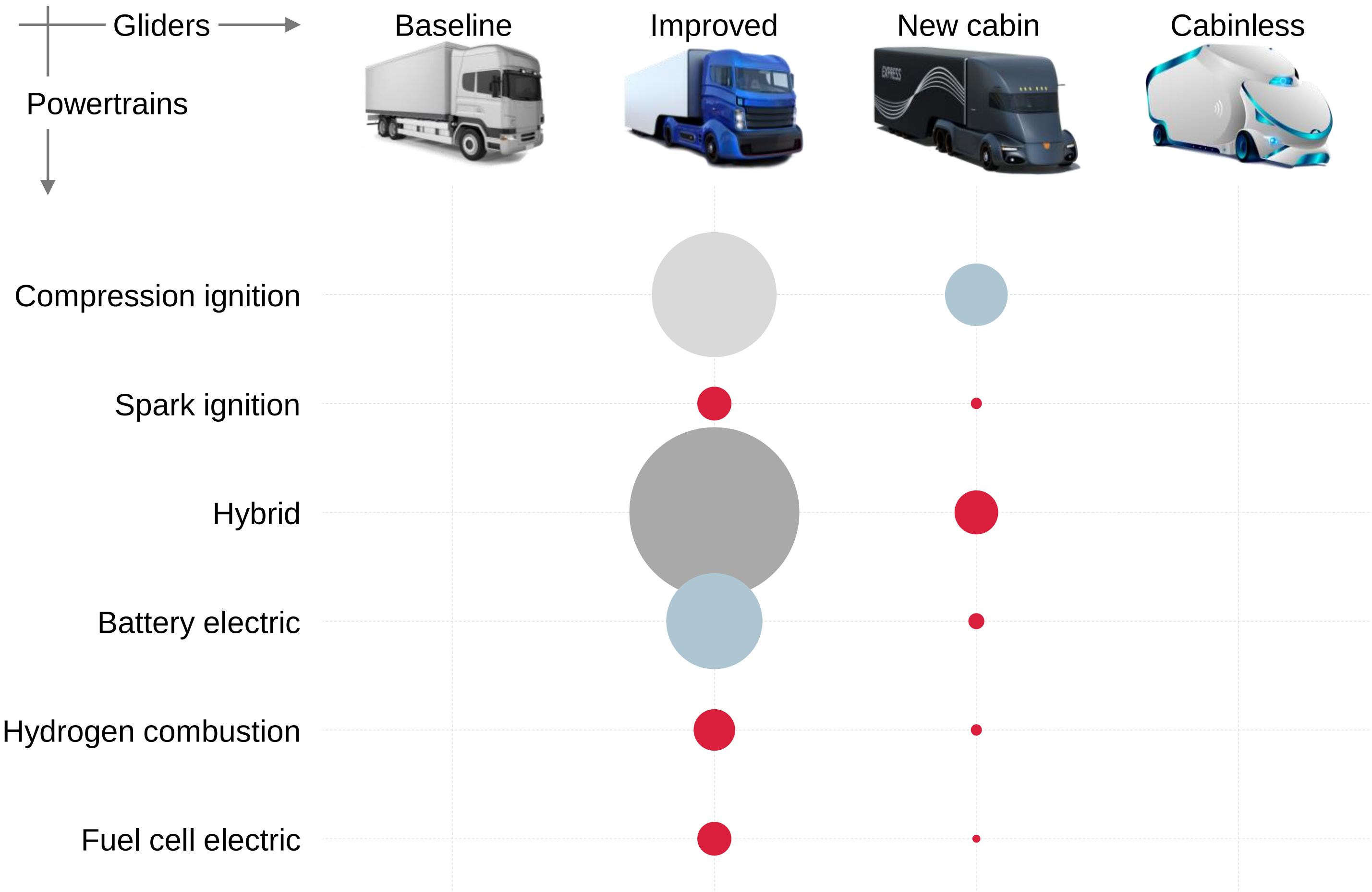
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

By 2030/2040, hybrid powertrains are especially relevant within the regional haul segment due to their high CO_2 reduction potential

FEV CONSULTING

RH 2030/40

2030/2040 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The most sold vehicle has a hybrid powertrain and an improved glider
- The majority of powertrains is hybrid and the majority of gliders is the improved one
- The battery electric powertrain exceeds 5% of sales share in the improved glider
- Hydrogen combustion and fuel cell electric powertrains are sold in low quantities in the improved and new cabin glider

Source: FEV

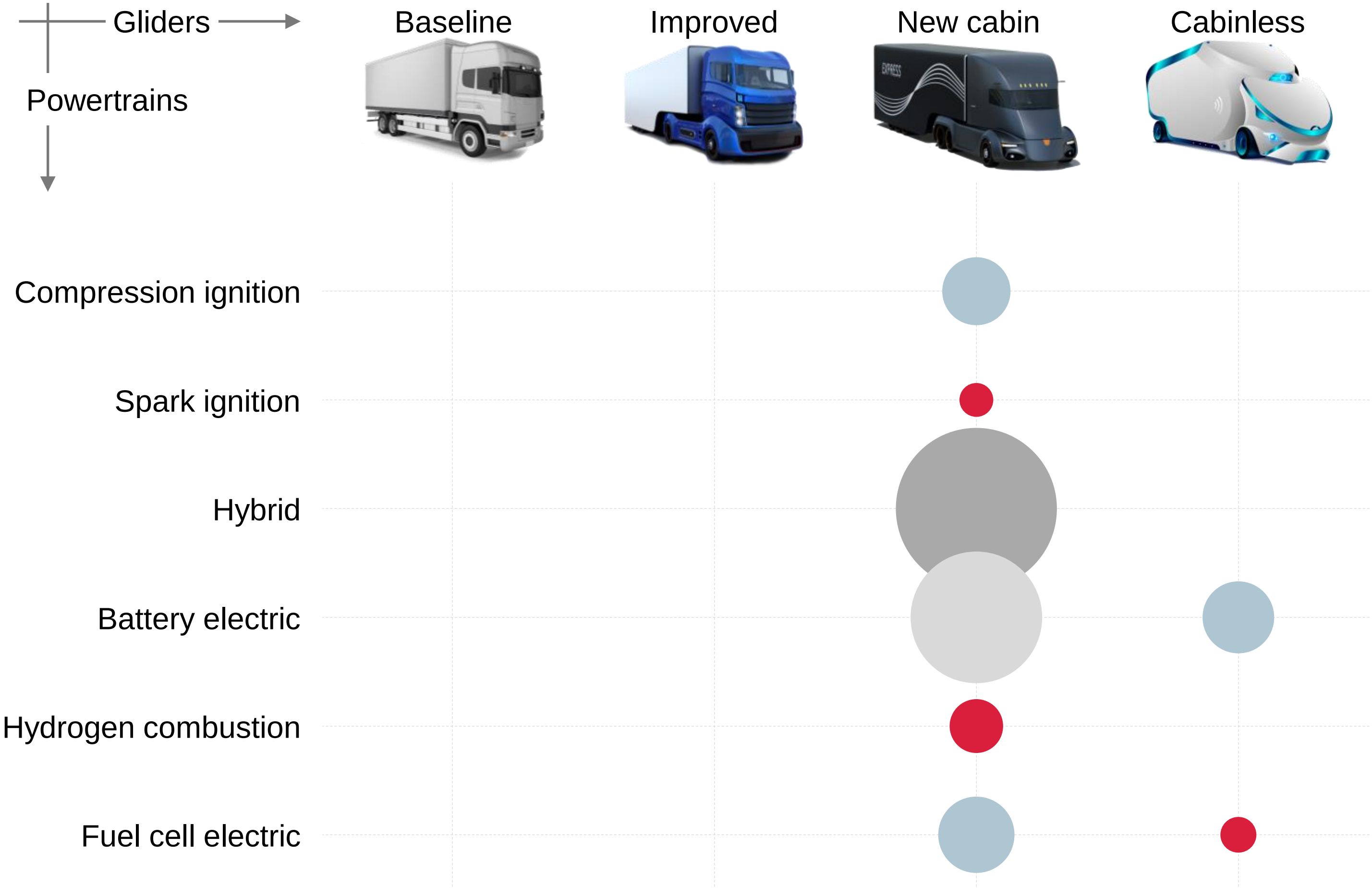
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2040/2050 timeframe FEV expects a high diversity of powertrains in the new cabin glider and considerable sales of cabinless gliders

RH

2040/50

2040/2050 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The most sold vehicle has a hybrid powertrain and new cabin glider, closely followed by a battery electric powertrain in that glider
- The zero CO_2 emission powertrains – battery electric, hydrogen combustion and fuel cell electric – combine around 50% of the market share
- Battery electric powertrain sales are strong in the new cabin and cabinless glider
- Hydrogen combustion and fuel cell electric powertrains are in the market at considerable numbers

Source: FEV

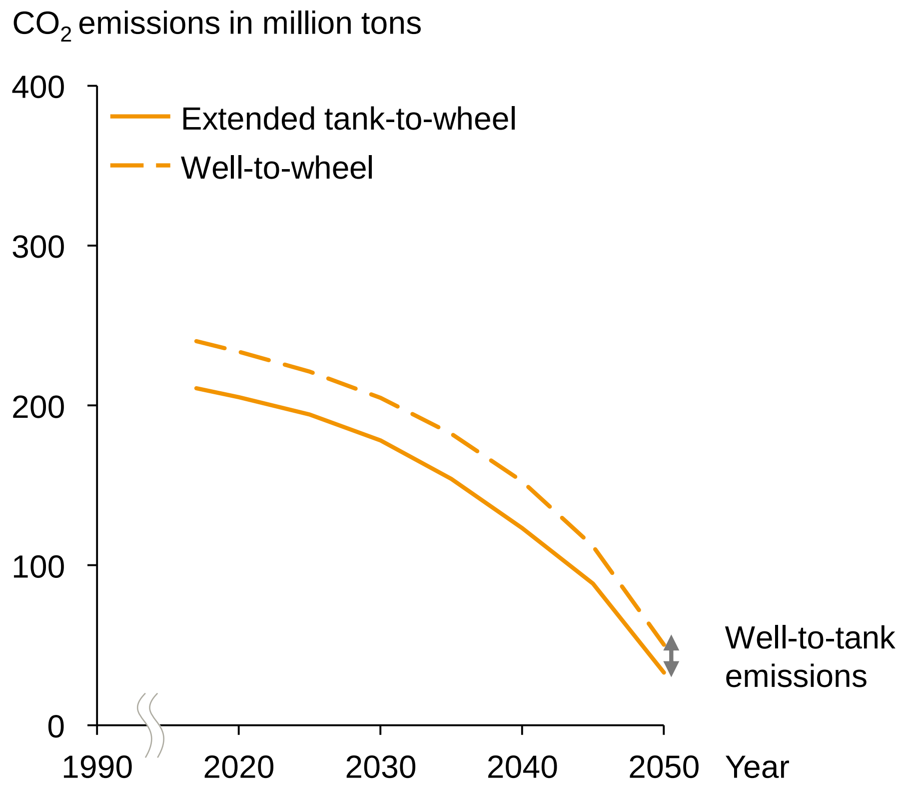
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

Agenda

- Reduced GHG emissions with holistic technology strategies
  - Energy demand model: Key functionalities and assumptions
  - Current policies scenario
  - Balanced energy carriers scenario
  - Accelerated electrification scenario
  - Approaching zero scenario

In the accelerated transformation scenario the CO_2 emission reduces strongly over time in both balances

CO_2 EMISSION REDUCTION IN BOTH BALANCES



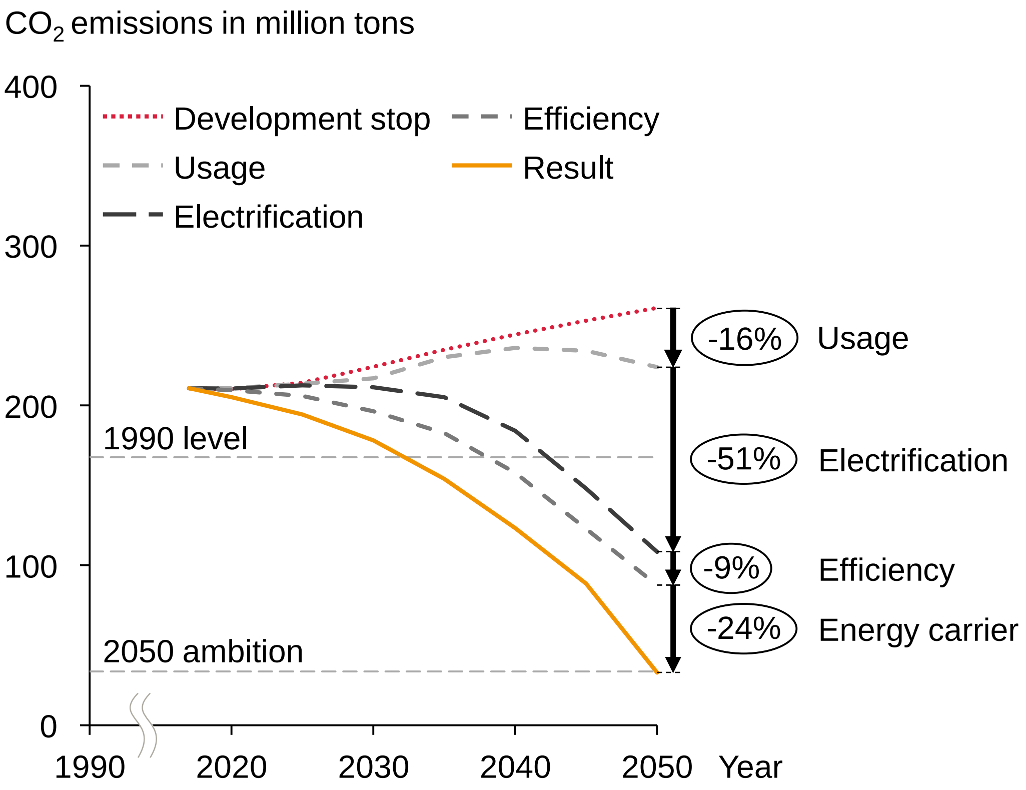
- In both the extended tank-to-wheel and the well-to-wheel balance the emissions reduce steadily and at an ever increasing pace
  - The reduction will be broken down to its drivers on the next pages
  - The resulting energy demand and vehicle stock will be presented at the end of the chapter
- The difference between the two balances are the emissions from well-to-tank
- The difference between the balances reduces due to improvements in the well-to-tank emissions
  - Led by fuels from power-to-x processes and electricity from renewables that nearly emit no CO_2 from well-to-tank

Source: FEV

In the accelerated transformation scenario the CO_2 emission reduction is dominated by electrification

DRIVERS OF THE CO_2 EMISSION REDUCTION IN AN EXTENDED TANK-TO-WHEEL BALANCE[1)]

Extended tank-to-wheel balance



- In the accelerated transformation scenario the CO_2 emissions can be reduced to 33 million tons per year and thus achieve the goal of a 80% reduction compared to 1990
- Usage contributes to the reduction by two factors that offset a 5%-point higher share of goods transported on-road compared to 2018
  - 10%-point reduction of the share of heavy-duty vehicles in on-road transport
  - 5%-point increase of average truck utilization
- Electrification represents a significant number of battery electric vehicles, hybrids and fuel cell electric vehicles
- Efficiency increase contributes to the CO_2 emission reduction by improvements of gliders and powertrains
- Energy carriers includes a blend share of renewables at 65 vol.-% in liquid and 70 mass-% in gaseous fuels

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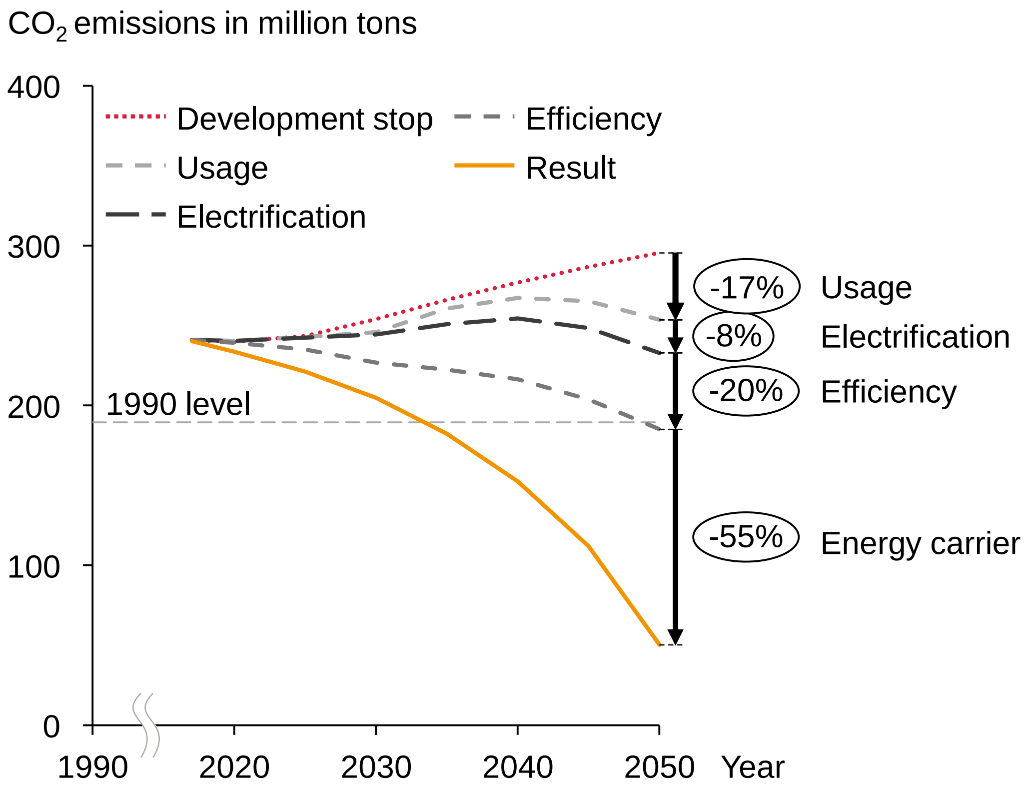
1) The extended tank-to-wheel balance considers the CO_2 emissions created when conversing the energy carrier to kinetic energy and a subtract of carbon storage that are realized during the production of the energy carrier.

Source: FEV

In the accelerated transformation scenario the change to electricity and fuels from renewables dominates CO_2 emission reduction

DRIVERS OF THE CO_2 EMISSION REDUCTION IN A WELL-TO-WHEEL BALANCE1)

Well-to-wheel balance



- In the accelerated transformation scenario CO_2 emissions are reduced to 50 million tons in 2050 which is a 73% reduction compared to 1990
- Usage contributes to the reduction by two factors that offset a higher share of goods transported on-road compared to 2018
  - Considerable reduction of the share of heavy-duty vehicles in on-road transport
  - Significant increase of average truck utilization
- Electrification leads to a small CO_2 emission reduction since the production of hydrogen and the electricity mix of 2018 emit a high amount of CO_2 that can only be in part off-set by tank-to-wheel savings
- Efficiency increase contributes to the CO_2 emission reduction and combines the results of upgraded gliders and improved powertrains
- Energy carriers reduce CO_2 emissions by the uptake of renewables, 43% of the reduction by liquid fuels, 44% by electricity and 13% by gaseous fuels

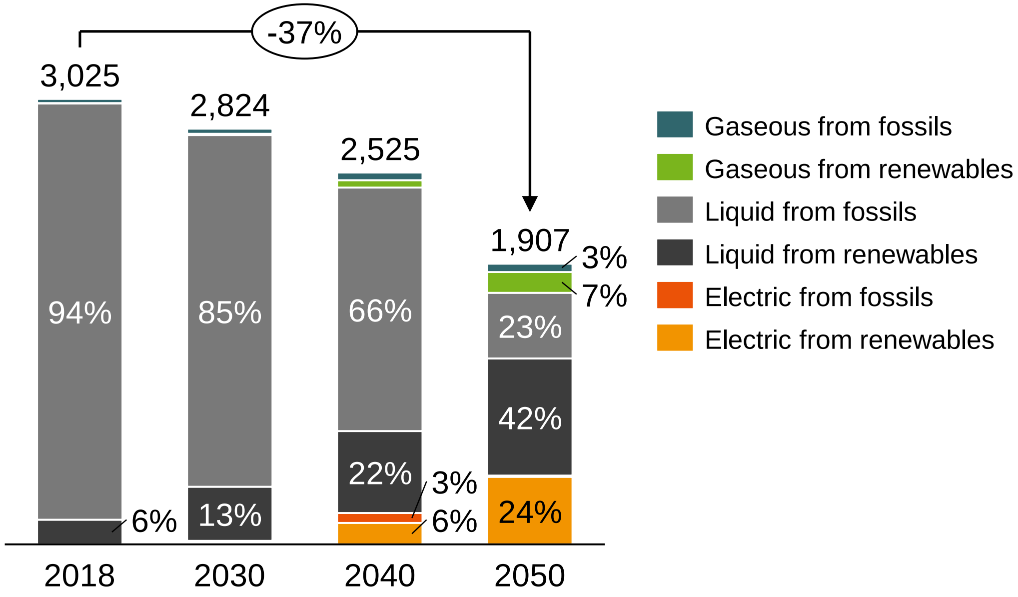
1) The well-to-wheel balance considers the CO_2 emissions created when producing, transporting and conversing the energy carrier to kinetic energy as well as a subtract of carbon storage that are realized during the production of the energy carrier.

Source: FEV

In the accelerated transformation scenario the final energy carrier demand is diversified in 2050

FINAL ENERGY DEMAND

Final energy demand by energy carrier in PJ



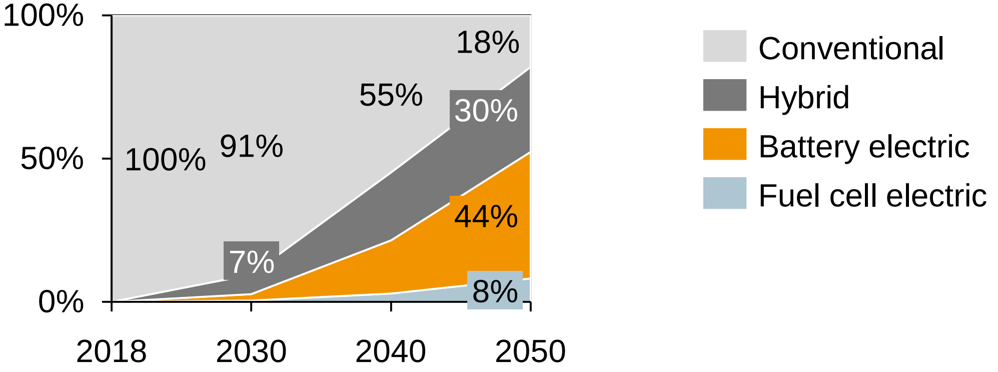
- Gaseous fuel include methane and hydrogen
  - Demand is dominated by hydrogen at about 2 billion kg in 2050
  - Until 2050 a change to a production dominated from renewables is considered
- Liquid fuels are split between such from fossils and renewables while almost all are diesel-type fuels, gasoline-type fuels being the remainder
  - Still 12 billion liters of diesel from fossils are demanded in 2050
  - Liquid fuels from renewables include paraffins, short and long chain alcohols, the demand adds-up to 23 billion liters in 2050
- Electricity demand rises significantly after 2030 up to about 500 PJ in 2050 which will also be supported by an uptake of electrified road systems
  - The production of electricity needs to be dominated by renewables by 2050 according to European targets

Source: FEV

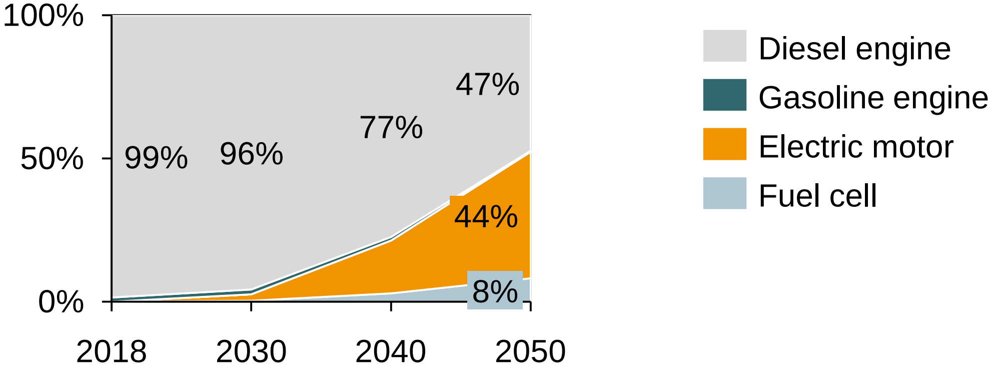
In the accelerated transformation scenario the stock is dominated by battery electric vehicles in 2050

STOCK OF HEAVY-DUTY VEHICLES

Stock of heavy-duty vehicles by electrification level



Stock of heavy-duty vehicles by main energy conversion system



Source: FEV

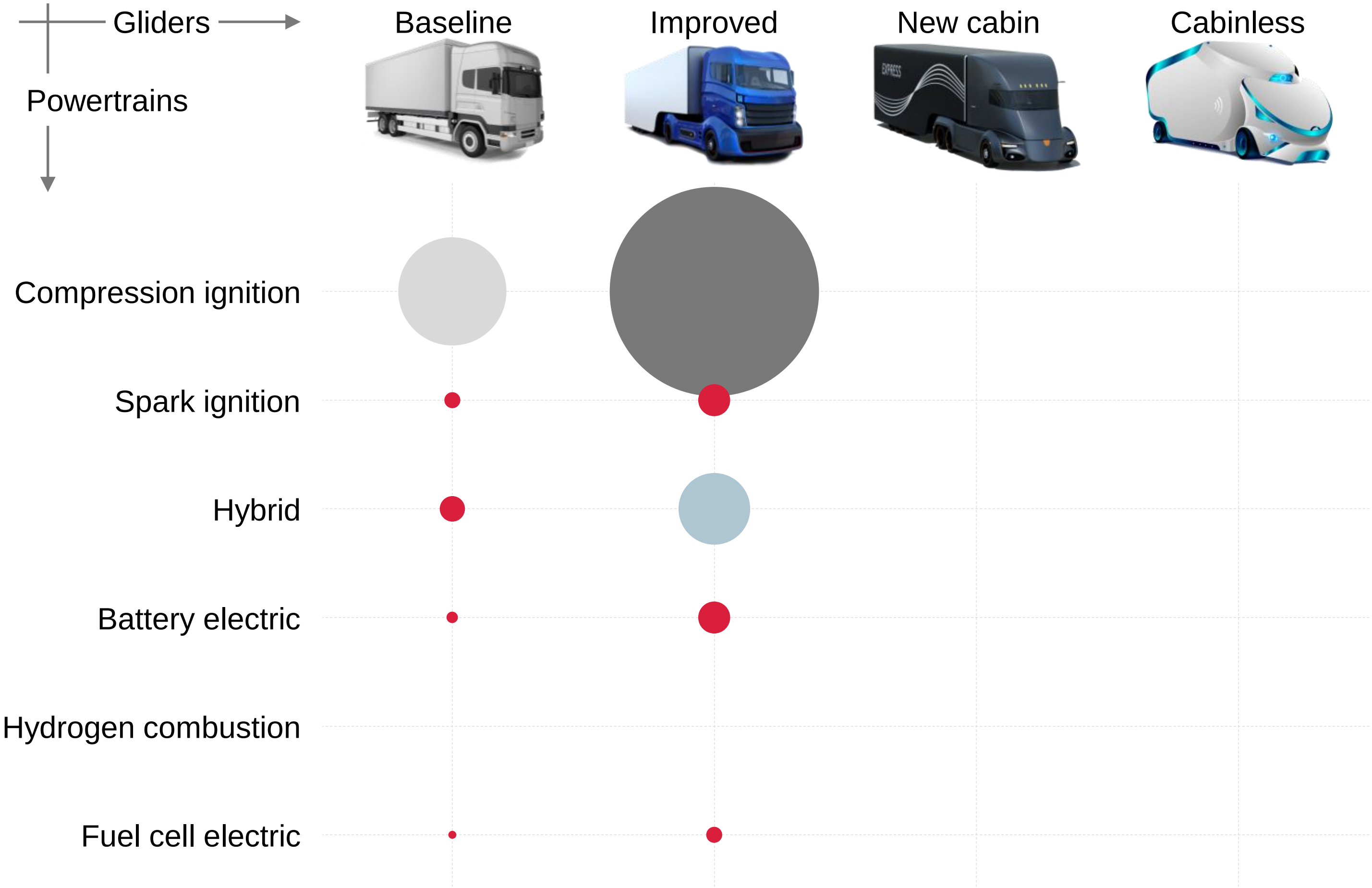
- The vehicle stock is defined by the sales and the average time a vehicle stays in the European market
  - The average age of the stock is higher in 2050 than in 2018, mainly by a reduction of sales numbers due to automation
- In 2050 3.7 million vehicles are in stock which is less than the 4 million vehicles in 2018
- The vehicle stock is dominated by battery electric powertrains in 2050 with an uptake after 2030, which accelerates again after 2040
  - The uptake of battery electric powertrains is supported by reduction of costs, increase in charger availability and electrified road systems
- Hybrid powertrains experience an uptake in the stock already towards 2030, increase the pace of adoption between 2030 and 2040 and stay approximatively constant after 2040
- Fuel cell electric vehicles are represented in the vehicle stock in considerable numbers after 2040

In the 2020/2030 timeframe long haul trucks are expected to be mostly sold with a compression ignition powertrain in an improved glider

LH

2020/30

2020/2030 TIMEFRAME – OVERVIEW OF LONG HAUL SALES



- The most sold vehicle has a compression ignition powertrain and an improved glider
- There is still a considerable number of sales of compression ignition powertrains in the baseline glider
- The majority of powertrains is compression ignition and the majority of gliders is the improved one
- Hybrid powertrains begin to emerge in the improved glider
- Battery electric and fuel cell powertrains are sold in low quantities

Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2030/2040 timeframe most of the long haul trucks are based on a new cabin design, equipped with hybrid, BEV or CI powertrains

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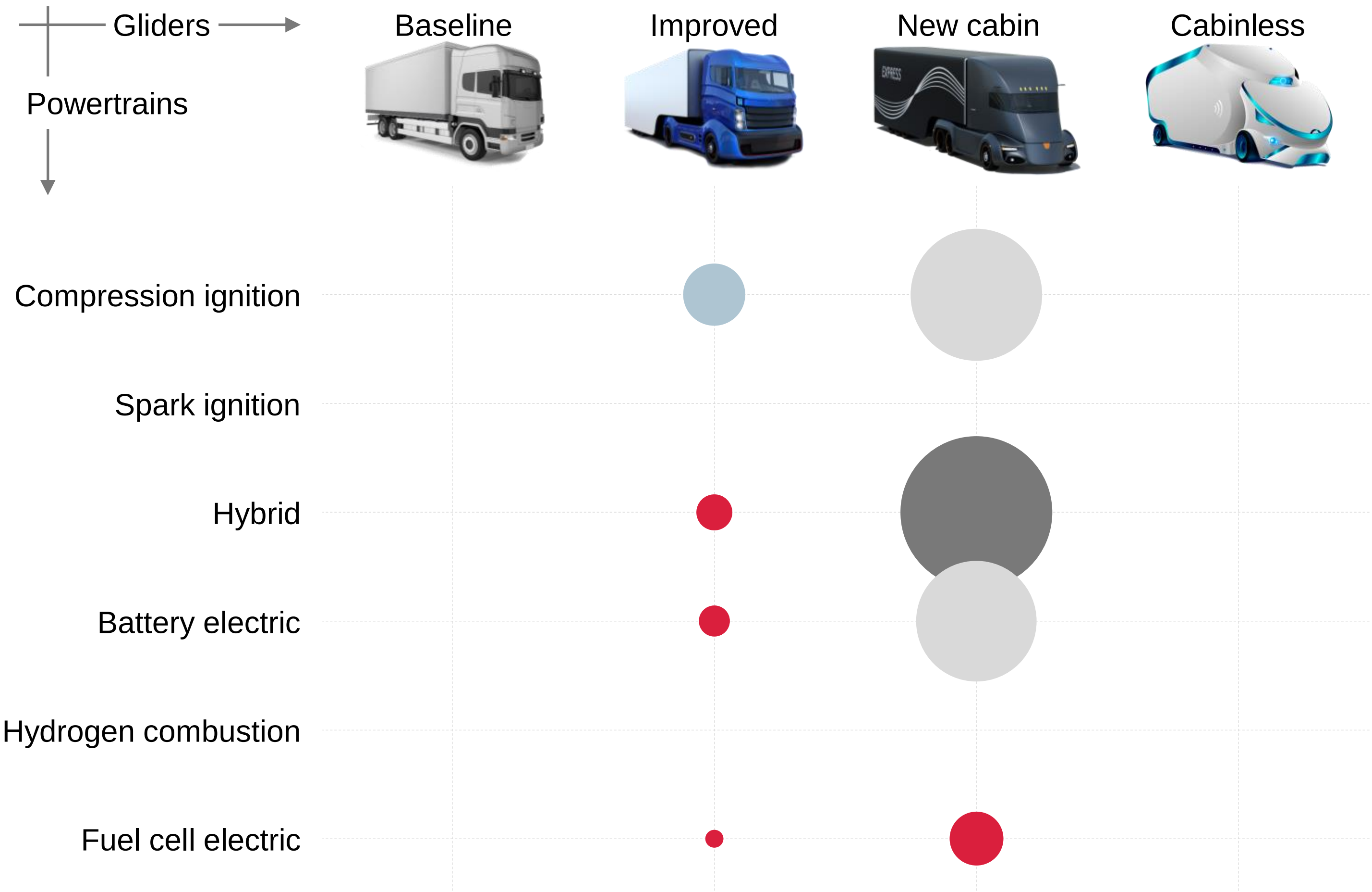
2030/2040 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

LH

2030/40



- The most sold vehicle has a hybrid powertrain and a new cabin glider
  - Compression ignition and battery electric powertrains in the new cabin glider follow with significant sales shares
- The sales shares of compression ignition and hybrid powertrain are similar, while the majority of gliders sold is the new cabin one
- Fuel cell electric powertrains are sold in the improved and new cabin glider but the market shares does not exceed 5%

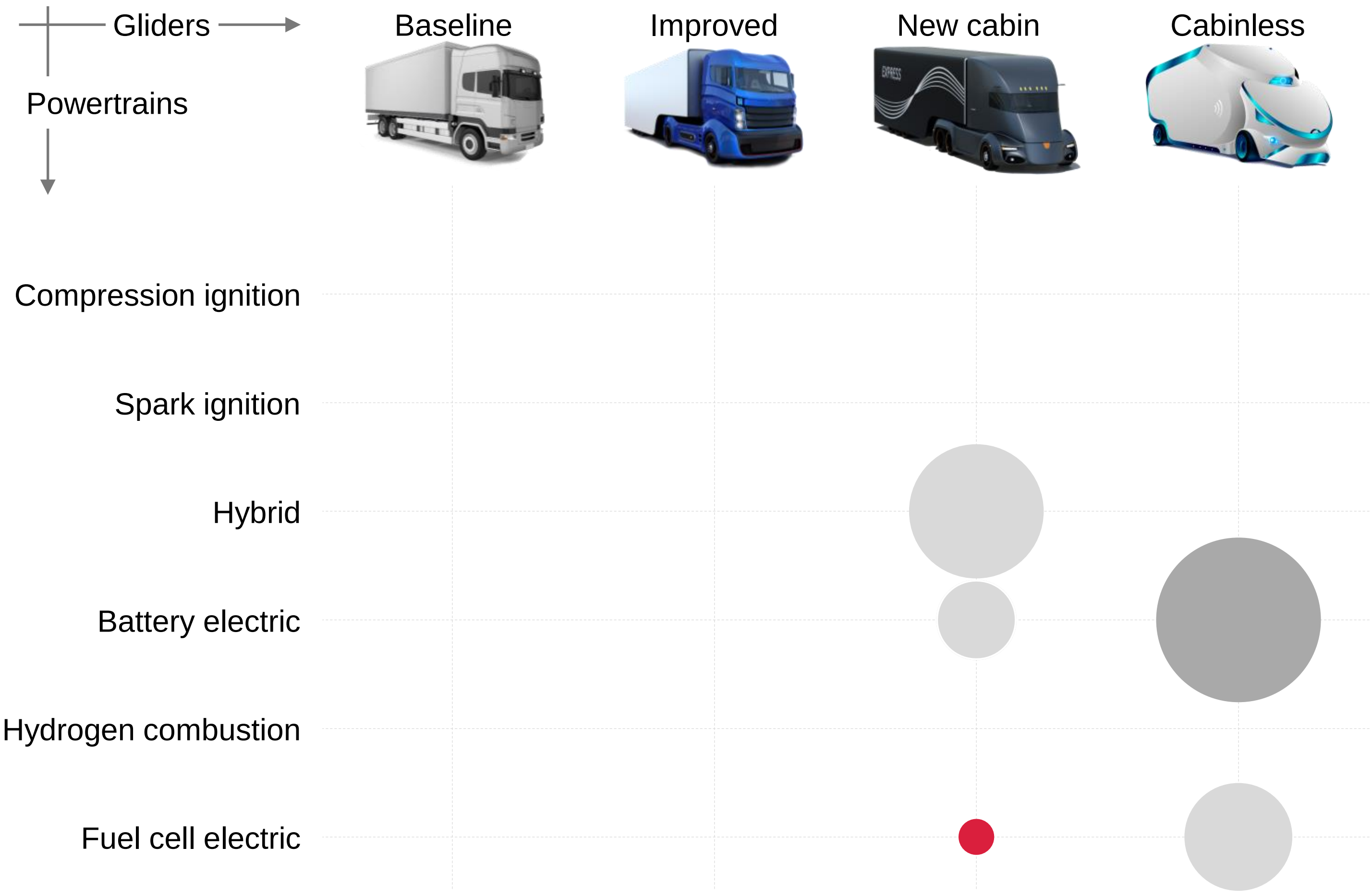
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the long run until 2040/2050 most of the sold vehicles have a zero CO_2 emission powertrain and a cabinless glider; automation share is high

2040/2050 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

LH 2040/50



- The most sold vehicle has a battery electric powertrain and a cabinless glider
- The most sold glider type is the cabinless glider reflecting high shares of automated trucks in sales
- No compression ignition and spark ignition powertrains are sold
- Combustion engines are only sold in hybrid powertrains
- Battery electric and fuel cell electric powertrains account for more than 70% of the market share of sales

Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In 2020/2030 most of regional haul sales are baseline gliders with compression ignition powertrains; improved gliders gain importance

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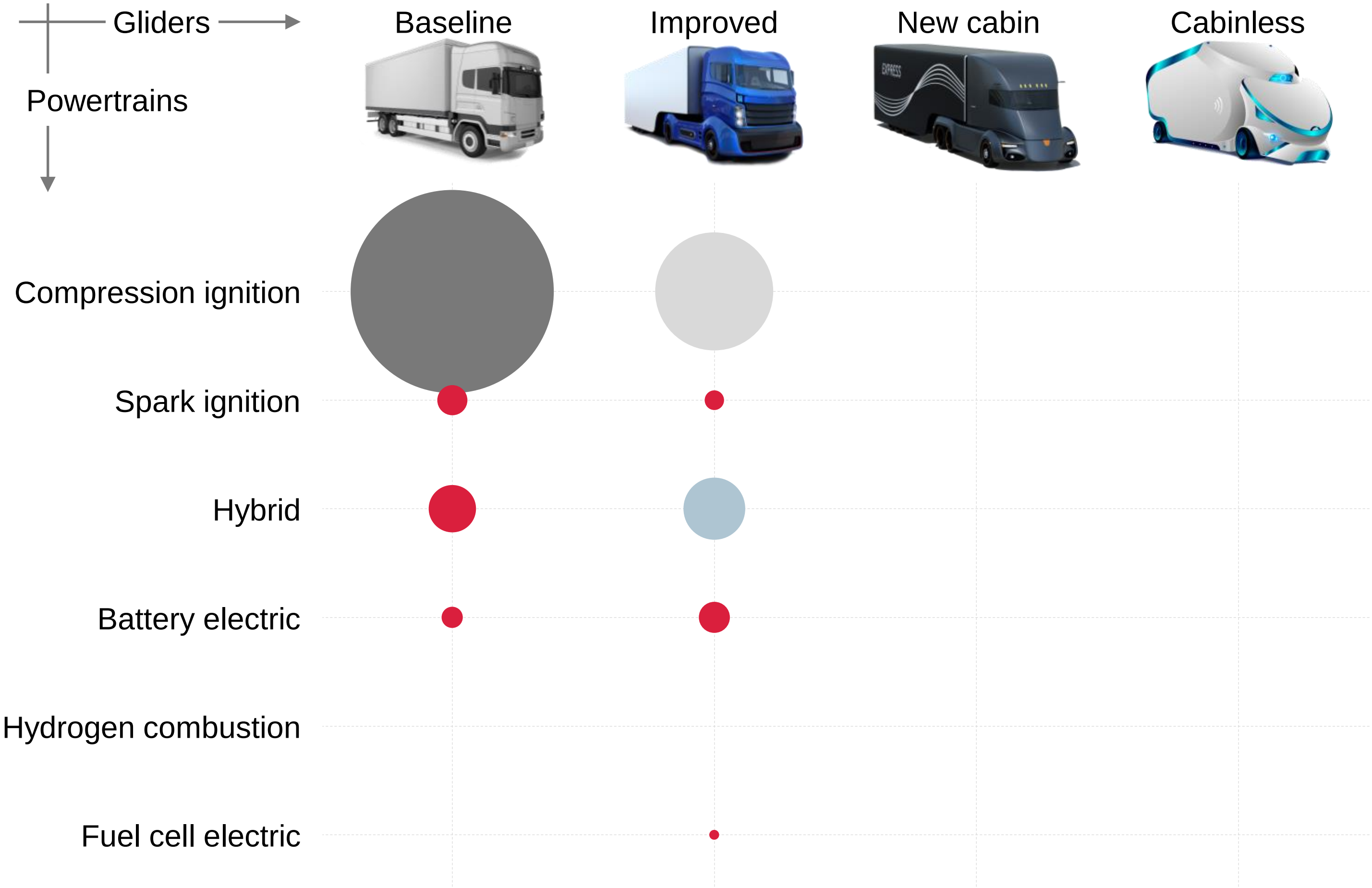
2020/2030 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES

RH

2020/30



	Baseline	Improved	New cabin	Cabinless
Compression ignition	● >50%	● 15-30%		
Spark ignition	● 0-5%	● 0-5%		
Hybrid	● 0-5%	● 5-15%		
Battery electric	● 0-5%	● 0-5%		
Hydrogen combustion				
Fuel cell electric		● 0-5%		

- The most sold vehicle has a compression ignition powertrain and the baseline glider
- Some vehicles are already being sold with the compression ignition powertrain in the improved glider
- The majority of powertrains is compression ignition and the majority of gliders is the baseline one
- Hybrid powertrains begin to emerge in the baseline and improved glider
- Battery electric and fuel cell powertrains are sold in low quantities

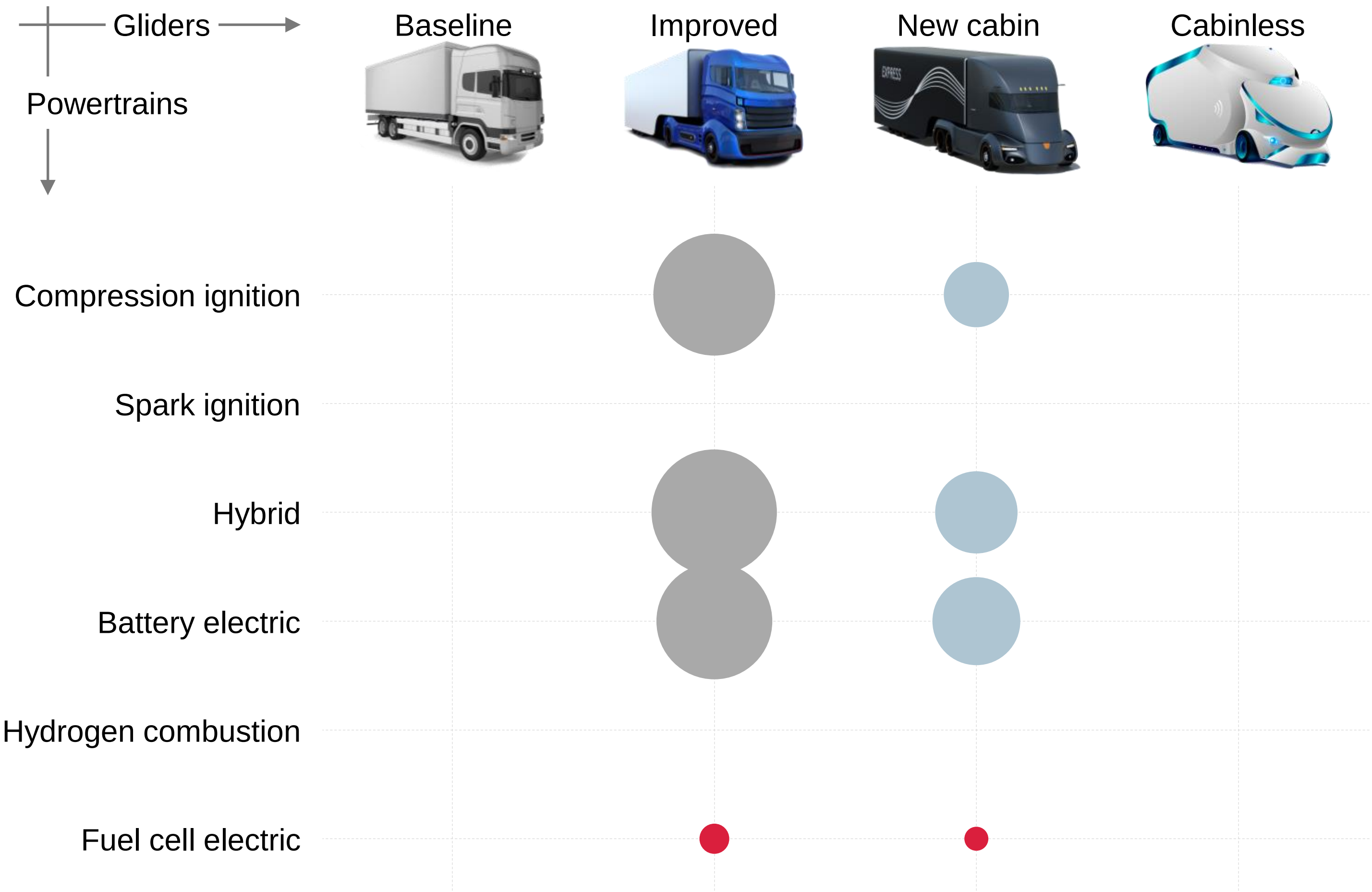
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2030/2040 timeframe FEV expects sales shares to be diversified in powertrains and gliders

RH 2030/40

2030/2040 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- No powertrain dominates sales: Compression ignition, hybrid and battery electric are similar in sales
- The majority of gliders is the improved one, yet also a considerable share of the sales are new cabin gliders
- Fuel cell electric powertrains are sold in low quantities in the improved and new cabin glider

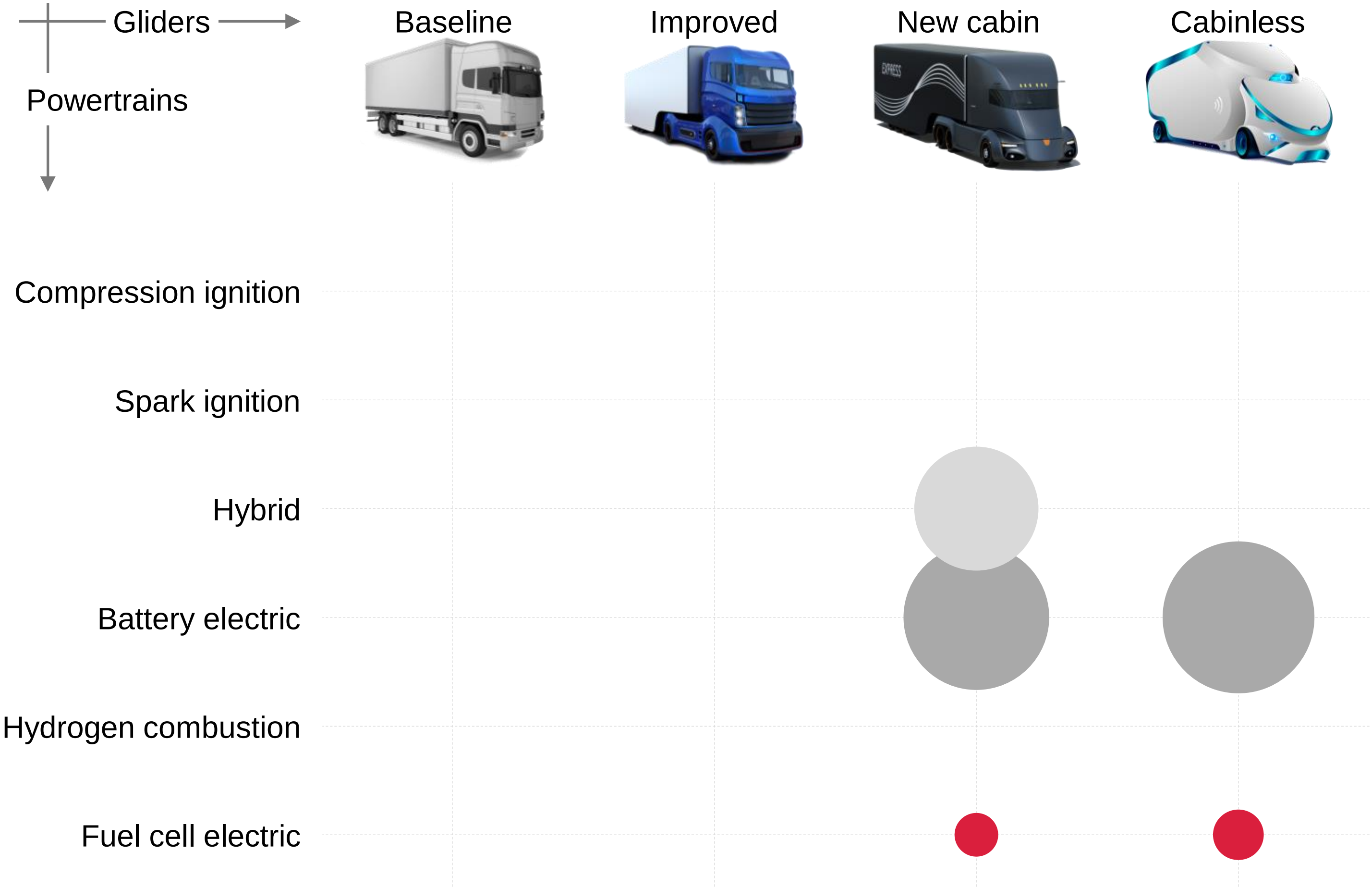
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the long run until the 2040/2050 timeframe the battery electric powertrain dominates sales and the cabinless glider covers a significant market share

RH 2040/50

2040/2050 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The battery electric powertrain is the mainstream in sales of this segment
- Nearly as many cabinless gliders are sold as new cabin ones
- Combustion engines are only sold in hybrid powertrains in new cabin gliders
- Fuel cell electric powertrains are sold in low quantities in the improved and new cabin glider

Source: FEV

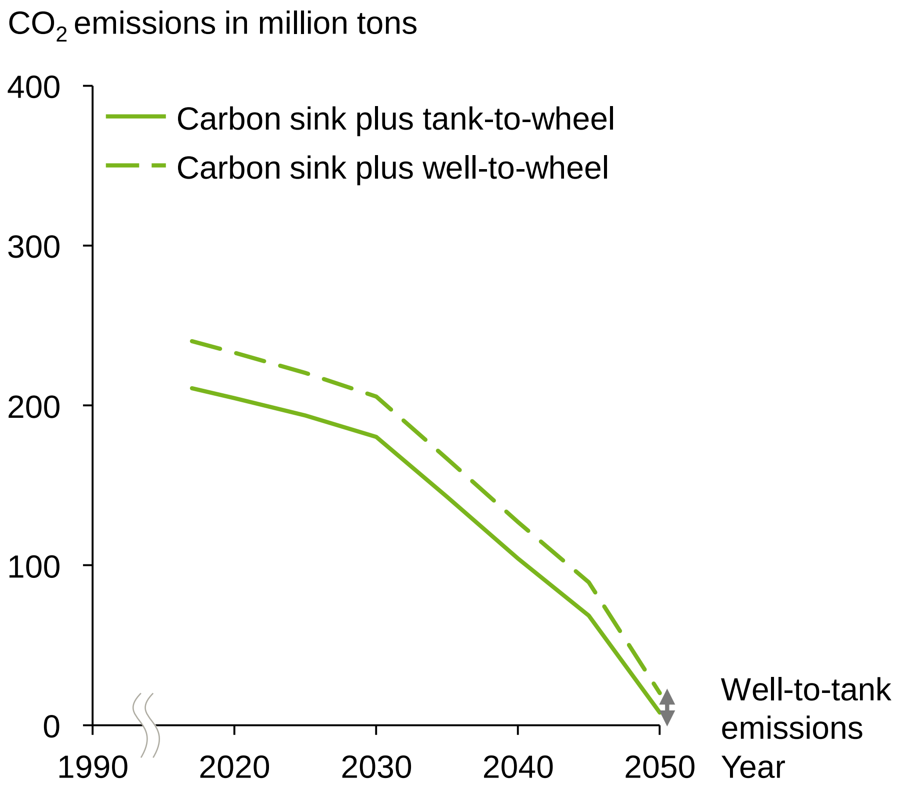
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

Agenda

- Reduced GHG emissions with holistic technology strategies
  - Energy demand model: Key functionalities and assumptions
  - Current policies scenario
  - Balanced energy carriers scenario
  - Accelerated electrification scenario
  - Approaching zero scenario

In the approaching zero scenario the CO_2 emission reduces strongly over time and accelerates after 2030 and 2045 in both balances

CO_2 EMISSION REDUCTION IN BOTH BALANCES



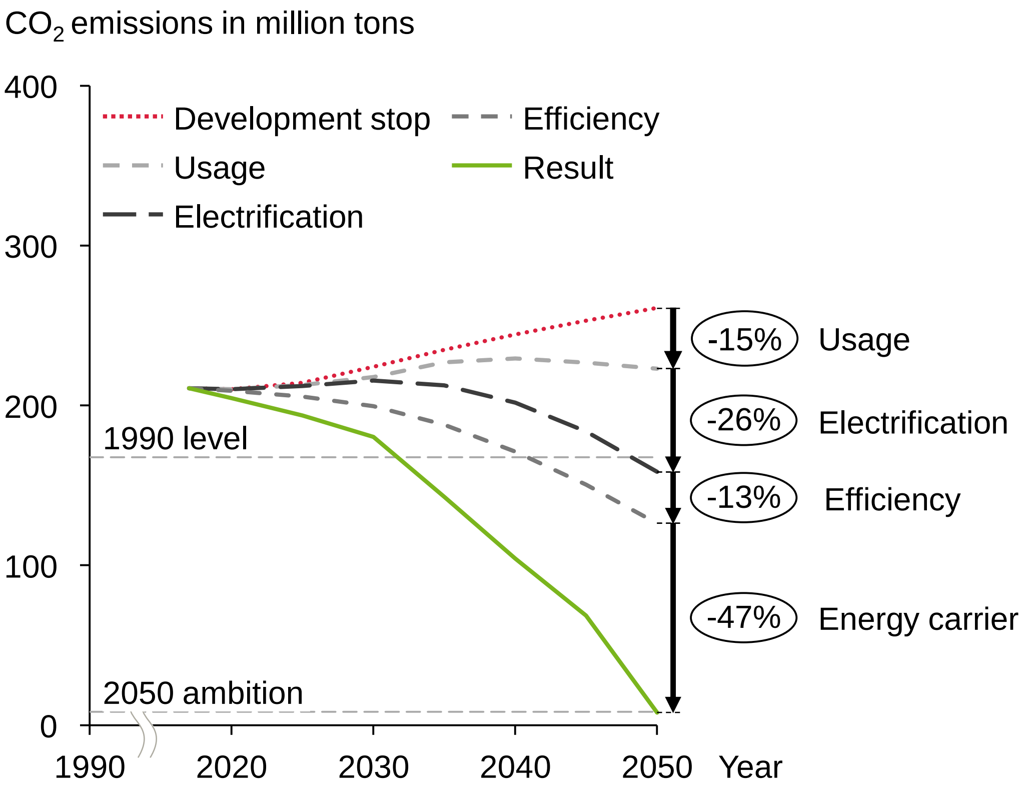
- In both the extended tank-to-wheel and the well-to-wheel balance the emissions reduce steadily and at an increasing pace after 2030 and 2045
  - The reduction will be broken down to its drivers on the next pages
  - The resulting energy demand and vehicle stock will be presented at the end of the chapter
- The difference between the two balances are the emissions from well-to-tank
- The difference between the balances reduces due to improvements in the well-to-tank emissions
  - Led by fuels from power-to-x processes and electricity from renewables that nearly emit no CO_2 from well-to-tank

Source: FEV

In the approaching zero scenario the CO_2 emission reduction comes mostly from electrification and energy carriers

DRIVERS OF THE CO_2 EMISSION REDUCTION IN AN EXTENDED TANK-TO-WHEEL BALANCE[1)]

Extended tank-to-wheel balance



- In the approaching zero scenario the CO_2 emissions can be reduced to 8 million tons per year and thus achieve the goal of a 95% reduction compared to 1990
- Usage contributes to the reduction by two factors that offset a 3%-point higher share of goods transported on-road compared to 2018
  - 5%-point reduction of the share of heavy-duty vehicles in on-road transport
  - 5%-point increase of average truck utilization
- Electrification represents a significant number of hybrid, followed by battery electric and fuel cell electric vehicles in considerable numbers
- Efficiency increase contributes to the CO_2 emission reduction by improvements of gliders and powertrains
- Energy carriers includes an effective blend share of renewables at 93 vol.-% in liquid fuels and 95 mass-% in gaseous fuels

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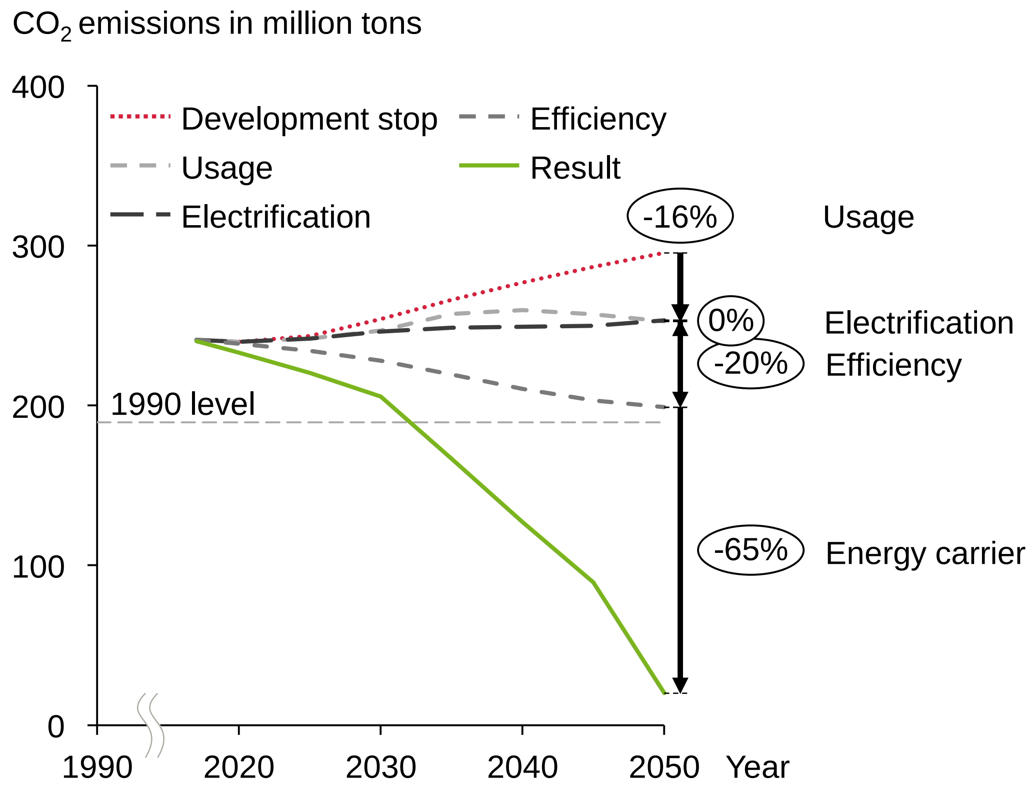
1) The extended tank-to-wheel balance considers the CO_2 emissions created when conversing the energy carrier to kinetic energy and a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

In the approaching zero scenario and the well-to-wheel balance the CO_2 emission reduction comes mostly from energy carriers

DRIVERS OF THE CO_2 EMISSION REDUCTION IN A WELL-TO-WHEEL BALANCE[1)]

Well-to-wheel balance



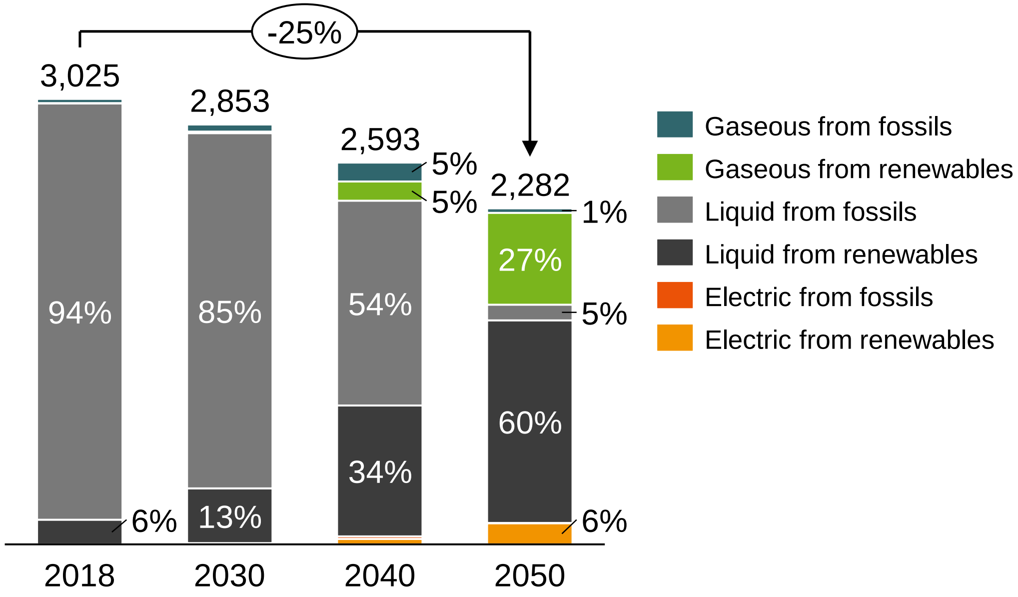
- In the approaching zero scenario CO_2 emissions are reduced to 20 million tons in 2050 which is a reduction of 89% compared to 1990
- Usage contributes to the reduction by two factors that offset a 3%-point higher share of goods transported on-road compared to 2018
  - 5%-point reduction of the share of heavy-duty vehicles in on-road transport
  - 5%-point increase of average truck utilization
- Electrification is about CO_2 emission neutral since the production of hydrogen and the electricity mix of 2018 emit a high amount of CO_2 that compete with CO_2 emission reduction from tank-to-wheel
- Efficiency increase contributes to the CO_2 emission reduction by improvements of gliders and powertrains
- Energy carriers reduce CO_2 emissions by the uptake of renewables, 71% of the reduction by liquid fuels, 8% by electricity and 21% by gaseous fuels

1) The well-to-wheel balance considers the CO_2 emissions created when producing, transporting and conversing the energy carrier to kinetic energy as well as a subtract of carbon storage that are realized during the production of the energy carrier.
Source: FEV

In the approaching zero scenario the final energy demand is dominated by liquid fuels from renewables

FINAL ENERGY DEMAND

Final energy demand by energy carrier in PJ



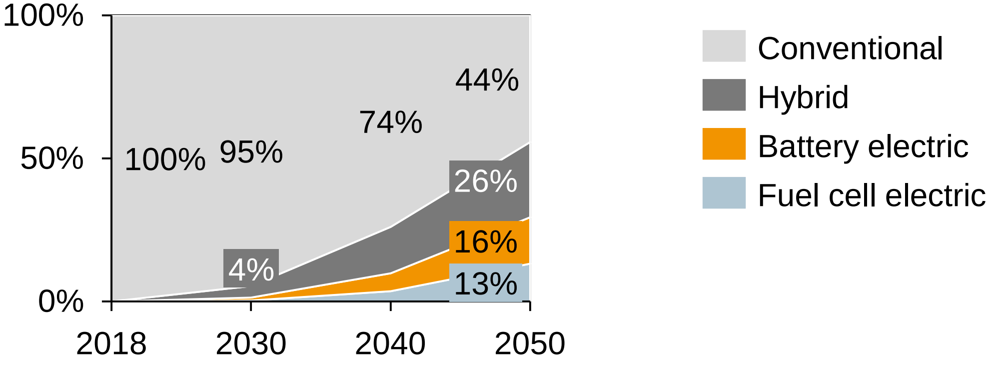
- Gaseous fuel include methane and hydrogen
  - Demand dominated by hydrogen at over 5 billion kg in 2050
  - Until 2050 a change to a production dominated from renewables is considered
- Liquid fuels are dominated by fuels from renewables while almost all are diesel-type fuels, gasoline-type fuels being the remainder
  - Only 3 billion liters of diesel from renewables
  - Liquid fuels from renewables include paraffins, short and long chain alcohols, the demand adds-up to 40 billion liters in 2050
- Electricity demand rises until 2050 up to 150 PJ
  - The production of electricity needs to be dominated by renewables by 2050 according to European targets

Source: FEV

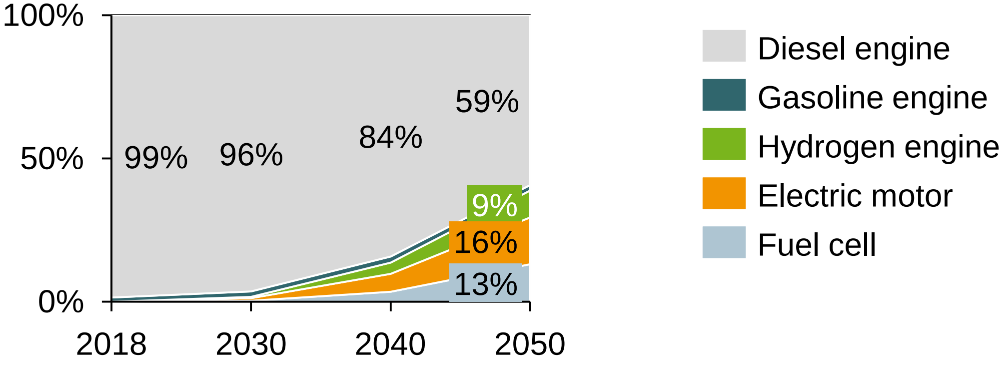
In the approaching zero scenario the vehicle stock is diversified in 2050

STOCK OF HEAVY-DUTY VEHICLES

Stock of heavy-duty vehicles by electrification level



Stock of heavy-duty vehicles by main energy conversion system



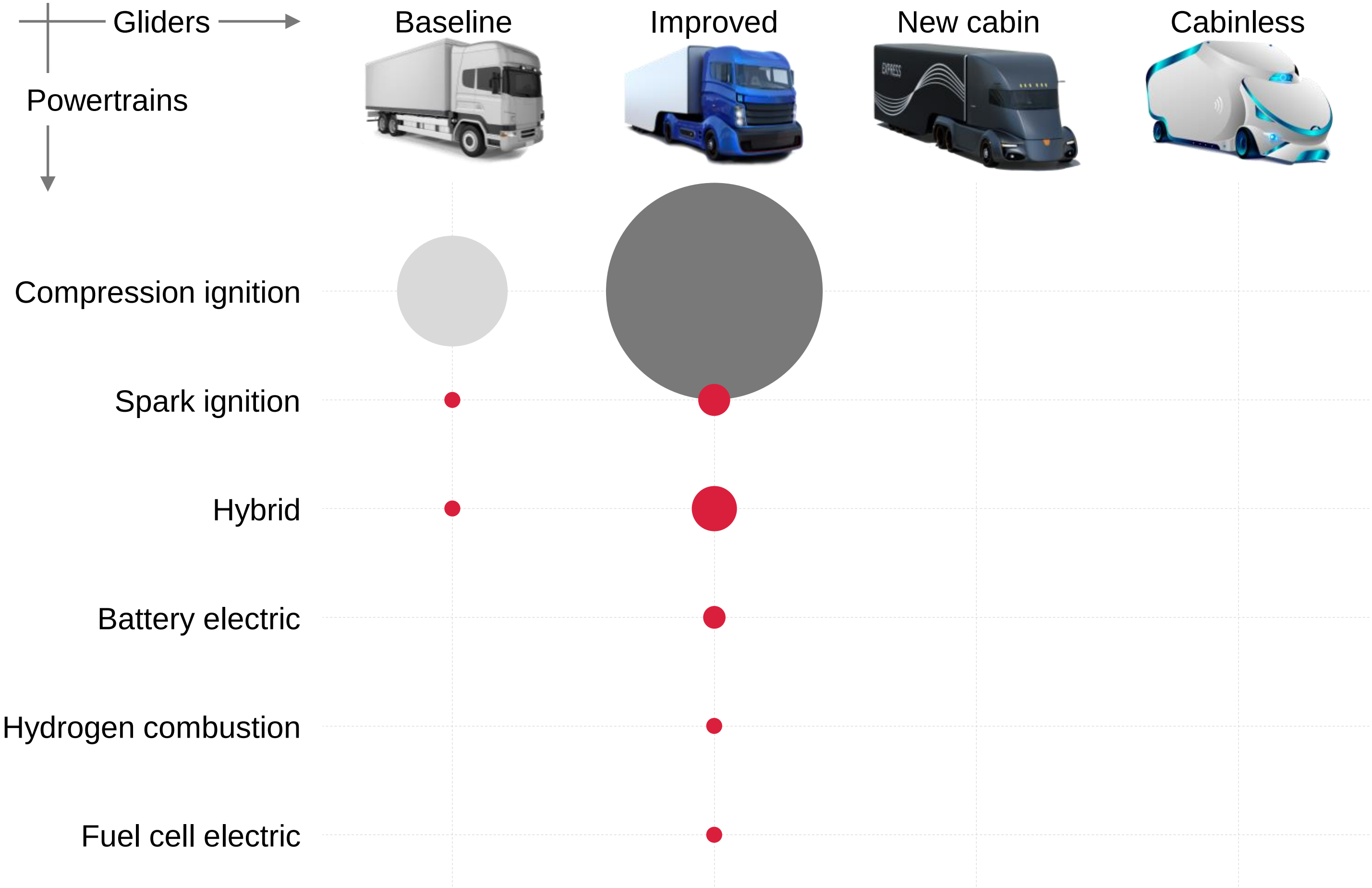
Source: FEV

- The vehicle stock is defined by the sales and the average time a vehicle stays in the European market
  - The average age of the stock is higher in 2050 than in 2018, mainly by a reduction of sales numbers due to automation
- In 2050 4.1 million vehicles are in stock which is nearly equal to 2018
- The vehicle stock is diversified in 2050, while conventional and hybrid powertrains have the highest shares in terms of electrification level
- Battery electric powertrains experience a steady uptake in the vehicle stock
  - Introduced towards 2030 in considerable numbers to ensure the OEMs meet their respective targets
  - After 2030 the uptake accelerates since more and more use-cases get favorable
- Fuel cell electric vehicles are represented in the vehicle stock at an increasing pace after 2040

In the 2020/2030 timeframe long haul trucks are expected to be mostly sold with a compression ignition powertrain in an improved glider

2020/2030 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

CO_2 0 LH 2020/30



- The most sold vehicle has a compression ignition powertrain and an improved glider
- There is still a considerable number of sales of compression ignition powertrains in the baseline glider
- The majority of powertrains is compression ignition and the majority of gliders is the improved one
- Hybrid powertrains begin to emerge in the improved glider
- Battery electric and fuel cell powertrains are sold in low quantities in improved gliders

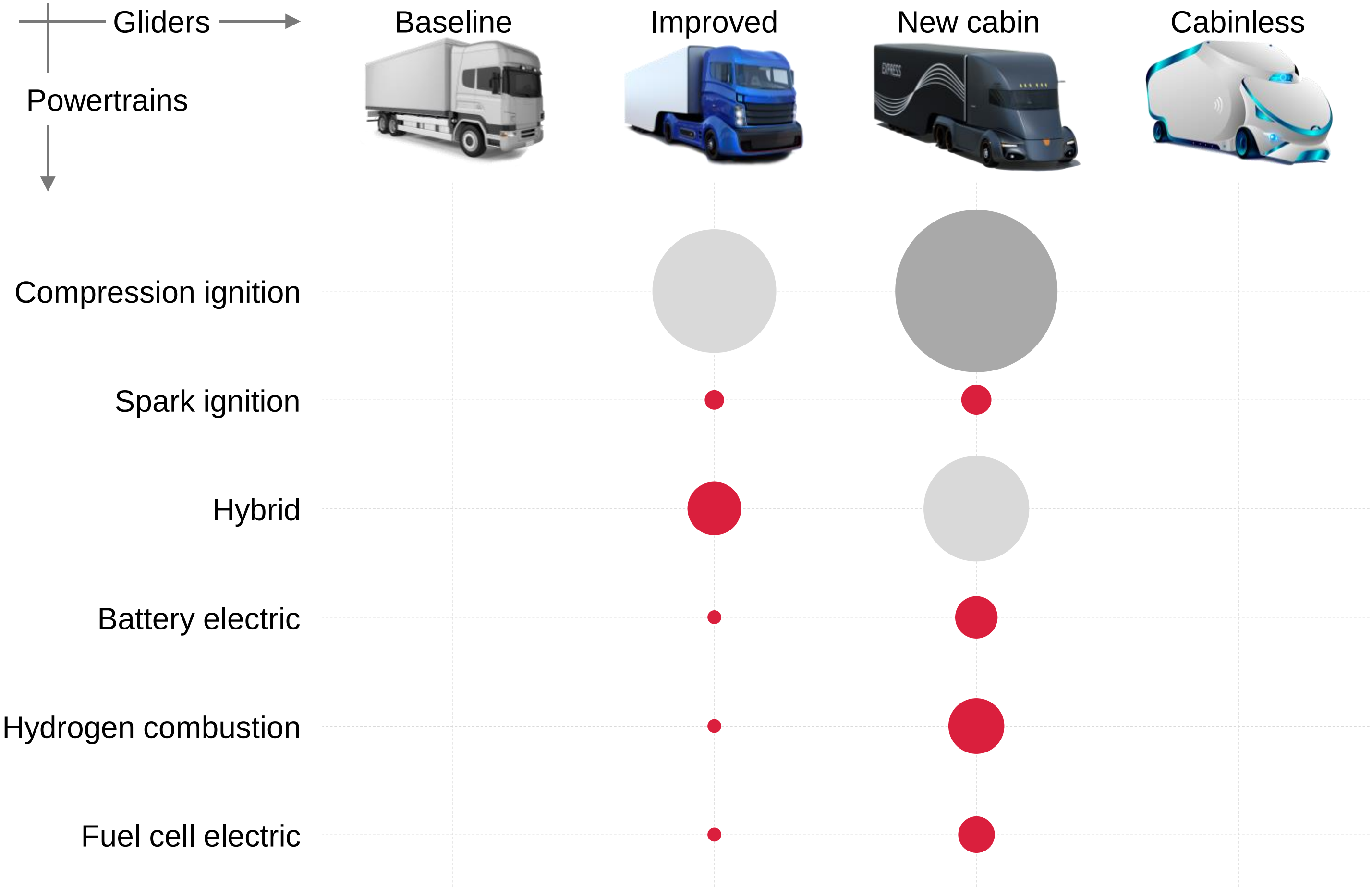
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2030/2040 timeframe the sales are divided on multiple powertrains and are shifted towards the new cabin glider

LH 2030/40

2030/2040 TIMEFRAME – OVERVIEW OF LONG HAUL SALES



- The most sold vehicle has a compression ignition powertrain and a new cabin glider
- The majority of powertrains is compression ignition, the majority of gliders is the new cabin one
- Hybrid powertrains are sold in the improved and new cabin glider, where they already exceed 15% of market share
- Battery electric, hydrogen combustion and fuel cell electric powertrains are sold in the improved and new cabin glider at comparably low quantities

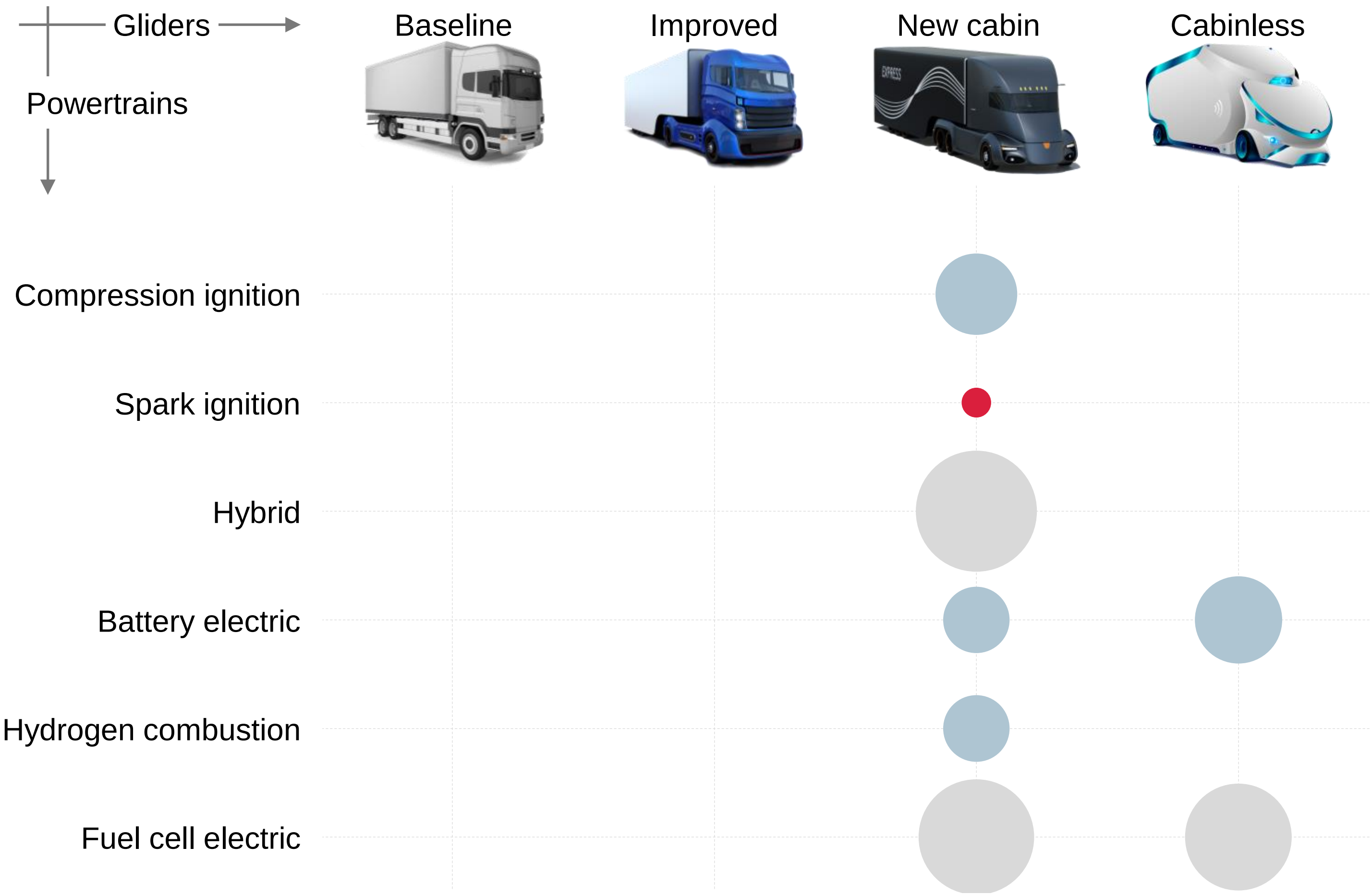
Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2040/2050 timeframe zero CO_2 emission powertrains combine a relevant amount of the sales share

2040/2050 TIMEFRAME – OVERVIEW OF LONG HAUL SALES

CO_2 0 LH 2040/50



- Sales of hybrid powertrains in the new cabin glider and fuel cell electric powertrains in new cabin and cabinless glider hold the highest market share
- In the cabinless glider only battery electric and fuel cell electric powertrains get sold
- The zero CO_2 emission powertrains – battery electric, hydrogen combustion and fuel cell electric – account for around 50% of the market share

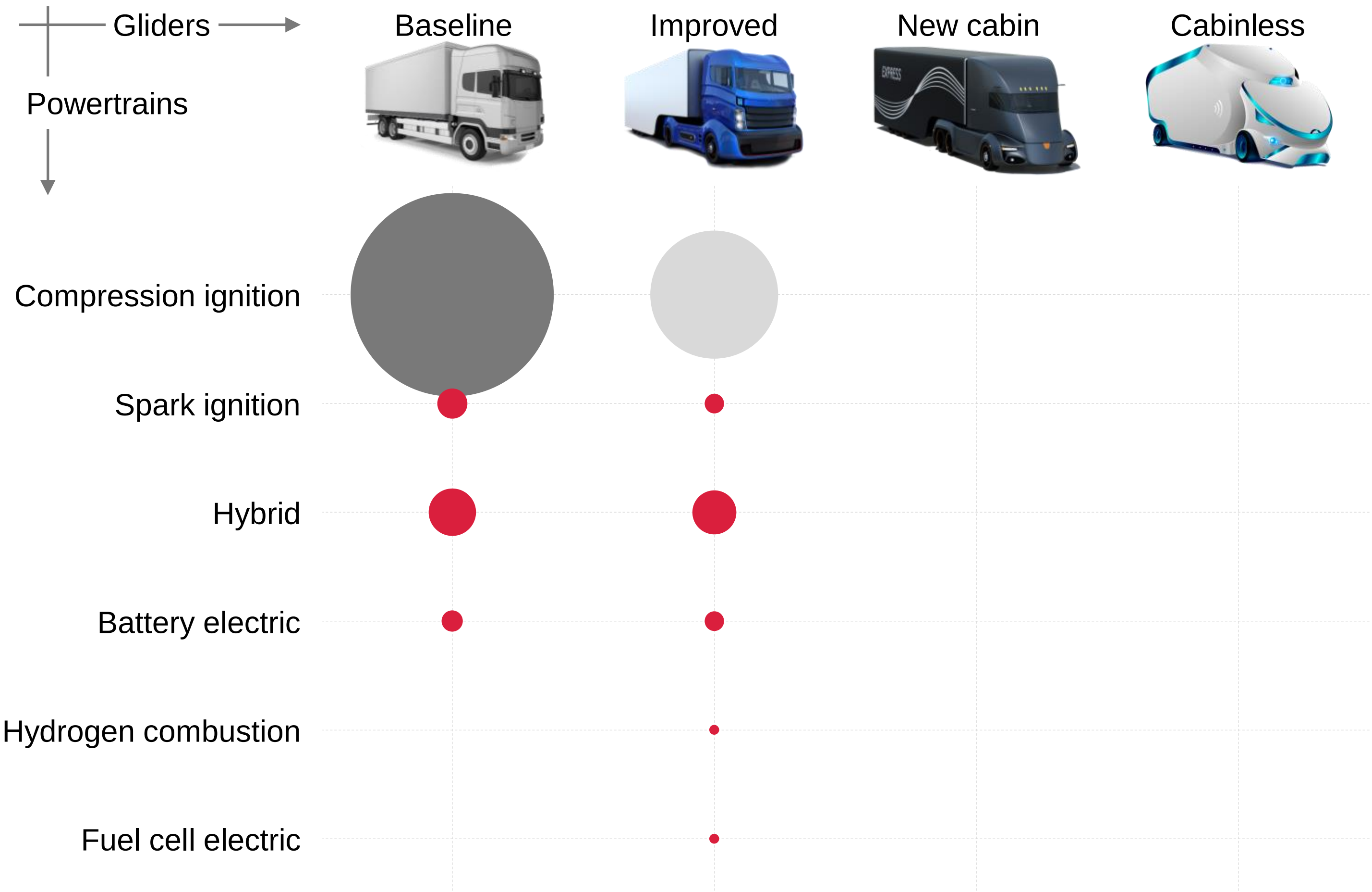
Source: FEV

🟥 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In 2020/2030 most of regional haul sales are in the compression ignition powertrain and baseline glider – some sales already in the improved glider

2020/2030 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES

RH 2020/30



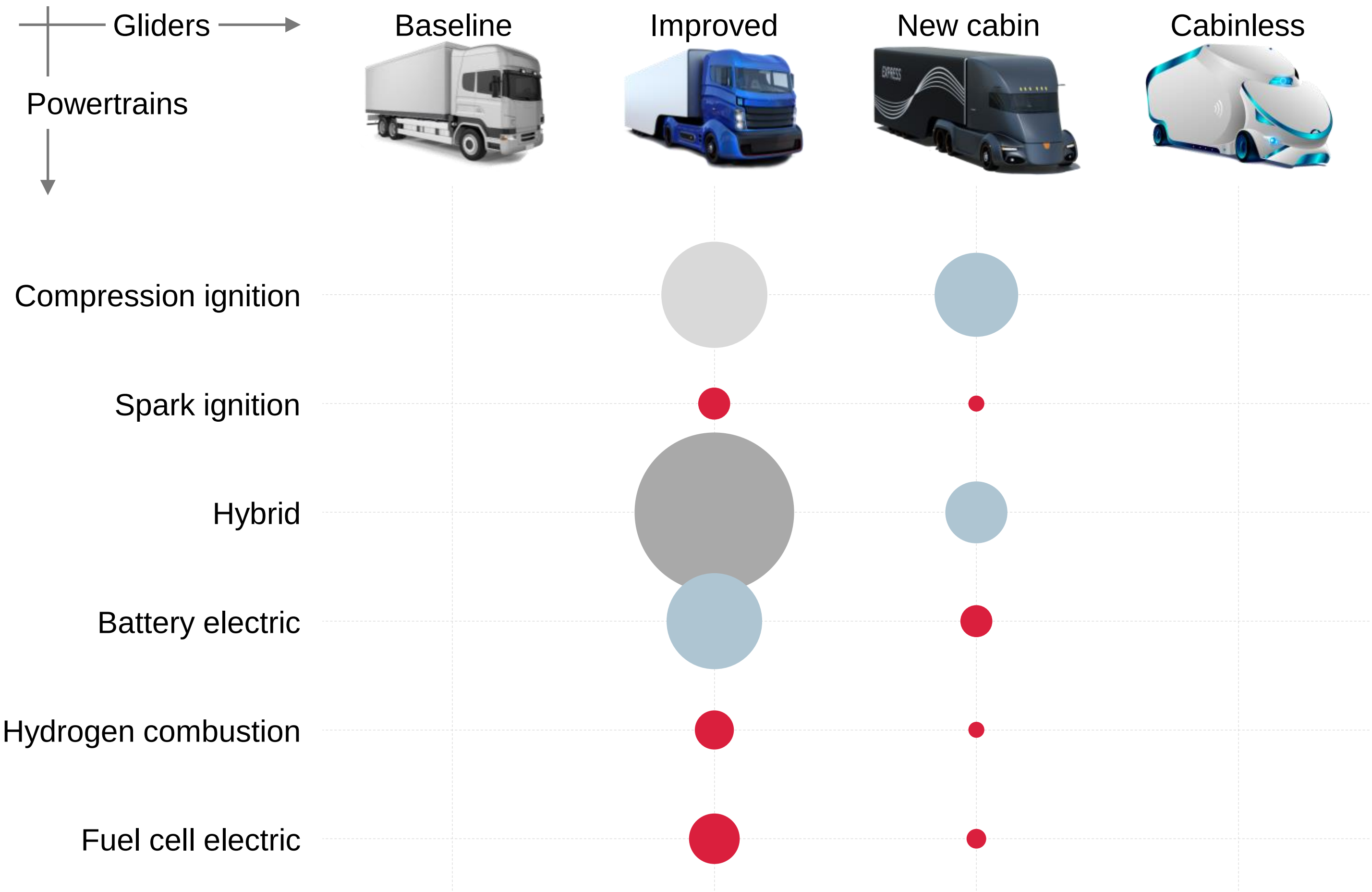
- The most sold vehicle has a compression ignition powertrain and the baseline glider
- Some vehicles are already being sold with the compression ignition powertrain in the improved glider
- The majority of powertrains is compression ignition and the majority of gliders is the baseline one
- Hybrid powertrains begin to emerge in the baseline and improved glider
- Battery electric and fuel cell powertrains are sold in low quantities

Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

2030/2040 hybrid powertrains are expected to have the highest sales share while the improved glider remains dominant

2030/2040 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The most sold vehicle has a hybrid powertrain and an improved glider
- The majority of powertrains is hybrid and the majority of gliders is the improved one
- The battery electric powertrain exceeds 5% of sales share in the improved glider
- Hydrogen combustion and fuel cell electric powertrains are sold in low quantities in the improved and new cabin glider

Source: FEV

● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

In the 2040/2050 timeframe FEV expects a high diversity of powertrains in the new cabin glider and considerable sales of cabinless gliders

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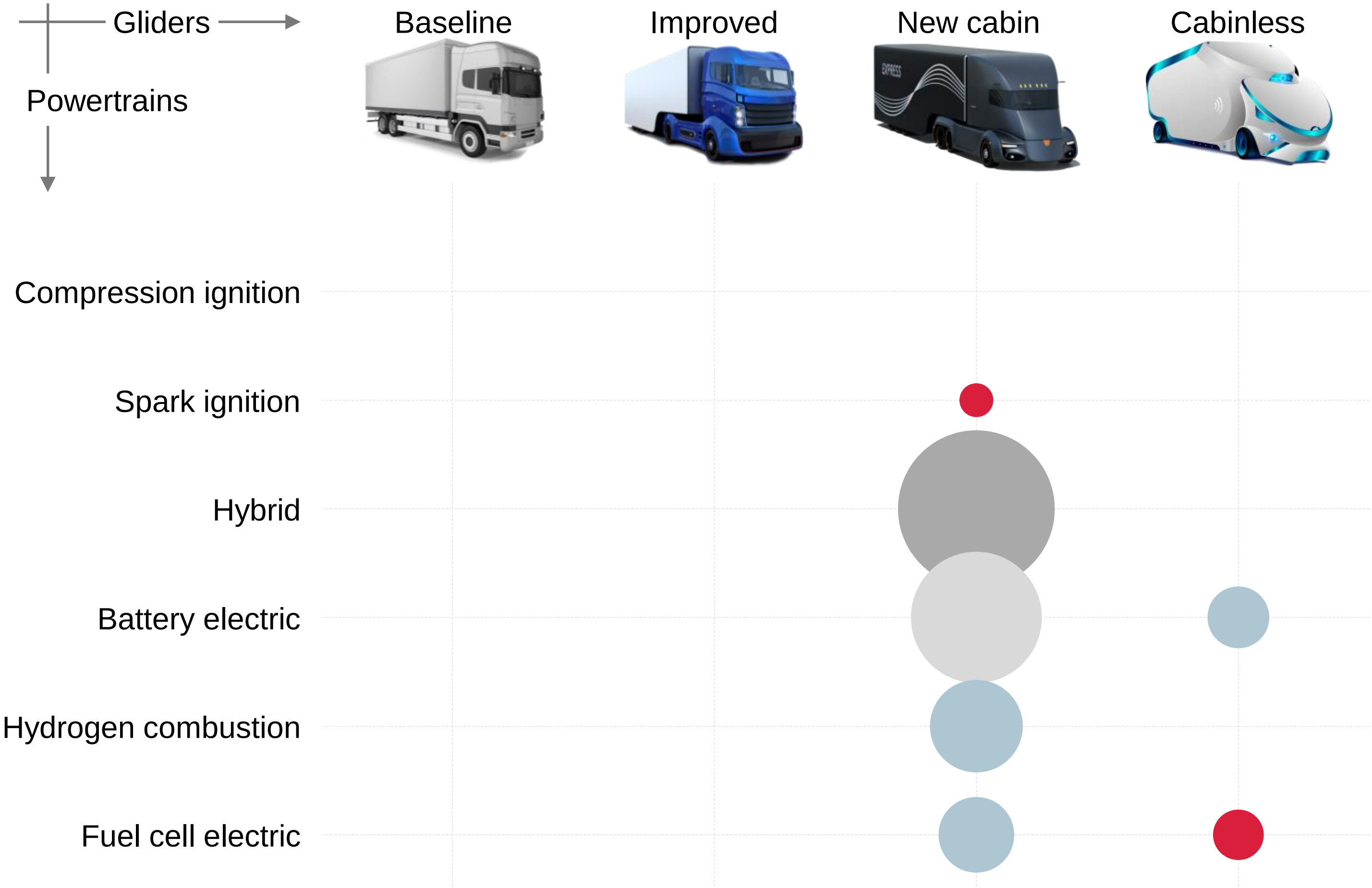
CO_2 0 RH 2040/50

2040/2050 TIMEFRAME – OVERVIEW OF REGIONAL HAUL SALES



- The most sold vehicle has a hybrid powertrain in a new cabin design; battery electric versions in that same glider follow second
- The zero CO_2 emission powertrains – battery electric, hydrogen combustion and fuel cell electric – account for around 50% of the market share
- Battery electric powertrain sales are strong in the new cabin and cabinless glider
- Hydrogen combustion and fuel cell electric powertrains are in the market at considerable numbers

Source: FEV

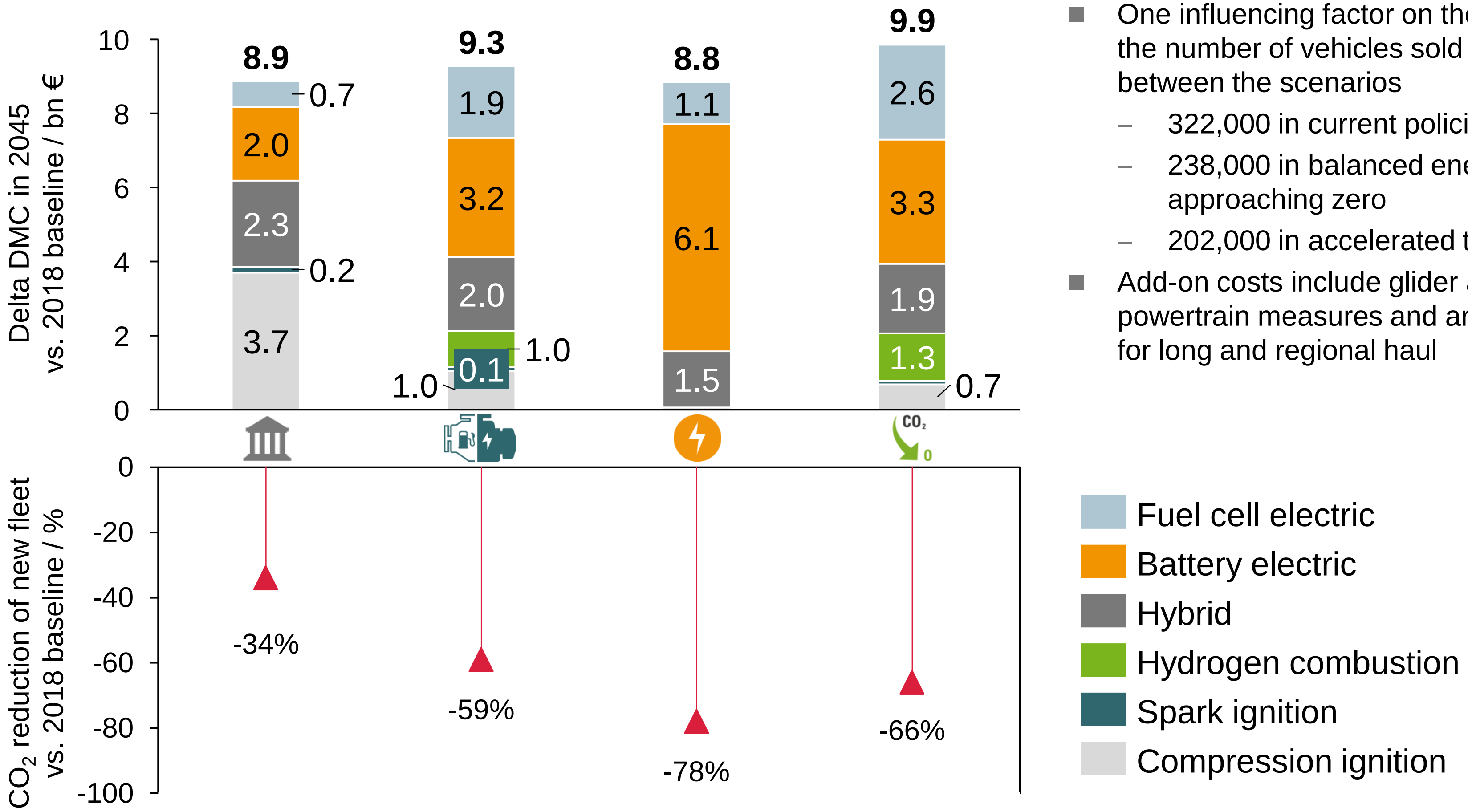
● 0-5% sales share ● 5-15% sales share ● 15-30% sales share ● 30-50% sales share ● >50% sales share

Agenda

- Executive summary
- Framework and long-term scenarios for HD on-road transportation
- Technology options towards 2050
- Future pathways towards clean on-road transportation
- Reduced GHG emissions with holistic technology strategies
- CO_2 abatement costs for selected reference trucks
- TCO performance of underlying reference trucks
- Life-cycle analysis for HD trucks

The approaching zero scenario requires the highest add-on costs – in 3 of 4 scenarios battery electric trucks account for highest add-on costs

SUMMARY OF TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS ACROSS SCENARIOS



- One influencing factor on the total add-on costs is the number of vehicles sold in 2045 which differ between the scenarios
  - 322,000 in current policies
  - 238,000 in balanced energy carriers and approaching zero
  - 202,000 in accelerated transformation
- Add-on costs include glider and powertrain measures and are shown combined for long and regional haul

Source: FEV

In the current policies scenario for long haul trucks add-on costs of 5.4 billion € are spend while a CO_2 emission reduction of 34% is achieved

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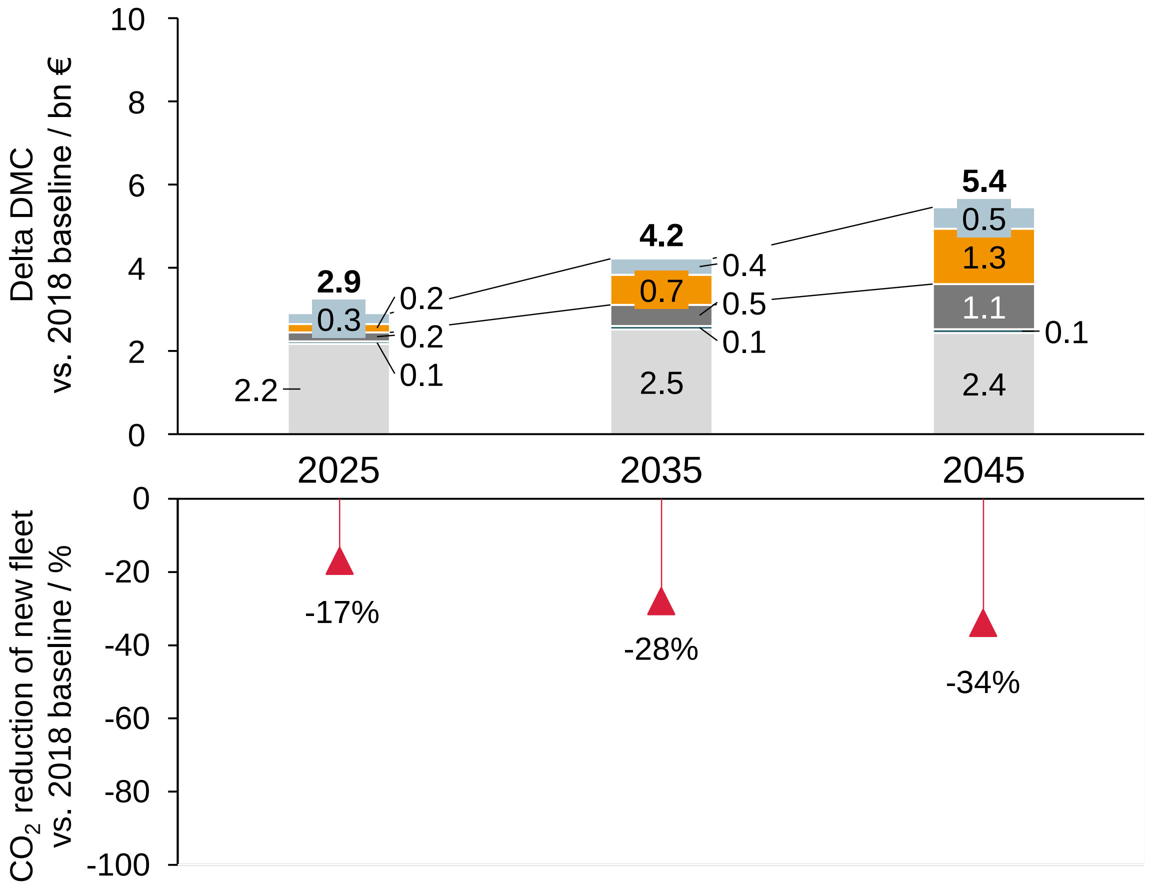
TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)



- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles are comparably constant while an increase is predicted for FCEVs and BEVs
- Resulting decrease in CO_2 emissions is 34% by 2045 compared to 2018 in a tank-to-wheel balance

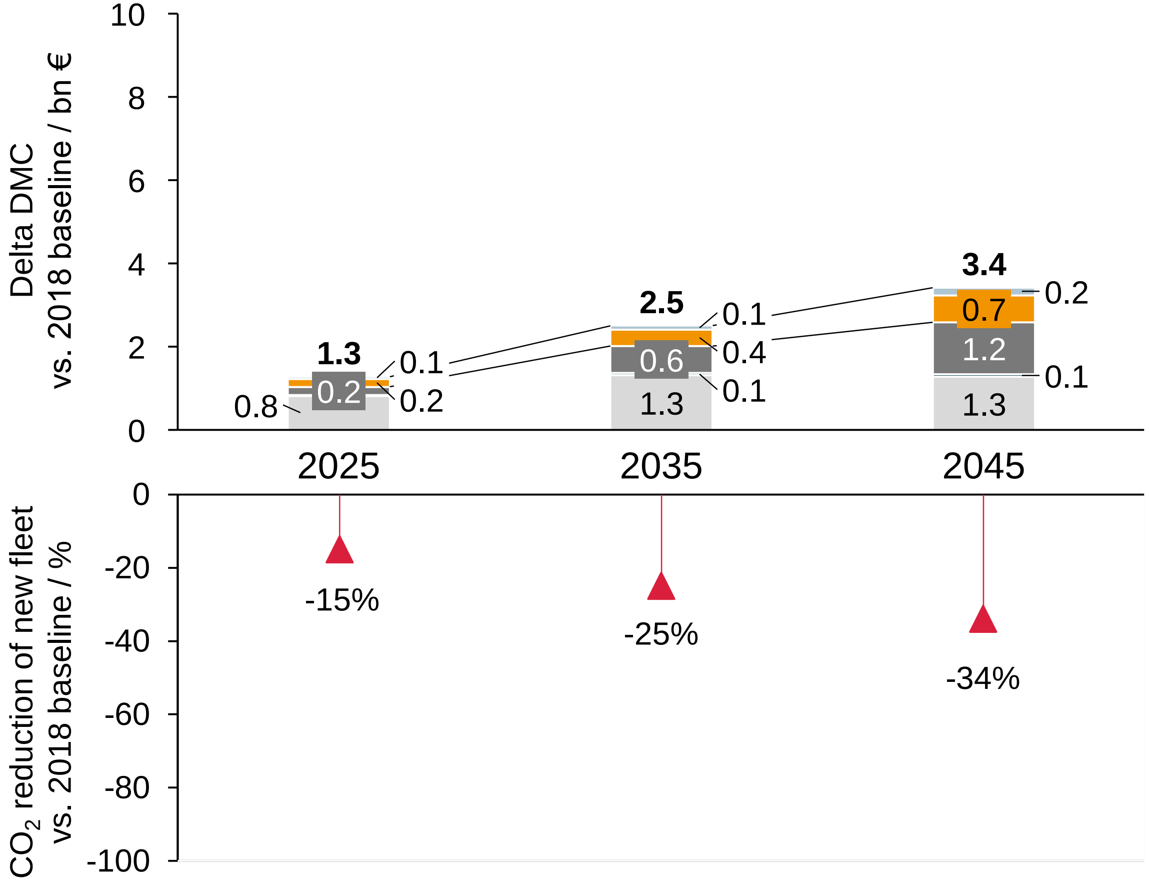
▨ Fuel cell electric
▨ Battery electric
▨ Hybrid
▨ Hydrogen combustion
▨ Spark ignition
▨ Compression ignition

Source: FEV

In the current policies scenario for regional haul trucks add-on costs of 3.4 billion € are spend while a CO_2 emission reduction of 34% is achieved

FEV CONSULTING

TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)



- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles are comparably constant while an increase is predicted for FCEVs and BEVs
- Resulting decrease in CO_2 emissions is 34% by 2045 compared to 2018 in a tank-to-wheel balance

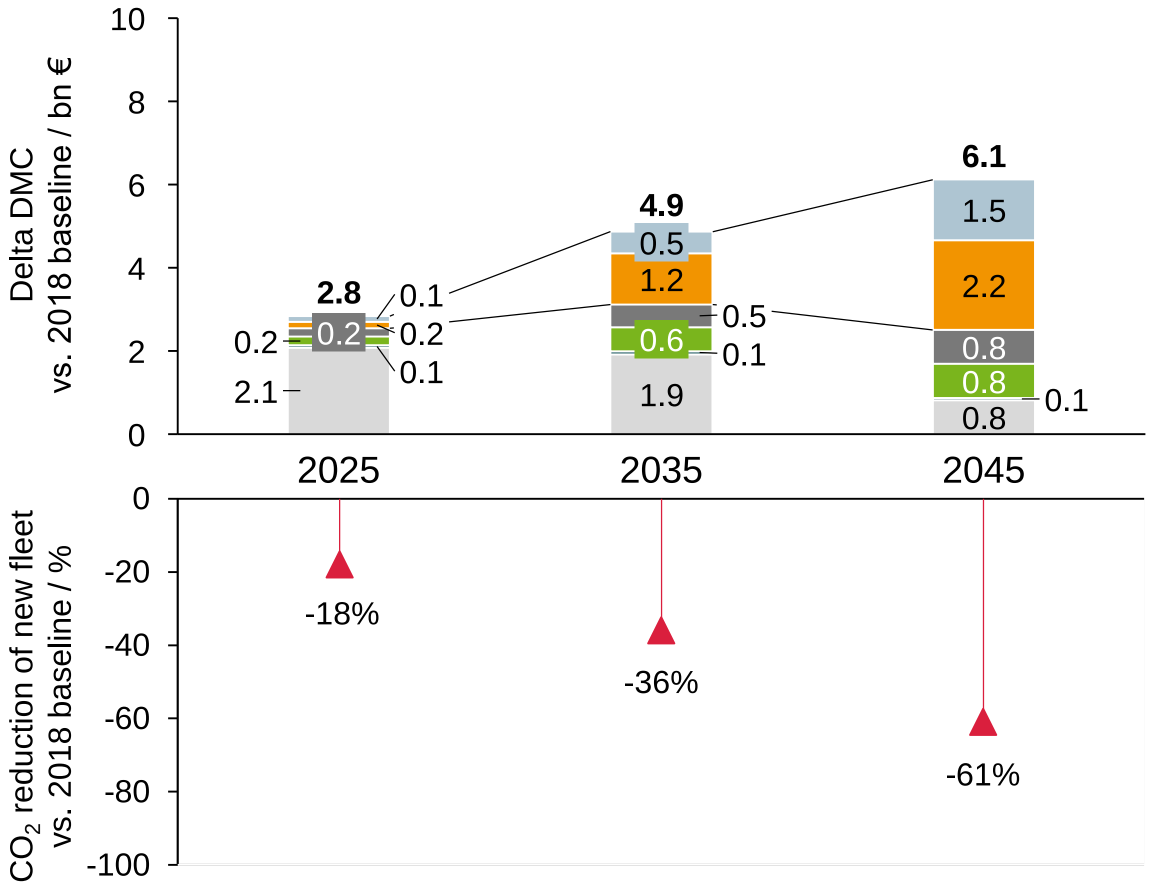
Source: FEV

In the balanced energy carriers scenario add-on costs of the sold long haul fleet in 2045 are ~6 bn € in comparison to 2018; CO_2 is reduced by >60%

FEV CONSULTING

TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)

LH



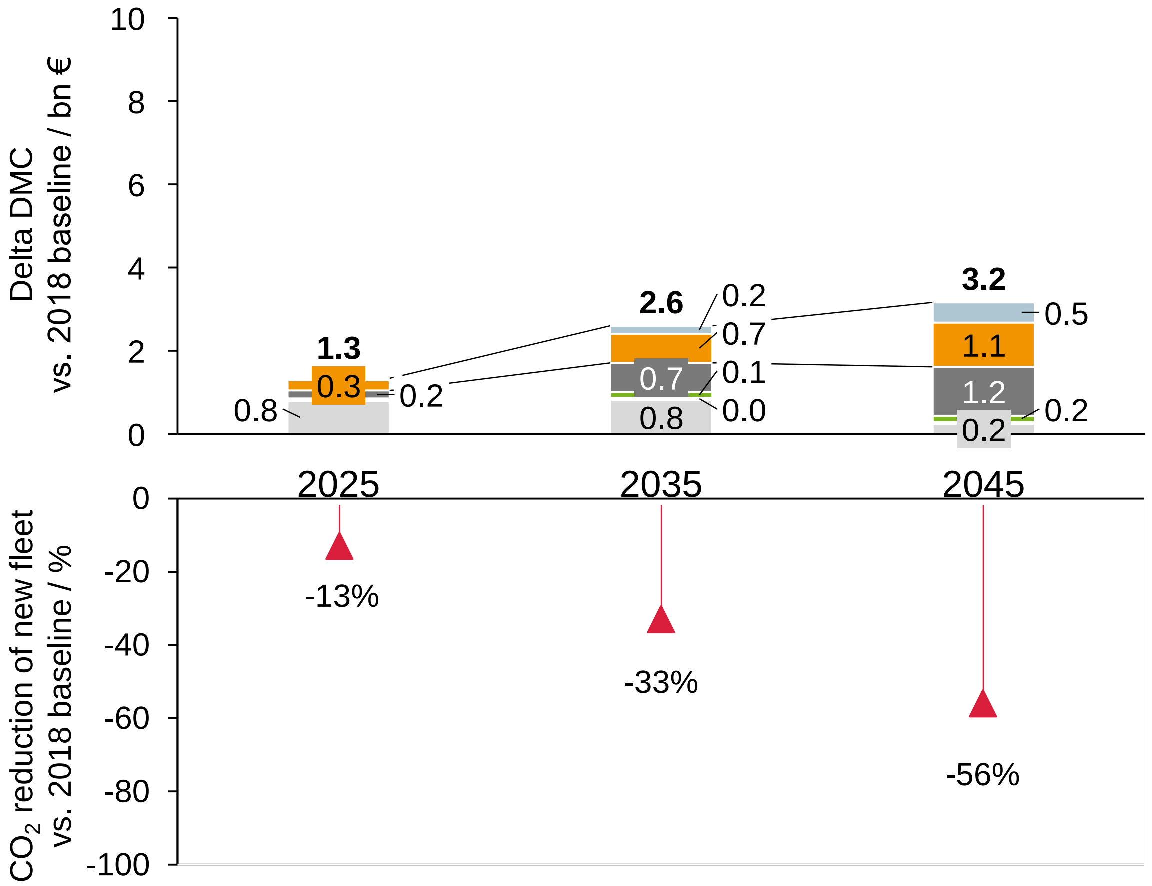
- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles shrink over time; a significant increase is predicted for FCEVs and BEVs
- Resulting decrease in CO_2 emissions is >60% by 2045 compared to 2018 in a tank-to-wheel balance

Source: FEV

For the regional haul vehicles the picture is different: add-on costs are halved (~3 bn €) but CO_2 reduction performance remains on a similar level

FEV CONSULTING

TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)



- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles shrink over time; a significant increase is predicted for FCEVs, BEVs and hybrids (relevant CO_2 effect on regional haul applications)
- Resulting decrease in CO_2 is ~56% by 2045 (tank-to-wheel)

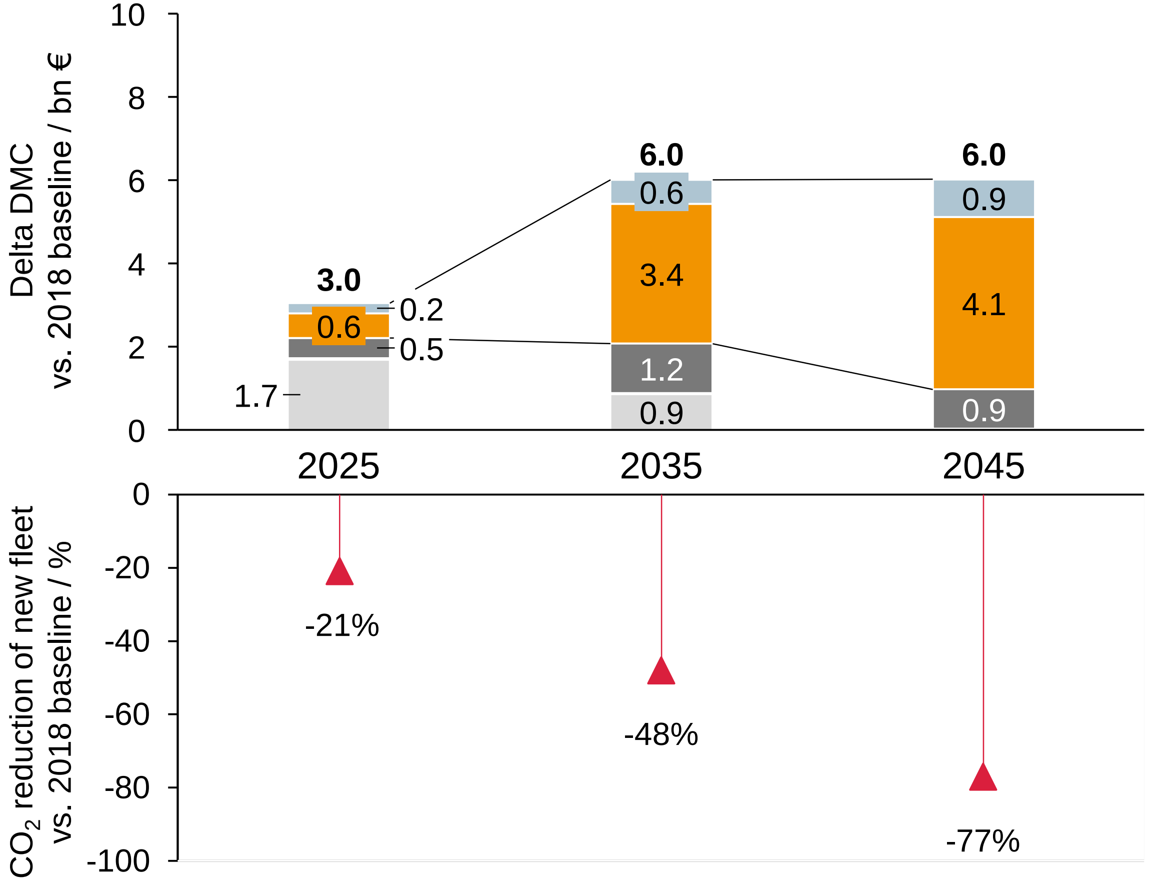
Source: FEV

In the accelerated transformation scenario 6 billion € of additional costs are spend on long haul trucks to achieve 77% CO_2 emission reduction

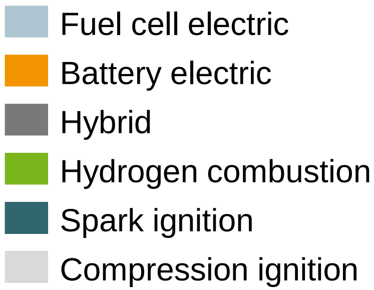
FEV CONSULTING

TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)

LH



- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles reduce to near zero together with the number of units sold, while the additional costs spend on battery electric powertrains increase at a high pace
- Resulting decrease in CO_2 emissions is 77% by 2045 compared to 2018 in a tank-to-wheel balance



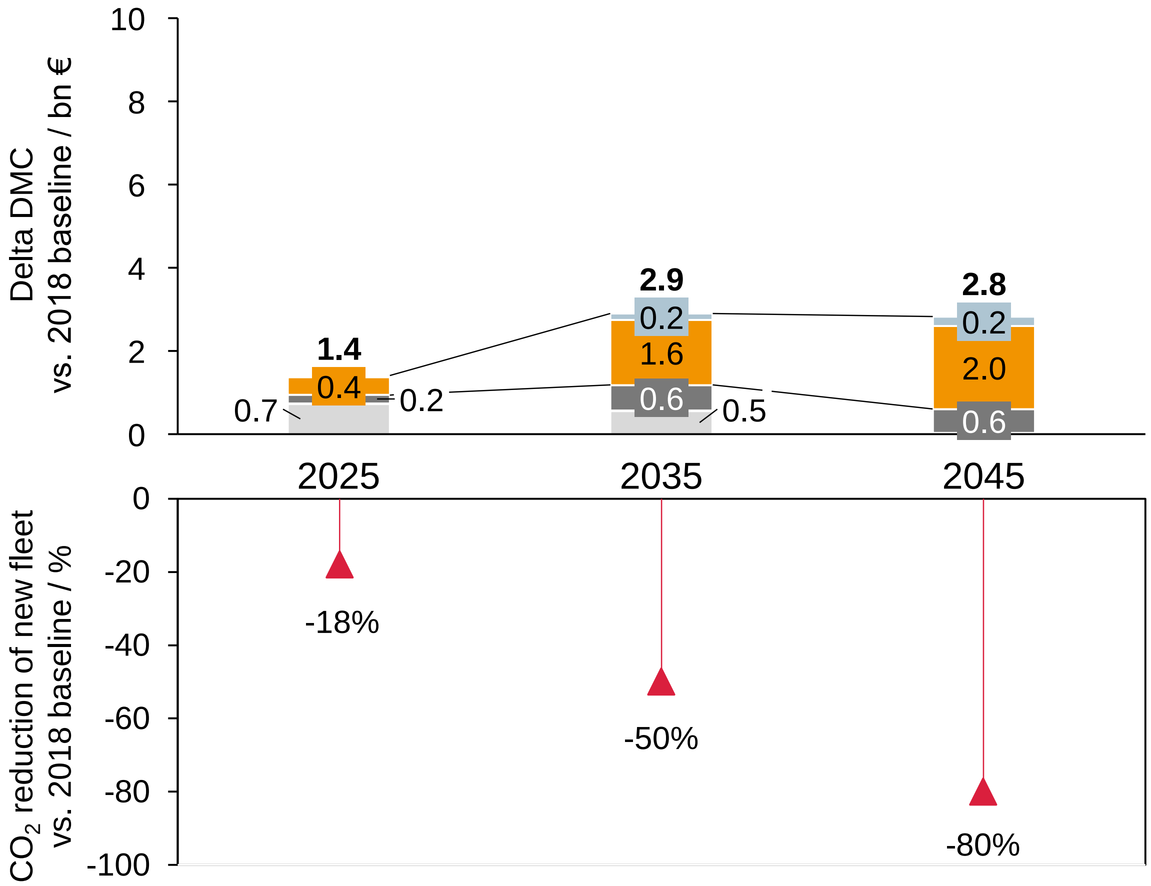
Source: FEV

In the accelerated transformation scenario 2.8 billion € of additional costs are spend on regional haul trucks to achieve 80% CO_2 emission reduction

FEV CONSULTING

TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)

RH

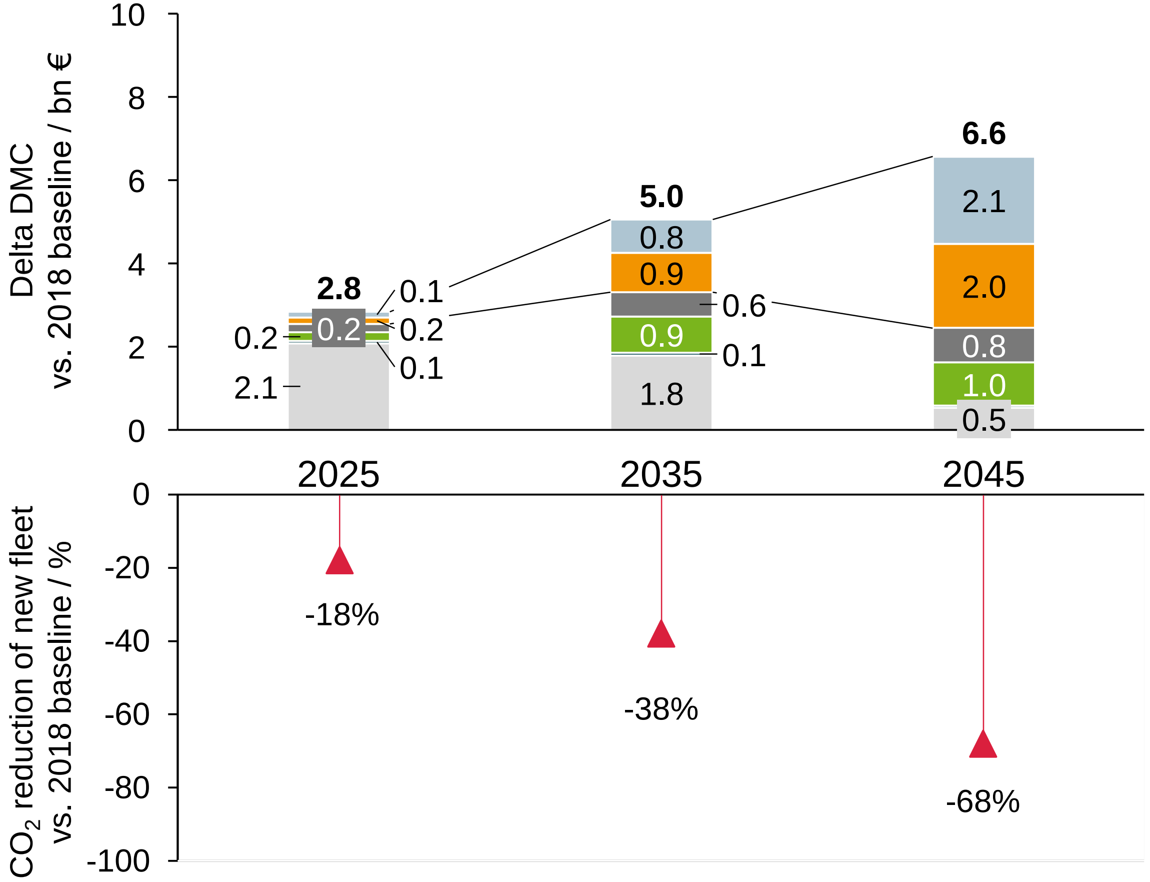


- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles reduce to near zero together with the number of units sold, while the additional costs spend on battery electric increase
- Resulting decrease in CO_2 emissions is 80% by 2045 compared to 2018 in a tank-to-wheel balance

Source: FEV

In the approaching zero scenario 6.6 billion € of add-on costs are spend on long haul trucks to achieve 68% CO_2 emission reduction compared to 2018

TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)



- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles reduce to near zero together with the number of units sold, while the additional costs spend on zero CO_2 emission powertrains increase significantly
- Resulting decrease in CO_2 emissions is 68% by 2045 compared to 2018 in a tank-to-wheel balance

▨ Fuel cell electric
▨ Battery electric
▨ Hybrid
▨ Hydrogen combustion
▨ Spark ignition
▨ Compression ignition

Source: FEV

In the approaching zero scenario 3.3 billion € of add-on costs are spend on long haul trucks to achieve 63% CO_2 emission reduction compared to 2018

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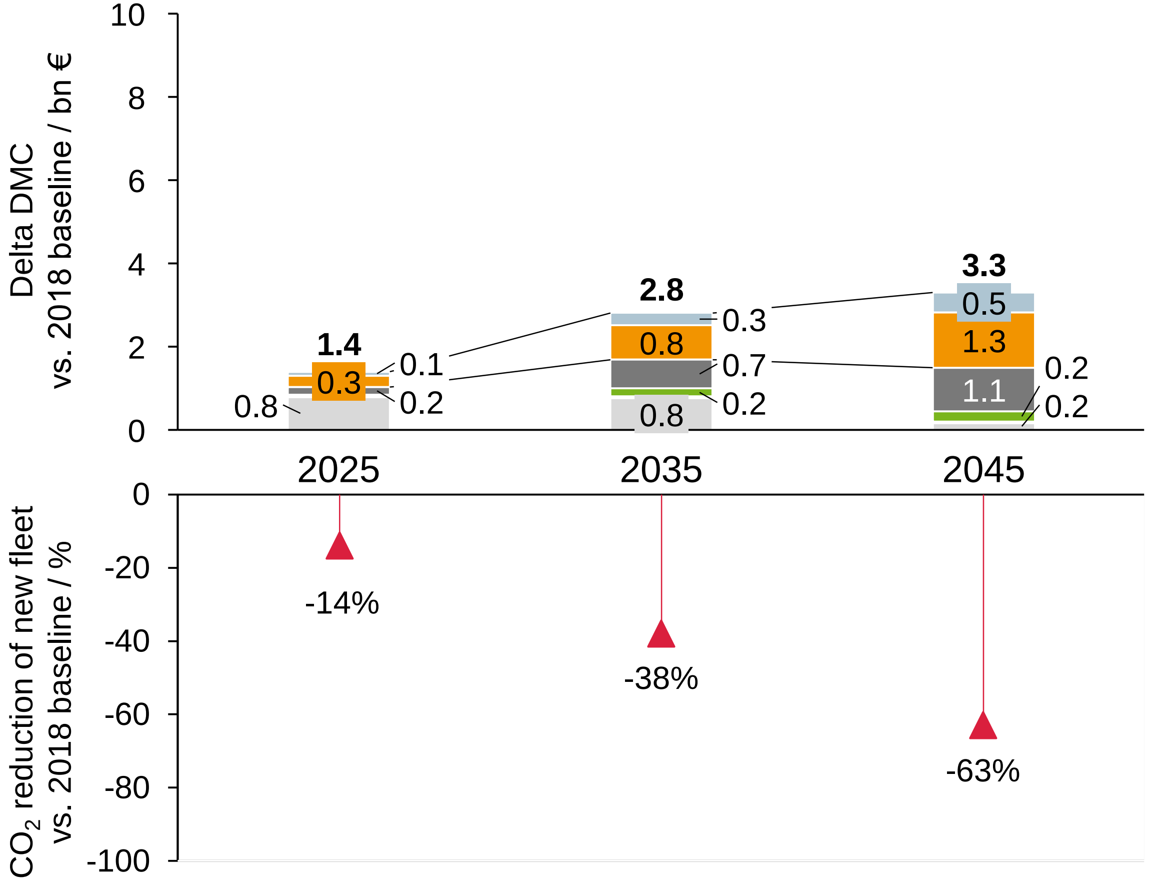
TOTAL ADD-ON COSTS AND ACCORDING CO_2 REDUCTION POTENTIALS (SOLD UNITS ONLY)



- Add-on costs include glider and powertrain measures
- Add-on costs for conventional vehicles reduce to near zero together with the number of units sold, while the additional costs spend on zero CO_2 emission powertrains increase significantly, especially for battery electric powertrains
- Resulting decrease in CO_2 emissions is 63% by 2045 compared to 2018 in a tank-to-wheel balance

Source: FEV

The template combines the different CO_2 reduction potentials of glider / powertrain combinations and adds information on add-on costs

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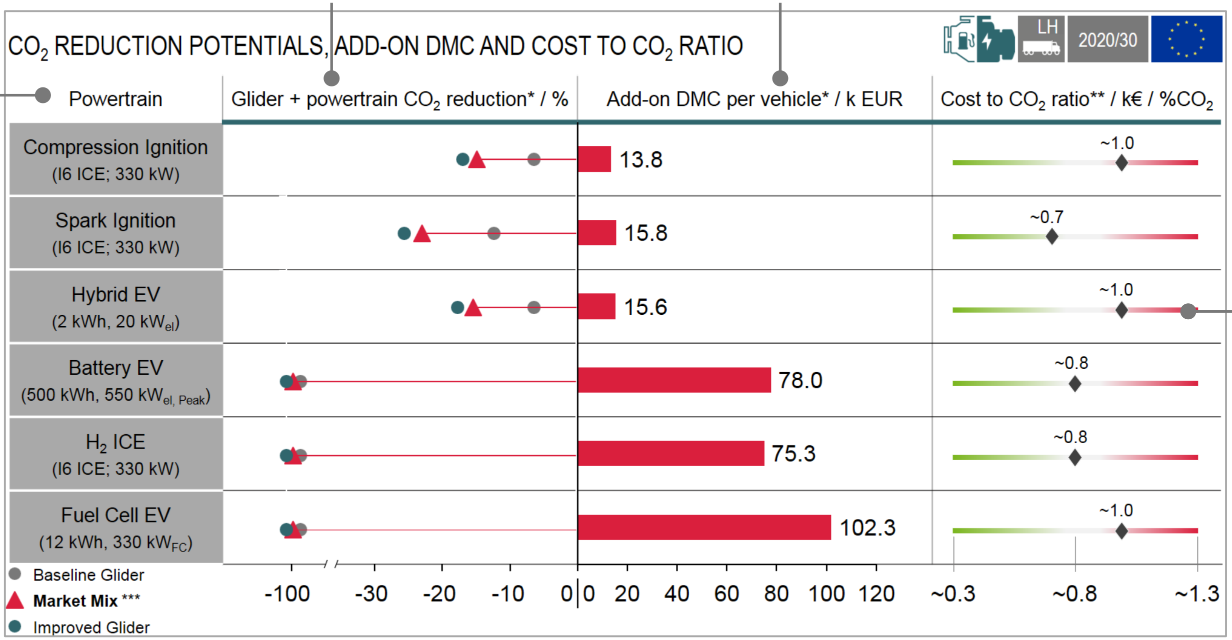
EXPLANATION OF TEMPLATE

CO_2 reduction potential vs. 2018 Diesel baseline vehicle; considers 2 gliders (e.g. baseline and improved) and the assumed market mix

Add-on Direct Manufacturing Costs (DMC) vs. 2018 Diesel baseline vehicle; refers to the market mix

List of considered powertrains incl. selected (key) specifications

Vehicle class, scenario, timing and region



Cost to CO_2 ratio for assumed glider / powertrain combination in market mix and related add-on costs

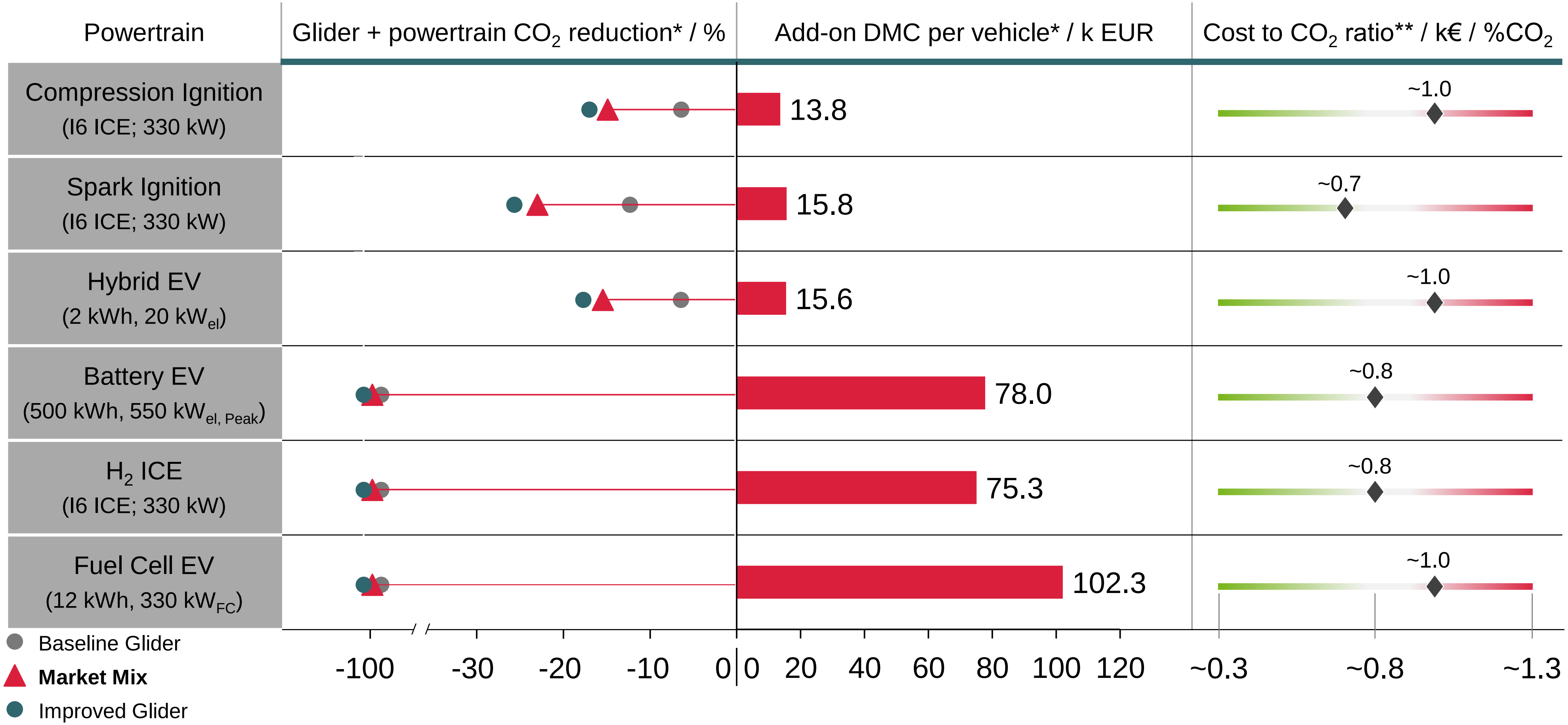
Source: FEV

By 2025, the cost to CO_2 ratio is between 0.7 and 1.0 k € / % CO_2 reduction for considered technologies; market is dominated by CI engines

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

LH

2020/30



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

By 2035, the relevance of hydrogen and battery electric powered vehicles increases; add-on costs vs. Diesel baseline are ~70 to 100 k € respectively

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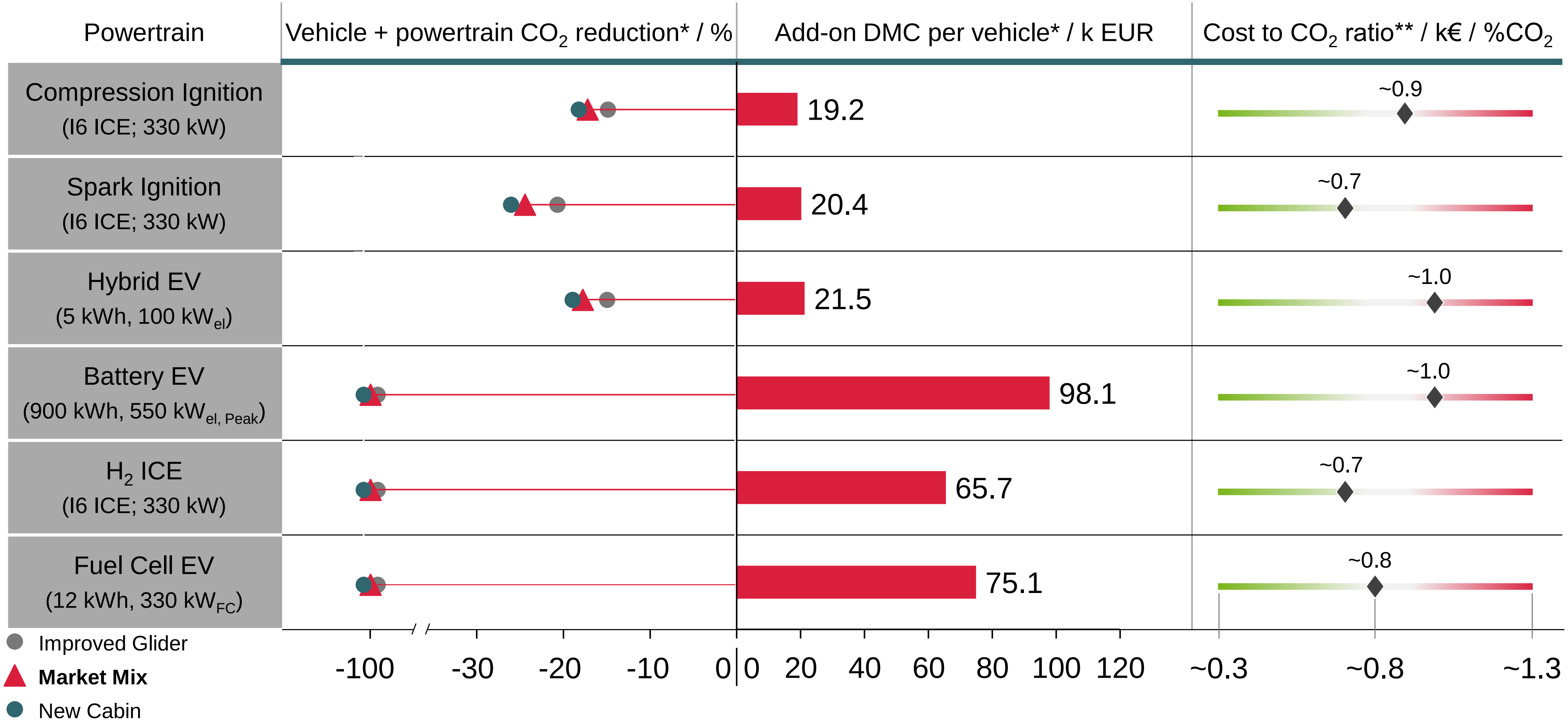
CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

LH

2030/40



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

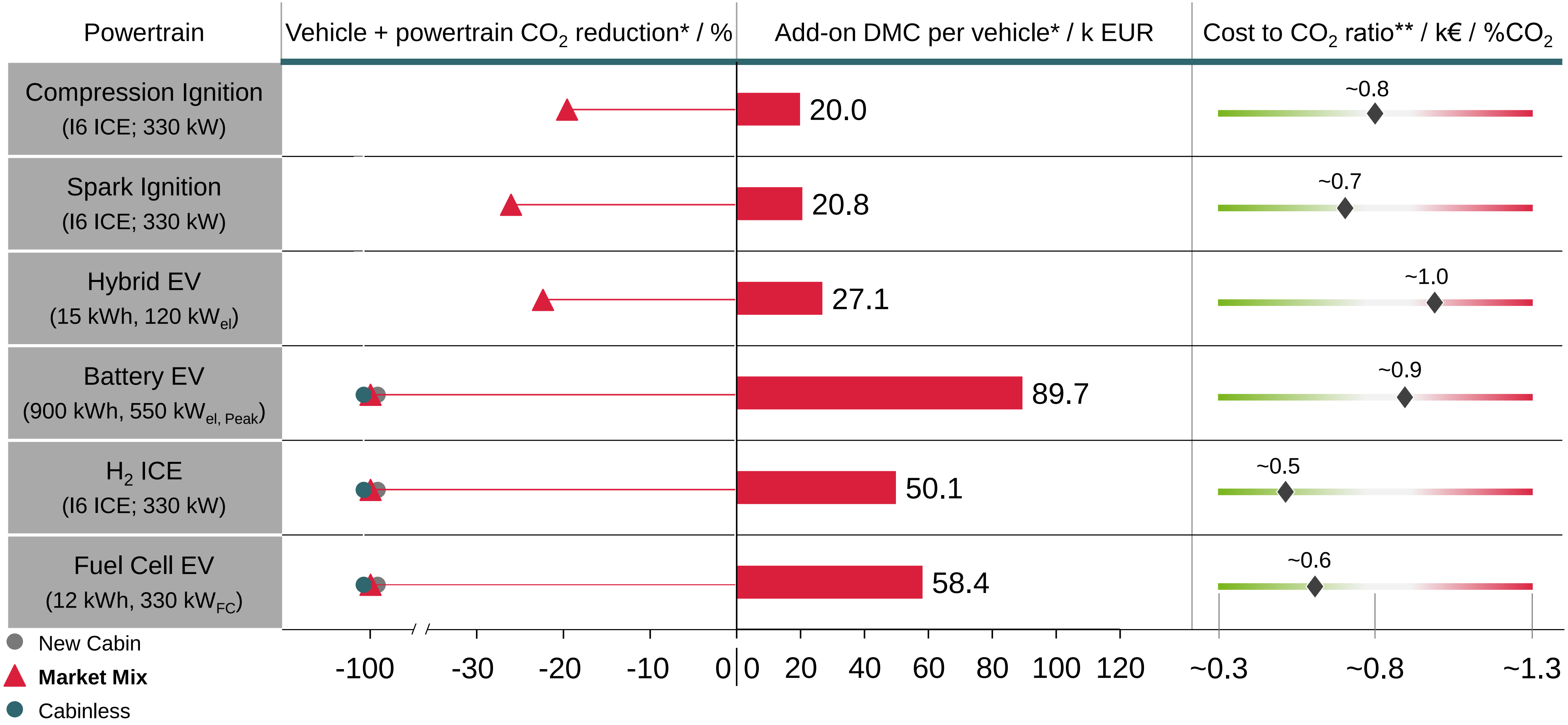
Source: FEV

CO_2 emitting vehicles (CI, SI, Hybrid) achieve their efficiency maximum, values beyond ~25% are not achieved; add-on costs for BEV shrink

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

LH

2040/50



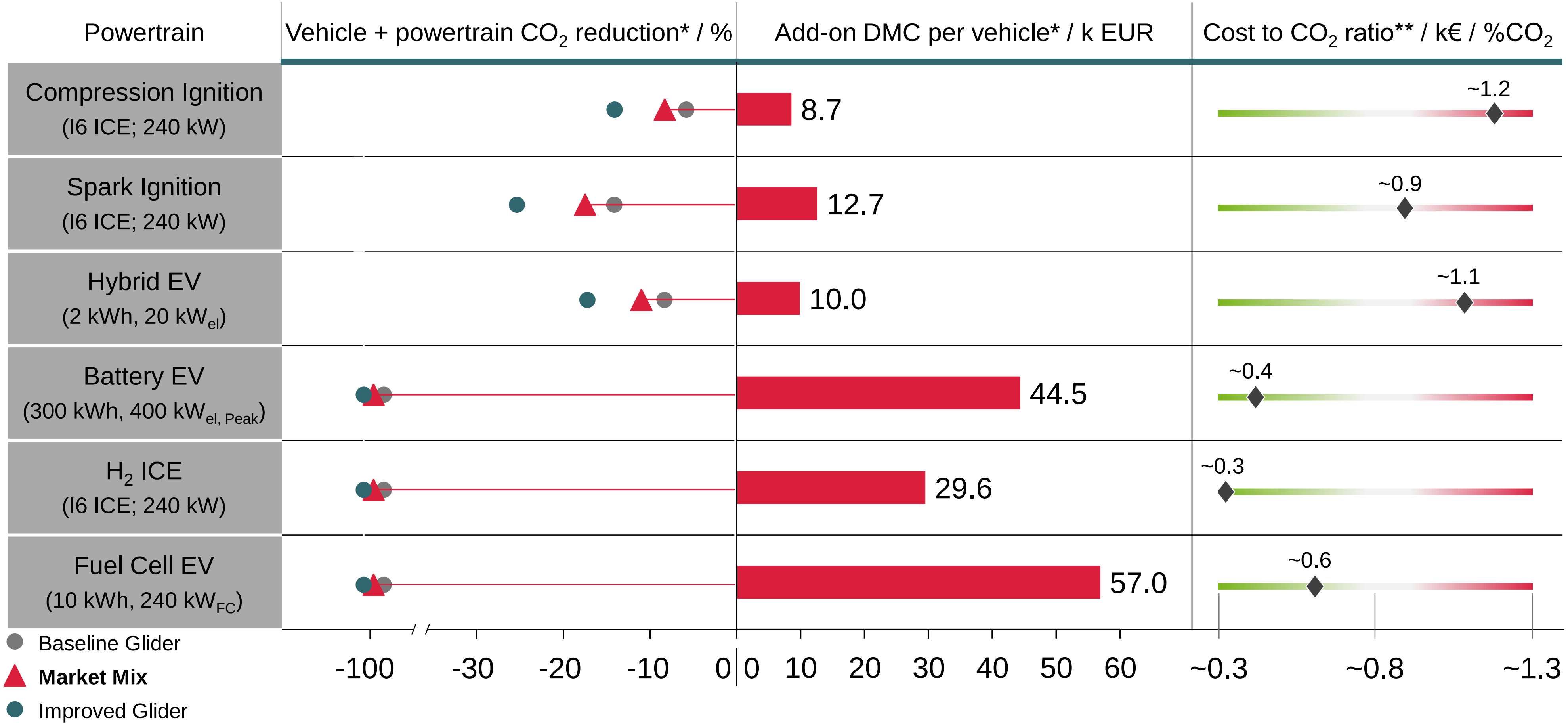
*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

The RH segment comes with lower daily distances, add-on costs for hydrogen and battery electric vehicles are 30-50% lower than for LH

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

RH 2020/30



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values
Source: FEV

By 2035, BEV and H_2 powered vehicles are relevant in the EU market; cost to CO_2 reduction ratio is attractive and below ~0.5 k € / % CO_2

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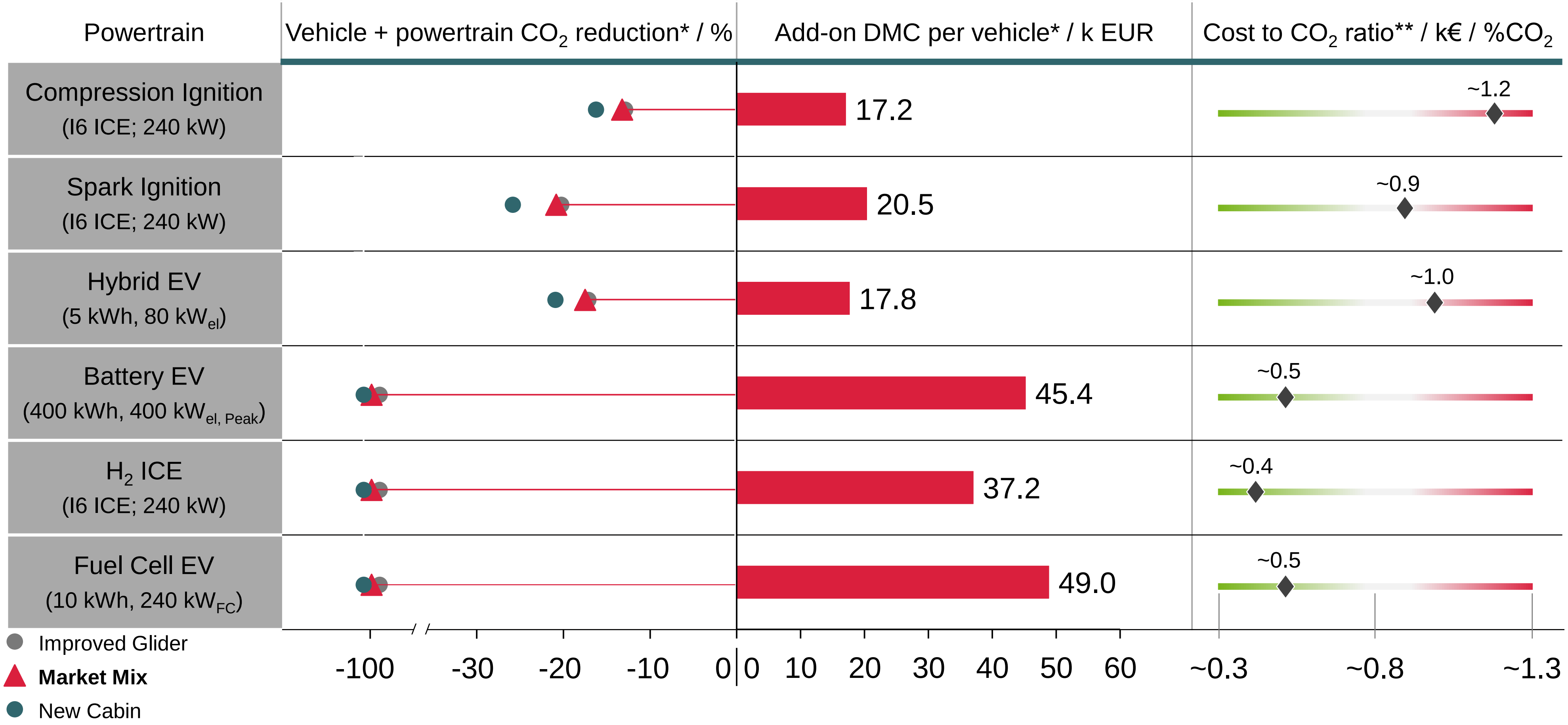
CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

RH 2030/40



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

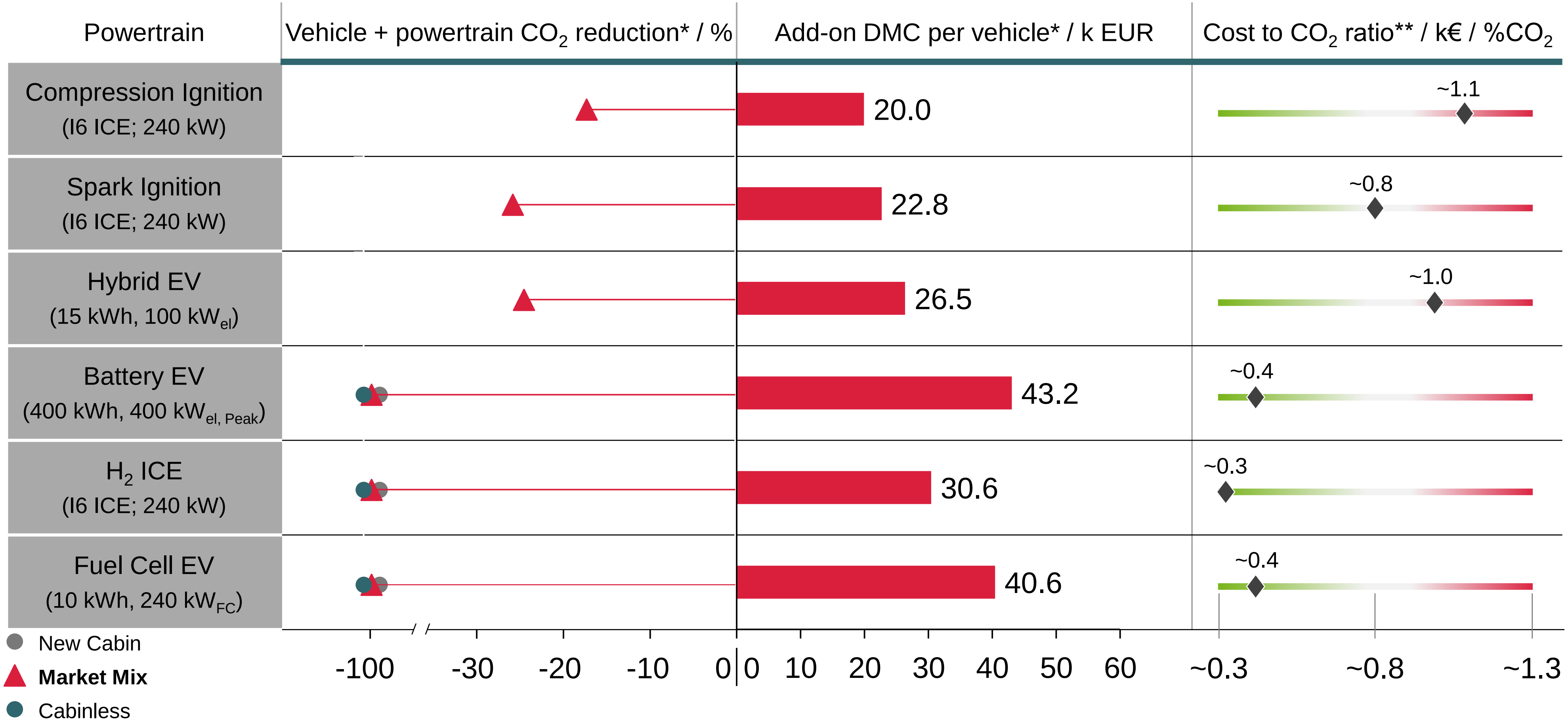
Source: FEV

In the very long run, add-on costs for battery electric and H_2 powered vehicles further decrease (~30-40 k €)

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

RH

2040/50



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

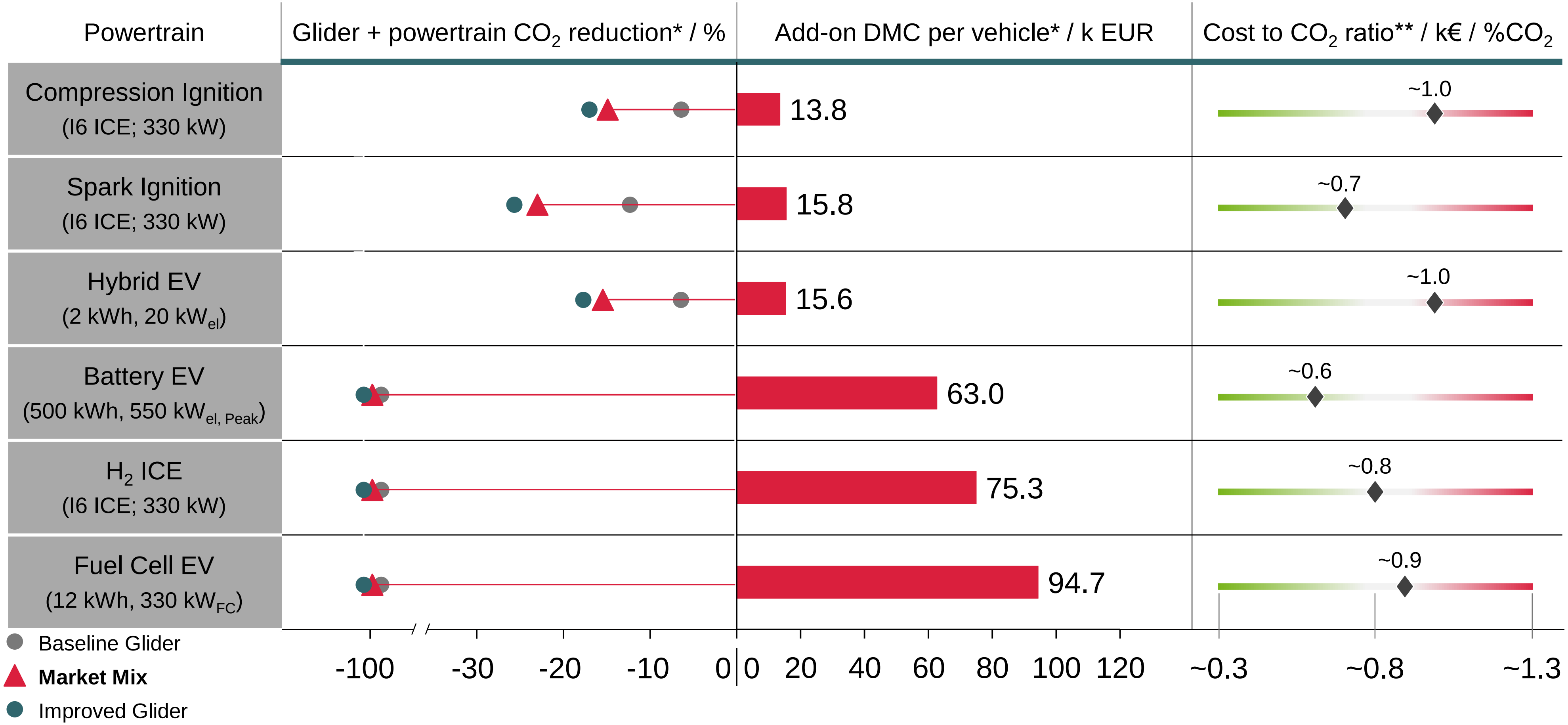
By 2025, the cost to CO_2 ratio is between 0.7 and 1.0 k € / % CO_2 reduction for considered technologies; market is dominated by CI engines

FEV CONSULTING

LH

2020/30

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

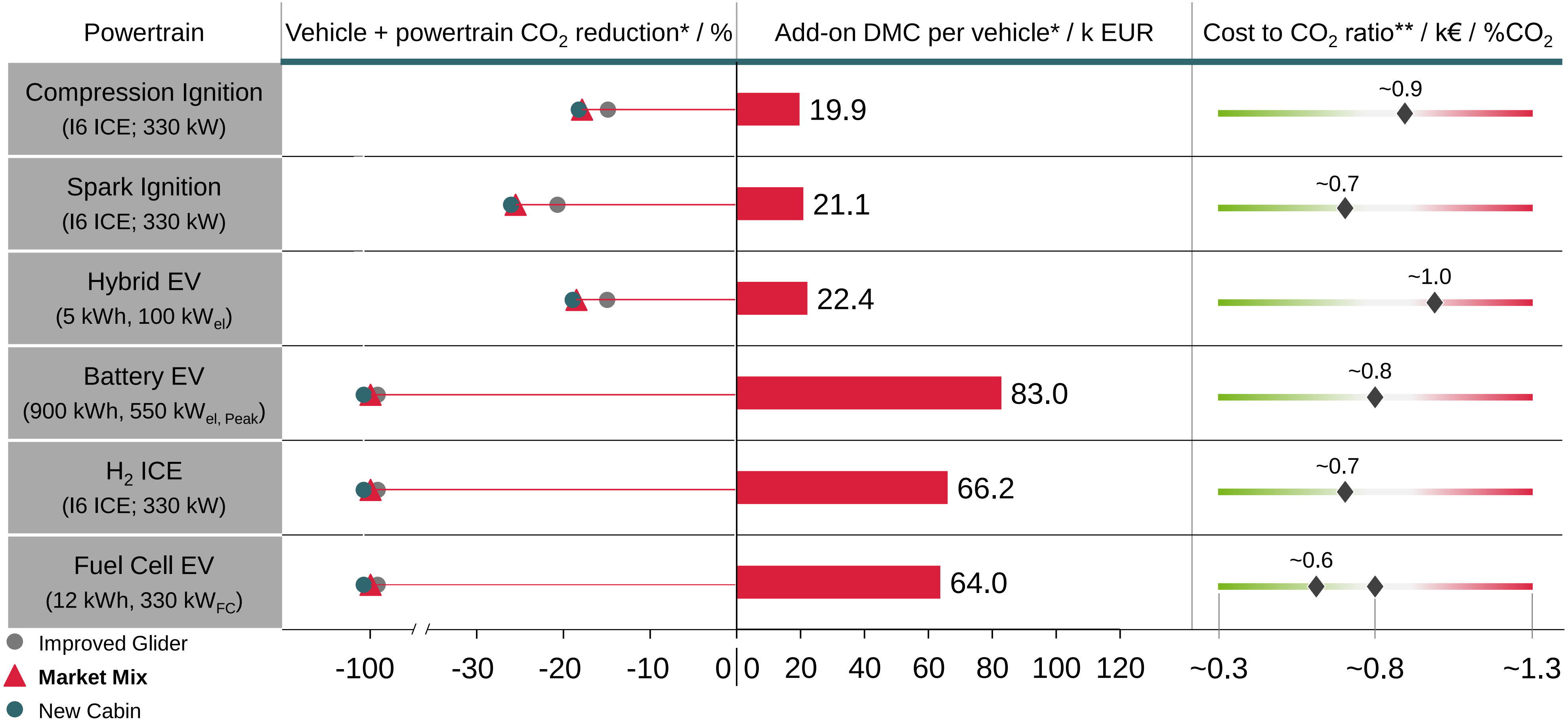
By 2035, the relevance of hydrogen and battery electric powered vehicles increases; add-on costs vs. Diesel baseline are ~70 to 100 k € respectively

FEV CONSULTING

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

LH

2030/40



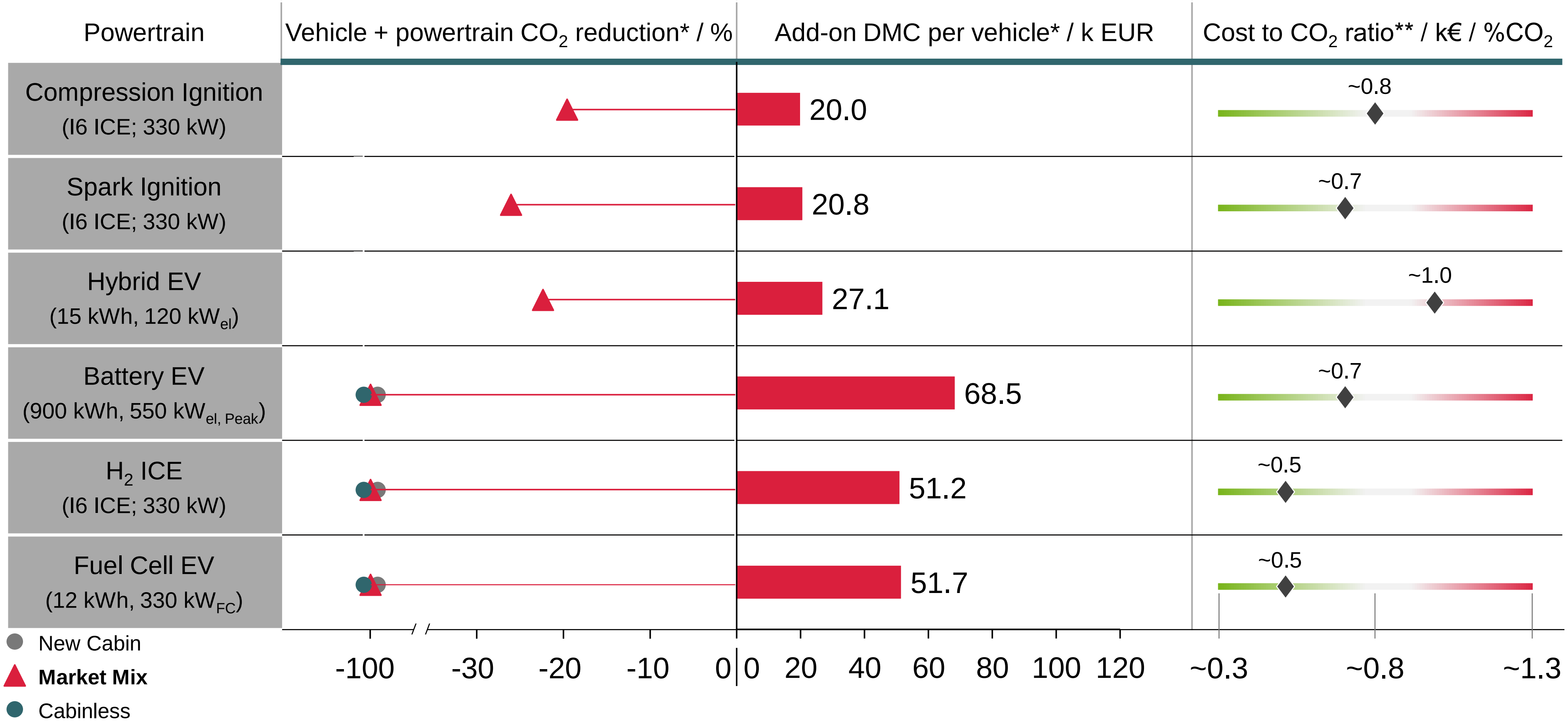
*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

CO_2 emitting vehicles (CI, SI, Hybrid) achieve their efficiency maximum, values beyond ~25% are not achieved; add-on costs for BEV shrink

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

LH
2040/50



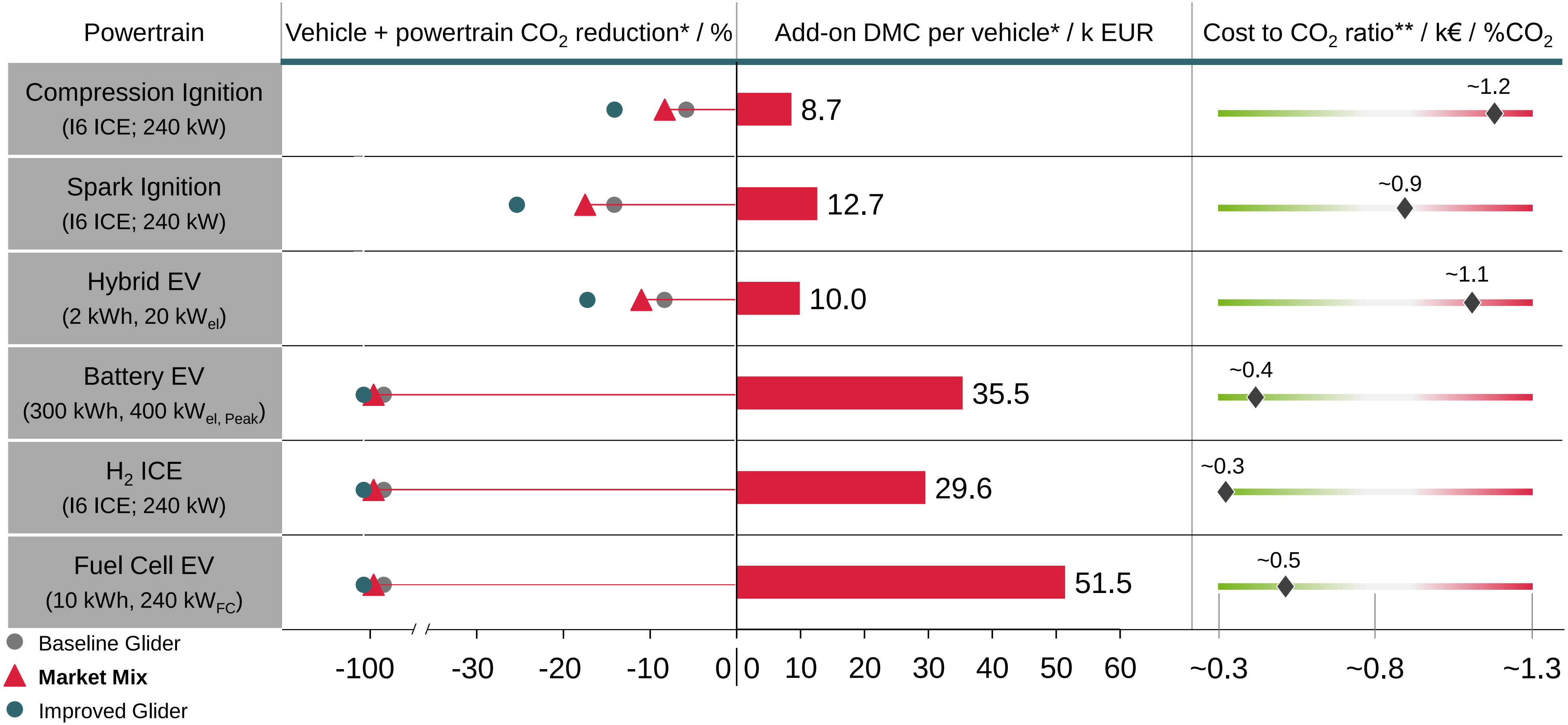
*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

The RH segment comes with lower daily distances, add-on costs for hydrogen and battery electric vehicles are 30-50% lower than for LH

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

RH 2020/30



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

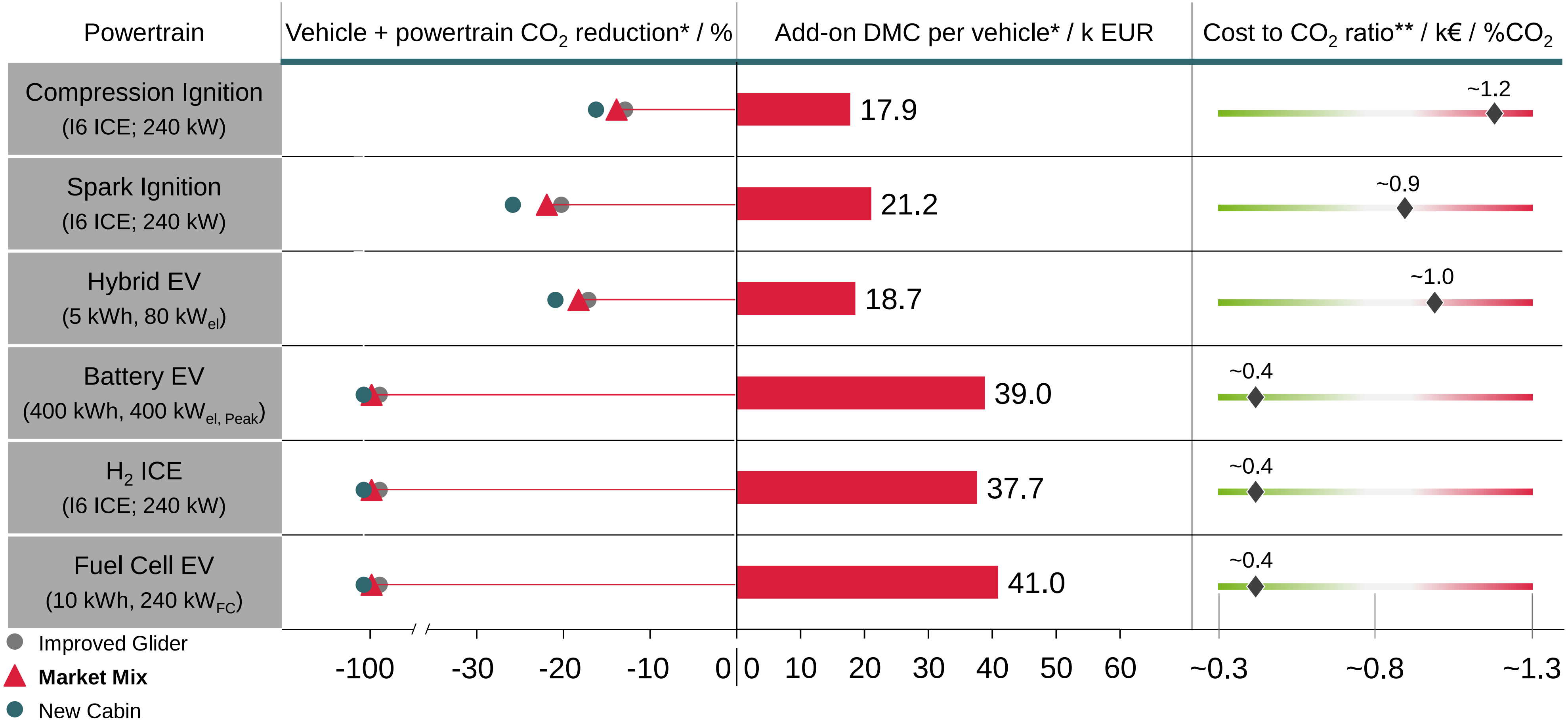
Source: FEV

By 2035, BEV and H_2 powered vehicles are relevant in the EU market; cost to CO_2 reduction ratio is attractive and below ~0.5 k € / % CO_2

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

RH

2030/40



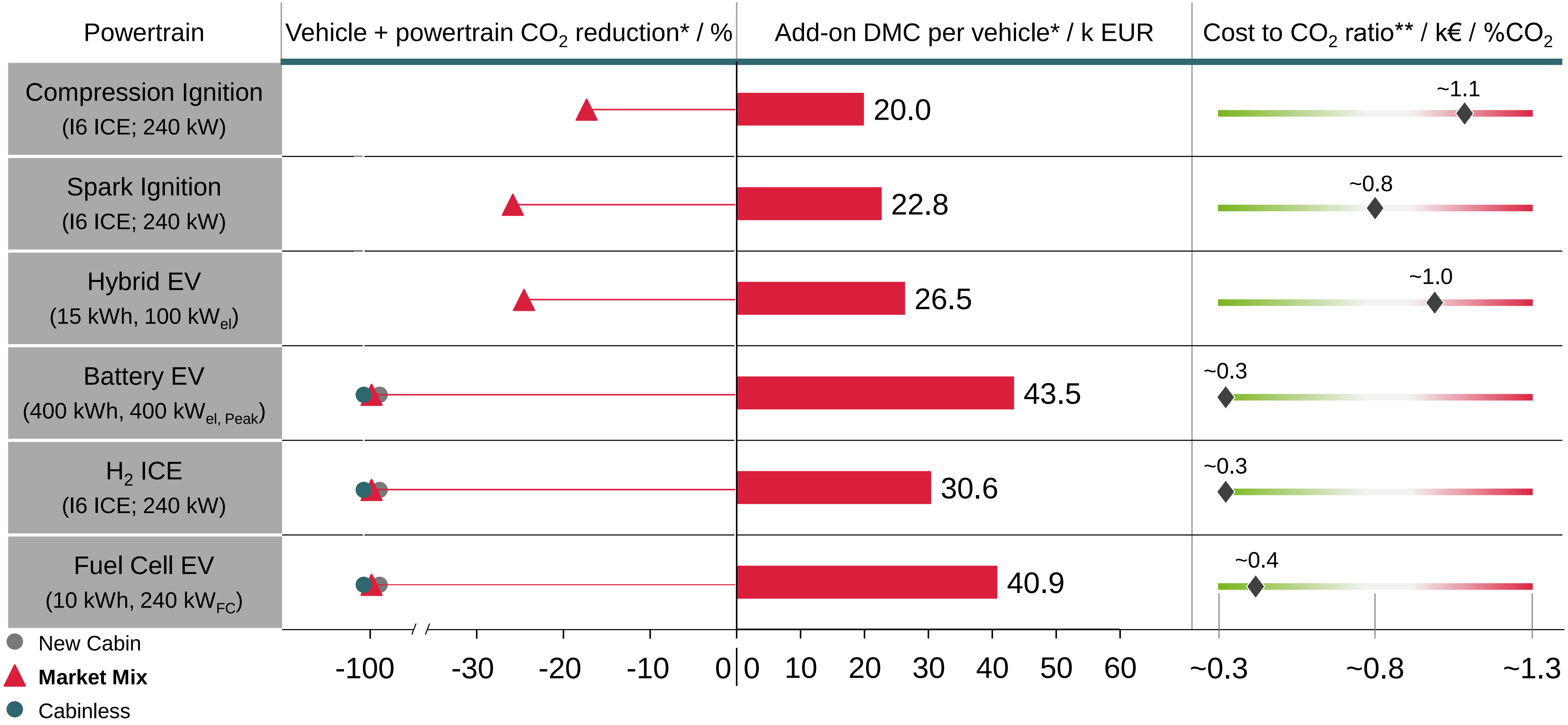
*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact values

Source: FEV

In the very long run, add-on costs for battery electric and H_2 powered vehicles further decrease (~30-40 k €)

CO_2 REDUCTION POTENTIALS, ADD-ON DMC AND COST TO CO_2 RATIO

RH 2040/50



*: Both vs. 2018 Diesel Baseline; **: Refers to glider and powertrain (full vehicle performance); qualitative scale with exact value

Source: FEV

Independently from the scenario, the following overview summarizes CO_2 potentials and corresponding direct costs (long-haul)

UNDERLYING CO_2 AND COST ASSUMPTIONS[1]

	2020/30				2030/40				2040/50			
	€	CO_2	€	CO_2	€	CO_2	€	CO_2	€	CO_2	€	CO_2
Compression ignition	5.6	6.1%	15.9	16.6%	16.9	18.0%	20.3	22.1%	20.0	23.8%	*Not existing*	
Spark ignition	7.6	12.0%	17.9	25.2%	18.1	25.2%	21.4	31.8%	20.8	31.7%		
Hybrid EV	6.6	6.2%	17.9	17.3%	18.3	18.2%	22.8	23.0%	27.1	27.2%		
Battery EV	70.3	100%	79.9	100%	96.2	100%	99.0	100%	88.6	100%	92.2	100%
H_2 ICE	*Not existing*		77.2	100%	63.7	100%	66.5	100%	49.0	100%	52.6	100%
Fuel Cell EV	94.6	100%	104.2	100%	73.2	100%	76.0	100%	57.3	100%	60.9	100%

€ Cost values are “Add. Direct Manufacturing Costs” (DMC) and are shown in “’000 EUR” vs. the 2018 Diesel baseline

CO_2 CO_2 decrease (T2W, in % vs. Diesel baseline)

[1] Cost and efficiency values (T2W) reflect an average based on multiple existing products / vehicle specifications

Source: FEV

Independently from the scenario, the following overview summarizes CO_2 potentials and corresponding direct costs (regional-haul)

UNDERLYING CO_2 AND COST ASSUMPTIONS*

RH

	2020/30				2030/40				2040/50			
	€	CO_2	€	CO_2	€	CO_2	€	CO_2	€	CO_2	€	CO_2
Compression ignition	5.6	4.8%	15.9	12.0%	16.9	13.7%	20.3	17.4%	20.0	18.5%	*Not existing*	
Spark ignition	9.6	12.0%	19.9	21.7%	20.2	21.7%	23.6	27.7%	22.8	27.7%	*Not existing*	
Hybrid EV	6.6	7.0%	17.9	14.7%	17.3	18.3%	21.8	22.4%	26.5	26.3%	*Not existing*	
Battery EV	41.6	100%	51.2	100%	45.1	100%	47.9	100%	42.8	100%	46.4	100%
H_2 ICE	*Not existing*		36.4	100%	36.9	100%	39.7	100%	30.6	100%	34.2	100%
Fuel Cell EV	54.1	100%	63.8	100%	48.7	100%	51.5	100%	40.2	100%	43.8	100%

€ Cost values are "Add. Direct Manufacturing Costs" (DMC) and are shown in "'000 EUR" vs. the 2018 Diesel baseline

CO_2 CO_2 decrease (T2W, in % vs. Diesel baseline)

*Cost and efficiency values (T2W) reflect an average based on multiple existing products / vehicle specifications

Source: FEV

Agenda

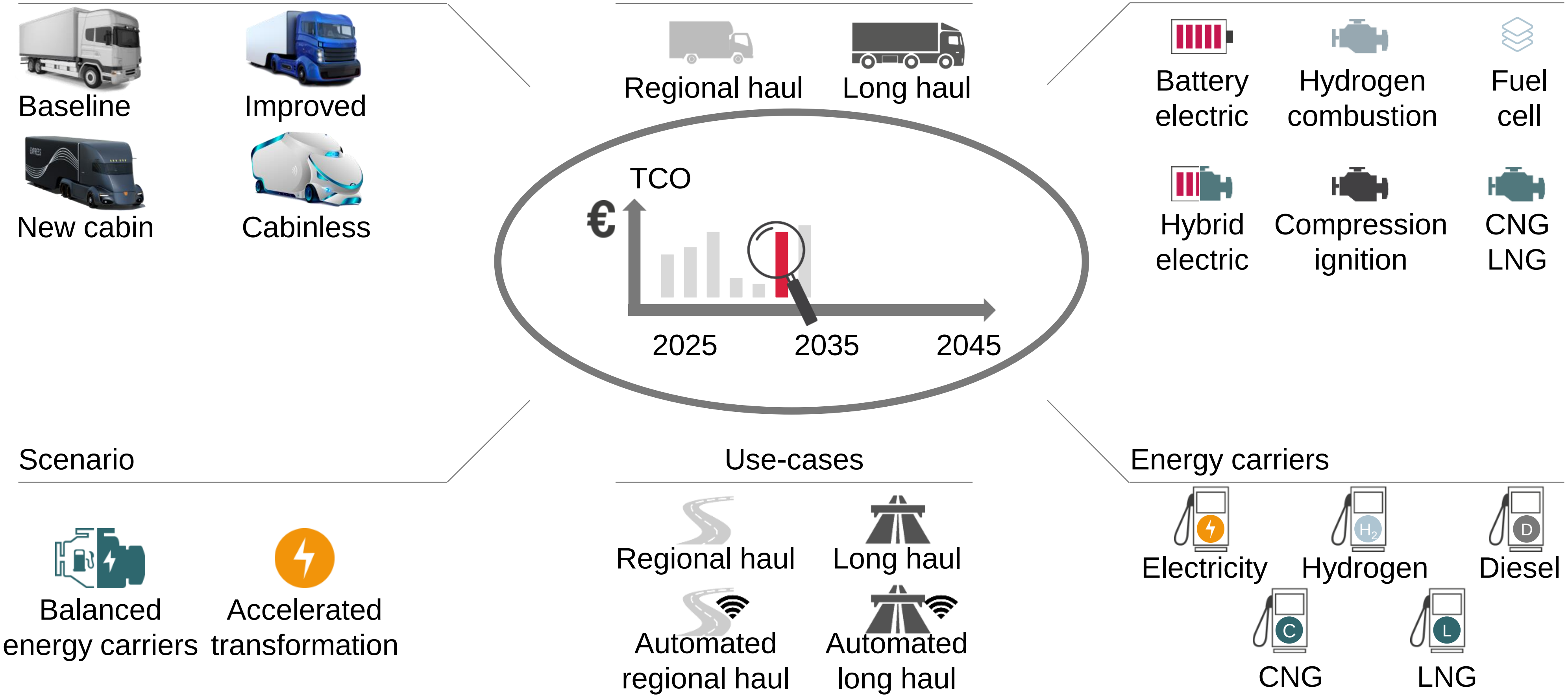
- Executive summary
- Framework and long-term scenarios for HD on-road transportation
- Technology options towards 2050
- Future pathways towards clean on-road transportation
- Reduced GHG emissions with holistic technology strategies
- CO_2 abatement costs for selected reference trucks
- TCO performance of underlying reference trucks
- Life-cycle analysis for HD trucks

Agenda

- TCO performance of underlying reference trucks
  - Boundary conditions and assumptions
  - Scenario dependent analysis results

The TCO considers at various years different glider types, vehicle classes, powertrains, energy carriers, use-cases and scenarios

INTRODUCTION – TOTAL COST OF OWNERSHIP MODEL



Gliders

- Baseline
- Improved
- New cabin
- Cabinless

Vehicle classes

- Regional haul
- Long haul

Powertrain type

- Battery electric
- Hydrogen combustion
- Fuel cell
- Hybrid electric
- Compression ignition
- CNG LNG

Scenario

- Balanced energy carriers
- Accelerated transformation

Use-cases

- Regional haul
- Long haul
- Automated regional haul
- Automated long haul

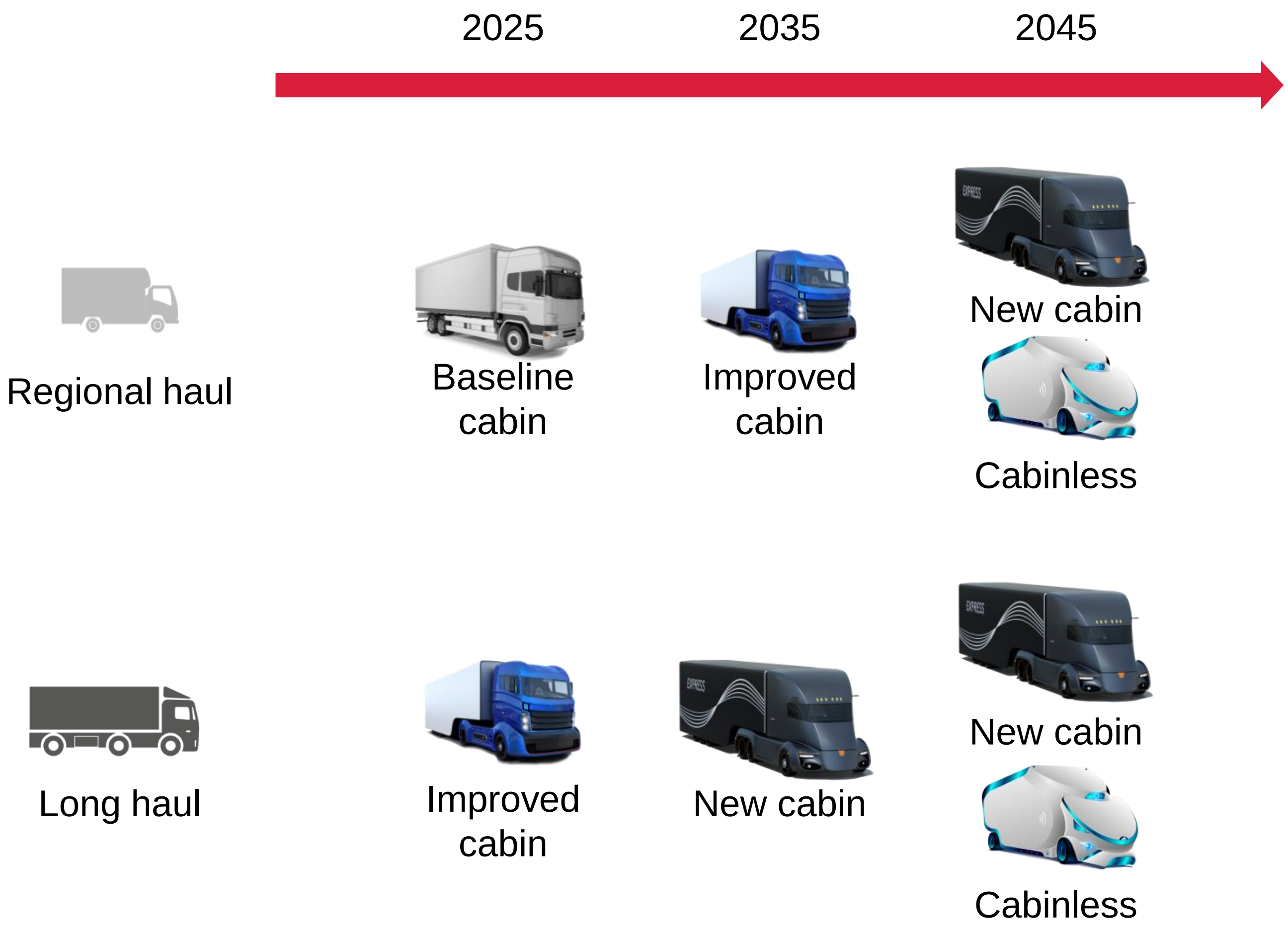
Energy carriers

- Electricity
- Hydrogen
- Diesel
- CNG
- LNG

Source: FEV

Different gliders for long haul and regional applications between 2025 and 2045 were considered

INTRODUCTION – MATCHING OF GLIDERS AND USE-CASE



	2025	2035	2045
Regional haul	Baseline cabin	Improved cabin	New cabin Cabinless
Long haul	Improved cabin	New cabin	New cabin Cabinless

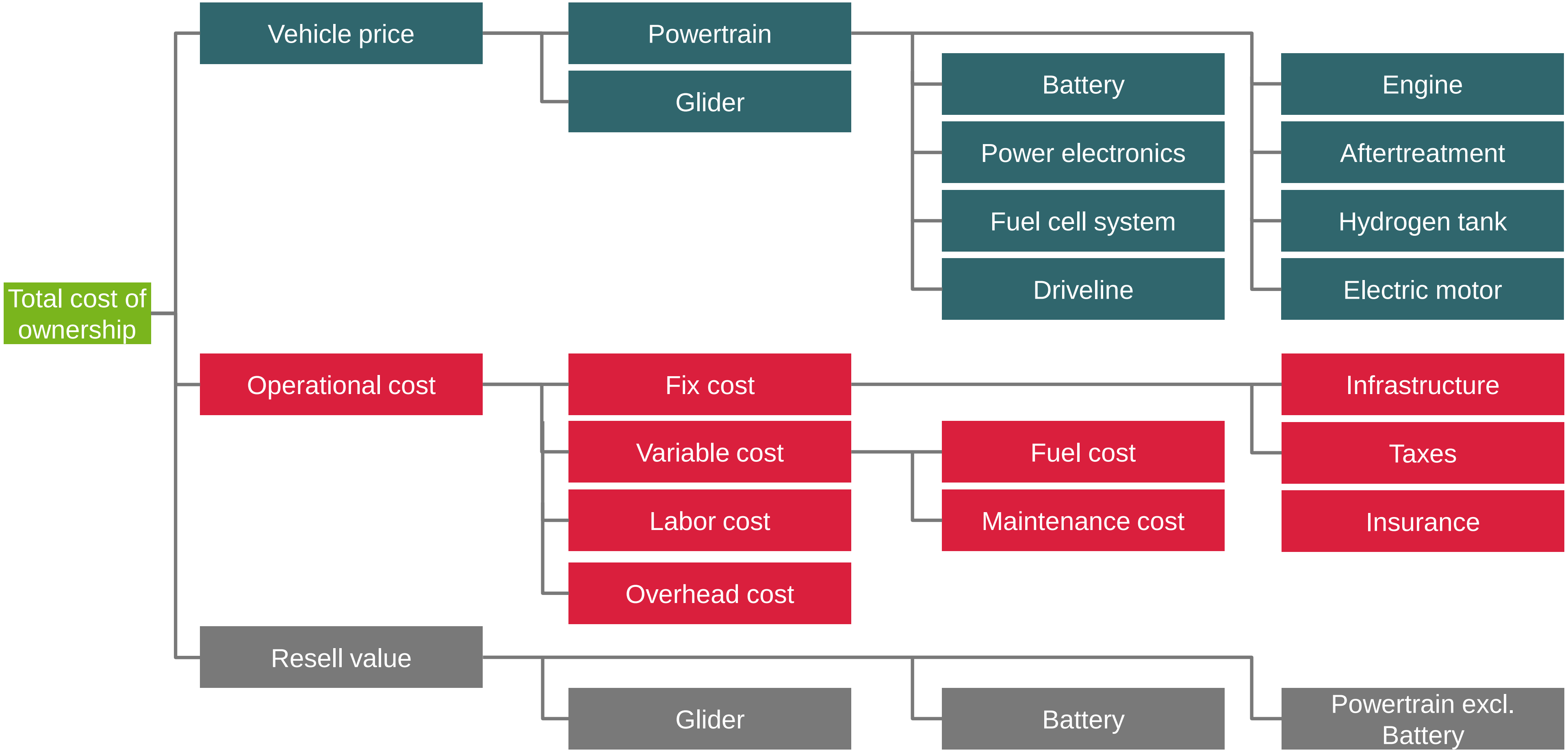
Comment

- Deployment of new gliders will occur at different points of time
- The improved and new cabin will be implemented earlier in long-haul than in regional haul
  - Higher impact of aerodynamic improvements in long haul vehicles

Source: FEV

FEV considers key impact factors for its TCO analysis

INTRODUCTION – FACTORS CONSIDERED IN TCO



Total cost of ownership

- Vehicle price
  - Powertrain
    - Battery
    - Power electronics
    - Fuel cell system
    - Driveline
    - Engine
    - Aftertreatment
    - Hydrogen tank
    - Electric motor
  - Glider
- Operational cost
  - Fix cost
    - Infrastructure
    - Taxes
    - Insurance
  - Variable cost
    - Fuel cost
    - Maintenance cost
  - Labor cost
  - Overhead cost
- Resell value
  - Glider
  - Battery
  - Powertrain excl. Battery

Source: FEV

The TCO is driven by key influencing factors such as peak power, electric target range or costs which come with the considered vehicle

FEV CONSULTING

BALANCED ENERGY CARRIERS – KEY INFLUENCING FACTORS OF THE TCO CALCULATION

Use-case	Powertrain	Peak power in kW	Tank system	Tank capacity	Battery cell type	Battery capacity in kWh	Vehicle price in '000 €		
							2025	2035	2045
Long haul	Compression ignition	330	Liquid	500 L			110	117	119
	Hybrid	330	Liquid	500 L	High power	2, 5, 15[3]	113	129	132
	Hydrogen combustion	330	700 bar Liquid[2]	80 kg			212	203	191
	Battery electric, small battery	550			High energy	500	252	214	199
	Battery electric, large battery	550			High energy	900	355	293	278
	Fuel cell electric	330 550[1]	700 bar Liquid[2]	50 kg	High power	12	275	237	241
	CNG LNG	330		300 kg			120 114	125 119	126 120

1) 220 kW of peak power for the fuel cell system, 286 kW of peak power for the electric system 2) 700 bar considered in 2025 and 2035, liquid hydrogen tank considered in 2045
3) Small battery considered in the 48 V system in 2025, medium battery considered in the 350 V system in 2035 and the large battery considered in the 800 V system in 2045
Source: FEV

The TCO is driven by key influencing factors such as peak power, electric target range or costs which come with the considered vehicle

FEV CONSULTING

BALANCED ENERGY CARRIERS – KEY INFLUENCING FACTORS OF THE TCO CALCULATION

Use-case	Powertrain	Peak power in kW	Tank system	Tank capacity	Battery cell type	Battery capacity in kWh	Vehicle price in '000 €		
							2025	2035	2045
Regional haul	Compression ignition	240	Liquid	200 L			75	87	95
	Hybrid	240	Liquid	200 L	High power	2, 5, 15 3)	78	97	107
	Hydrogen combustion	240	700 bar Liquid 2)	40 kg			128	132	130
	Battery electric, small battery	400			High energy	300	155	140	135
	Battery electric, large battery	400			High energy	400	178	157	155
	Fuel cell electric	240 400 1)	700 bar Liquid 2)	25 kg	High power	10	172	154	154
	CNG LNG	240		200 kg			83 78	94 89	100 96

1) 220 kW of peak power for the fuel cell system, 286 kW of peak power for the electric system 2) 700 bar considered in 2025 and 2035, liquid hydrogen tank considered in 2045
3) Small battery considered in the 48 V system in 2025, medium battery considered in the 350 V system in 2035 and the large battery considered in the 800 V system in 2045
Source: FEV

The TCO is driven by key influencing factors as peak power and design range and the cost associated with the individual vehicle

FEV CONSULTING

ACCELERATED TRANSFORMATION – KEY INFLUENCING FACTORS OF THE TCO CALCULATION

Use-case	Powertrain	Peak power in kW	Tank system	Tank capacity	Battery cell type	Battery capacity in kWh	Vehicle price in '000 €		
							2025	2035	2045
Long haul	Compression ignition	330	Liquid	500 L			110	117	119
	Hybrid	330	Liquid	500 L	High power	2, 5, 15[3]	113	129	132
	Hydrogen combustion	330	700 bar Liquid[2]	80 kg			212	202	191
	Battery electric, small battery	550			High energy	500	223	186	173
	Battery electric, large battery	550			High energy	900	308	247	233
	Fuel cell electric	330 550[1]	700 bar Liquid[2]	50 kg	High power	12	259	213	207
	CNG LNG	330		400 kg			120 114	125 119	126 120

1) 220 kW of peak power for the fuel cell system, 286 kW of peak power for the electric system 2) 700 bar considered in 2025 and 2035, liquid hydrogen tank considered in 2045
3) Small battery considered in the 48 V system in 2025, medium battery considered in the 350 V system in 2035 and the large battery considered in the 800 V system in 2045
Source: FEV

The TCO is driven by key influencing factors as peak power and design range and the cost associated with the individual vehicle

ACCELERATED TRANSFORMATION – KEY INFLUENCING FACTORS OF THE TCO CALCULATION

Use-case	Powertrain	Peak power in kW	Tank system	Tank capacity	Battery cell type	Battery capacity in kWh	Vehicle price in ‘000 €		
							2025	2035	2045
Regional haul	Compression ignition	240	Liquid	200 L			75	87	95
	Hybrid	240	Liquid	200 L	High power	2, 5, 15 3)	78	97	107
	Hydrogen combustion	240	700 bar Liquid 2)	40 kg			128	132	130
	Battery electric, small battery	400			High energy	300	137	123	119
	Battery electric, large battery	400			High energy	400	156	136	134
	Fuel cell electric	240 400 1)	700 bar Liquid 2)	25 kg	High power	10	161	137	140
	CNG LNG	240		200 kg			83 78	94 89	100 96

1) 220 kW of peak power for the fuel cell system, 286 kW of peak power for the electric system 2) 700 bar considered in 2025 and 2035, liquid hydrogen tank considered in 2045
3) Small battery considered in the 48 V system in 2025, medium battery considered in the 350 V system in 2035 and the large battery considered in the 800 V system in 2045
Source: FEV

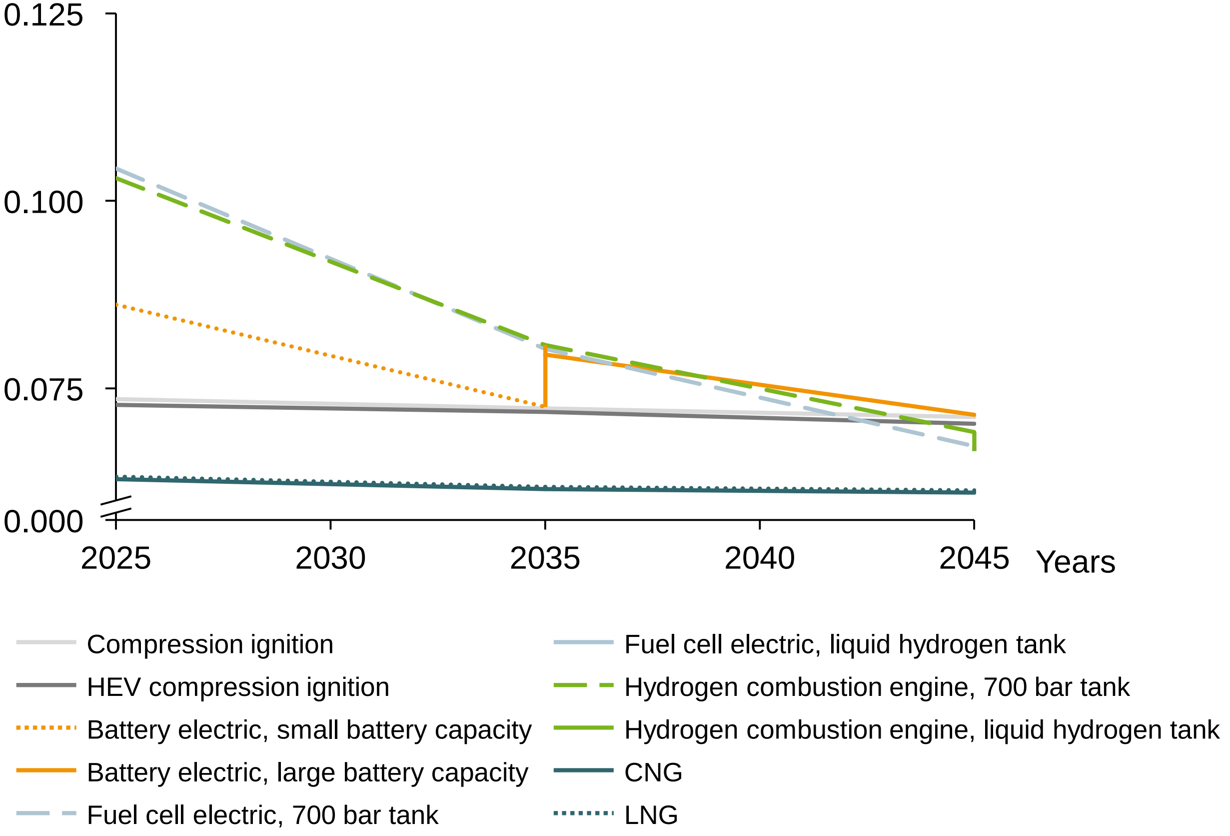
Agenda

- TCO performance of underlying reference trucks
  - Boundary conditions and assumptions
  - Scenario dependent analysis results

TCO gap between zero CO_2 concepts and conventional solutions shrinks at a high pace; full competitiveness is ensure ~2040 and beyond

BALANCED ENERGY CARRIERS – LONG HAUL AT 110,000 KM PER YEAR

Total cost of ownership in € per ton-kilometer

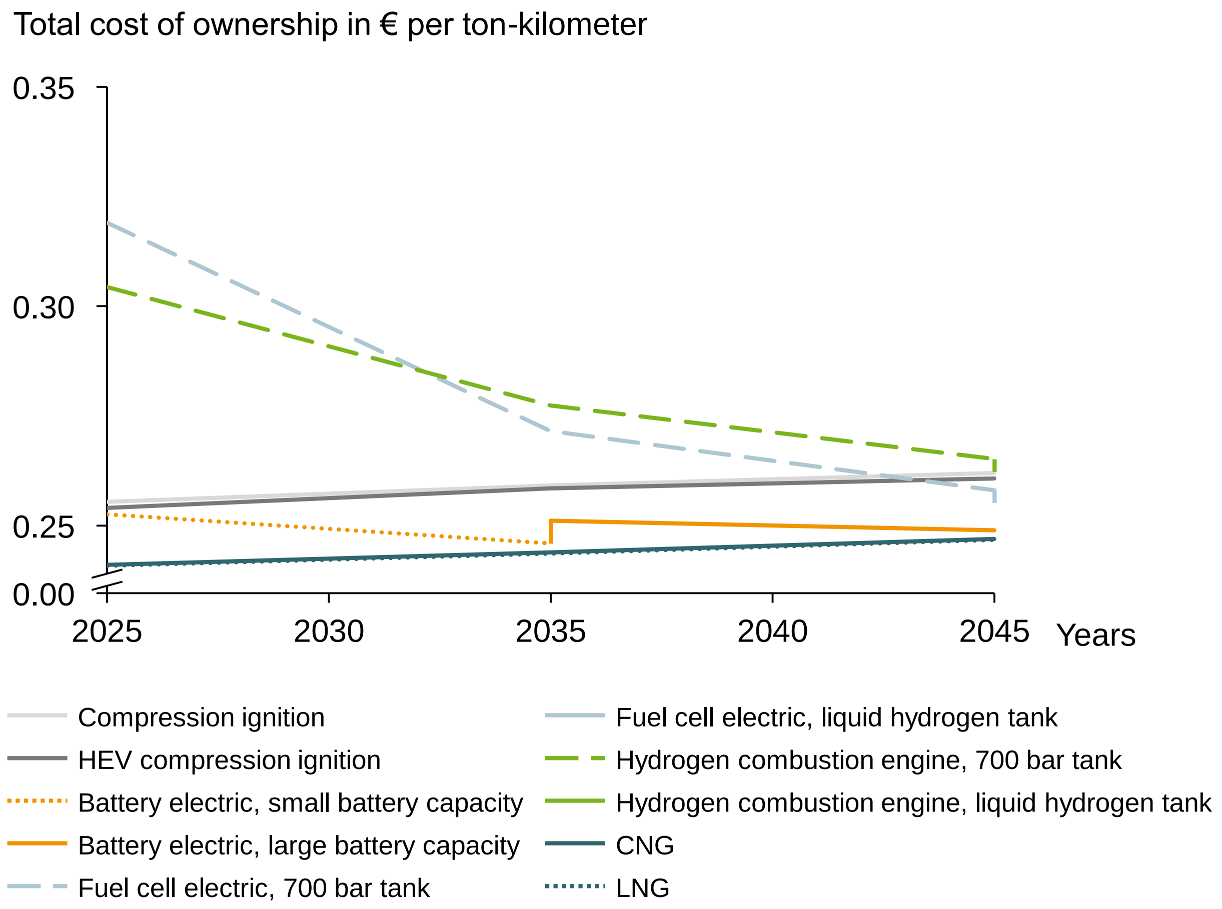


- For all vehicles FEV considers the improved glider in 2025 and the new cabin glider in 2035 and 2045
- For all powertrains FEV considers improvements over their baseline in 2025, 2035 and 2045
- In 2035 FEV considers an upgrade of battery capacities and in 2045 a change of hydrogen tanks from 700 bar to liquid
- In 2025 compression ignition and hybrid powertrains have lower TCO than battery electric and hydrogen powertrains
- In 2045 fuel cell electric and hydrogen combustion engine powertrains have lower TCO than compression ignition and hybrid powertrains
- For the battery electric powertrain with a large battery capacity a reduction of freight capacity needs to be considered since otherwise weight limits could not be met

Source: FEV

For regional haul vehicles, attractiveness of zero CO_2 concepts occurs earlier due to lower specification, hence reduced costs (e.g. smaller battery)

BALANCED ENERGY CARRIERS – REGIONAL HAUL AT 50,000 KM PER YEAR



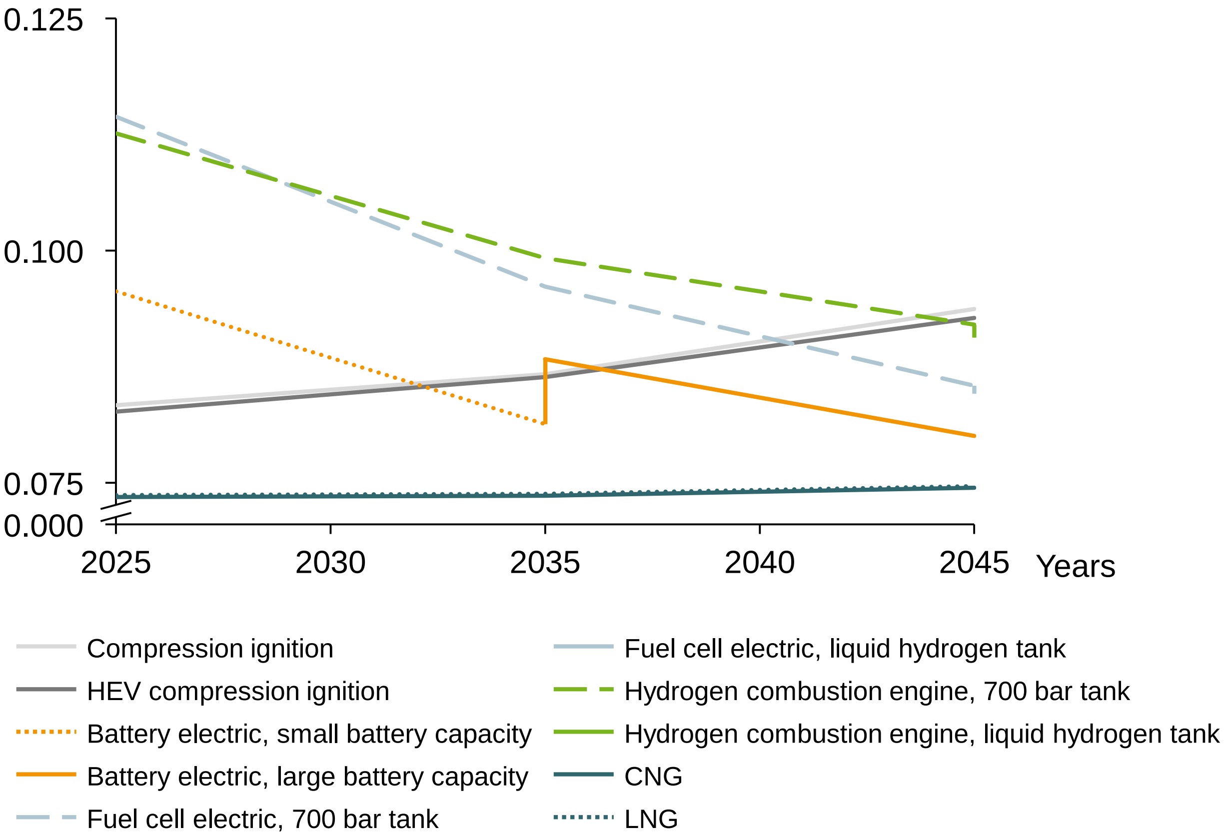
- For all vehicles FEV considers the baseline glider in 2025, the improved glider in 2035 and the new cabin glider in 2045
- For all powertrains FEV considers improvements over their baseline in 2025, 2035 and 2045
- In 2035 FEV considers an upgrade of battery capacities and in 2045 a change of hydrogen tanks from 700 bar to liquid
- Already in 2025 battery electric powertrains have lower TCO than compression ignition and hybrid
- In 2045 battery electric and fuel cell powertrains have lower TCO than compression ignition and hybrid powertrains

Source: FEV

The accelerated scenario shows the TCO competitiveness of BEVs already 2035; 2040+, hydrogen powered vehicles are competitive as well

ACCELERATED TRANSFORMATION – LONG HAUL AT 110,000 KM PER YEAR

Total cost of ownership in € per ton-kilometer



- For all vehicles FEV considers the improved glider in 2025 and the new cabin glider in 2035 and 2045
- For all powertrains FEV considers improvements over their baseline in 2025, 2035 and 2045
- In 2035 FEV considers an upgrade of battery capacities and in 2045 a change of hydrogen tanks from 700 bar to liquid
- In 2025 compression ignition and hybrid powertrains have lower TCO than battery electric and hydrogen powertrains
- Between 2030 and 2035 the small battery electric powertrain brakes even with conventional and hybrid powertrains
- In 2045 battery electric powertrains have lower TCO than compression ignition and hybrid powertrains although the freight capacity needs to be reduced to ensure that weight targets can be met

Source: FEV

The TCO competitiveness of zero CO_2 concepts comes at early stages in the accelerated scenario, e.g. driven by reduced electricity / hydrogen costs

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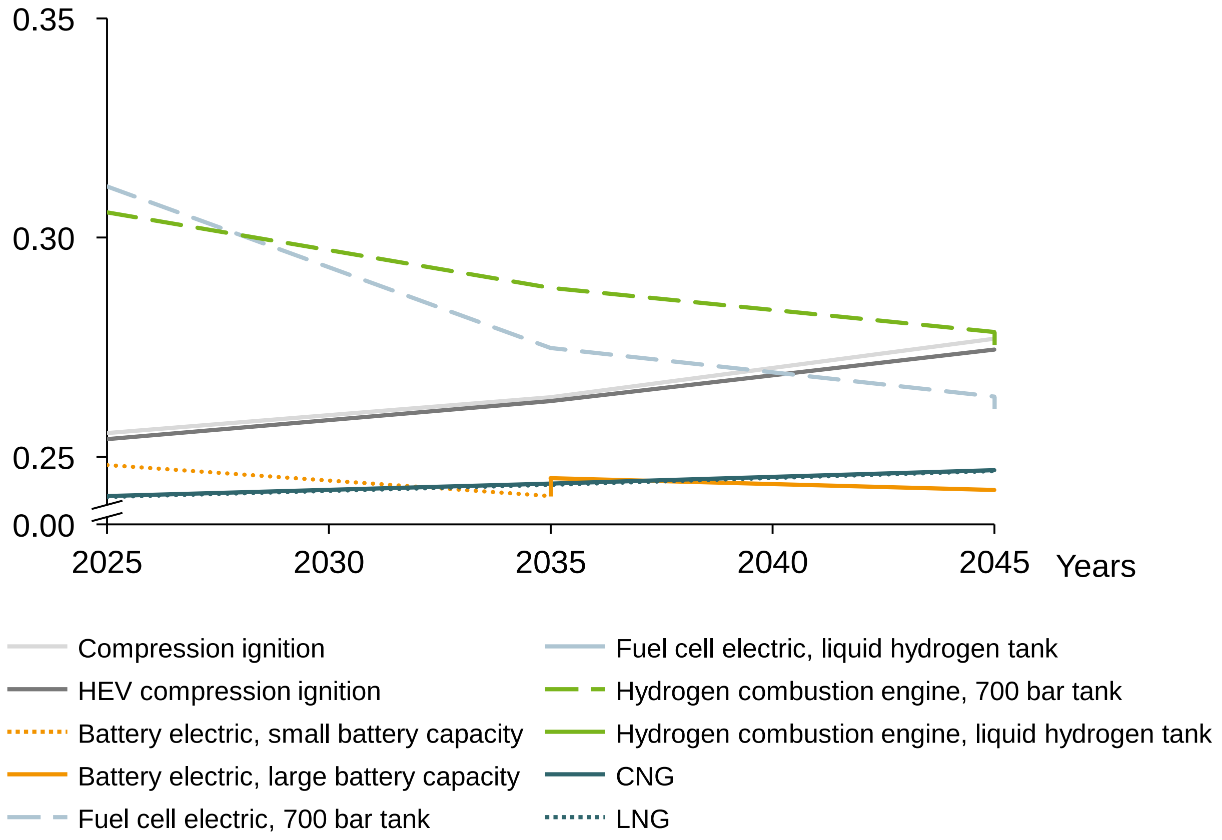
ACCELERATED TRANSFORMATION – REGIONAL HAUL AT 50,000 KM PER YEAR

Total cost of ownership in € per ton-kilometer

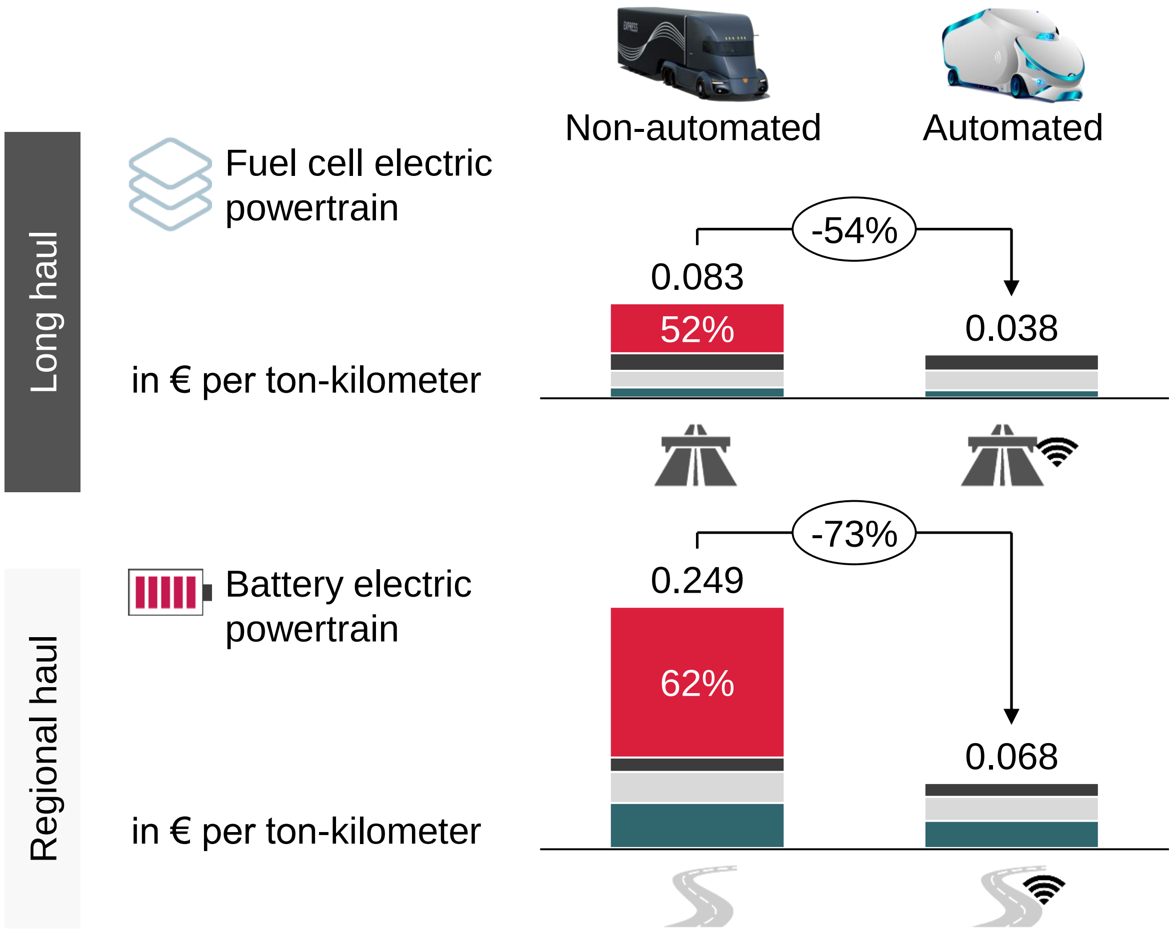


- For all vehicles FEV considers the baseline glider in 2025, the improved glider in 2035 and the new cabin glider in 2045
- For all powertrains FEV considers improvements over their baseline in 2025, 2035 and 2045
- In 2035 FEV considers an upgrade of battery capacities and in 2045 a change of hydrogen tanks from 700 bar to liquid
- Already in 2025 battery electric powertrains have lower TCO than compression ignition and hybrid
- From 2035 battery electric powertrains are TCO optimal
- From around 2040 fuel cell electric powertrains are cheaper in TCO than compression ignition and hybrid powertrains

Source: FEV

Automated trucks are significantly cheaper than non-automated once since they do not require a driver which holds the largest cost category

COST BREAKDOWN OF AUTOMATED AND NON-AUTOMATED USE-CASES IN 2045



- In both, long and regional haul, the driver costs are the largest cost category
- Moreover, fewer insurance and handling costs as well as energy demand are considered for the automated use-cases
- The additional depreciation for the more complex cabinless glider with all the necessary sensor systems has a comparably small influence
- Therefore, a significant cost reduction can be achieved
- In all other scenarios and powertrains the cost differences between automated and non-automated use-cases are similar

Source: FEV

Agenda

- Executive summary
- Framework and long-term scenarios for HD on-road transportation
- Technology options towards 2050
- Future pathways towards clean on-road transportation
- Reduced GHG emissions with holistic technology strategies
- CO_2 abatement costs for selected reference trucks
- TCO performance of underlying reference trucks
- Life-cycle analysis for HD trucks

FEV has followed a 3-step approach for the LCA; key outcome is that the usage is major driver for overall lifetime truck CO_2 emissions

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1 Meta-data collection and breakdown of considered components

2 Calculation of the contribution of each life-cycle phase

3 Deep dive on the most impacting aspect of the overall balance

APPROACH

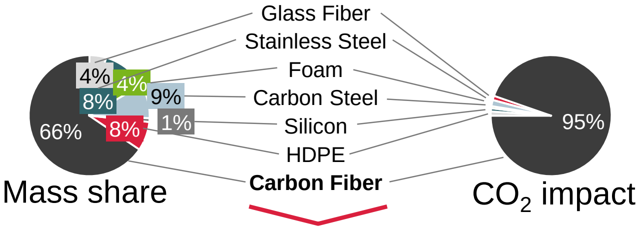
- Which materials and which processes are used to build up the powertrain?
- Where is the production taking place and with which impact?
- What are CO_2 emissions of such materials and processes?

- Considering the average fuel consumption and GHG emissions required to produce the fuel, how much is an average truck polluting?
- How much does powertrains' maintenance impact the life-cycle emissions?

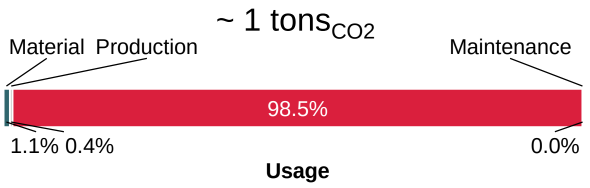
- At which distance the payback of CO_2 emissions is achieved for a determined propulsion system?
- What should be the GHG emission of a fuel to be the “greenest” solution?
- How much will future trucks emit during their usage?

EXAMPLE

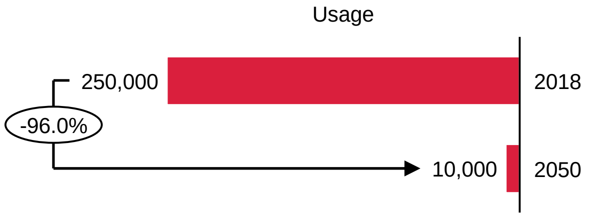
- Type IV, 700 bar, H_2 tank:



- Long haul, Diesel truck:



- Regional haul, fully-electric truck:



RESULT

Trough research in publications and experts' workshop, FEV assessed the CO_2 impact of the component in scope

Results are shown on next slides

Results are shown on next slides

HDPE: High-Density Polyethylene
Source: FEV

The LC analysis compares the total CO_2 footprint of different powertrains; FEV focuses on Diesel, BEV and FCEV with different energy carriers

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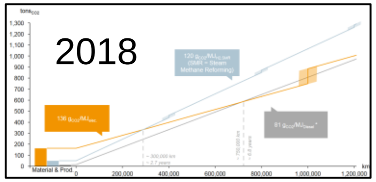
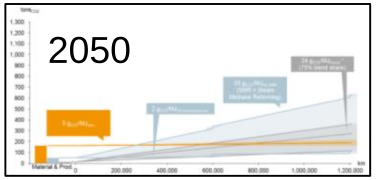
LIFE-CYCLE ANALYSIS* (LCA) INPUTS

		Vehicles' properties		Considered Powertrains	Well-to-Tank CO_2 emissions	
		Long haul; 110,000 km per year; 11.0 years usage	Reg. haul; 50,000 km per year; 11.0 years usage	Diesel BEV FCEV	 2018	 2050
Diesel	Engine power	330 kW	240 kW	ICE, gearbox, EAT	7.2 g_{CO2}/MJ (~7 % blend share)	3.4 g_{CO2}/MJ (75 % blend share)
BEV	E-motor power$_{peak}$	500 kW	400 kW	E-motor, battery, gearbox, power electronics, wiring	136 g_{CO2}/MJ (electricity mix)	5 g_{CO2}/MJ (electricity mix)
	Battery capacity	900 kWh	400 kWh			
FCEV	E-motor power$_{peak}$	500 kW	400 kW	Fuel cell stack, H_2 pressurized tank, e-motor, battery, gearbox, power electronics, balance of plant, wiring	120 g_{CO2}/MJ (SMR)	55 g_{CO2}/MJ (SMR)
	FC stack power	300 kW	200 kW			
	Battery capacity	12 kWh	10 kWh		-	2 g_{CO2}/MJ (electrolysis from ren.)
	H_2 tank size	50 kg	25 kg			

*: LCA focuses on Europe, hence "first life" including all (in Europe) occurring CO_2 emissions; "second life" is assumed to take place outside Europe and therefore is not in scope
BEV: Battery Electric Vehicle; FCEV: Fuel Cell Electric Vehicle; ICE: Internal Combustion Engine; EAT: Exhaust After-Treatment; SMR: Steam Methane Reforming
Source: FEV

The analysis shows that, although running “emission free”, the fuel cell is the most polluting powertrain assuming today’s H_2 production

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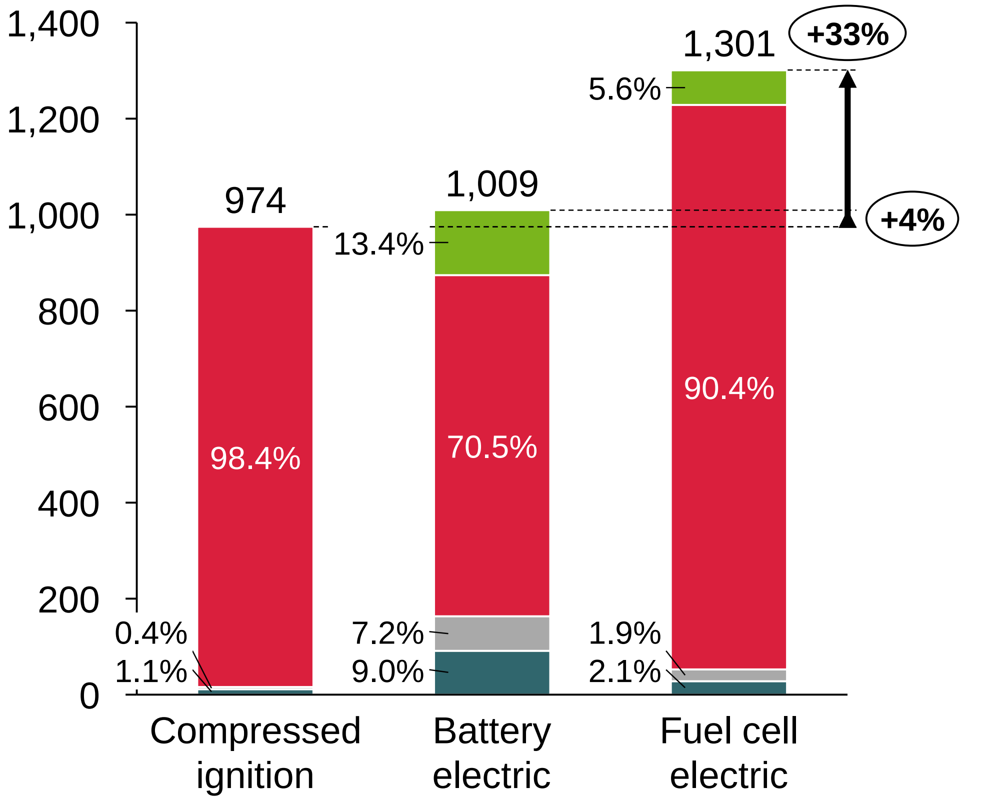
LONG-HAUL HEAVY-DUTY TRUCK – LIFE-CYCLE ANALYSIS – 2018

CO_2 footprint comparison of “first-life” in Europe ($tons_{CO2}$)*



*: Powertrain only
Source: FEV

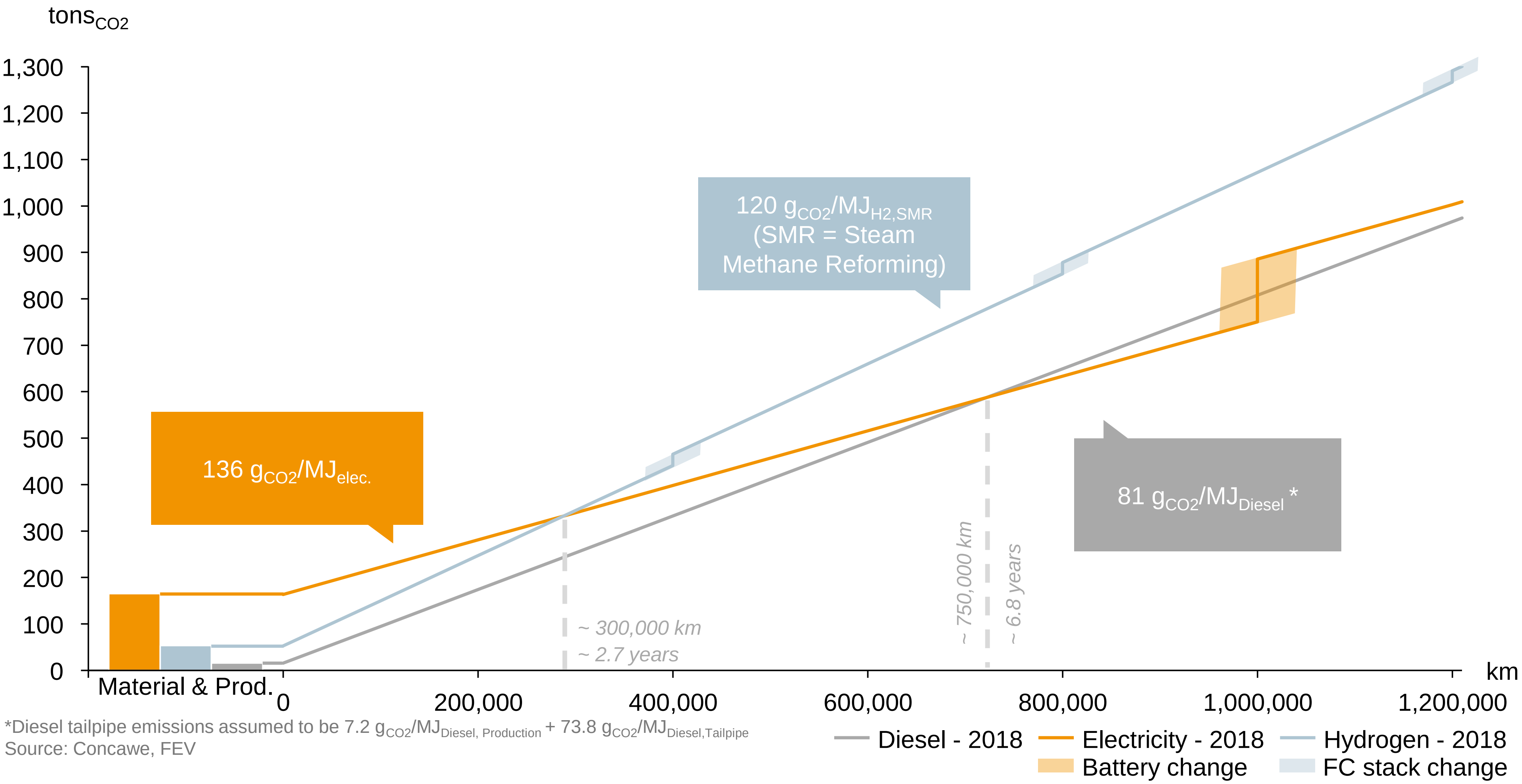
- Due to the high mileage and energy requirements of HD trucks, the usage is accounting for >70% of the total life-cycle CO_2 emissions
- Battery’s production and raw materials are by far the most impacting ones for the LCA of a BEV
- Although there are no tailpipe emissions, FCEV as the highest life-cycle impact due to the high-CO_2 emissions of today’s H_2 production
- “Maintenance” includes battery/stack changes through vehicle’s usage
- Truck’s glider is not considered

🟩 Maintenance 🟥 Usage ▨ Production ■ Material

Assuming today’s electricity production, a BEV performs comparable to a CI truck; FC is not competitive due to the high CO_2 footprint of H_2 production

LH

LONG-HAUL TRUCK – CO_2 LIFE-CYCLE IMPACT IN EUROPE – 2018



*Diesel tailpipe emissions assumed to be 7.2 $g_{CO2}/MJ_{Diesel, Production}$ + 73.8 $g_{CO2}/MJ_{Diesel,Tailpipe}$

Source: Concawe, FEV

LCA performance heavily depend on the energy carrier and its CO_2 footprint of future production

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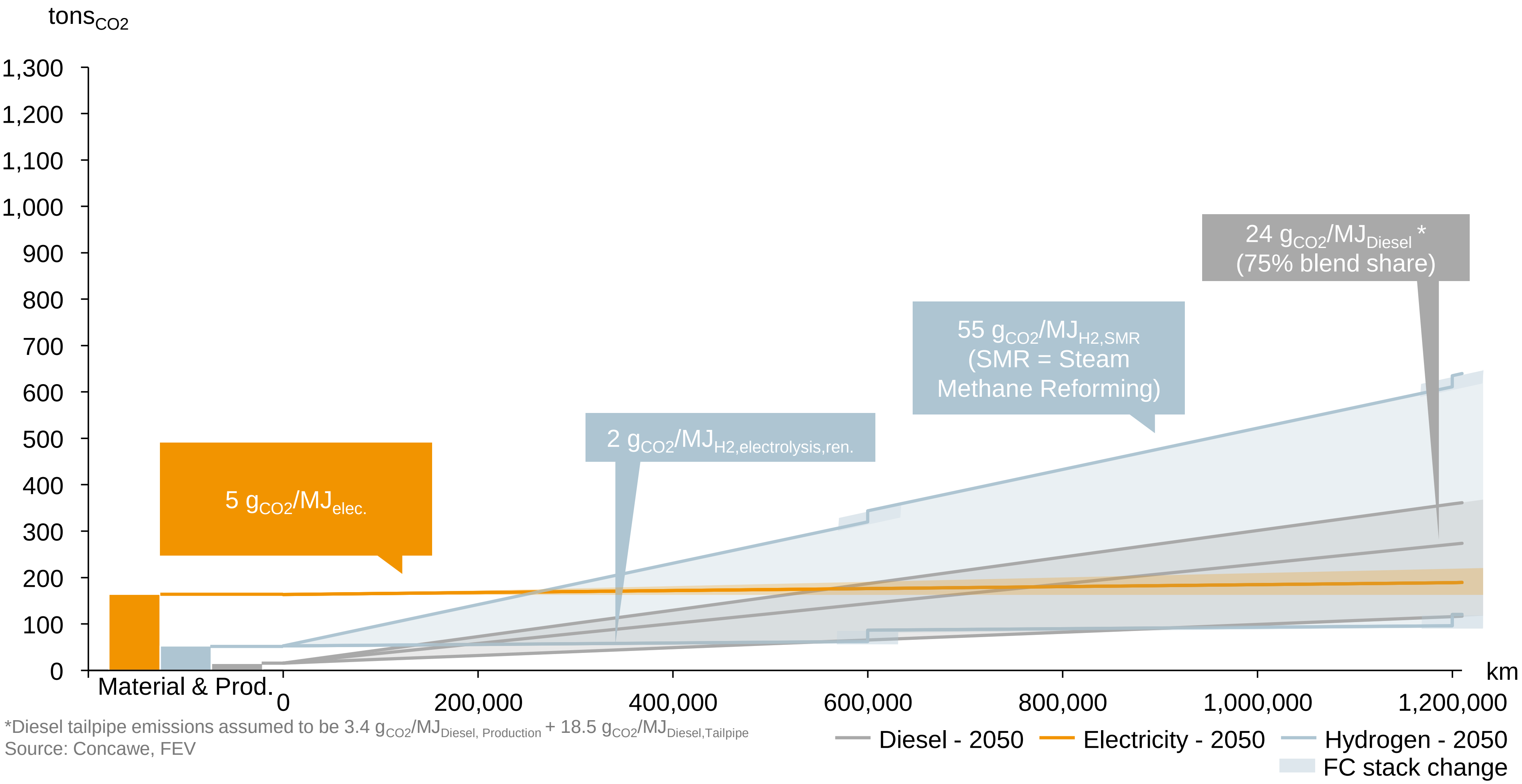
LONG-HAUL TRUCK – CO_2 LIFE-CYCLE IMPACT IN EUROPE – 2050 ENERGY CARRIERS



*Diesel tailpipe emissions assumed to be 3.4 $g_{CO2}/MJ_{Diesel, Production}$ + 18.5 $g_{CO2}/MJ_{Diesel,Tailpipe}$

Source: Concawe, FEV

For RH applications, not requiring an extremely high mileage and a thus not needing a battery change, electricity is the “greenest” choice

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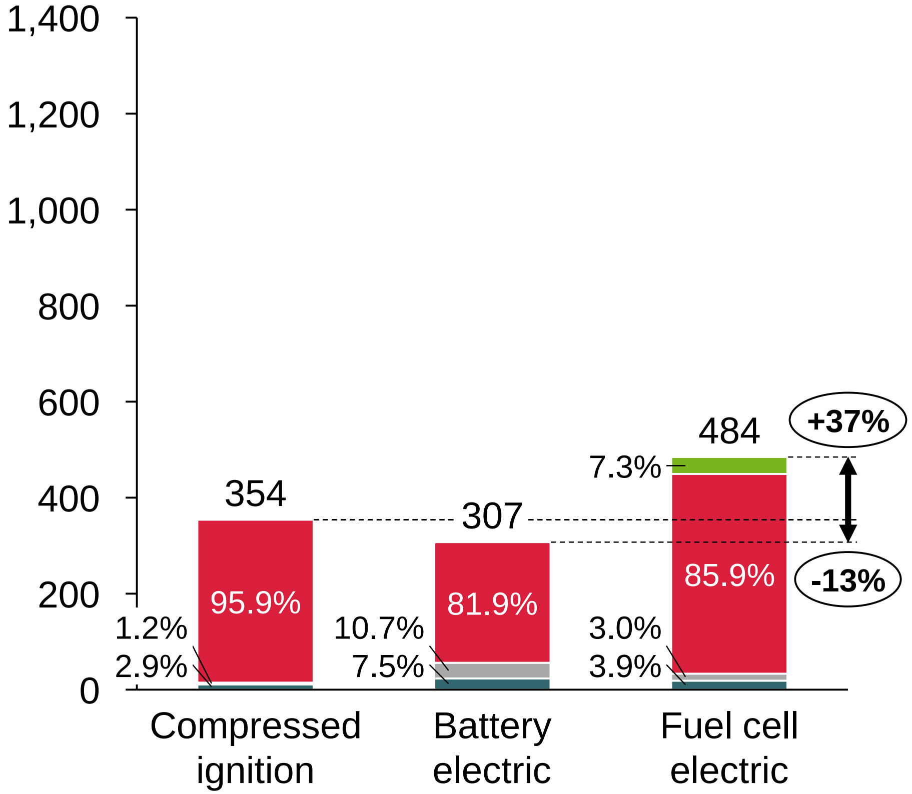
RH

REGIONAL-HAUL HEAVY-DUTY TRUCK – LIFE CYCLE ANALYSIS – 2018

CO_2 footprint comparison of “first-life” in Europe ($tons_{CO2}$)*



- In RH applications the usage is less important than in LH applications, mainly due to the reduced mileage
- It still constitutes the largest share of life-cycle emissions
- No battery change in BEV applications is required due to the low mileage
- For fuel cell vehicles, FEV assumes two stack changes over the considered 11-years period
- “Maintenance” includes stack changes through vehicle’s usage
- Truck’s glider is not considered

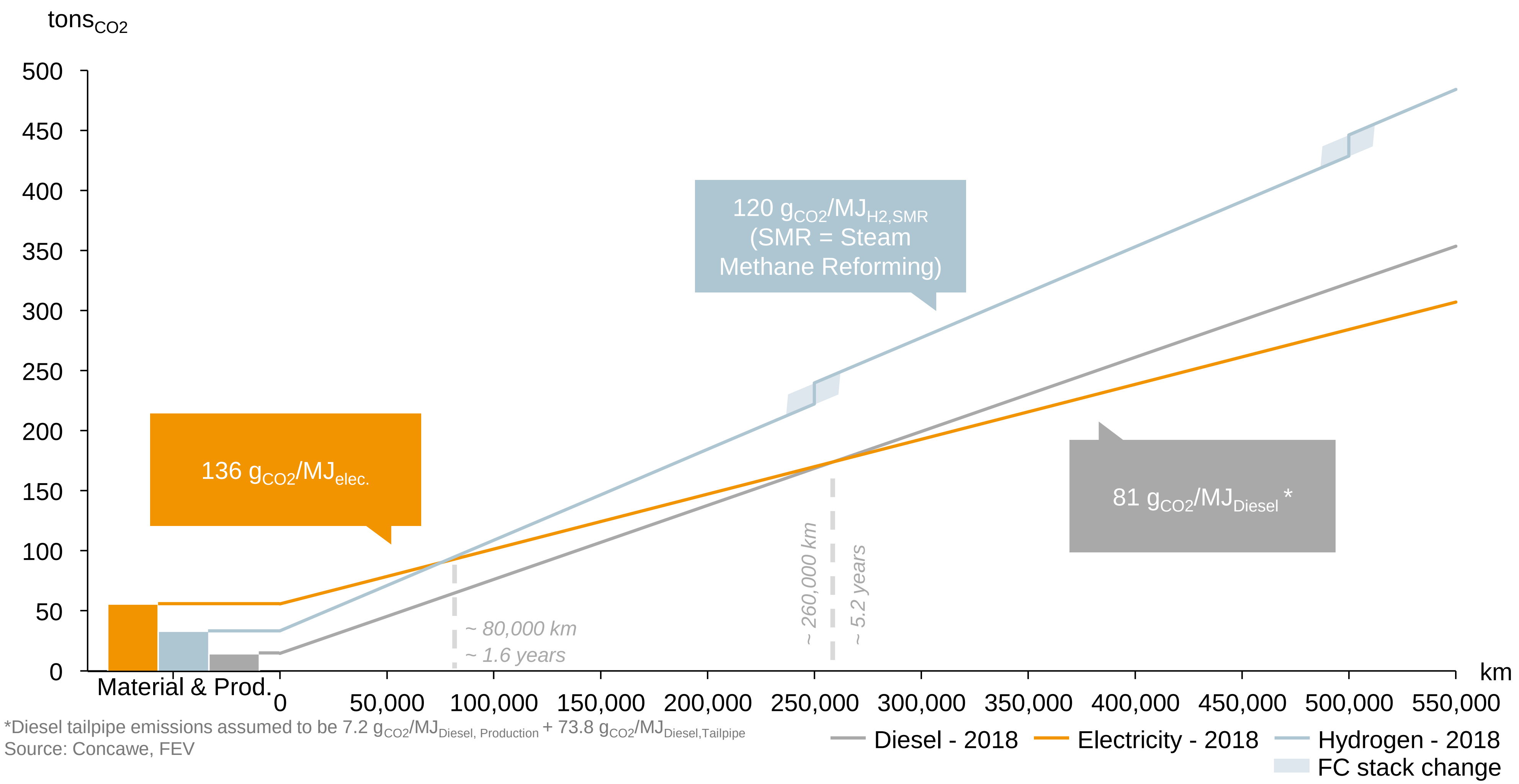
🟩 Maintenance 🟥 Usage ▨ Production ■ Material

*: Powertrain only
Source: FEV

On regional applications, BEV is the most attractive solution on a lifecycle basis (smaller battery, no battery change)

REGIONAL-HAUL TRUCK – CO_2 LIFE-CYCLE IMPACT IN EUROPE – 2018

RH



*Diesel tailpipe emissions assumed to be 7.2 $g_{CO2}/MJ_{Diesel, Production}$ + 73.8 $g_{CO2}/MJ_{Diesel,Tailpipe}$

Source: Concawe, FEV

Even with a “green” H_2 production the regional haul BEV remains a very competitive solution; CI with high blend shares remain attractive

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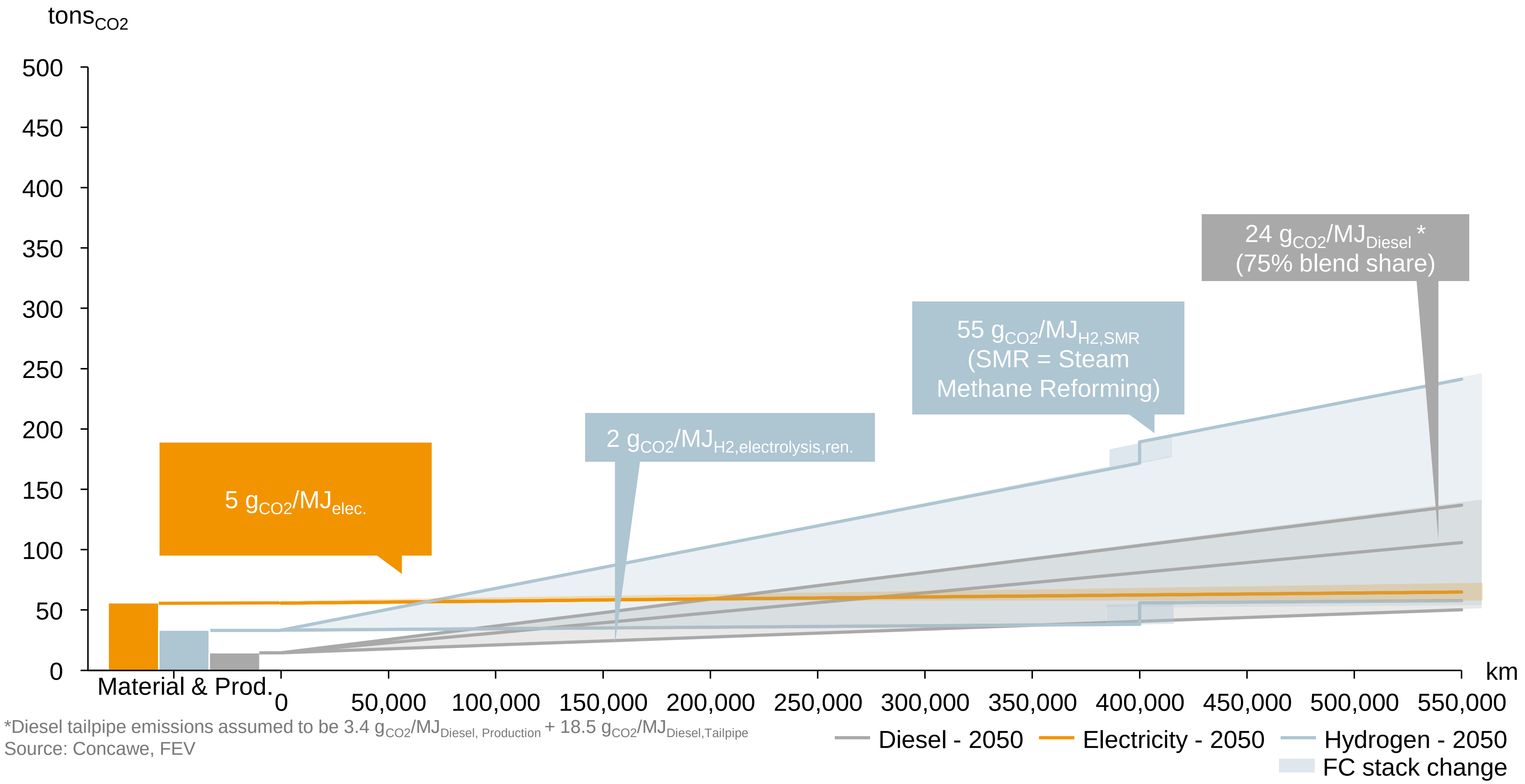
RH

REGIONAL-HAUL TRUCK – CO_2 LIFE-CYCLE IMPACT IN EUROPE – 2050



*Diesel tailpipe emissions assumed to be 3.4 $g_{CO2}/MJ_{Diesel,\ Production}$ + 18.5 $g_{CO2}/MJ_{Diesel,Tailpipe}$

Source: Concawe, FEV