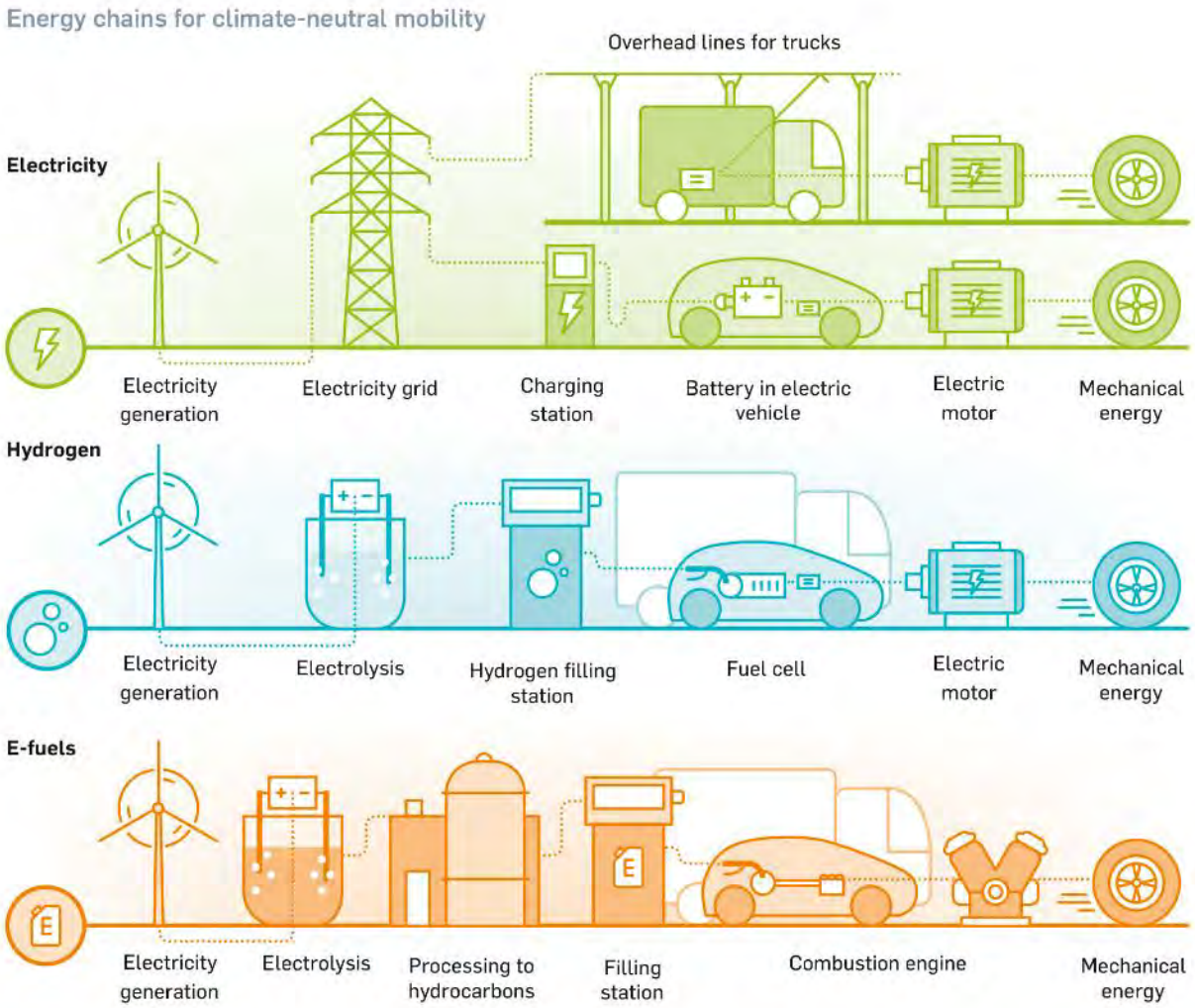


» Climate-neutral Driving in 2050 «

Options for the Complete Defossilization of the Transport Sector. Considerations Based on Results of the "FVV Fuel Study 2018".

40th International Vienna Motor Symposium, 17 May 2019

Dr. Ulrich Kramer	Ford-Werke GmbH, Köln
Stephan Stollenwerk	Innogy SE, Essen
Felix. Ortloff	DVGW Research Centre at EBI-KIT, Karlsruhe
Dr. Xavier Sava	BASF New Business GmbH, Ludwigshafen
Dr. A. Janssen	Shell Global Solutions GmbH, Hamburg
Steffen Eppler	Robert Bosch GmbH, Ludwigsburg
Harry Schüle	CPT Group GmbH, Regensburg
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Dr. Martin Lohrmann	Volkswagen AG, Wolfsburg
Arndt Döhler	Opel Automobile GmbH, Rüsselsheim
Dr. Lars Menger	BMW Group, München
Sebastian Barth	Honda R&D Europe, Offenbach
Werner Kübler	MAN Truck & Bus SE, Nürnberg
Ralf Thee	FVV, Frankfurt

FVV

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

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

Members of the FVV Working Group

Fuel production – WtT



Involved companies:

- BASF
- BP
- Continental (Emitec)
- DVGW (EBI/KIT)
- Innogy
- Shell

Jointly defined evaluation matrix

Joint well-to-wheel assessment

Vehicle manufacturing – TtW



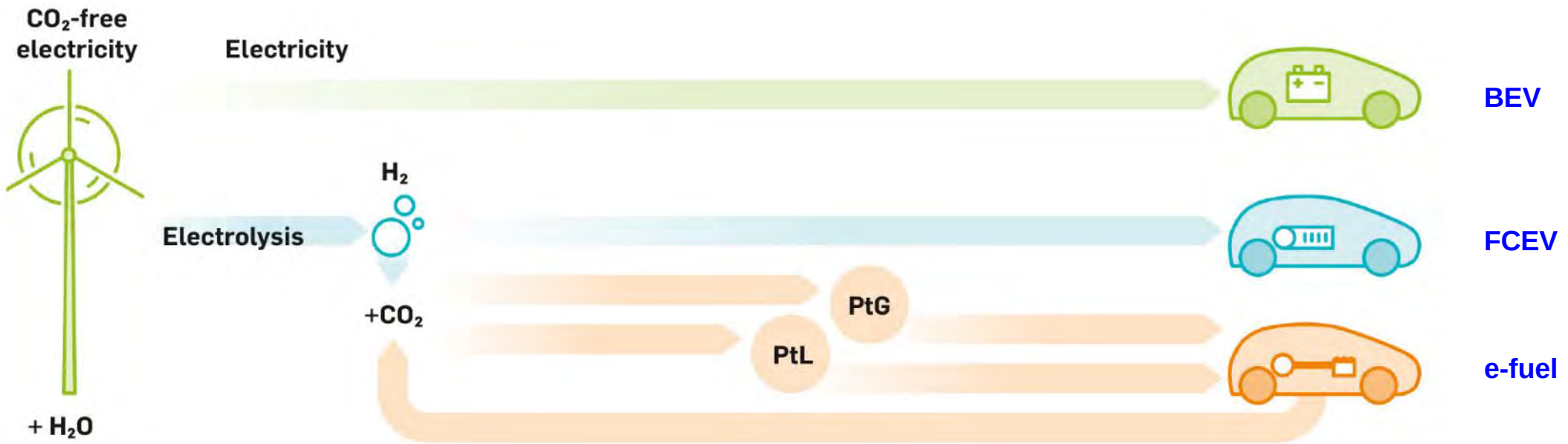
Involved companies:

- Audi
- BMW
- Bosch
- Continental
- Ford
- Honda
- MAN
- MTU
- Opel
- Volkswagen
- Volvo Cars

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

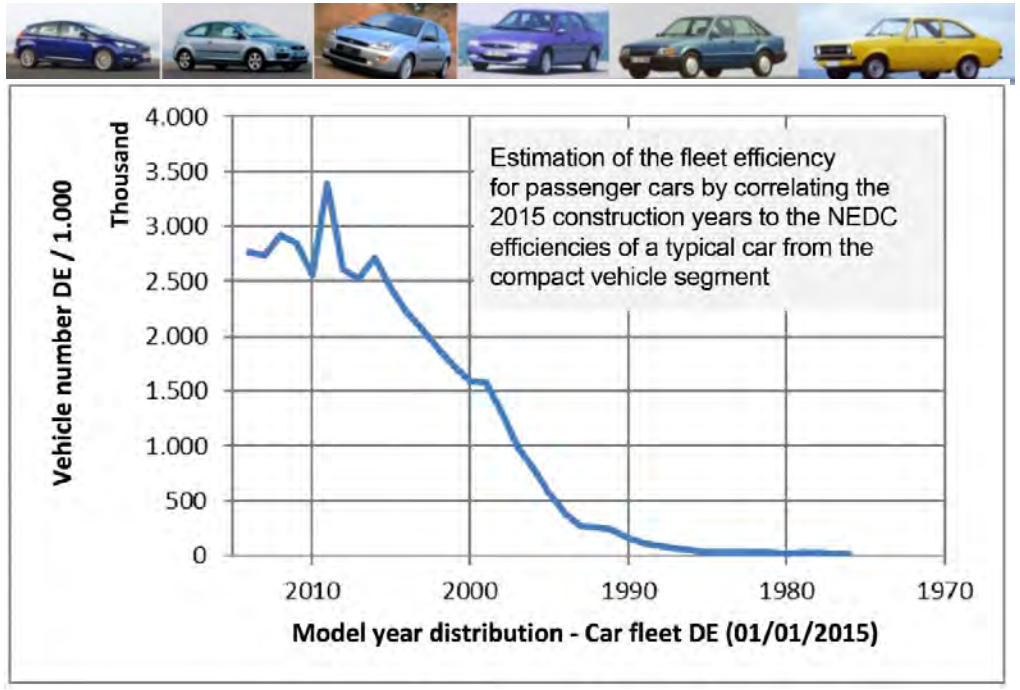
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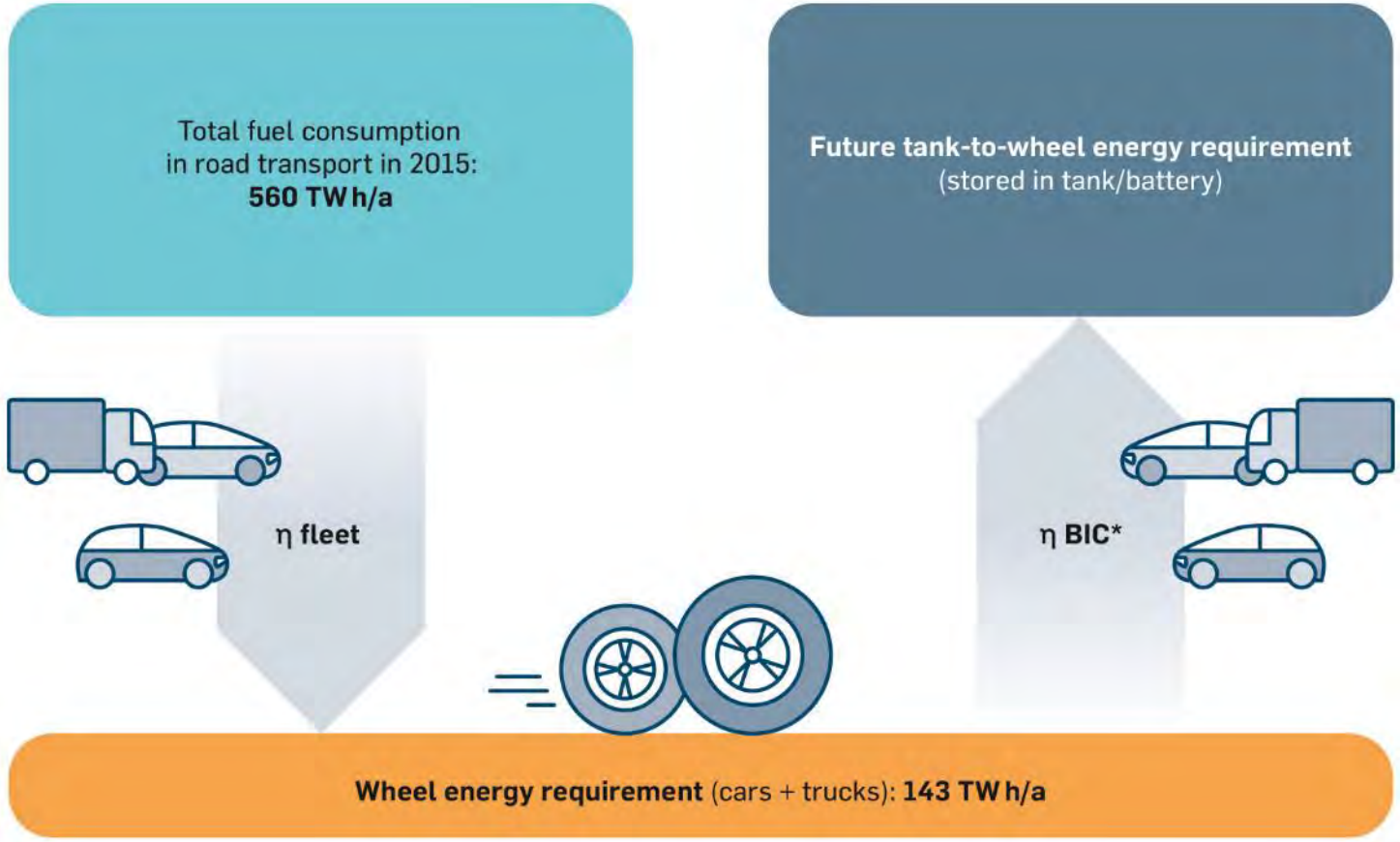
ASSUMPTIONS: ESTIMATION OF “FUTURE ENERGY DEMAND”

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:** **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) 2018 price lists OEMs retro fitter price lists  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**
CO2 Source for PTX-Production	Ambient air (**approx. 125 €** / t CO2)	Ambient air (**approx. 188 €** / t CO2)
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





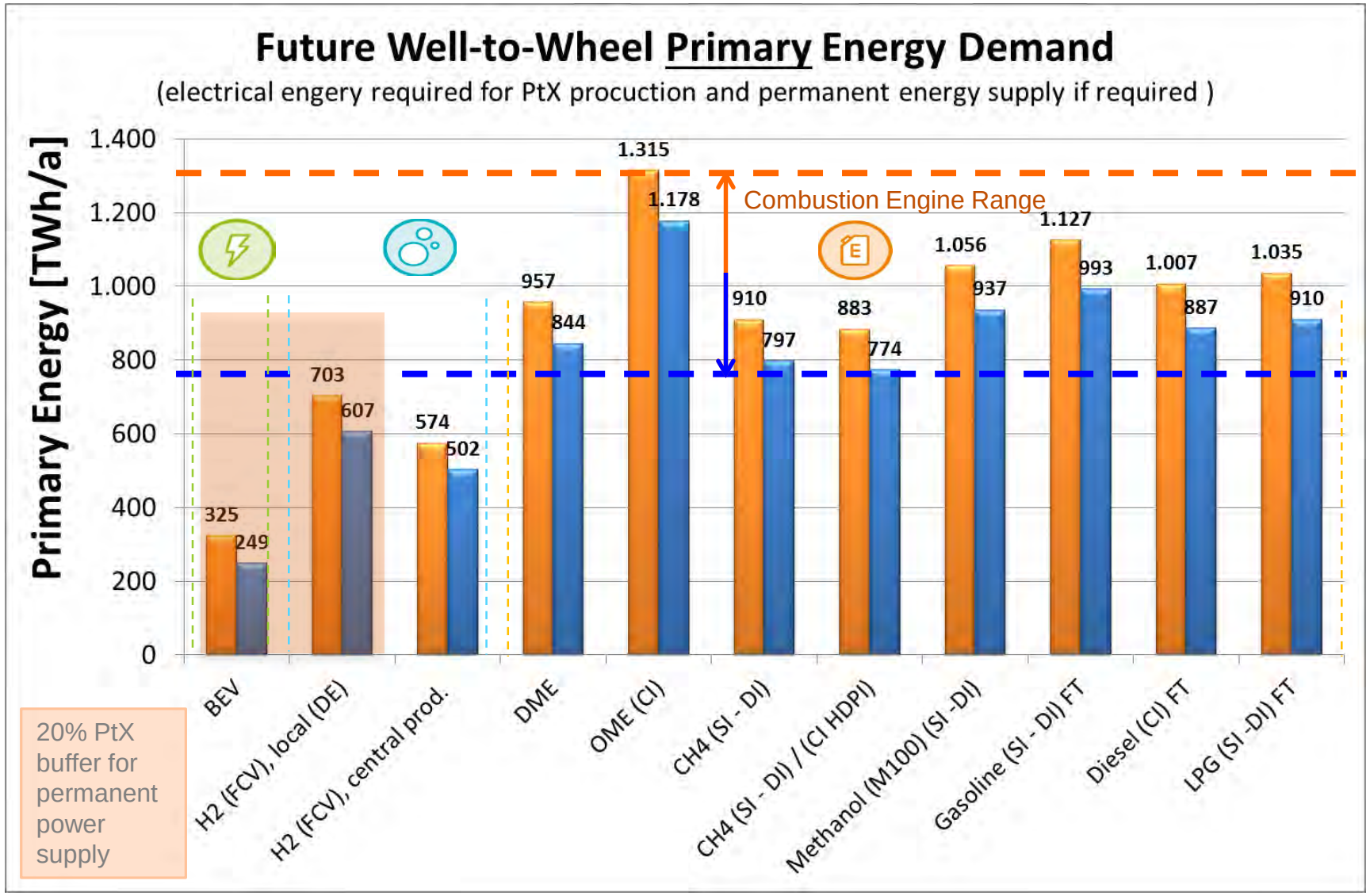




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RESULTS - PRIMARY ENERGY DEMAND



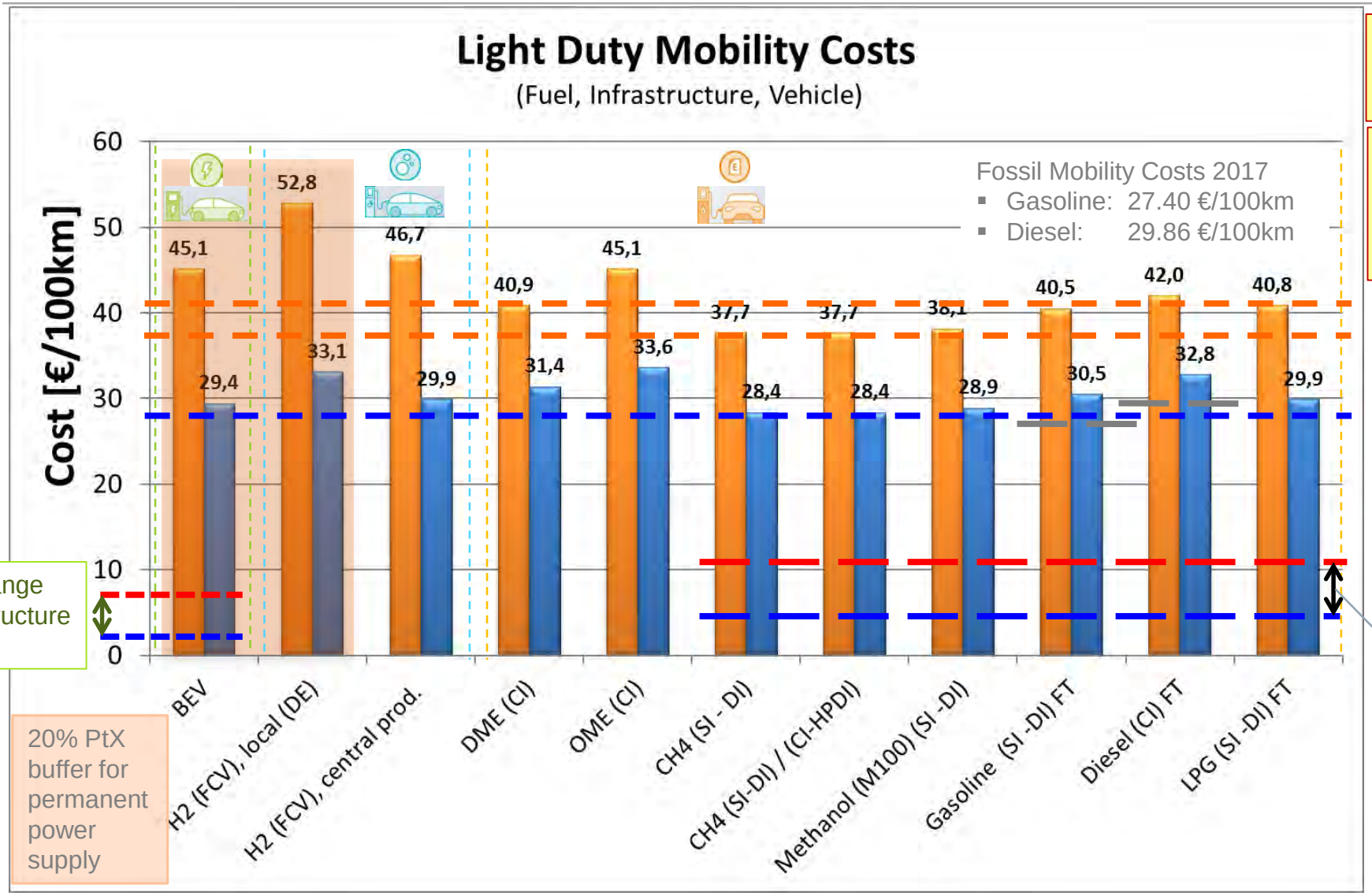
- **Lowest primary energy demand for BEV: 7 - 9% Primary Energy DE 2015 (PE_{2015})**
- **E-$H_{2\ (Central)}$ 14-16% PE_{2015}**
- **E-$CH_{4\ (HPDI)}$ 21-24% PE_{2015}**
- **E-$FT_{(50/50)}$ 26-29% PE_{2015}**

- 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 – MOBILITY COSTS - LD



BEV range Infrastructure + Fuel

20% PtX buffer for permanent power supply

- **All pathways more expensive than fossil fuel**
- **LD mobility cost opportunities e-fuels → same ball park as BEV / FCEV**

Max E-FT-Diesel/Gasoline (50/50)
Max E-Methane

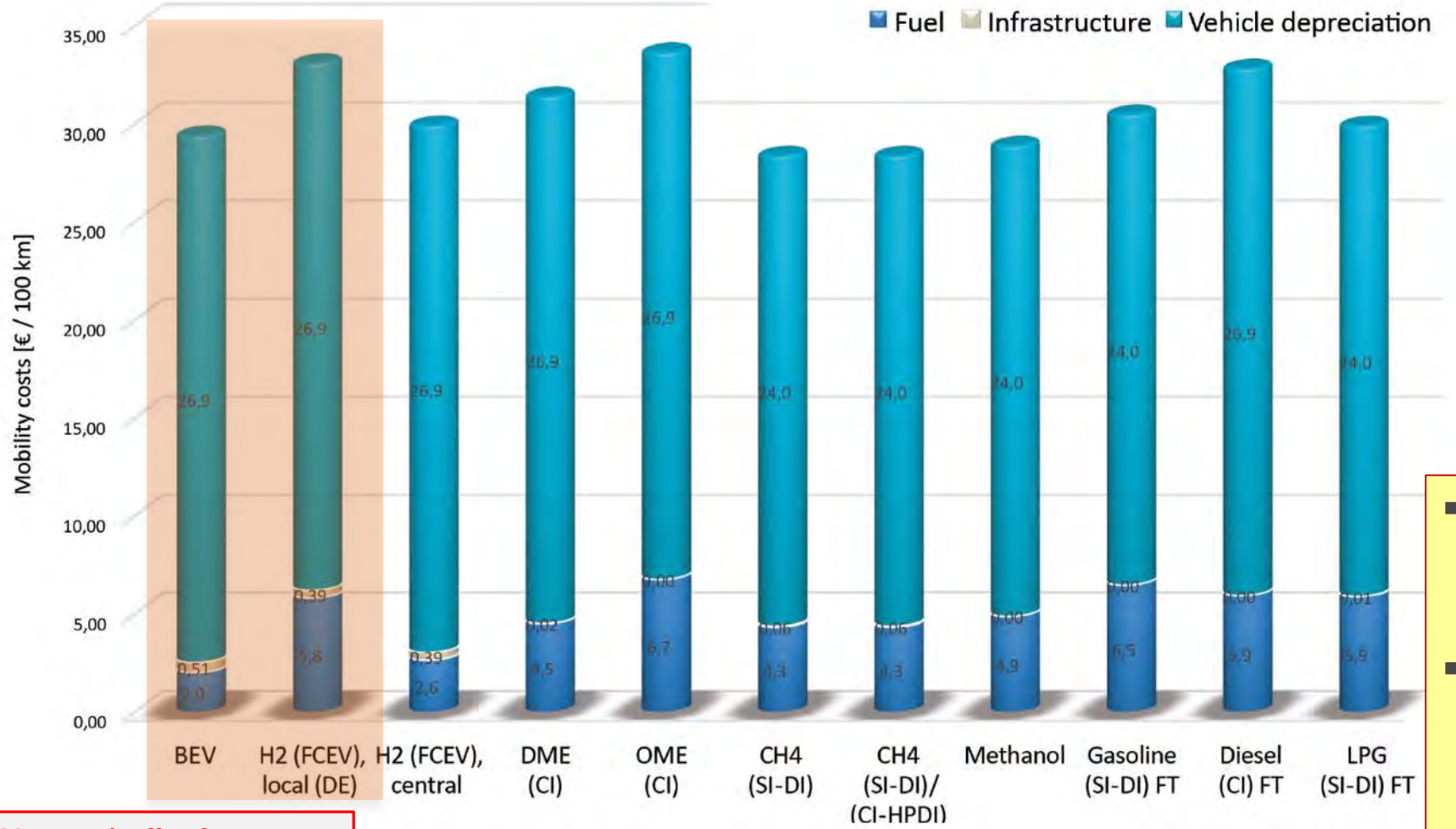
Min E-Fuel (E-Methane)

- **Cost Risk for BEV and FCEV higher than for E-Fuel pathways**

E-Methane range (Infrastructure + Fuel)

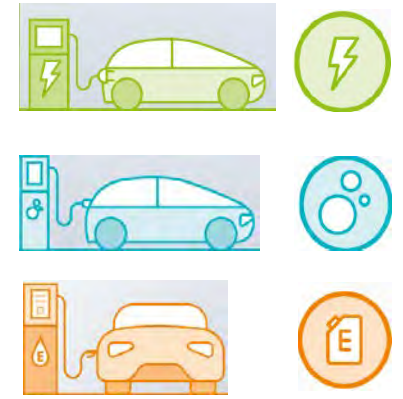
- Max. Cost: min. process efficiency, CO_2 form air, production in Germany
- Min. Cost: max. process efficiency, CO_2 form air, production in MENA (except of BEV, H2-local)

RESULTS – MIN. MOBILITY COSTS - LD



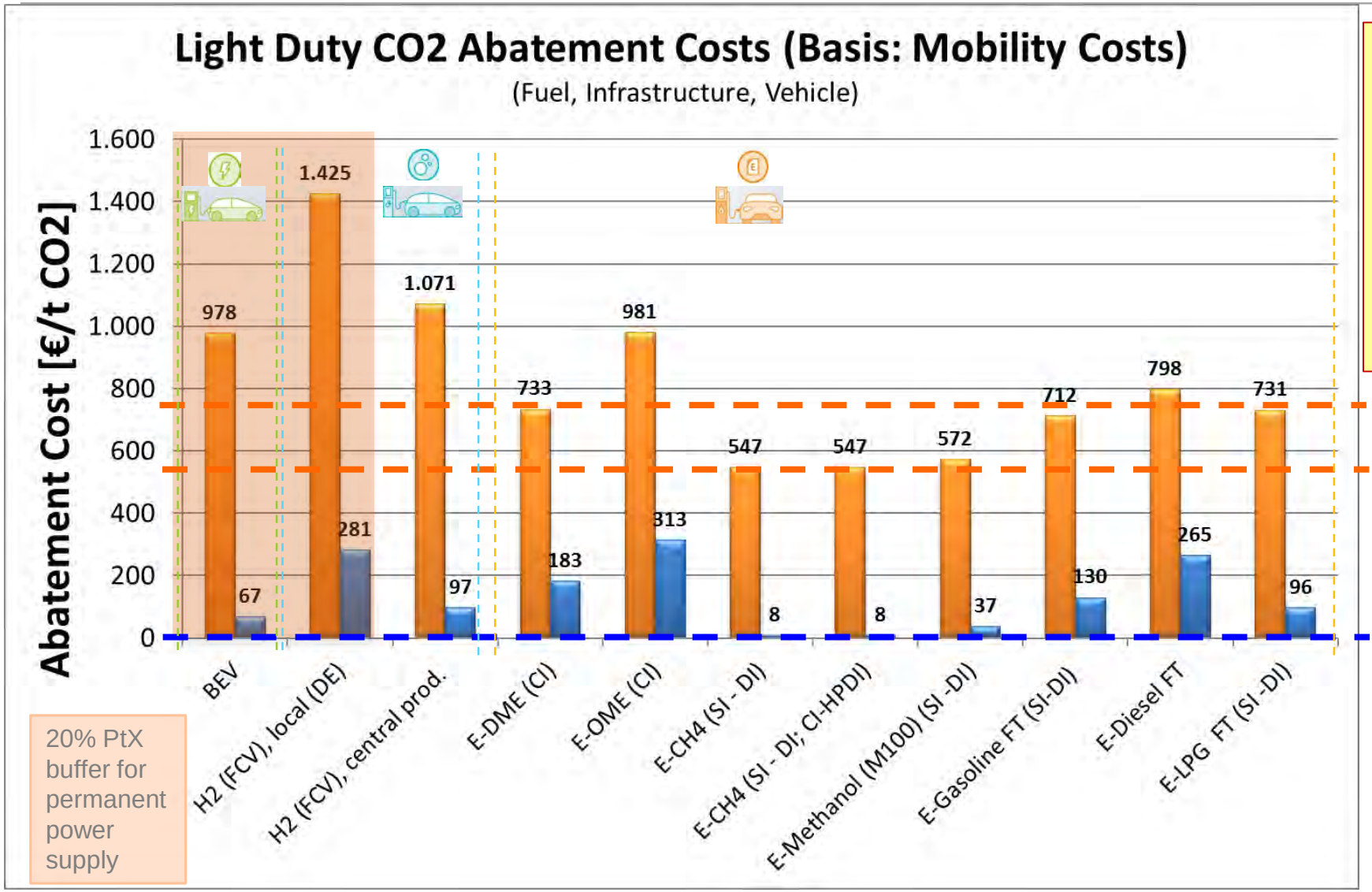
20% PtX buffer for constant power supply

LD Mobility Cost Brake Down (Min. Cost Scenario)



- LD vehicle depreciation dominates the mobility costs
- MEMO: Vehicle depreciation difficult to predict, in particular for BEV / FCEV → Research Demand

RESULTS – CO_2 ABATEMENT COSTS - LD



20% PtX buffer for permanent power supply

- **Min LD CO_2 abatement costs (E-Methane 8 €/tCO_2) 8.4x lower than BEV (67 €/tCO_2)**
- **Max cost risk BEV (978 €/tCO_2) 1.8x higher than E-Methane (547 €/tCO_2)**

Max E-FT-Diesel/Gasoline (50/50)

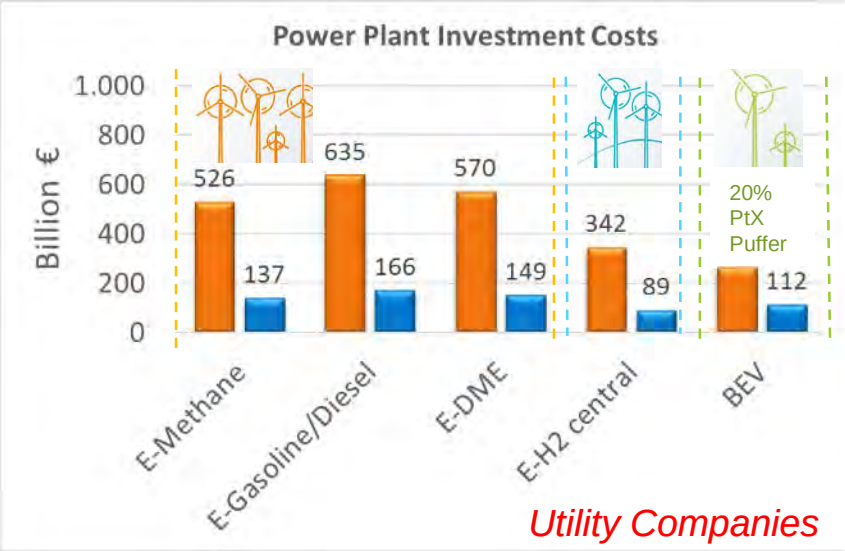
Max E-Methane

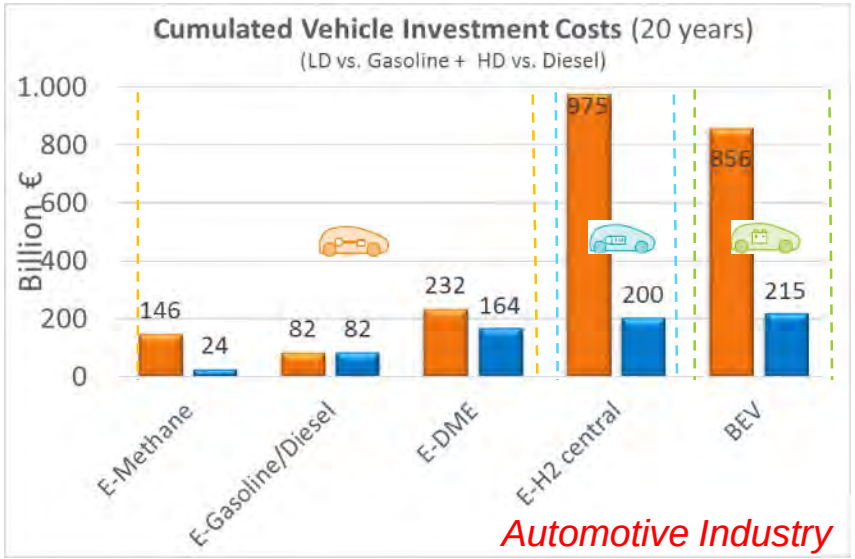
- **.. & 1.3x higher than E-Diesel/ Gasoline (50/50) (755 €/tCO_2)**

Min E-Fuel (E-Methane)

- 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)

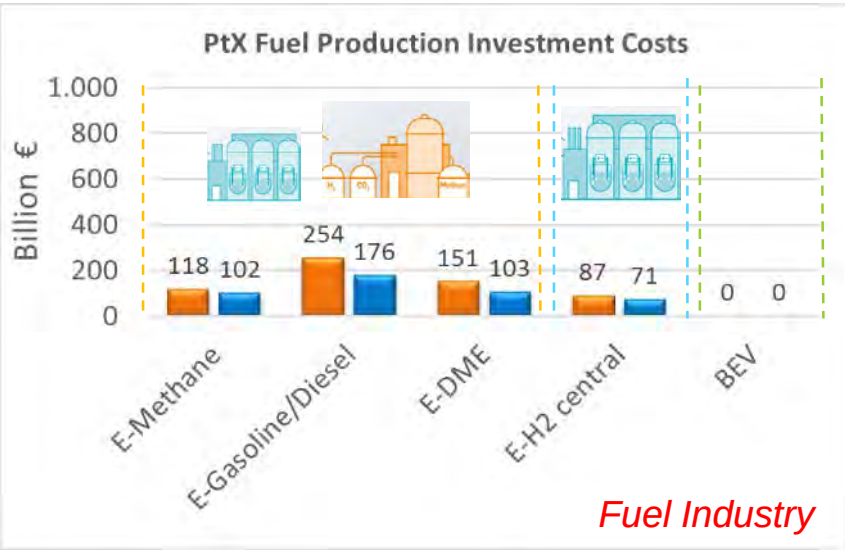
RESULTS – INVESTMENT COSTS

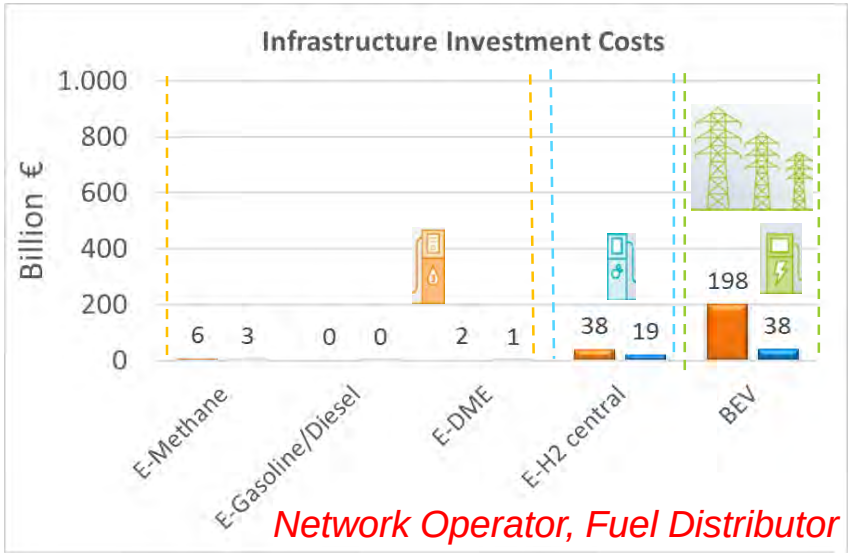




**Cumulated vehicle on-costs (LD vs. Gasoline; HD vs. Diesel) over 20 years: 3.4 Mio. LD pa & 50k HD pa*

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



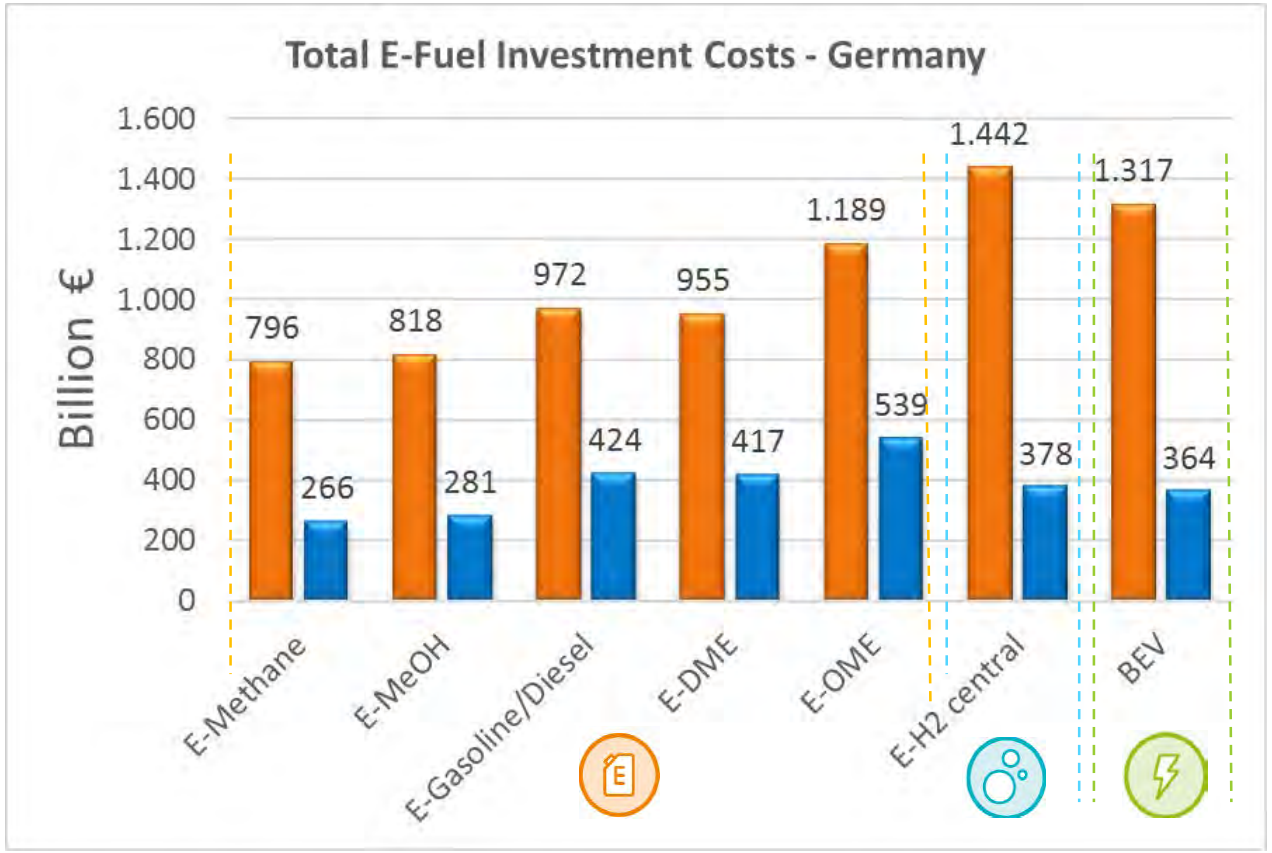


- **Highest cost risk at automotive industry for BEV and FCEV.**

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.**

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PARAMETER VARIATION - ASSUMPTIONS: LD HYBRIDIZATION

	Min Cost Scenario (Hybrid)	Max Cost Scenario (Hybrid)
LD Vehicle Costs **Basis:** **Gasoline Vehicle** **C-segment** **(Non-Hybrid)** **Base Price 20.000 €** **Depreciation** (according to ADAC 15.000 km/a, 4 years): **300 € / month**	Assumption for 2050: Cost Parity of BEV and FCEV to non-hybrid diesel BEV500: (20,000 +2,400) € = 22,400 € FCEV (20,000 +2,400) € = 22,400 € **Gasoline: (20,000 +1,460) € = 21,460 €** Diesel/OME (20,000 +2,400 +1,460) € = 23,860 € Methane (20,000 +1,460) € = 21,460 €	On-cost according to Roland Berger Auto-Oil Study (2030) 2018 OEM retro fitter price lists BEV500: (20,000 +11,300) € = 31,300 € FCEV: (20,000 +12,500) € = 32,500 € **Gasoline: (20,000 +1,460) € = 21,460 €** Diesel/OME: (20,000 +2,400 +1,460) € = 23,860 € Methane (20,000 +1,800 +1,460) € = 23,260 €
	  	
	• **Hybridization on-cost** according to Roland Berger Auto-Oil Study (2030). Average of Mild Hybrid and Full Hybrid": **1,460 €.** • **Hybridization efficiency benefit:** Average "Mild & Full Hybrid": **15 %**	

PARAMETER VARIATION - ASSUMPTIONS: ALL-SEASON OPERATION

Pathway	Assumptions
All	**Temperature basis** for energy consumption in Fuel Matrix: **20°C** (in accordance to NEDC conditions). **Average Temperature Germany*: 9.05 °C** Average trip distance/speed**: 14.7 km / 42.2 km/h (3.4 trips /day) Average mileage per vehicle per year***: 14.416 km → 39.5 km/day → 0.926 driving hours / day Assumption: 1/3 of the daily trips require cold starts → 1.133 cold starts / day
BEV 	Losses for cabin heating (PTC) and battery heating at -10°C****: 42.1 % Permanent Heating at -10°C required **Efficiency reduction: 15.4 %**
FCEV 	Losses for cabin heating (PTC) and battery heating at -10°C*****: 19 % Heating time until PTC off (60°C FC temp.): 640 s **Efficiency reduction: 1.5 %**
E-Fuel 	Losses for cabin heating (PTC) at -10°C******: 13% Heating time until PTC off (engine warm): 600 s **Efficiency reduction: 1.0 %**

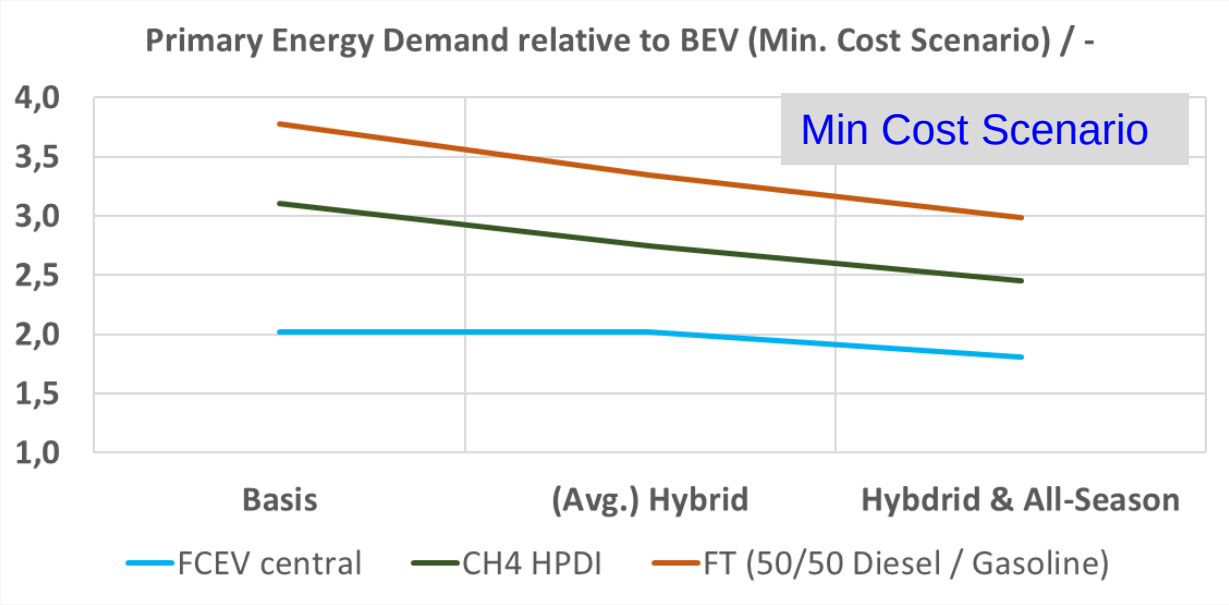
* https://www.wetter.de/klima/europa/deutschland/berlin-s99000032.html
** https://www.adac.de/_mmm/pdf/statistik_mobilitaet_in_deutschland_0111_46603.pdf
*** http://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/verkehr_in_kilometern_node.html

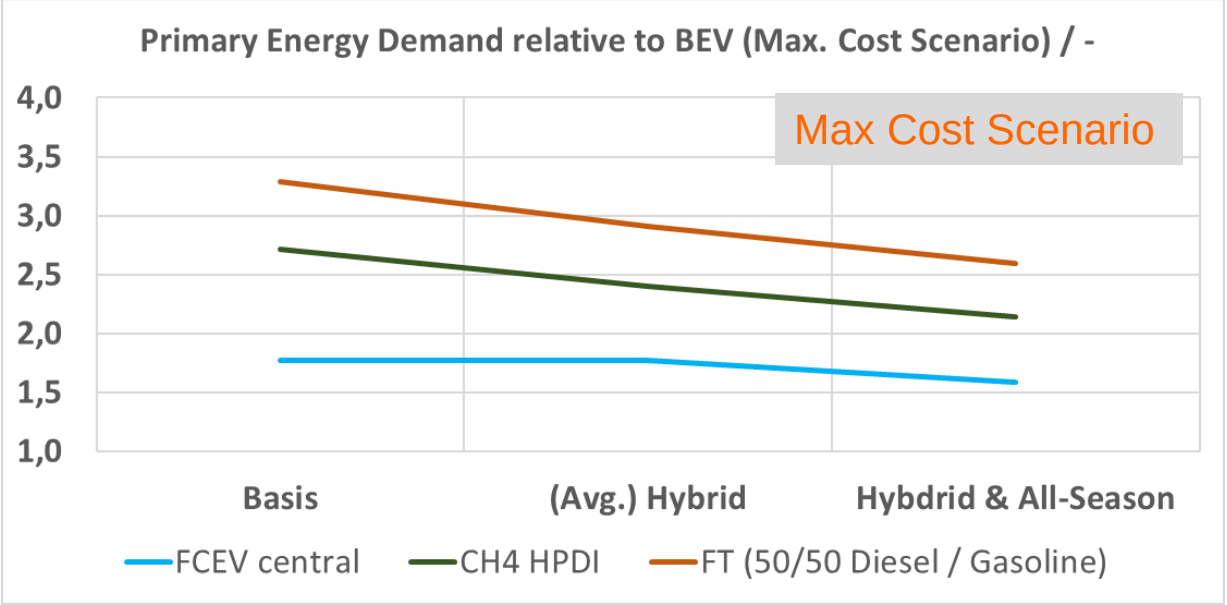
**** Prof. Pischinger 2nd International FEV Conference Zero CO_2 Mobility, Aachen, Nov. 13th 2018, p. 15
***** Internal FCEV Simulation CD-segment Vehicle: Ford-Werke GmbH
****** Internal Assessment Ford-Werke GmbH

PARAMETER VARIATION - PRIMARY ENERGY DEMAND - LD HYBRID/ALL-SEASON WALK

Passenger Car (LD) Walk → LD Avg. Hybrid → All-Season Operation Primary Energy Demand vs. BEV (Selected Pathways)

- 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)





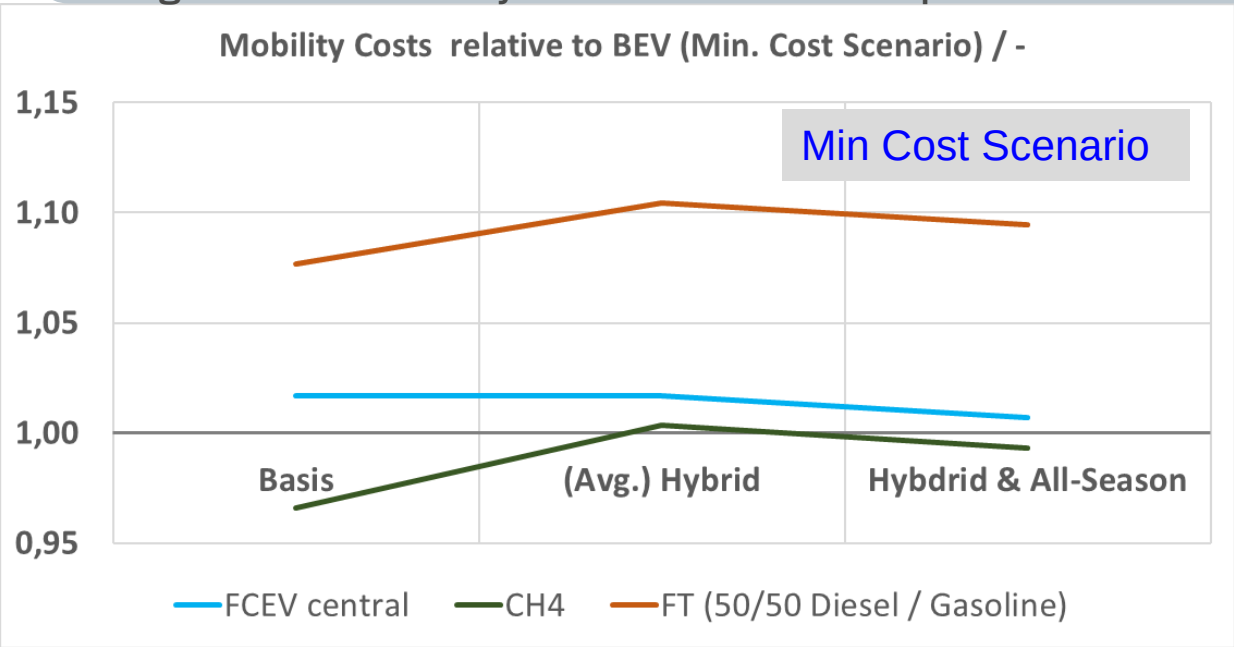
Primary Energy Demand relative to BEV decreases under <u>average hybrid and all-season conditions to …</u>:

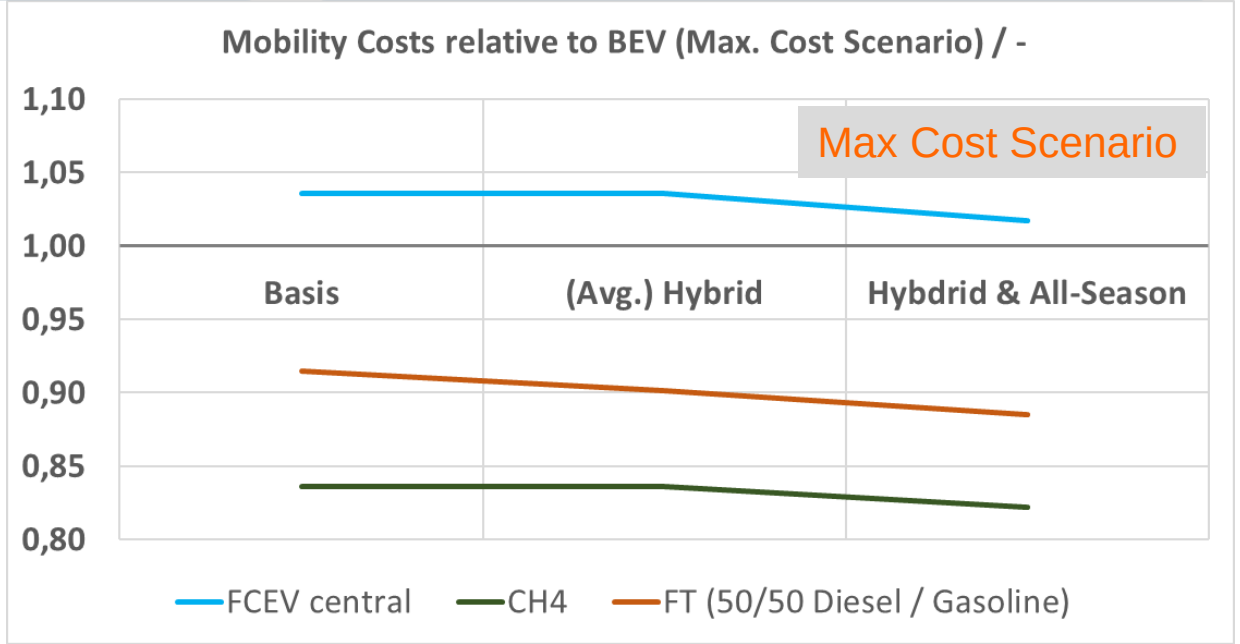
- **E-$H_{2\ (Central)}$: 1.6 – 1.8 x Primary Energy Demand BEV**
- **E-$CH_{4\ (HPDI)}$: 2.1 – 2.5 x Primary Energy Demand BEV**
- **E-$FT_{(50/50)}$: 2.6 – 3.0 x Primary Energy Demand BEV**

PARAMETER VARIATION - MOBILITY COSTS - LD HYBRID/ALL-SEASON WALK

MEMO:
- No taxes on fuel
- Fuel cost prediction for future (2030...2050) high volume fuel production
- Mobility costs dominated by vehicles costs
- Significant insecurity in future vehicle cost prediction

⇒ Hybridization reasonable for "transition to 100 % sustainable" and as long as fuel cost targets are not met





LD Mobility Costs relative to BEV increase with hybridization when e-fuel costs are low (min cost scenario):

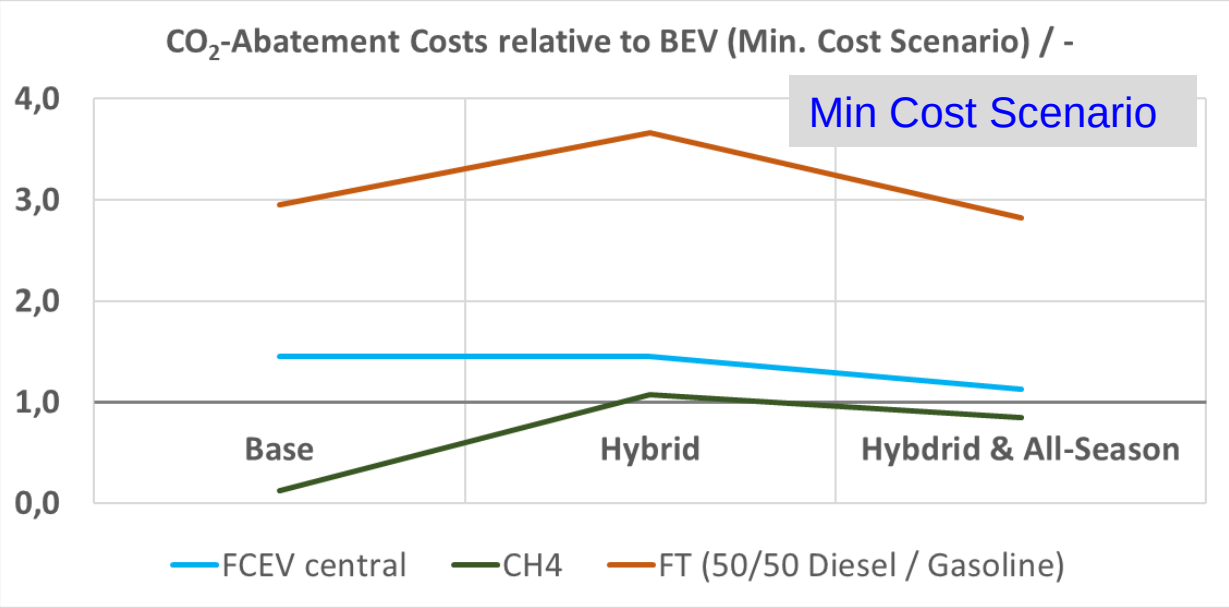
- **E-$H_{2\ (Central)}$: 1.01– 1.02 x LD Mobility Costs BEV***
- **E-$CH_{4\ (HPDI)}$: 0.82 – 0.99 x LD Mobility Costs BEV***
- **E-$FT_{(50/50)}$: 0.88 – 1.09 x LD Mobility Costs BEV***

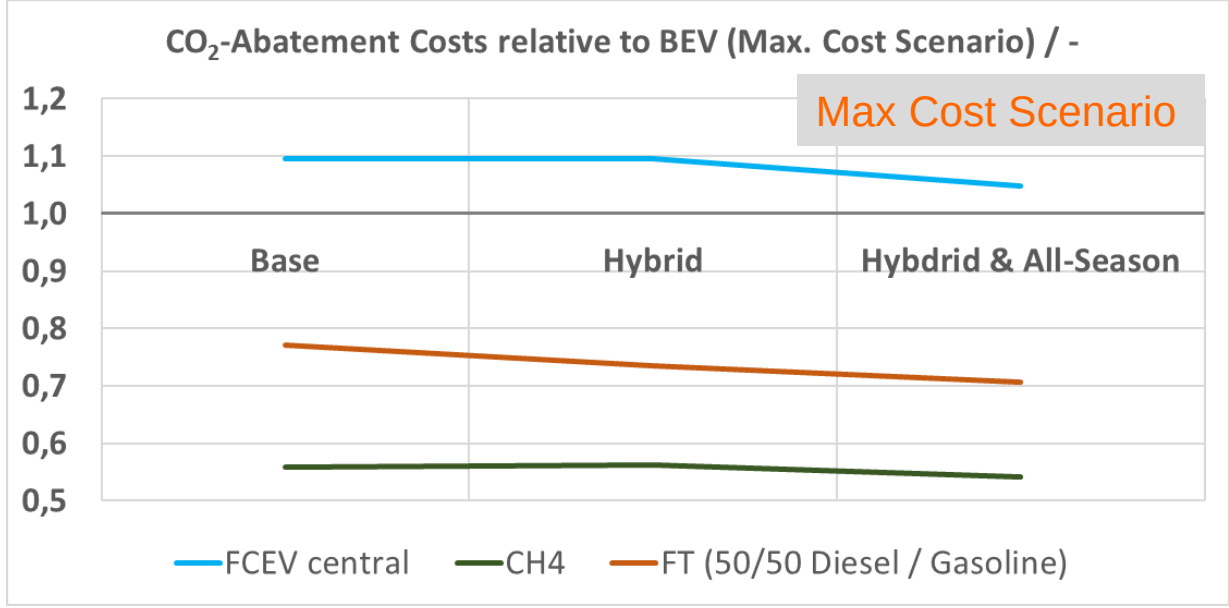
**average hybrid & all-season conditions*

PARAMETER VARIATION - LD CO_2 ABATEMENT COSTS - LD HYBRID/ALL-SEASON WALK

Passenger Car (LD) Walk → LD Avg. Hybrid → All-Season Operation
LD CO_2 Abatement Costs vs. BEV (Selected Pathways)

- 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)





LD CO_2 Abatement Costs rel. to BEV increase with hybridization when e-fuel costs are low (min cost sc.):

- **E-$H_{2\ (Central)}$: 1.05 – 1.13 x LD CO_2 Abatement Costs BEV***
- **E-$CH_{4\ (HPDI)}$: 0.54 – 0.84 x LD CO_2 Abatement Costs BEV***
- **E-$FT_{(50/50)}$: 0.71 – 2.82 x LD CO_2 Abatement Costs BEV***

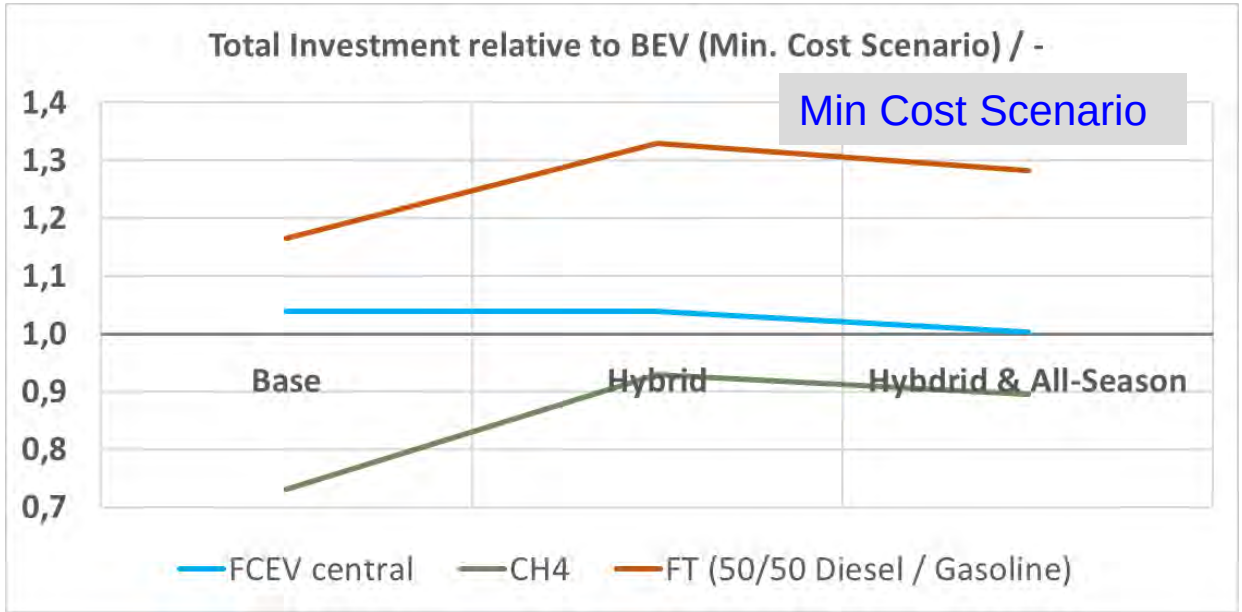
**average hybrid & all-season conditions*

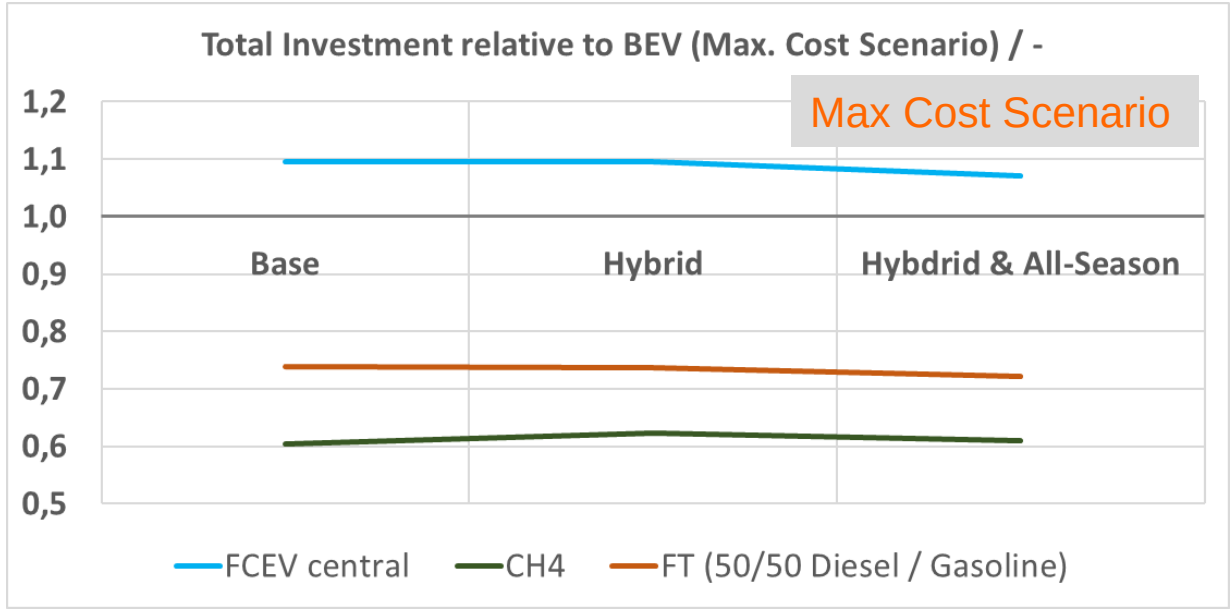
MEMO:
CO_2 abatement cost based on future high volume fuel production and vehicle costs (100% scenarios!)

PARAMETER VARIATION – TOTAL INVESTMENT – LD HYBRID/ALL-SEASON WALK

Passenger Car (LD) Walk → LD Avg. Hybrid → All-Season Operation
Total Investment Costs vs. BEV (Selected Pathways)

- 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)





Total Investment Costs relative to BEV increase with hybridization and decrease under all-season conditions:

- **E-$H_{2\ (Central)}$:** 1.00 – 1.07 x Total Investment BEV*
- **E-$CH_{4\ (HPDI)}$:** 0.61 – 0.89 x Total Investment BEV*
- **E-$FT_{(50/50)}$:** 0.72 – 1.28 x Total Investment BEV*

**average hybrid & all-season conditions*

MEMO:
CO_2 abatement cost based on future high volume fuel production and vehicle costs (100% scenarios!)

CONTENT

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

SUMMARY *(for the long-term 100% scenario consideration)*

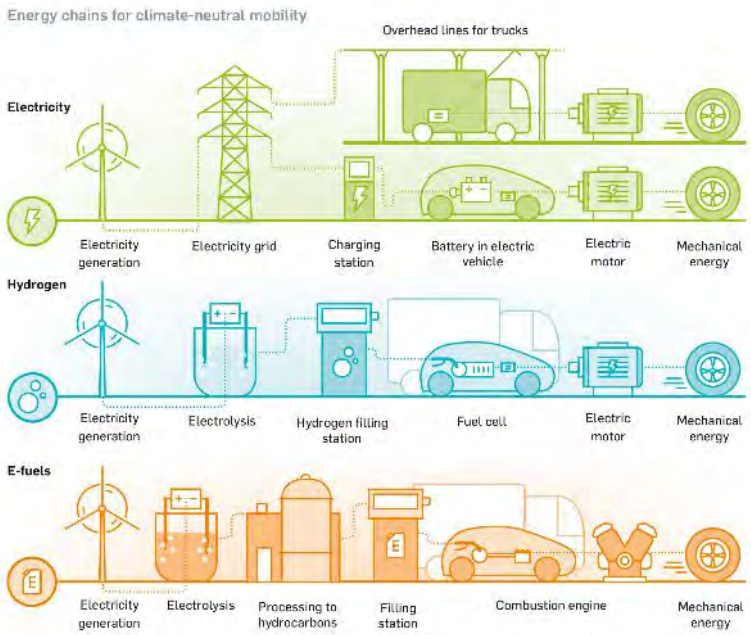
- **Even if not realistic, “100% scenarios” are an effective tool for a simple technology comparison**
- **100% sustainable mobility in 2050 possible with BEV, FCEV and E-Fuel (-HEV)**
- **Primary energy demand of E-Fuel pathways relative to BEV is in the range of 1.6 – 3.0.**

- **The vehicle costs dominate the mobility costs (not the E-Fuel costs).**
  - **On-costs for BEV and FCEV have a significant impact, but are difficult to predict**
- **E-Fuel based LD mobility costs relative to BEV are in the range of 0.8 – 1.1.**

- **All pathways require significant investment costs.**
- **Total investment costs for E-Fuel relative to BEV are in the range of 0.6 – 1.3.**
- **Long term investment is the key hurdle for E-Fuel**
- **Appropriate legislative conditions mandatory, e.g. recognition of E-Fuel CO_2 benefit.**

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.

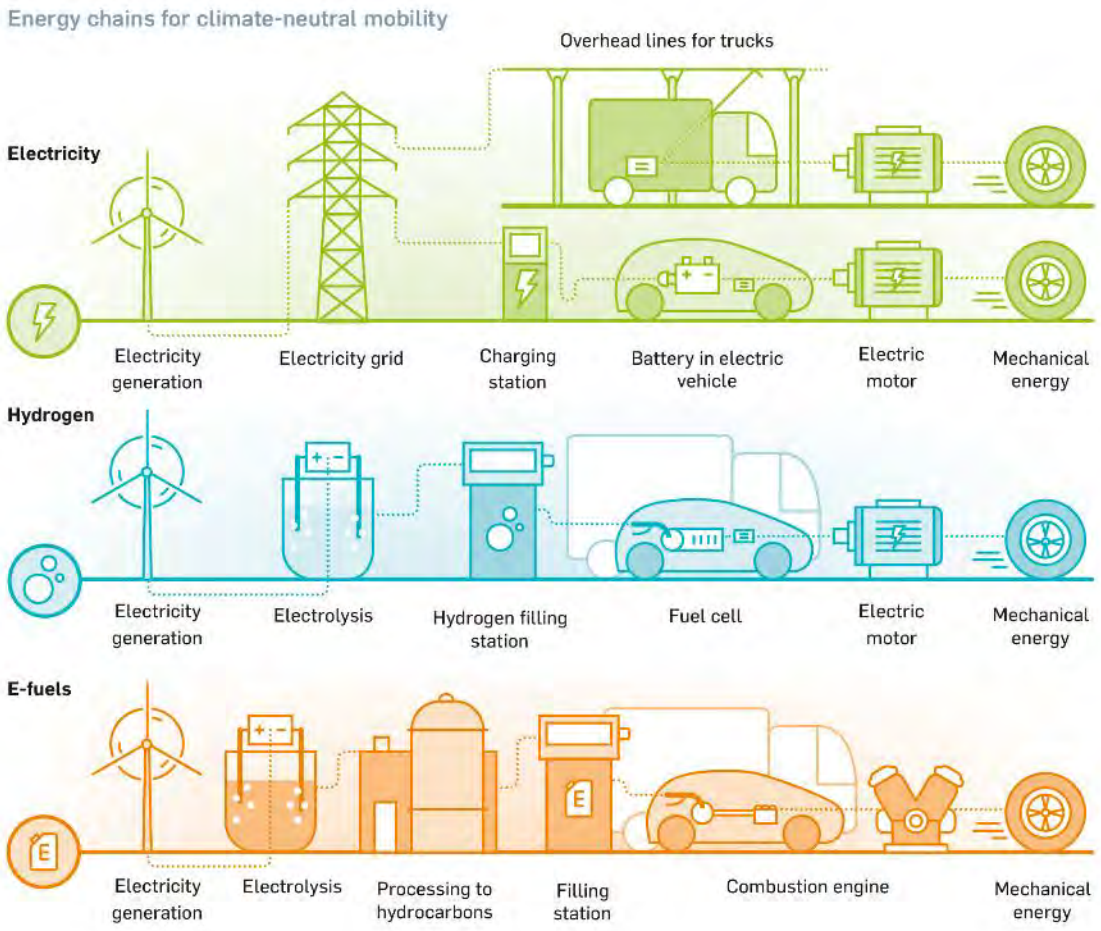


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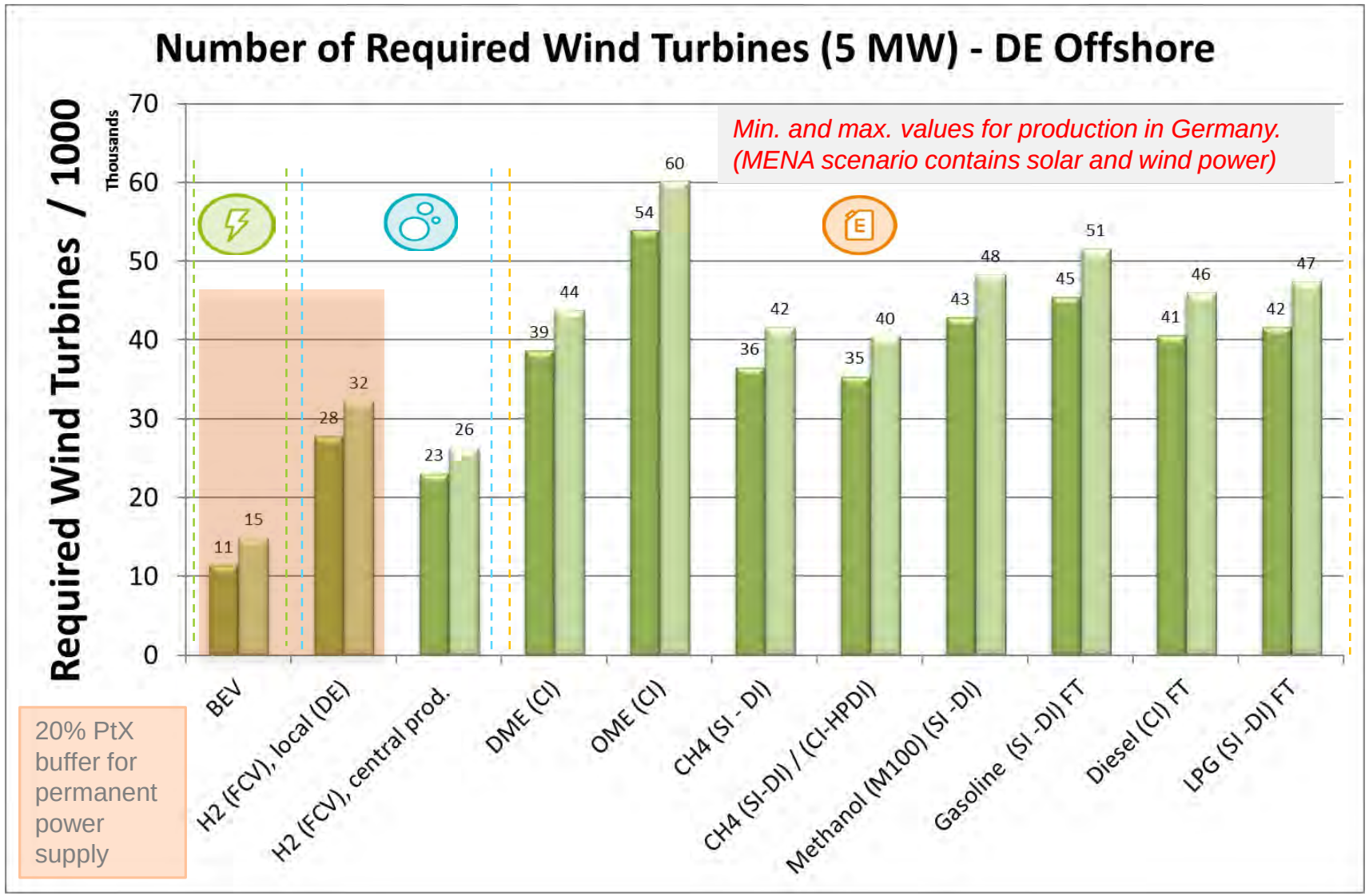
Thank you very much for your attention.

Questions?

FVV Working Group Future Fuels

Dr. Ulrich Kramer
Ford-Werke GmbH

RESULTS - NUMBER OF WIND TURBINES



20% PtX buffer for permanent power supply

- **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*

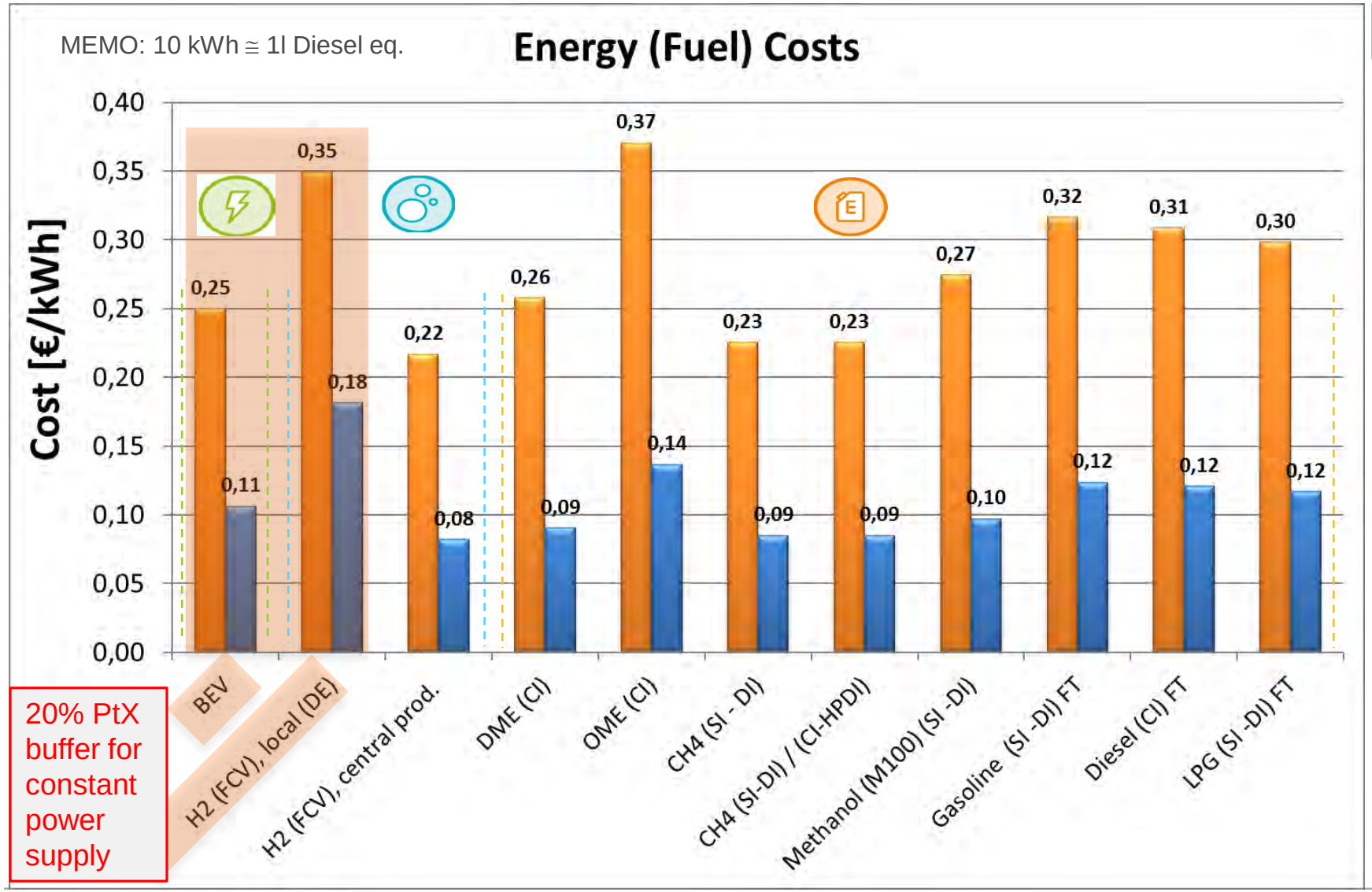
** 5 MW offshore North Sea*

- 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

RESULTS – FUEL COSTS PER ENERGY UNIT



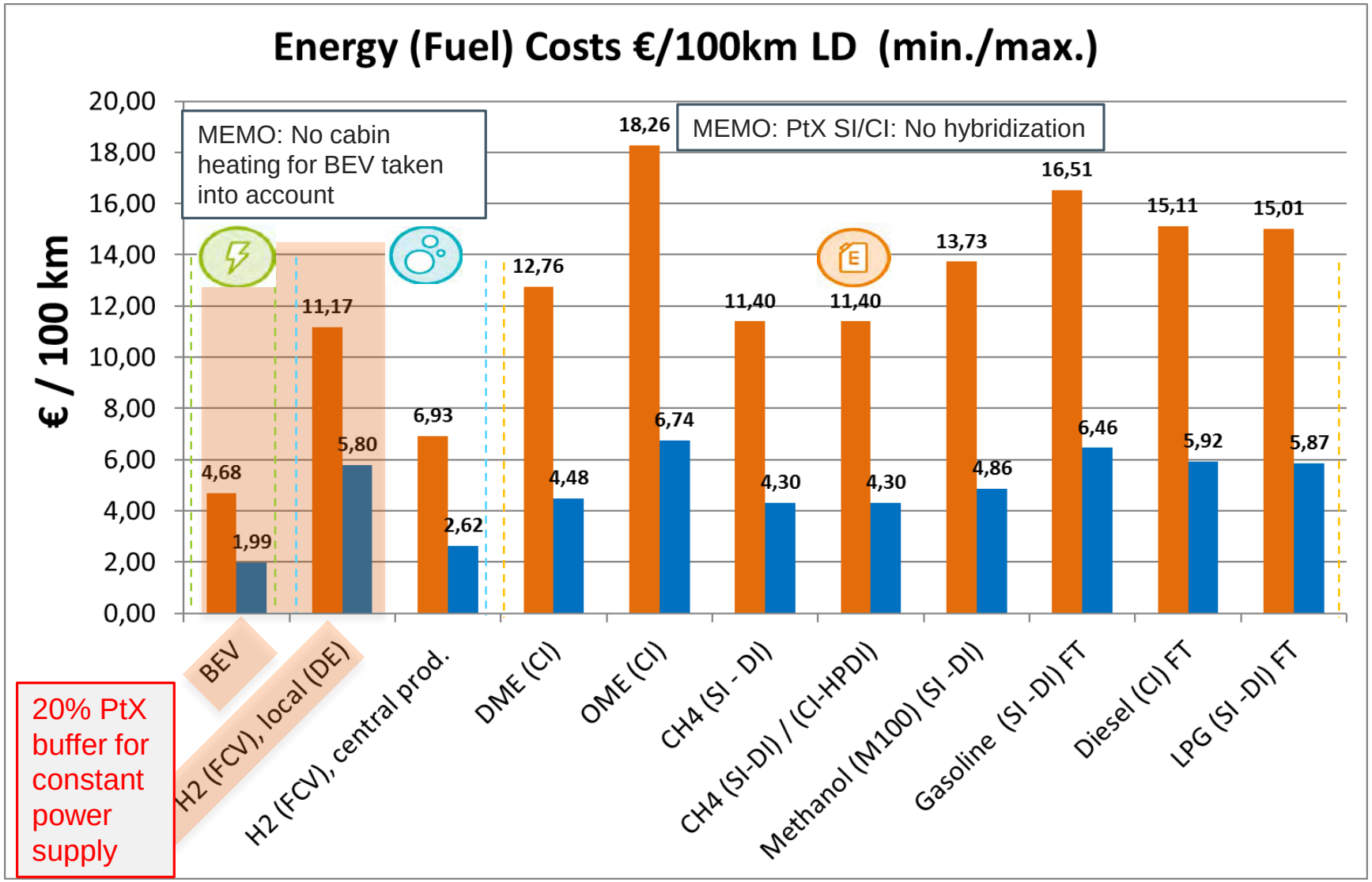
20% PtX buffer for constant power supply

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



20% PtX buffer for constant power supply

Electricity Costs [€/MWh]

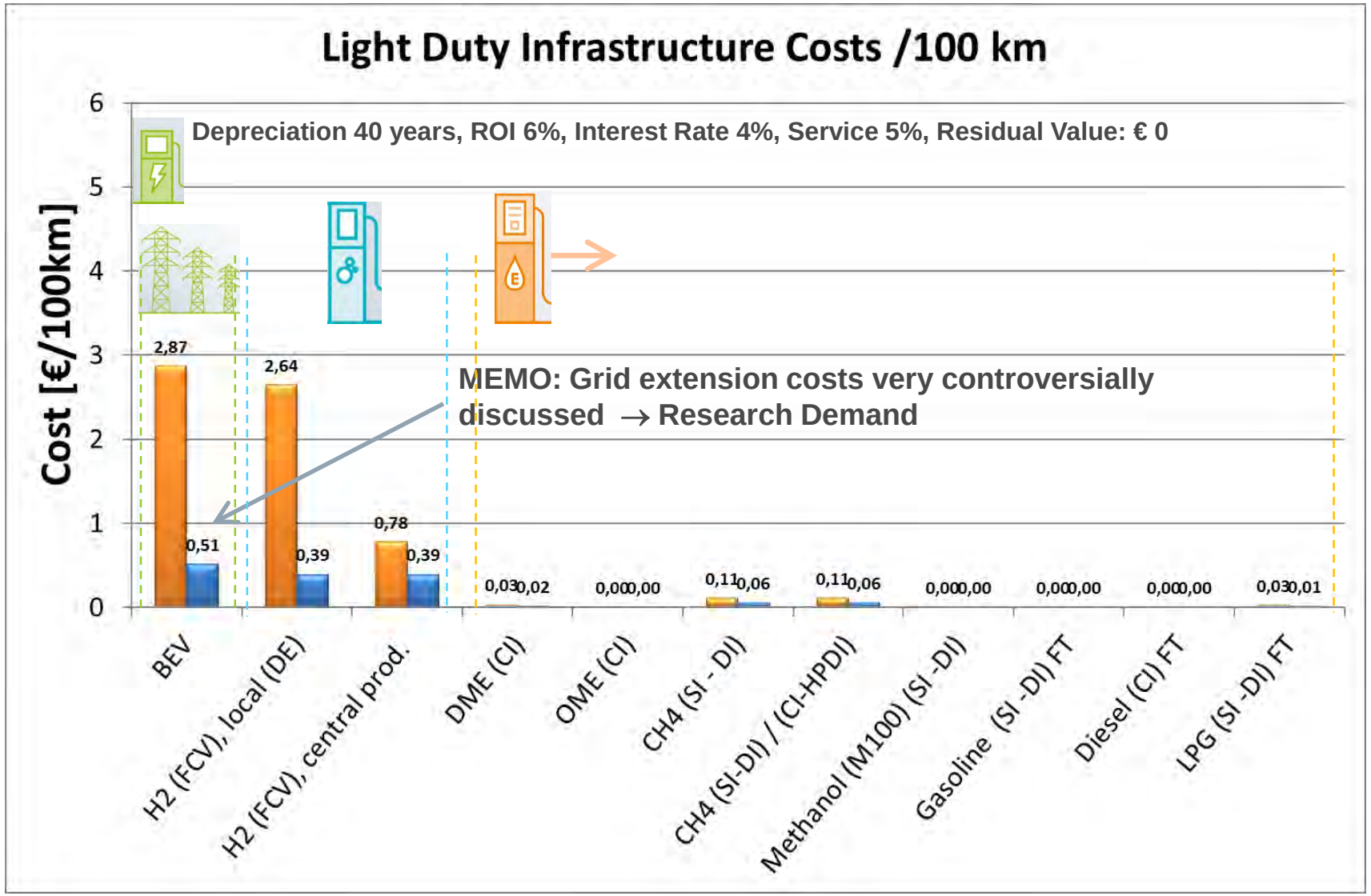
Scenario	Constant DE	Intermittent DE	Intermittent MENA
2017	180	88.1	
2030	100		24.3

- **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

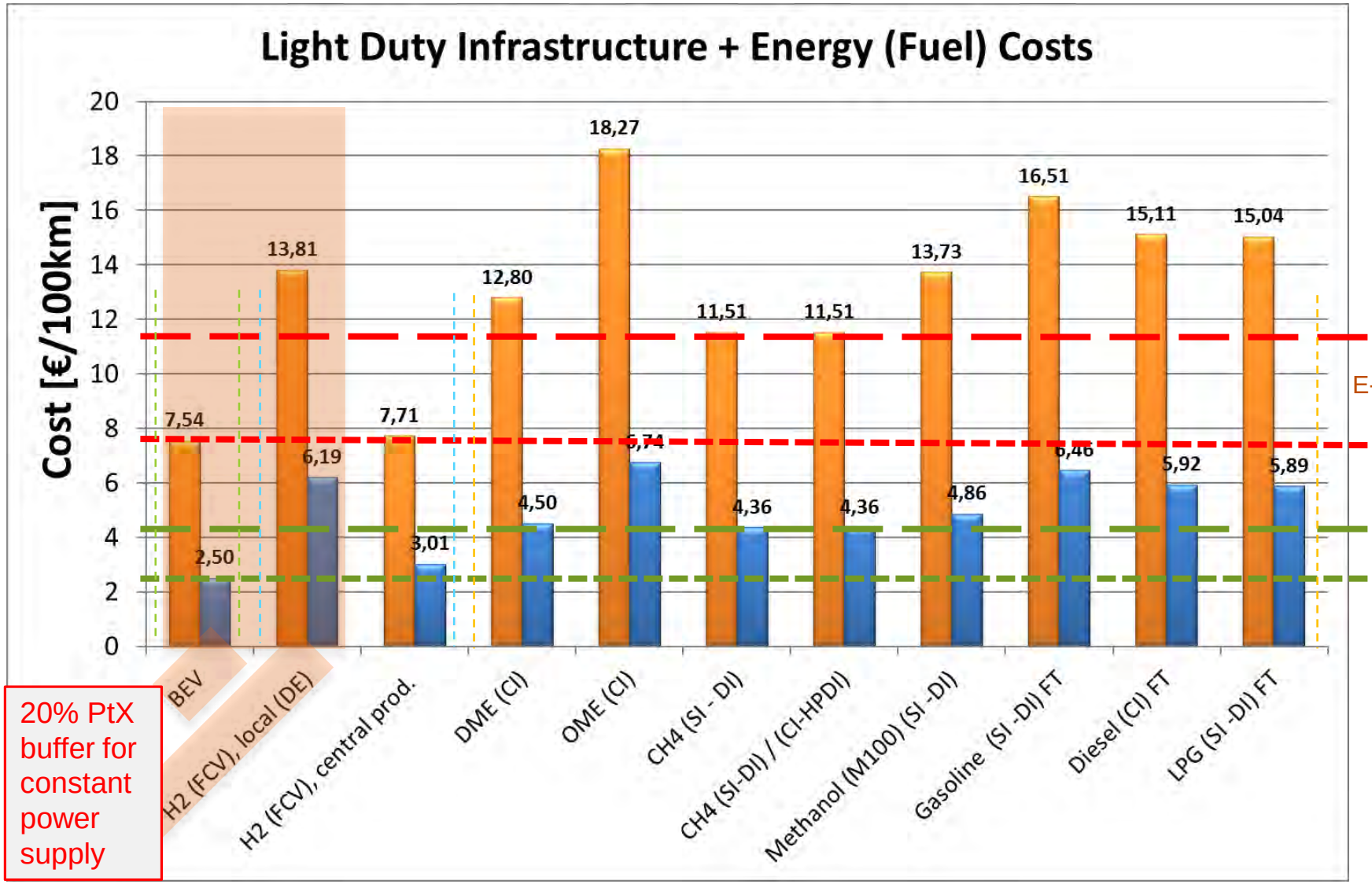


- **Lowest infrastructure costs for PtX fuels.**

- 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)

RESULTS – INFRASTRUCTURE + ENERGY COSTS - LD



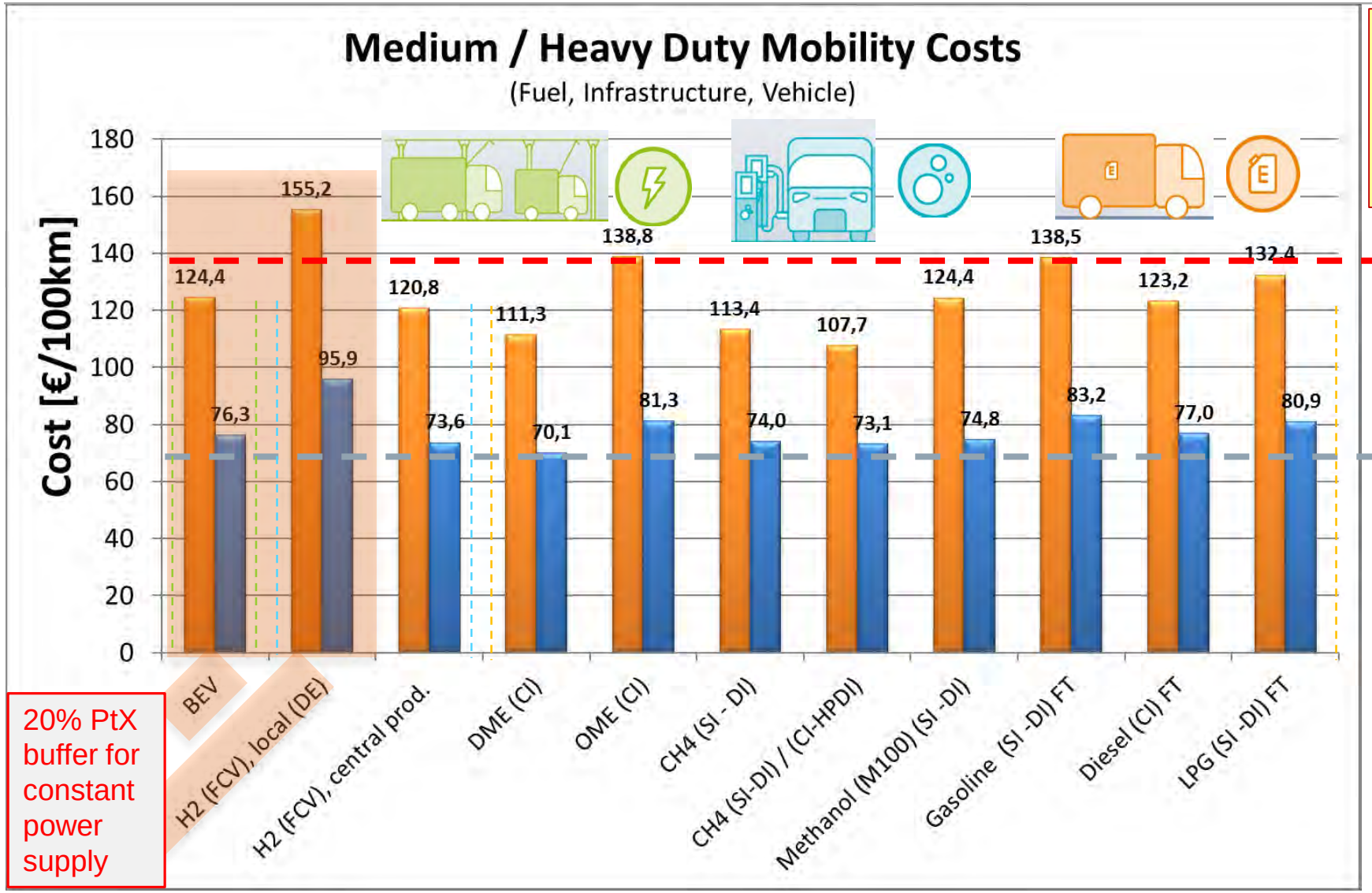
20% PtX buffer for constant power supply

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 - HD



20% PtX buffer for constant power supply

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

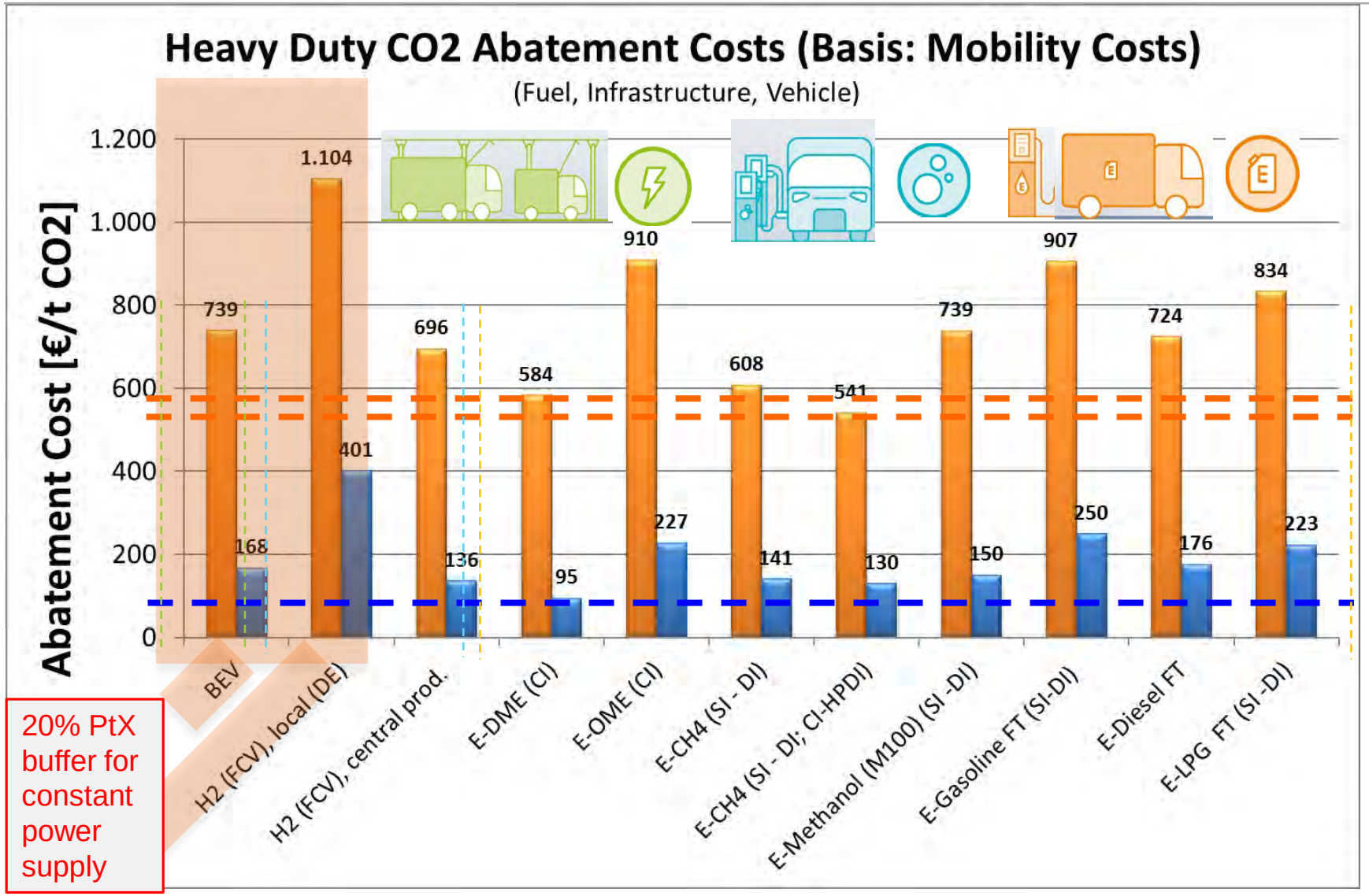
- **Most cost efficient PtX fuels: DME, CH4, MeOH**

- 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 – CO_2 ABATEMENT COSTS - HD



20% PtX buffer for constant power supply

- **Min HD CO_2 abatement costs for E-DME (95 €/tCO_2) 1.8x lower than BEV (168 €/tCO_2)**
- **Max cost risk BEV (739 €/tCO_2) 1.4x > E-Methane HPDI (541 €/tCO_2)**

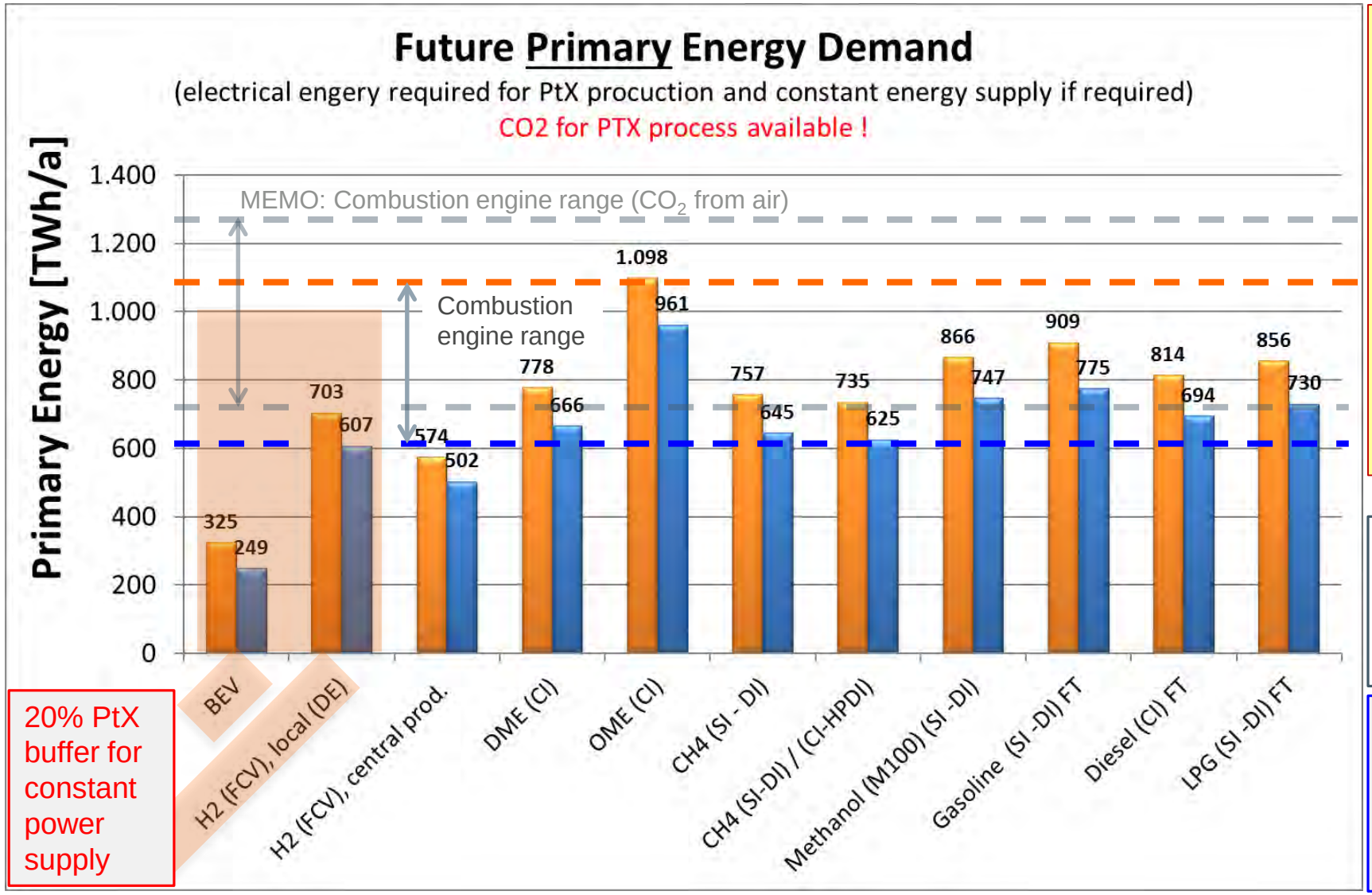
Max E-DME

Max E-Methane (HPDI)

Min E-Fuel (E-DME)

- 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)

PARAMETER VARIATION - PRINAMRY ENERGY DEMAND – CO_2 AVAILABLE



20% PtX buffer for constant power supply

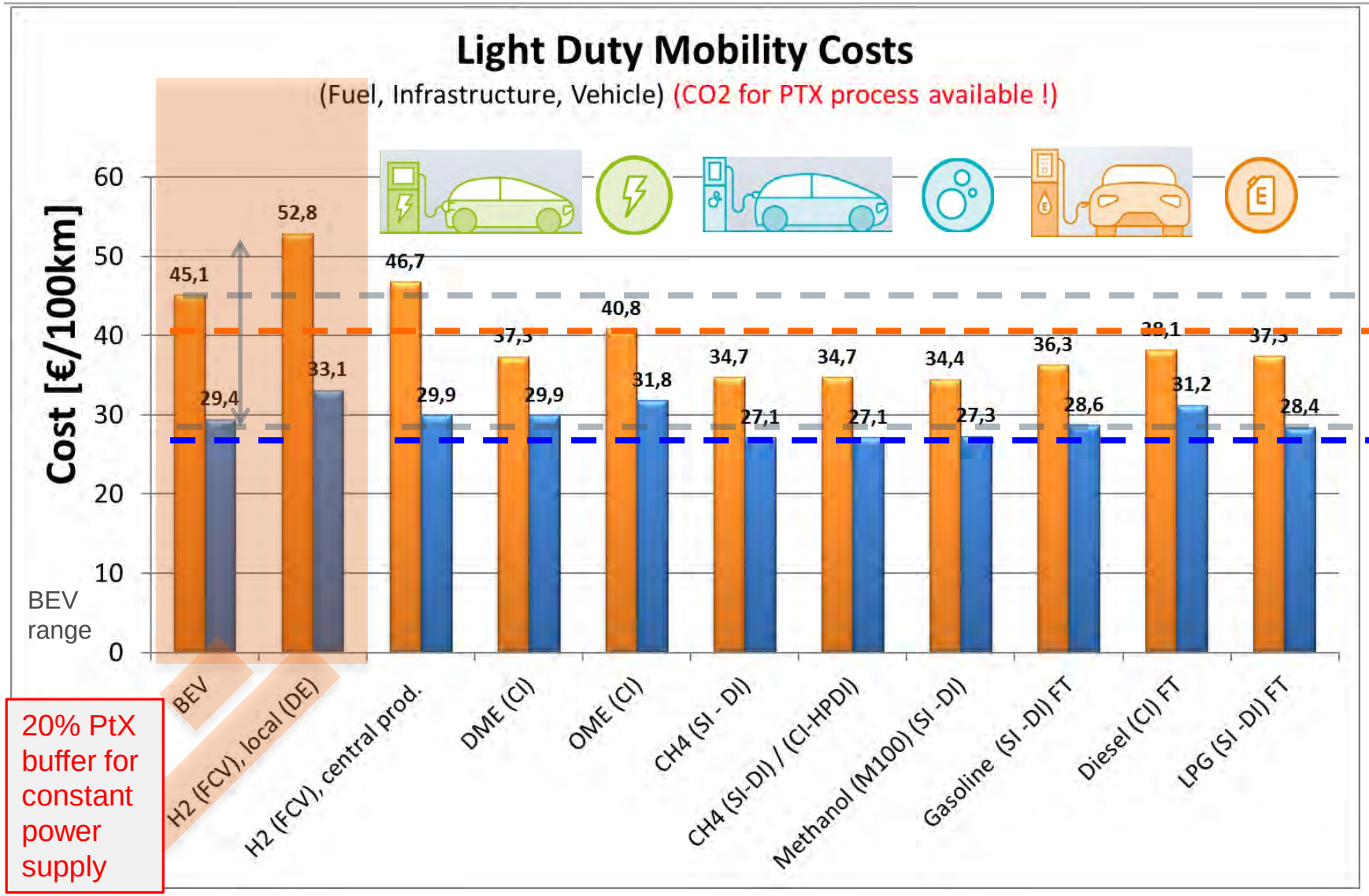
- **Lowest primary energy demand for BEV: 7 - 9% Primary Energy DE 2015 (PE_{2015})**
- **E-$H_{2\ (Central)}$ 14-16% PE_{2015}**
- **E-$CH_{4\ (HPDI)}$ reduction from 21-24% to 17-20% PE_{2015}**
- **E-$FT_{(50/50)}$ reduction from 26-29% to 20-24% PE_{2015}**

- 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

PARAMETER VARIATION – MOBILITY COSTS LD - CO_2 AVAILABLE



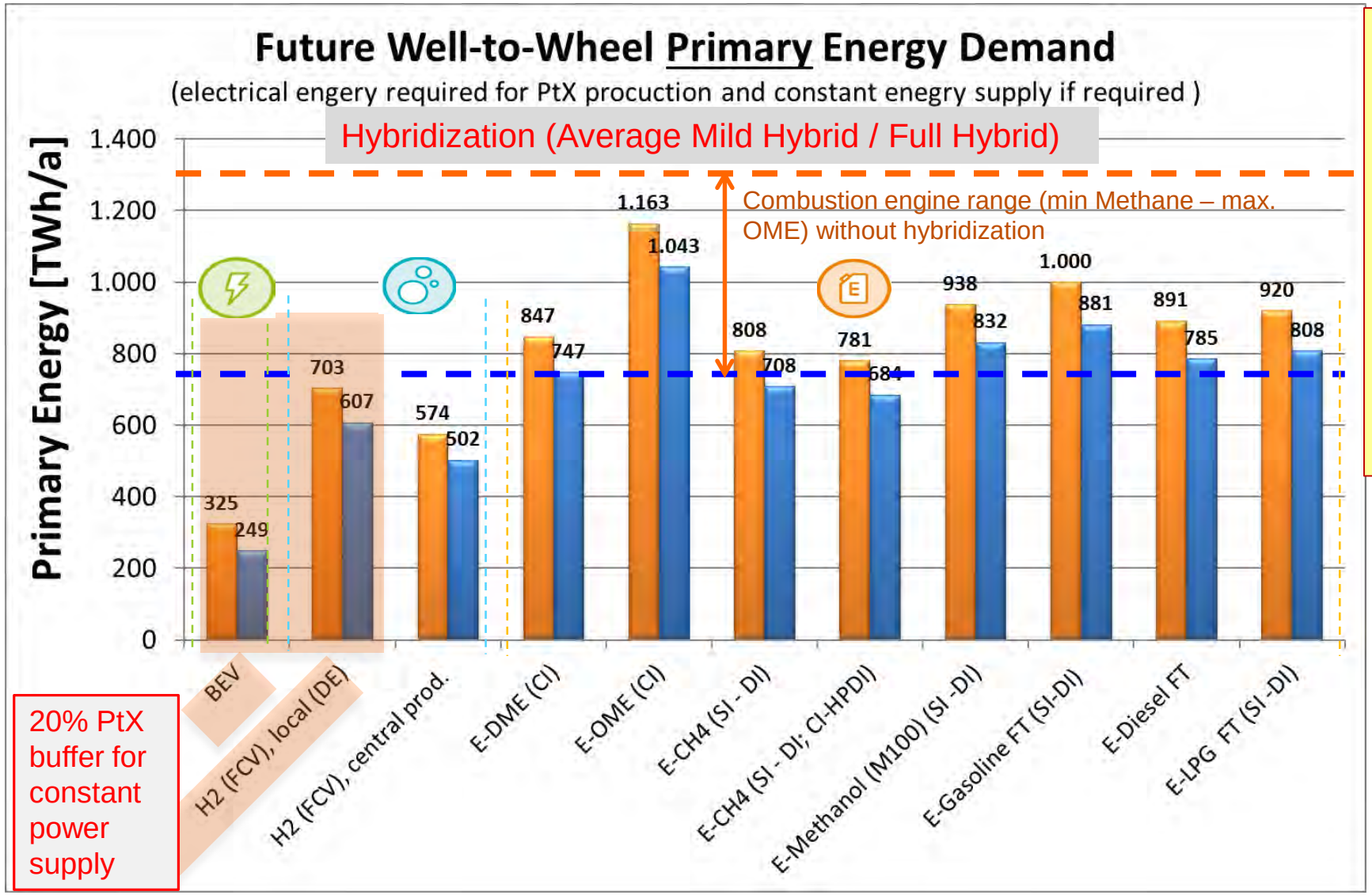
20% PtX buffer for constant power supply

- **With CO_2 from available sources: E-Fuel Mobility Cost reduction of 4 … 10 %**

- **Hardly any CO_2 source available in a 100 % sustainable world. → Theoretical scenario for a transition phase.**

- 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)

PARAMETER VARIATION - PRIMARY ENERGY DEMAND - LD HYBRIDIZATION



20% PtX buffer for constant power supply

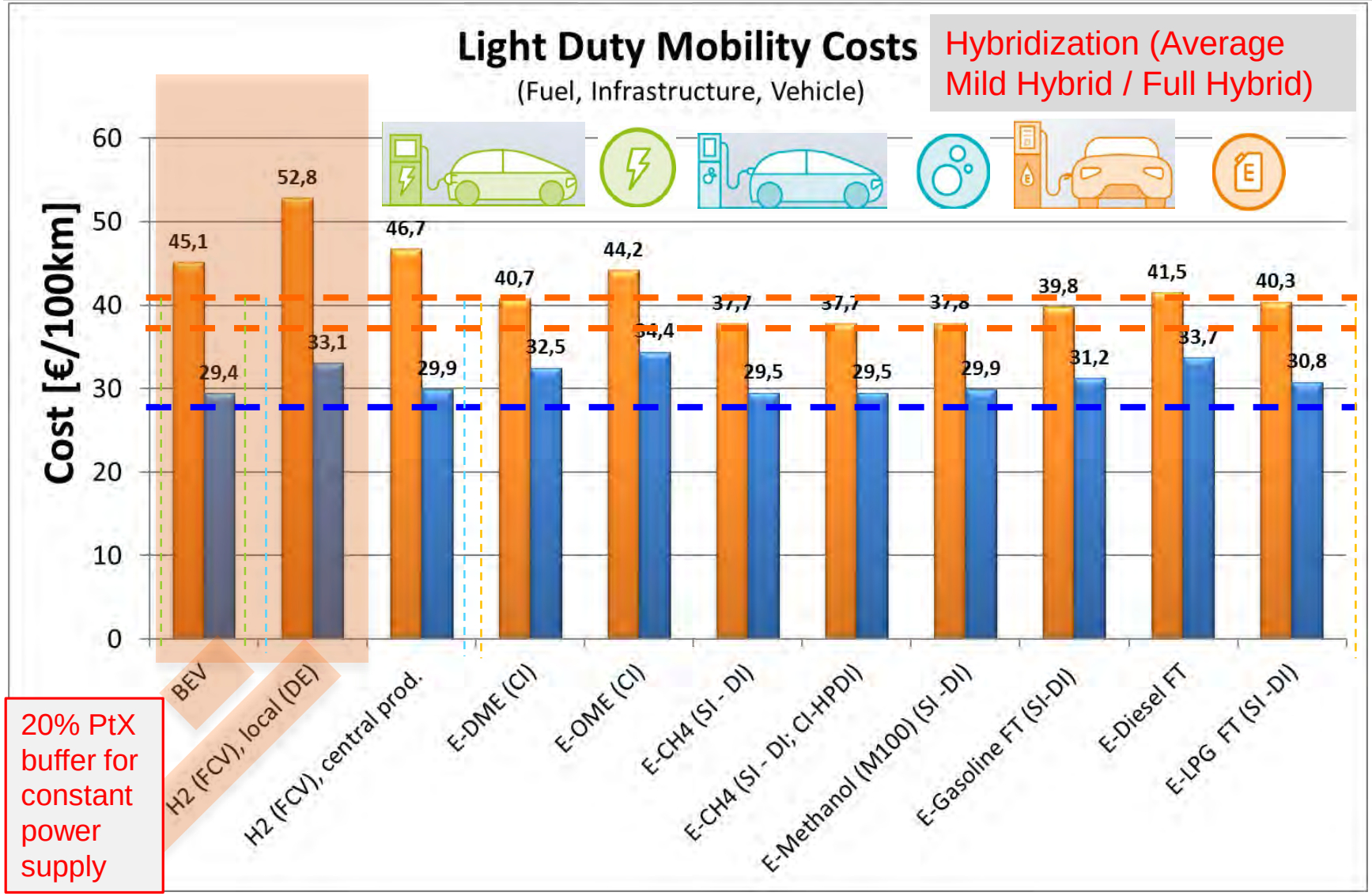
- **Lowest primary energy demand for BEV: 7 - 9% Primary Energy DE 2015 (PE_{2015})**
- **E-$H_{2\ (Central)}$ 14-16% PE_{2015}**
- **E-$CH_{4\ (HPDI)}$ reduction from 21-24% to 19-22% PE_{2015}**
- **E-$FT_{(50/50)}$ reduction from 26-29% to 23-26% PE_{2015}**

- 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

PARAMETER VARIATION– MOBILITY COSTS - LD HYBRIDIZATION



20% PtX buffer for constant power supply

- **Avg. Hybridization: Minimum E-Fuel Mobility Costs rise by 0.8 – 1.1 € / 100 km**

Max E-FT-Diesel/Gasoline w/o Hybridization

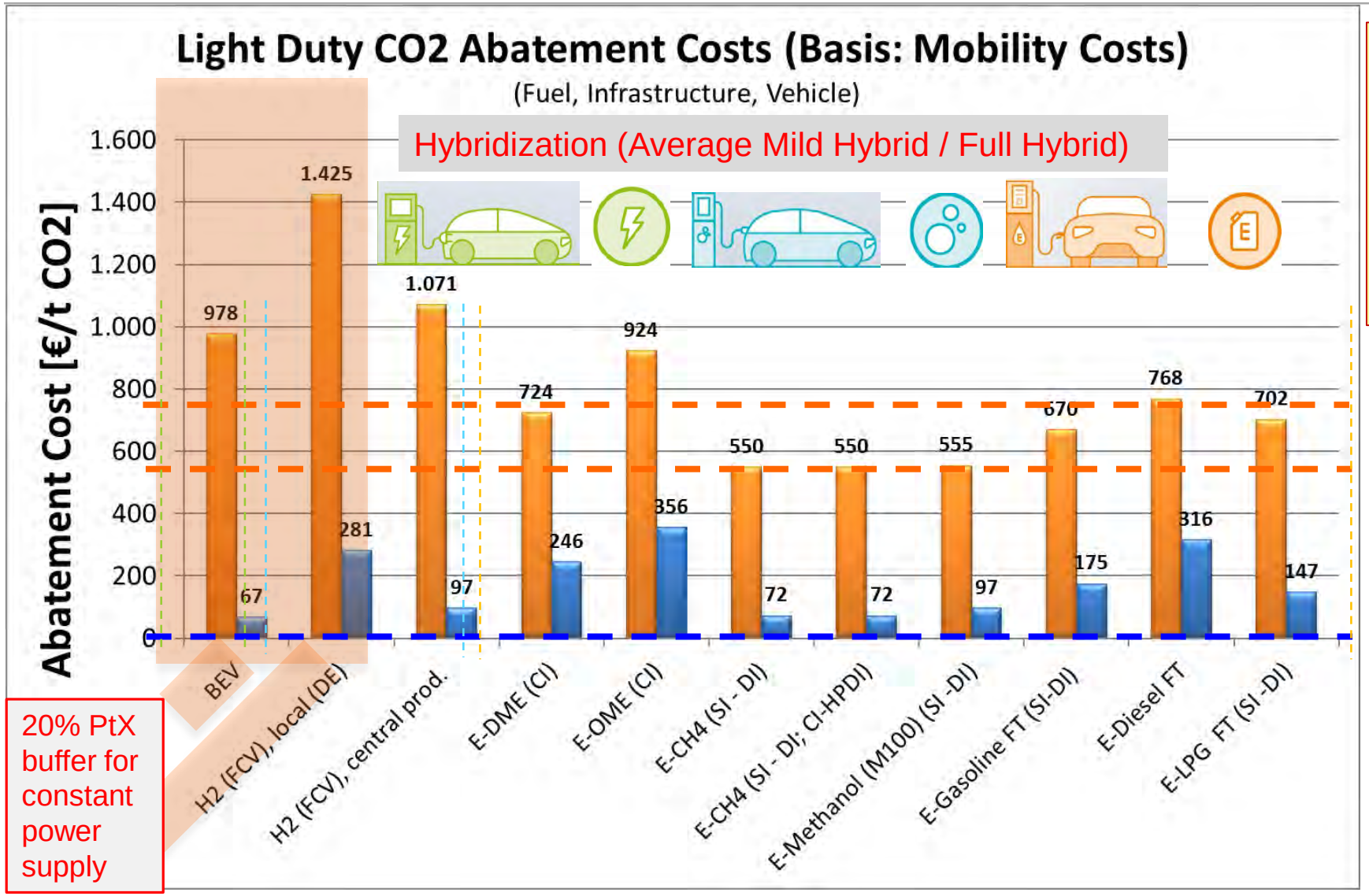
Max E-Methane w/o Hybridization

Min E-Fuel (E-Methane) w/o Hybridization

- **Avg. Hybridization: Reduction of Maximum E-Fuel Mobility Costs by 0 – 0.9 € / 100 km**

- 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)

PARAMETER VARIATION – LD CO_2 ABATEMENT COSTS - LD HYBRIDIZATION



20% PtX buffer for constant power supply

- **Avg. Hybridization: Min CO_2 Abatement Costs for E-Fuels pathways rise by 43 - 64 €/t CO_2**
- **Max CO_2 Abatement Costs rise by 3 - 57 €/t CO_2**

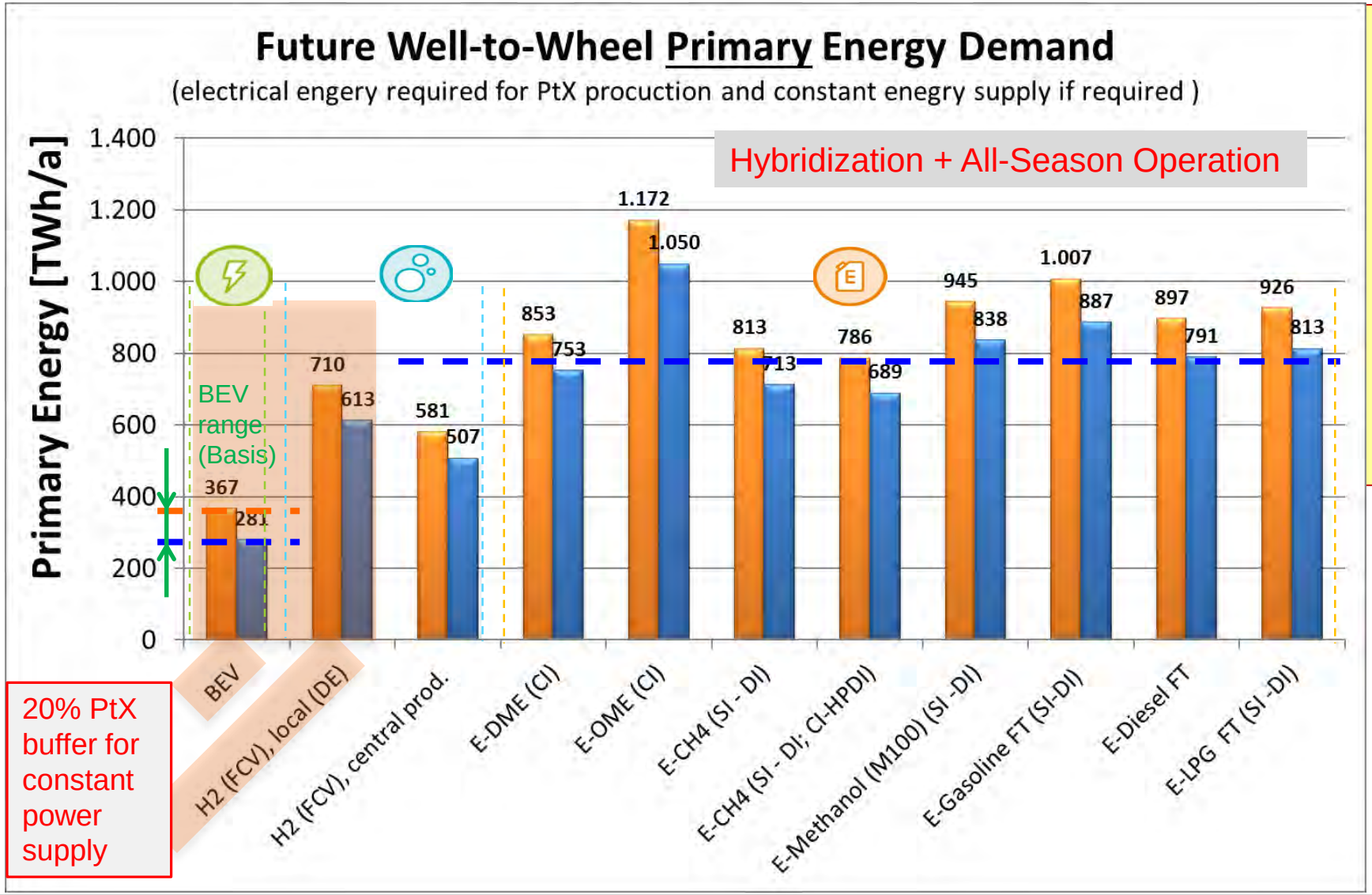
Max E-FT-Diesel/Gasoline w/o Hybridization

Max E-Methane w/o Hybridization

Min E-Fuel (E-Methane) w/o Hybridization

- 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)

PARAMETER VARIATION - PRIMARY ENERGY DEMAND - LD HYBRIDIZATION, ALL-SEASON



20% PtX buffer for constant power supply

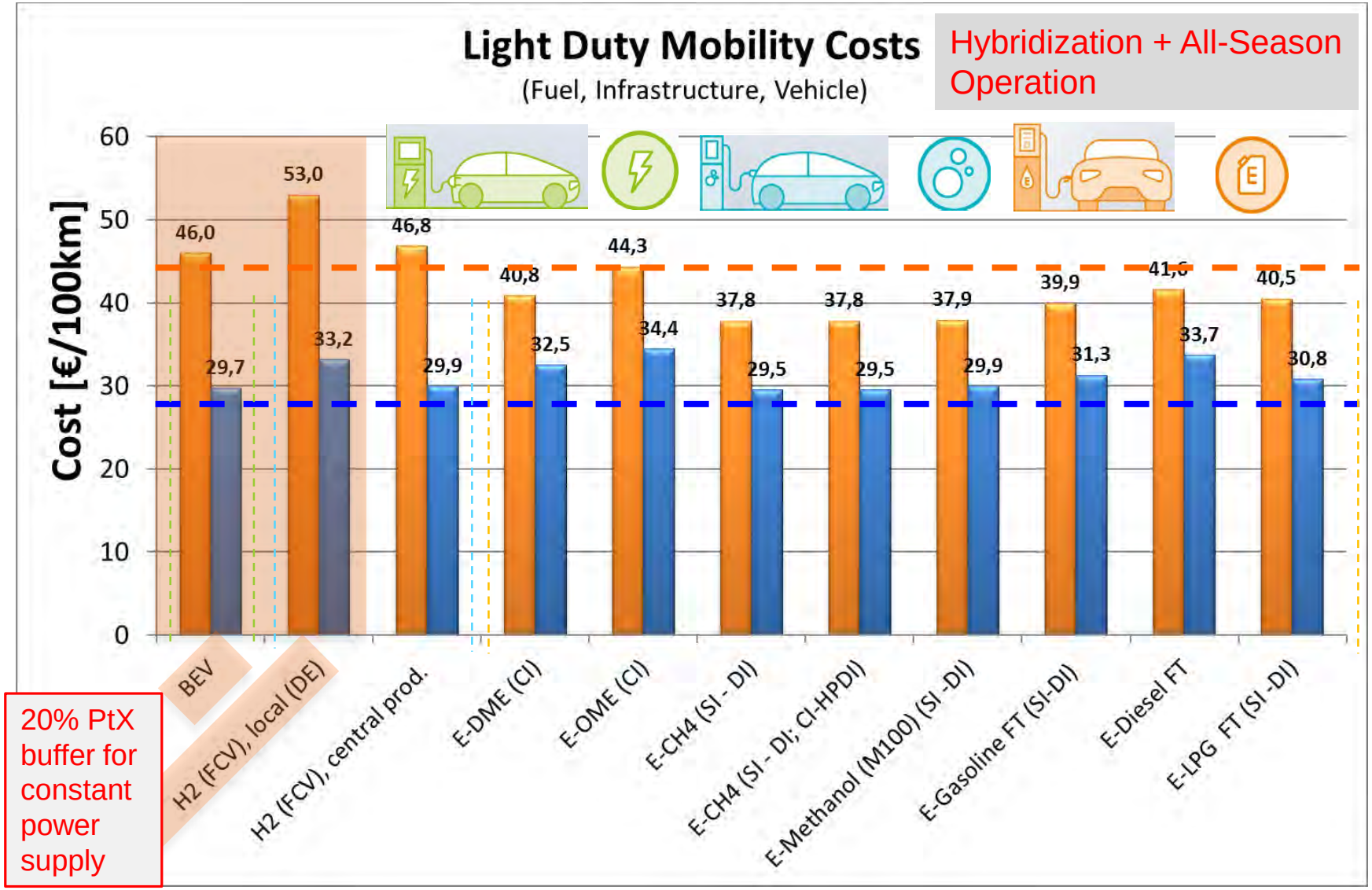
- **Lowest primary energy demand for BEV rises from: 7-9% to 8-10% PE_{2015}**
- **E-Fuel concepts and FCEV hardly affected by all-season operation**
- **E-$H_{2\ (Central)}$ 14-16% PE_{2015}**
- **E-$CH_{4\ (HPDI)}$ 19-22% PE_{2015}**
- **E-$FT_{(50/50)}$ 23-26% PE_{2015}**

- 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
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**https://www.bmwi.de/Redaktion/DE/Infografiken/Energie/energie-primaerverbrauch.html

PARAMETER VARIATION – MOBILITY COSTS - LD HYBRIDIZATION, ALL-SEASON



20% PtX buffer for constant power supply

- **All-season operation**
- **Min/Max BEV Mobility Costs rise by 0,3 – 0.9 €/100km**

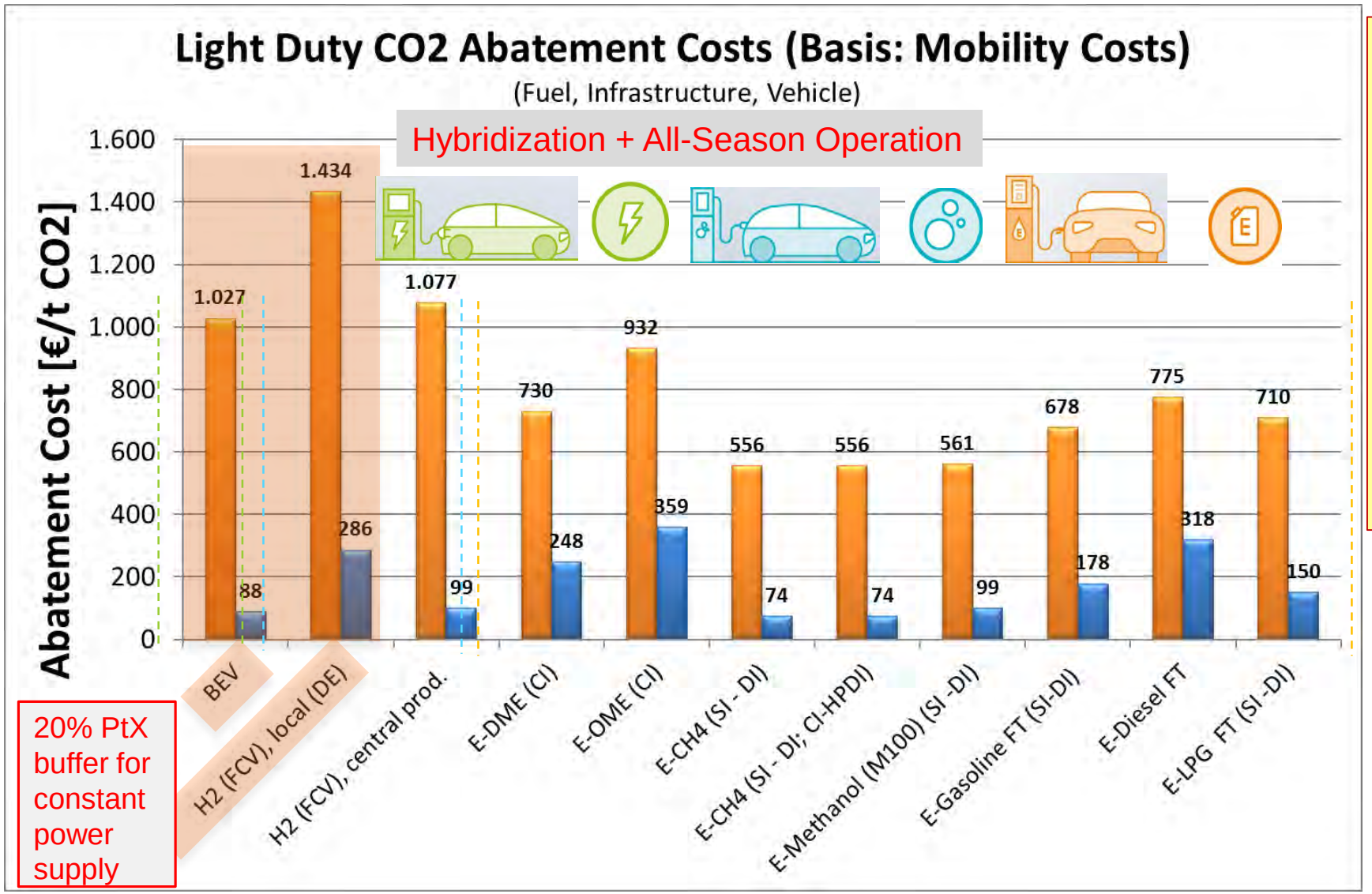
Max BEV (Basis)

Min BEV (Basis)

- **E-Fuel concepts and FCEV costs hardly affected by all-season operation (approx. 0.1 €/100km)**

- 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)

PARAMETER VARIATION – LD CO_2 ABATEMENT COSTS - LD HYBRIDIZATION, ALL-SEASON



20% PtX buffer for constant power supply

- Min CO_2 Abatement Costs for BEV rise by 21 €/t CO_2
- Max CO_2 Abatement Costs rise by 49 €/t CO_2
- FCEV costs hardly affected by all-season operation (+ 2…11 €/t CO_2)
- E-Fuel pathways hardly affected by all-season operation (+ 2…8 €/t CO_2)

- 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)