Solid Oxide Cell (SOC) Technology – Gamechanger Towards Highly Efficient Production of Hydrogen and Derivatives

Vortragsreihe: Innovationen in der Fahrzeugtechnik 2023/2024

Josef Macherhammer

Curriculum Vitae (CV)
Josef Macherhammer

Education

Matura - Mechanical Engineering
HTL
Wels / Austria
2005

BSc - Chemical and Process Engineering
University of Technology
Graz / Austria
2010

MSc - Chemical and Process Engineering
University of Technology
Graz / Austria
2012

Professional Career

Development Engineer Exhaust Aftertreatment
AVL List GmbH
Graz / Austria
2012/11 – 2016/12

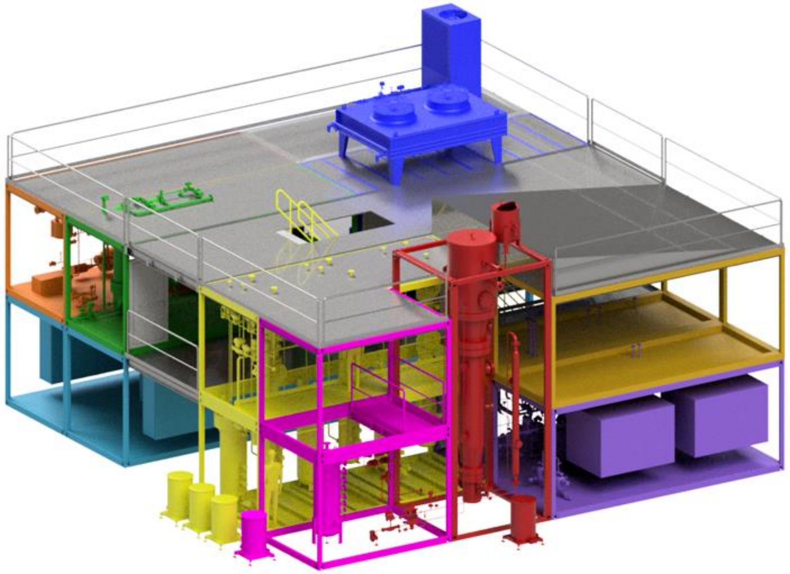
Technical Consulting
Perkins Engines
Peterborough / UK
2015/10 – 2016/2

Technical Expert Exhaust Aftertreatment
AVL List GmbH
Graz / Austria
2017/1 – 2018/12

Global Sales Administration Manager
AVL List GmbH
Graz / Austria
2019/1 – 2021/3

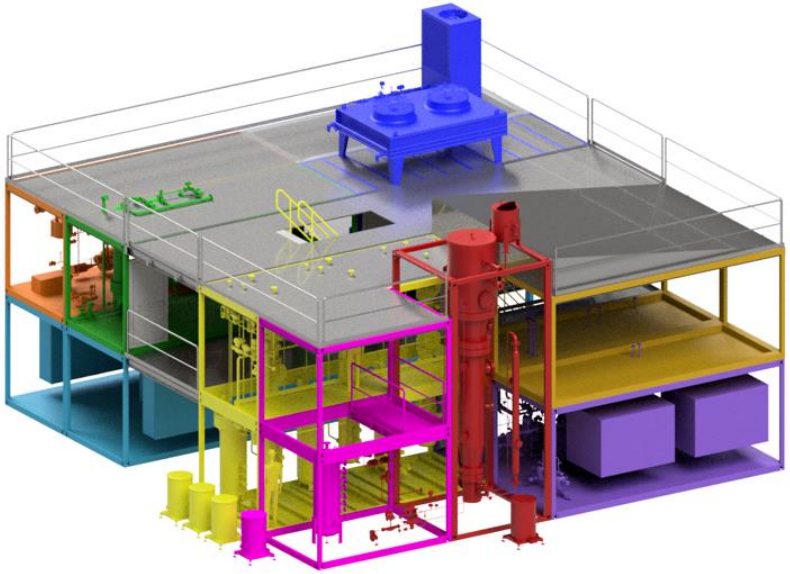
Product Manager Hydrogen and Fuel Cell
AVL List GmbH
Graz / Austria
2021/4 – today

Content



- AVL Company presentation
- Hydrogen and E-fuel application and market outlook
- Advantages and Disadvantages of SOC technology
- Insights into the AVL e-fuel production demonstration plant

Content



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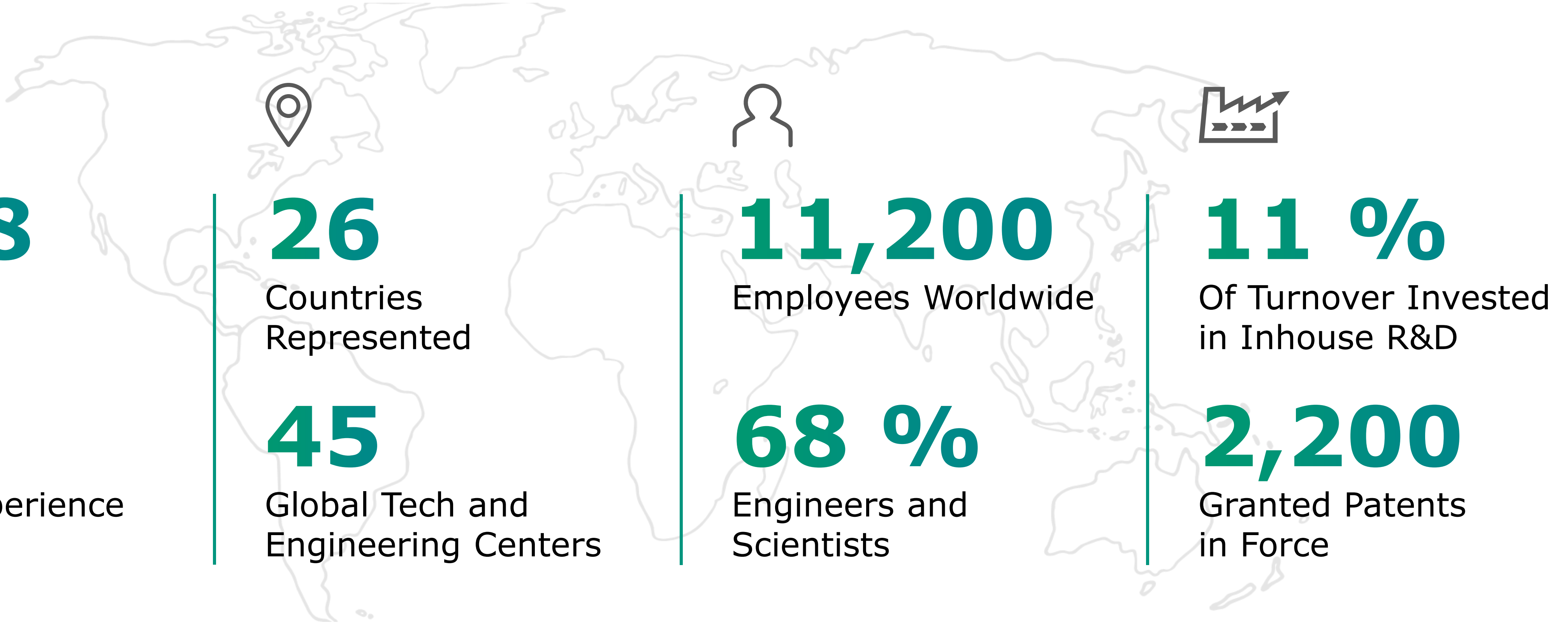
AVL at a Glance



1948
Founded

75
Years of Experience

26
Countries Represented

45
Global Tech and Engineering Centers

11,200
Employees Worldwide

68 %
Engineers and Scientists

11 %
Of Turnover Invested in Inhouse R&D

2,200
Granted Patents in Force

H2 & Fuel Cell Technology in numbers

AVL

2023

Commercial Share ~7%

Order Intake > 100 Mio€

Patents & Publications >200

Locations & People 6/650

Share outside automotive ~50%

TECO 2030 Produces First Fuel Cell Stack for Marine Applications

AVL Contribution to DLR Project: 1.5- Megawatt Composite Testbed for Fuel Cells

Graz Becomes Location for the Most Modern Power-To-Liquid Facility in Europe

AVL joins HZwo Innovation Cluster to Drive New Mobility Technologies

AVL Opens New Hydrogen and Fuel Cell Test Center in Graz

AVL Joins Collaborative Project to Develop Hydrogen-Powered Land Rover Defender Fuel Cell Prototype

AVL and Ceres Set to Combine Competencies for Solid Oxide Fuel Cell Systems Technology

Three Disciplines Under One Roof – Fuel Cell Expertise

Sub Component

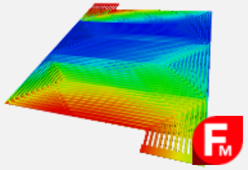
Component

System

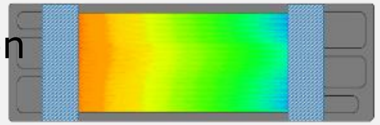
Integration

Advanced Simulation Technologies

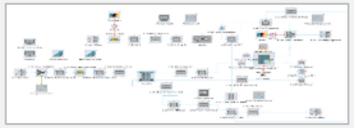
CFD & FEA



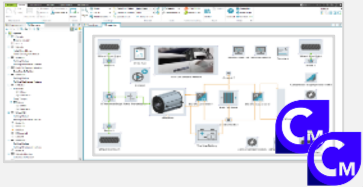
Perf. & Degradation Models



System Plant Models

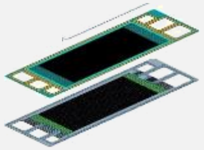


AVL CRUISE & Cameo



Powertrain Engineering

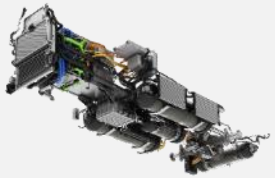
Cell & MEA Design



Stack Development

System & Software

Vehicle Integration



Instrumentation and Test Systems

Single Cell & Short Stack

Stack

FC System Test Station

VTB / MIL Test Station

Fuel Cell
Overview Testing Infrastructure

AVL HQ - Graz

PEM system test beds
1x up to 200 kW
1x up to 400 kW
(split option 200 kW/200 kW)
1 x up to 500 kW (Q3/2024)

PEM stack test bed
1x up to 200 kW

PEM system non-standard test beds
1x up to 400 kW Altitude test bed
1x up to 400 kW Climatic chamber

SOFC system test beds
2x SOFC 20 kW /SOEC 50kW

AVL Remscheid - Germany

Fuel Cell and Electrolyzer System Testing
up to 1,6 MW

AVL FCC - Vancouver

PEM single cell test stations
4x up to 0,5 kW

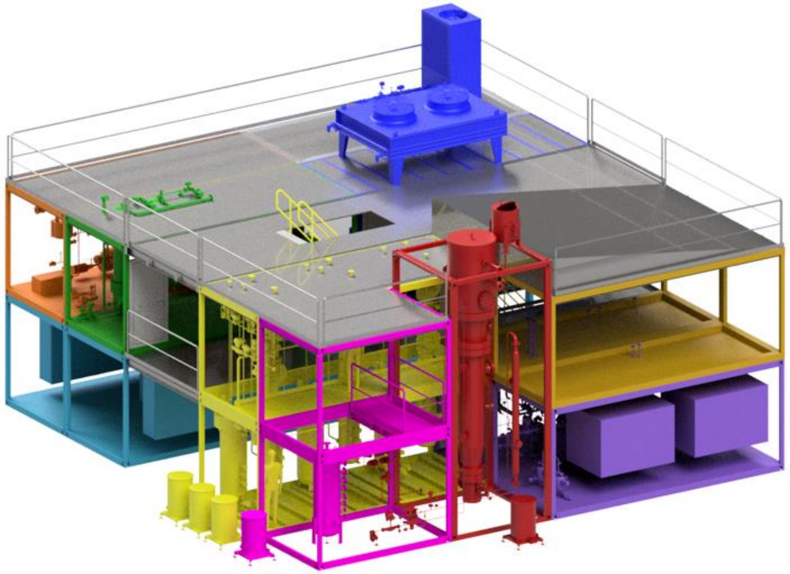
PEM short stack test stations
1x up to 3,3 kW
3x up to 10 kW

PEM full size stack test station
1x up to 100 kW

AVL Hungary - Kecskemet

SOFC system test bed
1x up to 50kW (Q4/2023)

Content



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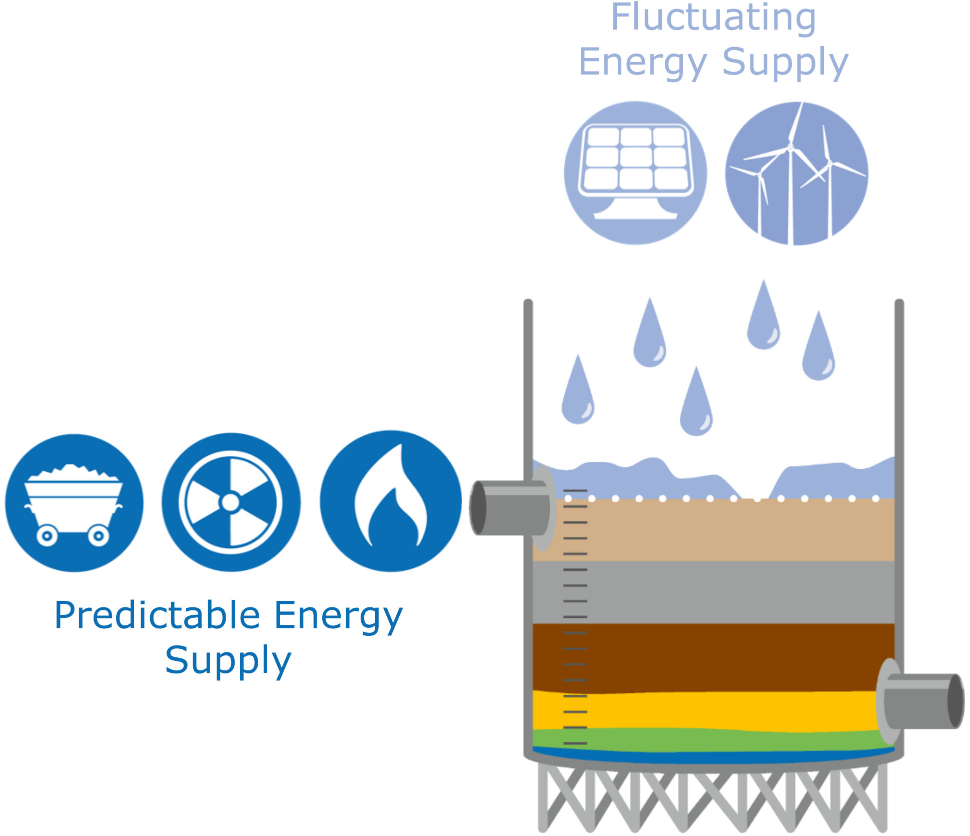
Future Energy Scenario
Metaphor: Water-Tower

Today

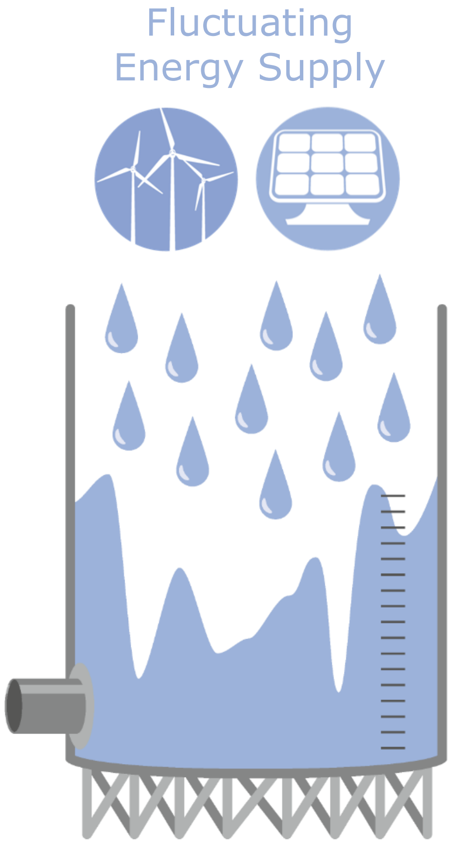

Fluctuating Energy Supply

Predictable Energy Supply

Major GOAL


Energy Security
for end consumer

2050


Fluctuating Energy Supply

Energy Buffer
- Global Renewable Energy Trading
- Chemical Energy Carrier

Grid Stabilisation
- Decentral Power and Heat Generation

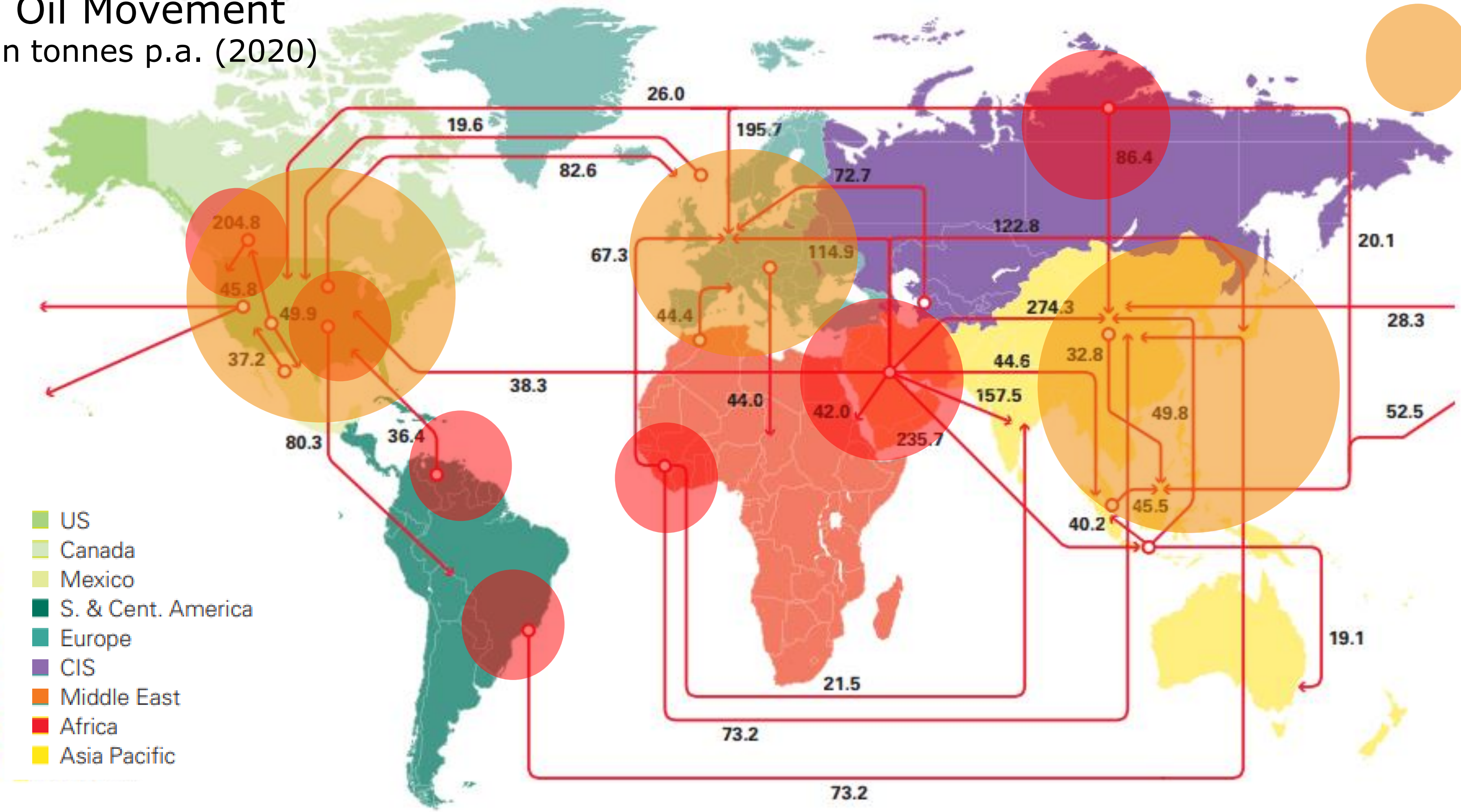
Energy Trade Today

Crude Oil Movement

in Million tonnes p.a. (2020)

🟥 „Supply Regions“

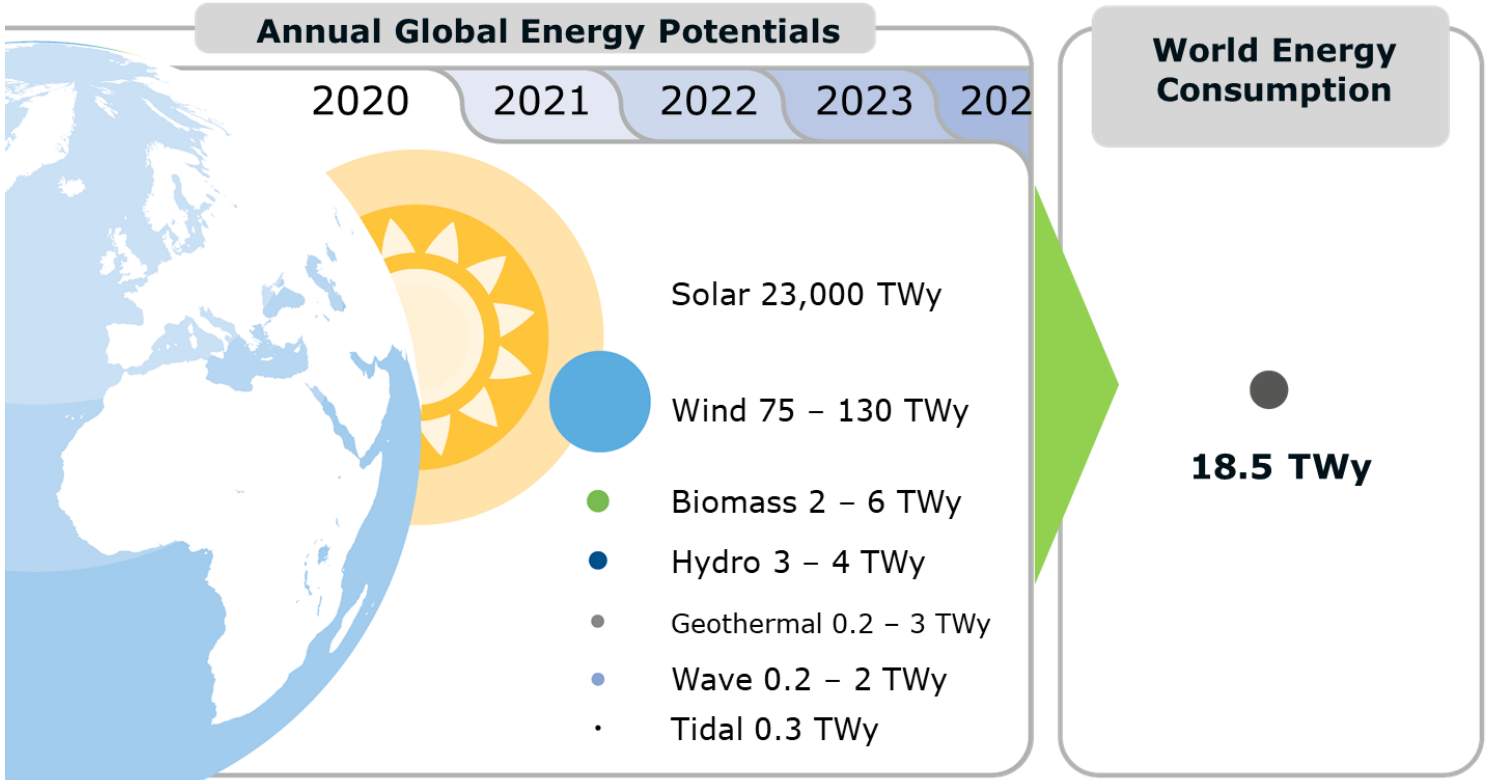
🟧 „Demand Centers“



Source: Source: BP Statistical Review of World Energy 2021

Page 35: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

The Challenge:
Storage and Transport of Wind and Solar Energy



Annual Global Energy Potentials

2020 2021 2022 2023 202

Solar 23,000 TWy

Wind 75 – 130 TWy

Biomass 2 – 6 TWy

Hydro 3 – 4 TWy

Geothermal 0.2 – 3 TWy

Wave 0.2 – 2 TWy

Tidal 0.3 TWy

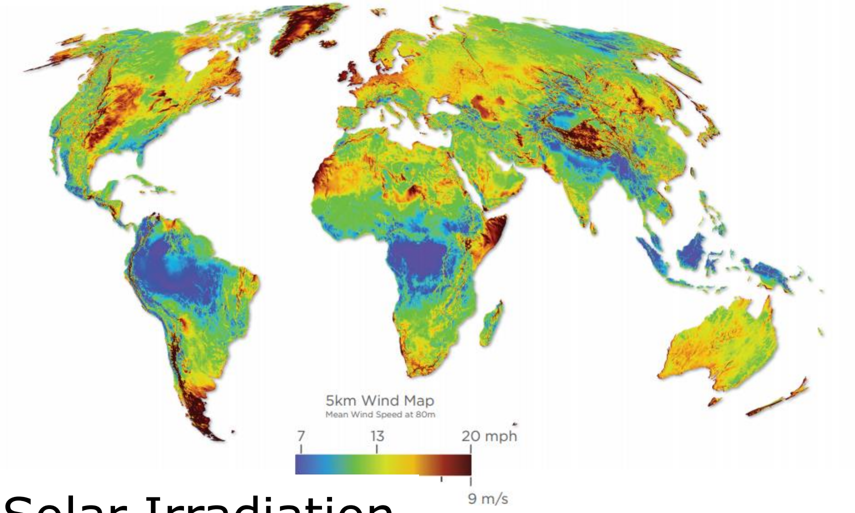
World Energy Consumption

18.5 TWy

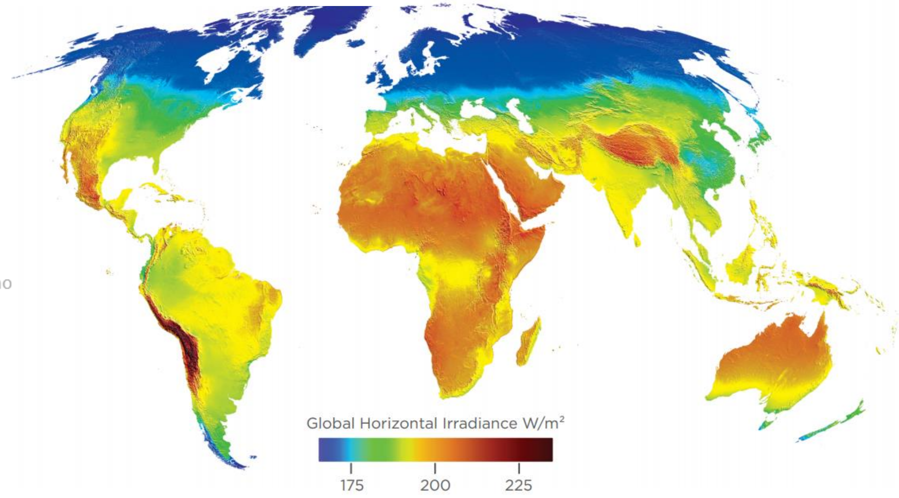
Source: Perez, A fundamental look at energy reserves for the planet, 11/2015

1TWy ... 1 Terra Watt year equals 8766 Terra Watt ho

Wind Speed



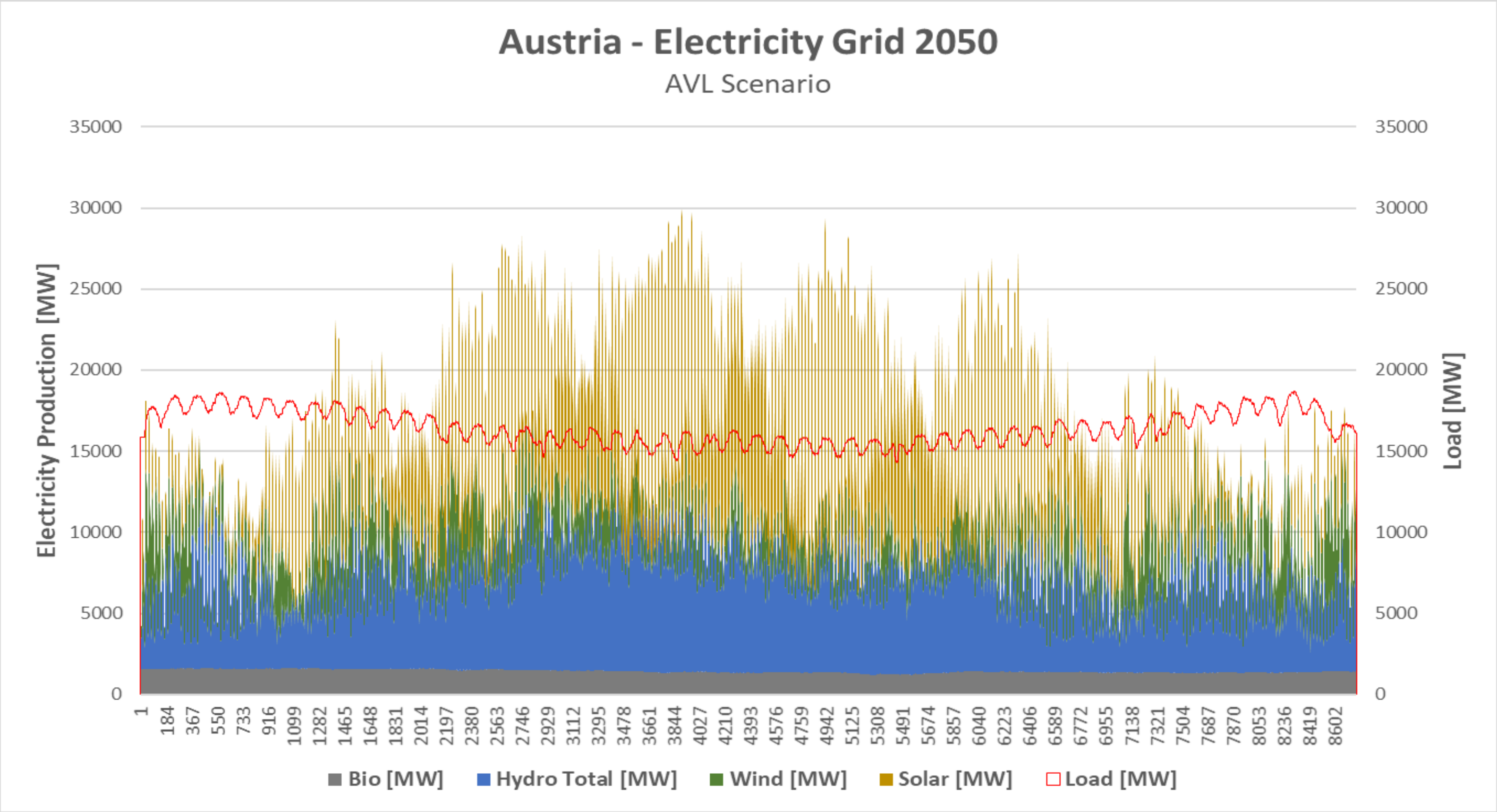
Solar Irradiation



Production Potential is far away from Demand Centers

Source:
https://www.vaisala.com/sites/default/files/documents/Vaisala_global_wind_map.pdf?utm_content=Wind-Map
https://www.vaisala.com/sites/default/files/documents/Vaisala_global_solar_map.pdf?utm_content=Solar-Map

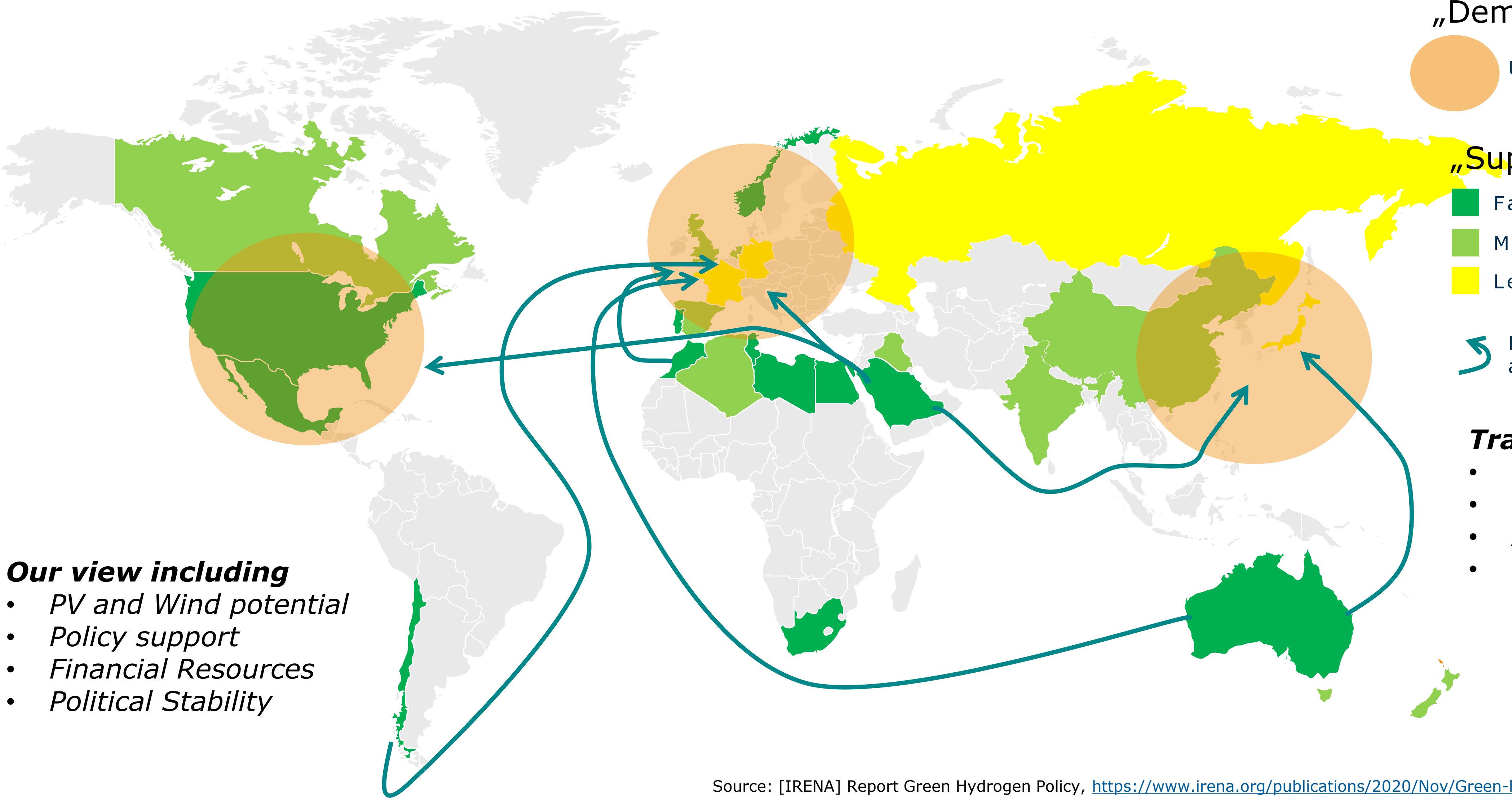
Austrian Electricity Grid – Scenario 2050



	2019	**2050**	**%**
Renewable Electricity Production	54TWh	**118TWh[1]**	+118%
Electricity Consumption	64TWh	**136TWh[2]**	+112%
Fossil Energy in End-Use	180TWh	**0TWh**	-100%
Electricity Shortage		**36TWh**	

1…IndustRiES Study, 2019 - actual build-up plan 81TWh (Erneuerbaren-Ausbau-Gesetz 2022)
2…113TWh end-use & additionally considered 30% local production of hydrogen (excl. losses)

Future Green Hydrogen Production and Demand



„Demand Centers“

● USA, SE Asia, Europe

„Supply Regions“

🟩 Favorable Conditions

🟩 Medium Conditions

🟨 Less favourable

↩ First global supply agreements (intended)

Transport medium:

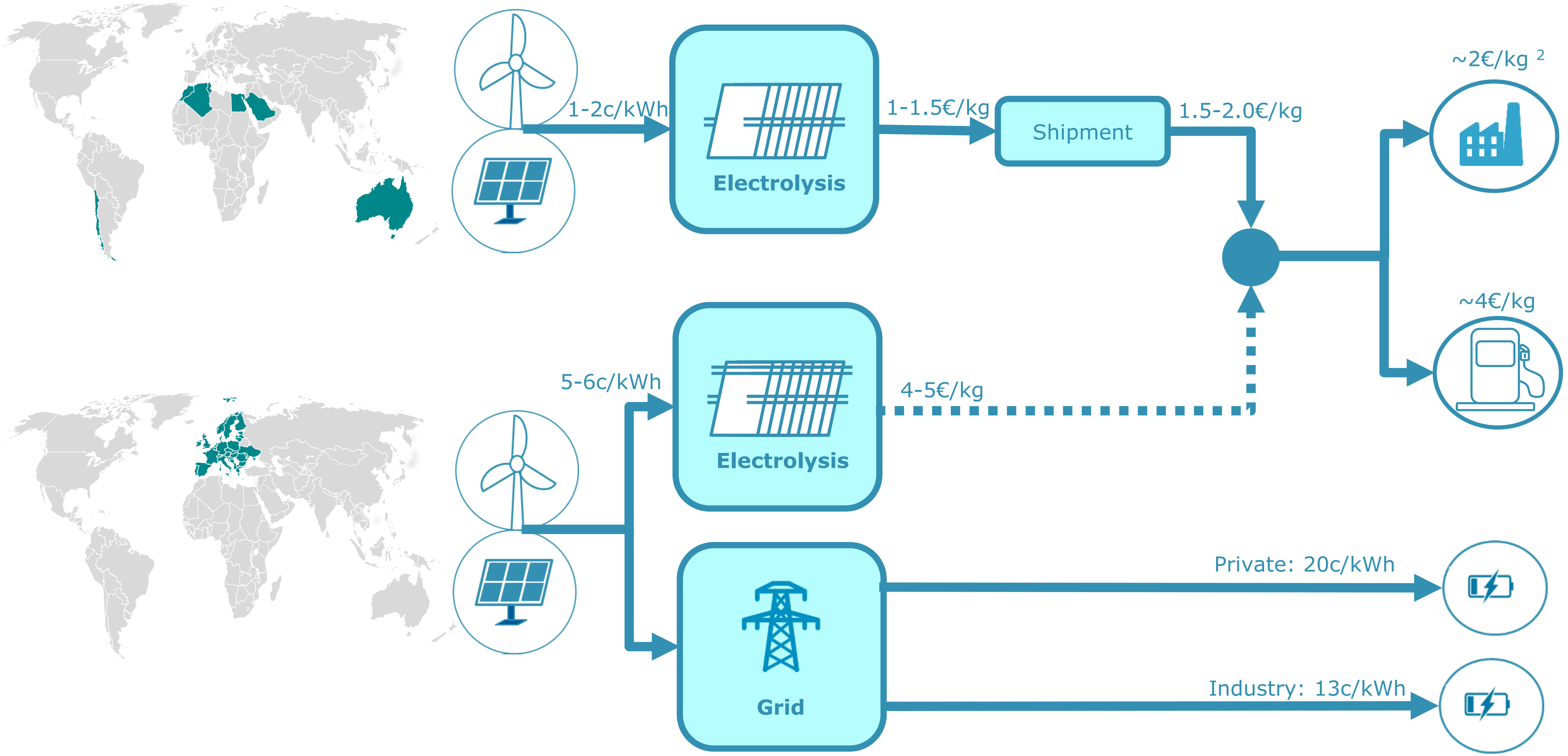
- *Liquid H_2*
- *Compressed H_2*
- *Ammonia*
- *Methanol*

Our view including

- *PV and Wind potential*
- *Policy support*
- *Financial Resources*
- *Political Stability*

Source: [IRENA] Report Green Hydrogen Policy, https://www.irena.org/publications/2020/Nov/Green-hydrogen ; AVL own research

Potential Future Hydrogen Prices (2040+)



1-2c/kWh

Electrolysis

1-1.5€/kg

Shipment

1.5-2.0€/kg

5-6c/kWh

Electrolysis

4-5€/kg

Grid

~2€/kg [2]

~4€/kg

Private: 20c/kWh

Industry: 13c/kWh

Energy equivalent Cost

6 c/kWh

12 c/kWh

20-(79)[1] **c/kWh**

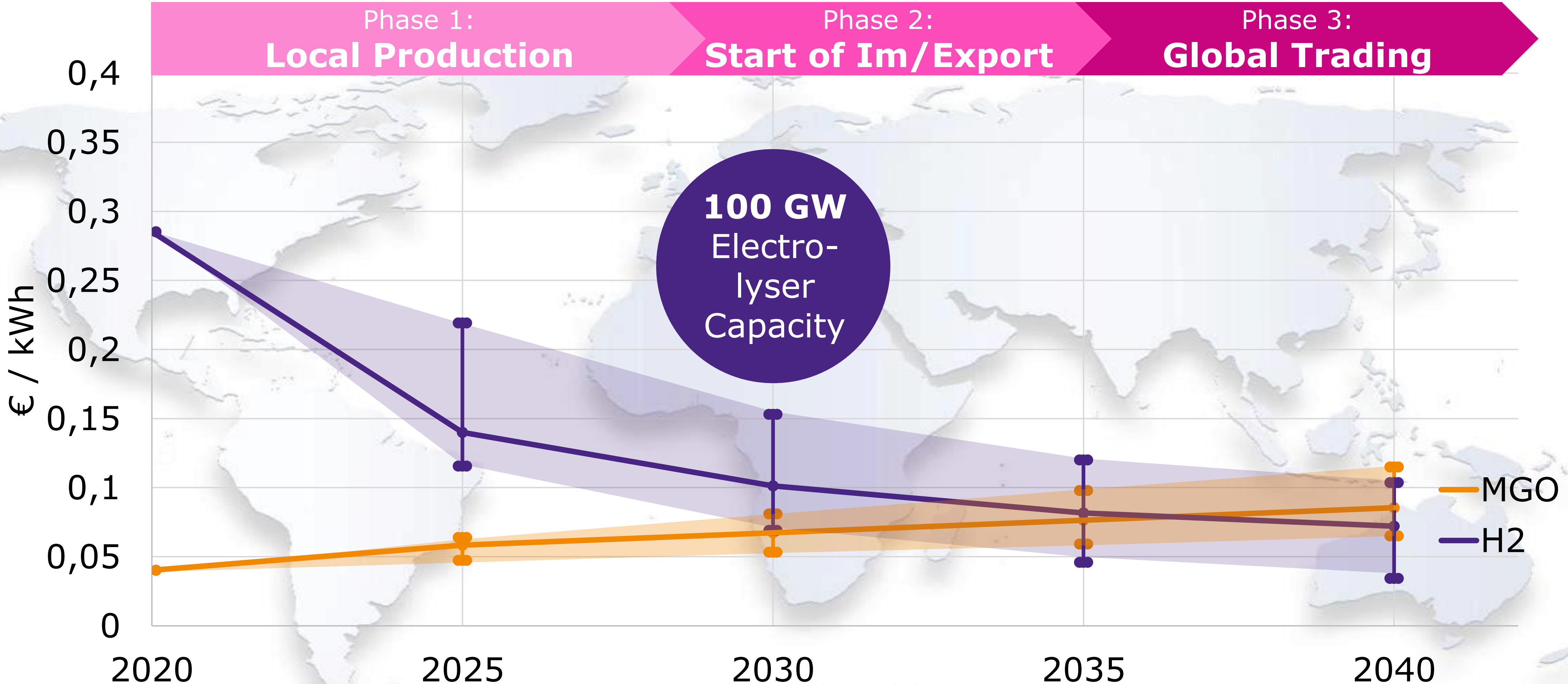
13-(40)[1] **c/kWh**

All prices in € or € cent

1…charging and quick charging cost Austria
2…Target of the European Commission

Boundaries:
MGO w/o CO2 taxes = 0,475 €/kg

Hydrogen and Diesel price development



Sources H2:
1) DIW = German Institute for Economic Research (Berlin)
2) MCC = Mercator Research Institute on Global Commons and Climate Change (Berlin)
3) PIK = Potsdam Institute for Climate Impact Research (Potsdam) 4) Pess. Scenario: Climate Cabinet (D)

Sources CO2:
1) Öko Institut e.V. (independent, private environmental research institute, Freiburg i.Br. / Germany,
2) Bloomberg L.P. (NY / USA),
3) McKinsey (NY / USA)

Hydrogen Market Update

Cumulative electrolysis capacity (announced),[1] GW

+73 GW

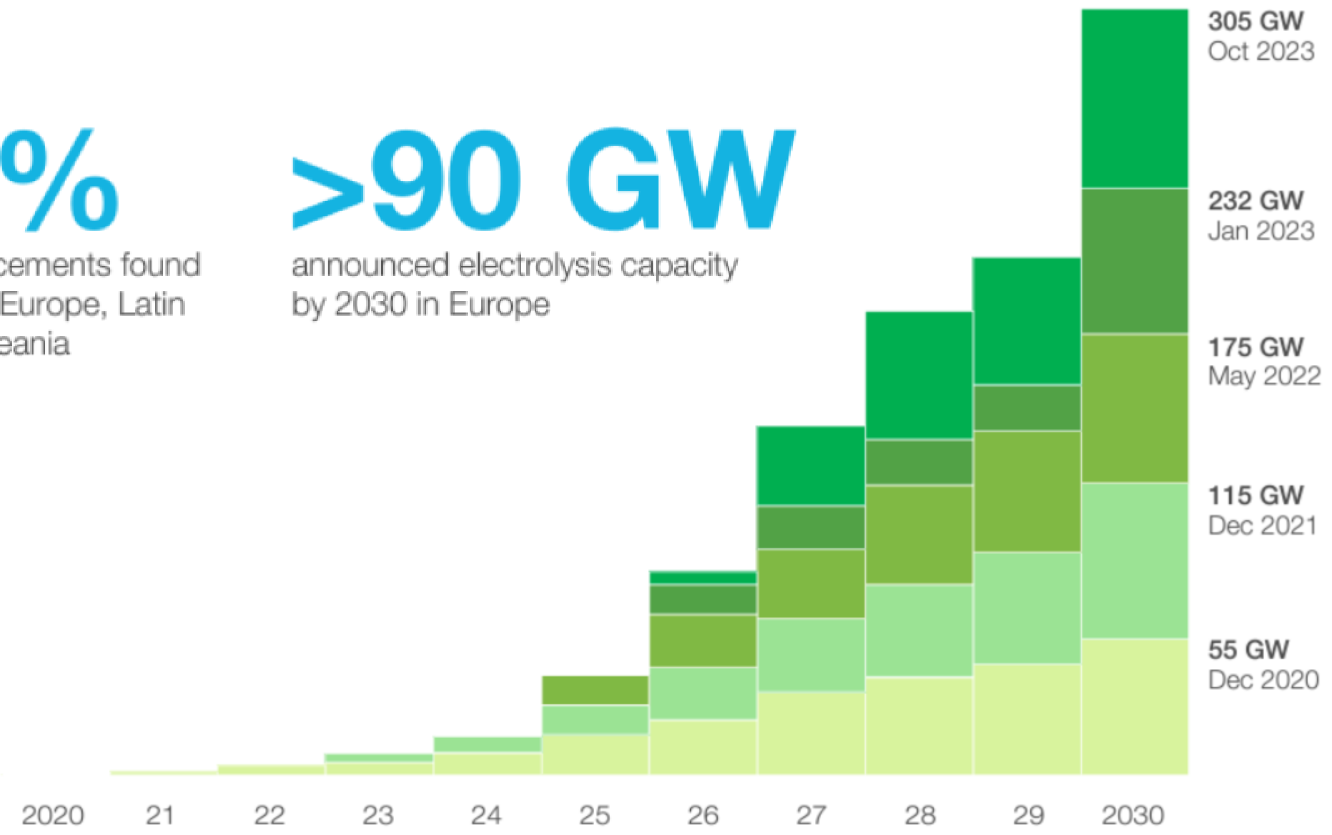
increase in announced electrolysis capacity by 2030 in the past 9 months

>60%

capacity announcements found in 3 regions, i.e., Europe, Latin America, and Oceania

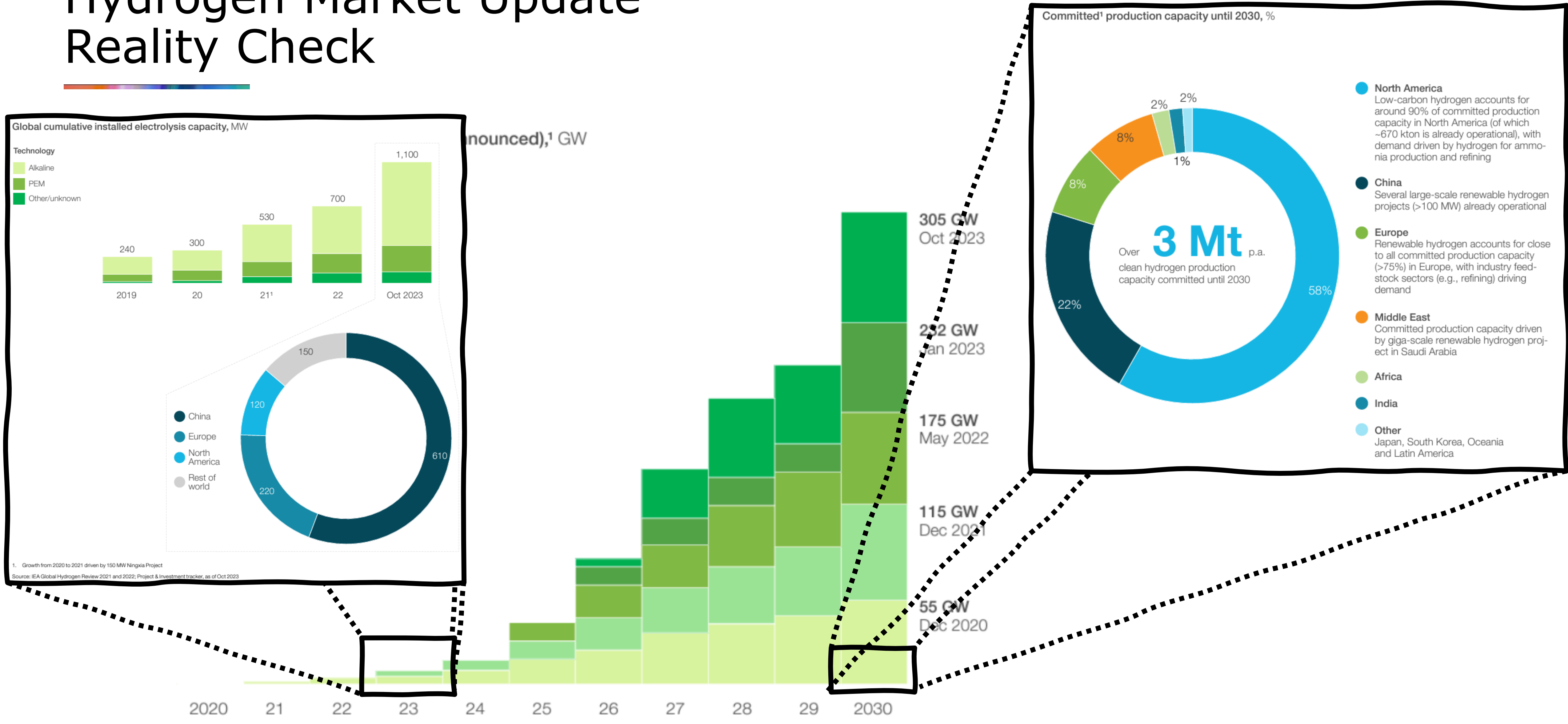
>90 GW

announced electrolysis capacity by 2030 in Europe



Source: Hydrogen-Insights-Dec-2023-Update.pdf(Review) - Adobe cloud storage, MCKinsey & Company

Hydrogen Market Update
Reality Check



1. Growth from 2020 to 2021 driven by 150 MW Ningxia Project

Source: IEA Global Hydrogen Review 2021 and 2022; Project & Investment tracker, as of Oct 2023

North America
Low-carbon hydrogen accounts for around 90% of committed production capacity in North America (of which ~670 kton is already operational), with demand driven by hydrogen for ammonia production and refining

China
Several large-scale renewable hydrogen projects (>100 MW) already operational

Europe
Renewable hydrogen accounts for close to all committed production capacity (>75%) in Europe, with industry feedstock sectors (e.g., refining) driving demand

Middle East
Committed production capacity driven by giga-scale renewable hydrogen project in Saudi Arabia

Africa

India

Other
Japan, South Korea, Oceania and Latin America

Source: Hydrogen-Insights-Dec-2023-Update.pdf(Review) - Adobe cloud storage, MCKinsey & Company

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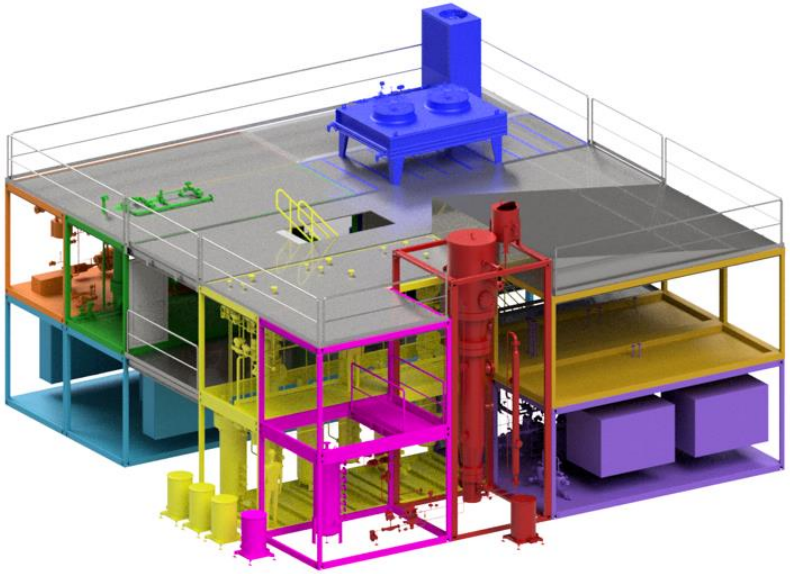

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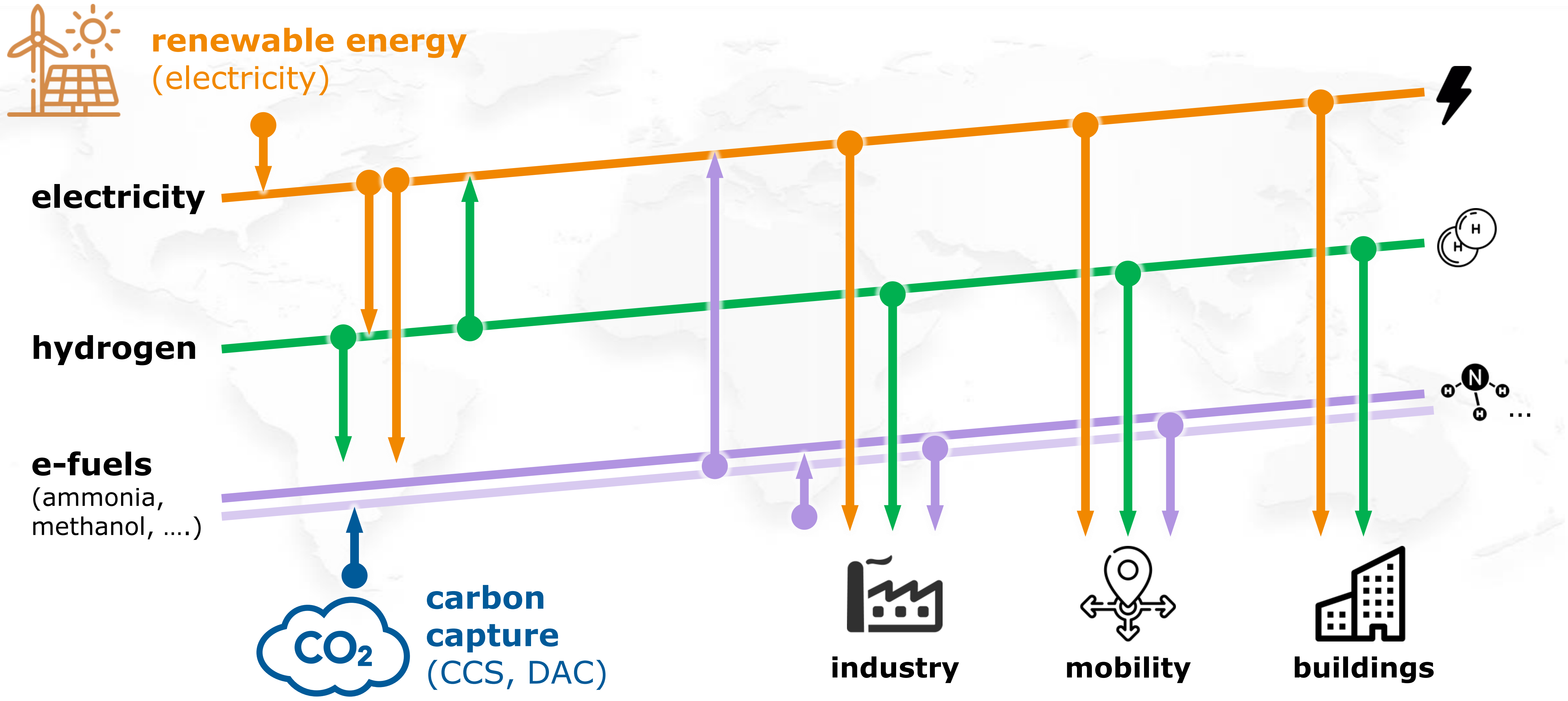
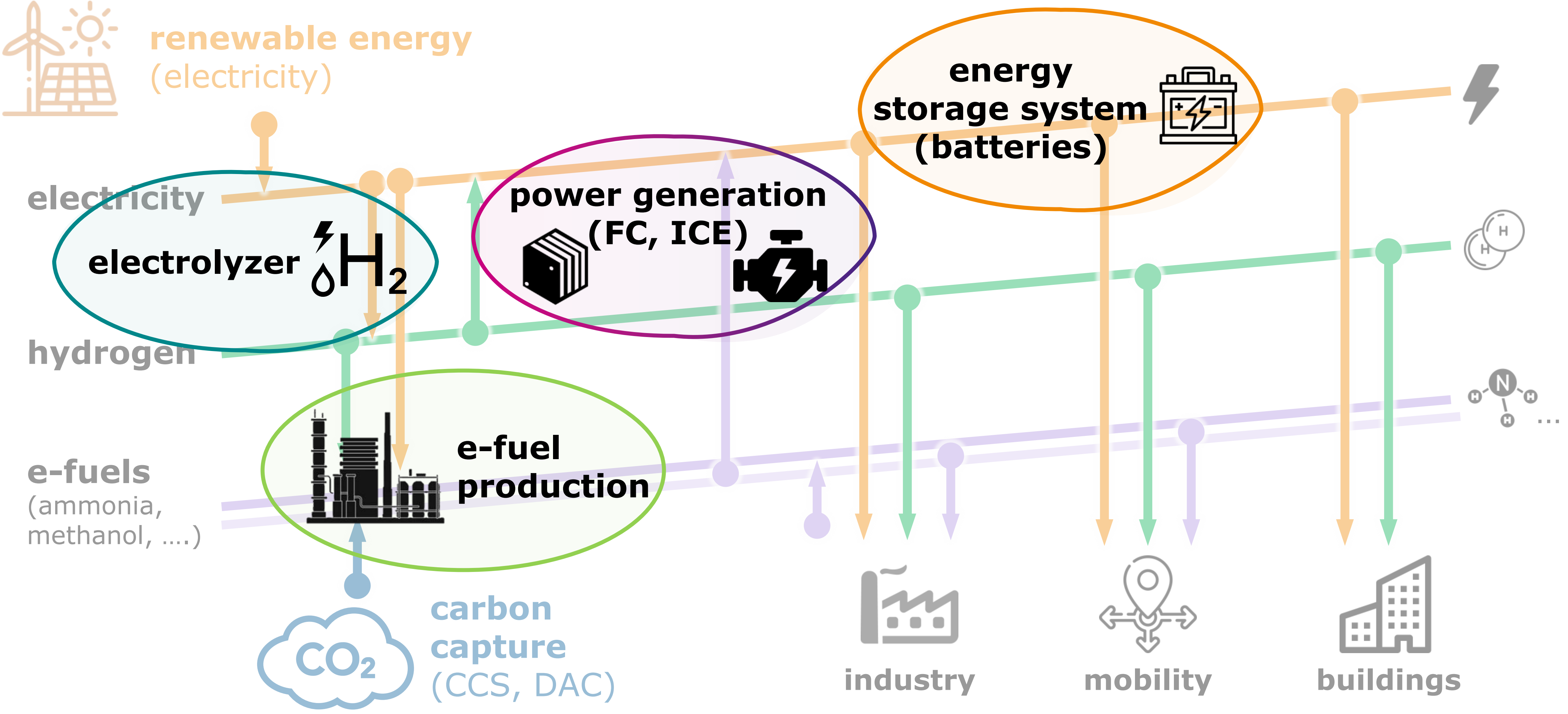
Future Energy Vectors

CCS - Carbon Capture Storage
DAC - Direct Air Capture
ESS - Energy Storage System
FC - Fuel Cell
ICE - Internal Combustion Engine



AVL Offering
to support industrial green energy transformation

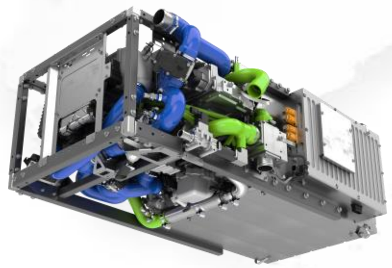
CCS - Carbon Capture Storage
DAC - Direct Air Capture
ESS - Energy Storage System
FC - Fuel Cell
ICE - Internal Combustion Engine



PEM FC … Polymer Electrolyte Membrane Fuel Cell
SOFC … Solid Oxide Fuel Cell
PEM EL … Polymer Electrolyte Membrane Electrolysis
SOEC … Solid Oxide Electrolysis Cell

AVL Fuel Cell and Electrolysis Solutions
H_2 Ecosystem Implementation

PEM FC



#Mobility and Power Generation

- Automotive
- Marine
- Rail
- Aviation

SOFC

#Combined Heat and Power

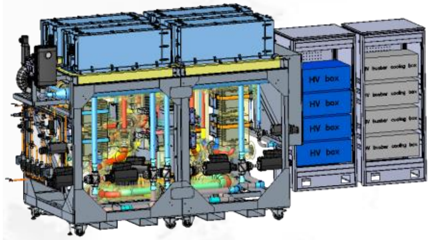
- Decentral Power
- BEV Charging stations
- Marine APUs

PEM EL

#Hydrogen Production

- Renewable Power Plants
- Decentral Hydrogen Production

SOEC



#Hydrogen, Syngas and Power-to-X

- Industry
- Refining
- Synthesis
- Waste Heat Usage

PEMFC … Proton Exchange Membrane Fuel Cell
HT-PEMFC … High temperature Proton Exchange Membrane Fuel Cell
DMFC … Direct Methanol Fuel Cell
SOFC … Solid Oxide Fuel Cell

Fuel Cell Technology Comparison

PEMFC

Hydrogen

- 🟩 High Efficiency
- 🟩 High power density
- 🟩 Quick start-up and load following
- 🟥 Very clean hydrogen needed

HT-PEMFC

Hydrogen

- 🟩 Suitable for CHP and CCHP
- 🟩 Hydrogen impurities can be handled easier
- 🟥 Larger and less efficient than PEMFC
- 🟥 Durability Challenging

DMFC

Methanol

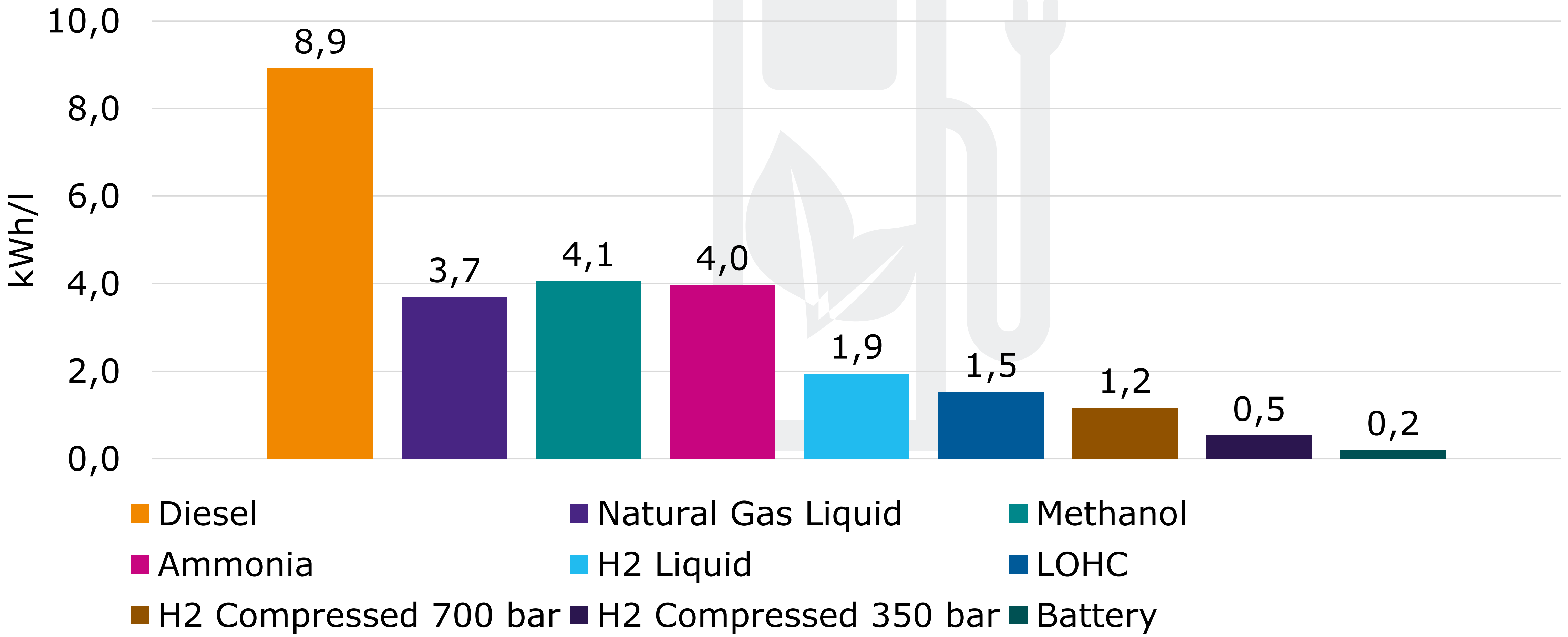
- 🟩 Direct use of methanol
- 🟥 Low efficiency
- 🟥 Low Power Density

SOFC

Flexible

- 🟩 High efficiency
- 🟩 Suitable for CHP and CCHP
- 🟥 Low power density
- 🟥 Slow start-up and response time

Estimated Volumetric Energy Power Density
Fuel plus Tank



Fuel Choice for Fuel Cell Systems

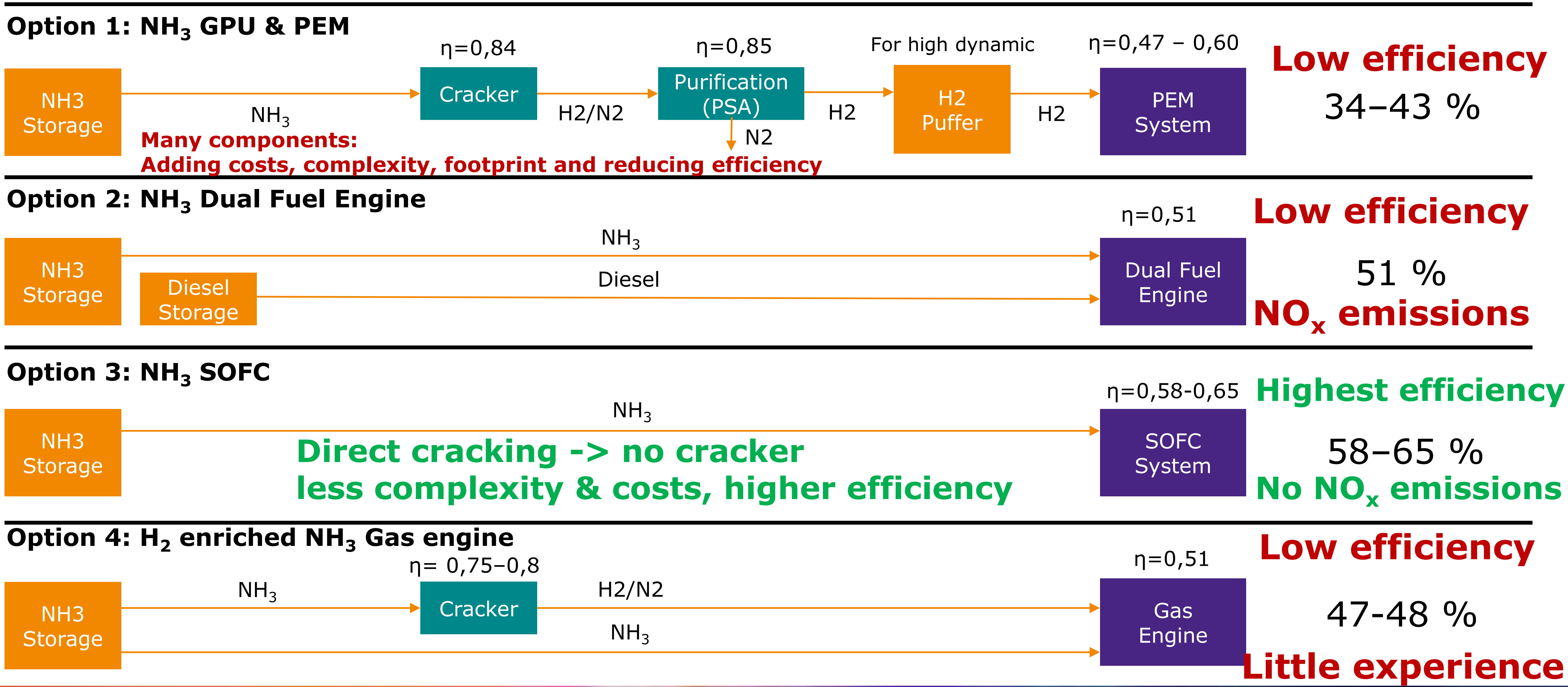
	HFO	Diesel MGO	Natural Gas	Methanol	Ammonia	LOHC	Hydrogen
PEMFC	-	-	~	~	~	~	+
SOFC	-	-	+	+	+	+	+

\+ … Good efficiency, simple architecture
~ … Medium efficiency, complex fuel processing
\- … Low efficiency, very complex fuel processing, durability problems

Ammonia as Marine Fuel

Efficiency Chain - NH_3 FC (PEM, SOFC) & ICE

η_{el}



Option 1: NH_3 GPU & PEM

NH3 Storage → NH_3 → η=0,84 Cracker → H2/N2 → η=0,85 Purification (PSA) (↓ N2) → H2 → For high dynamic H2 Puffer → H2 → η=0,47 – 0,60 PEM System

Many components:
Adding costs, complexity, footprint and reducing efficiency

Low efficiency

34–43 %

Option 2: NH_3 Dual Fuel Engine

NH3 Storage → NH_3 → η=0,51 Dual Fuel Engine

Diesel Storage → Diesel → Dual Fuel Engine

Low efficiency

51 %

NO_x emissions

Option 3: NH_3 SOFC

NH3 Storage → NH_3 → η=0,58-0,65 SOFC System

Direct cracking -> no cracker
less complexity & costs, higher efficiency

Highest efficiency

58–65 %

No NO_x emissions

Option 4: H_2 enriched NH_3 Gas engine

NH3 Storage → NH_3 → η= 0,75–0,8 Cracker → H2/N2 → η=0,51 Gas Engine

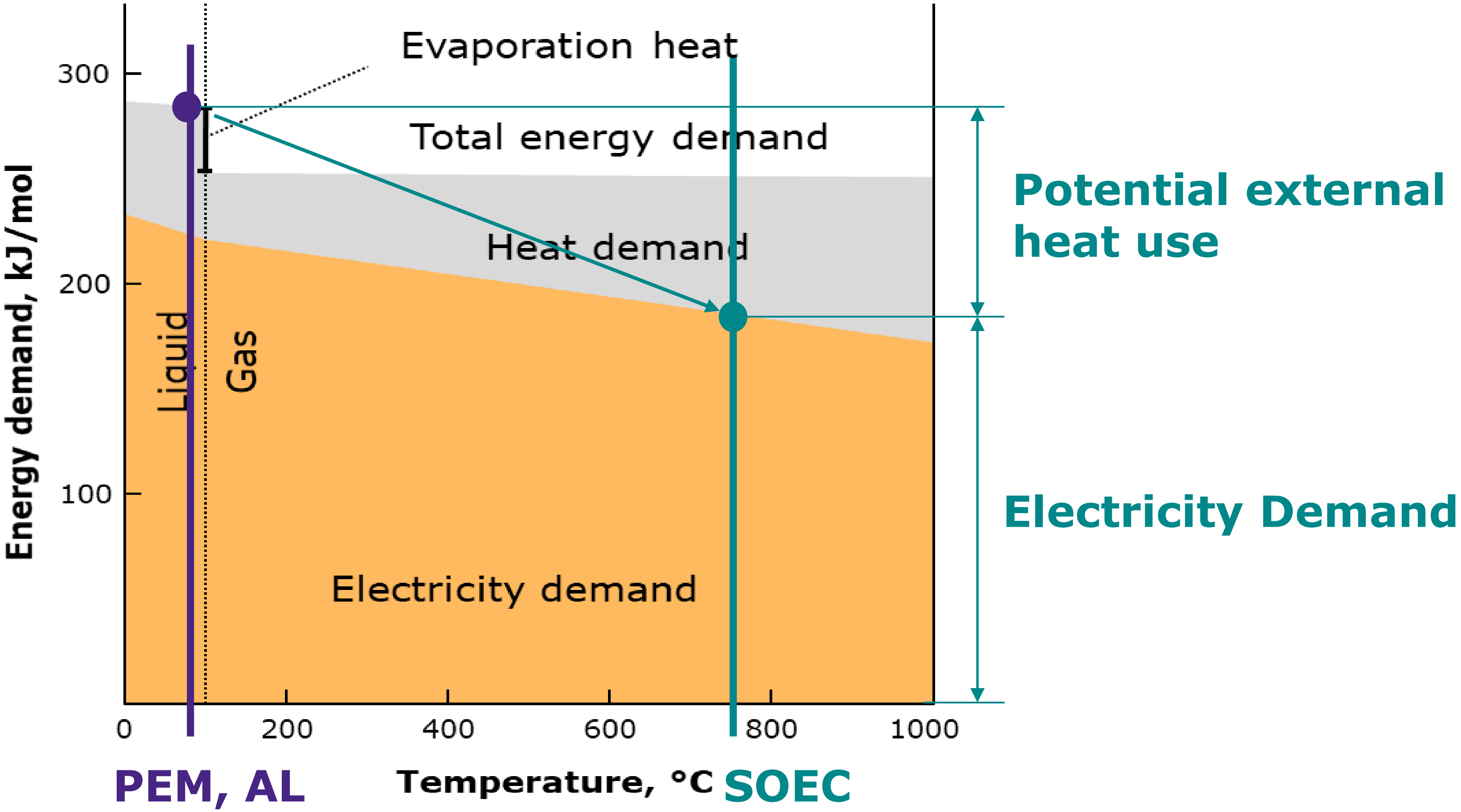
NH3 Storage → NH_3 → Gas Engine

Low efficiency

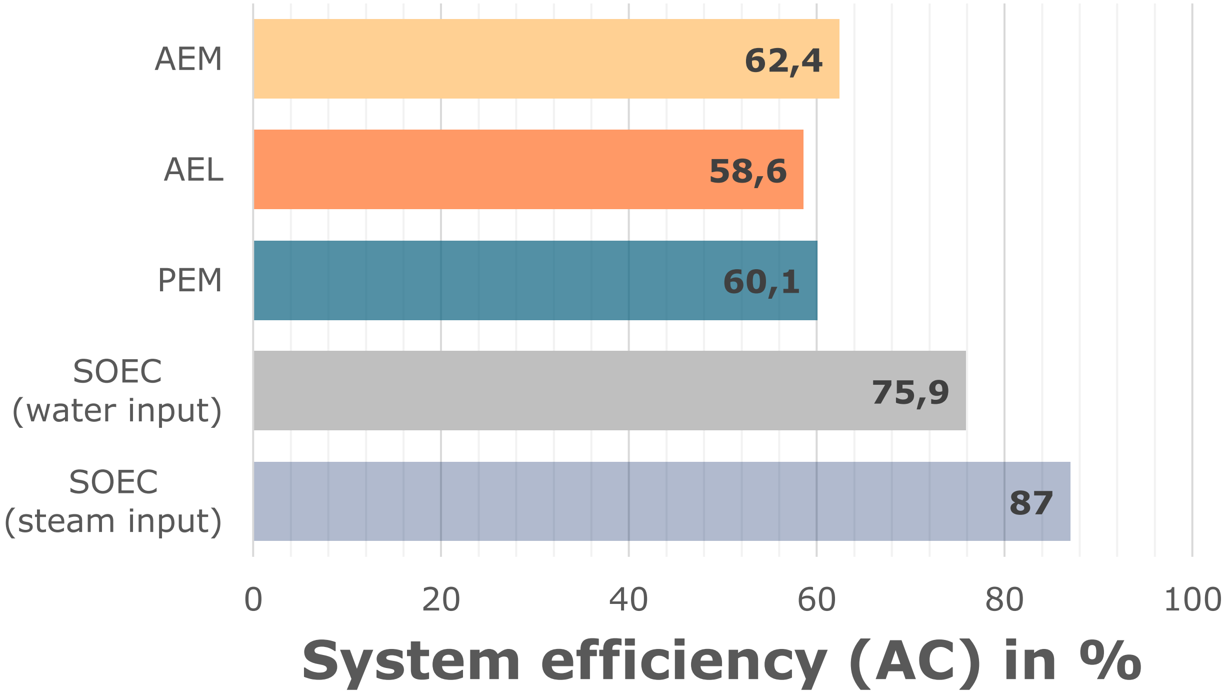
47-48 %

Little experience

Efficiency Advantage of SOEC



Electrolyzers comparison



	Advantages	Disadvantages
AEM	No expensive or critical minerals	Low kW stack sizes
	Compact design and small footprint	Shorter stack lifetime than PEM and AEL due to membrane degradation
	High pressure suitable, fast start up and load changing	High ramp up time
AEL	Mature technology (GWs deployment, TRL 8-9)	High material effort (alkaline liquid as electrolyte)
	Multi MW stacks available	Low power density and large footprint
	Usage of available and inexpensive materials	High idle load, slow start up
PEM	High power density (compact design and small footprint)	Expensive materials (titanium and PGM)
	Fast start up and load changing capability	Long term stability unproven at MW scale
	Relatively mature (TRL 8-9)	Reliant on hardly degradable chemicals
SOEC	Lowest idle load	Low TRL
	High efficiency (fast kinetics and conductivity)	Highest physical footprint (3.5x PEM)
	Reversible operation	Low output pressure and long cold starts
	Co-electrolysis of water and carbon-based molecules	Poor durability - thermally accelerated aging

Next Generation Electrolyzer Technologies
1MW 40ft Container Solid Oxide Electrolysis System

- 87% efficiency demonstrated - water steam electrolysis on SOEC module level
- Module Integration, Container Build Up, Testing, Commissioning by AVL

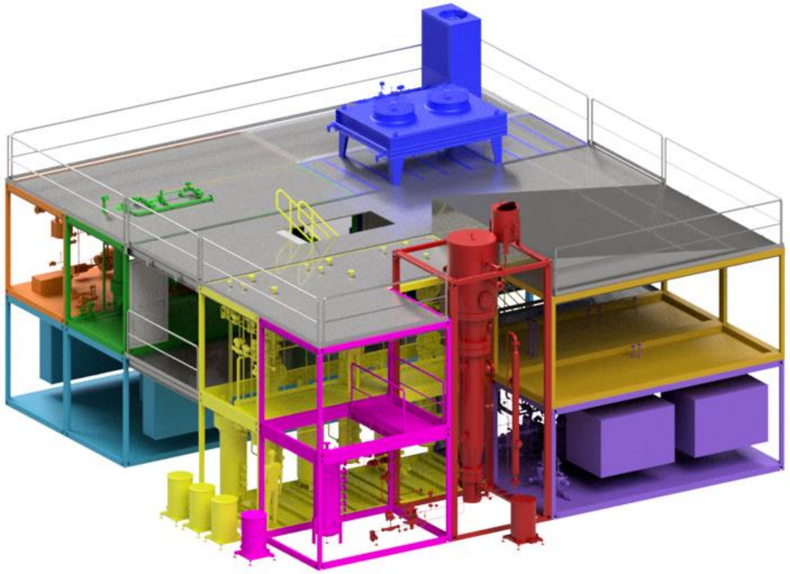
NEWS

Ceres and Shell sign agreement for green hydrogen

28 June 2022

- Megawatt scale demonstrator to be located in Bangalore, India
- Aim to deliver low-cost green hydrogen for industrial decarbonisation

Content



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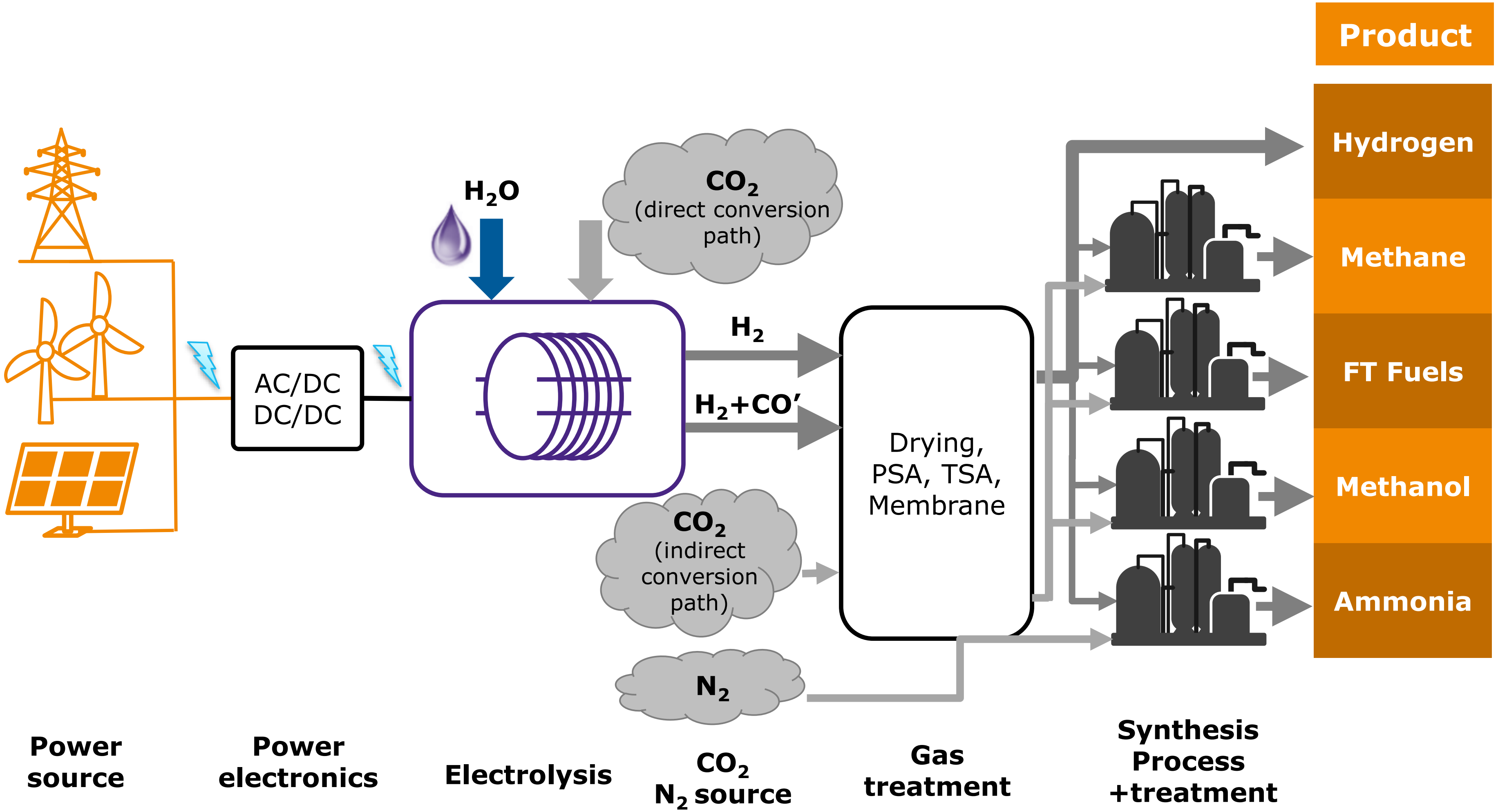
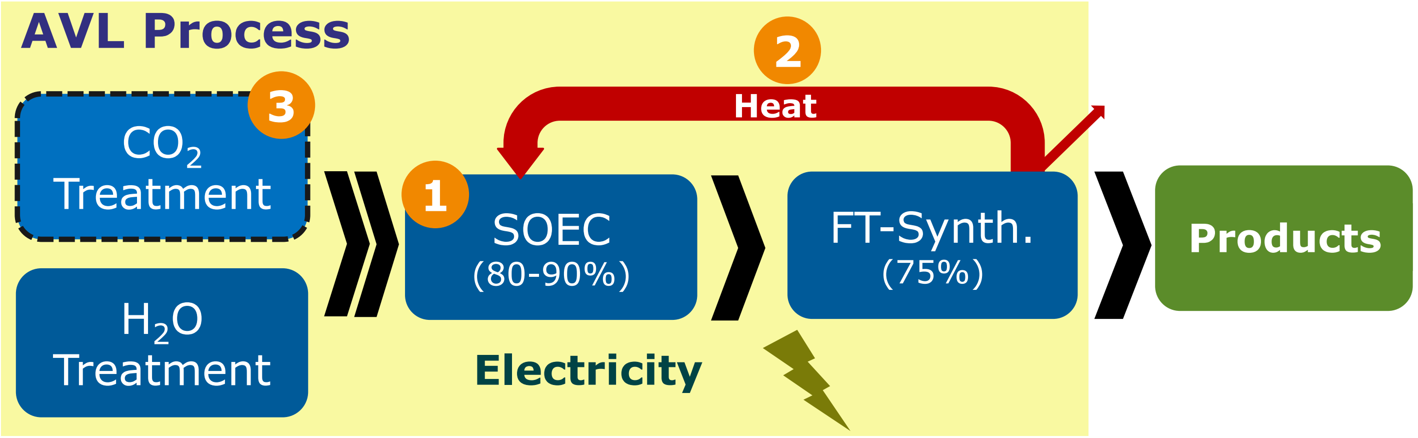
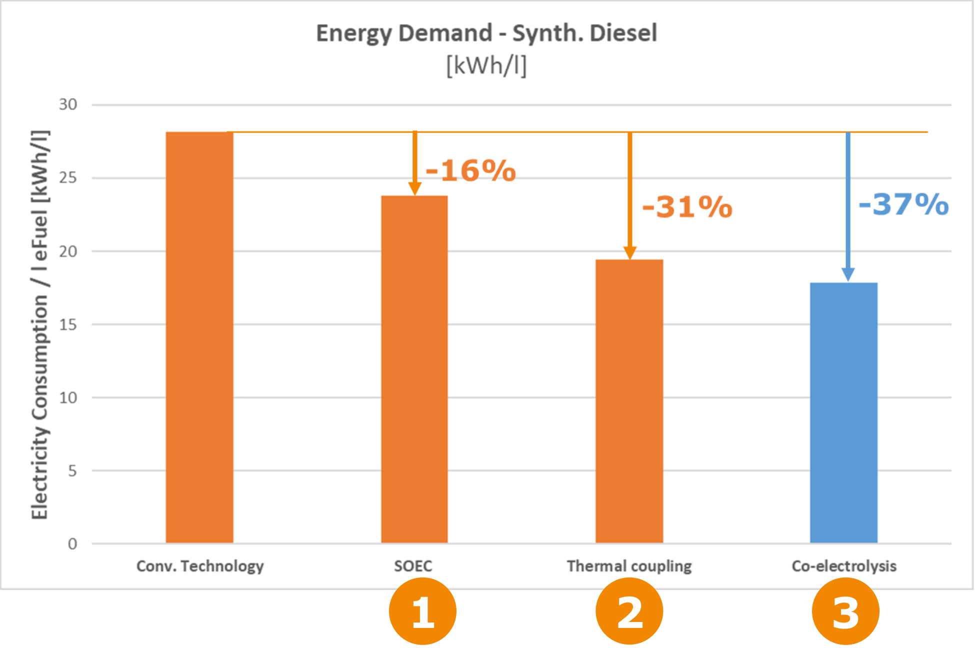
SOEC Power-to-X Routes



Efficiency Improvement Potential of e-Fuel Production with SOEC



AVL Process

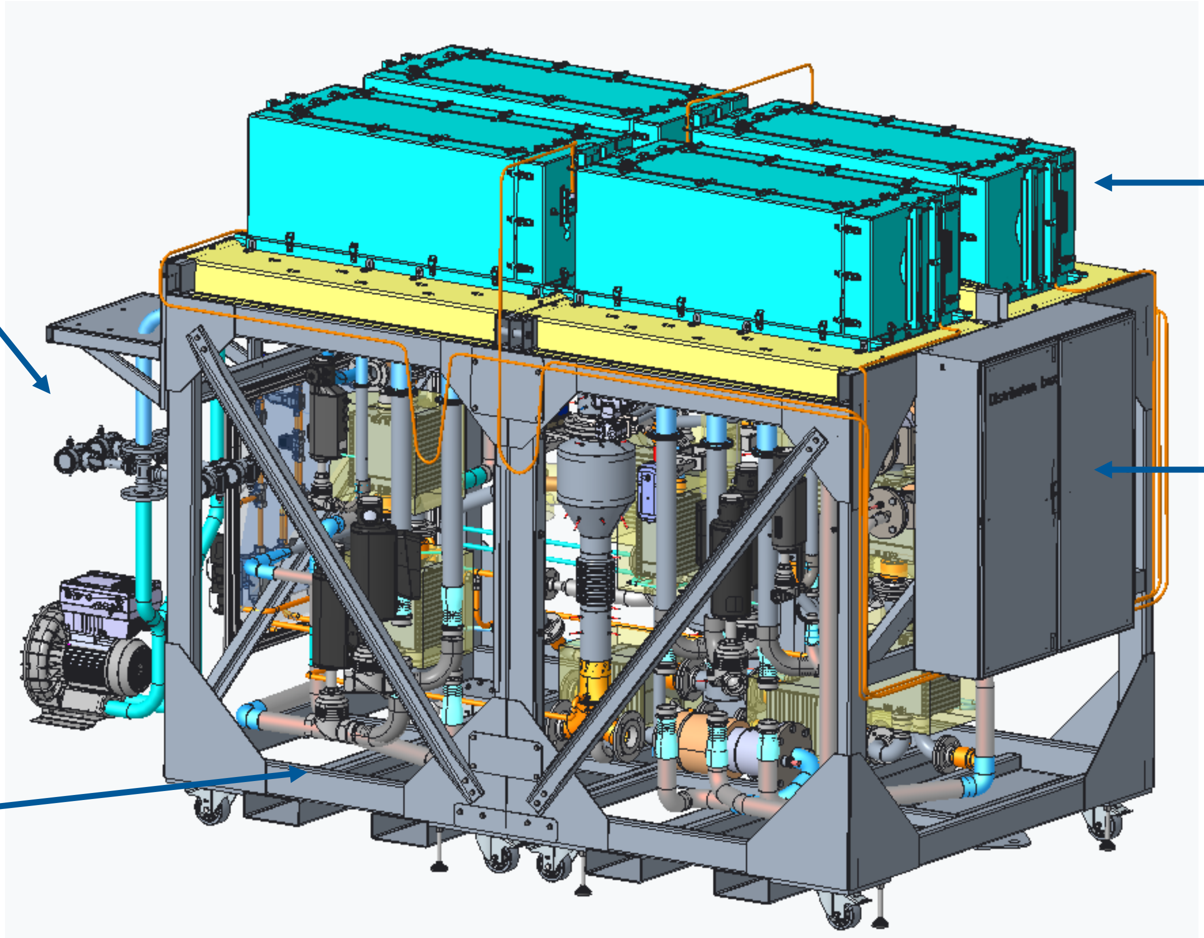


1. High-temperature electrolysis
2. Thermal Coupling
3. Co-electrolysis

Combined SOEC-FT process allows 30-40% higher efficiency compared to PEM and AL EL

FT…Fischer Tropsch, PEM EL…Polymer Electrolyte Membrane Electrolysis, AL EL…Alkaline Electrolysis

CO-SOEC Module



Cold BoP components:
- Blower
- Air filter
- Mass flow controllers
- Water supply + purifier
- Steam generator

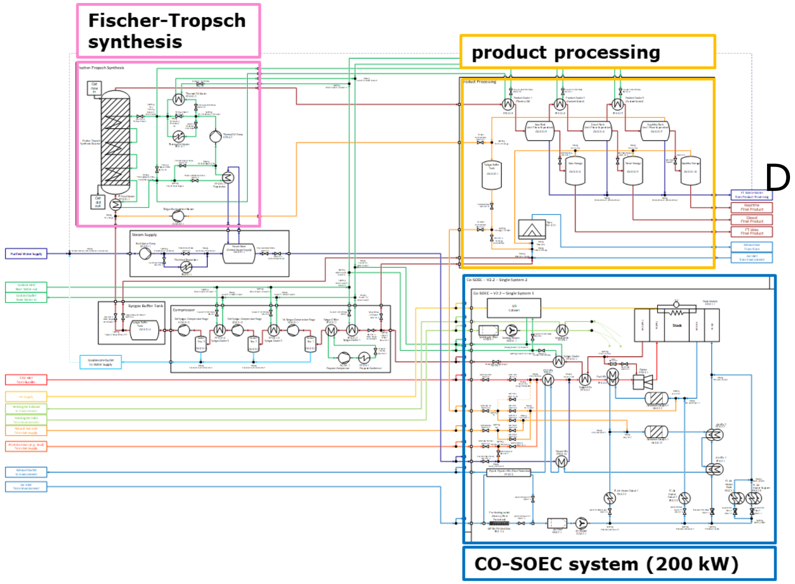
Hot BoP components:
- Heat exchangers
- Ejector
- Afterburner/OxiCat
- Heaters

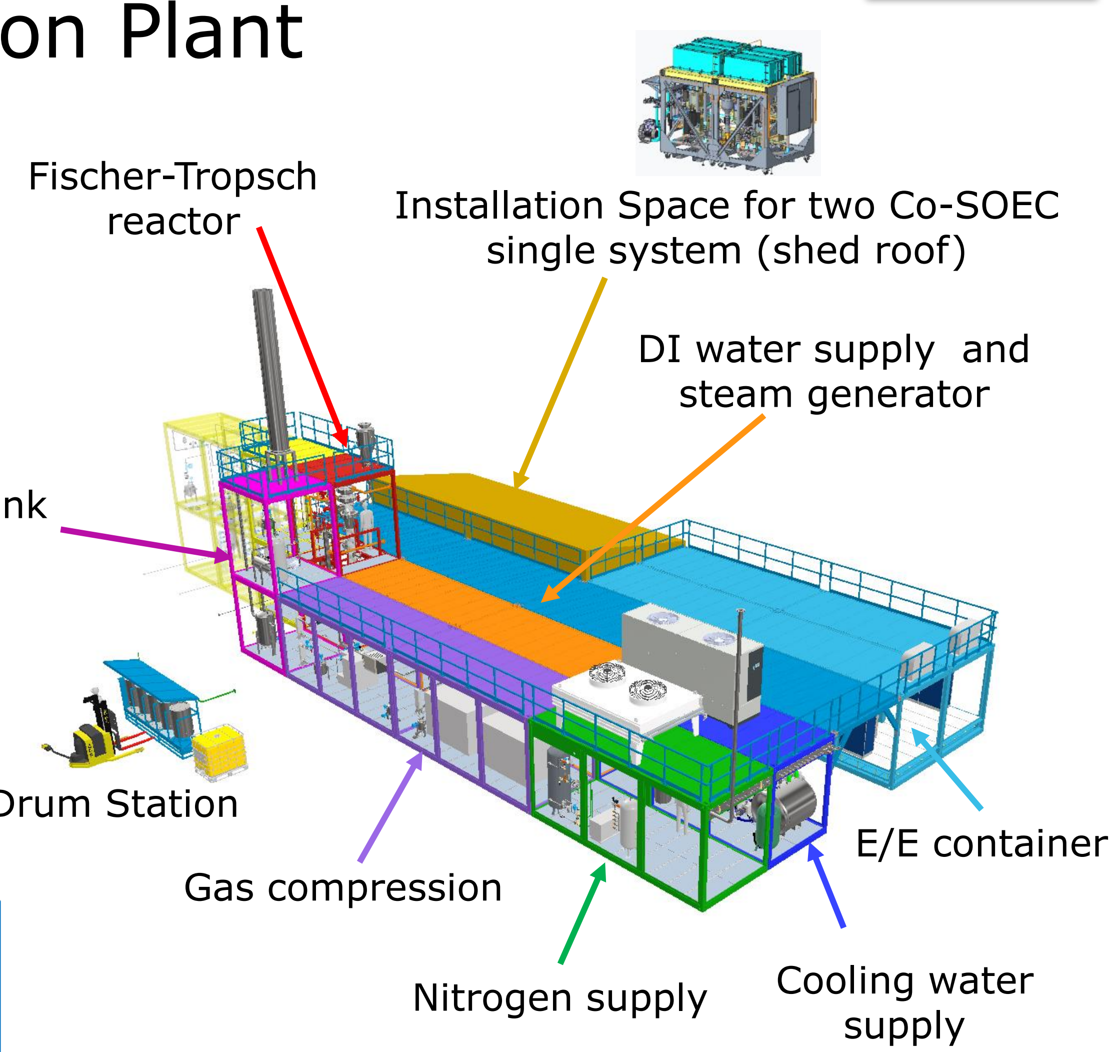
Co-SOEC Stack modules

E-cabinet

SOEC Power-to-Liquid Demonstration Plant

- 200kWel SOEC capacity
- ~100.000l production capacity of e-fuels per year
- Focus: Diesel and SAF (sustainable aviation fuels)
- Commissioning in Q4/2024
- >30% Efficiency Improvement in e-fuel production



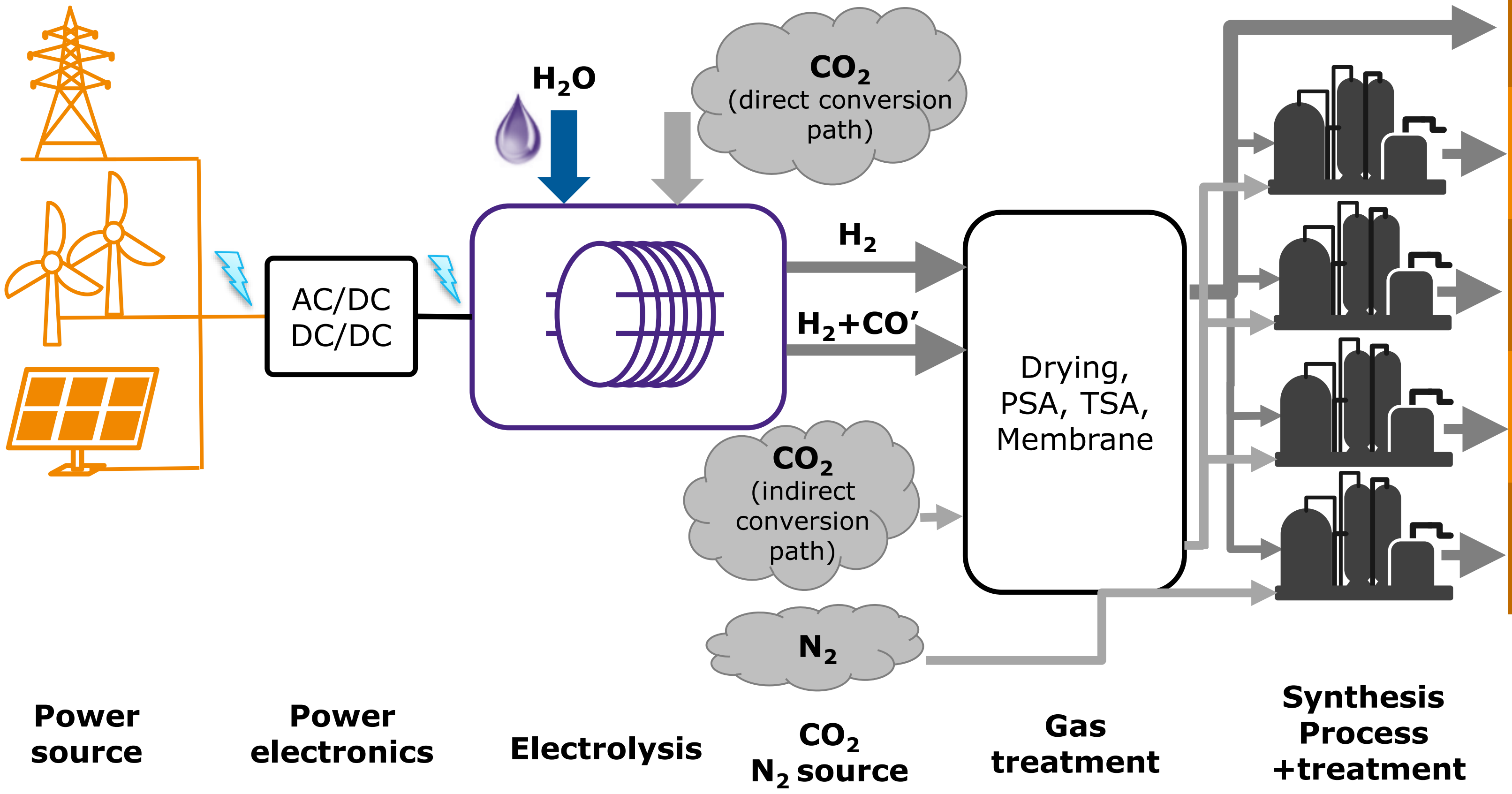


Power-to-Liquid Demonstration Plant

Process Design

Scenarios	Demo Plant # 1	# 2	# 3	# 4
Product tailgas recirculation to FT	✓	✓	✓	✓
CO_2 separation before Co-SOEC	✗ (CO_2 tank)	✓ (AmineWasher)	✓ (AmineWasher)	✓ (AmineWasher)
CO_2 separation after Co-SOEC	✗	✗	✓ (PSA)	✗
rWGS for recirc. tailgas	✗	✗	✗	✓
FT heat integration	✓ to steam generation (150°C)	✓ to amine washing	✓ to amine washing	✓ to amine washing
PtL efficiency	**>55%**	**~47%**	**~55%**	**~57%**
Carbon efficiency	**~66%**	**~60%**	**>95%**	**>95%**

SOEC Power-to-X Routes



	Process Efficiency	
Product	**SOEC**	**SoA**
Hydrogen	**~85%**	~70%
Methane	**~80%**	~50%
FT Fuels	**~55%**	~40%
Methanol	**~70%**	~45%
Ammonia	**~70%**	~50%

SOEC improves the efficiency of all major eFuel production routes significantly

Thank you

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