CLEANTECH LANDSCAPES

TRENDS IN GREEN HYDROGEN

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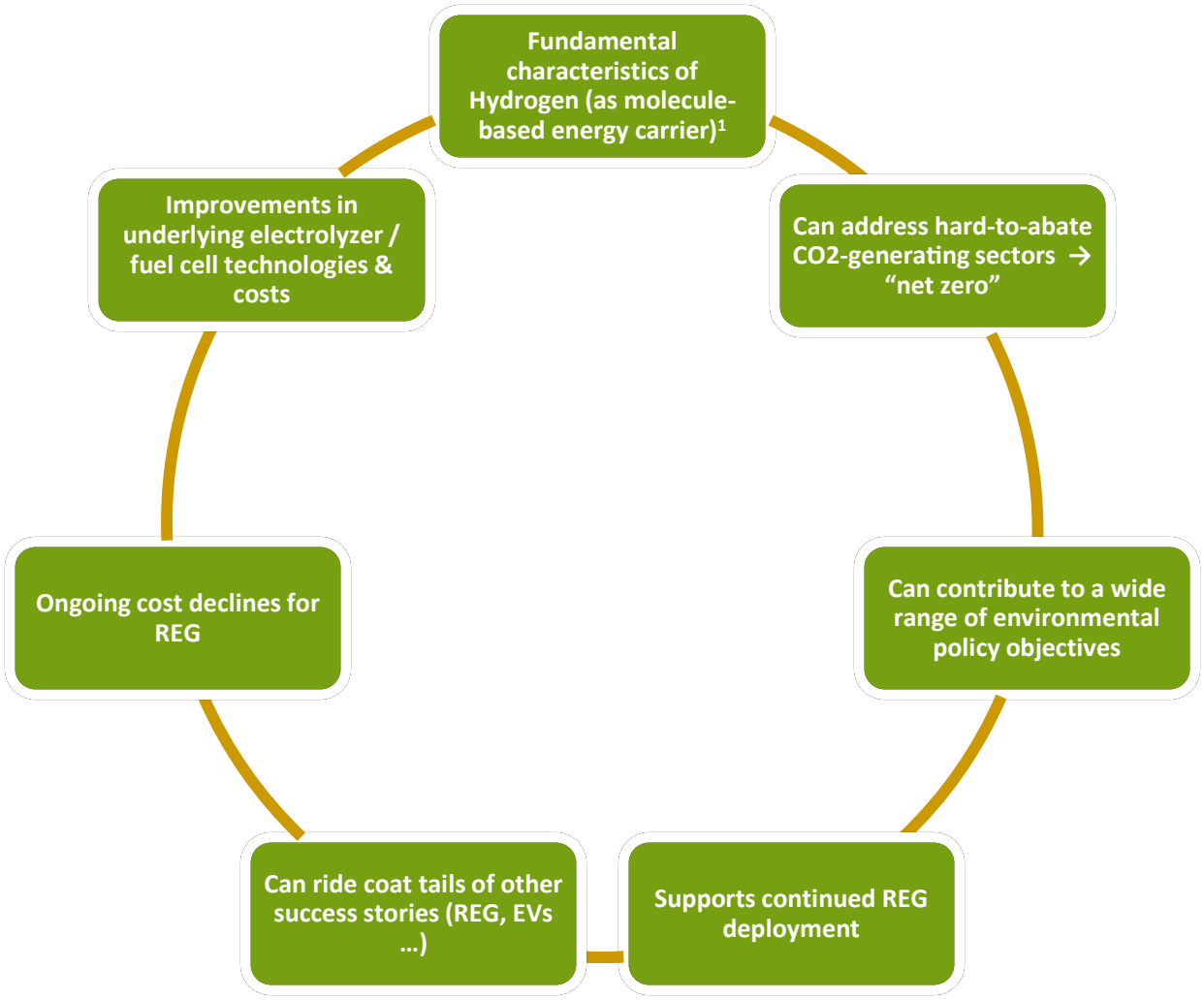
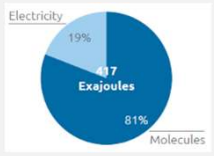
Drivers of the Hydrogen Economy

Various supporting factors are now aligned to make it "different this time" for the Hydrogen Economy



Global Final Energy Consumption



[1] no carbon, high energy density (by weight)

Source: CleanTech Capital Advisors

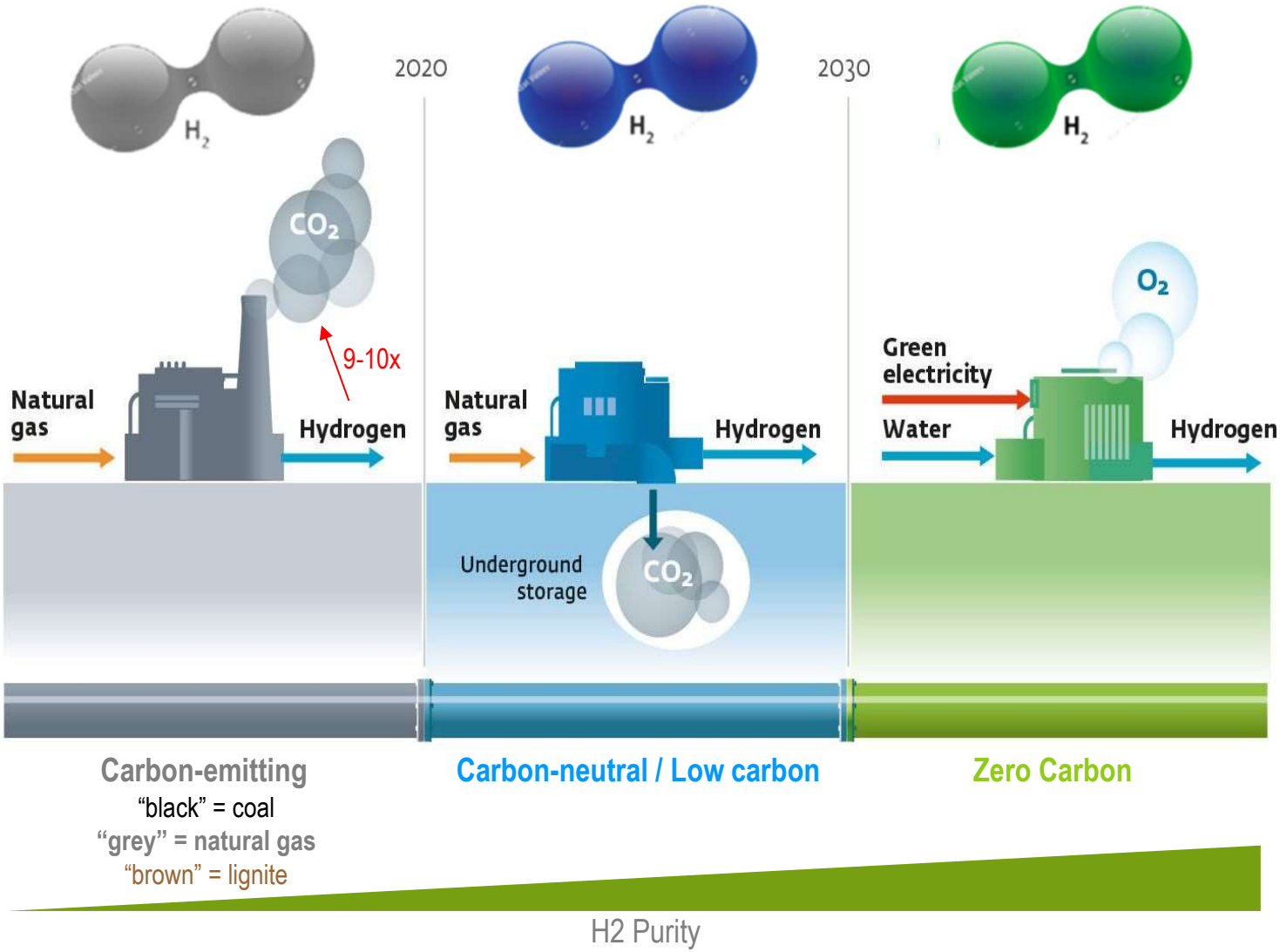
Hydrogen Categories

97% of H2 production today comes from hydrocarbons and is carbon-intensive

"Hydrogen Economy" relates to "Blue" & "Green" H2

While 100% CCS doesn't exist, Blue H2 is generally seen as an acceptable transition to Green H2

Its greater purity makes Green H" more suitable for fuel cells



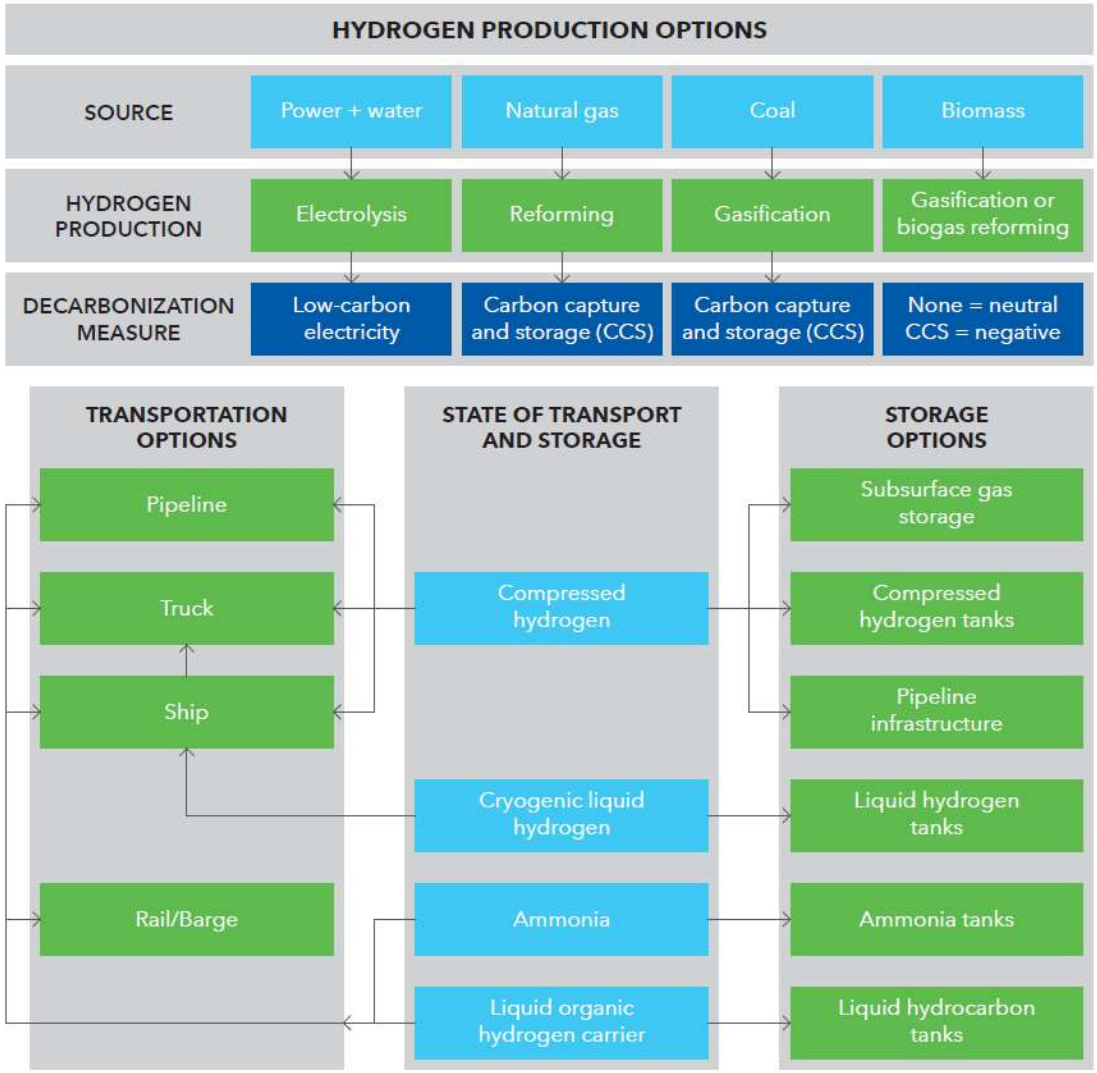
[1] with ideally 100% carbon capture is "carbon-neutral"; in reality is "low-carbon" (60%-90%)

Source: The World of Hydrogen ; CleanTech Capital Advisors

Hydrogen Economy Supply Chain

The H2 supply chain involves principally
- *Production*
- *Transport*
- *Storage*

Many different supply chain options exist and will co-exist for the HE

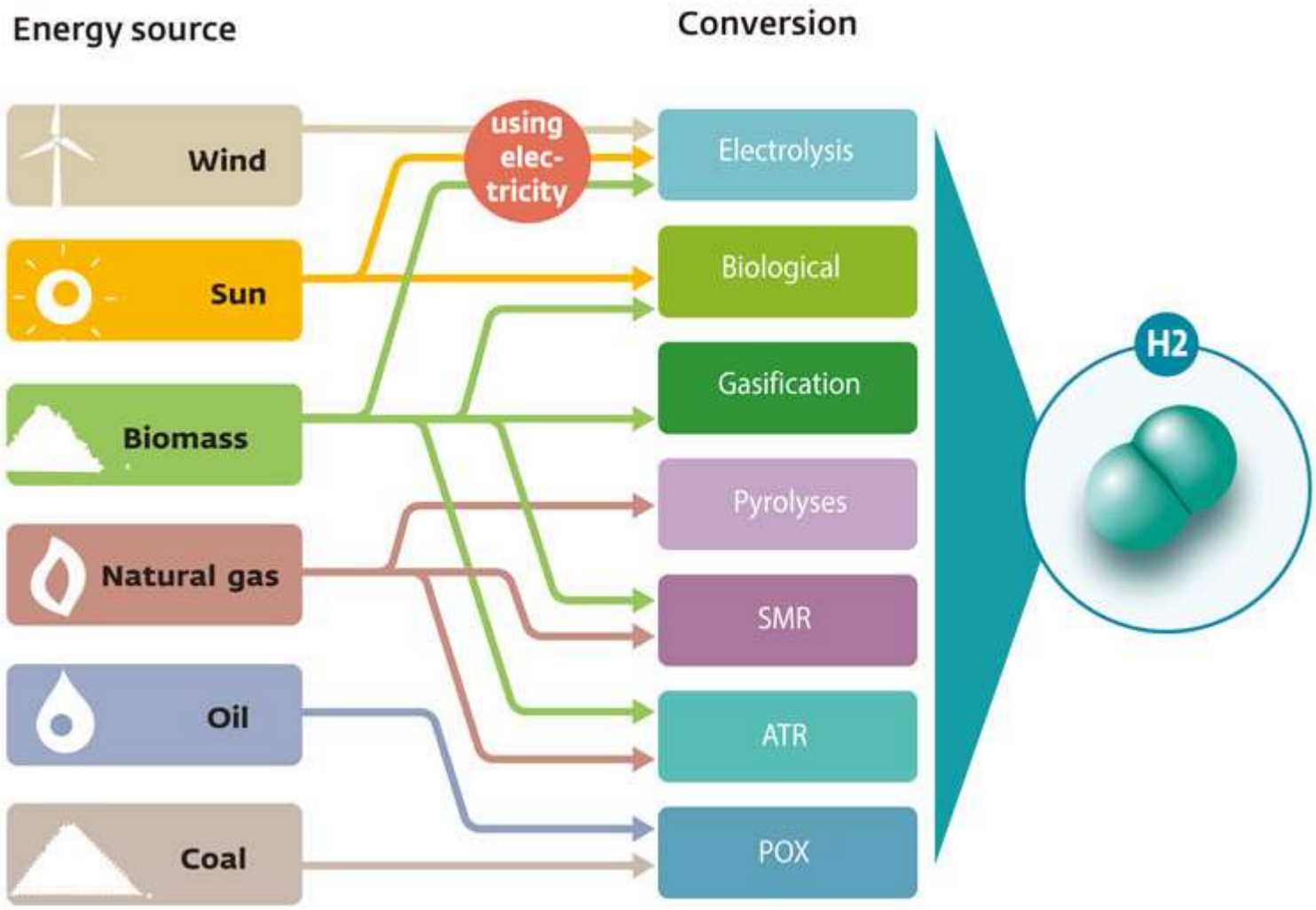


Source: DNV GL

Hydrogen Production Methods

Multiple existing and emerging pathways for high-volume production of H2

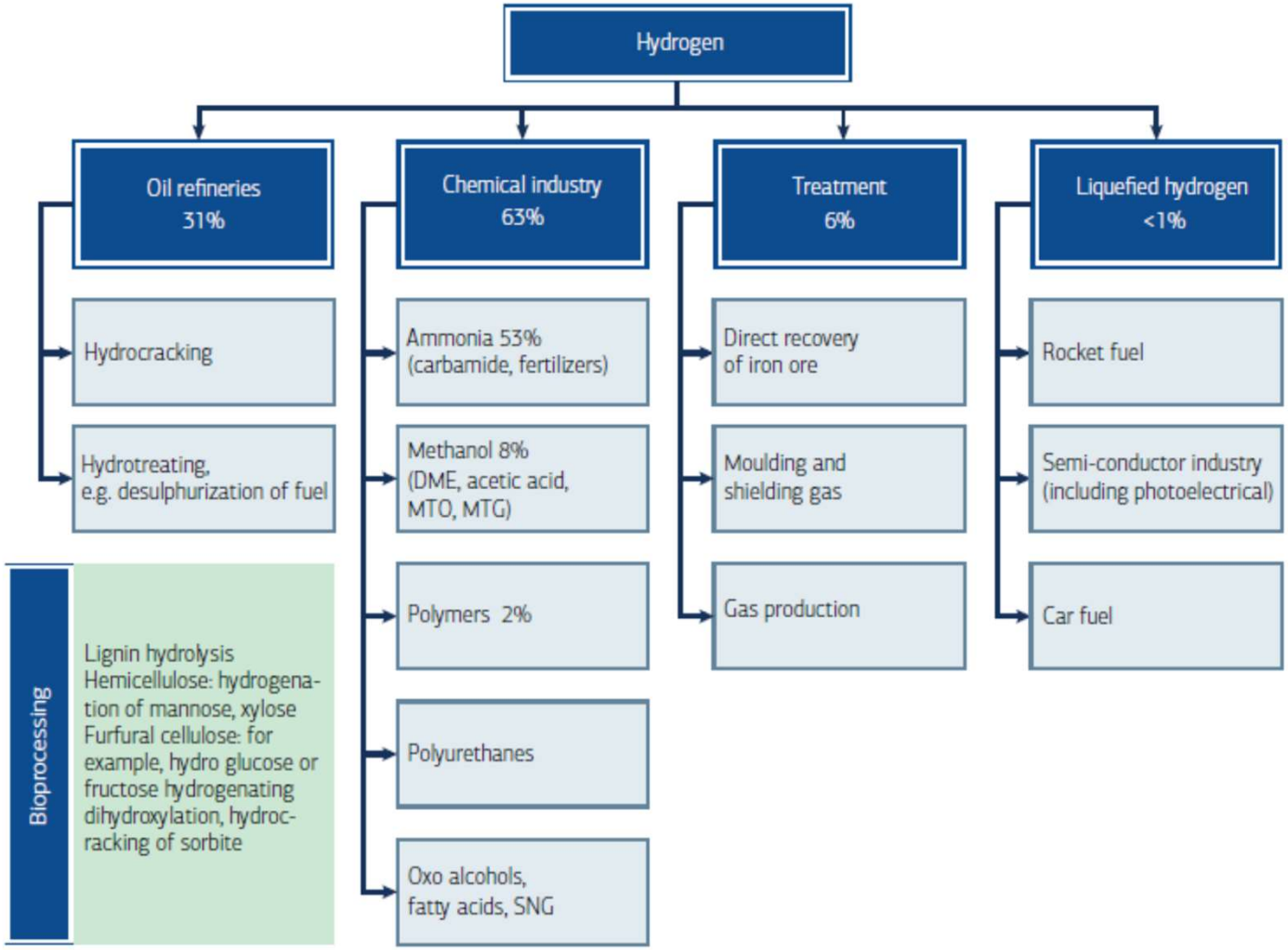
Steam reforming (SMR) if hydrocarbons is the dominant method today



Source: The World of Hydrogen

Current Hydrogen Applications

Chemicals (fertiliser) & Oil Refineries the principal consumers of H2 today

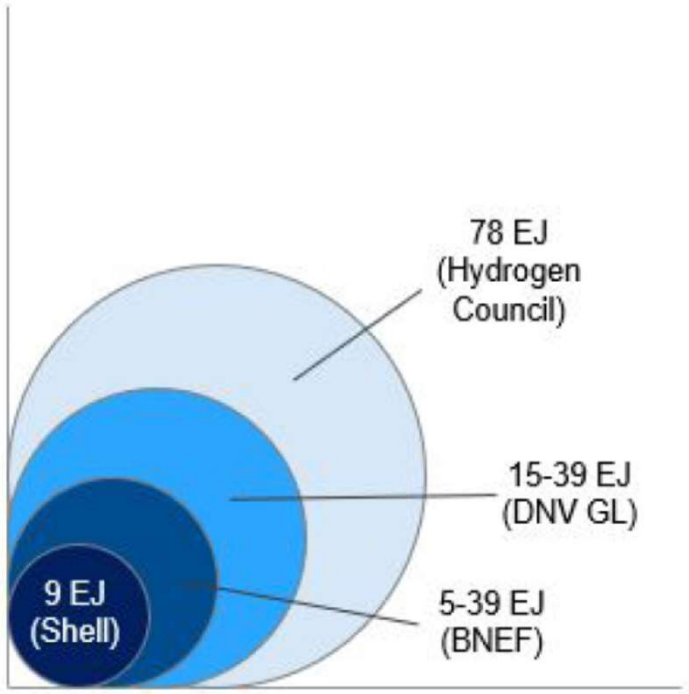


Source: DECHEMA; US DoE; Fair-PR; Linde

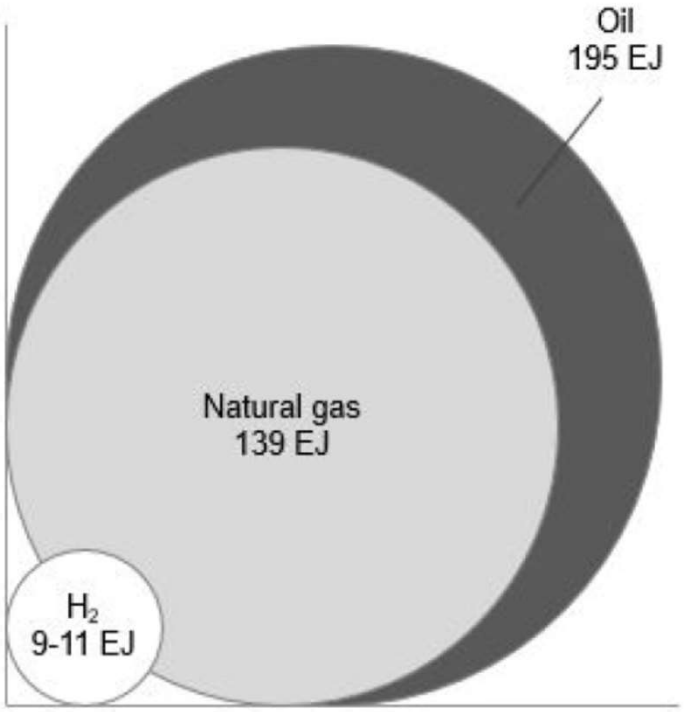
Hydrogen Market Potential Size

Most observers expect the H2 market to become very large, approaching traditional fossil fuel sector sizes

Estimated annual demand for H2 (2050) [Exajoule]



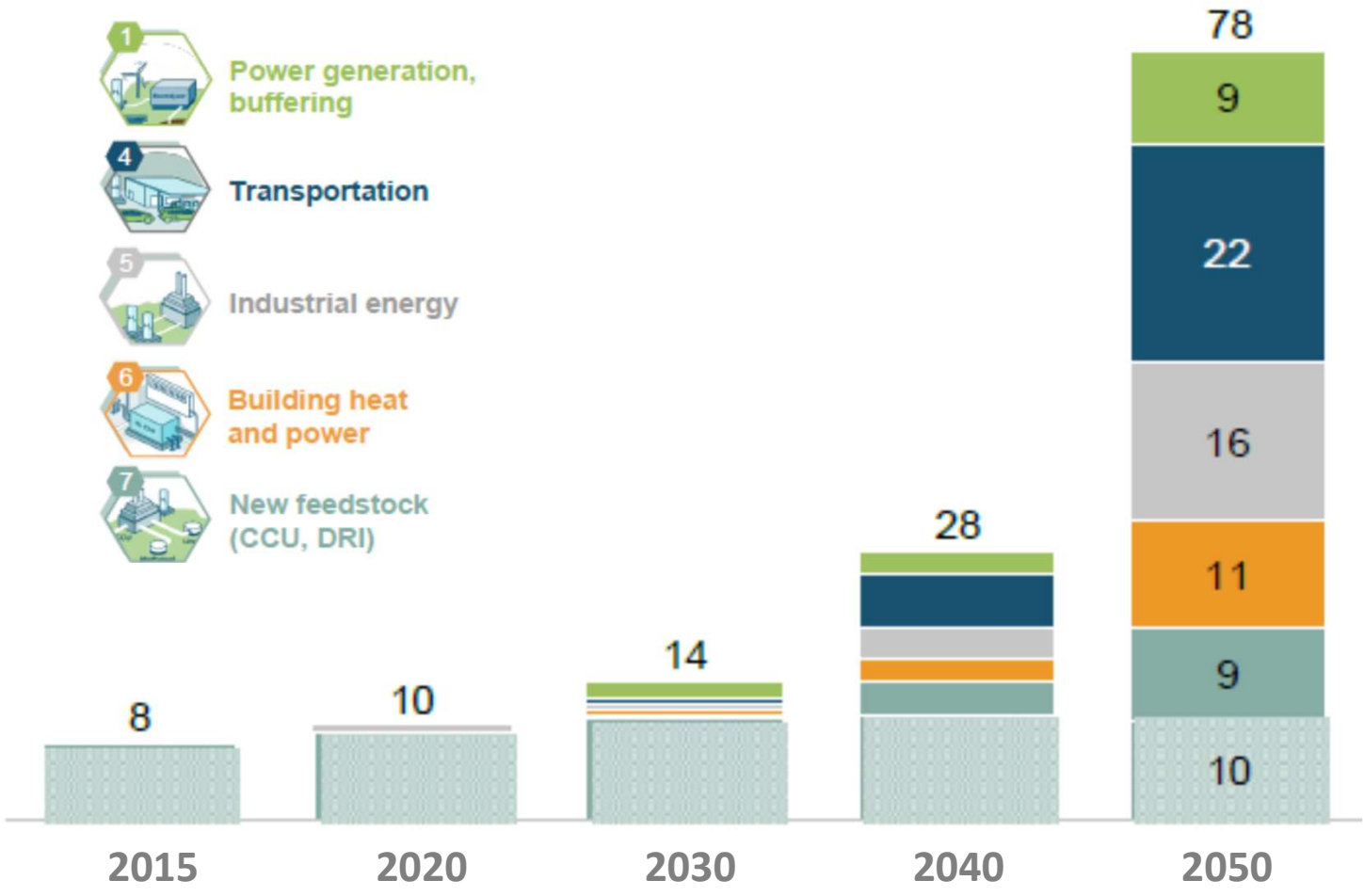
Current annual demand [Exajoule]



Source: Hydrogen Council 2017; BNEF 2019; DNV GL 2018; Shell 2018; IEA 2019; BP 2019

Hydrogen (Potential) Demand [EJ] - 2050

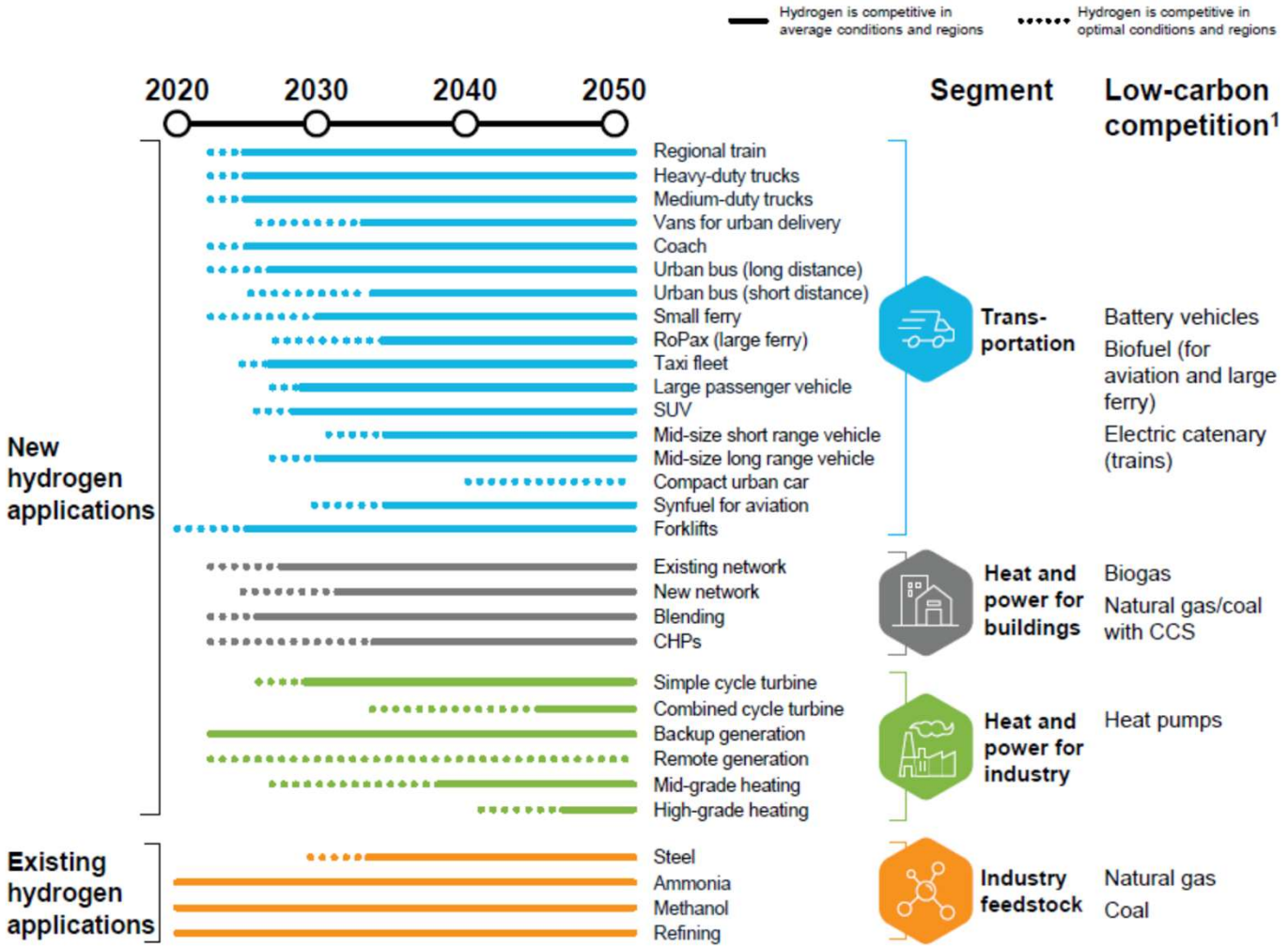
Growth is expected to come principally from new energy-related applications, in particular within Transport & Industrial sectors



Source: Hydrogen Council

Long-Term Competitiveness Trajectory

Heavy duty vehicles and Industrial Heat expected to be among leading initial applications for HE



1. In some cases hydrogen may be the only realistic alternative, e.g. for long-range heavy-duty transport and industrial zones without access to CCS

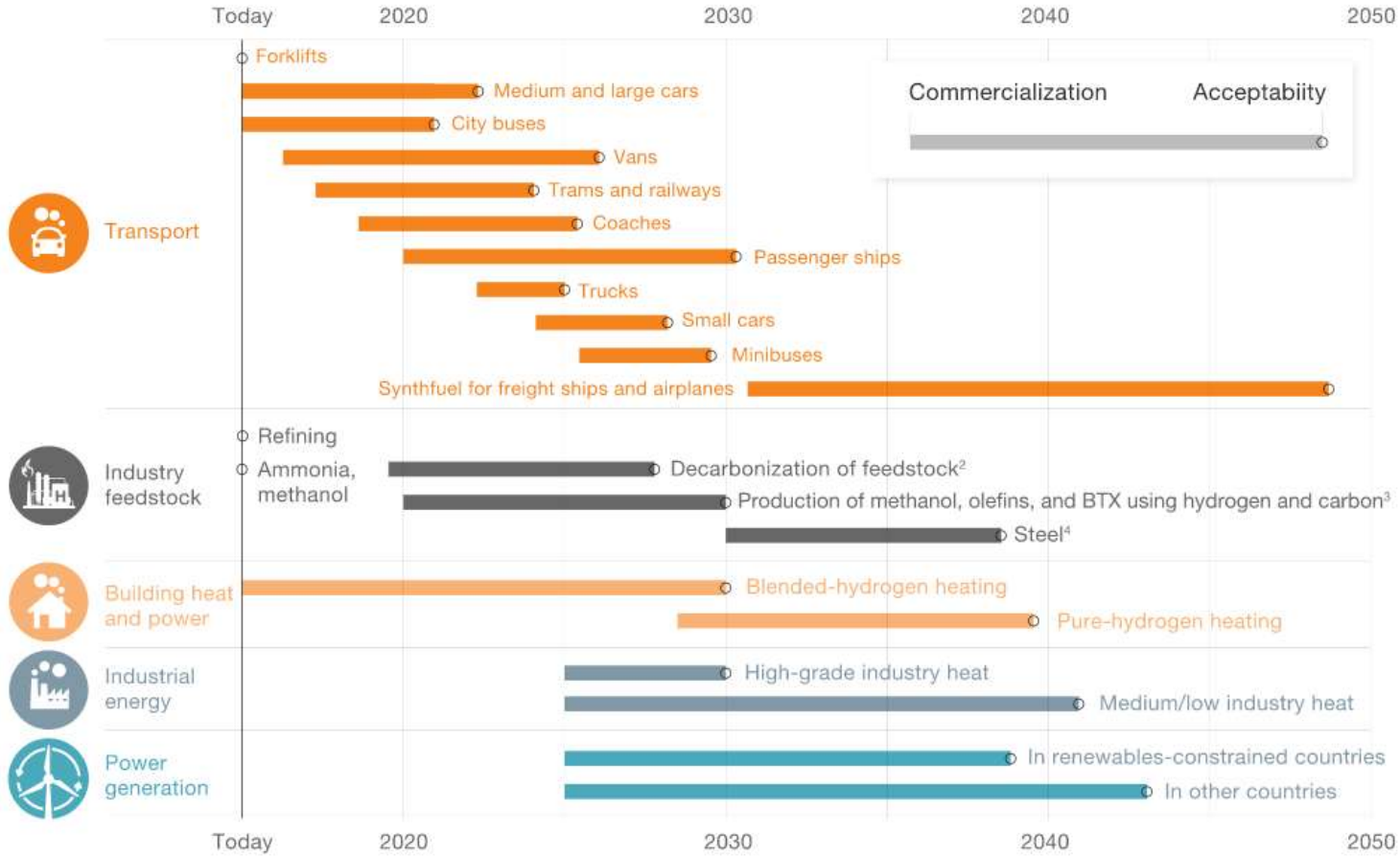
Source: Hydrogen Council

Hydrogen Rollout Roadmap

HE rollout is a multi-decadal process

Major H2 adoption expected to start with passenger cars & buses

Hydrogen use from initial commercialization to mass-market acceptability, years



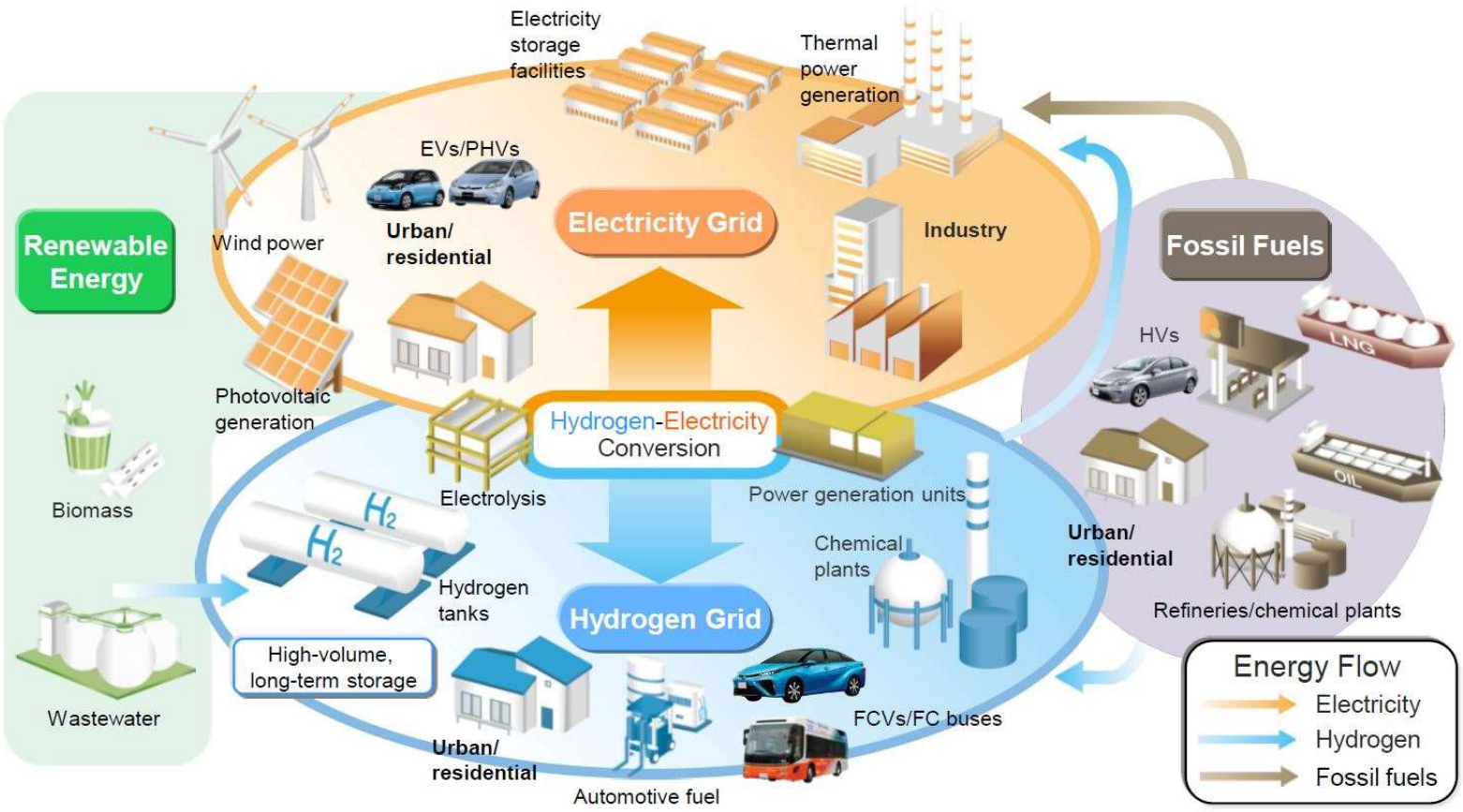
[1] Defined as sales >1% within segment; [2] Market share refers to feedstock amount produced from low-carbon sources; [3] BTX = benzene, toluene & xylene - market share refers to production % that uses hydrogen & captured carbon to replace feedstock; [4] Direct-reduced iron with green hydrogen, iron reduction in blast furnaces & other low-carbon processes using hydrogen

Source: McKinsey

Hydrogen & Electricity in Energy Ecosystem

H2 & electricity are highly synergistic in the broader energy ecosystem ...

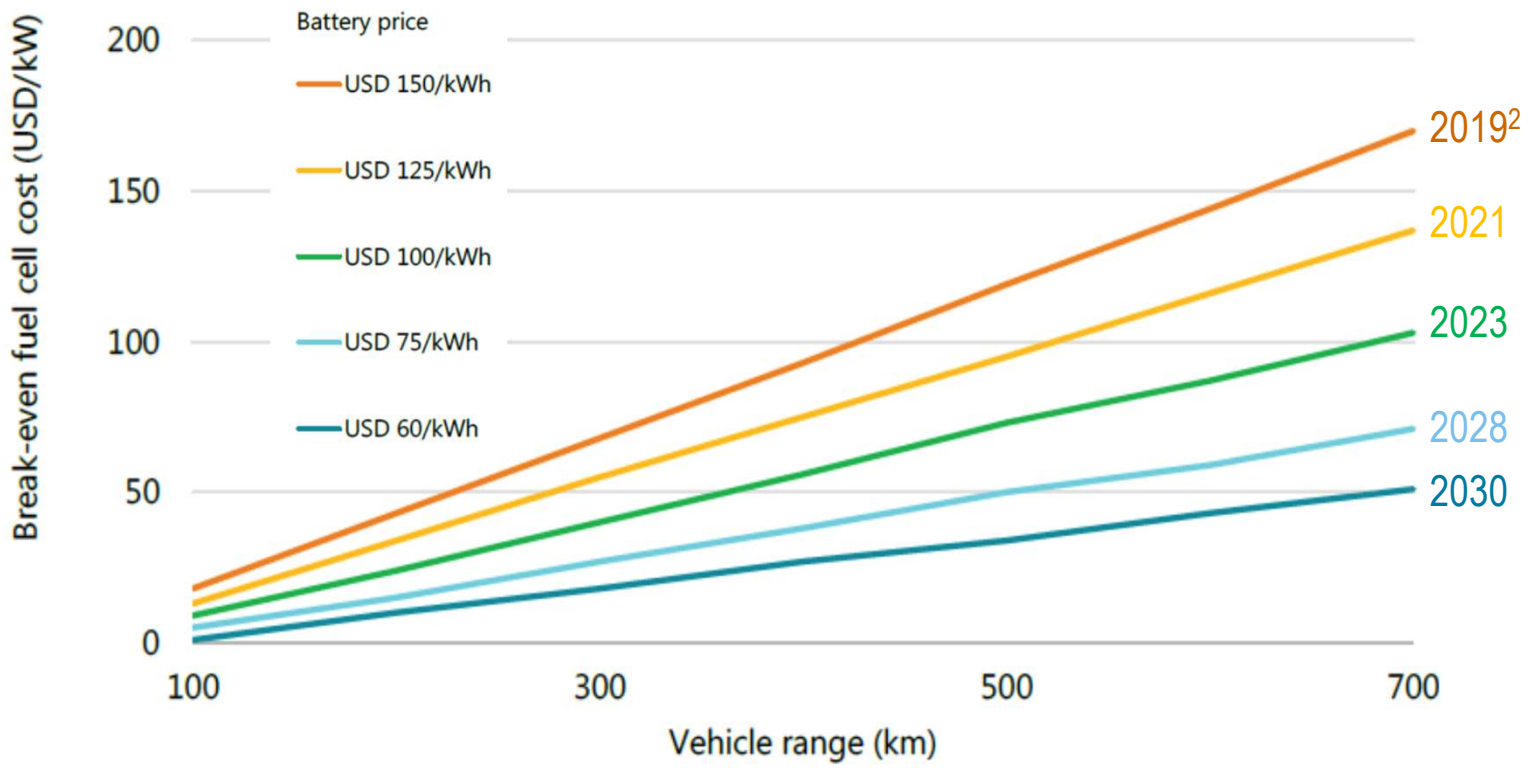
... though potential competitors in specific segments & applications



Source: Toyota Motor Company

Breakeven Costs FCEV vs. BEV[1]

Fuel cell EVs are most competitive on a TCO basis with battery EVs over longer driving ranges



[1] e.g. for a range of 400km, to break even with battery costs below USD 100/kWh could require achieving fuel cell costs below USD 60/kW; [2] battery price years forecast by BNEF

Source: IEA; BNEF

Hydrogen Delivery & Storage

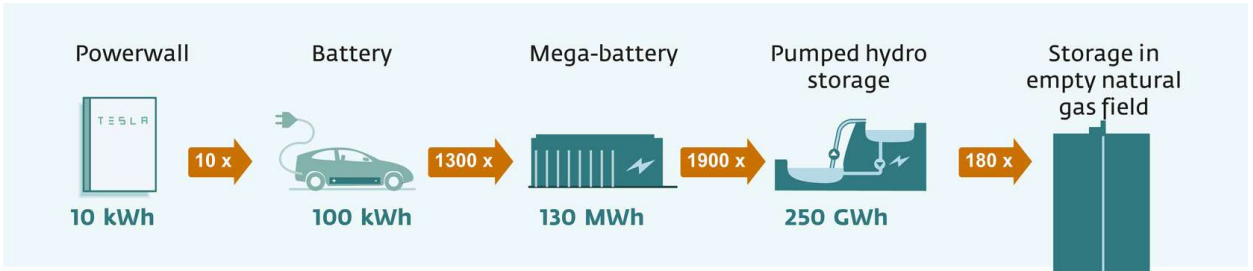
H2's characteristics (weight dense, not volume dense) make it challenging to transport from A → B

A H2 pipeline infrastructure would significantly reduce transport costs, but doesn't exist today

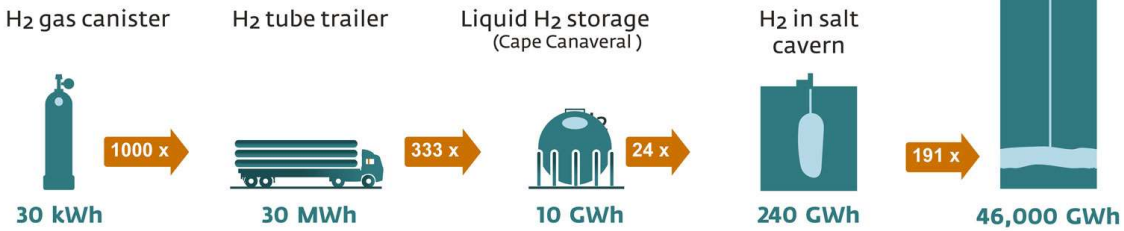
Liquid H2 is most space efficient but requires complex conversion processes & storage

Storage

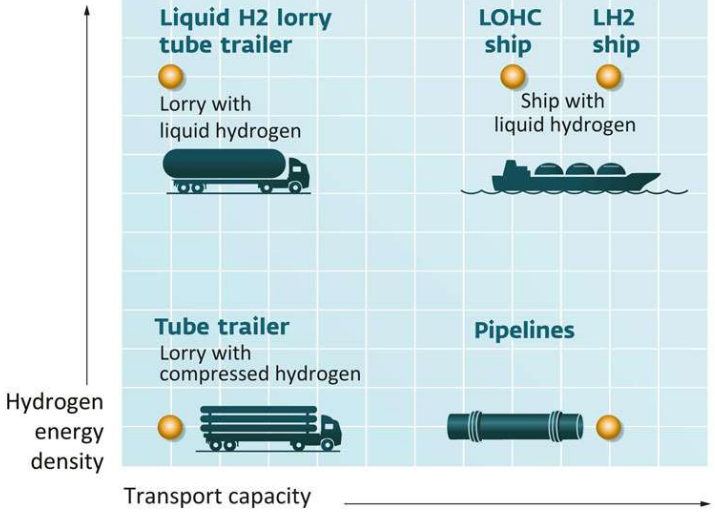
Electricity



Direct H2



Transport

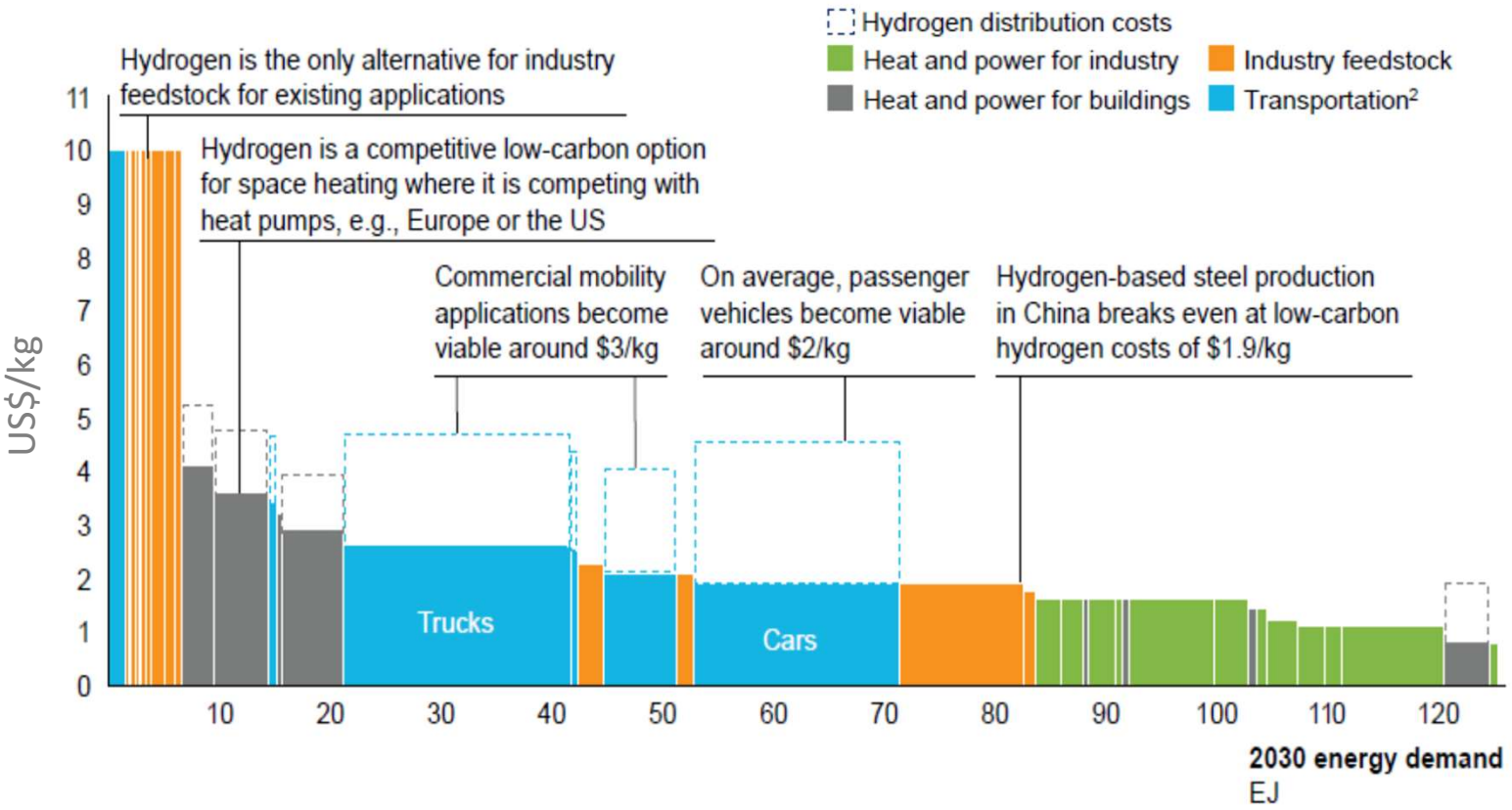


Source: The World of Hydrogen

Application Competitiveness - Production[1]

The most attractive segments for H2 still require steep cost-downs

H2 starts to be very competitive across a range of applications around US$2-3/kg (production cost)



[1] vs. low-carbon alternative in segment (regions assessed are US, China, Japan/Korea & Europe); [2] Transportation segments breakeven calculated on weighted average

Source: McKinsey & Co.; HIS Markit; US DoE; IEA; Hydrogen Council

Electrolyzer Technologies – Comparison (2020)

While Alkaline electrolyzers are the incumbent, PEM has many inherent advantages

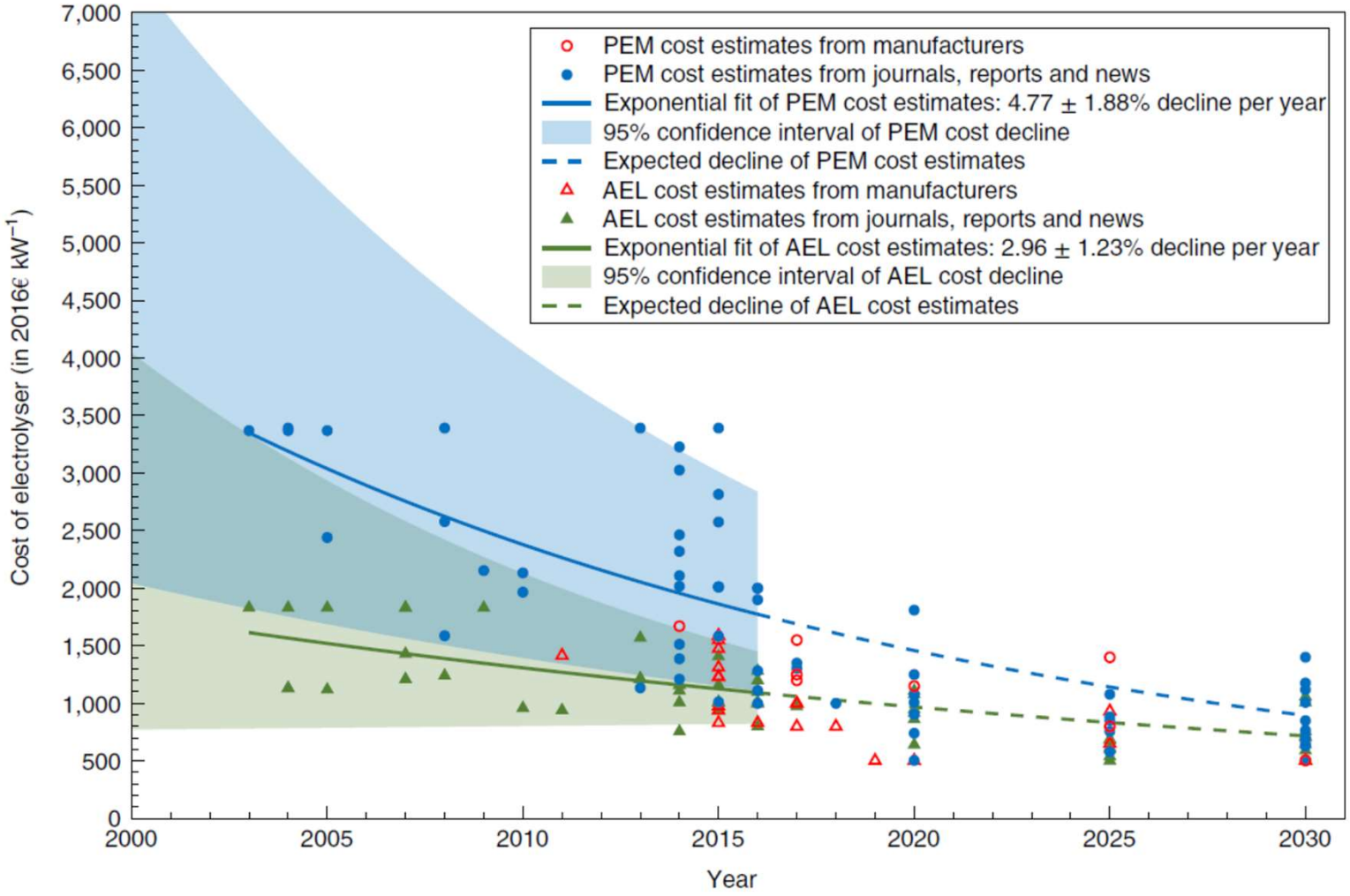
	#1	#2	#3
Maturity	AEL	PEM	SOEC
Efficiency	SOEC	AEL	PEM
Stack Lifetime	AEL	PEM	SOEC
Simplicity	PEM	AEL	SOEC
Response Time	PEM	AEL	SOEC
Safety	PEM / AEL		SOEC
Footprint	PEM	AEL	SOEC
CapEx	AEL		SOEC
Peak Power	PEM	AEL	SOEC
Min Power	PEM	AEL	SOEC

Note: AEL = electrolysis, PEM = proton exchange membrane, SOEC = solid-oxide electrolysis cells

Source: TNO

Electrolyzers – Cost Curves

PEM is rapidly catching up with AEL



Source: Gunther Glenk and Stefan Reichelstein

Dedicated to CleanTech & Resource Efficiency growth

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