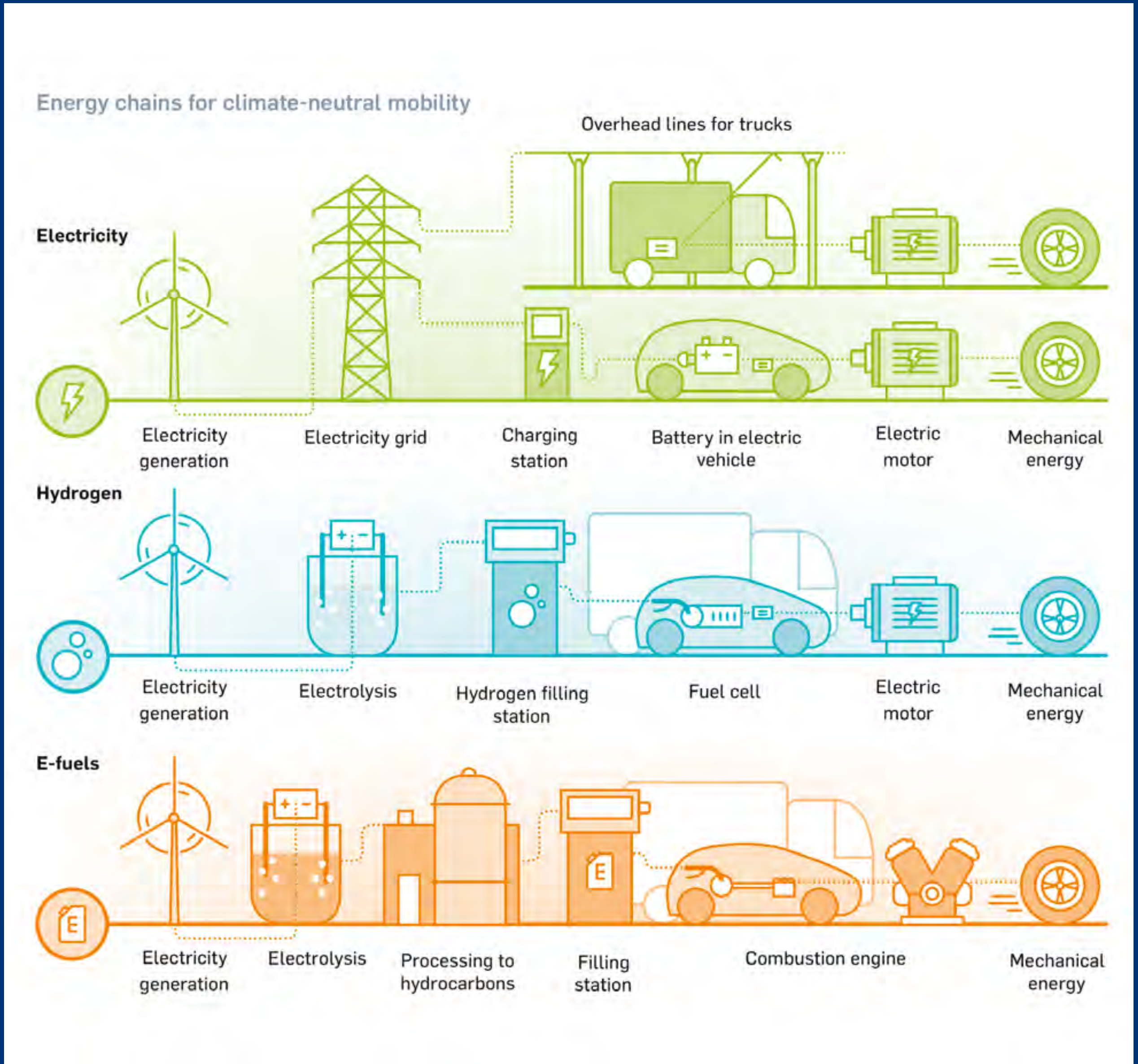

FVV Working Group Future Fuels
» Climate-neutral Driving in 2050 «

Options for the Complete Defossilization of the Transport Sector

7th International Conference on Fuel Science

Aachen, 13. May 2019

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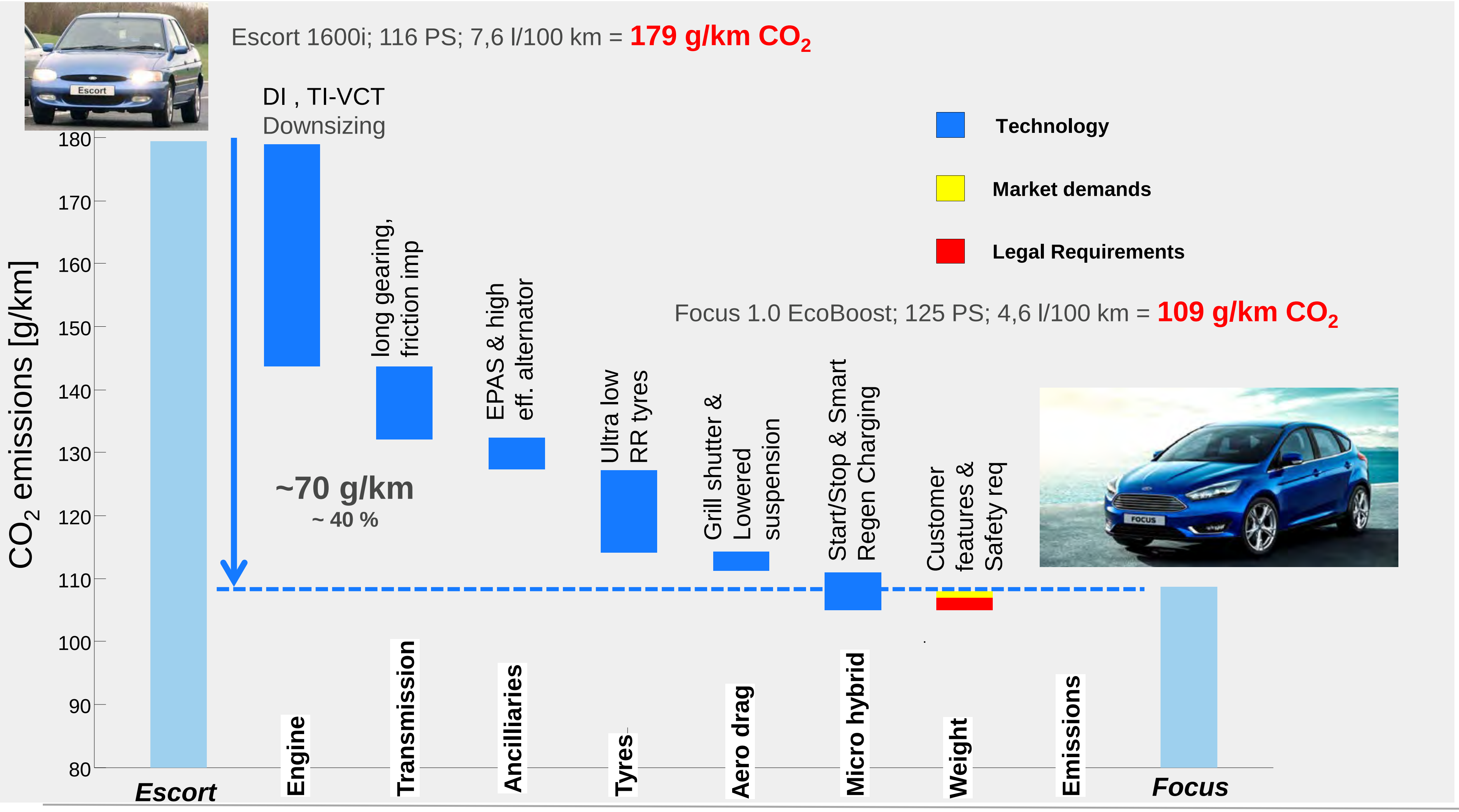
MOTIVATION

Ford Data (not content of FVV study)

CO_2 emission reductions in recent decades (NEDC*)

*NEDC: New European Drive Cycle



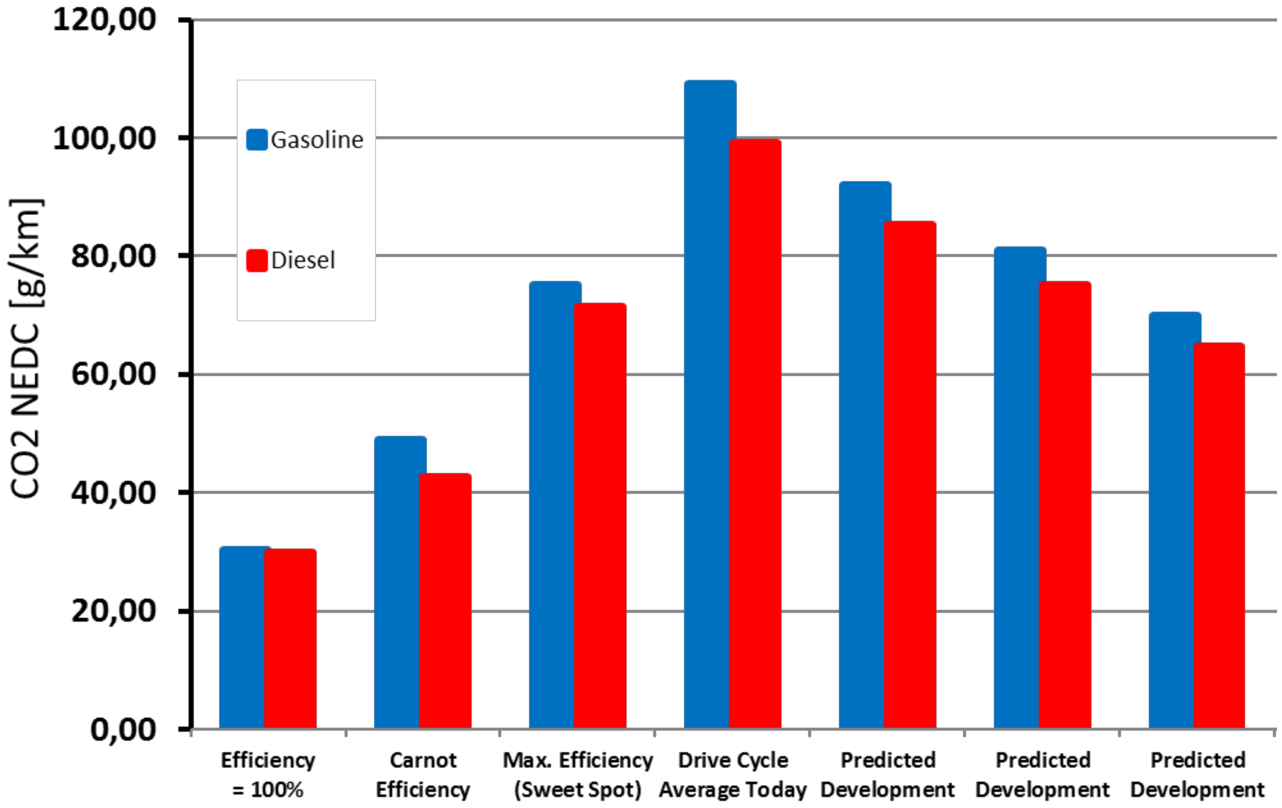
- **EU TtW CO_2 emissions reduced by ~ 40% within the last 3 decades**
- **Safety and comfort enhanced**
- **CO, NOx, HC emissions reduced and performance increased**

MOTIVATION

Ford Data (not content of FVV study)

CO_2 reduction potential with gasoline/diesel (NEDC*)

*NEDC: New European Drive Cycle



Typical C-Car: 1360kg, 1.3 kWh for NEDC

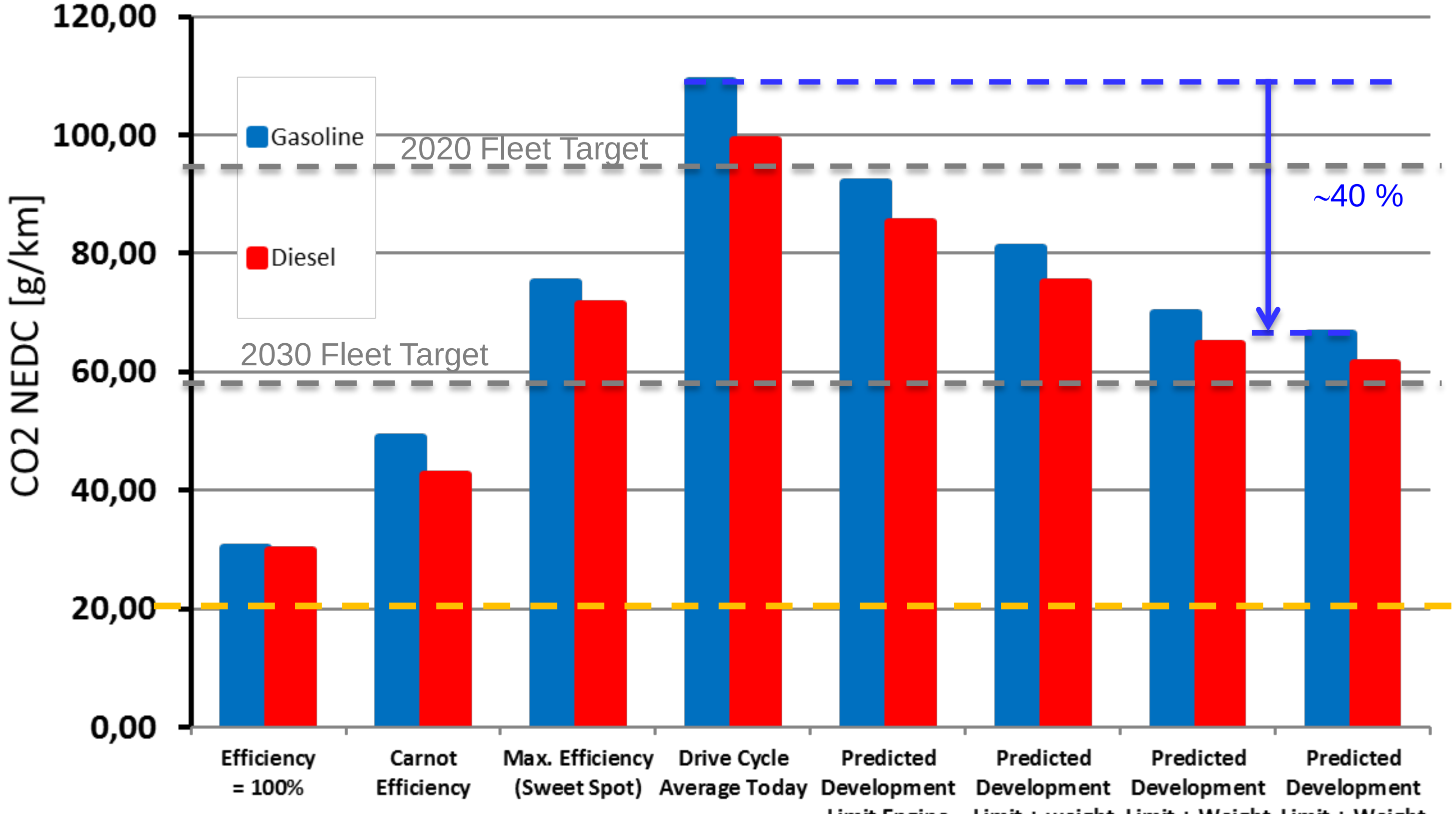
BEV: Battery Electric Vehicle
HEV: Hybrid BEV

MHEV: Mild HEV
FHEV: Full HEV

Ford Data (not content of FVV study)

CO_2 reduction potential with gasoline/diesel (NEDC*)

*NEDC: New European Drive Cycle



Typical C-Car:
1360kg, 1.3 kWh
for NEDC

BEV: Battery Electric Vehicle
HEV: Hybrid BEV

MHEV: Mild HEV
FHEV: Full HEV

For comparison:

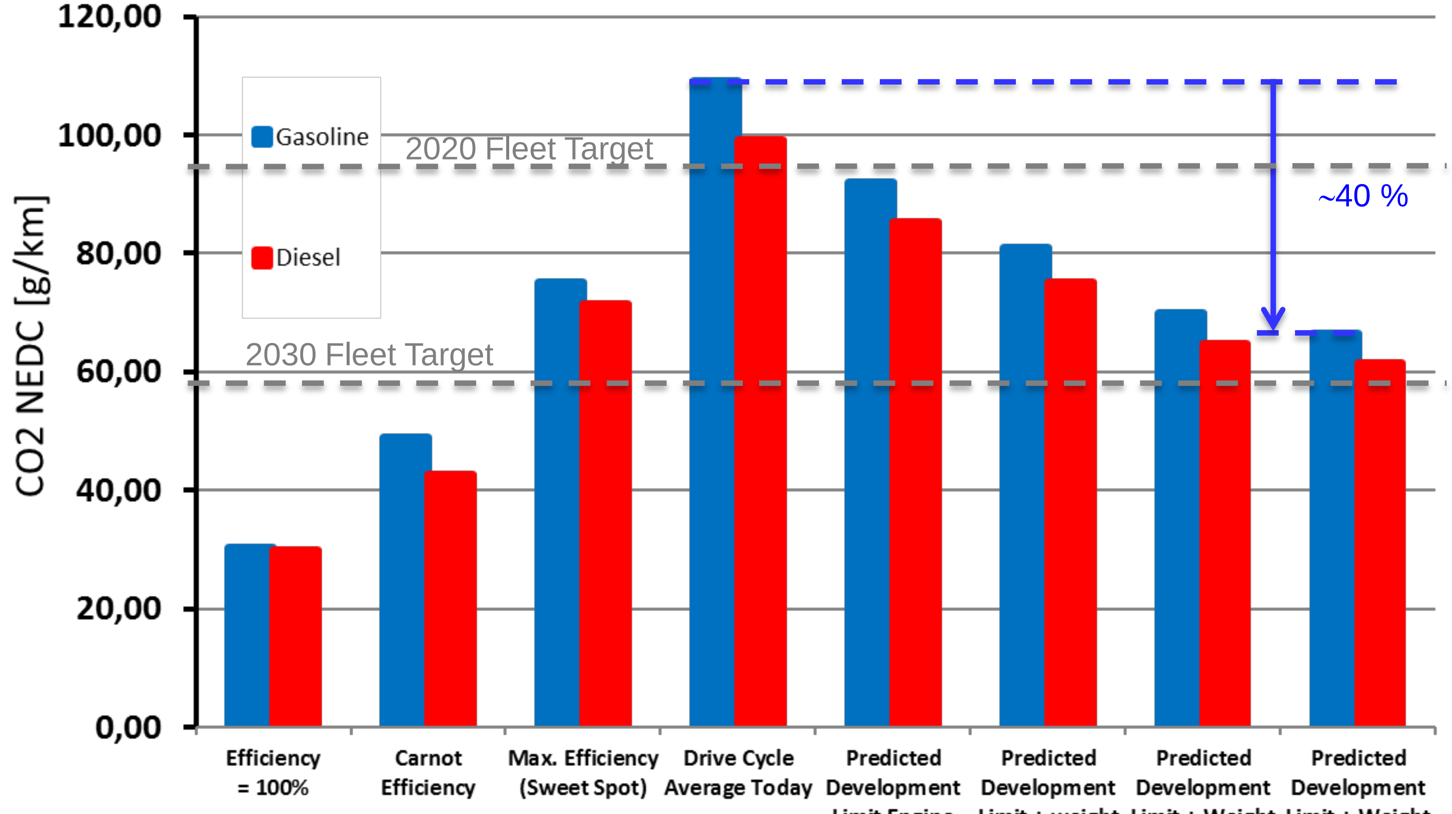
marathon runner
(75 kg man, 4:15 finisher)
~ 20 g CO_2/km
(additional to basal metabolic rate)

MOTIVATION

Ford Data (not content of FVV study)

CO_2 reduction potential with gasoline/diesel (NEDC*)

*NEDC: New European Drive Cycle



Typical C-Car: 1360kg, 1.3 kWh for NEDC

BEV: Battery Electric Vehicle
FCEV: Fuel Cell EV
HEV: Hybrid BEV

PHEV: Plug-in HEV
MHEV: Mild HEV
FHEV: Full HEV

- **EU TtW CO_2 targets (fleet):**
  - 2020: 95 g/km
  - 2030: -37.5% (~ 59 g/km, NEDC)
- **Standard C-segment vehicle with max. technology content misses 2030 target when operated with gasoline / diesel fuels.**
- **Further TtW (!) CO_2 reduction only possible via PHEV, BEV, FCEV → technological, economical limits !**
- New Cycle "WLTP"** → increases CO_2
- Customer demands for SUVs, larger cars and higher gasoline share intensify CO_2 challenge
- **Long-term (2050) EU/ German overall CO_2 reduction targets (80% / 95 %) impossible to achieve with fossil gasoline/diesel fuels.**
- **WtW option:** complete defossilisation with e-fuels (PtX) based on renewable electricity (wind/solar).

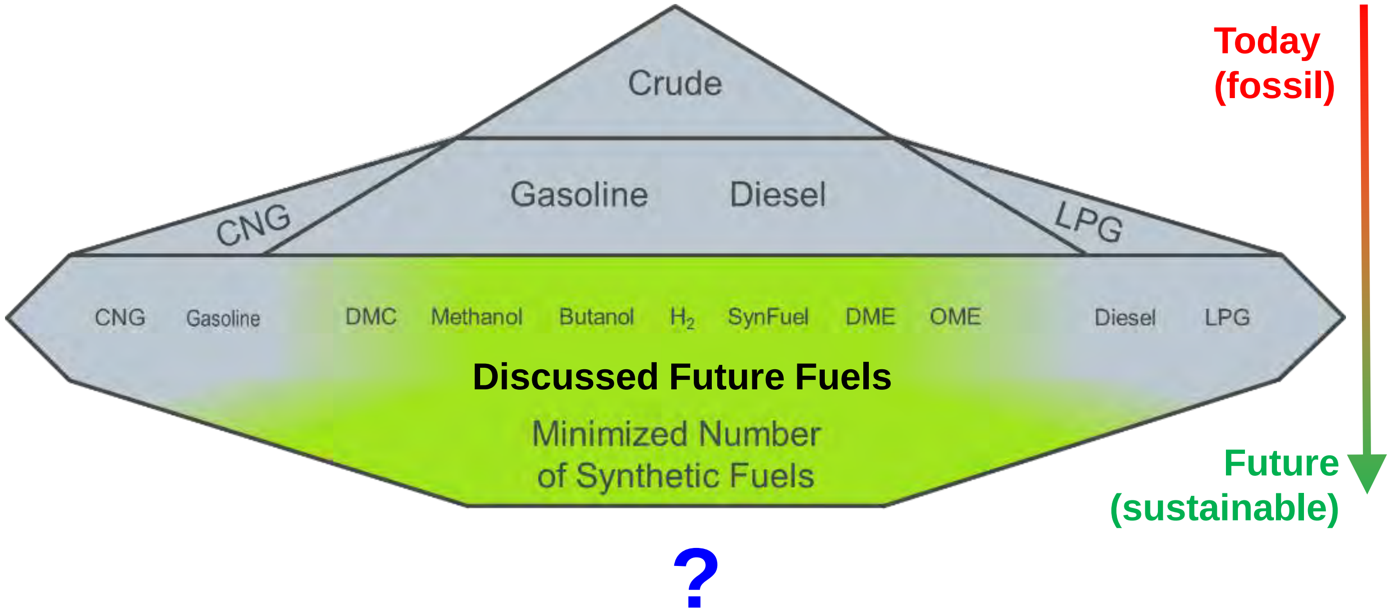
** WLTP: Worldwide harmonized Light vehicles Test Procedure

Overall 2050 Green-House-Gas (GHG) Reduction Targets

- **EU 80 %**
- **Germany 95 %**

→ Transport Sector needs nearly to reduce Well-to-Wheel (WtW) GHG emissions by 100%

- **How much powertrain and fuel diversification can we afford?**
- **What is the most efficient way to achieve those targets?**

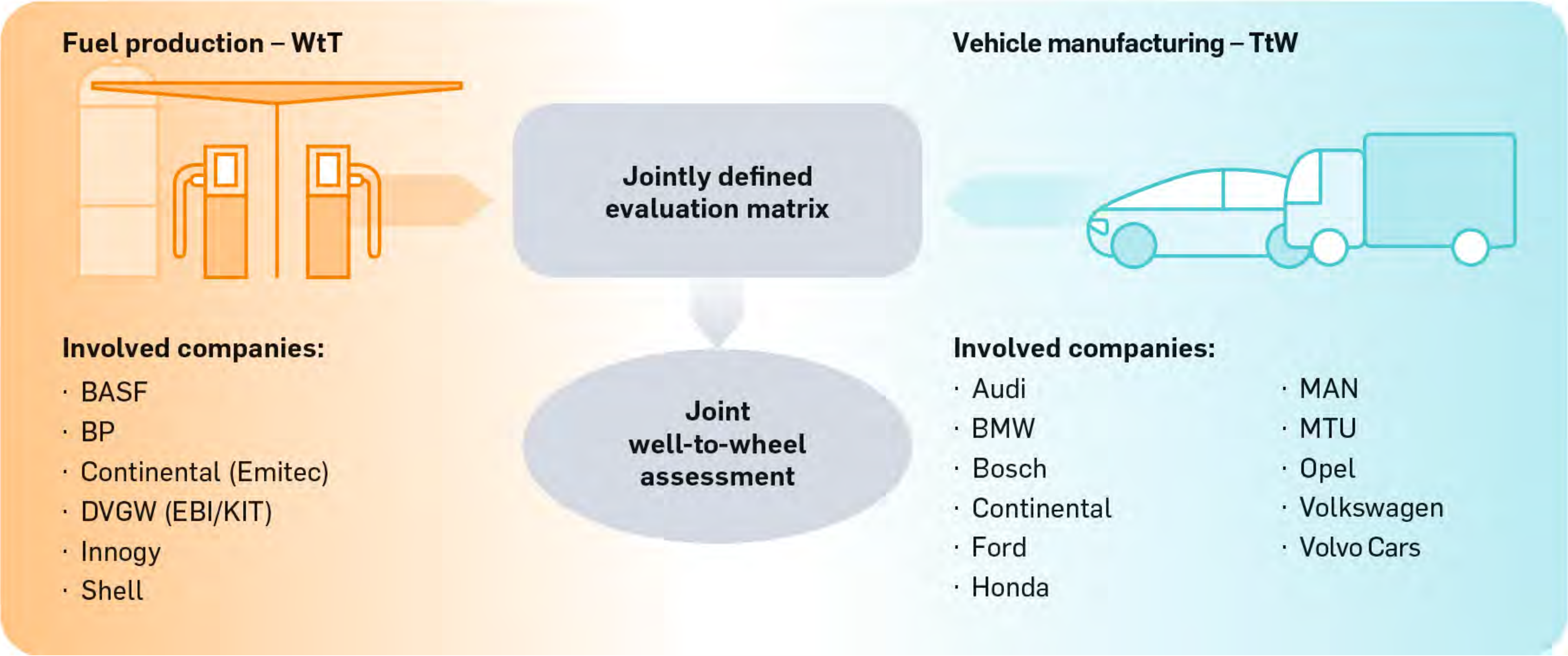


CONTENT

- Approach
- Assumptions
- Results
    - Energy Demand
    - Costs
    - Market Introduction Potential (Assessment)
- Summary

APPROACH “JOINT POSITION”: WORKING GROUP OF WTT & TTW STAKEHOLDERS

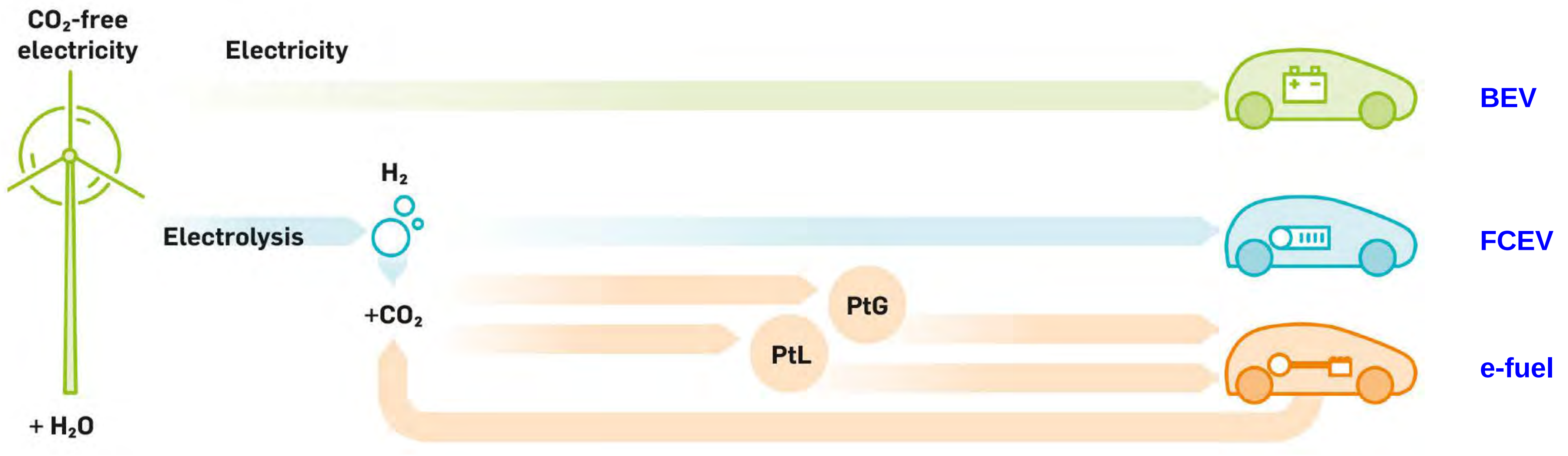
Members of the FVV Working Group



Task: comparison of future scenarios, enabling 100% CO_2 reduction for the road transport sector

APPROACH „FACTS & BASIC ASSUMPTIONS“ FOR 100 % CO_2 REDUCTION

- **Biofuels limited** in quantity, therefore **not suitable for 100% sustainable mobility**
- **100% sustainable mobility in 2050 possible** with regenerative electricity (→ see FVV/LBST)
- Assumption: in 2050+ exclusively regenerative electricity – 100% wind and solar – available
- Remaining mobility concepts: **battery electric vehicles (BEV)**, **fuel cell electric vehicles (FCEV)** and (hybridized) vehicles with internal **combustion engines** operated exclusively with **e-fuels (PtX)**



APPROACH: 100% SCENARIOS*

Fuel	Powertrain	Electrical Power Origin	Energy Storage	Energy Distribution
Electricity	BEV (Benchmark)	**Permanent** electrical power supply Low cost scenario: **Germany 2030** High cost scenario: **Germany 2017**	**20% energy buffer** (Pt-CH4) in electrical power supply	Electrical power grid
E-H_2 (compressed) (local production)	FCEV			Electrical power grid
E-H_2 (compressed) (central production)	FCEV	**Intermittent** electrical power supply, Low cost scenario: **MENA 2030** High cost scenario: **Germany 2017**	Fuel storage in PtX-Production	Local liquefaction (for CH_4 and H_2), ship (MENA) + truck (MENA/Germany)
E-Methan (compressed)	SI engine (λ=1)			
E-Methan Compressed & kryogen (> 3.5t)	SI engine (λ=1) CI HPDI (>3.5t)			
E-Methanol (M100)	SI engine (λ=1)			
E-Gasoline FT	**SI engine (λ=1)**			
E-Propane / Butane (LPG) FT	**SI engine (λ=1)**			
E-Diesel FT	**CI Engine**			
E-OME	CI Engine			
E-DME	CI Engine			

***100% Scenarios → For each scenario all 45 Mio vehicles use the same powertrain / fuel.**

(Even if not realistic, "100% scenarios" are considered as an effective tool for a simple technology comparison.)

*MENA = Middle East North Africa

CONTENT

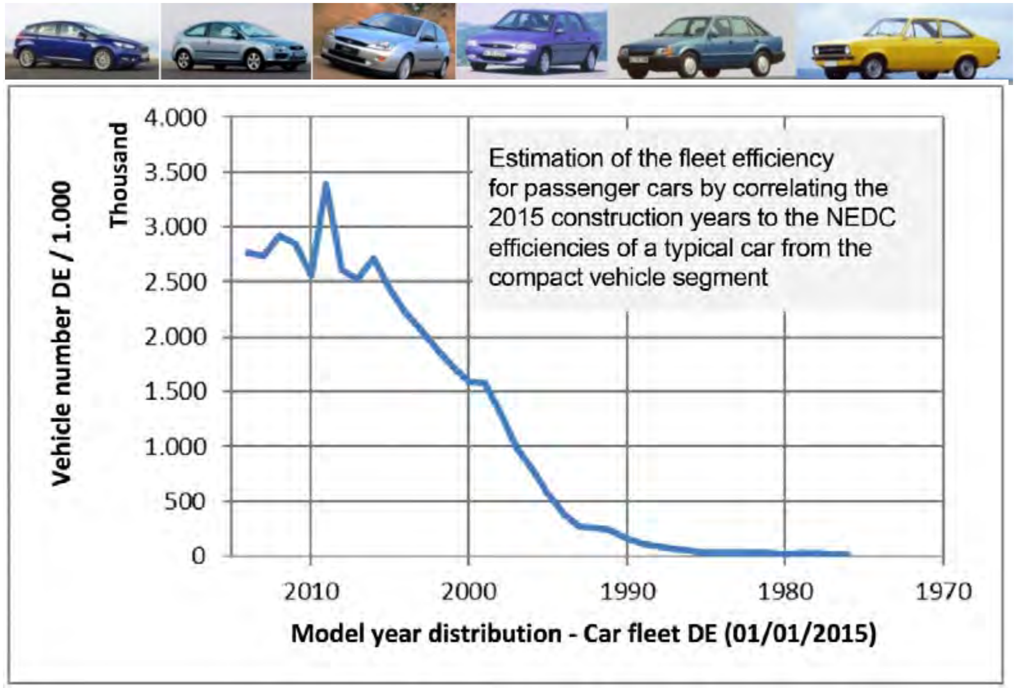
- Approach
- Assumptions
- Results
  - Energy Demand
  - Mobility Costs
  - CO_2 Abatement Costs
  - Investment Costs (Selected Scenarios)
- Parameter Variation
  - CO_2 Available
  - Hybridization
  - cold-season Operation (Incl. Cabin Heating, Cold Start)
- Summary

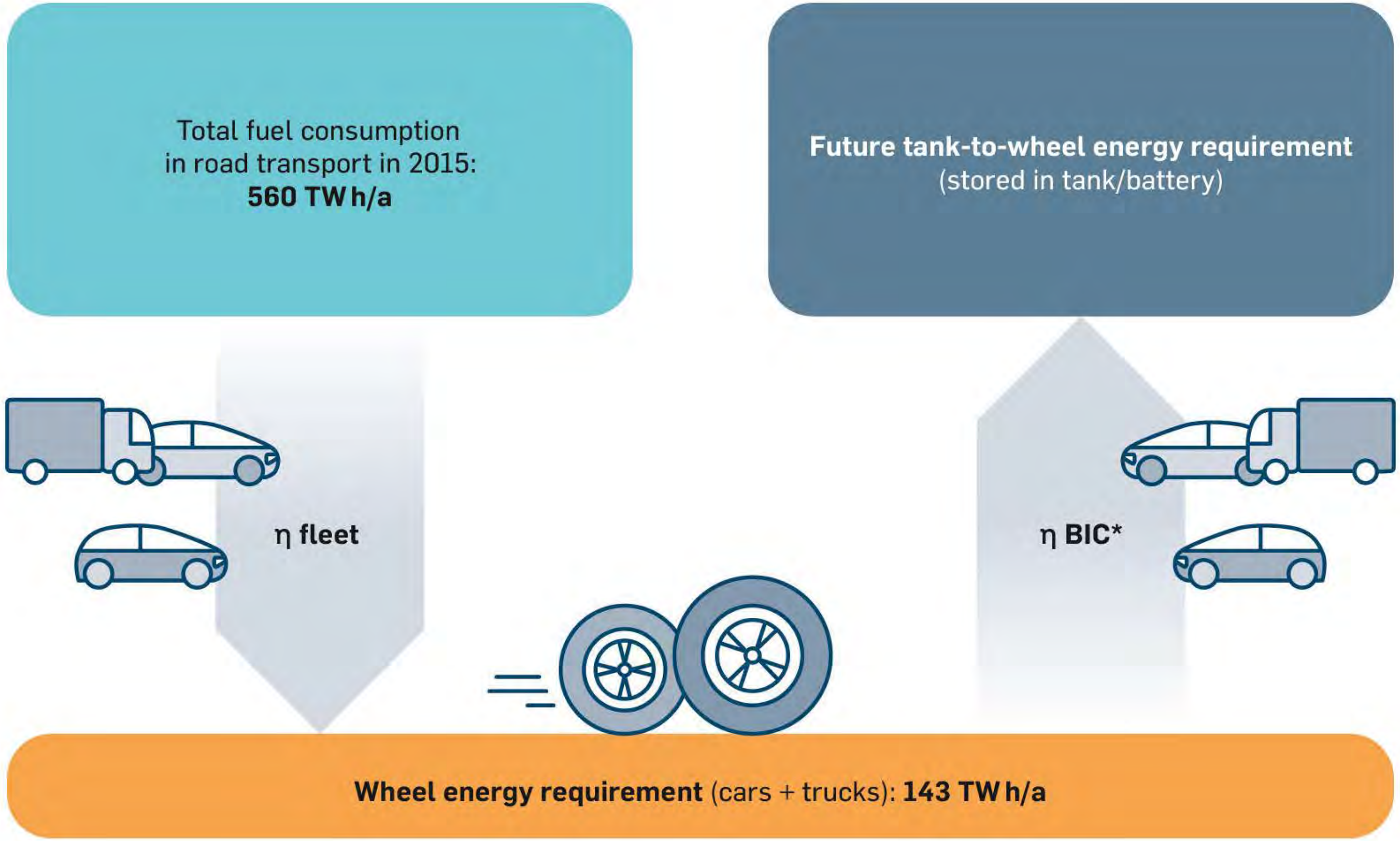
ASSUMPTIONS: ESTIMATION OF "FUTURE ENERGY DEMAND"

Calculation via „Wheel Energy Demand". → Calculation basis: total fuel consumed in 2015

Efficiency assumptions for existing fleet:

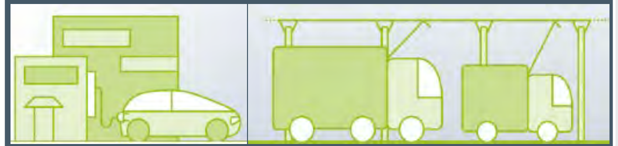
- LD Fleet Efficiency 23%
- HD Fleet Efficiency 35%



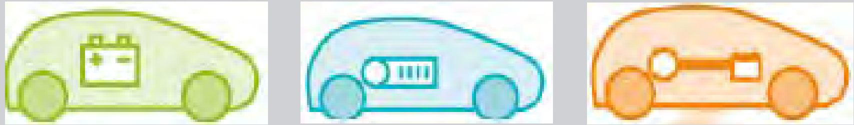


- Future LD fleet efficiency based on BIC (Best-in-Class) MY'17 C-Cars
- Future HD efficiencies assessed by expert group

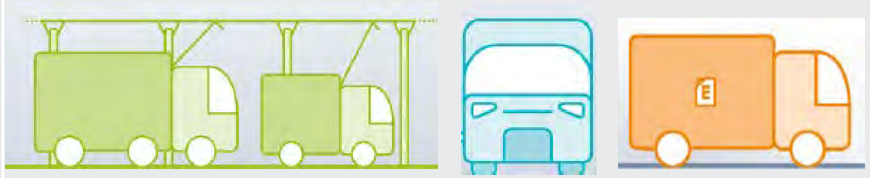
ASSUMPTIONS: EVALUATION MATRIX – INPUT DATA – INFRASTRUCTURE COSTS

	Min Cost Scenario	Max Cost Scenario
Depreciation Investment Infrastructure	40 years, ROI 6 %, Interest Rate 4 %, Maintenance 5 %, Residual Value 0	
Investment Infrastructure    	Number of Filling Stations (PtX, H2): - LD: 5.000 Filling Stations (40.000 Extraction Points) - HD: 6.000 Extraction Points LD - BEV Charging Point: - 80.000 Fast Charging Points - 12,5 Mio. Home Charging Points - 5 Mio. Charging Points at Work HD Truck: Trolley System 4.000 km Assumption **No** extension of electrical power grid required Grid connection local H2 electrolysis: **0 bil. €**	Number of Filling Stations (PtX, H2): - LD: 10.000 Filling Stations (80.000 Extraction Points) - HD: 12.000 Extraction Points LD - BEV Charging Point: - 160.000 Fast Charging Points - 25 Mio. Home Charging Points - 10 Mio. Charging Points at Work HD Truck: Trolley System 13.000 km Assumption extension costs electrical power grid**: 77 bil. € + 21 bil.** (trolley connection) Grid connection local H2 electrolysis: **90 bil. €**

ASSUMPTIONS: EVALUATION MATRIX – INPUT DATA – VEHICLE COSTS LD

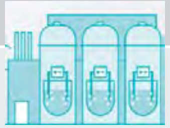
	Min Cost Scenario	Max Cost Scenario
LD* Vehicle Costs **Basis:** representative **gasoline vehicle C-segment**: **base price 20.000 €,** depreciation according to ADAC (15.000km/a, 4 years): 300 €/month (Assumption: depreciation of on-costs direct proportional to depreciation of base price)	Assumption for 2050: „Cost Parity** of BEV and FCEV to diesel vehicle“ • all **SI concepts**: no on-cost vs. gasoline vehicle • all **CI concepts +2.400 €** vs. SI (→ 2018 price lists OEMs***). • **BEV500 und FCV**: **+2.400 €** vs. SI BEV500: +2.400 € FCEV +2.400 € DME +2.400 € Diesel/OME +2.400 € Methane + 0 € Propane + 0 € Methanol + 0 €	On-cost based on **Roland Berger Auto-Oil Study** (2030) + price lists OEMs + retro fitter price lists (assumption: OME as Diesel, DME as Diesel + LPG tanks)  BEV500****: +11.300 € *(BEV400: + 9.500 €)* FCEV**** +12.500 € DME*** ***** +3.400 € *(Diesel + LPG tanks)* Diesel/OME*** +2.400 € Methane**** +1.800 € Propane***** +1.500 € Methanol****** + 300 €
**LD (Light Duty) passenger cars and delivery trucks up to 3.5t*	*** no technical basis, just a working group assumption* **** price list example: Opel Astra Edition: 1.4 Direct Injection Turbo 92 kW (125 PS): 21.645 – 21.845 € vs. 1.6 Diesel 81 kW (110 PS): 24.170 €*	***** Roland Berger Study* ****** Retrofit on-costs* ******* On-cost Flexi Fuel (E85) Ford Focus*

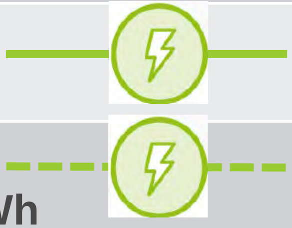
ASSUMPTIONS: EVALUATION MATRIX – INPUT DATA – VEHICLE COSTS MD/HD

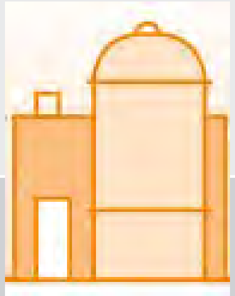
	Min Cost Scenario*	Max Cost Scenario*
MD/HD* Vehicle Costs Basis: 1 representative Trailer Truck as basis vehicle: Basis - Average „MAN TGS 18.440 FLS LX, EURO6; Scania R 450 LA Highline, EURO6; Volvo FH 460 Globetrotter, EURO6**“:** 90.400 €	**Reduced Price for FCV and BEV***** EV (hybrid trolley truck): **+ 51.978 €** FCV***: **+ 36.538 €** DME/Propane**** + 1.000 € Diesel/OME/Gasoline + 0 € Methane***** +14.000 € (λ 1) + 24.000 € (HDPI)	 EV (hybrid trolley truck): **+ 87.500 €** FCV: **+124.740 €** DME/Propane**** + 1.000 € Diesel/OME/Gasoline + 0 € Methane***** + 14.000 € (λ 1) + 24.000 € (HDPI)
**MD/HD (Mid Duty & Heavy Duty) trucks above 3.5t* ***Prices from „Lastauto & Omnibus Katalog 2017, S. 293 ff (DEKRA)“*	**** from: „Update DOE - Fuel Cell Technologies Office Kap. 3.3 + 3.4“* ***** Tank system retrofit on-costs* ******© 2014 FPInnovations*	

ASSUMPTIONS: EVALUATION MATRIX – INPUT DATA – FUEL PRODUCTION COSTS

	Min Cost Scenario	Max Cost Scenario
PTX Production Location	**MENA** (except of BEV and H2 local → DE)	**Germany**
Efficiency Electrolysis	**0,73**	**0,62**
CO_2 Source for PTX-Production	Ambient air (**approx. 125 €** / t CO_2)	Ambient air (**approx. 188 €** / t CO_2)
Electricity Price BEV and H2-local	Permanently available **(2030)** **Germany: 100 € / MWh**	Permanently available **(2017)** **Germany: 180 € / MWh**
Electricity Prices PTX Processes	Intermittent, MENA PV + Wind 2030 **24,26 €/MWh**	Intermittent Off-Shore Wind North Sea 2017: **88,10 €/MWh**
Depreciation Investment Fuel Production	20 years, ROI 6 %, Interest Rate 4 %, Maintenance 5 %, Residual Value 0	
Electrolysis Full Load Hours	5.782 h/a	5.623 h/a
Storage size (duration) H2 pressure tanks	FT, OME: 24 h Methanol, DME: 12 h H2-central: 6 h Methane: 1 h	FT, OME: 24 h Methanol, DME: 12 h H2-central: 6 h Methane: 1 h
PTX Full Load Hours	FT, OME: 7.813 h/a Methanol, DME: 7.149 h/a H2-central: 5.839 h/a Methane: 5.782 h/a	FT, OME: 5.758 h/a Methanol, DME: 5.692 h/a Methane, H2-central: 5.623 h/a







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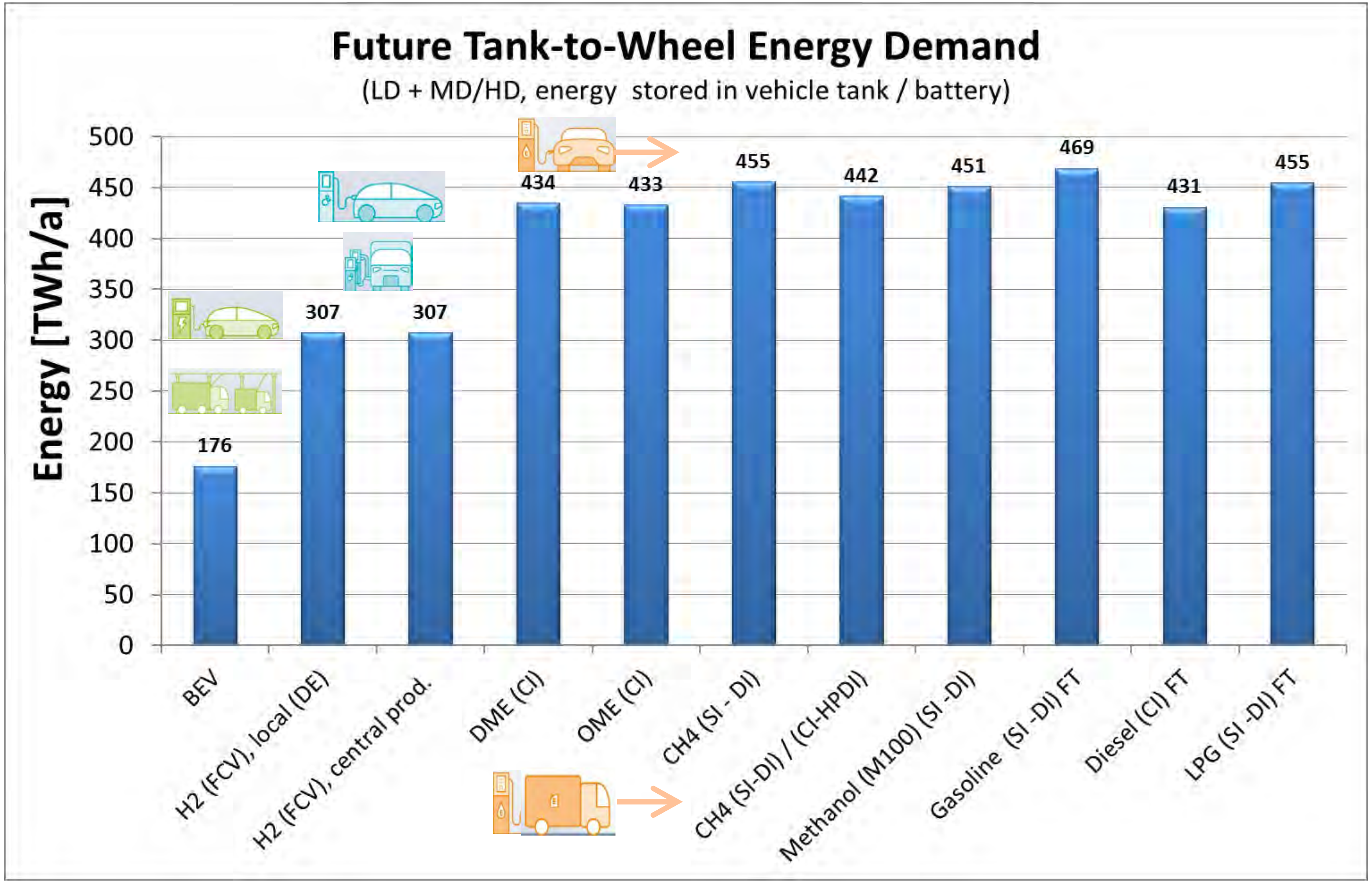
RESULTS - ENERGY DEMAND – TANK-TO-WHEEL



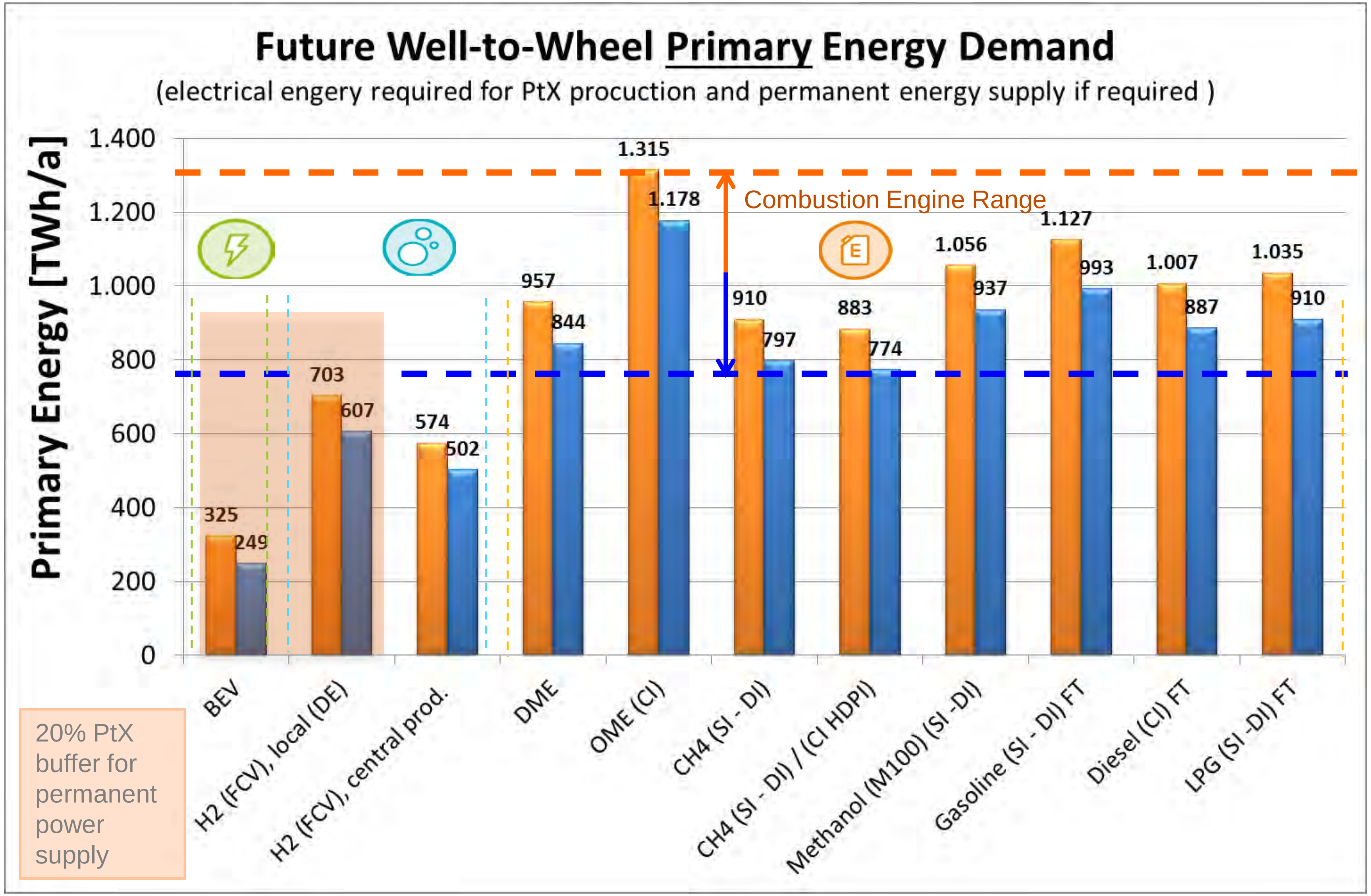
- **Reduction of TtW energy demand by increased vehicle efficiency**
- **Combustion engine** (w/o hybridization): **76 – 85 % of 2015 energy demand (560 TWh)**
- **FCEV: 55 %**
- **BEV** (HD: HO-BEV): **31%**

For comparison Germany (2015):

- Electrical power demand : 515 TWh/a
- Total primary energy demand : 3,632 TWh/a

Deviation of NEDC and real world efficiencies, e.g. heating demand of BEV, not accounted.

RESULTS - PRIMARY ENERGY DEMAND



- Lowest primary energy demand for BEV: 7 - 9% Primary Energy DE 2015 (PE_{2015})
- E-$H_{2\ (Central)}$ 14-16% PE_{2015}
- E-$CH_{4\ (HPDI)}$ 21-24% PE_{2015}
- E-$FT_{(50/50)}$ 26-29% PE_{2015}

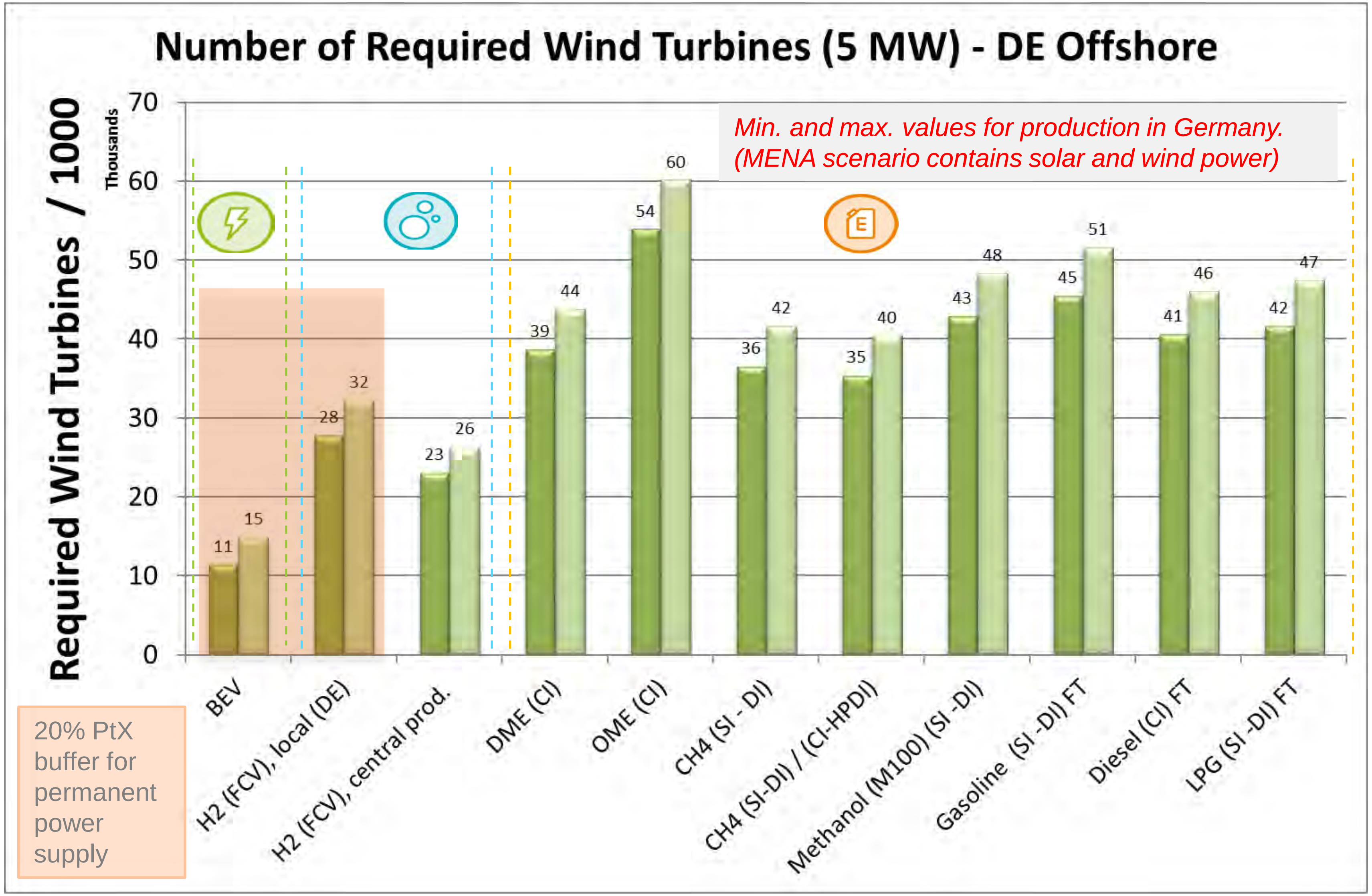
- Max. Energy: min. process efficiency, CO_2 form air, production in Germany
- Min. Energy: max efficiencies, CO_2 form air, PtX production in MENA (except BEV, H2-local)

For comparison Germany (2015):

- Electrical power demand: 521* TWh/a
- Total primary energy demand: 3,632** TWh/a

*http://www.umweltbundesamt.de/daten/energiebereitstellung-verbrauch/energieverbrauch-nach-energietraegern-sektoren
**https://www.bmwi.de/Redaktion/DE/Infografiken/Energie/energie-primaerverbrauch.html

RESULTS - NUMBER OF WIND TURBINES



- **11.000 - 15.000 wind turbines* for 100% BEV**
- **28.000 - 32.000 wind turbines* for central H_2**
- **35.000 - 40.000 wind turbines* E-$CH_{4\ (HDPI)}$**
- **43.000 - 49.000 wind turbines* for central FT***

*** Average FT-Diesel, FT-Gasoline*

** 5 MW offshore North Sea*

- Min. Number: max efficiencies, CO_2 form air, production in Germany
- Max. Number: min. process efficiency, CO_2 form air, production in Germany

Total number wind turbines DE 2016: 27.270*
Usual wind turbine size 2017:
Onshore: 0,6 – 7,5 MW**
Offshore: 5 – 8 MW***

*https://www.wind-energie.de/infocenter/statistiken/deutschland/windenergieanlagen-deutschland
**https://www.wind-energie.de/themen/onshore
***http://www.offshore-windindustrie.de/wea/offshore-wea-adwen

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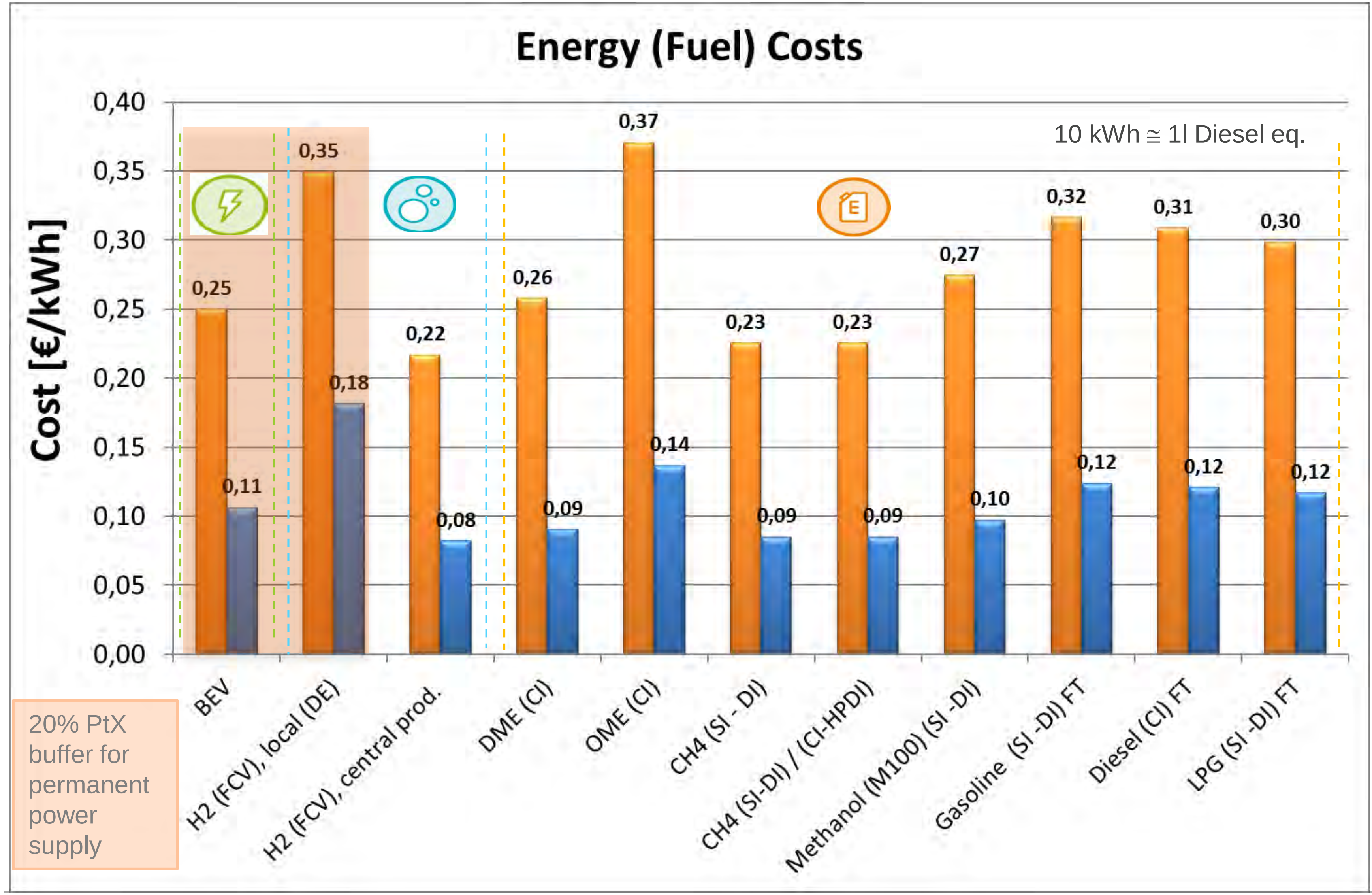
CONTENT

RESULTS – FUEL COSTS PER ENERGY UNIT



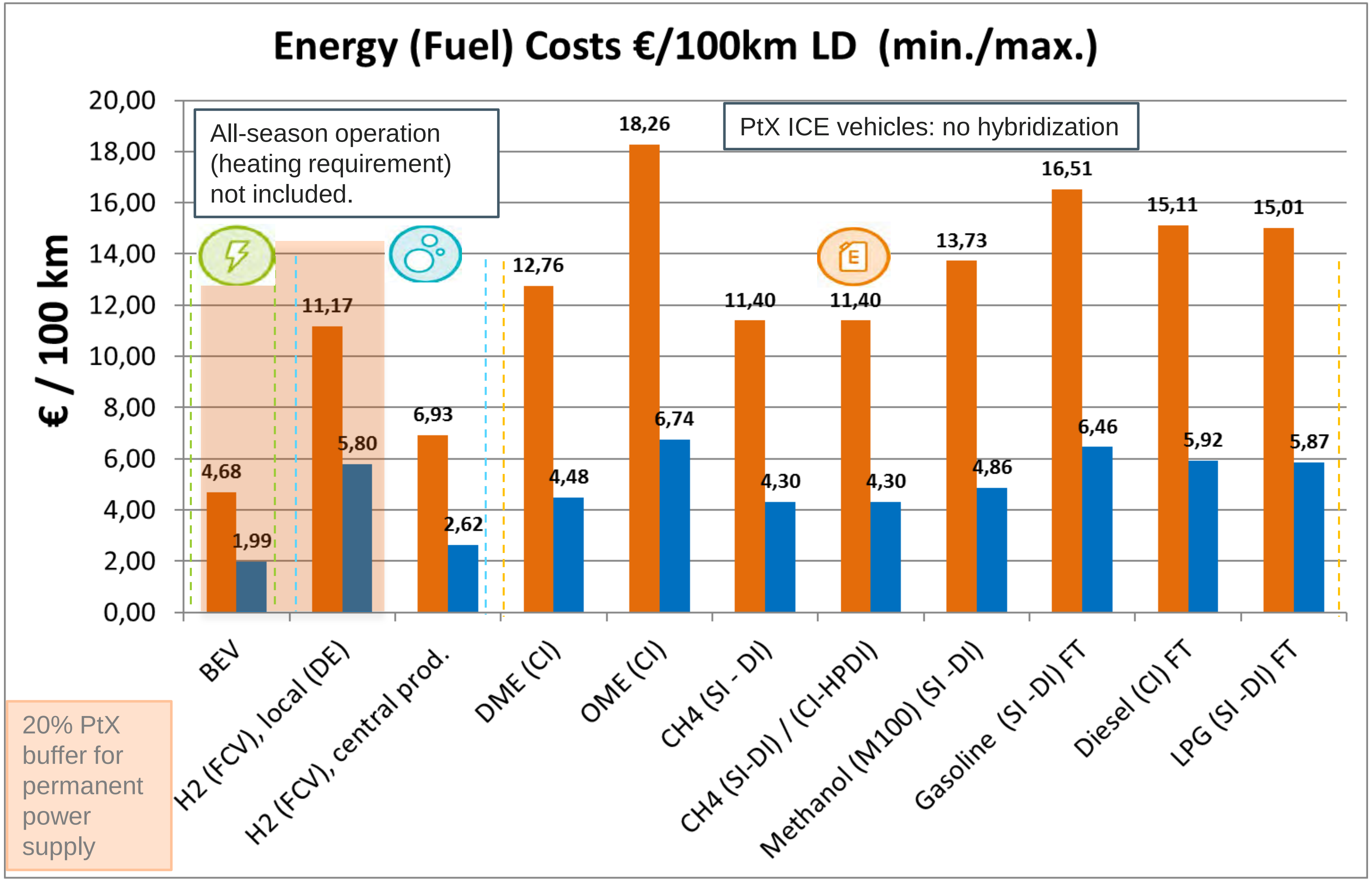
Electricity Costs [€/MWh]

Scenario	Constant DE	Intermittent DE	Intermittent MENA
2017	180	88.1	
2030	100		24.3

- **Lowest fuel cost for H_2 from MENA: 0.08 €/kWh**
- **DME and CH_4 from MENA: 0.09 €/kWh**
- **MENA H_2, DME, CH_4 and Methanol lower costs in €/kWh than buffered electricity for BEV in DE**

- Max. Cost: min. process efficiency, CO_2 form air, production in Germany
  Min. Cost: max. process efficiency, CO_2 form air, production in MENA (except of BEV, H2-local)

RESULTS – FUEL COSTS PER 100 KM - LD



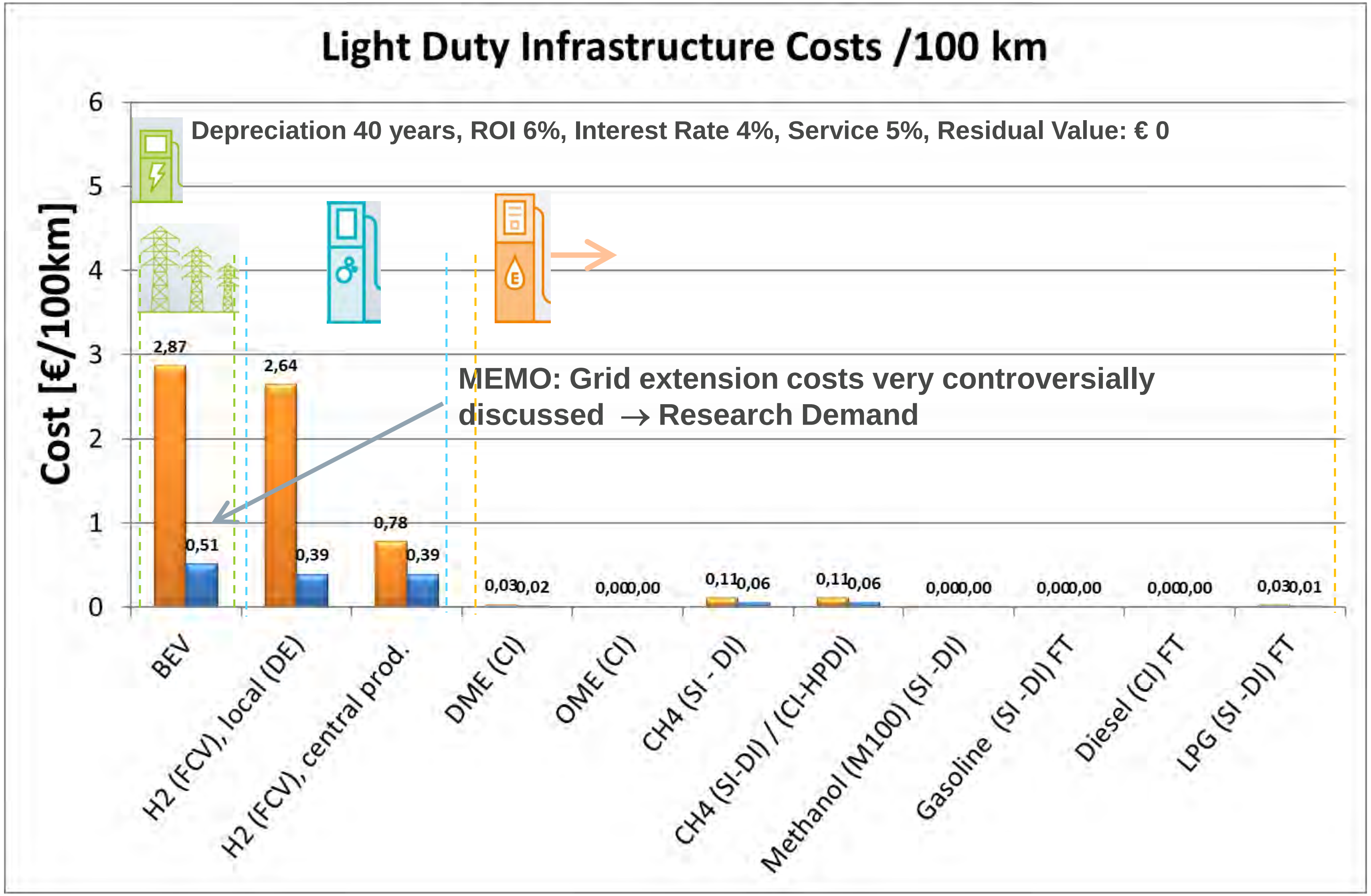
Electricity Costs [€/MWh]			
Scenario	Constant DE	Intermittent DE	Intermittent MENA
2017	180	88.1	
2030	100		24.3

- **Lowest "LD fuel costs" [€/100km] for BEV: 1.99 … 4.68 €/100 km**
- **$H_{2\ Central}$: min. + 32 %**
- **Pt–CH_4: min. + 116 %**
- **Pt–FT: min. + 211 %***

average FT-gasoline / FT-diesel

- Max. Cost: min. process efficiency, CO_2 form air, production in Germany
- Min. Cost: max. process efficiency, CO_2 form air, production in MENA (except of BEV, H2-local)

RESULTS – INFRASTRUCTURE COSTS - LD



- **Lowest infrastructure costs for PtX fuels.**

- Max. Cost PtX: 10k gas stations (80k LD refill points, 12k HD refill points)
- Max. Cost H2 local: € 90 billion for connection of local electrolysis to power grid
- Max. Cost BEV (LD): 160k fast chargers, 25 Mio. home chargers, 10 Mio chargers at work, grid extension costs (for home loading) € 77 billion
- Max. Cost HO-BEV (HD): 13k km overhrad line (€ 4 Million per km)

- Min. Cost PtX: 5k gas stations (40k LD refill points, 6k HD refill points)
- Min. Cost H2 local: € 0 billion for connection of local electrolysis to power grid
- Min. Cost BEV (LD): 80k fast chargers, 12,5 Mio. home chargers, 5 Mio chargers at work, NO grid extension costs (for home loading)
- Min. Cost HO-BEV (HD): 4 km overhead line (€ 4 Million per km)

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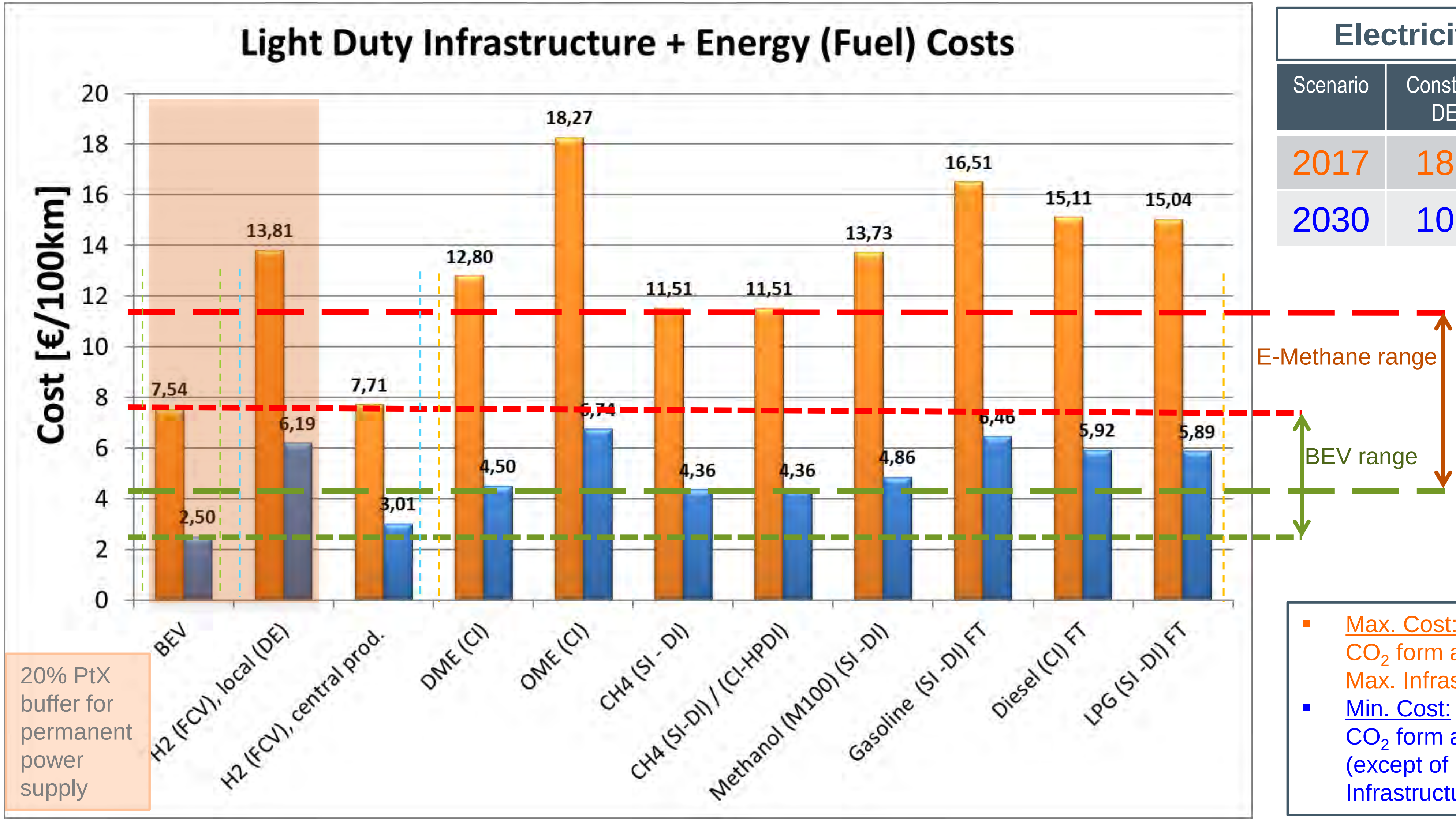
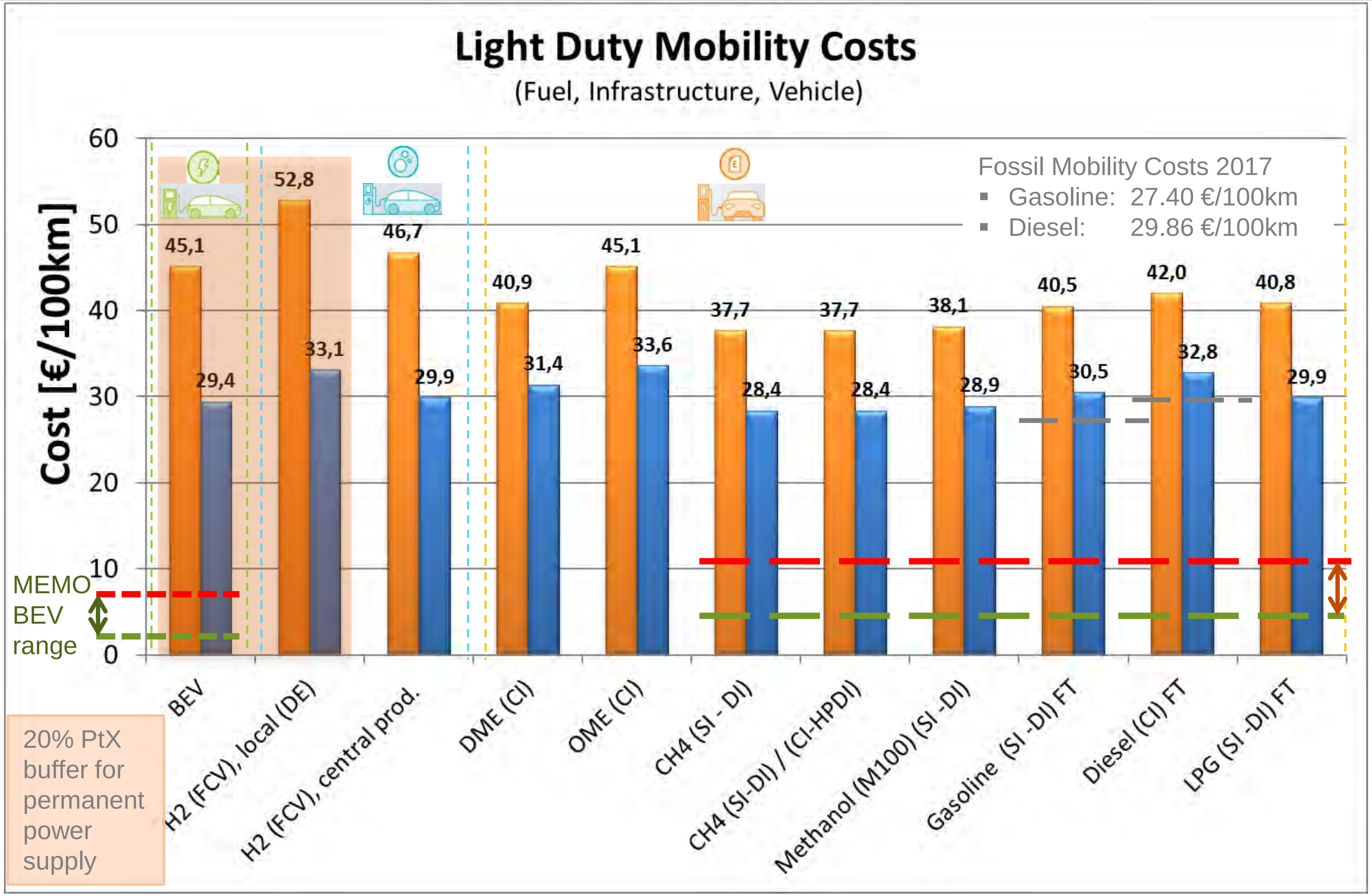
RESULTS – INFRASTRUCTURE + ENERGY COSTS - LD



Electricity Costs [€/MWh]			
Scenario	Constant DE	Intermittent DE	Intermittent MENA
2017	180	88.1	
2030	100		24.3

- Max. Cost: min. process efficiency, CO_2 form air, production in Germany Max. Infrastructure Costs
- Min. Cost: max. process efficiency, CO_2 form air, production in MENA (except of BEV, H2-local); Min. Infrastructure Costs

RESULTS – MOBILITY COSTS - LD



- **LD vehicle costs dominate the mobility costs**
- **LD mobility costs for PtX fuels are in the same ball park as BEV and FCEV**
- **Cost Risk for BEV and FCEV higher than for E-Fuel pathways**

- Max. Cost: min. process efficiency, CO_2 form air, production in Germany (CO_2 separation approx. 0.01€/kWh)
- Min. Cost: max. process efficiency, CO_2 form air, production in MENA (except of BEV, H2-local)

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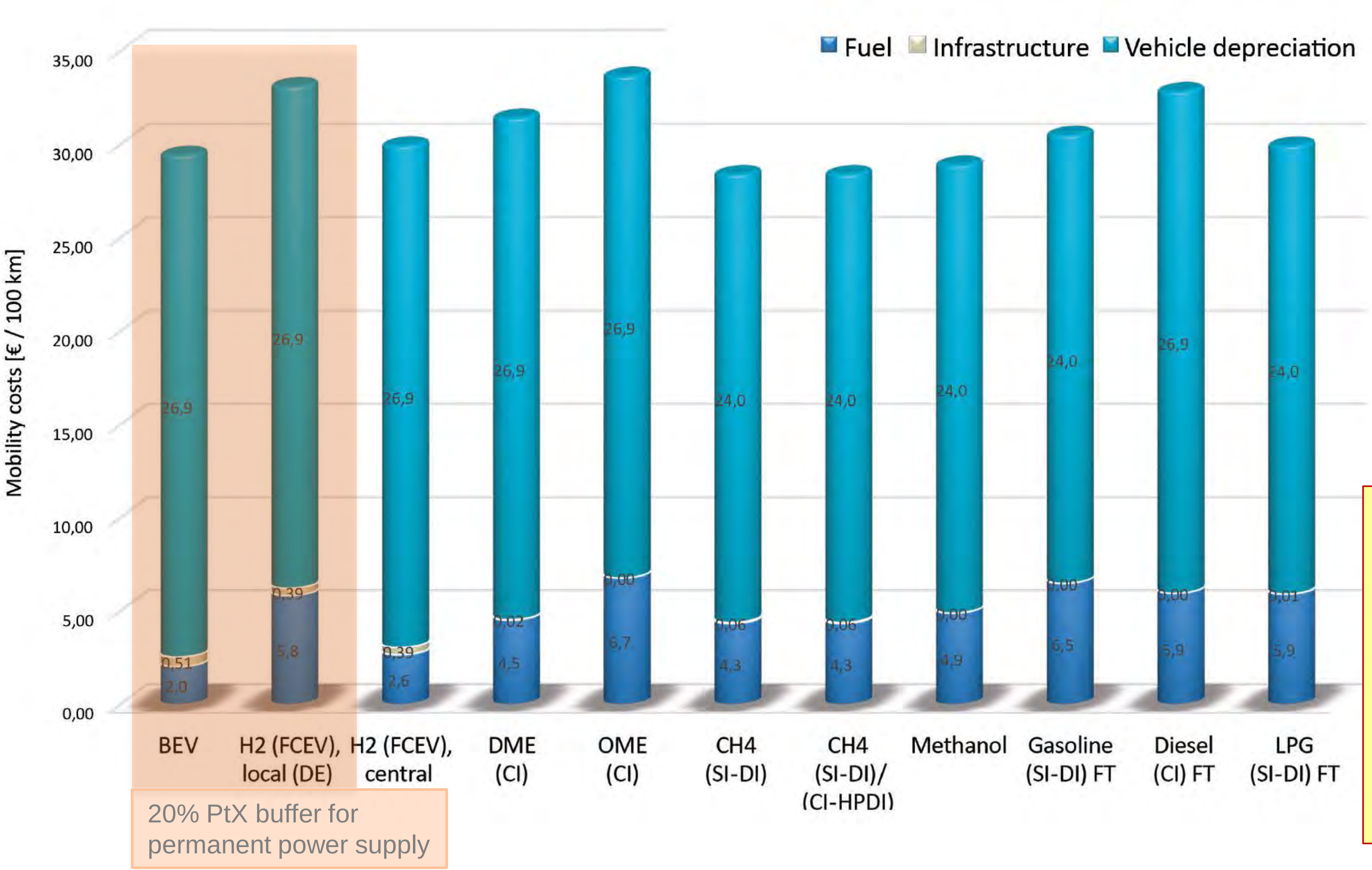
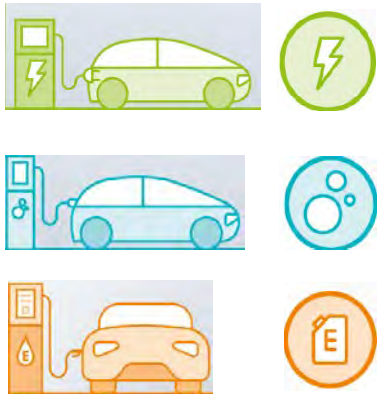
RESULTS – MIN. MOBILITY COSTS - LD

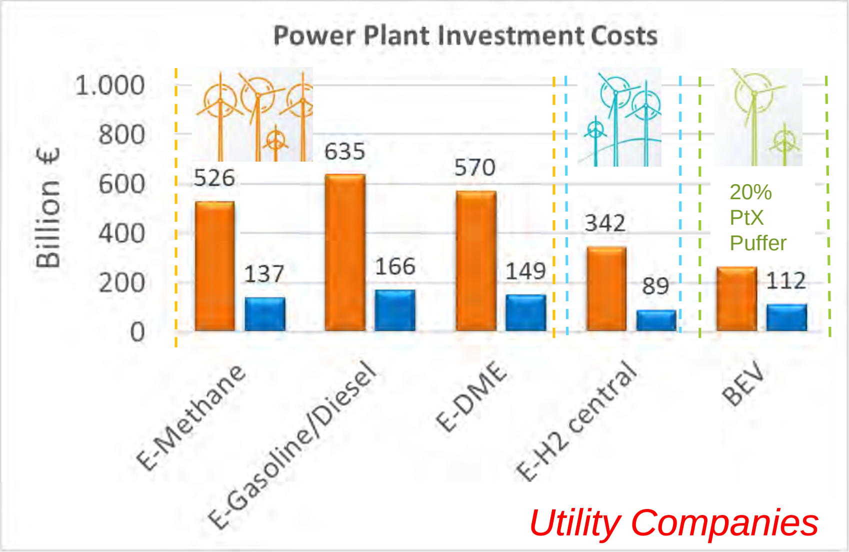


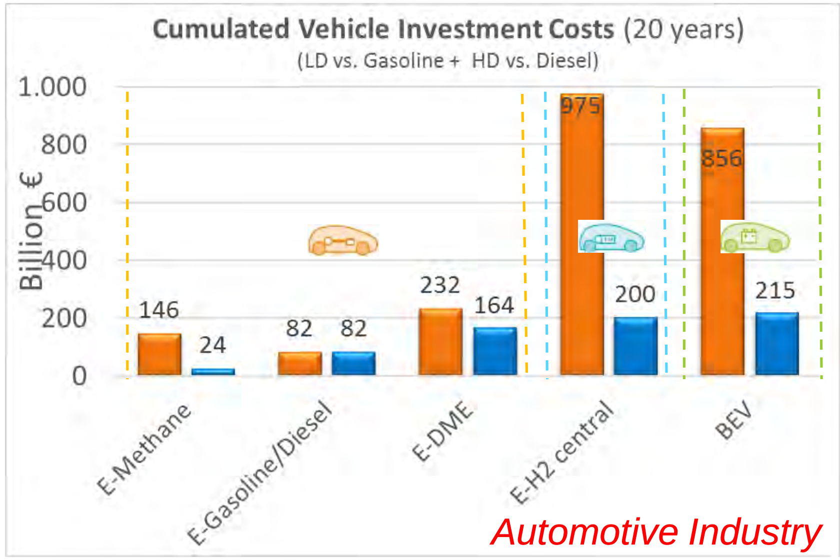
LD Mobility Cost Brake Down (Min. Cost Scenario)



- **LD vehicle costs dominate the mobility costs**
- **MEMO: Vehicle costs very controversially discussed → Research Demand**

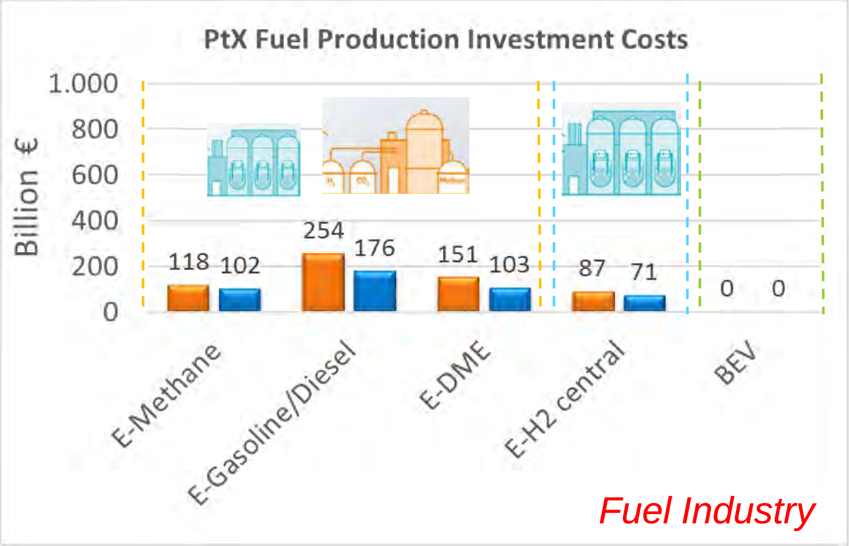
RESULTS – INVESTMENT COSTS

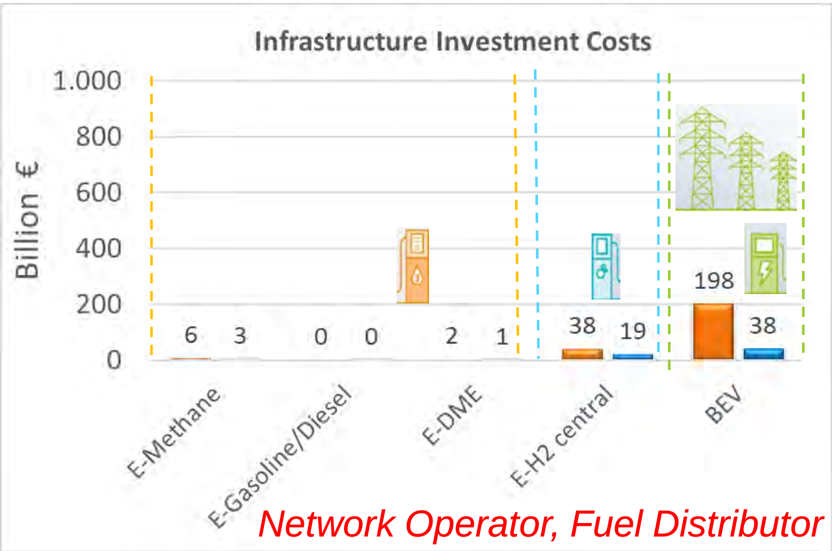




Cumulated vehicle on-costs (LD vs. Gasoline; HD vs. Diesel) over 20 years: 3.4 Mio. LD pa & 50k HD pa

- All pathways require significant upfront investment costs.
- Investment patterns differ significantly.





- Highest cost risk at automotive industry for BEV and FCEV.

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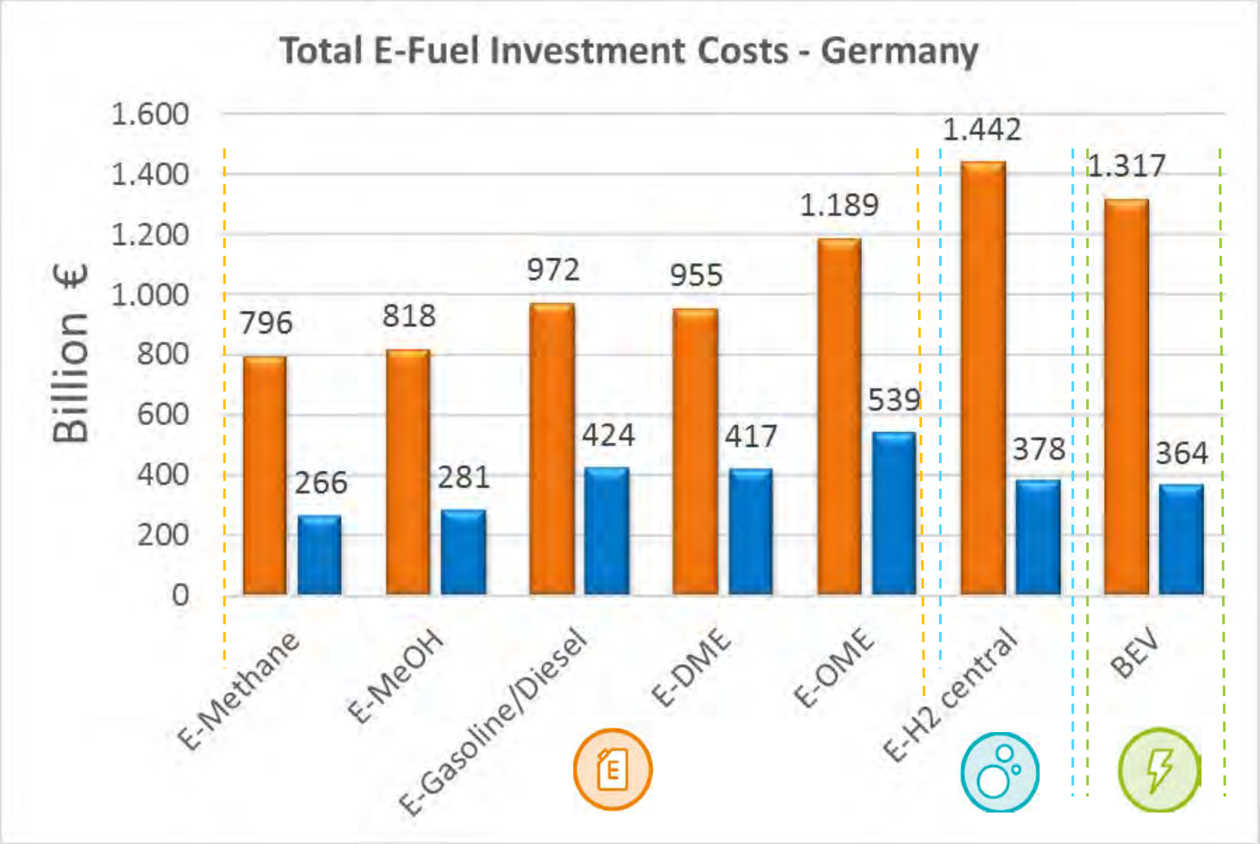
RESULTS – TOTAL INVESTMENT COSTS

Scenario	Min. Investment Costs / bil. €	Max. Investment Risk / bil. €
E-CH4	270	800
E-MeOH	280	820
E-FT*	420	970
E-DME	420	960
E-OME	540	1.190
E-H2 (central)	380	1.440
E-H2 (local)	540	1.740
BEV	360	1.320

**Assumption FT: ½ Gasoline + ½ Diesel*

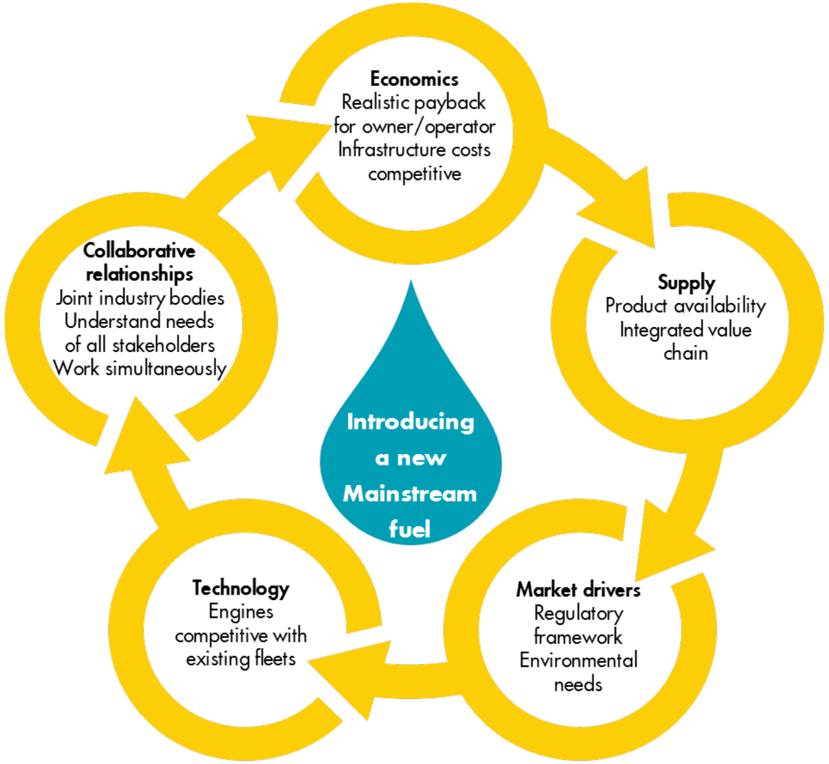


- Significant total investment costs for all pathways.
- Highest cost risk for FCEV.
- Best cost opportunities for E-Methane and E-Methanol.

CONTENT

RESULTS – MARKET INTRODUCTION POTENTIAL – INFRASTRUCTURE

Success of market introduction will depend on compatibility with existing car park and existing legislation



Fuel Standards:

- Quick PtX fuel market introduction requires the availability of decent **fuel standards**
- Fuel standardization usually requires **at least 5 years**
- European or German fuels standards only available for: FT-gasoline (EN 228), FT-diesel (EN 15940), FT-LPG (EN 589), PtG-Methane (EN16723-2, DIN 51624)

- **Appreciable infrastructure in Germany for 4 of the investigated fuels:**
  - FT-gasoline (14.000), FT-Diesel (14.000), FT-LPG (6.800), PtG-Methane (900)
- **Only 2 of the further investigated fuels are drop-in capable:**
  - Methanol (up to 3 % into gasoline – EN 228)
  - H_2 (up to 2 % to CNG / Methane - EN16723-2)

CONTENT

- Challenges
- Approach
- Assumptions
- Results
    - Energy Demand
    - Costs
    - Market Introduction Potential (Assessment)
- Summary

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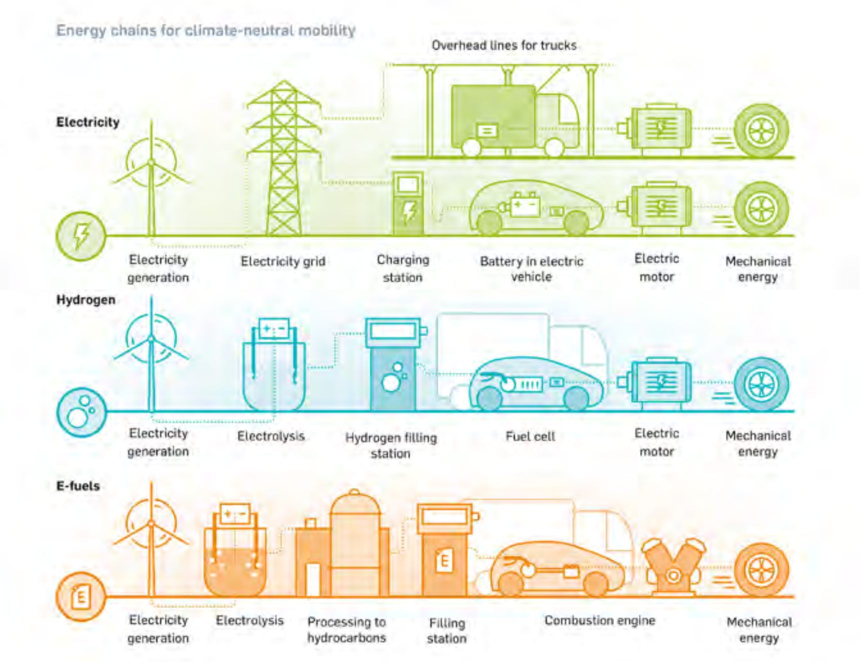
SUMMARY

- Even if not realistic, “100% scenarios” are an effective tool for a simple technology comparison
- 100% sustainable mobility in 2050 possible with BEV, FCEV and PtX (-HEV)
- The vehicle costs dominate the mobility costs (not the PtX costs).
  - On-costs for BEV and FCEV have a significant impact, but are difficult to predict
- Electricity grid extension cost prediction is also very difficult, while those costs also have a significant impact on mobility costs
- All pathways require significant investment costs.
  - E-fuels require significant investment costs for fuel production.
- Long term investment is the key hurdle for e-fuel production.
- Appropriate legislative conditions for investment stimulation required, e.g. recognition of e-fuel CO_2 benefit.
- Quick market introduction (< 5 years) is only possible with already standardized fuels
- Only a very limited number of fuels appear beneficial for all mobility stakeholders

Acknowledgment

We would like to thank all companies involved in the project and, in particular, the more than 40 experts from the cross-sector innovation network of the FVV, who assisted the authors of the study with their advice and contributed their specialist knowledge.



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Project support

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Dr. Lars Menger | BMW AG
Dr. Jörg Ullmann | Robert Bosch GmbH
Steffen Eppler | Robert Bosch GmbH
Andreas Schleiffer | BP Europa SE
Harry Schüle | Continental Automotive GmbH
Dr. Dietrich Gerstein | DVGW Deutscher Verein des Gas- und Wasserfaches eV
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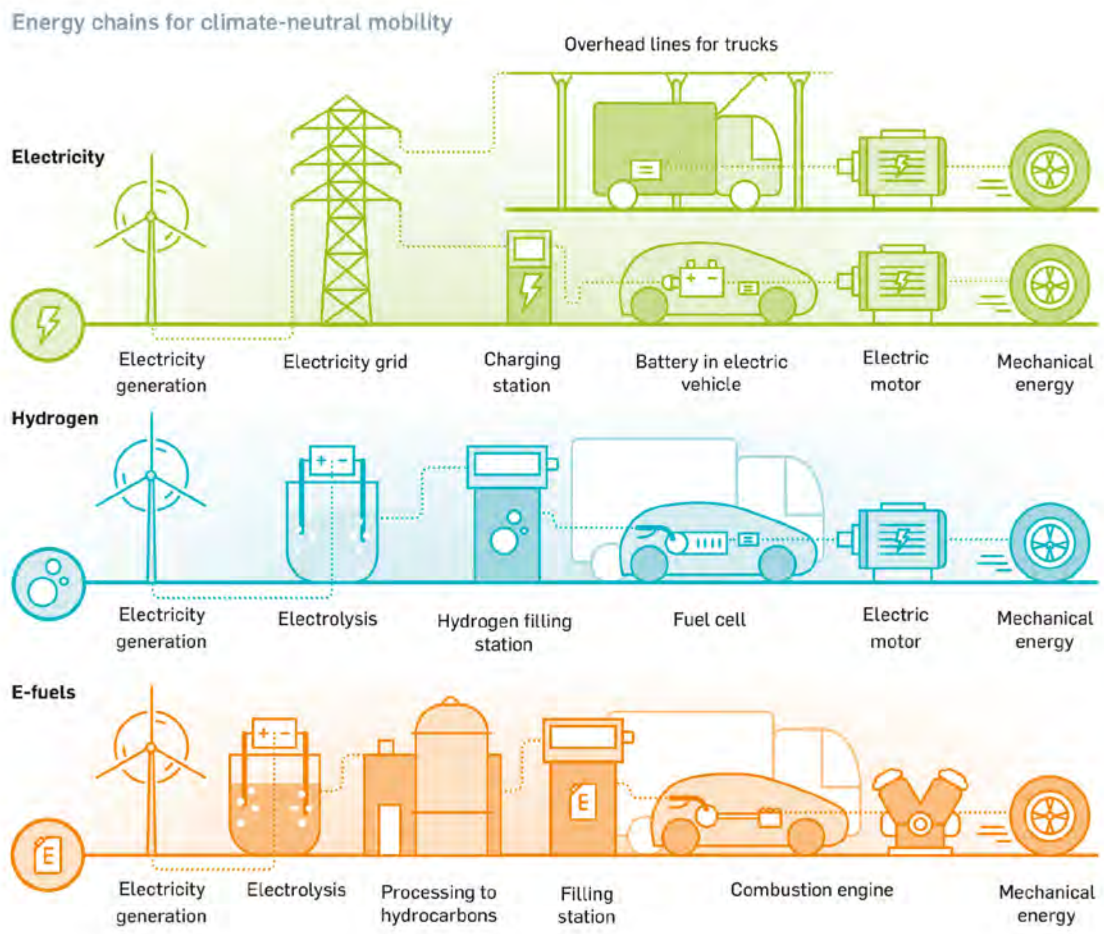


Thank you very much for your attention.

Questions?

FVV Working Group Future Fuels

Dr. Ulrich Kramer
Ford-Werke GmbH

APPENDIX

APPROACH - FUEL MATRIX CONTENT

Criteria compared in Fuel Matrix

Quantitatively:

- Energy demand (TtW, WtW, Primary)
- Mobility costs (fuel production, infrastructure, vehicle costs)

Qualitatively:

- Zero impact emission capability
- Safety & handling
- Market introduction potential
  - Charging time
  - Backwards compatibility
  - Available infrastructure
  - Technology readiness
  - Availability of standards

Approach: cost assessment

Price for electrical power [€/MWh] based on full costing as input for mobility cost assessment.

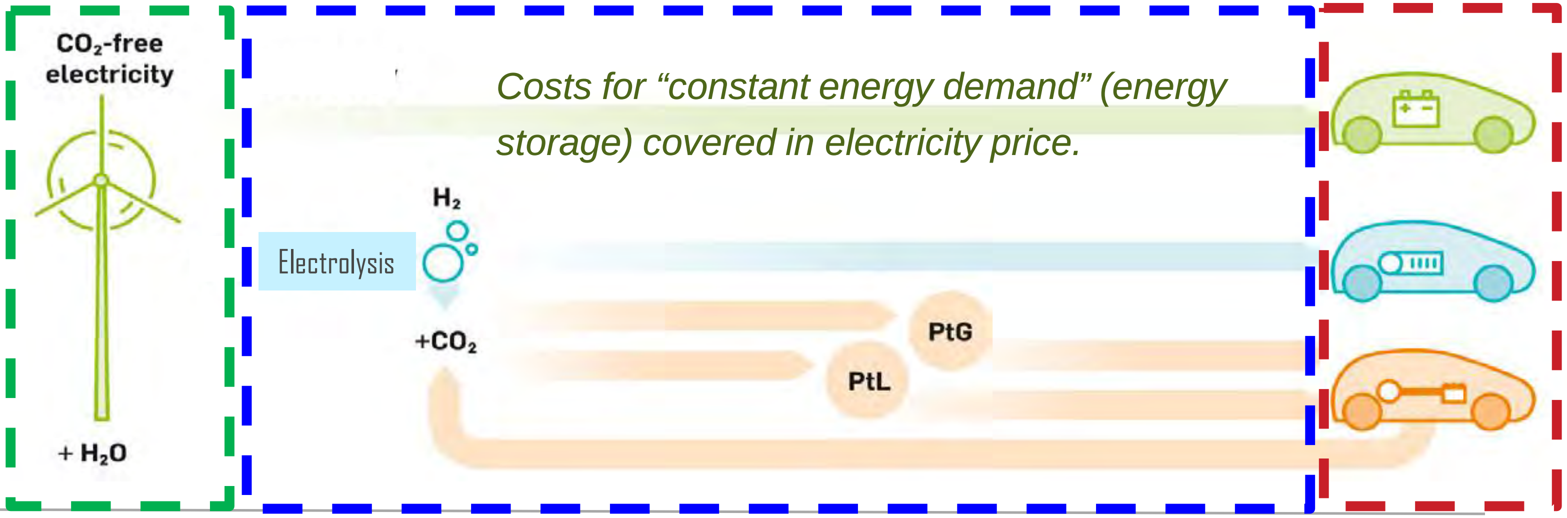
2 types of electrical power:

1. Intermittent *(when possible)*
2. Permanent *(when required)*

Mobility cost assessment [€/100 km]

- Fuel production (20 years depreciation)
- Infrastructure development (40 years depreciation)

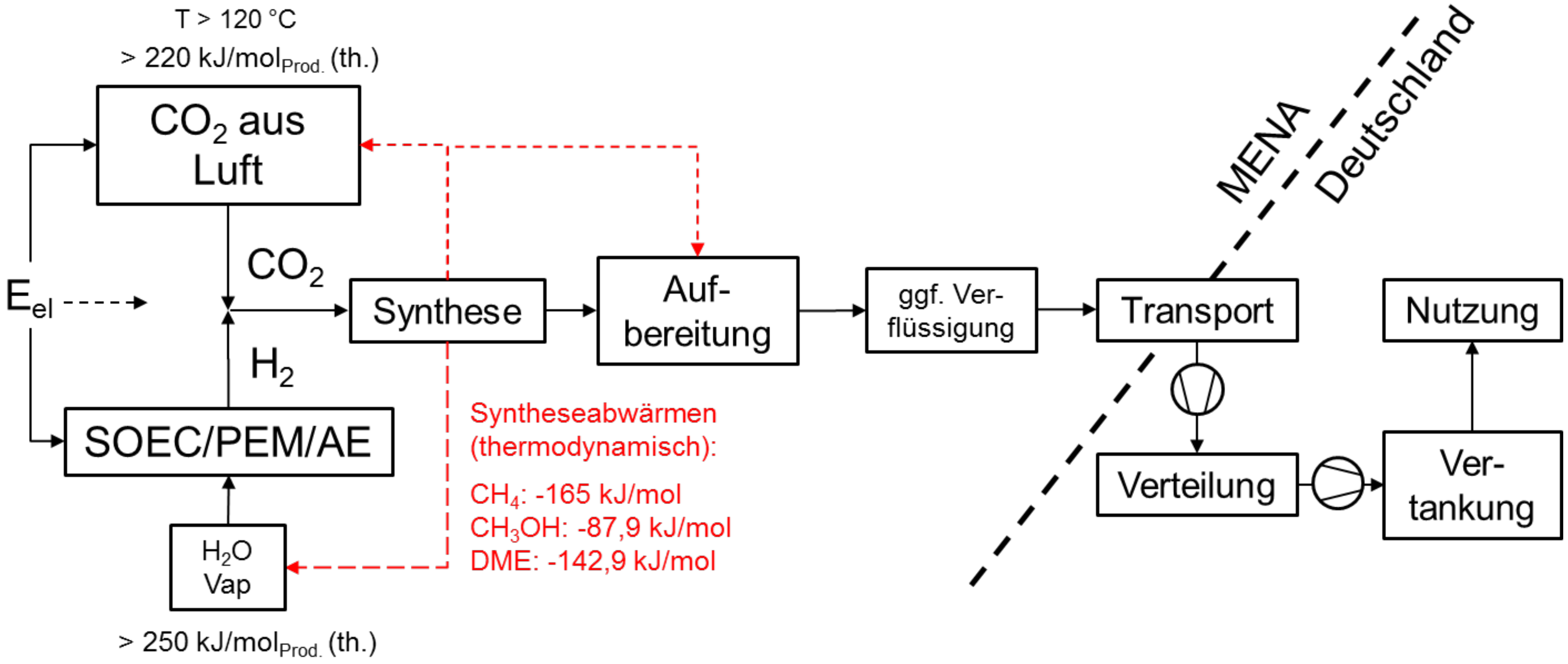
- Vehicle costs (LDV loss in value according to ADAC)



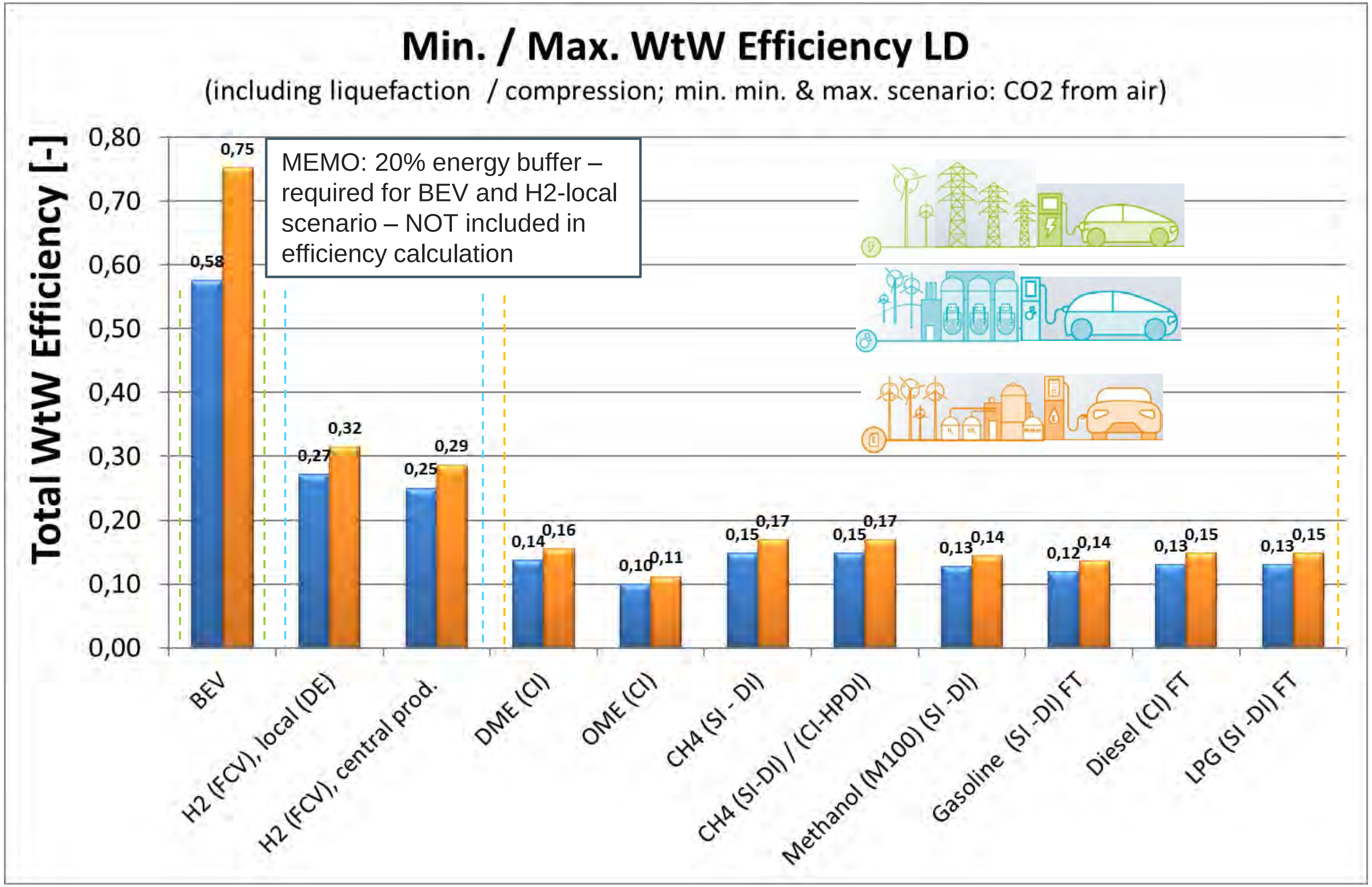
PTX PROCESS

- **PTX Process Assumptions**
  - Identical electrolysis efficiency assumed for each fuel
  - PTX process heat utilization taken into account (CO_2 separation)
  - 2 scenarios (min. / max.):
    - Min. Cost: max. process efficiency, CO_2 form air, production in MENA*
    - Max. Cost: min. process efficiency, CO_2 form air, production in Germany

* MENA: Middle East North Africa



RESULTS - WELL-TO-WHEEL EFFICIENCY LIGHT DUTY



- **Best LD WtW efficiency for BEV: 0.58 – 0.75** (20 % energy buffer not included!)
- **H2 central efficiency: 0.25 – 0.29**
- **PtX efficiency: 0.10…0.11 (OME) – 0.15….0.17 (CH4)**

- Max. Efficiency: max EL efficiency, CO_2 form air, BEV: slow charging
- Min . Efficiency: min. EL efficiency, CO_2 form air, BEV. fast (buffered) charging

WtW-PtX-Efficiencies include: electrolysis, PtX-synthesis, liquefaction, fuel transport in Germany, vehicle efficiency NEDC (w/o hybridization, w/o cabin heating BEV)

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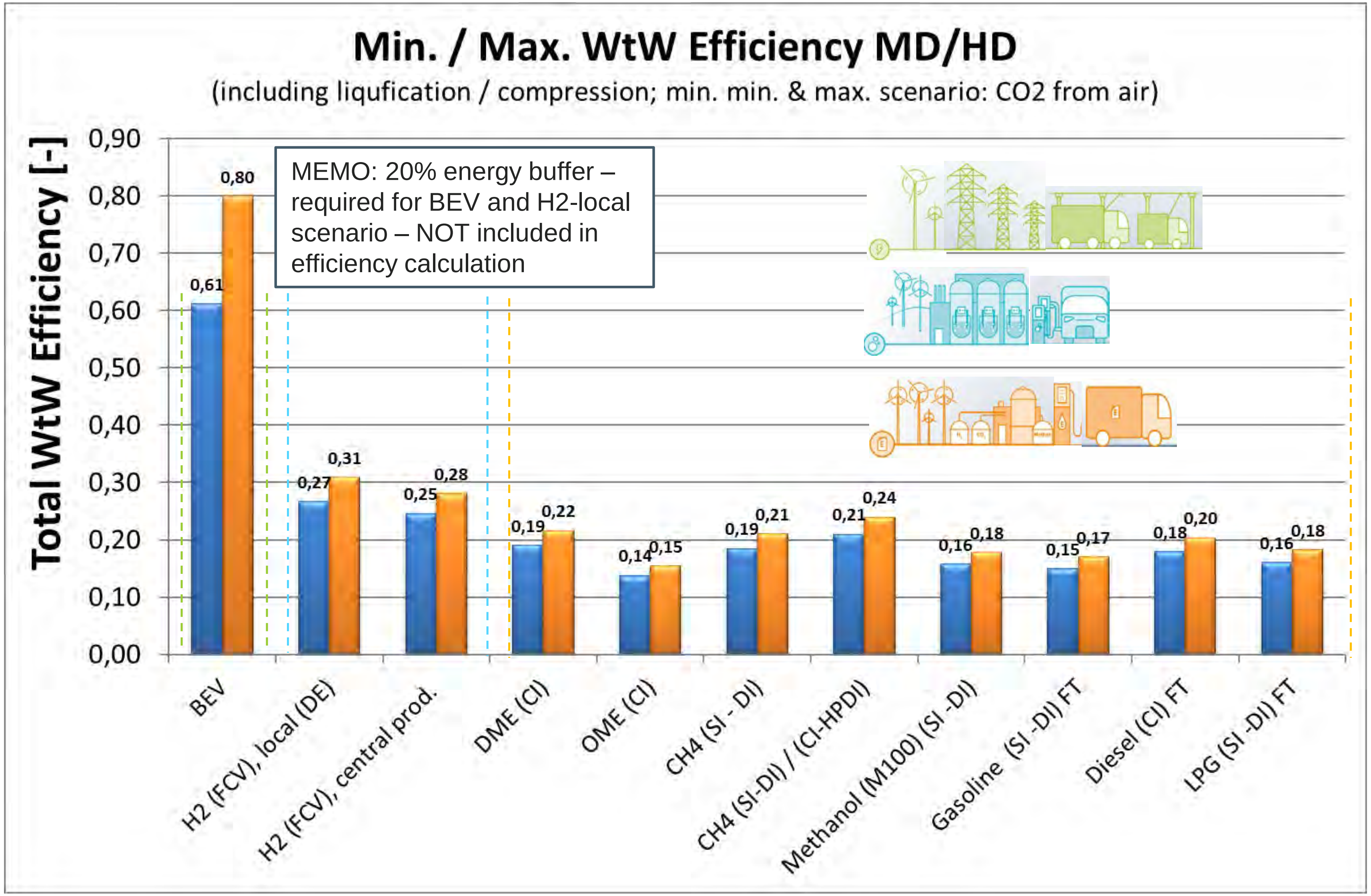
RESULTS - WELL-TO-WHEEL EFFICIENCY HEAVY DUTY

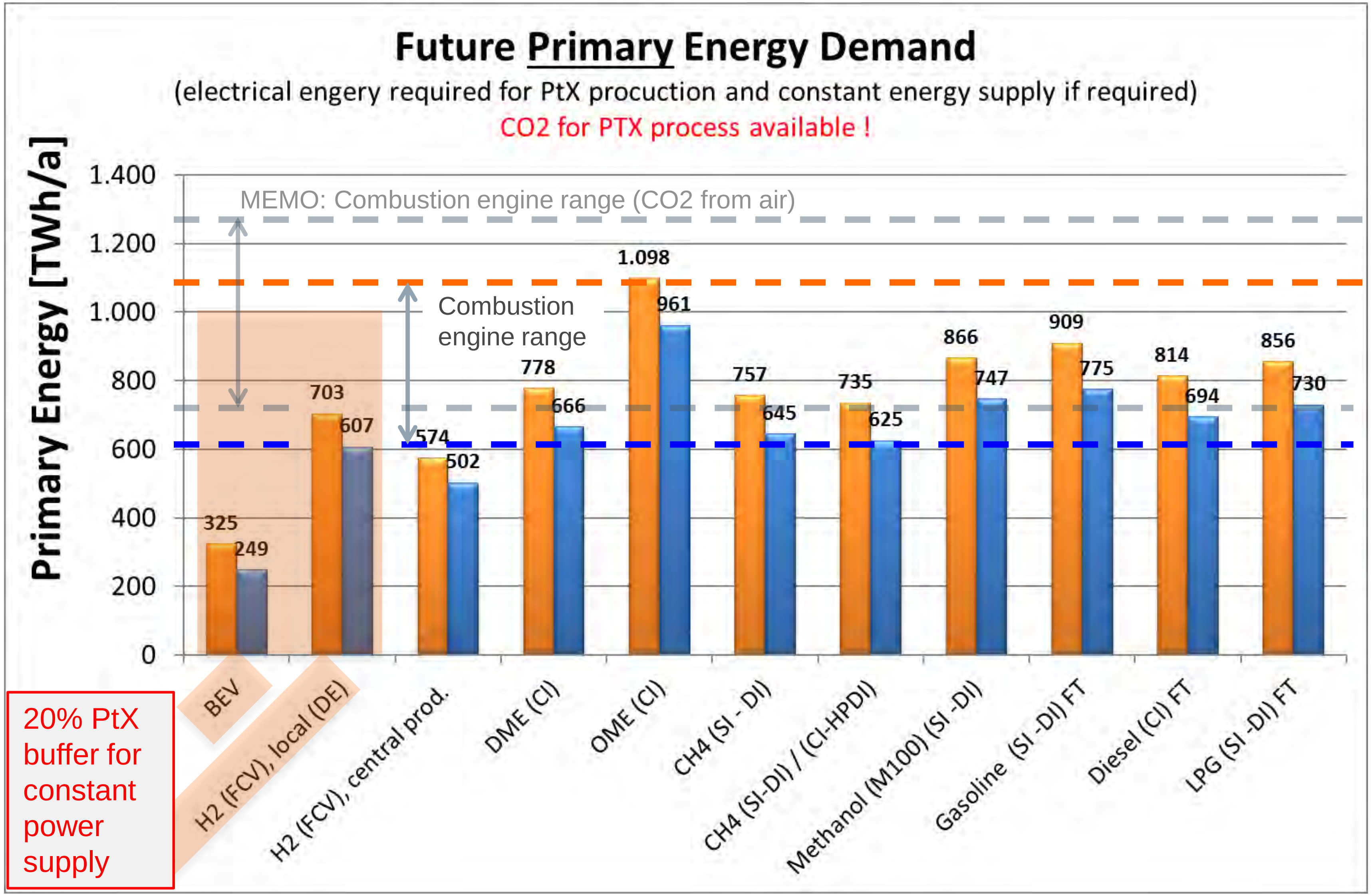


- **Best HD WtW Efficiency for HO-BEV: 0.61 – 0.80** (20 % energy buffer not included!)
- **H2 central efficiency: 0.25 – 0.28**
- **PtX efficiency: 0.14…0.15 (OME) – 0.21…0.24 (CH4 HPDI)**

- Max. Efficiency: max EL efficiency, CO_2 form air, BEV: slow charging
- Min . Efficiency: min. EL efficiency, CO_2 form air, BEV: fast (buffered) charging

WtW-PtX-Efficiencies include: electrolysis, PtX-synthesis, liquefaction, fuel transport in Germany, vehicle efficiency

RESULTS - PRINAMRY ENERGY DEMAND – CO2 AVAILABLE



20% PtX buffer for constant power supply

- **Lowest WtW energy demand for BEV: < 9% Primary Energy DE 2015 (PE_{2015})**
- **Pt-$H_{2\ (Central)}$ < 16% PE_{2015}**
- **Pt-CH4 < 20% PE_{2015}**
- **Pt-FT < 24% PE_{2015}**

- Max. Energy: min. process efficiency, **CO_2 available**, production in Germany
- Min. Energy: max efficiencies, **CO_2 available**, PtX production in MENA (except BEV, H2-local)

For comparison Germany (2015):
- Electrical power demand: 521* TWh/a
- Total primary energy demand: 3,632** TWh/a

*http://www.umweltbundesamt.de/daten/energiebereitstellung-verbrauch/energieverbrauch-nach-energietraegern-sektoren
**https://www.bmwi.de/Redaktion/DE/Infografiken/Energie/energie-primaerverbrauch.html

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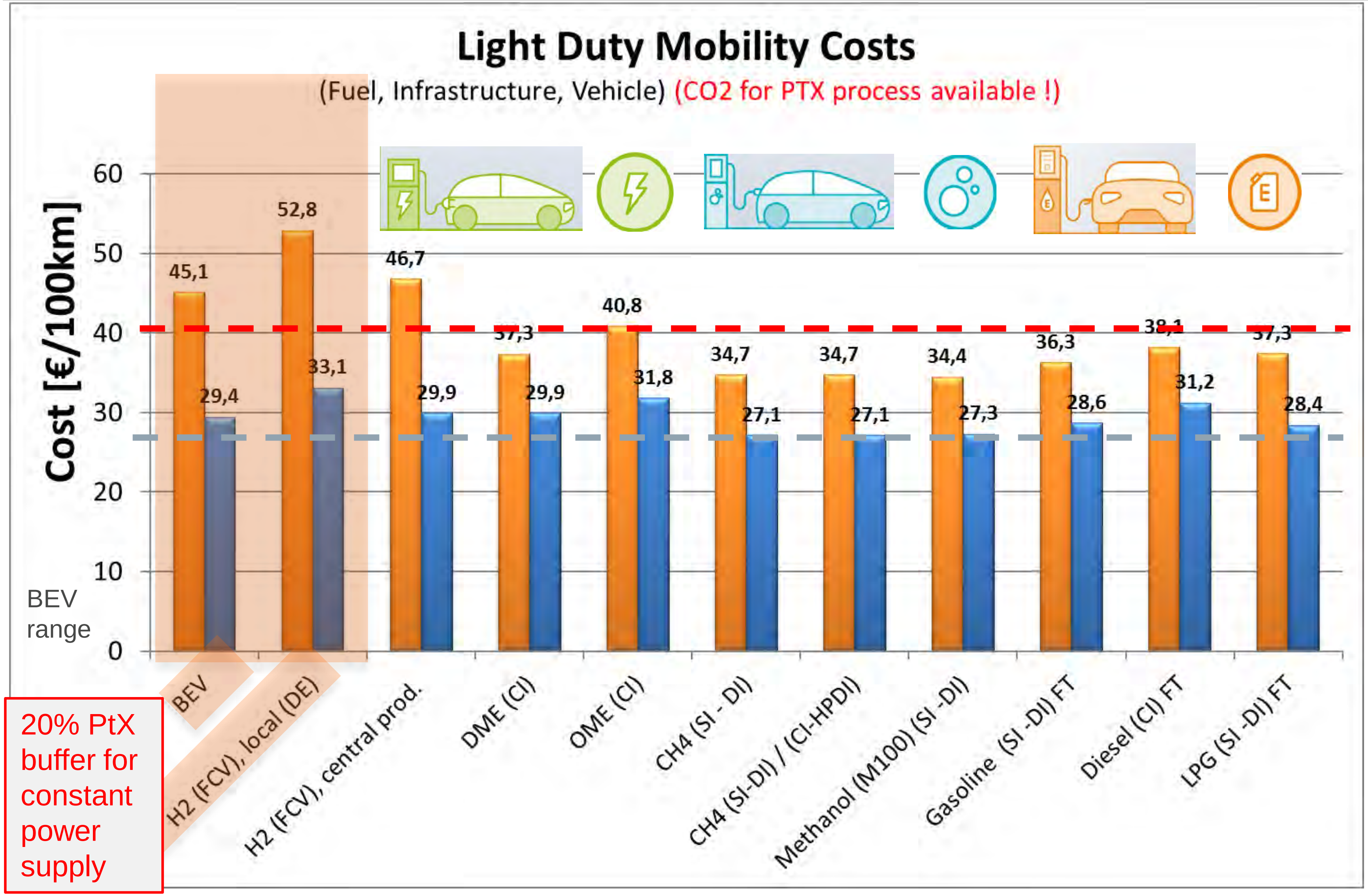
RESULTS – MOBILITY COSTS - LD - CO2 AVAILABLE



Max E-Fuel (E-OME)

Min E-Fuel (E-Methane)

- **With CO2 from available sources, cost benefit of PtX increases**

- Max. Cost: min. process efficiency, **CO_2 available**, production in Germany
- Min. Cost: max. process efficiency, **CO_2 available**, production in MENA (except of BEV, H2-local)

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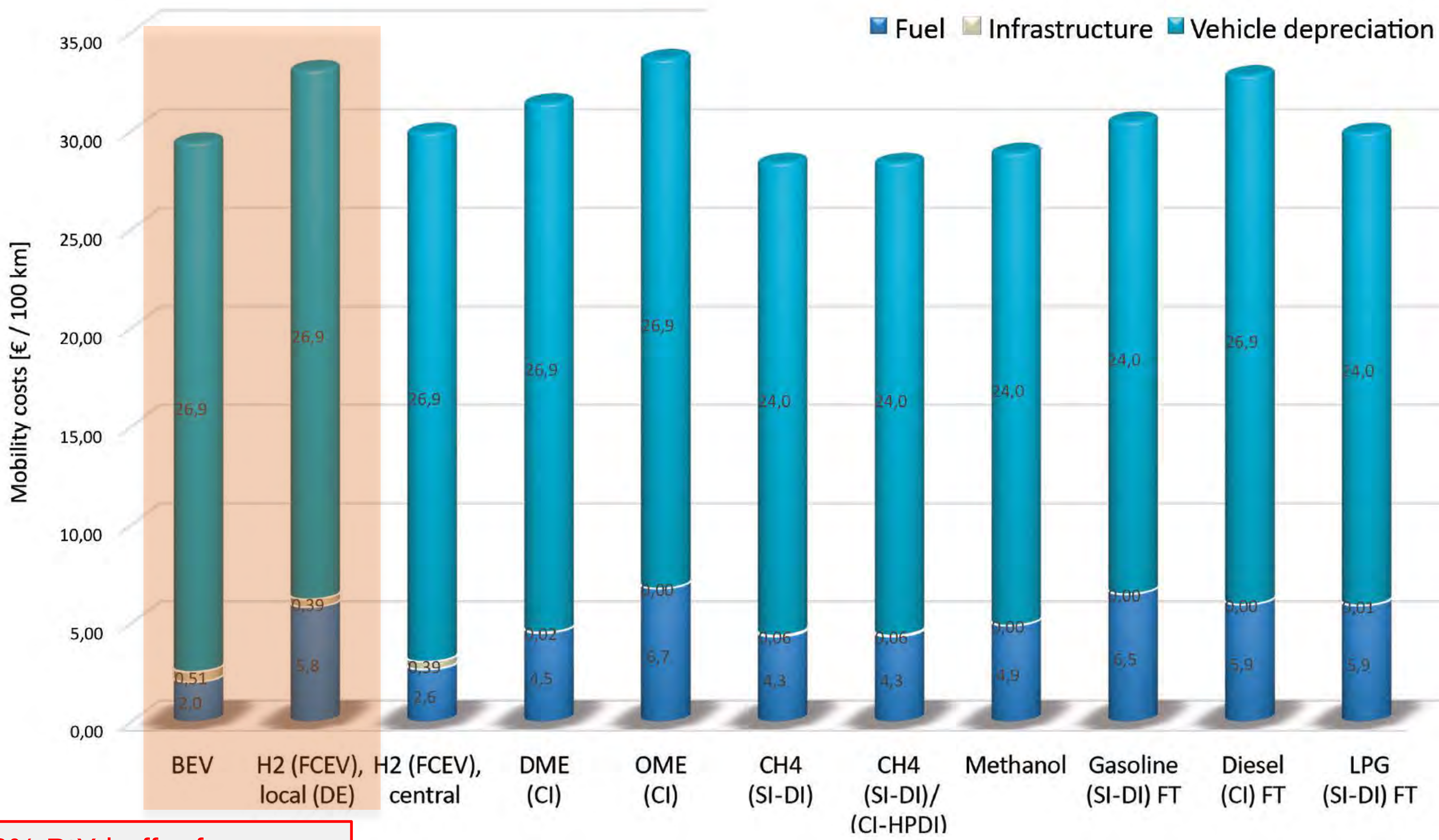
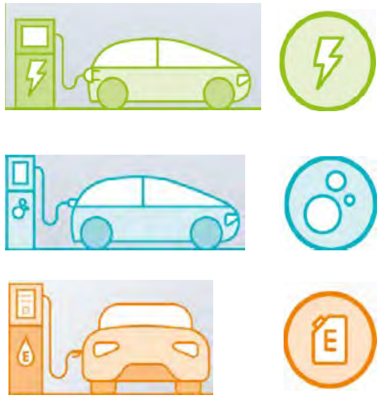
RESULTS – MIN. MOBILITY COSTS - LD



20% PtX buffer for constant power supply

LD Mobility Cost Brake Down (Min. Cost Scenario)



- **LD vehicle costs dominate the mobility costs**

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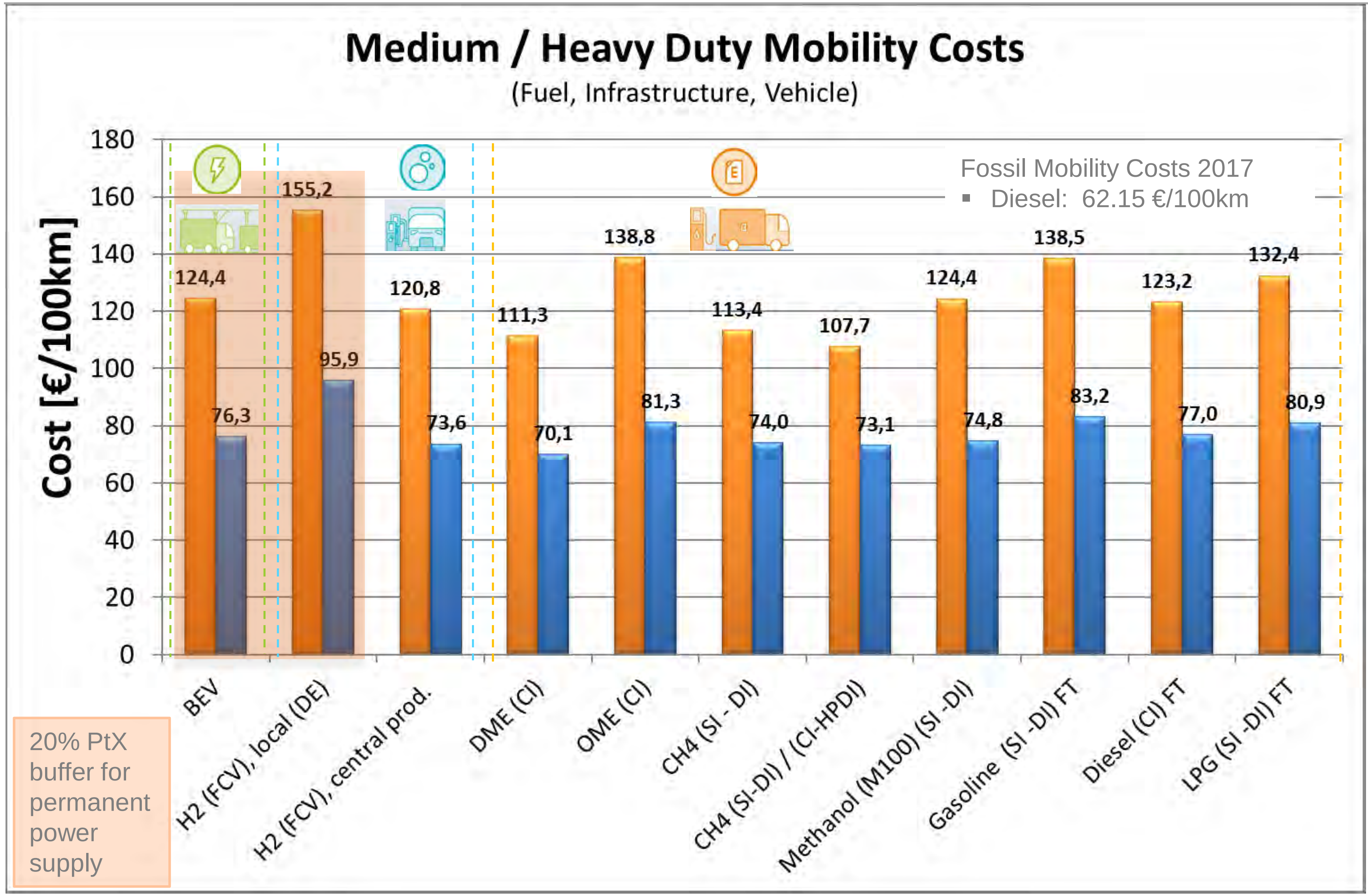
RESULTS – MOBILITY COSTS - HD



- **HD mobility costs for PtX fuels are in the same ball park as HO-BEV and FCEV**

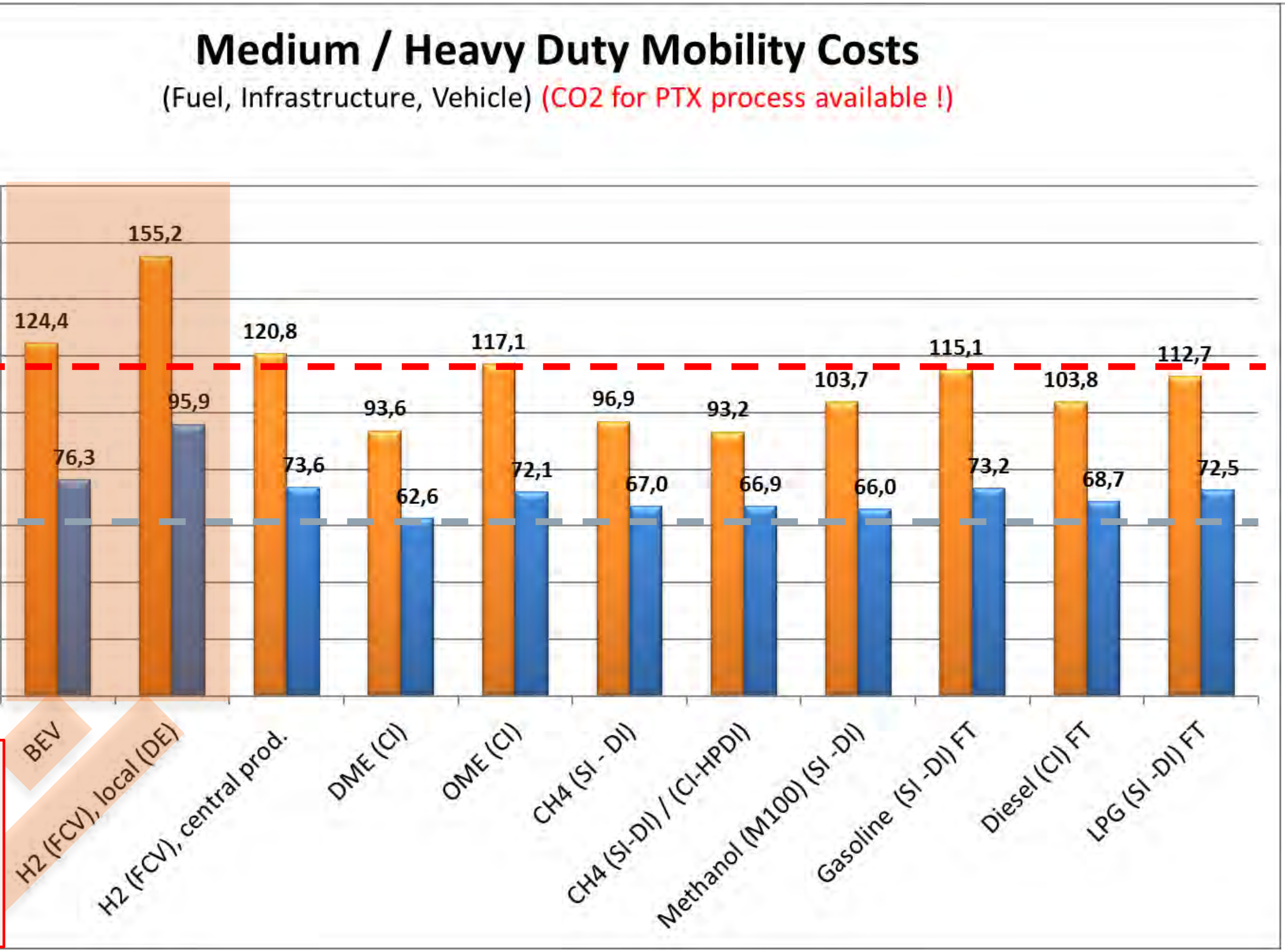
- **Most cost efficient PtX fuels: DME, CH4, MeOH**

- Max. Cost: min. process efficiency, CO_2 form air, production in Germany (CO_2 separation approx. 0.01€/kWh)
- Min. Cost: max. process efficiency, CO_2 form air, production in MENA (except of BEV, H2-local)

MEMO: Energy (Fuel) + Infrastructure Costs [€/100km]

BEV:	30.37– 70.11 (x 3 - 2)	FCV (central H2)	20.04 – 53.04 (x 4 – 2)
FCV (local H2)	69.55 – 114.60 (x 2)	CH4	19.46 – 86.59 (x 3 – 1.5)
		FT Diesel	27.70 – 102,91 (x 3 – 1.5)

RESULTS – COSTS – CO2 AVAILABLE

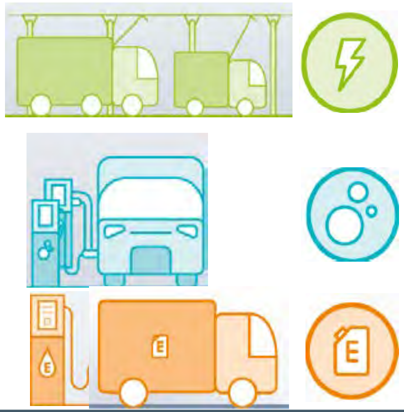


20% PtX buffer for constant power supply

- With CO2 from available sources, cost benefit of PtX increases
- Most cost efficient PtX fuels:
  - o DME
  - o CH4
  - o MeOH

Max E-Fuel (E-OME)

Min E-Fuel (E-DME)



- Max. Cost: min. process efficiency, CO_2 available, production in Germany (CO_2 separation approx. 0.01€/kWh)
- Min. Cost: max. process efficiency, CO_2 available, production in MENA (except of BEV, H2-local)

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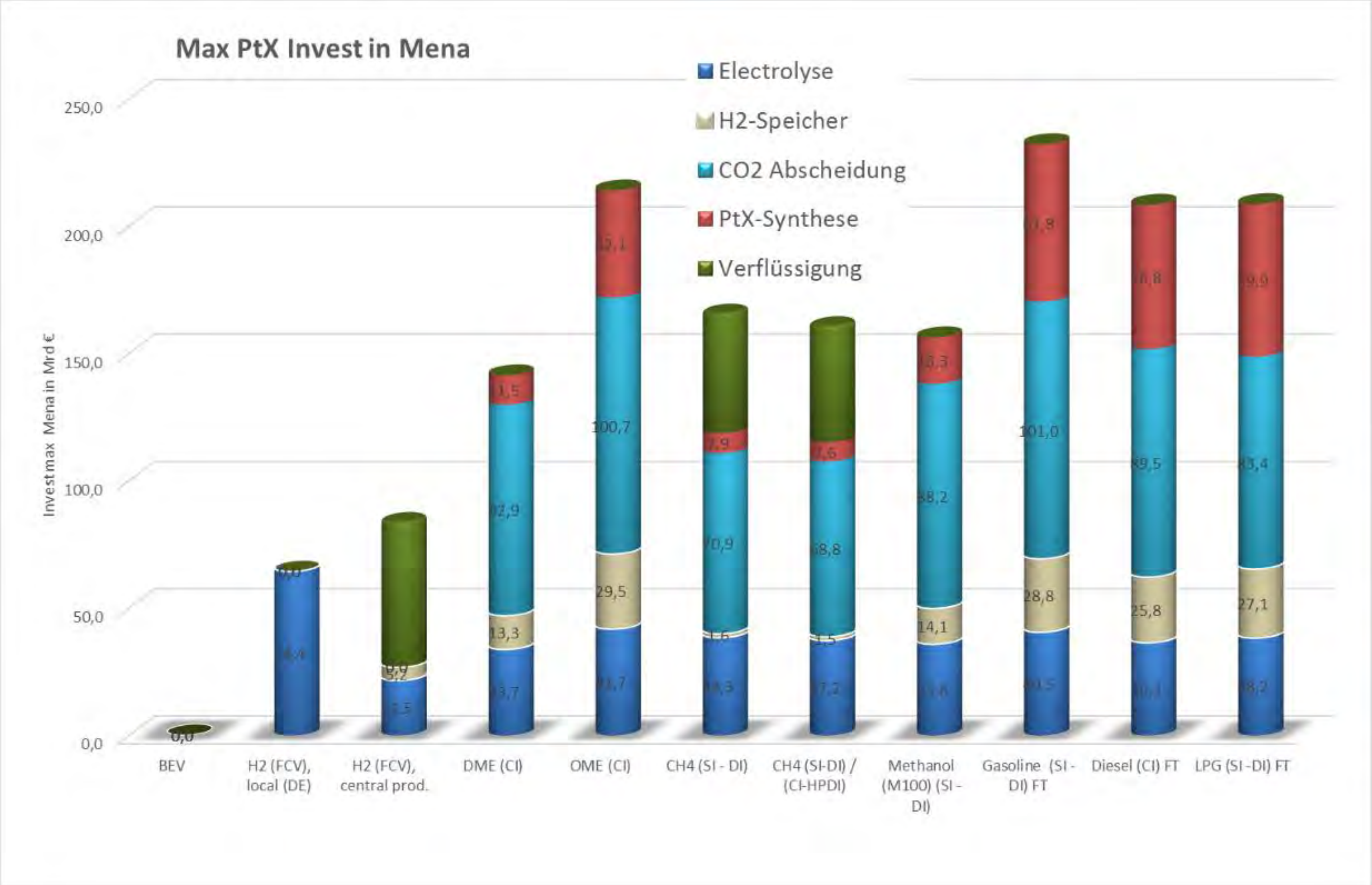
MEMO: Energy (Fuel) + Infrastructure Costs [€/100km]		FCV (central H2)	20.04 – 53.04 (x 4 – 2)
BEV:	30.37– 70.11 (x 3 - 2)	CH4	19.46 – 86.59 (x 3 – 1.5)
FCV (local H2)	69.55 – 114.60 (x 2)	FT Diesel	27.70 – 102,91 (x 3 – 1.5)

RESULTS – COSTS

Max. PtX-Synthesis investment costs in MENA incl. CO2 separation



- All PtX fuels require significant upfront investment costs
- Invest costs to substitute German fuel demand are:
  - 70 bln € for H2 central
  - 160 bln € for PTG (CH4)
  - 220 bln € for FT
- FT and OME likely to require highest invest costs due to complex process / lower efficiency
- Numbers do **not** include investment costs for solar / wind farm and infrastructure cost

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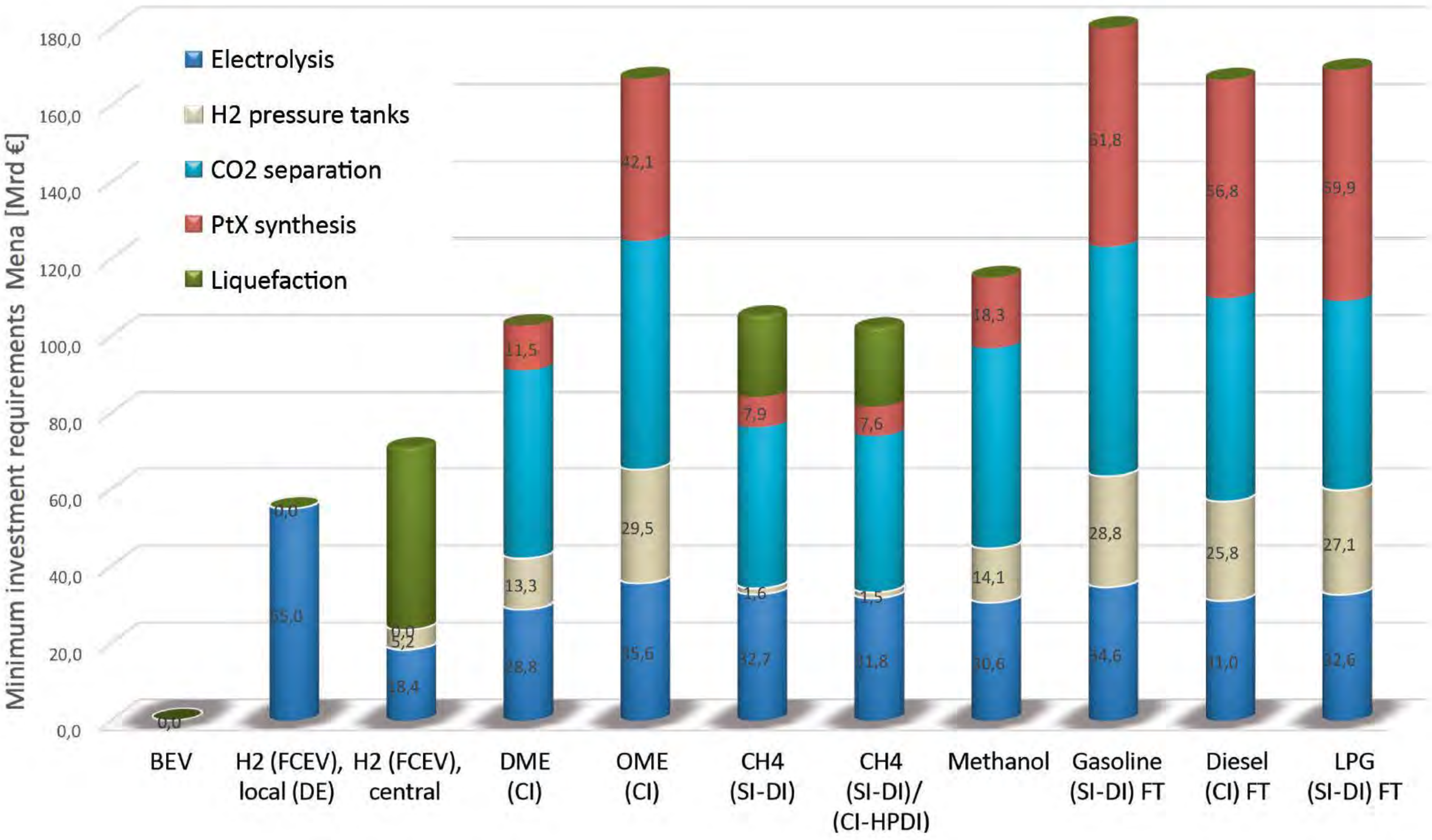
- **Invest risk is key hurdle for PtX!**

RESULTS – COSTS

Min. PtX-Synthesis investment costs in MENA (incl. CO2 separation)



- All PtX fuels require significant upfront investment costs
- Invest costs to substitute German fuel demand are:
  - ➢ 70 bln € for H2 central
  - ➢ 100 bln € for PTG (CH_4)
  - ➢ 170 bln € for FT
- FT and OME likely to require highest invest costs due to complex process / lower efficiency
- Numbers do **not** include investment costs for solar / wind farm and infrastructure cost

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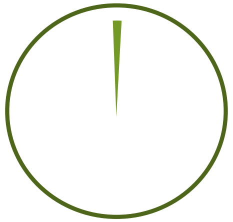
- **Invest risk is key hurdle for PtX!**

RESULTS – MARKET INTRODUCTION POTENTIAL – CHARGING TIME

E-Diesel / E-Gasoline

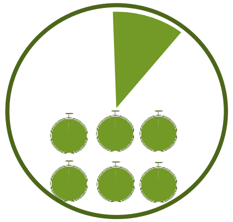
< 10 sec / 100km



35 l/min filling station
~20.5 MW charging power

BEV

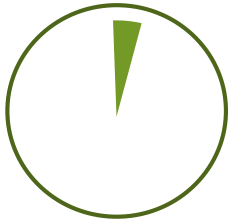
~ 6 hours to
~ 6 min / 100km



2,3 kW (household)
50 kW – 120 kW
(fast charging)

BEV (future)

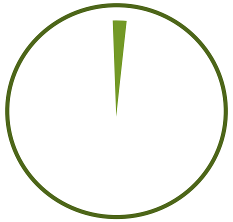
~ 3 min / 100km



Up to 350 kW planned
(German consortium)

FCEV

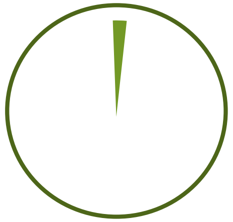
~ 30 sec / 100km



3-5 min for 4-7kg H_2
880 bar filling station, H_2 preconditioned to -40°C
~3 MW charging power

E-Methane

~ 30 sec / 100km



2-3 min for 20kg CH_4
≤ 300 bar filling station
(30 – 40 kW compressor: parallel re-fueling of 2 vehicles possible)
~6.5 MW charging power

- **Acceptable re-fill time (100 km in < 0.5 min) for all LD e-fuel scenarios and for FCEV. Similar for HD/MD.**
- **Today's BEV re-charging time (100 km in min. 6 min) requires changes in customer behavior.**
- **Customer acceptance for long distance travel questionable.**
- **Supplementary concepts required.**

RESULTS – ZERO IMPACT EMISSIONS CAPABILITY ASSESSMENT

- **Locally zero emissions only achievable with BEVs, FCEV and PHEV.**
- ***Zero-Impact-Emission-Mobility assessed to be achievable with all investigated combustion engine concepts.**
- **The research demand to achieve Zero-Impact-Emission-Mobility varies depending on the fuel /powertrain combination.**
- **CI concepts require more research than stoic. SI concepts**

** Exhaust gas emissions below accuracy limit of detection method; environmental impact below allowed immission limit according to BImSchG)*

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