JULY, 5TH 2022

DR. CHRISTOPH MENNE

EXECUTIVE VP FEV EUROPE

HYDROGEN FOR FUTURE MOBILITY

H_2 ENGINE AND FUEL CELLS

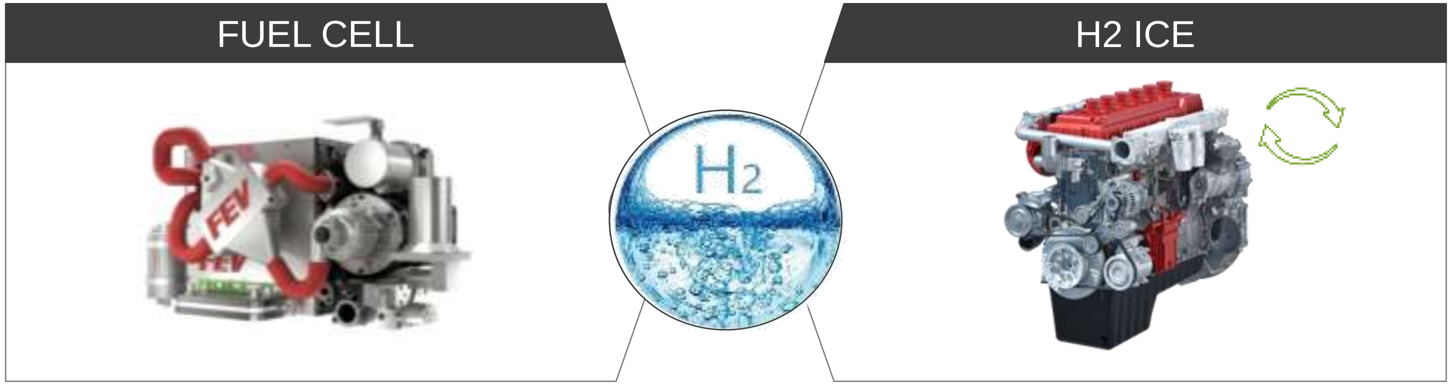
PREPARED FOR

H_2 SCIENTIFIC EVENT

UNIVERSITY OF PITESTI

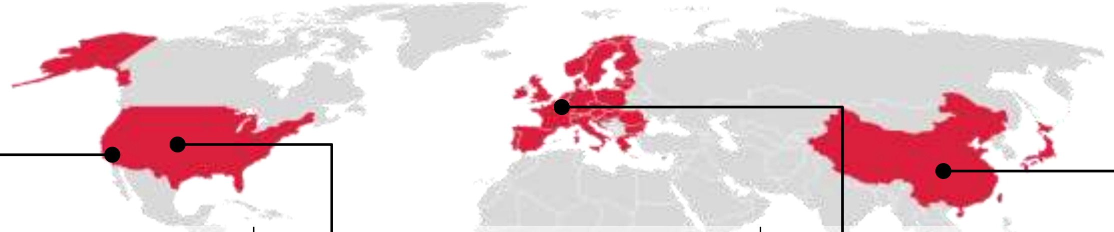
Over 20 years of experience in hydrogen combustion engine and fuel cell development

TWO TECHNOLOGIES : FUEL CELL AND H2 ICE



All major markets stipulate regulations pushing for low and zero (CO_2) emission commercial vehicles; EU and California regulations most challenging

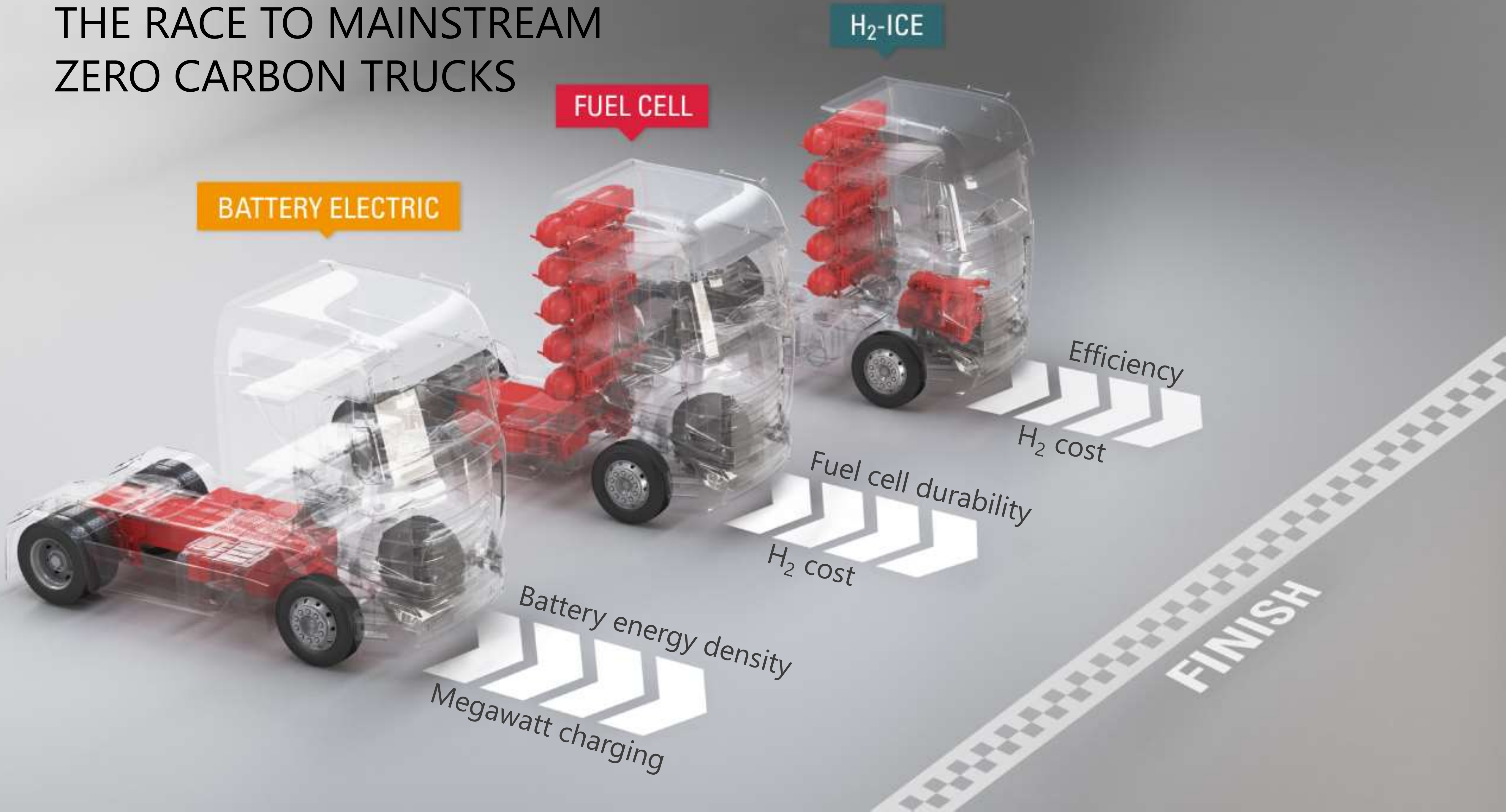
CO_2 EMISSION REGULATION FOR HD[1)] COMMERCIAL VEHICLE FLEETS – OVERVIEW



	California	USA	Europe	China
Regulatory metric / KPI	Zero emission vehicle sales: in % of total sales	CO_2 emissions: Fleet average		Fuel consumption: Individual vehicle
Reference	N/A	Relative to 2017	Relative to 2019	Relative to 2015
Targets (2020 – 2025 – 2030)	2025: **7%** ZEVs (class 7/8 tractors) **11%** ZEVs (class 4-8) 2030: **30%** ZEVs (class 7/8 tractors) **50%** ZEVs (class 4-8)	2021: **6-14%** reduction[1)] 2024: **11-20%** reduction[1)] 2027: **12-27%** reduction[1)] Post 2027 targets under discussion	2025: **15%** reduction More stringent target currently under discussion (decision expected in 2022) 2030: **30%** reduction	2019 / 2021: **15%** reduction Stage IV fuel consumption targets (for 2025/26) targets under discussion

1) depending on truck class
Source: FEV, Public domain,

THE RACE TO MAINSTREAM ZERO CARBON TRUCKS



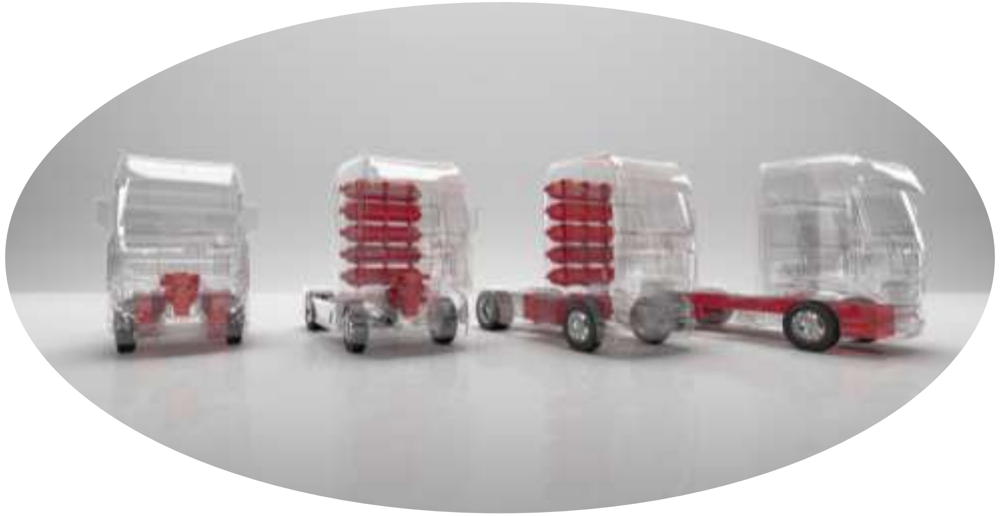
There are various factors influencing the attractiveness of zero carbon truck solutions; among these, TCO is the single most important criteria

Attractiveness of zero carbon trucks

Financial criteria

- Purchasing cost
- Energy cost
- Road tolls
- S&M cost
- Incentives
- ...

Total cost of ownership (TCO)



Usability / Utility

- Payload
- Interoperability
- Public infrastructure
- Depot infrastructure
- Local access restrictions
- Green image

Multi-dimensional

Urban delivery

Regional delivery

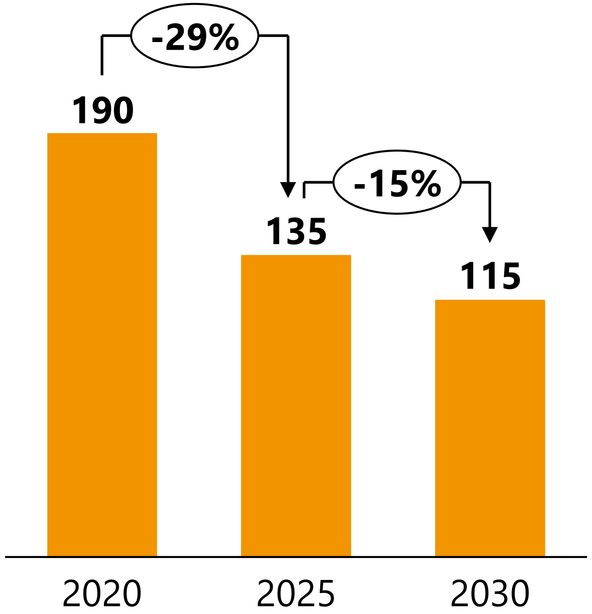
Long-haul

focus on following slides

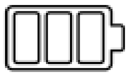
Battery cost decrease is already happening, whereas cost of hydrogen propulsion technologies will decrease especially towards 2030 and after

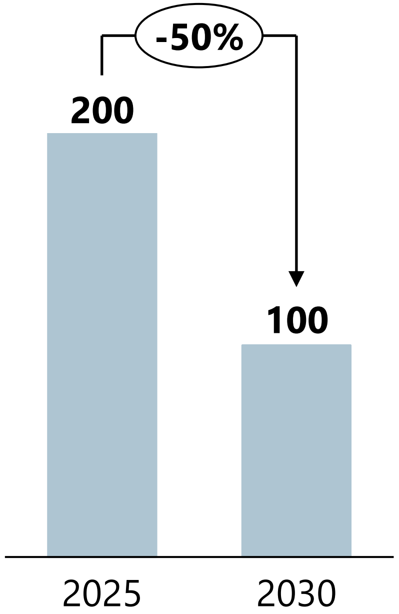
KEY TECHNOLOGIES: COST ANALYSIS FOR **HEAVY-DUTY TRUCKS**

» FEV BASE SCENARIO

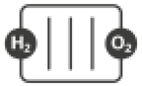


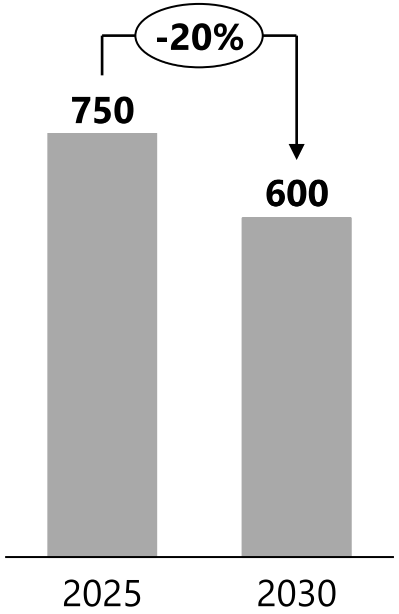
Battery pack cost
in EUR / kWh $_{installed}$



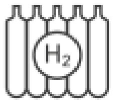


Fuel cell system cost
in EUR / kW $_{net}$





H_2 tank system cost[1)]
in EUR / kg $_{net}$



Cost development already visible in our vehicle benchmarks

BENCHMARKING

1) 700 bar compressed hydrogen
Source: FEV

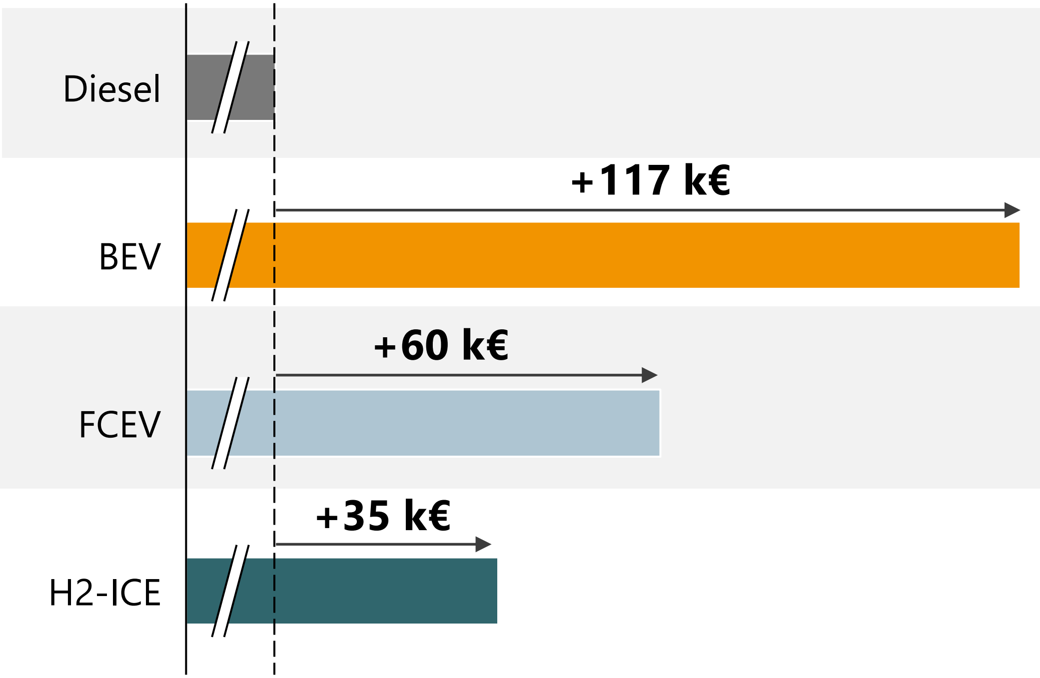
For a 40 ton long-haul truck in 2030 (EoL range 600 km) a battery electric powertrain is most expensive, followed by fuel cell and hydrogen ICE

POWERTRAIN COST COMPARISON: 40 TON LONG-HAUL TRUCK

» FEV BASE SCENARIO

POWERTRAIN COSTS IN 2030

» DRIVING RANGE: 600 KM



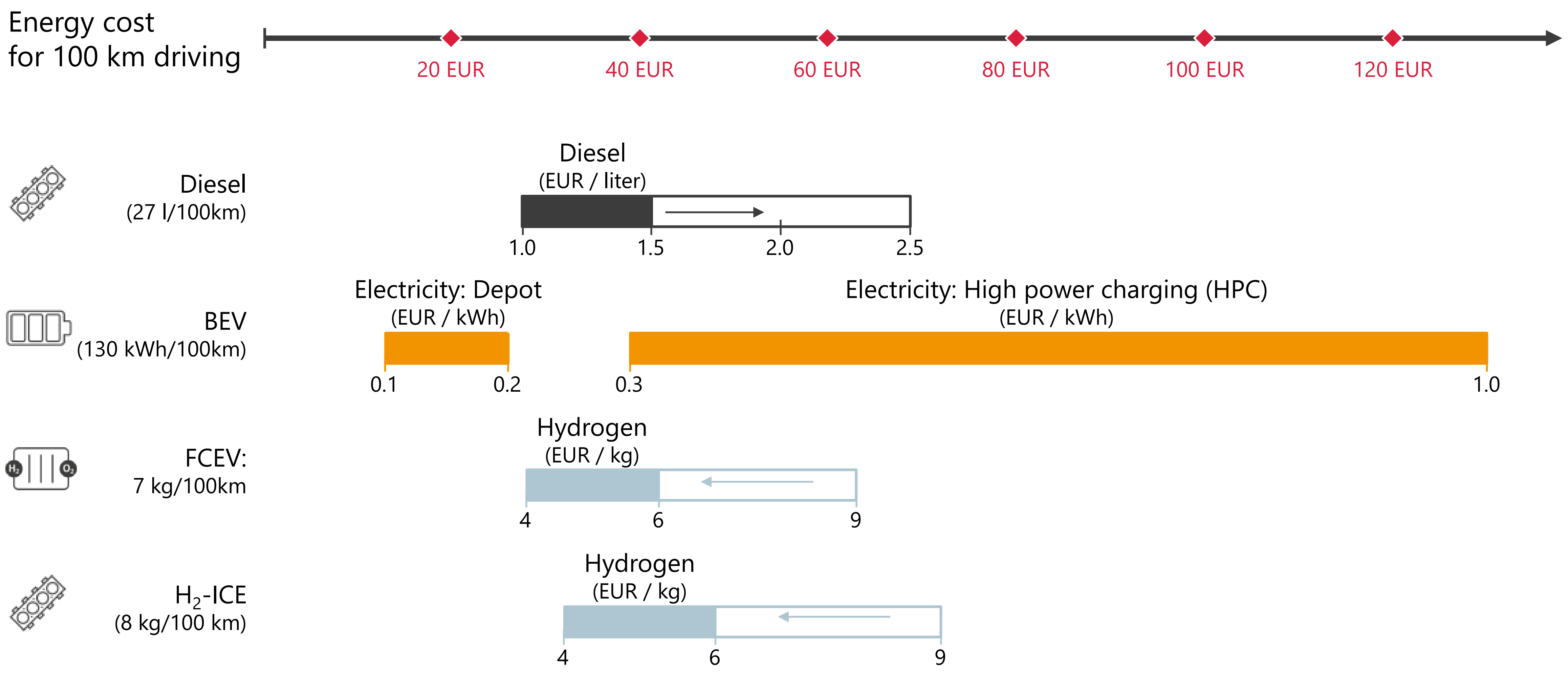
POWERTRAIN SPECIFICATIONS

» DRIVING RANGE (END OF LIFE): 600 KM

	ICE / e-drive	Fuel cell system	Battery	H_2 tank system
Diesel	350 kW			
BEV	400 kW		1,185 kWh	
FCEV	400 kW	300 kW	80 kWh	50 kg
H2-ICE	350 kW			52 kg

Energy cost of FCEVs and H_2-ICEs can become competitive to diesel towards 2030; BEVs are cheap when charged in depot, while HPC is most expensive

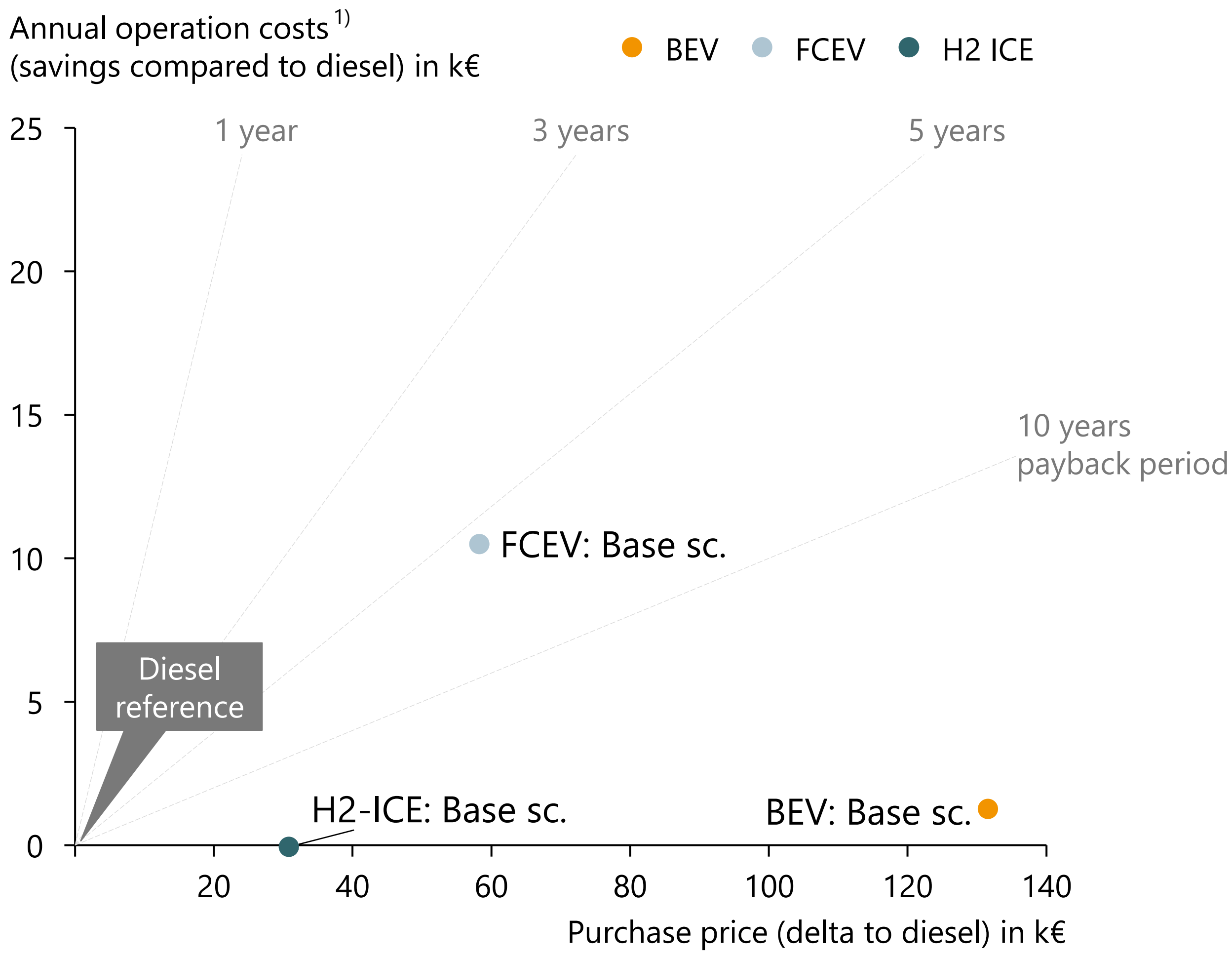
ENERGY COST COMPARISON: 40 TON LONG-HAUL TRUCK



Source: FEV

In our 2030 base scenario for a 40 t truck, TCO parity with diesel is still a challenge for all solutions; fuel cell is most attractive

TCO ANALYSIS: 40 TON LONG-HAUL TRUCK, YEAR 2030



KEY BOUNDARY CONDITIONS

"Base" scenario (for 2030):

- FEV base scenario for energy prices: Diesel, electricity, hydrogen
- FEV base scenario for technology maturity and costs: Battery, fuel cell system, H2 tank system
- FEV base scenario for taxation and incentives

	Base scenario
Diesel price2)	1.25 € / liter
H_2 price2)	5.75 € / kg
Electricity price: Depot2)	0.18 € / kWh
Electricity price: HPC2)	0.41 € / kWh
Battery costs3): c-rate 1-3	115 € / kWh
Battery costs3): c-rate 3-8	150 € / kWh
Fuel cell system costs	100 € / kW
Fuel cell replacement	No
H2 tank system costs	600 € / kg
Road toll reduc. for ZEVs	75%
BEV: Depot charge share	30%

1) Operation costs include energy costs, service & maintenance, road tolls, battery and fuel cell replacement; 2) Net prices (for commercial consumers); 3) On battery pack level; 4) over vehicle lifetime
Source: FEV

In an "ideal" charging situation, a 1+ MW charger can provide enough energy for the trip within the mandatory break duration; however, little margin exists

FEV

LONG-HAUL TRUCK USE-CASE: CHARGING DURING MANDATORY BREAK

- 40 min net charging time @ 1 MW constant charging power
- 10% charging losses
- LH truck e-consumption: 1.3 kWh/km

350 kW charger: 210 kWh / 150 km

1,000 kW charger: 600 kWh / 430 km

2,000 kW charger: 1.200 kWh / 860 km or
400 km in 19 minutes

✗ **350 kW power is not enough** to charge required amount of energy within the mandatory break duration

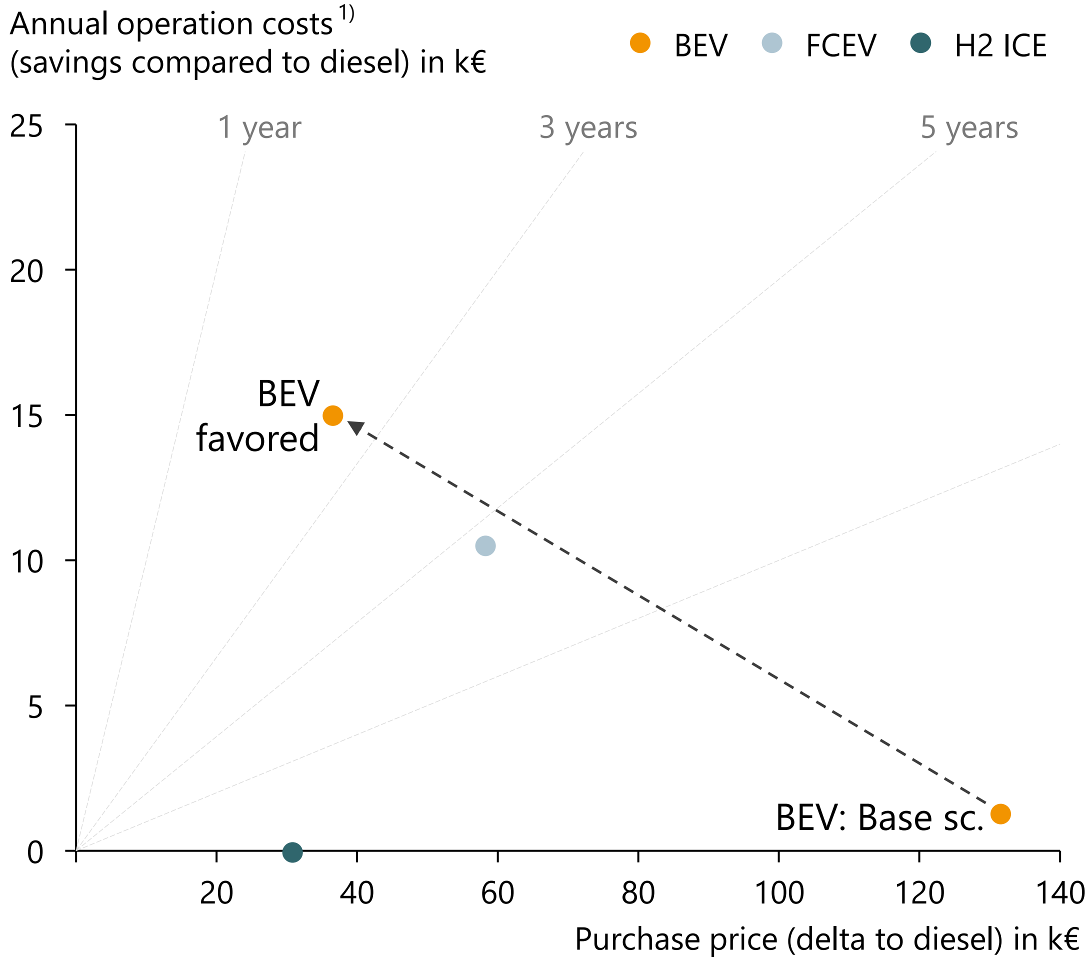
✓ **1+ MW power is enough** to charge required amount of energy within the mandatory break duration

! However, little margin exists; Occupation of charger or other interferences poses **risk for truck operator**

! Additionally, impact of MW charging on **battery concept / cost / lifetime** needs to be considered in TCO

In case megawatt charging is established broadly and cheaply, and battery prices further decrease, BEVs can become quite attractive - even in LH trucks

TCO ANALYSIS: 40 TON LONG-HAUL TRUCK, YEAR 2030



KEY BOUNDARY CONDITIONS

"BEV favored" scenario:

- Megawatt charging is established: 400 km driving range of BEVs is sufficient (instead of 600 km) → battery capacity reduction by 33%
- High utilization leads to reduced HPC electricity costs
- "Optimistic" battery cost scenario

	Base scenario	"BEV favored" scenario
Diesel price[2)]	1.25 € / liter	1.25 € / liter
H_2 price[2)]	5.75 € / kg	5.75 € / kg
Electricity price: Depot[2)]	0.18 € / kWh	0.18 € / kWh
Electricity price: HPC[2)]	0.41 € / kWh	0.30 € / kWh
Battery costs[3)]: c-rate 1-3	115 € / kWh	80 € / kWh
Battery costs[3)]: c-rate 3-8	150 € / kWh	105 € / kWh
Fuel cell system costs	100 € / kW	100 € / kW
Fuel cell replacement	No	No
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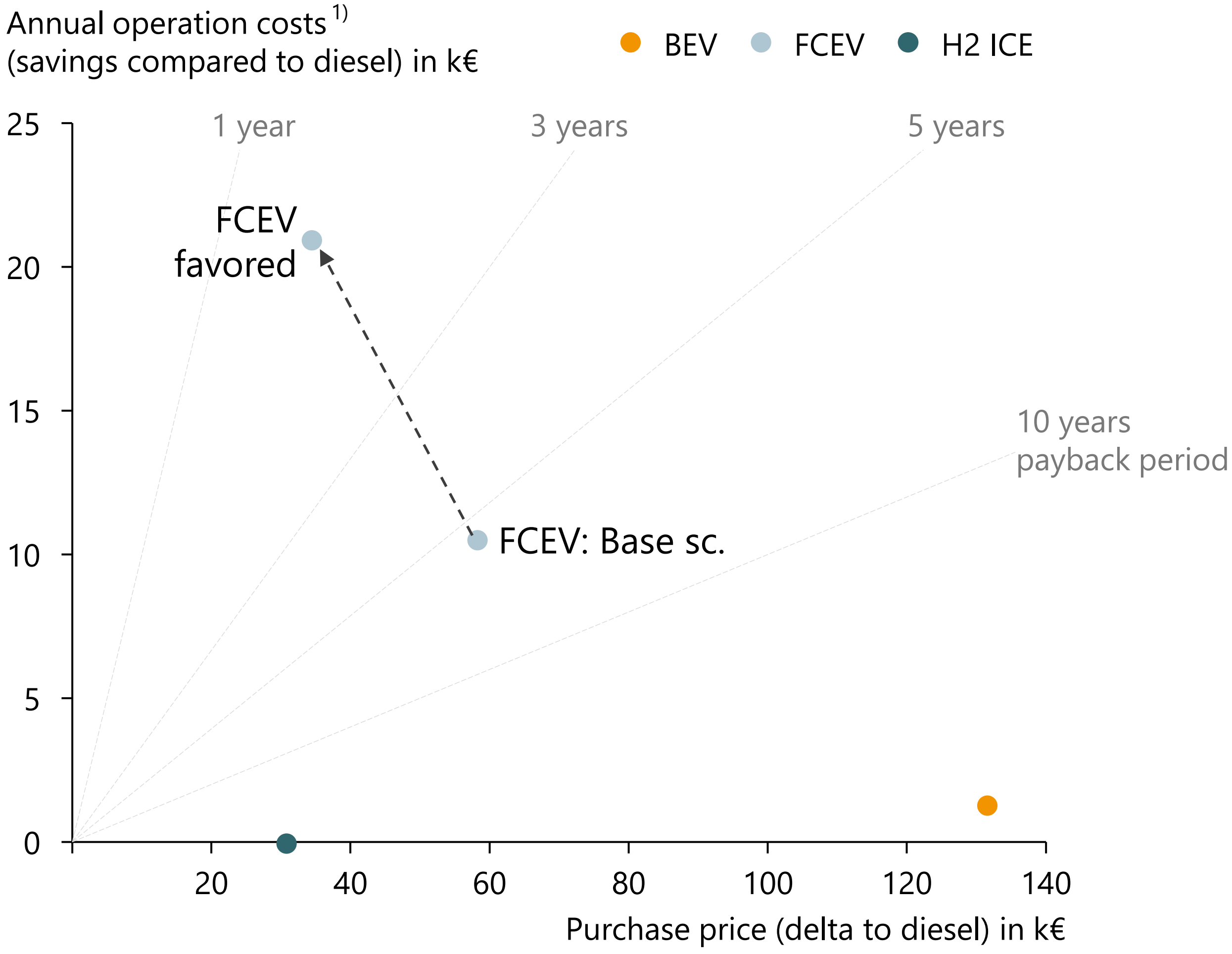
1) Operation costs include energy costs, service & maintenance, road tolls, battery and fuel cell replacement; 2) Net prices (for commercial consumers); 3) On battery pack level; 4) over vehicle lifetime
Source: FEV

In case H_2 prices are well below 5 €/kg and fuel cell powertrain costs further decrease, FCEVs can become the most attractive solution for LH trucks

TCO ANALYSIS: 40 TON LONG-HAUL TRUCK, YEAR 2030



KEY BOUNDARY CONDITIONS

"FCEV favored" scenario:

- Large scale H_2 production and distribution as well as taxation policies lead to reduced H_2 price
- "Optimistic" fuel cell system and H_2 tank cost scenario
- "Optimistic" battery system cost scenario

	Base scenario	"FCEV favored" scenario
Diesel price[2)]	1.25 € / liter	1.25 € / liter
H_2 price[2)]	5.75 € / kg	4.70 € / kg
Electricity price: Depot[2)]	0.18 € / kWh	0.18 € / kWh
Electricity price: HPC[2)]	0.41 € / kWh	0.41 € / kWh
Battery costs[3)]: c-rate 1-3	115 € / kWh	80 € / kWh
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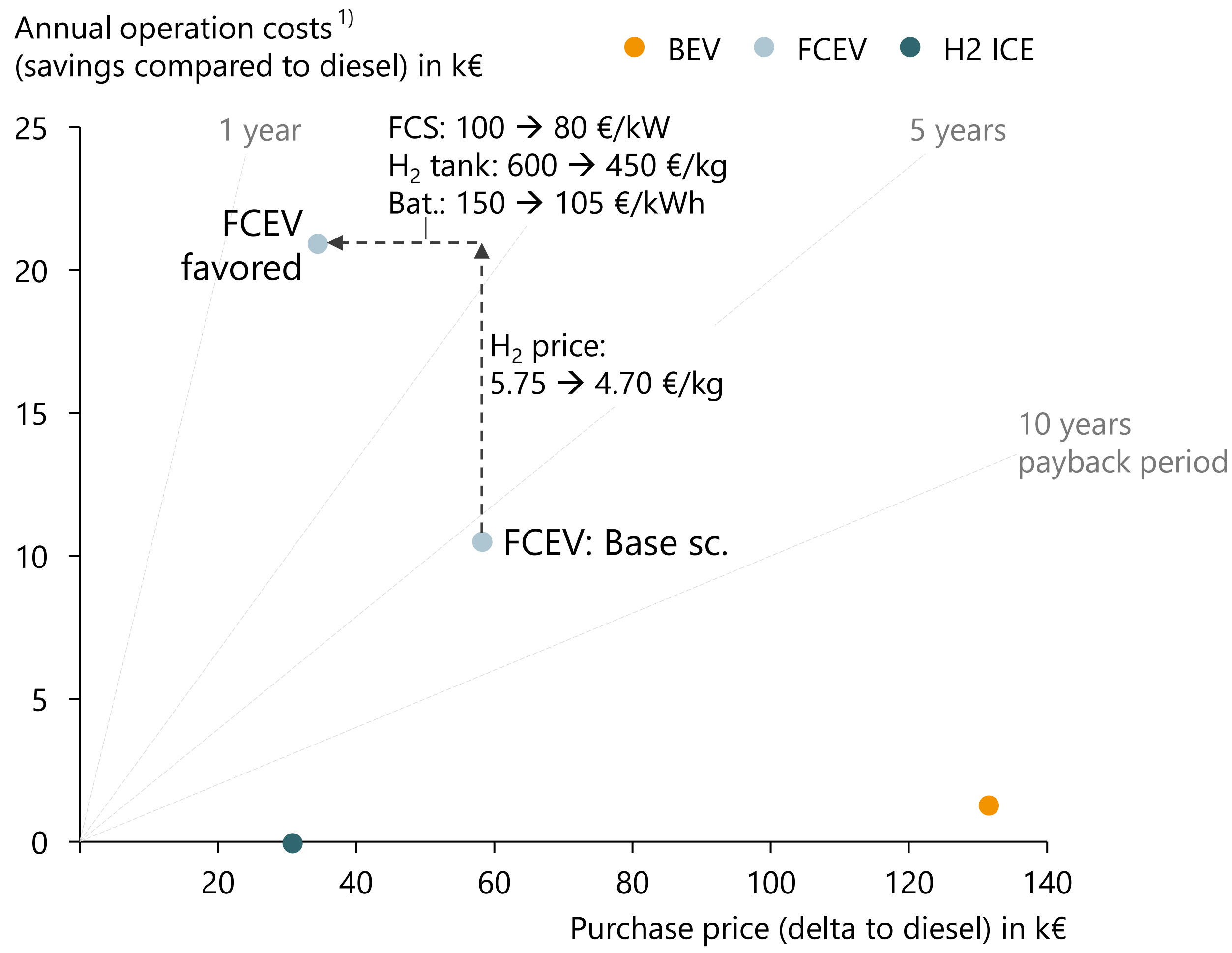

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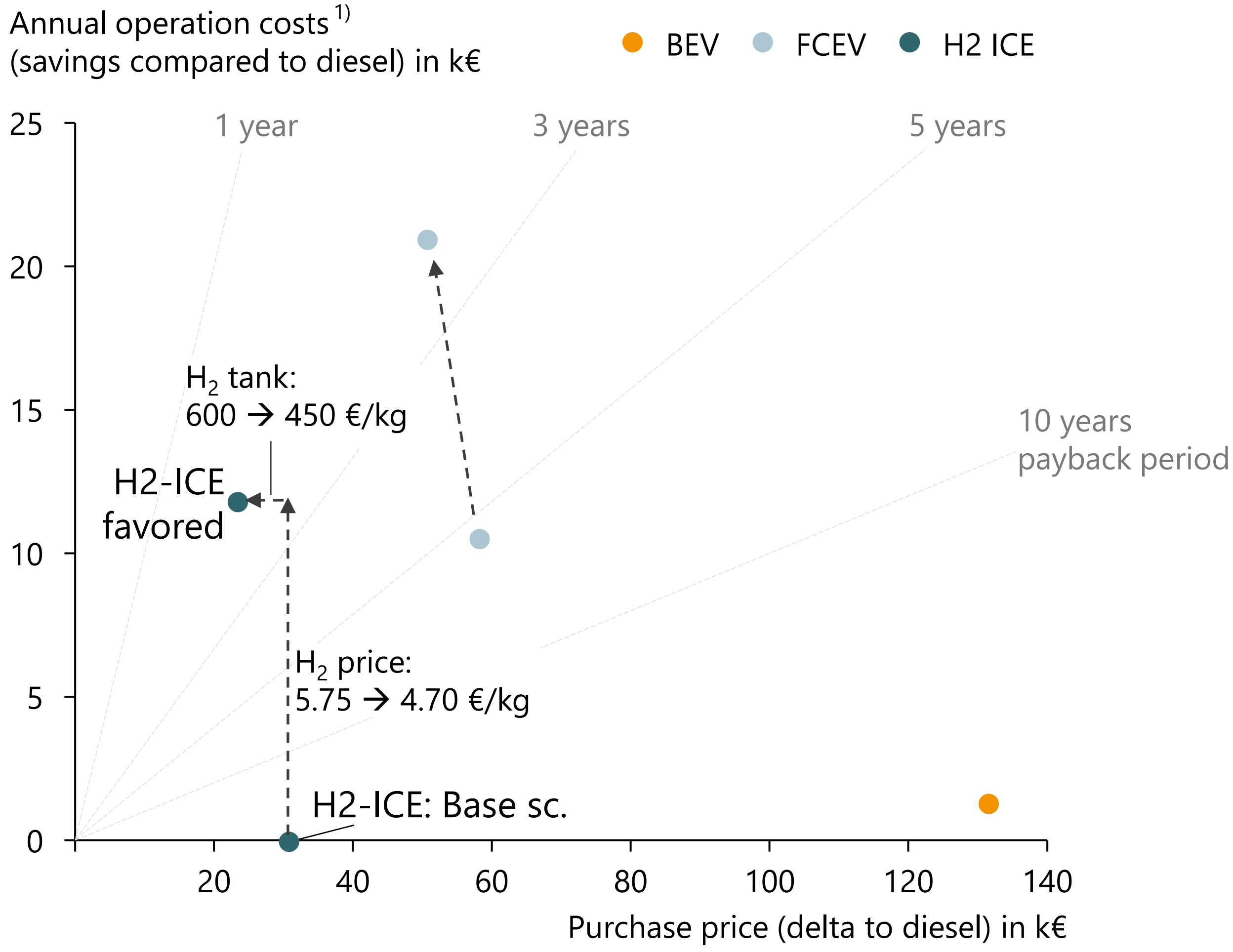
Source: FEV

H_2-ICEs can become the most attractive solution, in case H_2 prices are low…

TCO ANALYSIS: 40 TON LONG-HAUL TRUCK, YEAR 2030



KEY BOUNDARY CONDITIONS

"H_2-ICE favored" scenario:

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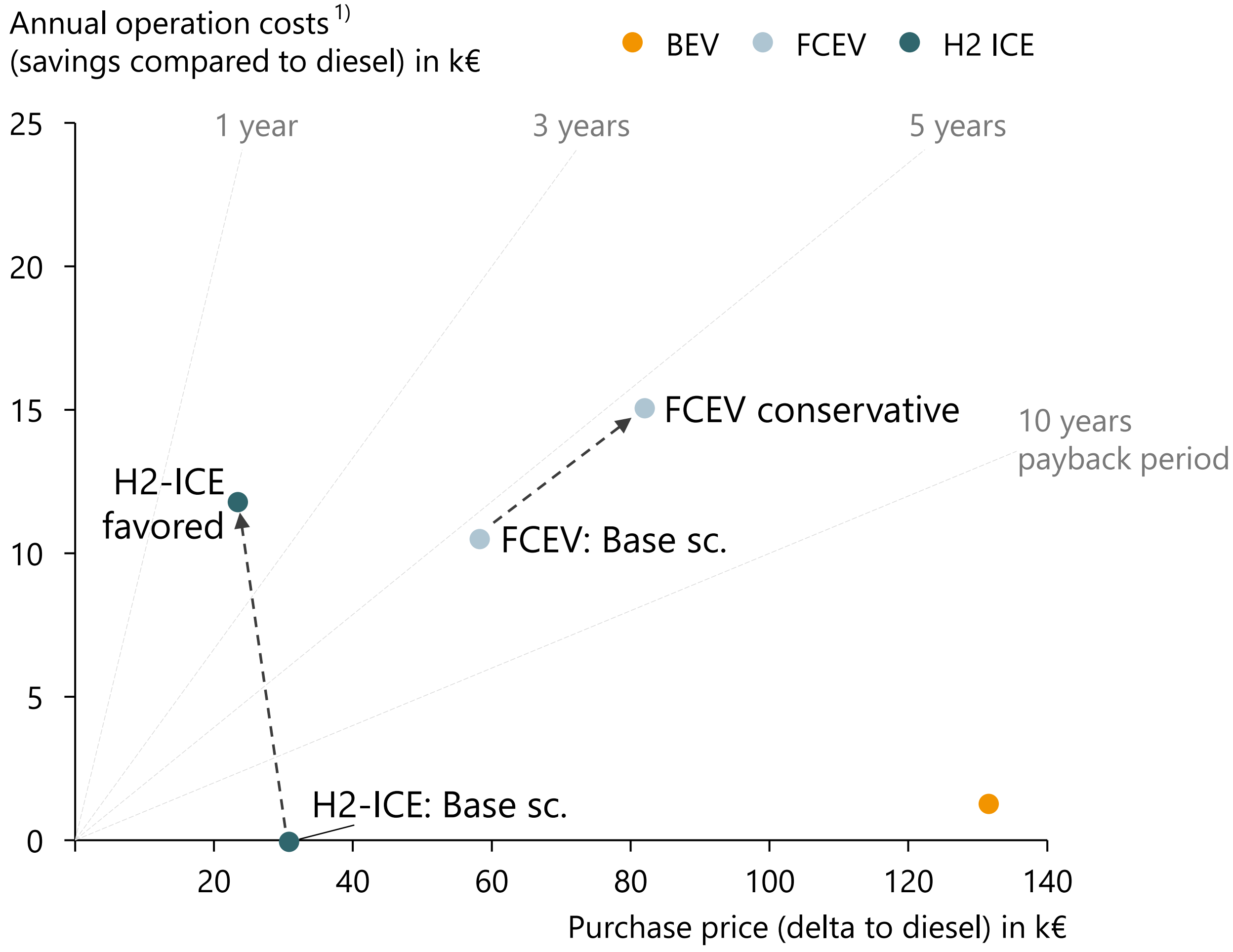
Source: FEV

H_2-ICEs can become the most attractive solution, in case H_2 prices are low… …and especially, if fuel cell technology develops slower than expected

TCO ANALYSIS: 40 TON LONG-HAUL TRUCK, YEAR 2030



KEY BOUNDARY CONDITIONS

"H_2-ICE favored" scenario:

- Large scale H_2 production and distribution as well as taxation policies lead to reduced H_2 price
- "Conservative" scenario for fuel cell trucks:
  - "Conservative" fuel cell cost scenario
  - Fuel cell durability: Exchange over truck lifetime is required

	Base scenario	"H_2-ICE favored" scenario
Diesel price[2)]	1.25 € / liter	1.25 € / liter
H_2 price[2)]	5.75 € / kg	4.70 € / kg
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Fuel cell system costs	100 € / kW	150 € / kW
Fuel cell replacement	No	Yes (after 6 y.)
H2 tank system costs	600 € / kg	450 € / kg
Road toll reduc. for ZEVs	75%	75%
BEV: Depot charge share	30%	30%

1) Operation costs include energy costs, service & maintenance, road tolls, battery and fuel cell replacement; 2) Net prices (for commercial consumers); 3) On battery pack level; 4) over vehicle lifetime
Source: FEV

In EU we expect a significant shift towards zero emission trucks; MD and HD regional delivery mainly BEV; HD long-haul mainly fuel cell or H2-ICE

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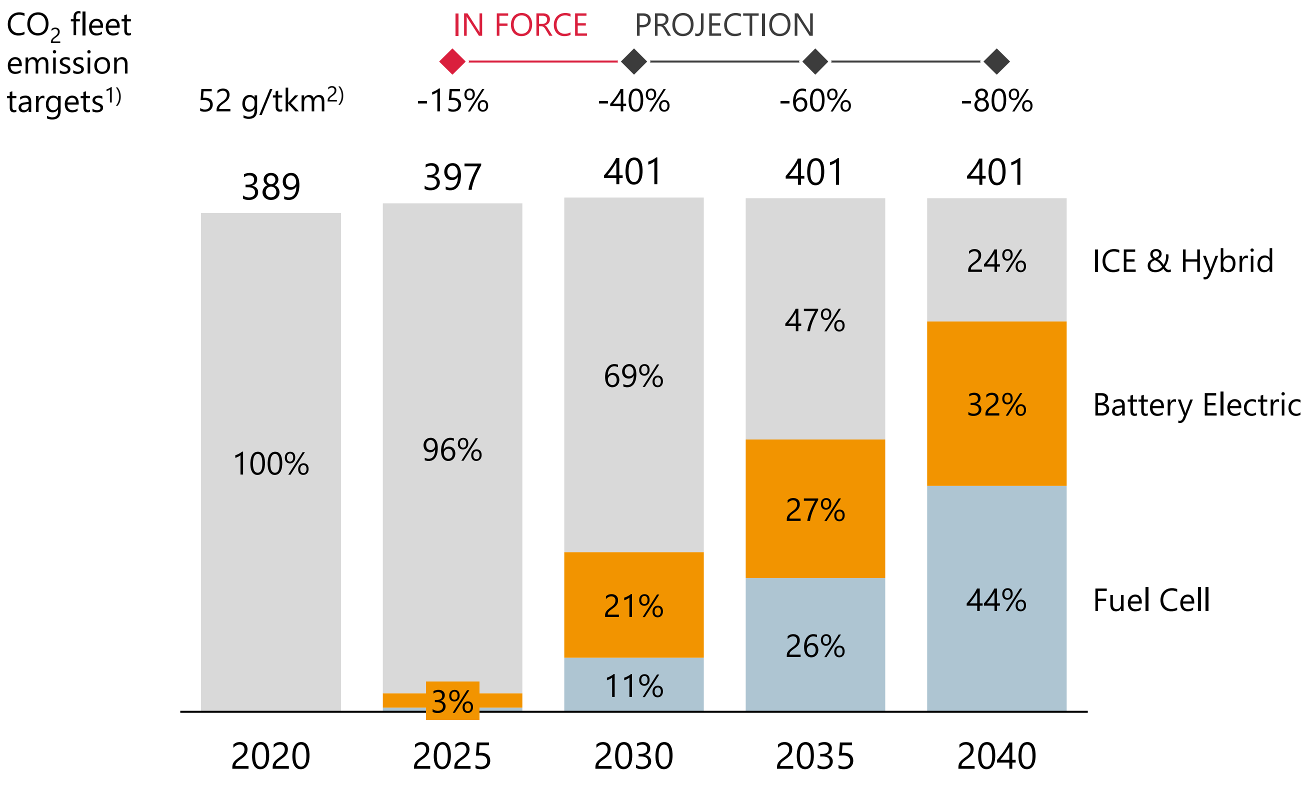
MEDIUM + HEAVY COMMERCIAL VEHICLE ELECTRIFICATION – SALES FORECAST

CV

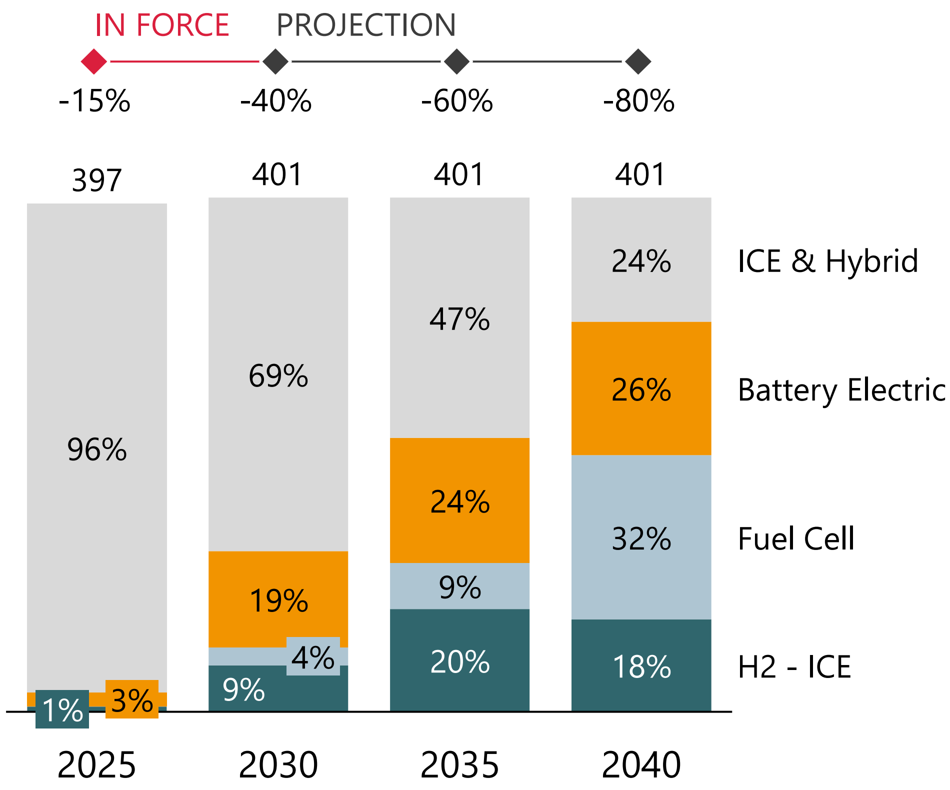
"ACCELERATED ELECTRIFICATION" SCENARIO

Sales in '000 units



ALTERNATIVE SCENARIO

Sales in '000 units



1) CO2 targets are **tailpipe** emissions values; 2025 targets expected to pertain to HD vehicles only, while 2030+ targets are expected to pertain to MD and HD vehicles
2) 2019 average CO2 emission value for HD only fleet (Vecto groups 4, 5, 9, 10)
Source: FEV

H_2 ICE has some unique advantages over other zero-emission powertrains, but regulatory acceptance and long-term TCO competitiveness are uncertain

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HIGH-LEVEL OF PROS AND CONS OF THE H_2 ICE VERSUS FCEV

+

- Lower powertrain costs - especially in the short-term
- Lower development and production effort, quicker market introduction (also, possibility of retrofit solutions)
- Powertrain durability, less sensitive to environmental impacts
- Good efficiency in high load / constant operation (i.e. highway use-case)
- Higher robustness against hydrogen impurity

−

- Non-zero emissions
- Lower efficiency (esp. in urban operation) → Lower range, higher energy cost (TCO impact)
- Potentially higher costs in the long-term
- Higher powertrain noise level
- Higher maintenance effort (comparable to today's ICEs)

The interest in H2-ICE originated from HD segment in Europe has spread out to various applications and regions around the world.

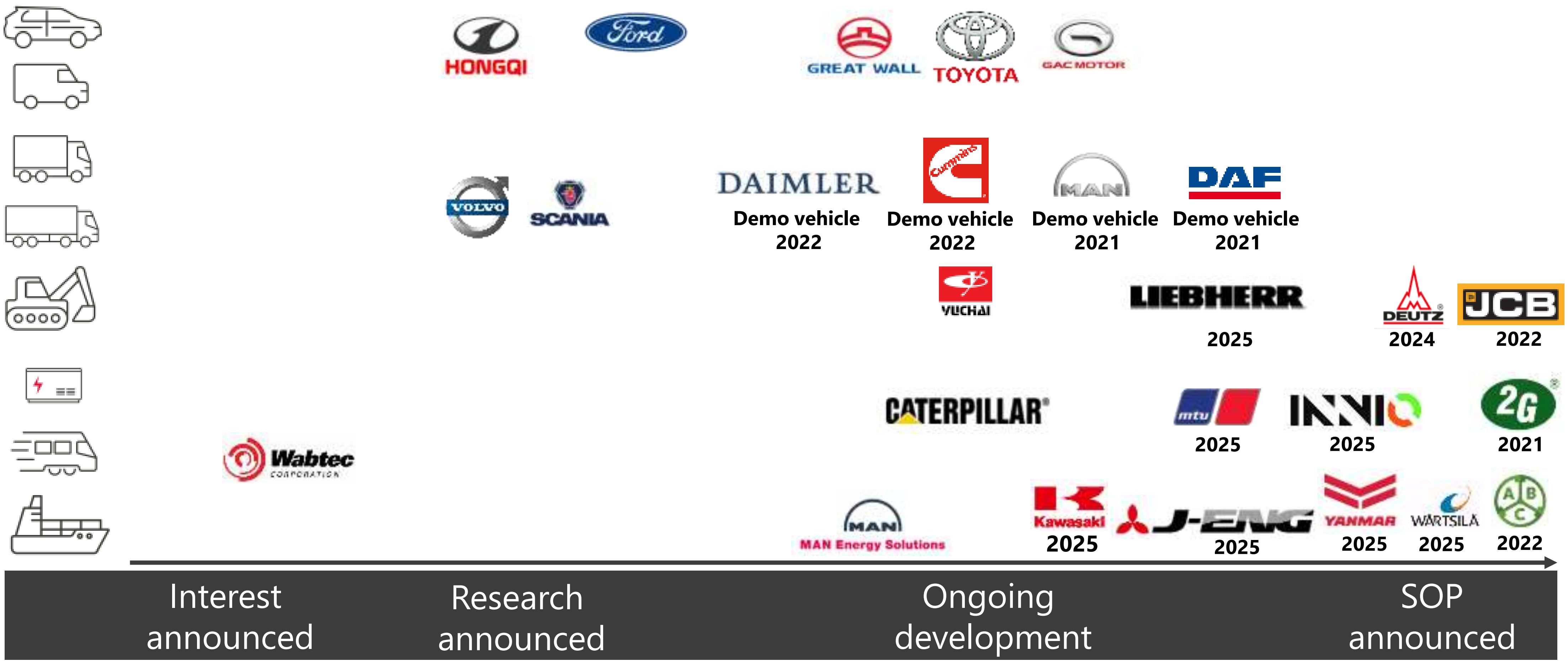
Application					
Passenger car & LCV	◔	◔	○	◑	○
Medium- & heavy-duty CV (UD)	◔	◔	◔	◔	◔
Medium- & heavy-duty CV (RD, LH)	●	◑	◔	◑	◑
Construction	●	◑	◔	◔	◔
Agriculture	◕	◔	○	◔	◔
Power generators	◕	◑	◔	○	○
Rail	◑	○	◔	○	○
Marine	◔	◑	◔	○	○

MAIN DRIVERS

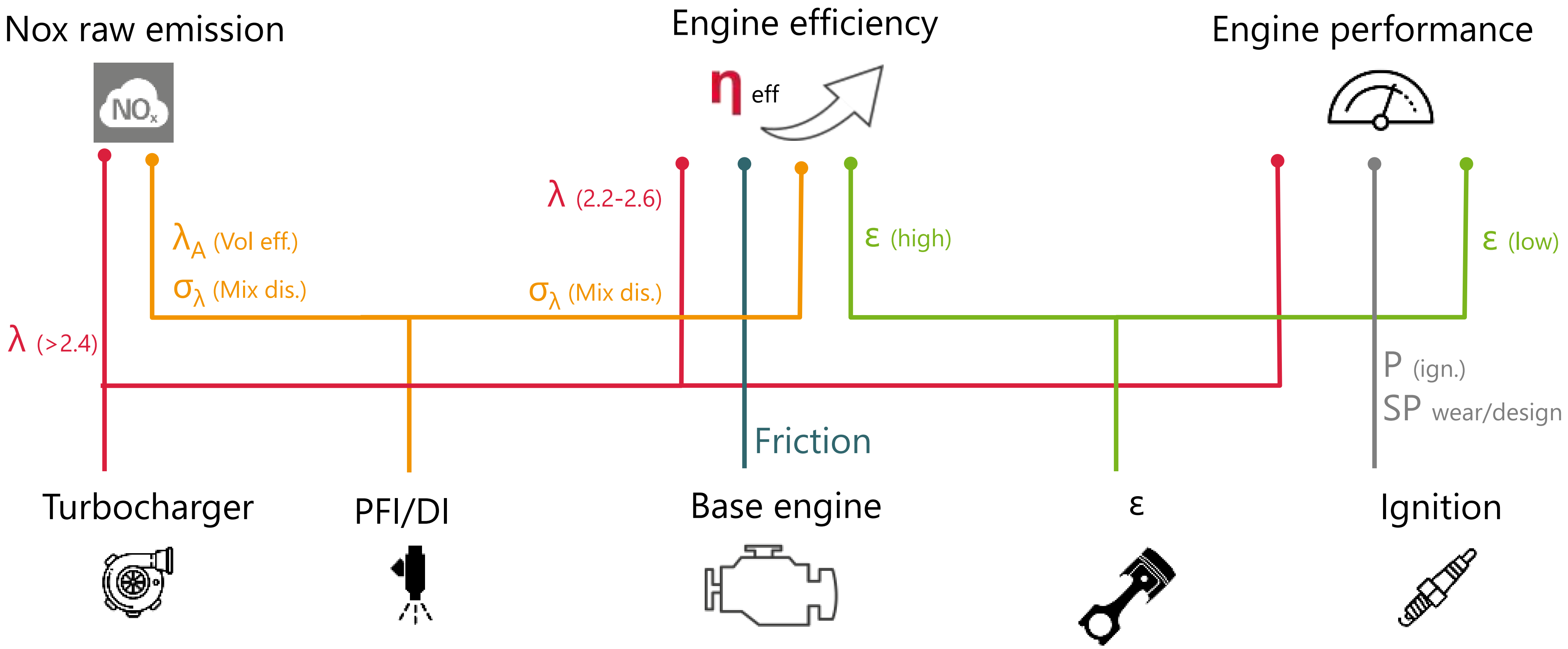
- MD/HD market in Europe forcing the development of hardware (esp. Direct Injection system)
- Hardware can be used in other classes as well and makes business case attractive
- Certain applications see major drawbacks for fuel cell
  - OFFROAD
  - AGRICULTURE
- For larger bore size dedicated injectors might be developed at a later timing but PFI solutions available soon

Publicly announced interest and investment in H_2-Engine development is now growing strongly amongst on-and off-highway industry players

FEV



Three main output parameters performance, emissions and efficiency are mainly influenced by five major components



SP: spark plug, PFI: Port fuel injection, DI: Direct injection, AFR: Air fuel ratio, Mix dis.: mixture distribution, Vol. eff.: Volumetric efficiency

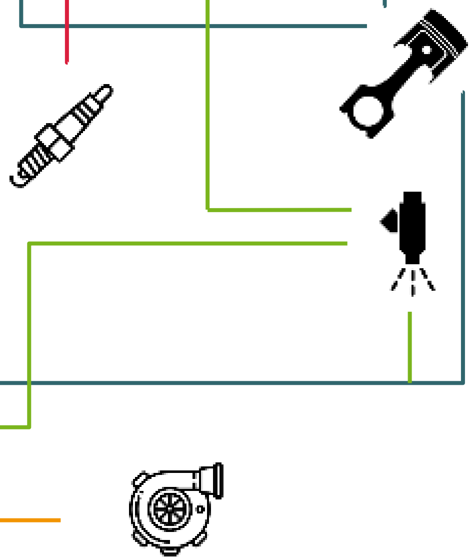
DRAFT

What are the difficulties for H2 ICE engine development regarding performance (BMEP/BTE) reachable and components availability

HYDROGEN COMBUSTION ENGINE – OUTLOOK

BMEP level of today´s engine can be improved by

- Avoiding preignition at high BMEP level
  - Hot spot induced pre ignition
    - Update design to create well distributed temperature level on cylinder head and piston
    - Improve mixture homogeneity to avoid rich zones
    - Use optimized spark plug design
  - Lube oil induced preignition
    - Update piston ring design and lubrication composition
- Crank Case Ventilation
  - Increasing content of H2 in crankcase
    - Install active ventilation of crankcase system
- Ignition system
  - Spark occurrence on unwanted timing
    - Redesign electrical setup of standard ignition system
  - Required ignition energy
    - Use optimized spark plug design
    - Increase supplied ignition energy
- Improved mixture homogeneity
  - Higher injection pressure
    - Only possible if liquid hydrogen is stored onboard
- Increased air fuel ratio



Source: FEV

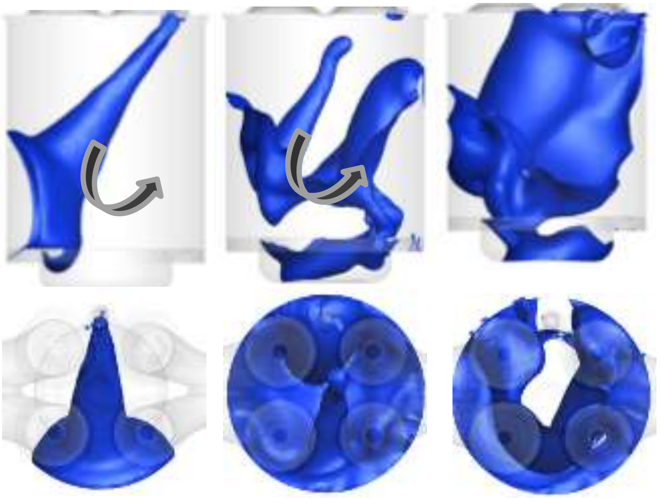
H_2-ICE Development Methodologies and existing Production Infrastructure allow fast Market Introduction of H_2 ICE, several SOP Developments ongoing

SELECTED KEY DEVELOPMENT TOPICS IN H_2 ICE DEVELOPMENT ON THE WAY TO SOP

COMBUSTION SYSTEM

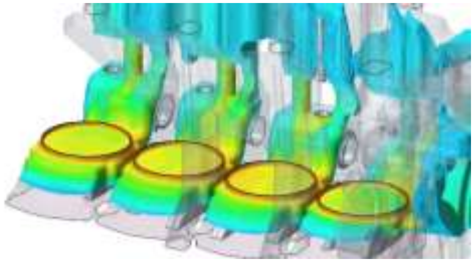
- Good mixture homogeneity despite late direct injection needs to be ensured

550° CA 570° CA 590° CA

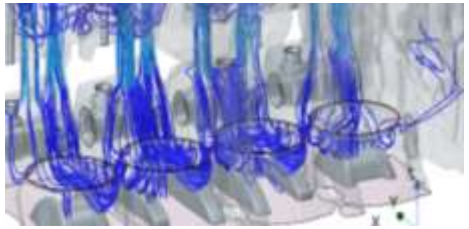


CRANKCASE VENTILATION

- Explosive mixture to be avoided



H_2 concentration



H_2 gas flow

DURABILITY

- Fuel & Injection system and component durability needs to be developed

Public announcements on fuel cell partnerships for commercial vehicle applications

FEV

Hyzon Motors Delivers 29 Hydrogen Fuel Cell Electric Heavy Duty Trucks to Reduce Carbon Emissions in the Steel Industry

By FuelCellsWorks | December 8, 2021 | 2 min read (478 words)

Solaris fuel cell bus: the Urbino 12 hydrogen takes the road

Solaris Urbino 12 hydrogen. T... its zero-emission bus portfo... the fuel cell module by Ballar... eir hydrogen Urbino at the...

May 2021 by Editorial Staff

Sep 28, 2020

Ballard and MAHLE to Collaborate on Fuel Cell Propulsion Systems for Heavy- and Medium-Duty Trucks

29. APRIL 2021

Daimler Truck AG und Volvo Group bekennen sich klar zur wasserstoffbasierten Brennstoffzelle – Start des neuen Joint Ventures cellcentric

VW: Audi Fuel Cells will First be Introduced in Larger Vehicles

By FuelCellsWorks | February 8, 2020 | 2 min read (304 words)

Sep 15, 2021 - 04:06 pm

Iveco & Nikola getting closer to truck plant in Germany

CNH INDUSTRIAL | ELECTRIC TRUCKS | FCEV | FUEL CELL | GERMANY | HYDROGEN | IVECO | NIKOLA MOTOR | NIKOLA TRE | S-WAY

Brussels, 02 May 2022

Toyota Motor Europe to supply Toyota Fuel Cell Module to second bus OEM

Toyota Motor Europe will supply its fuel cell technology for Daimler Buses' new city bus, the Mercedes-Benz eCitaro Range Extender

HYUNDAI: 1.600 H2 Xcient trucks in Switzerland

Planned / Rigid truck

share

Toyota and Hino to Jointly Develop Class 8 Fuel Cell Electric Truck for North America

Hydrogen-Powered Truck Will Offer Heavy-Duty Capability and Clean Emissions

News Release, Management, Environment, Hydrogen, Innovation, CASE, Electric, Region

Vila Nova de Gaia, 09 July 2021

Toyota co-brands with CaetanoBus

20.06.2018 Press release

Hyundai Motor Group and Audi partner in fuel cell technology

...TATION • EDITORS' PICK

Nikola Partners With Bosch On Fuel Cell Supp... Deal For Hydr...

AUTOS

Toyota, Paccar team up on clean hydrogen trucks for polluted LA ports

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Paul A. Eisenstein

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CUMMINS FUEL CELLS TO POWER SCANIA'S FUEL CELL ELECTRIC TRUCKS

Apr 28, 2022 • by Katherine de Guia, Communications Specialist - New Power

Bavarian fleet (Bayernflotte)

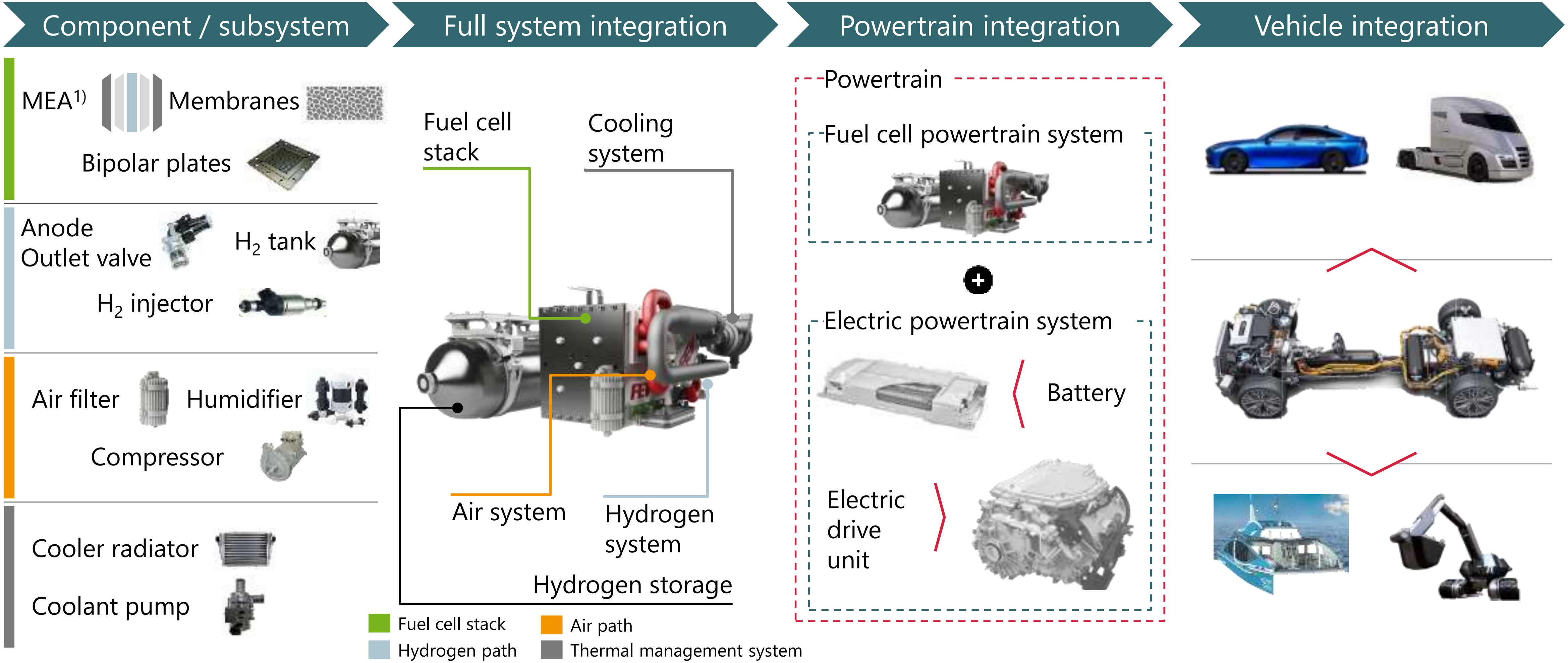
This also includes a further build-up of competence in the field of hydrogen technology. The state of Bavaria is funding the "Bavarian Fleet" research project as part of its own hydrogen strategy and is thus accelerating the development of competence. The funding amounts to 8.5 million euros.

In the Bayernflotte project, MAN is developing a fuel cell truck together with its industrial partners Bosch, Faurecia and ZF. This will be delivered to five customers in mid-2024. The companies BayWa, DB Schenker, GRESS Spedition, Rhenus Logistics and Spedition

The fuel cell component value chain can be divided into 4 major categories; complexity and required capabilities increase upstream

PEM FUEL CELL ELECTRIC VEHICLE COMPONENT VALUE CHAIN

» NON-EXHAUSTIVE



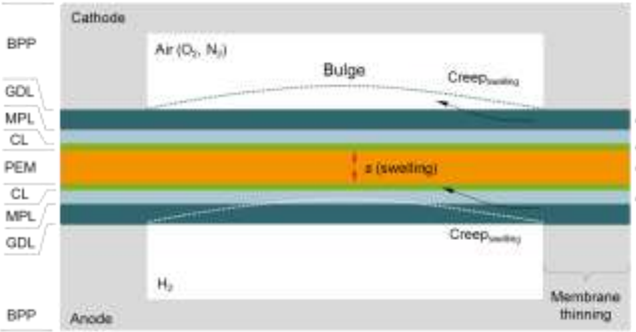
1) Membrane Electrode Assemblies
Source: FEV

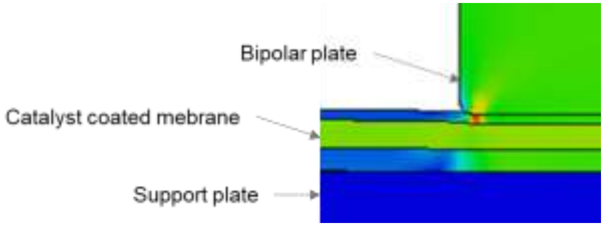
Fuel Cell development focusses on getting the systems ready for the first truck applications with more innovation to come afterwards

SELECTED KEY DEVELOPMENT TOPICS IN FC DEVELOPMENT ON THE WAY TO MATURITY FOR FURTHER APPLICATIONS

DURABILITY

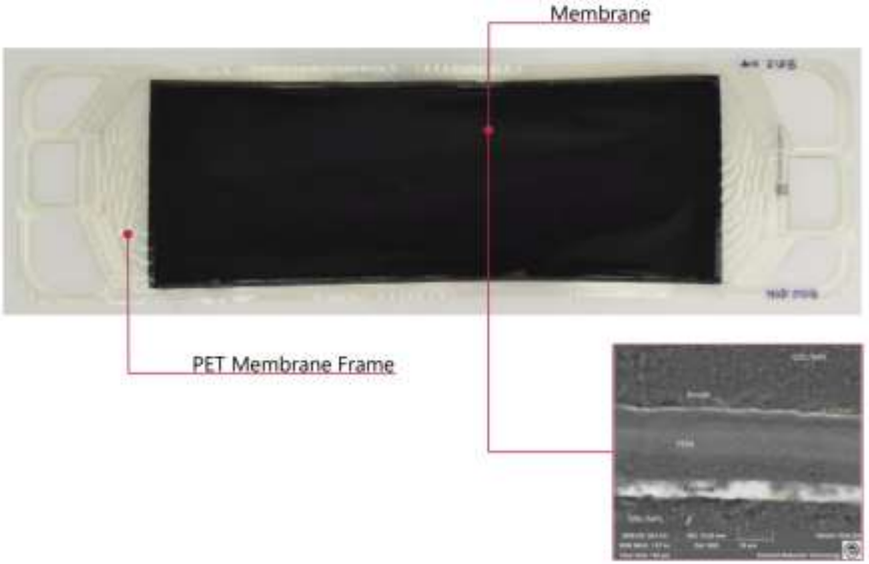
- Optimzed design and operation strategy
- Ageing prediction in control units





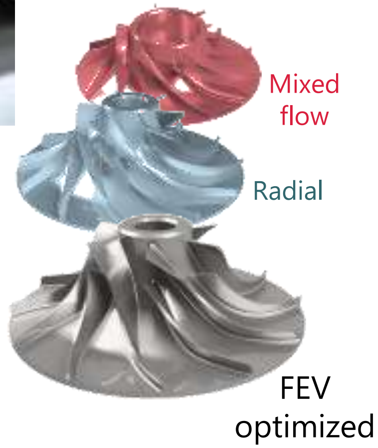
COST OPTIMIZATION

- Reduction of precious metal



POWER DENSITY

- Technologies for compact stacks
- Advanced & tailored boosting systems



Reference Project: DAKAR RACE !
Fuel Cell for Battery Electric Vehicles (2021)

FEV

FEV & GCK TO DEVELOP
FUEL CELL RALLY CAR

Highlights

Development of complete fuel cell system >200kW :

- Design
- development
- Testing
- Integration

Fuel Cell in specific environment :

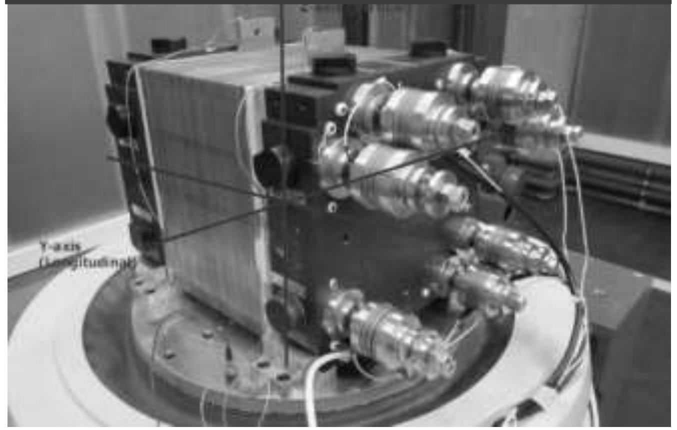
- Dust
- Race constraints
- Shocks
- Environmental conditions

Test management and validation for fuel cell systems

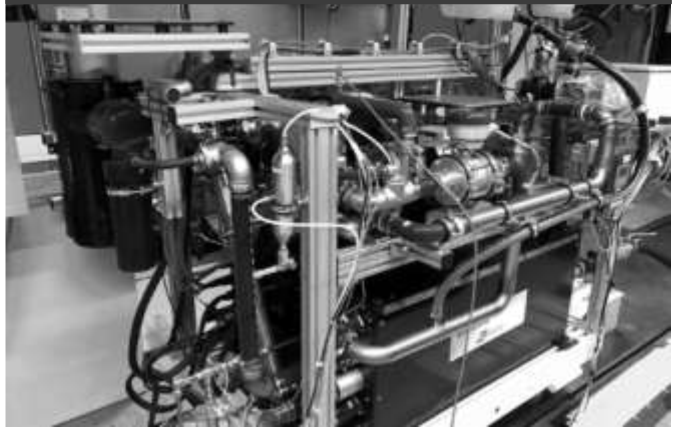
VERIFICATION AND VALIDATION

Design Validation Plan

Mechanical Testing



System Testing



Environmental Testing

Durability Testing

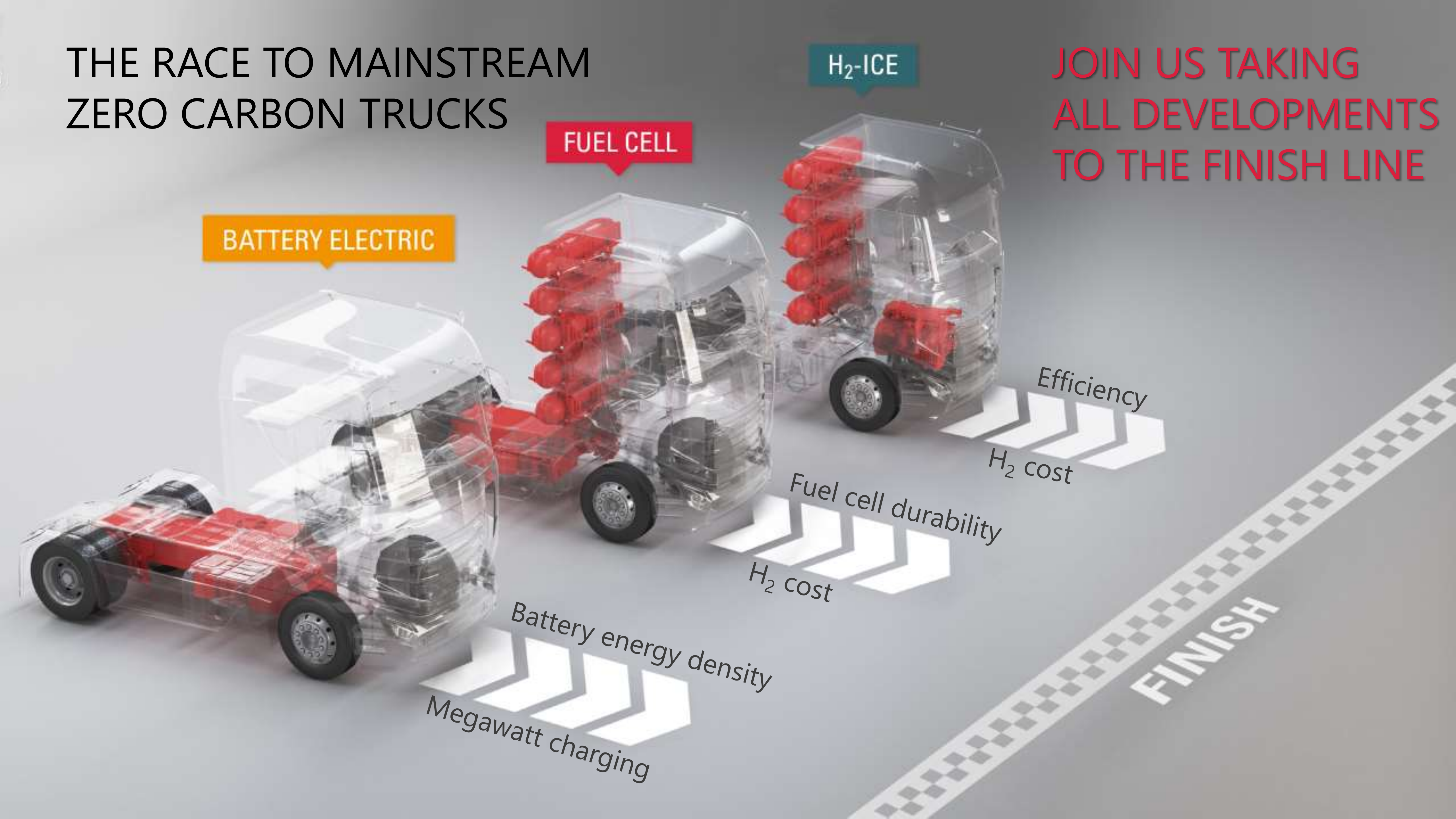
Certification support

DV Testing
Validation of mechanical design: 350 kN Shaker with climate hood

Source: IMV Corporation

KEY PERFORMANCE

- System specifications:
  - Frequency range: 0-2000 Hz
  - Rated force: 350 kN (sine); 315 kN (random rms); 700 kN (shock)
  - Max. acceleration: 1000 m/s² (sine); 700 m/s² (random rms); 2000 m/s² (shock)
  - Max. velocity: 2 m/s (sine); 3.5 m/s (shock, peak)
  - Max. displacement: 76.2 $mm_{peak\text{-}peak}$ (sine); 94 76.2 $mm_{peak\text{-}peak}$ (max. travel)
  - Max. load: 3000 kg


THE RACE TO MAINSTREAM
ZERO CARBON TRUCKS
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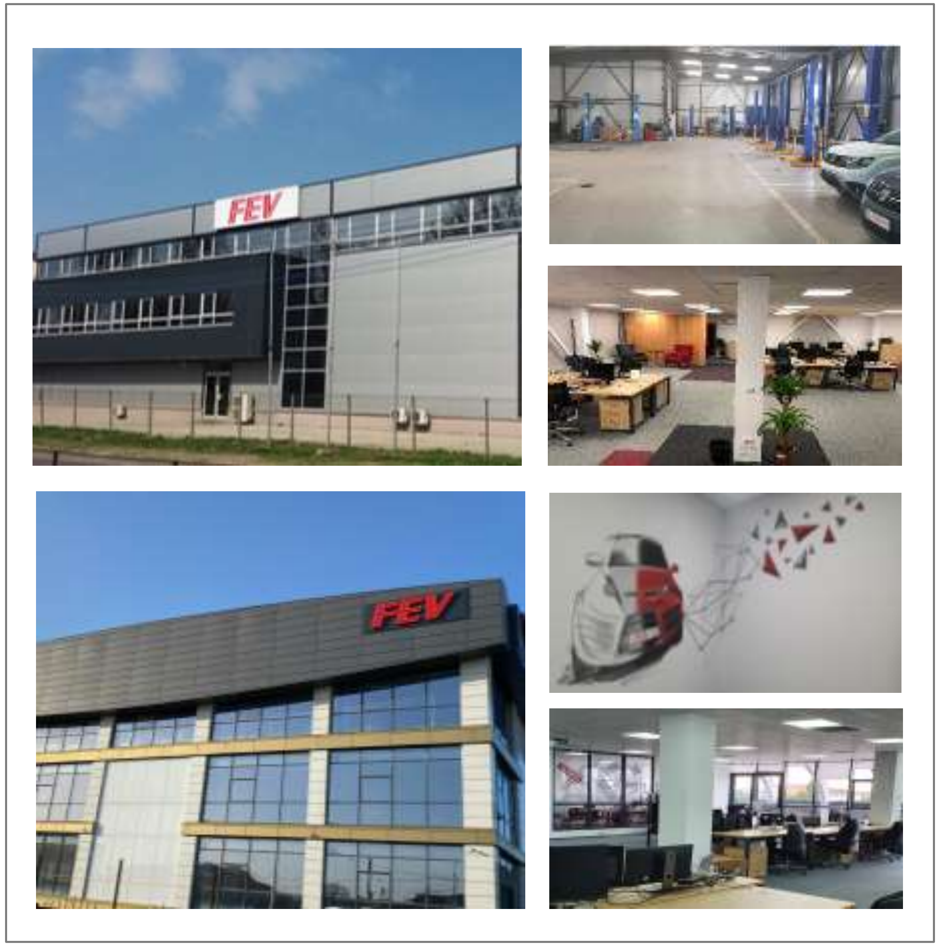
ALL DEVELOPMENTS
TO THE FINISH LINE
BATTERY ELECTRIC
FUEL CELL
H_2-ICE
Efficiency
H_2 cost
Fuel cell durability
H_2 cost
Battery energy density
Megawatt charging
FINISH

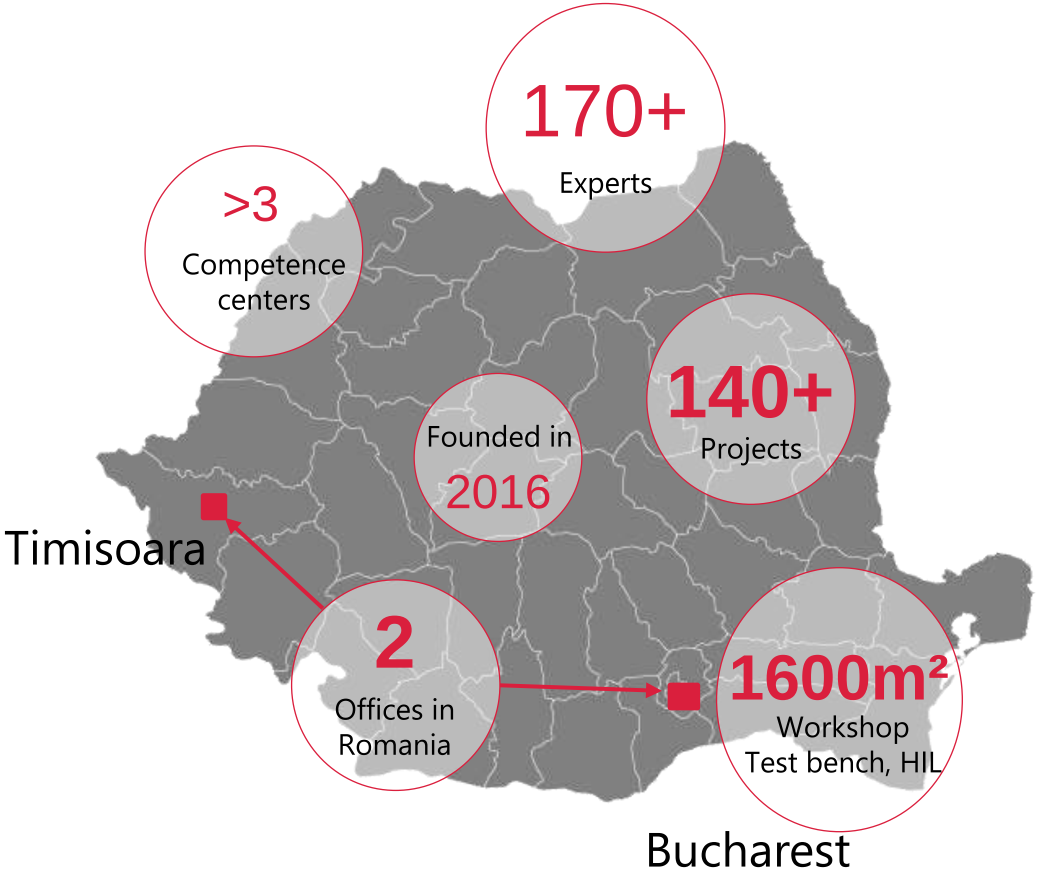
FEV Romania - Company Facts

FEV

INTRODUCTION



Global Reach – One face to the customer



FEV ROMANIA PORTFOLIO

YOUR engineering partner

From Requirement elicitation

To SOP

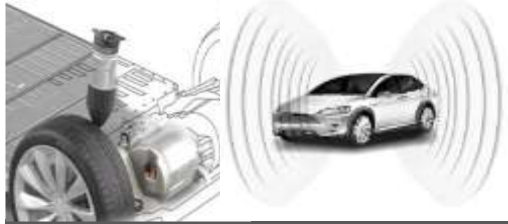
Basic Software & AUTOSAR

Functional Safety


Web & App Development


Electronics and Electrification


Model Based Development


HW Development and EMC


Fleet Validation


Powertrain Calibration


PVE

THE RACE TO MAINSTREAM ZERO CARBON TRUCKS

JOIN US TAKING ALL DEVELOPMENTS TO THE FINISH LINE