Hydrogen via Reforming & Gasification

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KAUST Hydrogen Panel

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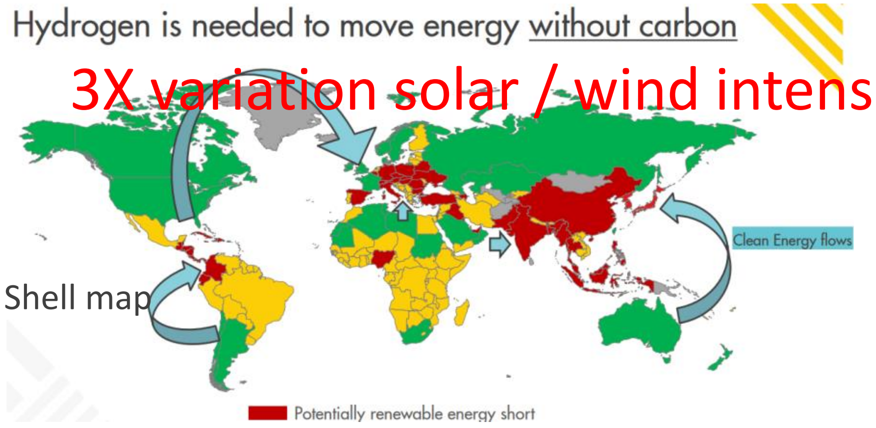
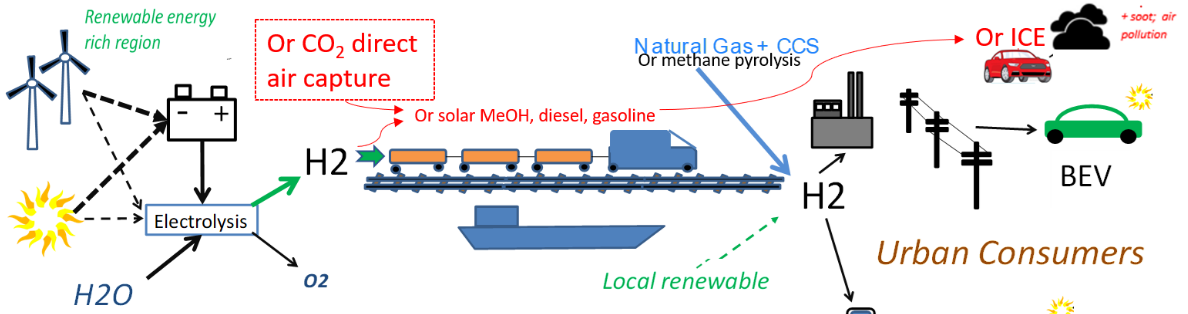
Disclaimer:

Any cost information is approximate and derived from open literature and data.   Do not take any observations as investment advice.

Energy Transition Institute
UH ENERGY
Shell
FOUNDING PARTNER

Hydrogen as Energy Vector

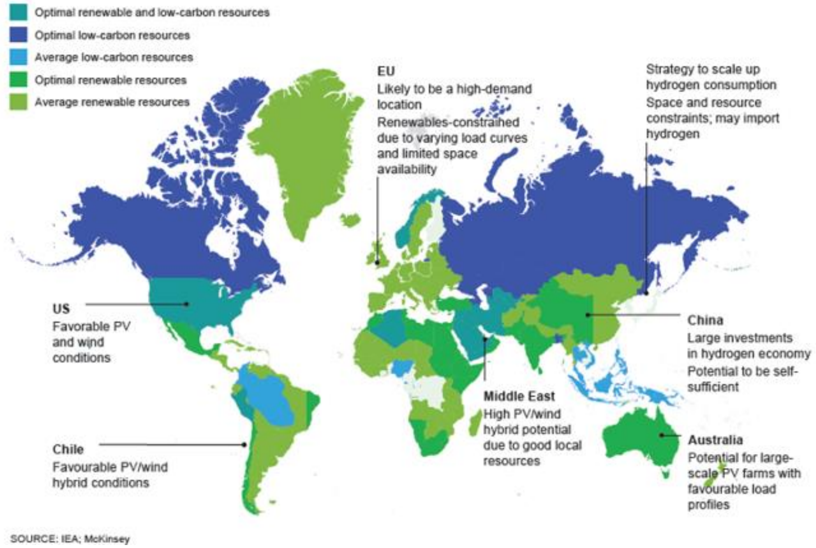




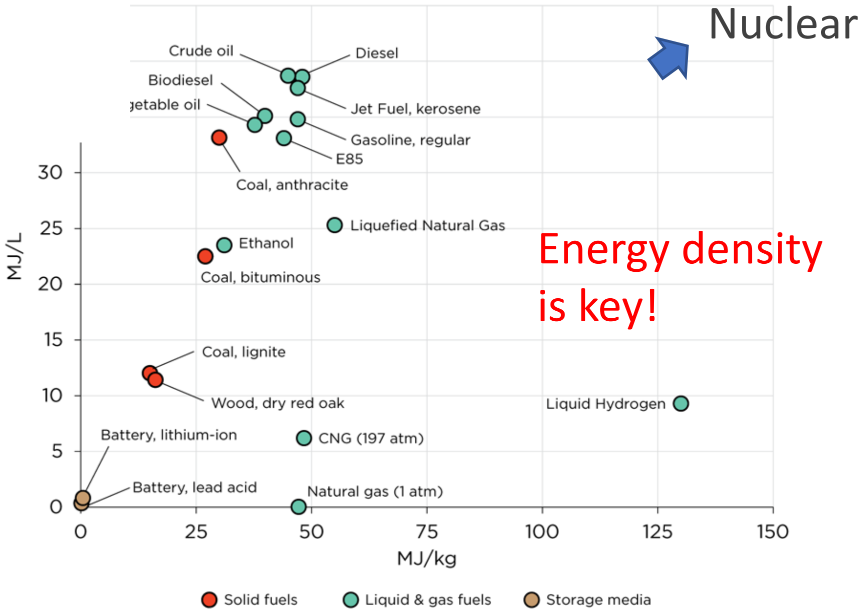
Future Hydrogen = today's diesel / NG!

Future Electricity = today's gasoline!

Best source of low carbon hydrogen:



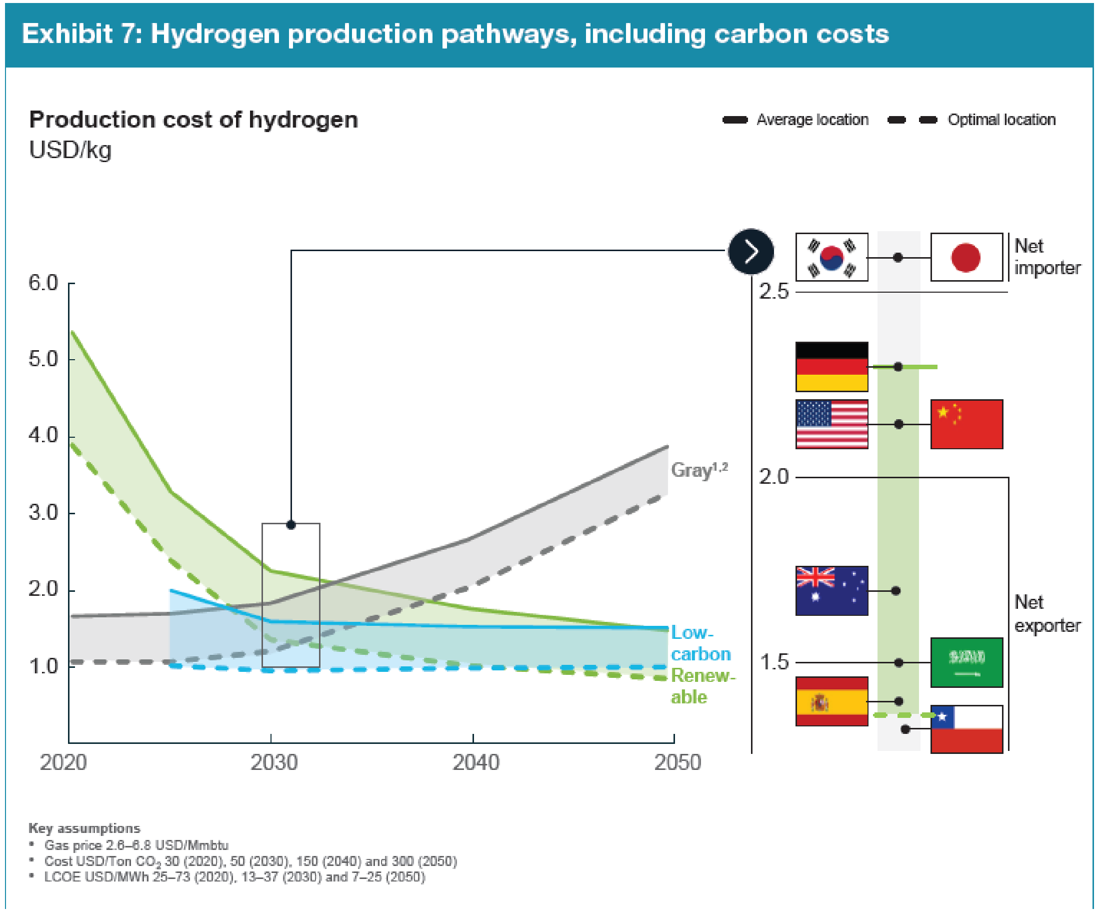
Hydrogen Council: Path to Hydrogen Competitiveness (2019)

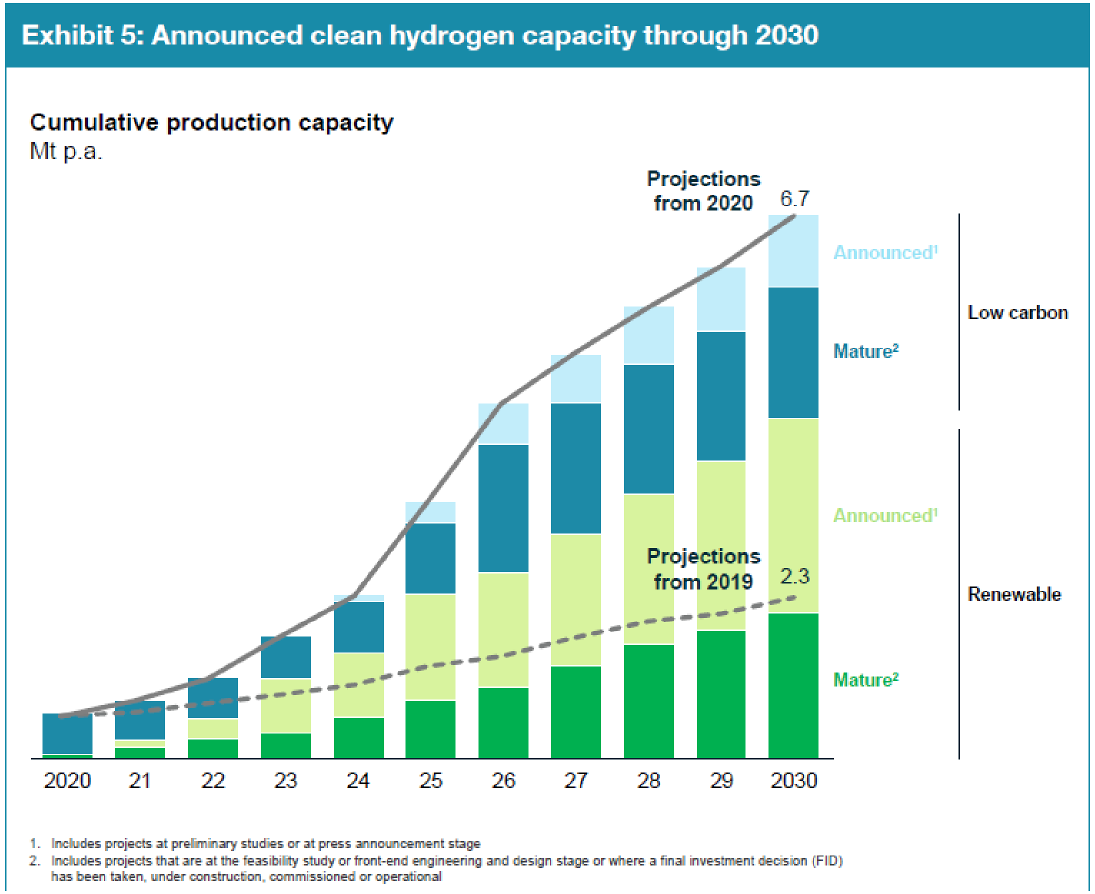


R. Heinberg and D. Fridley, *Our Renewable Future: Laying the path to One Hundred Precent Clean energy.*

- Improves local air quality
- Only water vapour emissions while driving
- Low-carbon transport if made via green or clean pathways
- High range – up to 700 km per refuel
- Minutes to refuel

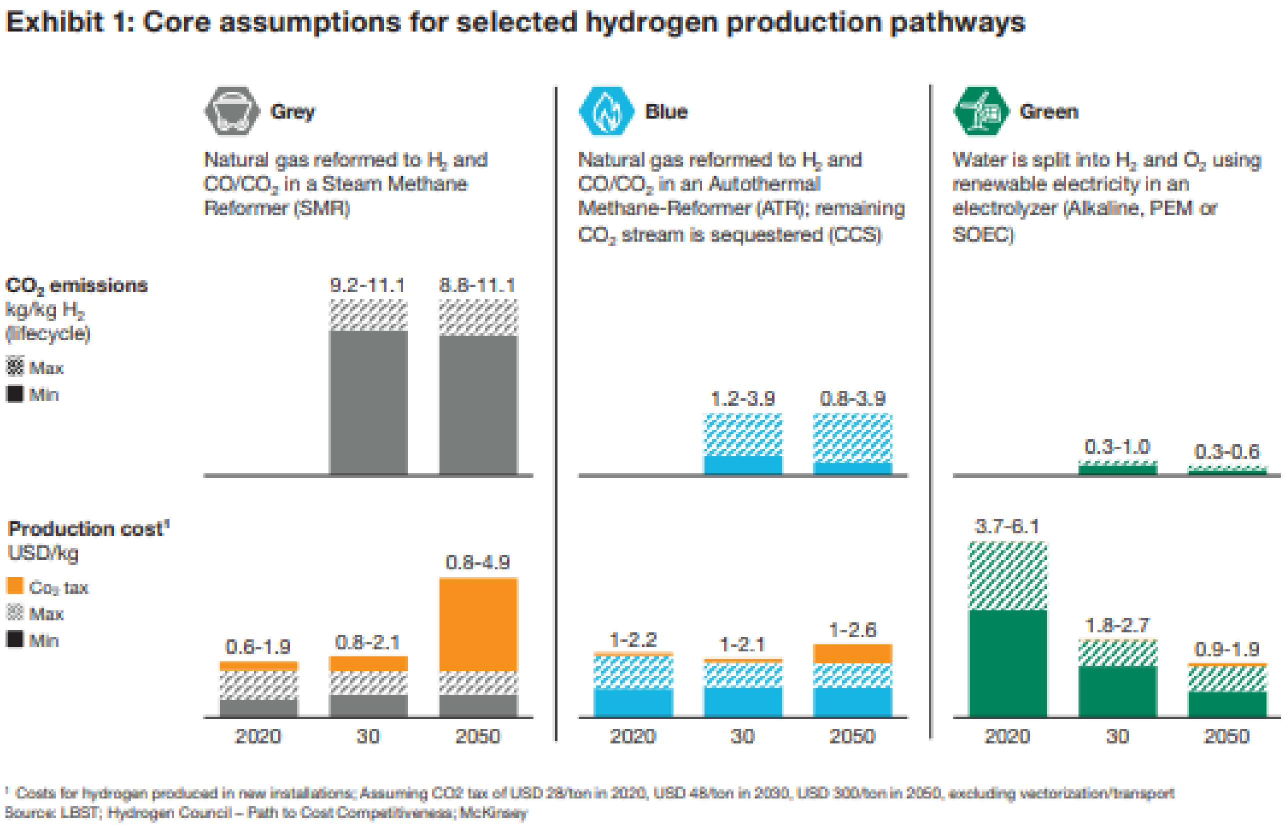
Blue vs. Grey vs Green: McKinsey / H2 Council

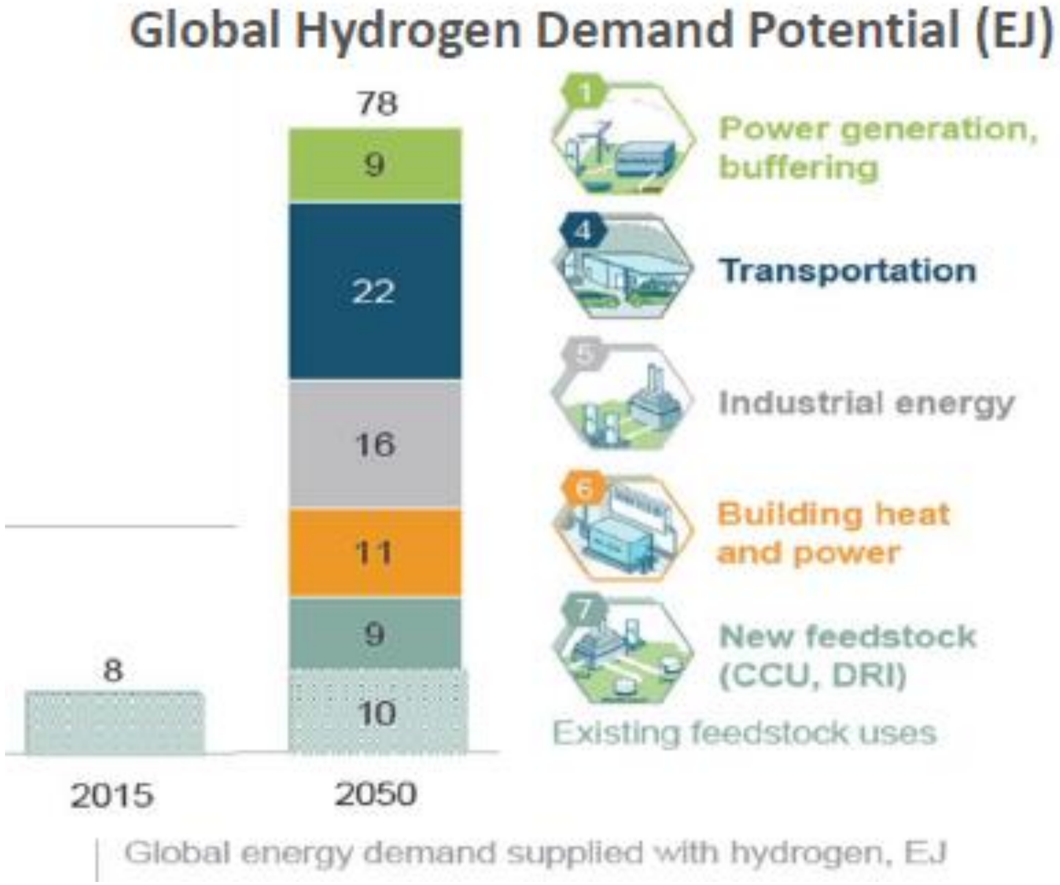




- Hydrogen Council / McKinsey: **Hydrogen Insights A perspective on hydrogen investment, market development and cost competitiveness February 2021** https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

Hydrogen cost and demand





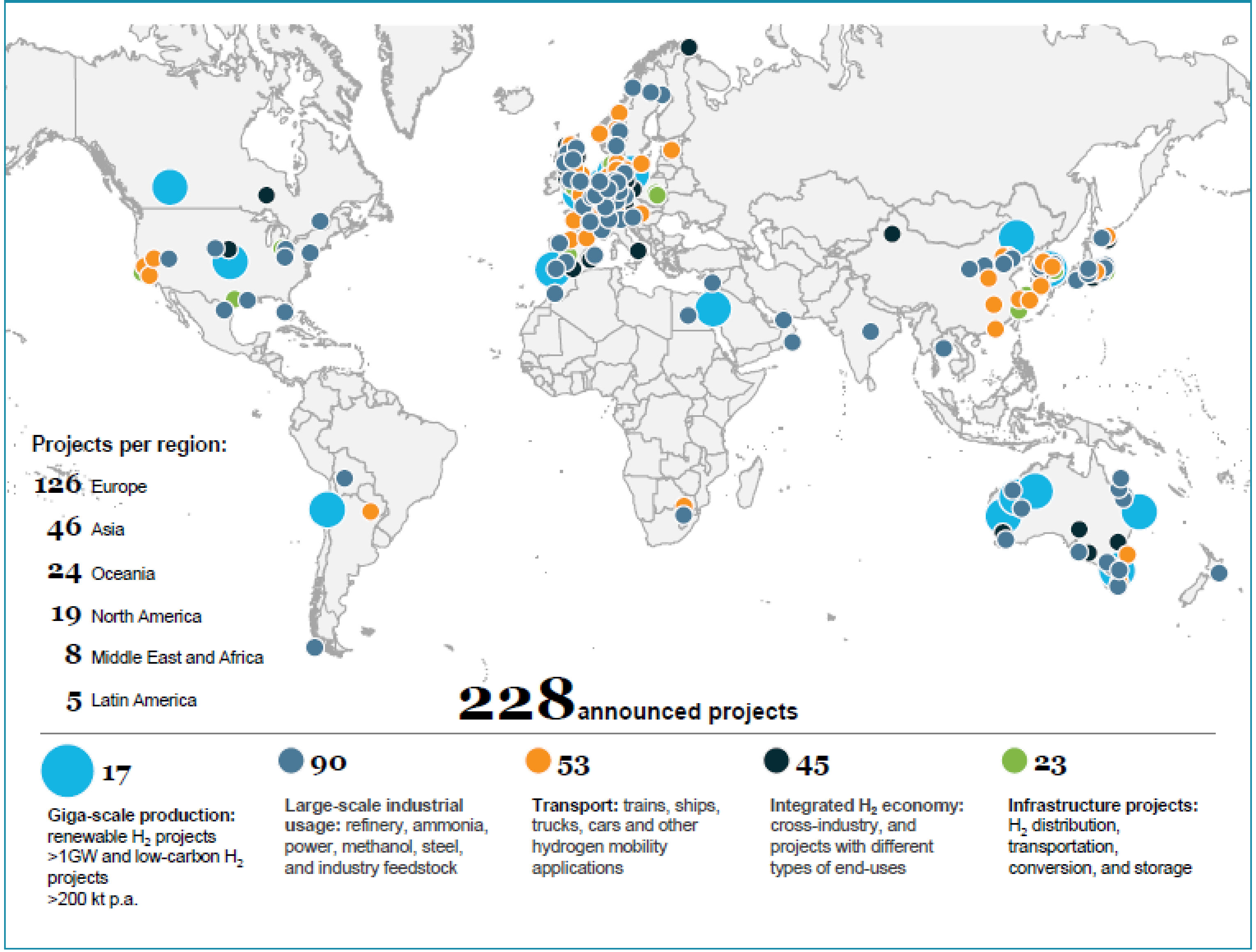
Hydrogen council: Scaling up reports 2017 and 2019; https://hydrogencouncil.com/wp-content/uploads/2019/02/HC_Influencers_FINAL.pdf

Where is hydrogen economy emerging?

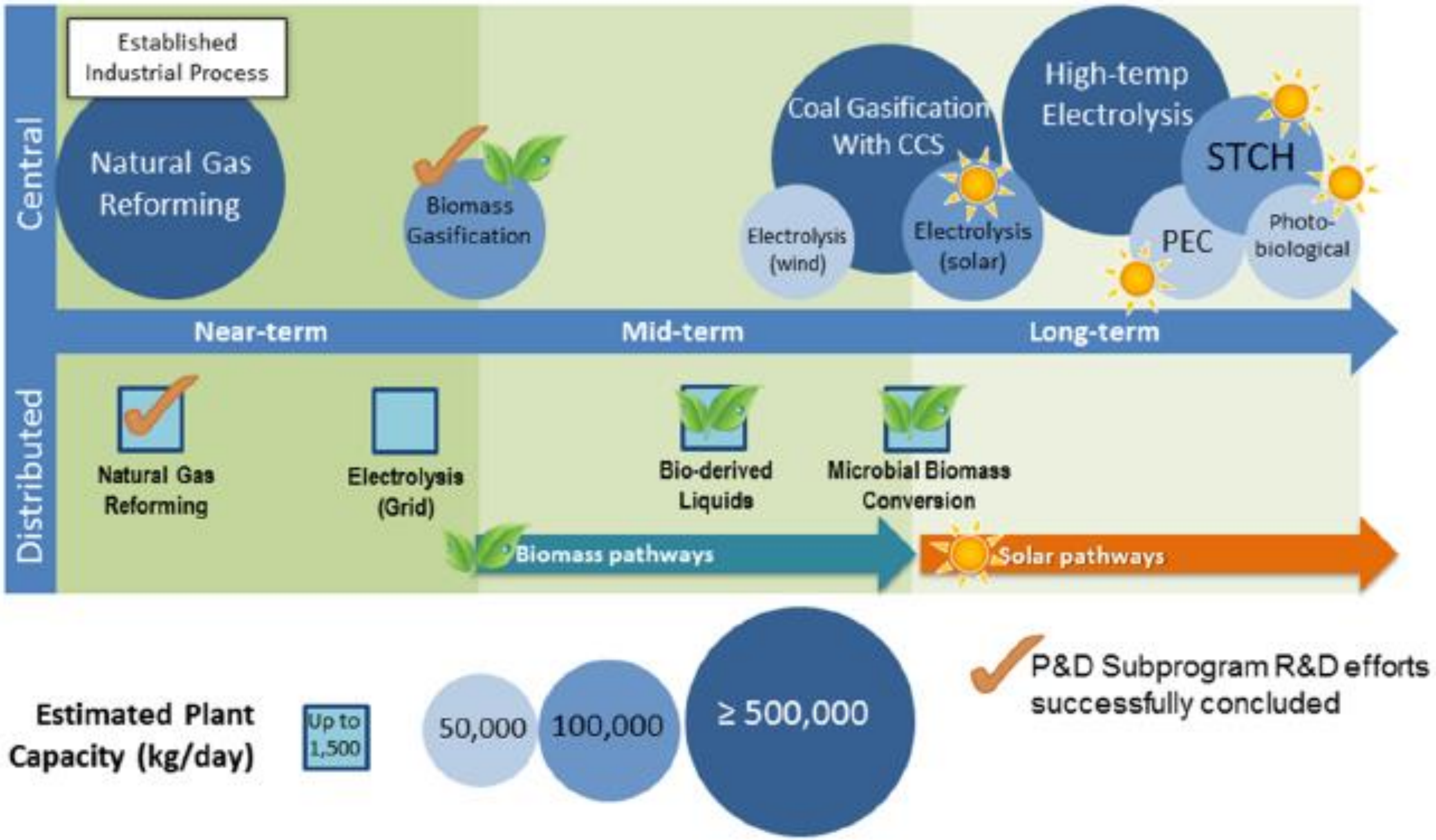
- Far east (Japan, China, Korea with sourcing from Australia); Europe
- Policy incentives important

Hydrogen Council / McKinsey % Co. (Feb 2021) Hydrogen Insights on hydrogen investment, market development and cost competitiveness https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

Exhibit 2: Global hydrogen projects across the value chain



Hydrogen production options



- https://www.eia.gov/energyexplained/hydrogen/; NACFE: Guidance on Hydrogen Fuel Vell Tractors, 121620 (2020)
- Mark Ruth et al., *The Technical and Economic Potential of the H2@Scale Concept within the United States*, NREL Report (2020). https://www.nrel.gov/docs/fy21osti/77610.pdf

Reactions to form Hydrogen

How many H2 formed per carbon fed? How much energy required?

Reaction	Stoichiometry	Energy Required*	Heat?
Electrolysis	$H_2O \rightarrow H_2 + ½ O_2$	+285.8 kJ/mole-H_2	Add energy + heat
Methane Pyrolysis	$CH_4 \rightarrow C_{(s)} + 2H_2$	+ 37.45 kJ/mole-H_2	Add heat
SMR	$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$	+ 41.25 kJ/mol-H_2	Add heat
POX	$CH_4 + ½ O_2 \rightarrow 2H_2 + CO_2$	- 159.3 kJ/mol-H_2	Export heat

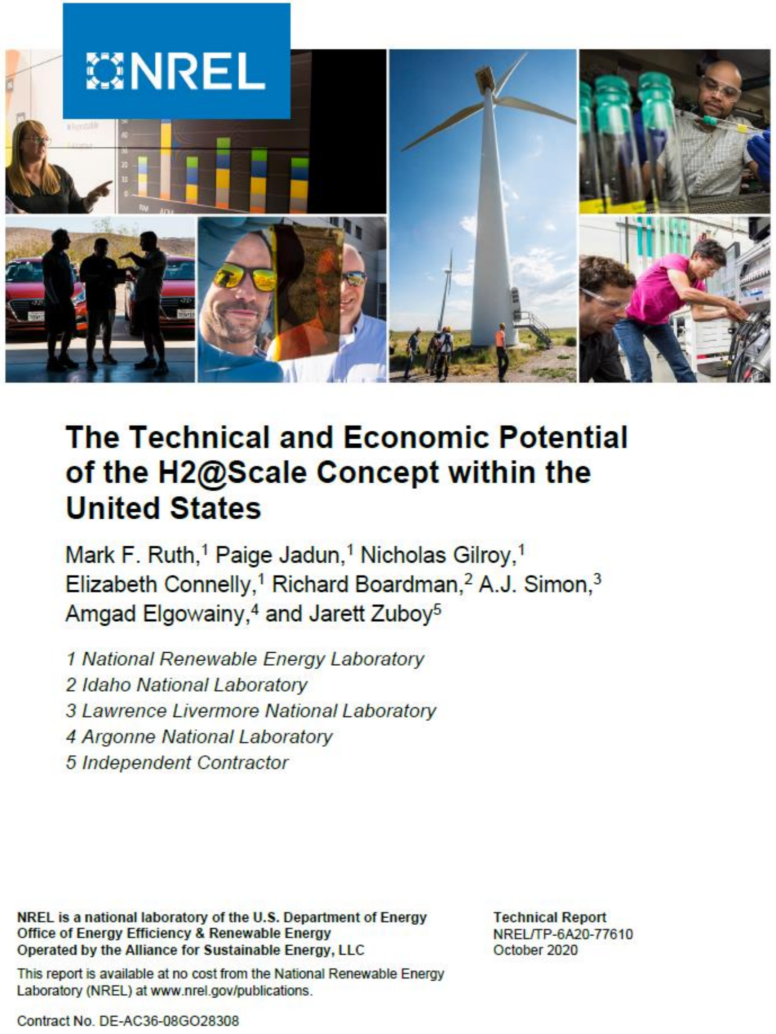
* For heat (enthalpy) of reaction (only)

→ Addition energy (methane) required for heat

NIST / Engineering Toolbox thermodynamic data

Do not look only at reaction stoichiometry to assess total energy requirement or carbon footprint!

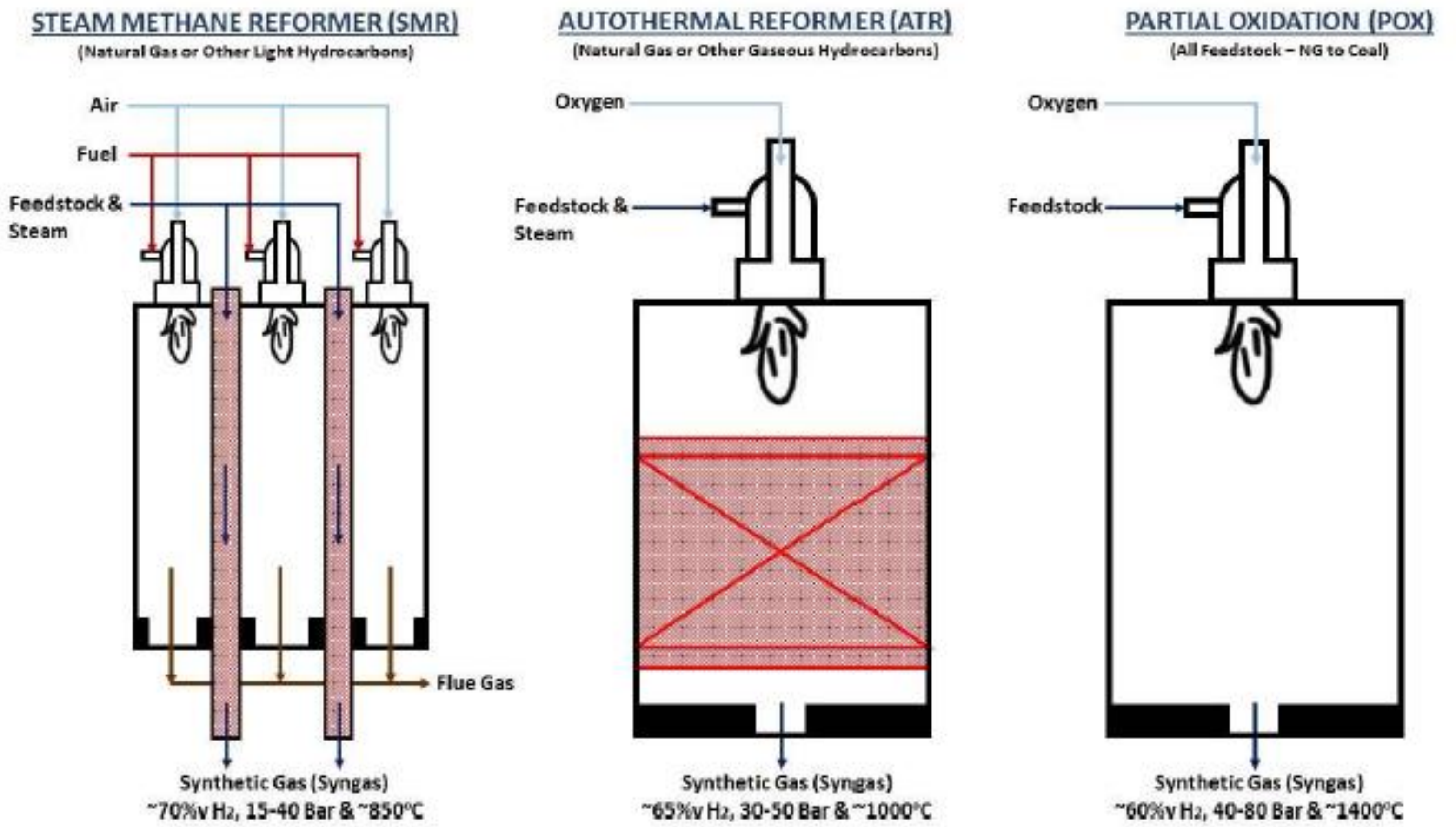
Key References



SMR BASED H2 PLANT WITH CCS, IEAGHG Technical Report 2017-TR3 https://ieaghg.org/publications/technical-reports

Mark Ruth et al., *The Technical and Economic Potential of the H2@Scale Concept within the United States*, NREL Report (2020). https://www.nrel.gov/docs/fy21osti/77610.pdf

Hydrogen formation from Natural Gas



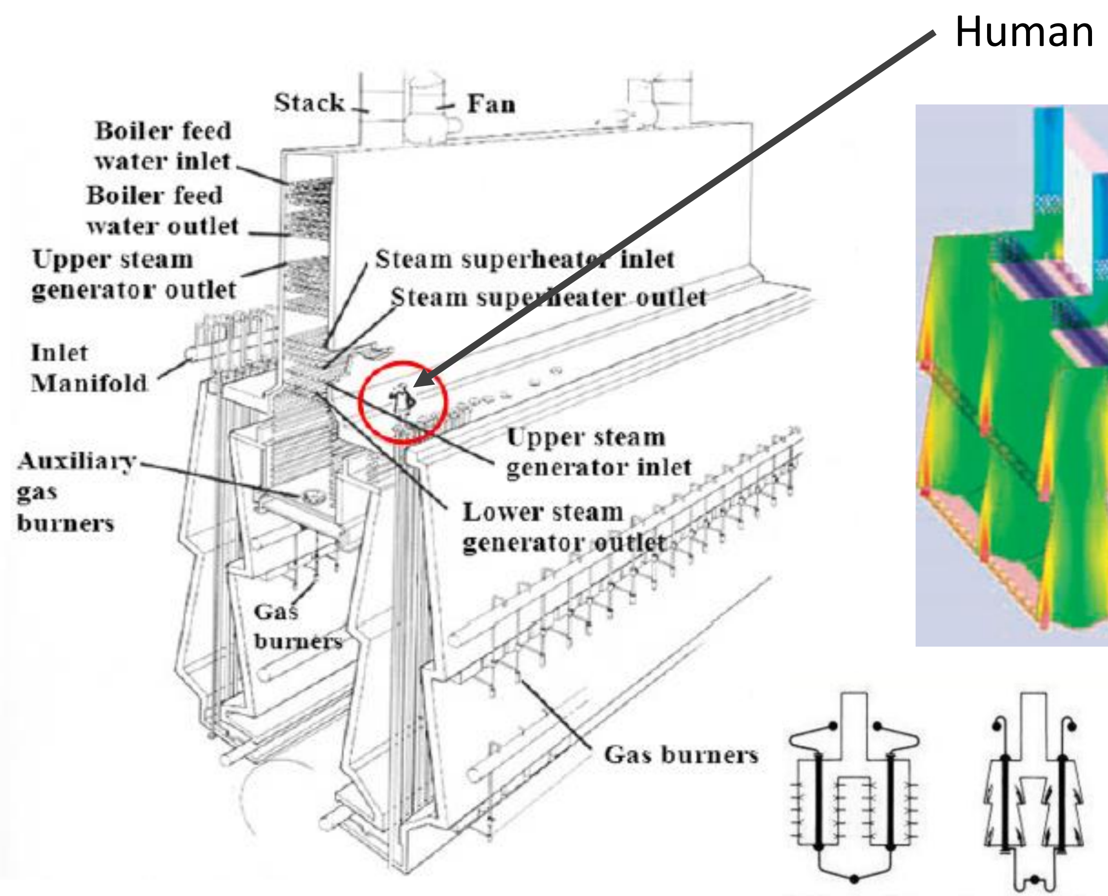
Endothermic: add heat

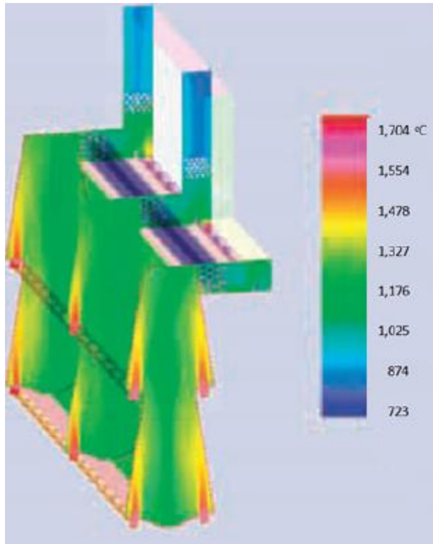
Heat balanced

Excess O_2 (Exothermic) = export steam for heat, electricity generation

IEAGHG, Reference data and supporting literature Reviews for SMR Based Hydrogen Production with CCS, March 2017.

SMR equipment





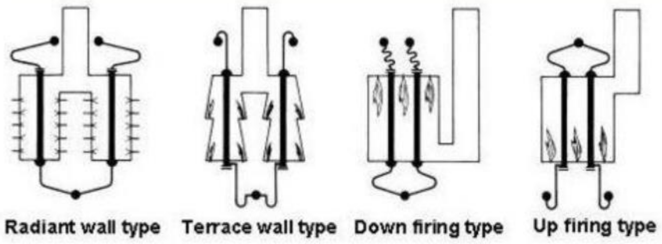
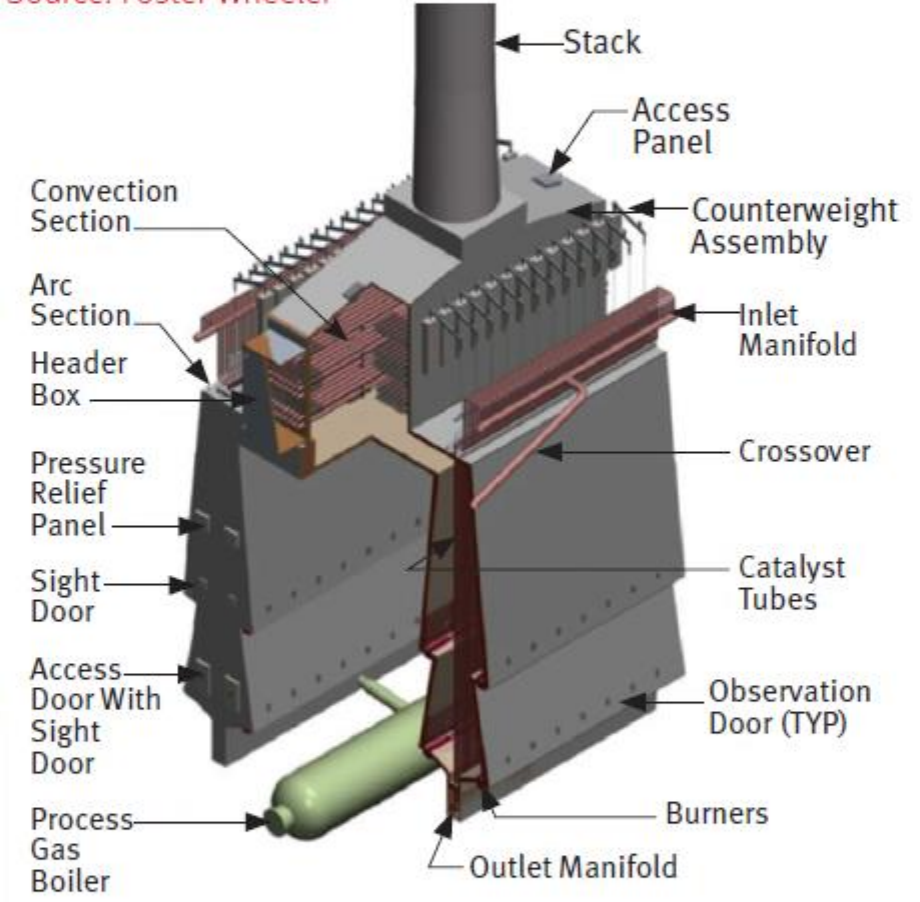


Figure 1. Steam Reformer Description
Source: Foster Wheeler



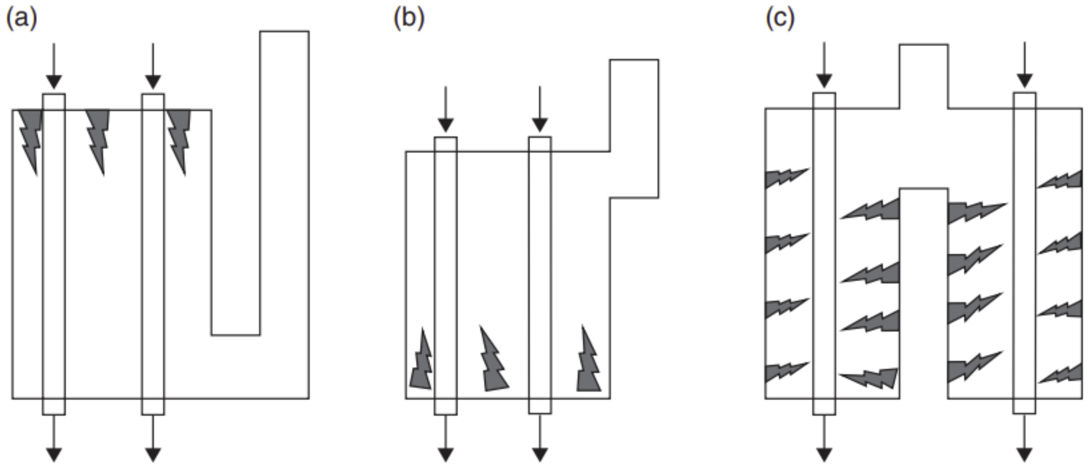
- **Luigi Bressan and Chris Davis, SMR Driving Down Cost of Production,** www.gasworld.com/specialfeatures, September, 2014. Terrace wall reformer
- W. Quon, PhD Thesis, U. of Houston (2012)

SMR reactor details

Table 11.3 Furnace construction data

Number of tubes	897
Furnace dimensions	21.8 × 35.5 × 13.7 m
Number of burners	204

Source: Data from Elnashaie and Elshishini, 1993.



11.2 Furnace configurations: (a) top-fired; (b) bottom-fired; (c) side-fired.

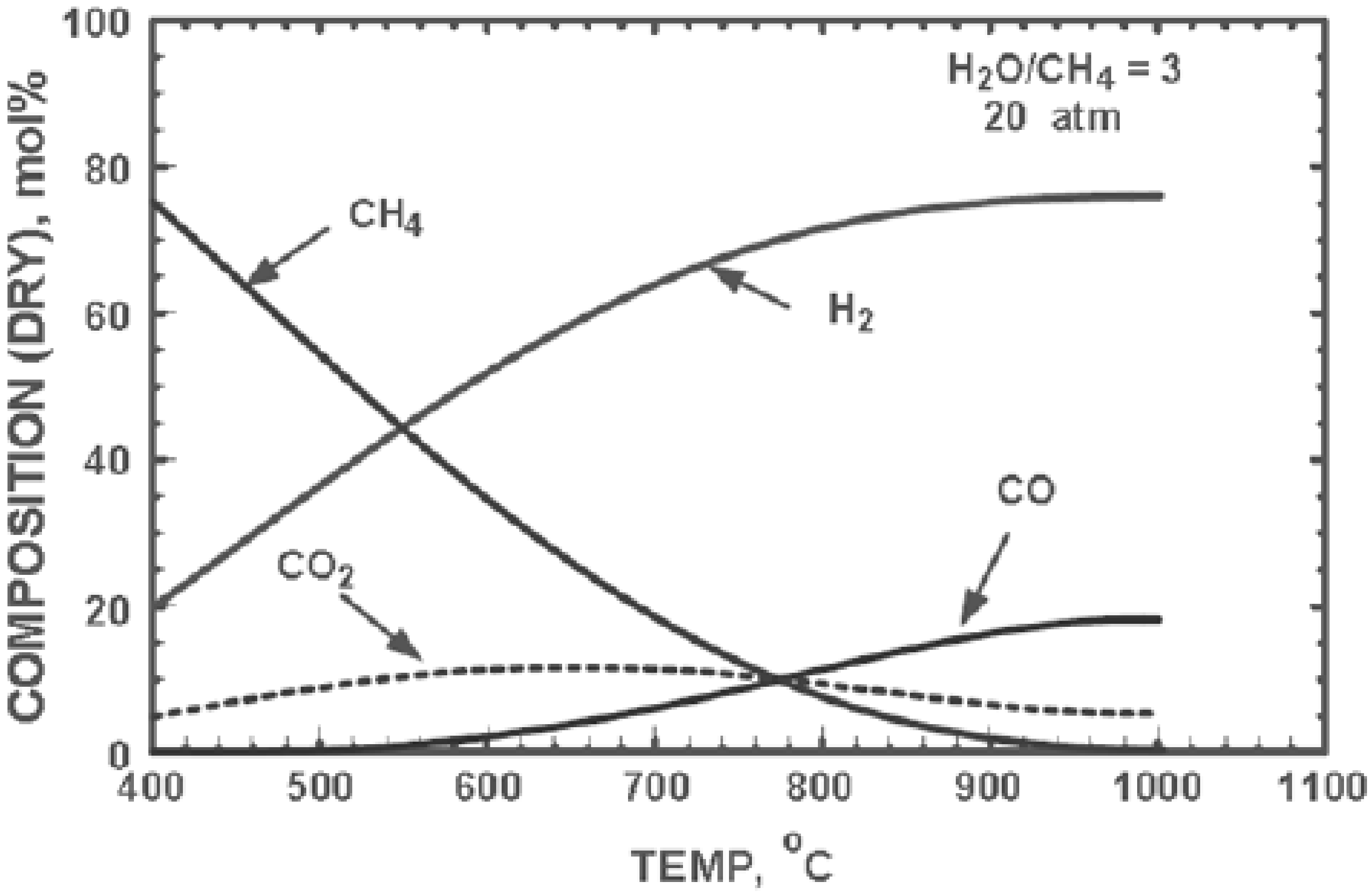
Length of the reformer tube	12–14 m
Inside diameter	0.09–0.11 m
Outside diameter	0.11–0.13 m
NG inlet flowrate	3–8 kmol/h
Process gas inlet temperature	673–800 K
Process gas pressure	25–40 bar

Table 11.4 Typical gas composition at the outlet of steam reforming

CH_4	2–6%
H_2O	35–55%
H_2	30–46%
CO	3–9%
CO_2	6–8%

- V. Piemonte, ... A. Basile, Hydrogen production using inorganic membrane reactors in Advances in Hydrogen Production, Storage and Distribution, Elsevier, 2014

SMR Equilibria

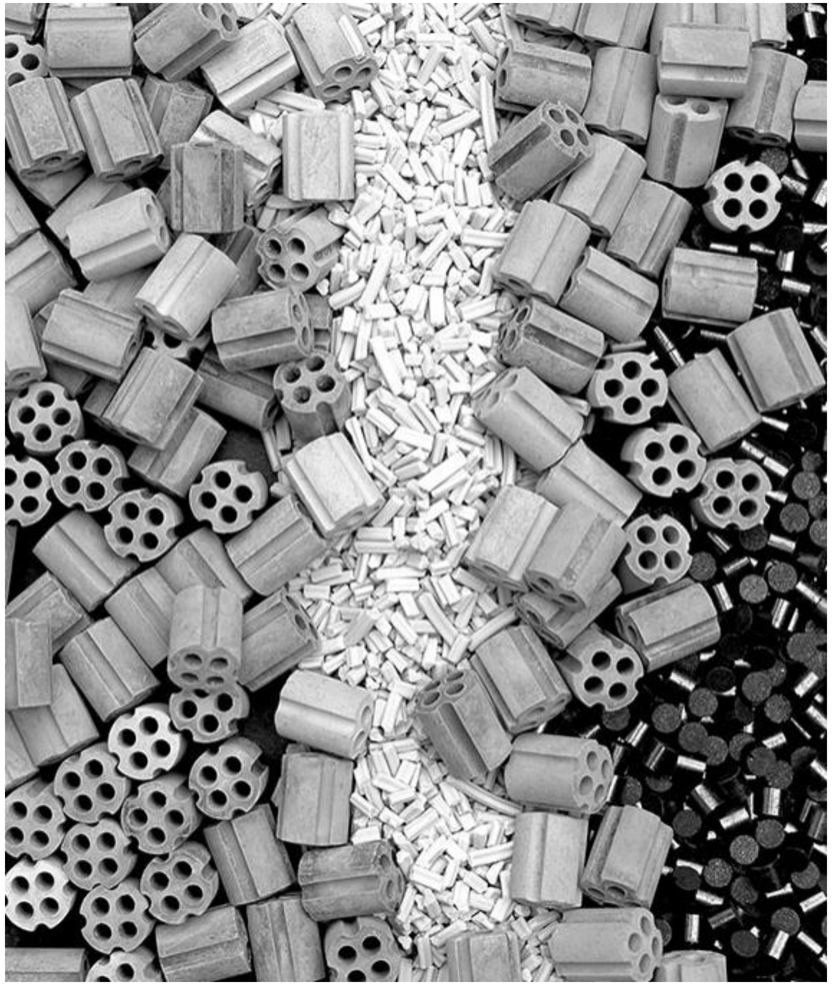


High temperature or novel reactor with separation needed!

W. Quon, U. of Houston PhD Thesis (2012)

SMR and WGS catalysts

- Nickel catalysts used for SMR.
  → Max. 20% loading
- High Temperature WGS (400 C) stage 1
  → Iron oxide / chromium
- Low Temperature WGS (200 C) stage 2
  → Copper



Johnson-Matthey
Generic catalyst picture from www.matthey.com

W. Quon, U. of Houston PhD Thesis (2012)

M. Twigg, **Catalyst Handbook <u>(2018)</u>**

SMR – world's largest plants

X 0.725 = tonnes H2/yr

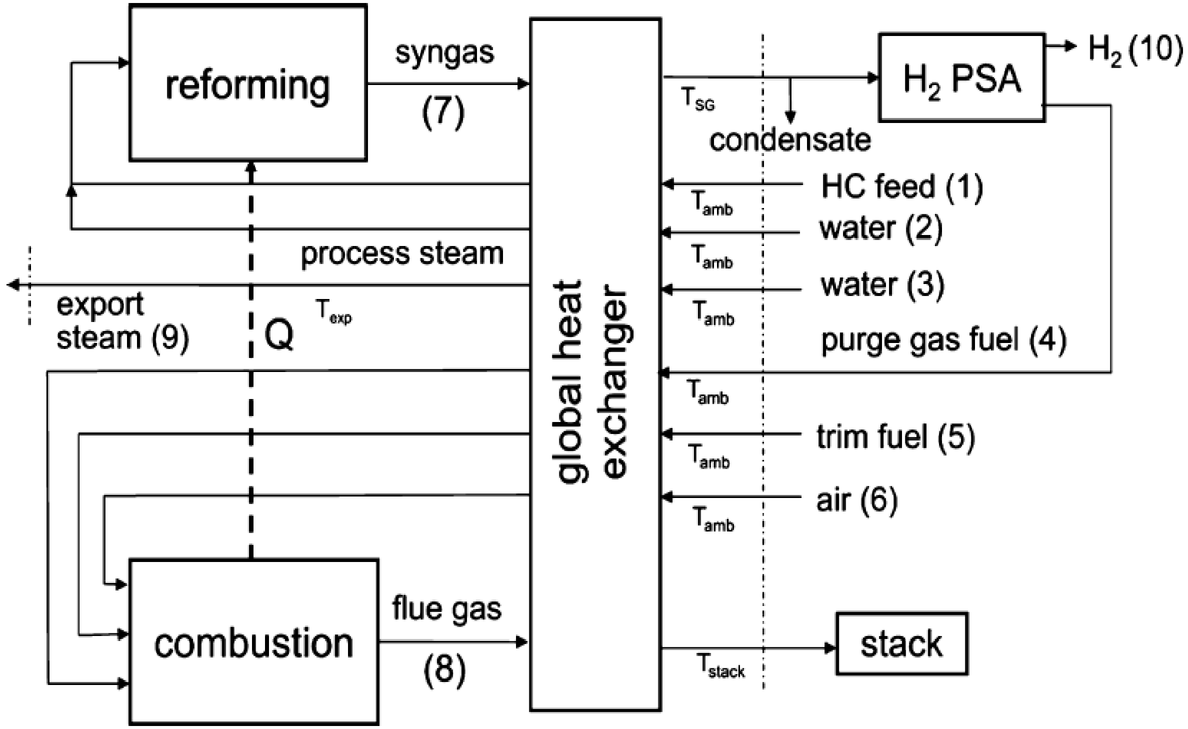
Table 3 – World's largest single train SMR hydrogen plants

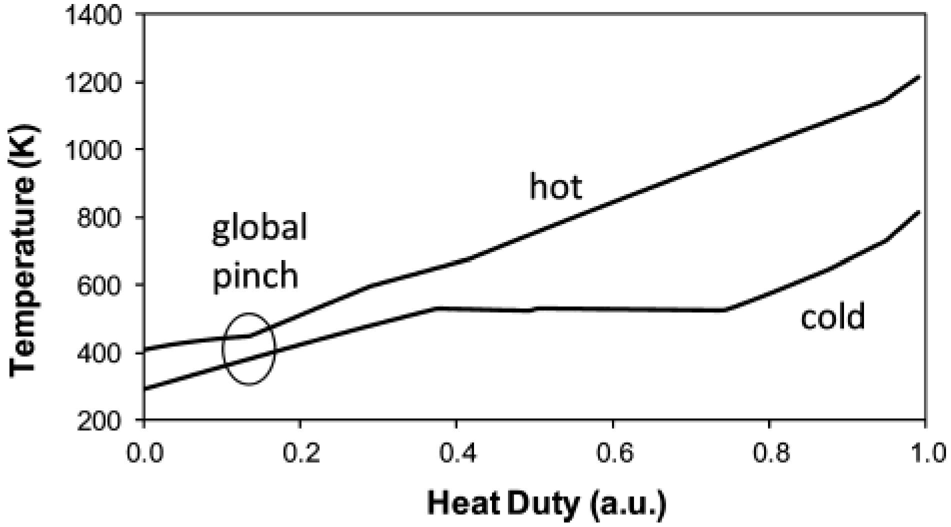
Owner	Plant Name	Location	Capacity [Nm^3 /h]	SMR Licensor
Tuapse Refinery	U-34 *	Sao Francisco do Conde, Brasil	240000	Technip
Kuwait National Petroleum Co Ksc	CFP2*	Mina Abdulla, Kuwait	203500 (per train, 3 trains)	Haldor Topsøe
JSC Bashneft NOVOIL	HPU	Ufa, Russia	165000	Amec Foster Wheeler
TUPRAS	HPU*	Izmit, Turkey	160000	Technip
Abu Dhabi Oil Refining Company (Tarter)	Hydrogen 2 UNIT 1300	Ruwais, U.A.E	151000	Haldor Topsøe

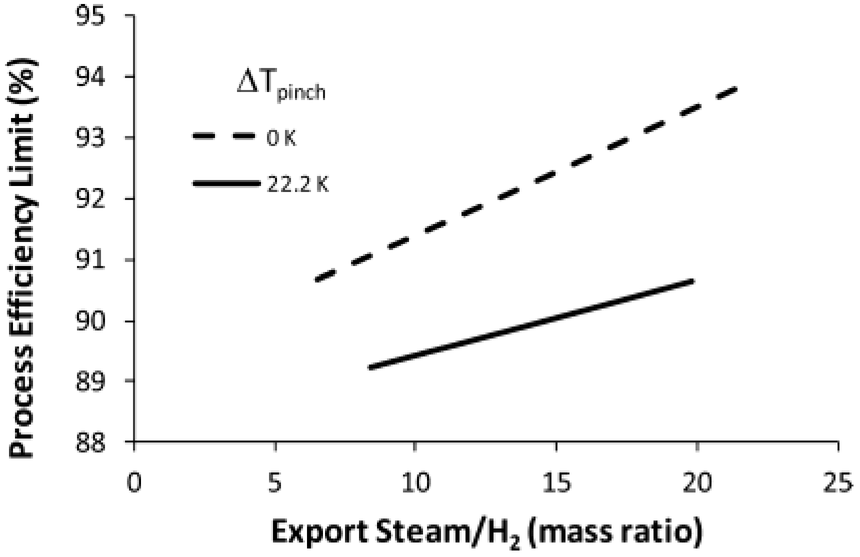
H2tools.org: normal m3 = 0.0899 kg
24*365 = 9240 h/yr (100% stream)
Nm3/hr = 0.83 tonnes/yr

SMR BASED H2 PLANT WITH CCS, IEAGHG Technical Report 2017-TR3
https://ieaghg.org/publications/technical-reports

SMR efficiency:

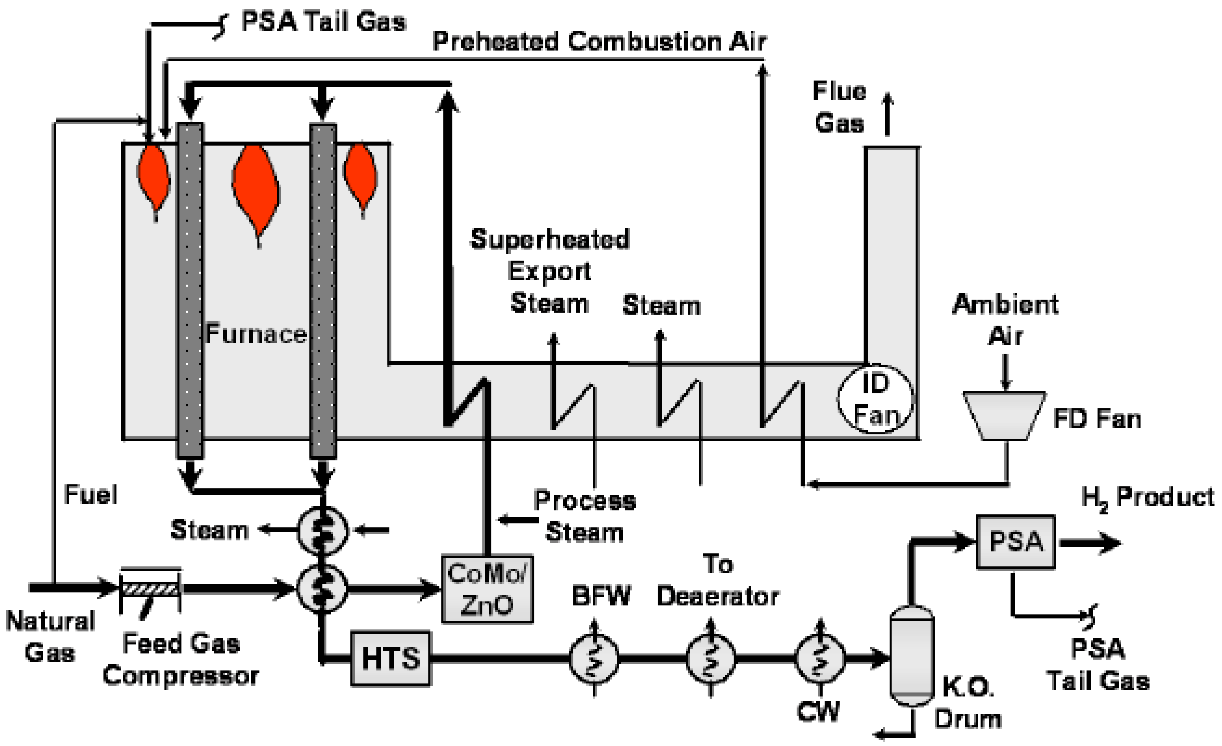






- X. D. Peng, Analysis of the Thermal Efficiency Limit of the Steam Methane Reforming Process, Ind. Eng. Chem. Res. 2012, 51, 16385−16392

SMR- minimum steam



- www.Praxair.com (2010)

Table 1 Hydrogen Plant Subsystems	
Typical Operating Conditions	1. Process gas outlet temperature: 1400°F to 1700°F. 2. Pressure: 200 psig to 450 psig.
Equipment	1. Catalyst size: 5/8-in. x 5/8-in. rings, Ni-based. 2. Reformer tubes: 4-in. to 5-in. diameter by 40 ft to 45 ft long. 3. Reformer tube life: 10 years. 4. Furnace type: Round (can) or box.
High Temperature Shift	
Function	Convert carbon monoxide to hydrogen.
Reaction	Water gas shift: $CO + H_2O \rightarrow CO_2 + H_2$ + Heat 1. Mildly exothermic reaction. 2. Reaction favored by mild temperature and excess steam. 3. Converts about 70 to 75 percent of carbon monoxide.
Catalyst	Iron/chrome
Catalyst Life	5 to 7 years
Typical Operating Temperature	650°F to 700°F
Typical Temperature Rise	125°F
H2 PSA	
Function	Purifies hydrogen-rich gas (purity hydrogen product >99.99 percent).
Adsorbents	Molecular sieve, activated carbon, alumina, and silica gel.
Typical Operating Conditions	1. Feed pressure: 200 to 900 psig. 2. Feed H_2 composition: 50 to 95 percent. 3. Tail gas pressure: 5 to 70 psig. 4. H_2 recovery: 65 to 90 percent.
Typical Operating Equipment	1. Adsorber vessels: 4 to 12. 2. Surge tank: 1 to 2 (12 to 13 ft diameter). 3. Valve skid and controls.

H2 Cost Green & Clean

•B. Parkinson, P. Balcombe, J.F. Speirs, A.D. Hawkes, K. Hellgardt, Levelized cost of CO 2 mitigation from hydrogen production routes, Energy Environ. Sci. 12 (2019) 19–40. https://doi.org/10.1039/C8EE02079E.
Sustainable Gas Institute, Imperial College London

	Literature estimates ($\$ \, kg^{-1} \, H_2$)			Our estimates ($\$ \, kg^{-1} \, H_2$)		
Technology	Low	Central	High	Low	Central	High
SMR	1.03	1.26	2.16	1.03	1.26	2.16
SMR w. CCS[a]	1.22	1.88	2.81	1.93	2.09	2.26
Coal	0.96	1.38	1.88	0.96	1.38	1.88
Coal w. CCS[b]	1.4	2.17	3.6	2.24	2.46	2.68
CH_4 pyrolysis[c]	1.03	1.75	2.45	1.36	1.76	1.79
Biomass	1.48	2.24	3.00	1.48	2.24	3.00
Biomass w. CCS[d]	—	2.27	—	3.15	3.37	3.6
Electrolysis wind[e]	3.56	5.24	10.82	4.61	7.86	10.01
Electrolysis solar[e]	3.34	8.87	17.3	7.1	12.00	14.87
Electrolysis nuclear[e]	3.29	4.63	6.01	4.99	6.79	8.21
S–I cycle	1.47	1.81	2.71	1.47	1.81	2.71
Cu–Cl cycle	1.47	2.13	2.7	1.47	2.13	2.7

Our "Low–Central–High" estimates use [a]an updated SMR CCS cost of \$96.15 t^{-1} CO_2 ±20% for a 90% point source capture scenario from the literature median hydrogen production cost of \$1.26 kg^{-1} H_2, [b]an updated coal gasification CCS cost of \$65.92 t^{-1} CO_2 ±20% for a 90% point source capture scenario from the literature average cost of \$1.38 kg^{-1} H_2, [c]adjusted carbon sale price from \$−10 to 150 t^{-1} carbon product for \$4 GJ^{-1} natural gas cost, [d]an updated biomass gasification CCS cost of \$65.92 t^{-1} CO_2 ±20% for a 90% point source capture scenario from the literature reference cost of \$2.27 kg^{-1} H_2, and [e]the technology specific LCOE and capital cost bounds shown in Table 2 and economic assumptions shown in Tables S9–S12 (ESI).

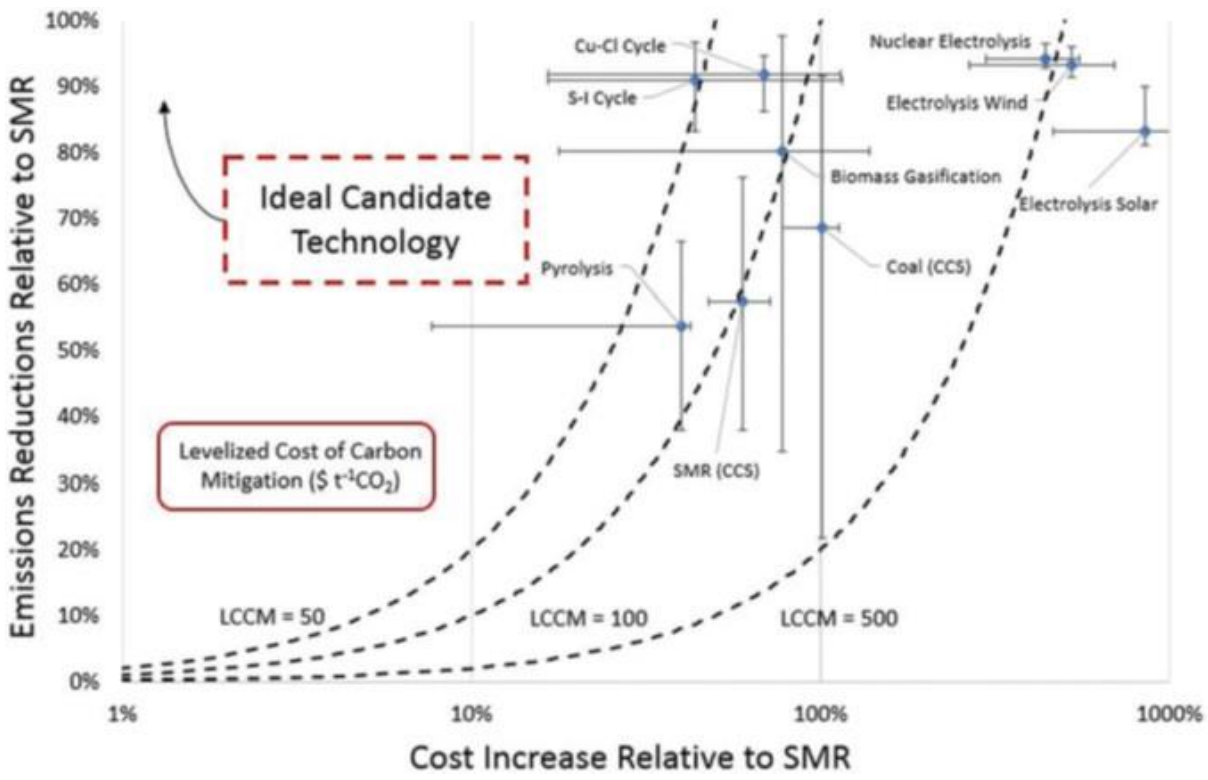


Fig. 6 Proportional reduction in emissions against percentage cost increase relative to SMR. The variability of emissions and cost parameters shown reflect the full ranges of emissions and costs values used in this study and presented in Table 5. Biomass with CCS, emissions reduction of 213% and a cost increase of 168%, has been omitted from the chart as an outlier to allow focus on other technologies.

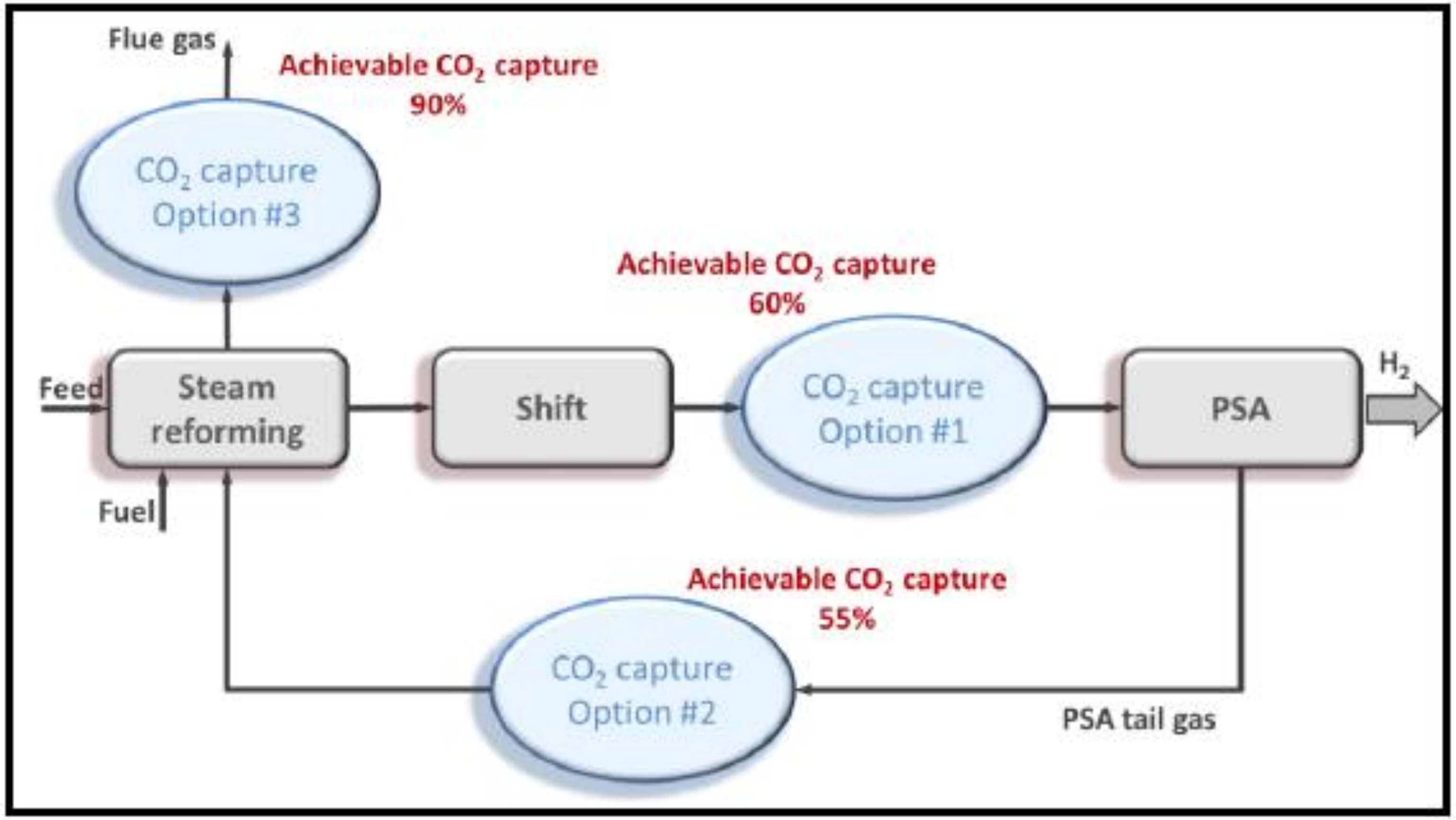
Carbon footprint of hydrogen manufacture

Technology	Literature estimates (kg CO_2e kg^{-1} H_2)			Our estimates (kg CO_2e kg^{-1} H_2)		
	Low	Central	High	Low	Central	High
SMR[a]	10.72	12.4	15.86	10.09	13.24	17.21
SMR w. CCS[a]	3.1	4.3	5.92	2.97	5.61	9.16
Coal[b]	14.4	19.14	25.31	14.72/16.9[e]	19.78/23.85[e]	26.09/30.9[e]
Coal w. CCS[b]	0.78	1.8	5.2	1.09/3.27[e]	2.11/6.2[e]	5.52/10.35[e]
CH_4 pyrolysis[a]	1.9	3.72	5.54	4.2	6.1	9.14
Biomass	0.31	2.6	8.63	0.31	2.6	8.63
Biomass w. CCS[c]		−14.58		−11.66	−14.58	−17.50
Electrolysis wind[d]	0.85	1.34	2.2	0.52	0.88	1.14
Electrolysis solar[d]	1.99	4.47	7.1	1.32	2.21	2.5
Electrolysis nuclear[d]	0.47	1.65	2.13	0.47	0.76	0.96
S–I cycle	0.41	1.2	2.2	0.41	1.2	2.2
Cu–Cl cycle	0.7	1.08	1.8	0.7	1.08	1.8

Our "Low–Central–High" estimates utilize [a] supply chain contributions of 0.6–1.4% (central 0.9%) fugitive methane emissions and 8.2–14.8 g CO_2 MJ^{-1} HHV (central 10 g CO_2 MJ^{-1} HHV) to the full emissions range presented in the literature, [b] the IPCC Tier 1 emissions ranges of 10–25 m^3 CH_4 t^{-1} for underground coal and 0.32–0.77 kg CO_2e kg^{-1} H_2 (central estimate of 0.45 kg CO_2e kg^{-1} H_2) for surface mined coal supply chain contributions to the full emissions range presented in the literature, [c] ±20% of the single reference study, [d] the interquartile ranges of the g kW h^{-1} emissions from power generation study reviews (Section 3.5) combined with electrolyser contributions of 40 g CO_2e kg^{-1} H_2. [e] First value represents total LCE estimates from surface mined coal and the second value total LCE estimates from underground mined coal.

B. Parkinson, P. Balcombe, J.F. Speirs, A.D. Hawkes, K. Hellgardt, Levelized cost of CO 2 mitigation from hydrogen production routes, Energy Environ. Sci. 12 (2019) 19–40. https://doi.org/10.1039/C8EE02079E. *Sustainable Gas Institute, Imperial College London*

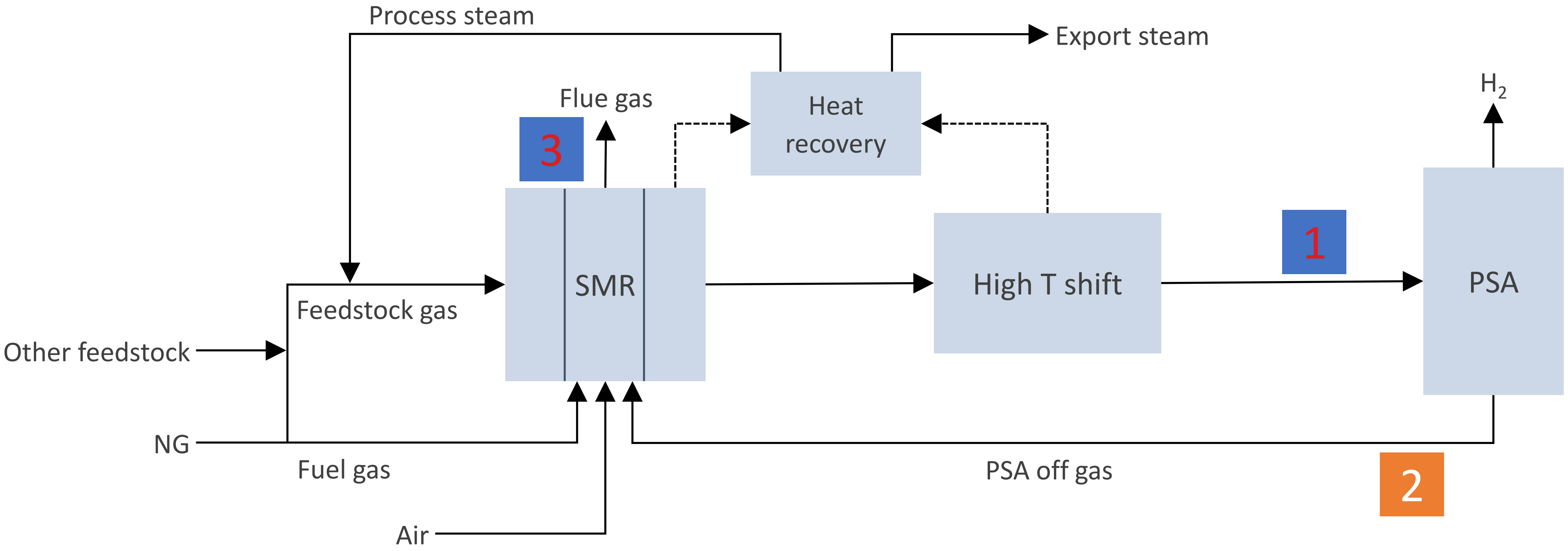
SMR: CO2 separation options



SMR BASED H2 PLANT WITH CCS, IEAGHG Technical Report 2017-02
https://ieaghg.org/publications/technical-reports

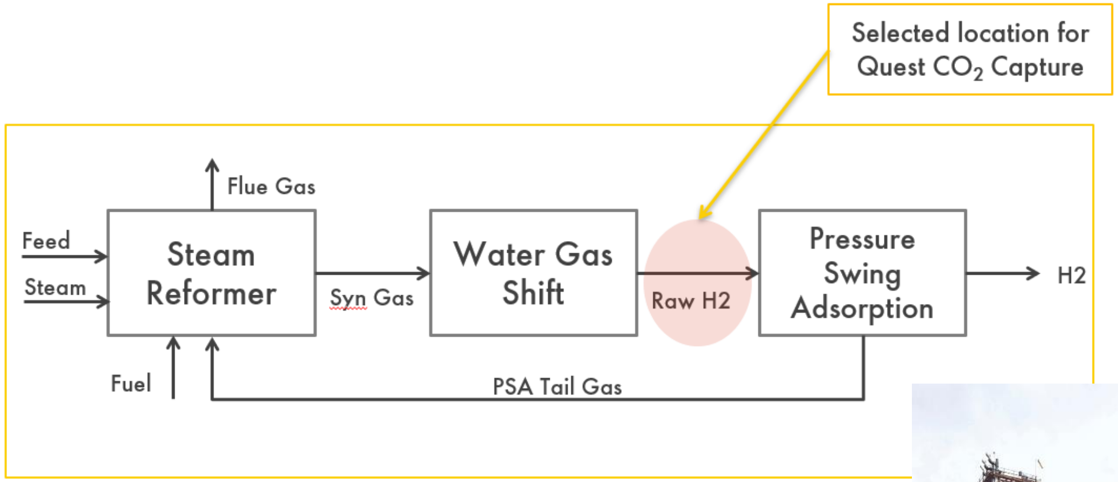
SMR = Hydrogen Manufacturing Unit (HMU): CO_2 capture options

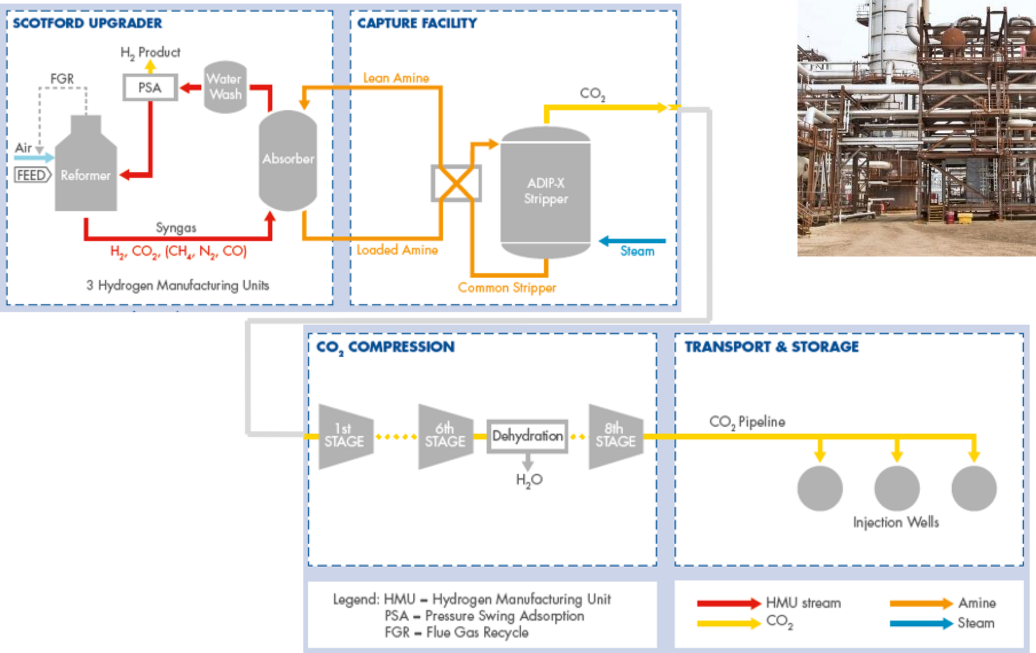
			Pressure, psig	Gas flow, acfm	CO_2, %mol	CO_2, psi	CO_2, Mt/mmscfH_2
1	Pre-combustion	Pre–PSA	350–435	4,500 (@360 psig)	15–20	50–70	13
2		Post–PSA	~ 10	25,000 (@7 psig)	48–55	< 10	13
3	Post-combustion		0	200,000 (@105°F)	16–19	~ 3	23



Shell Quest CCS: Scotford, Alberta

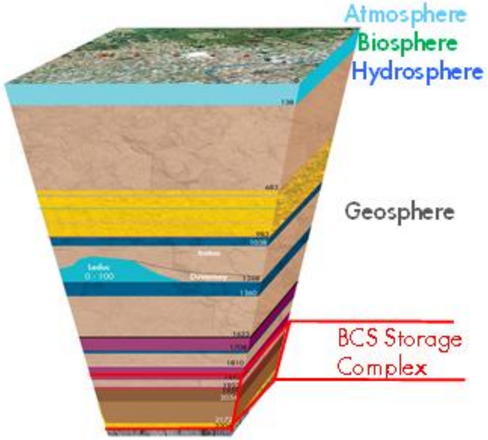
- CO_2 capture: One million tonnes CO_2 per year from 3 hydrogen manufacturing units at Scotford Upgrader
- Permanent storage: 2 km underground in the Basal Cambrian Sands
- Performance: Quest has captured, transported, and safely stored over **5 million tonnes of CO_2**
  - Reliability, cost, and storage performance are all better than projected.
- Shell's ADIP-X amine technology utilized for CO_2 removal from raw H_2
  - HMU emissions reduced by almost 50%
- Integrated facility design in excess of 1.2 Mt/a



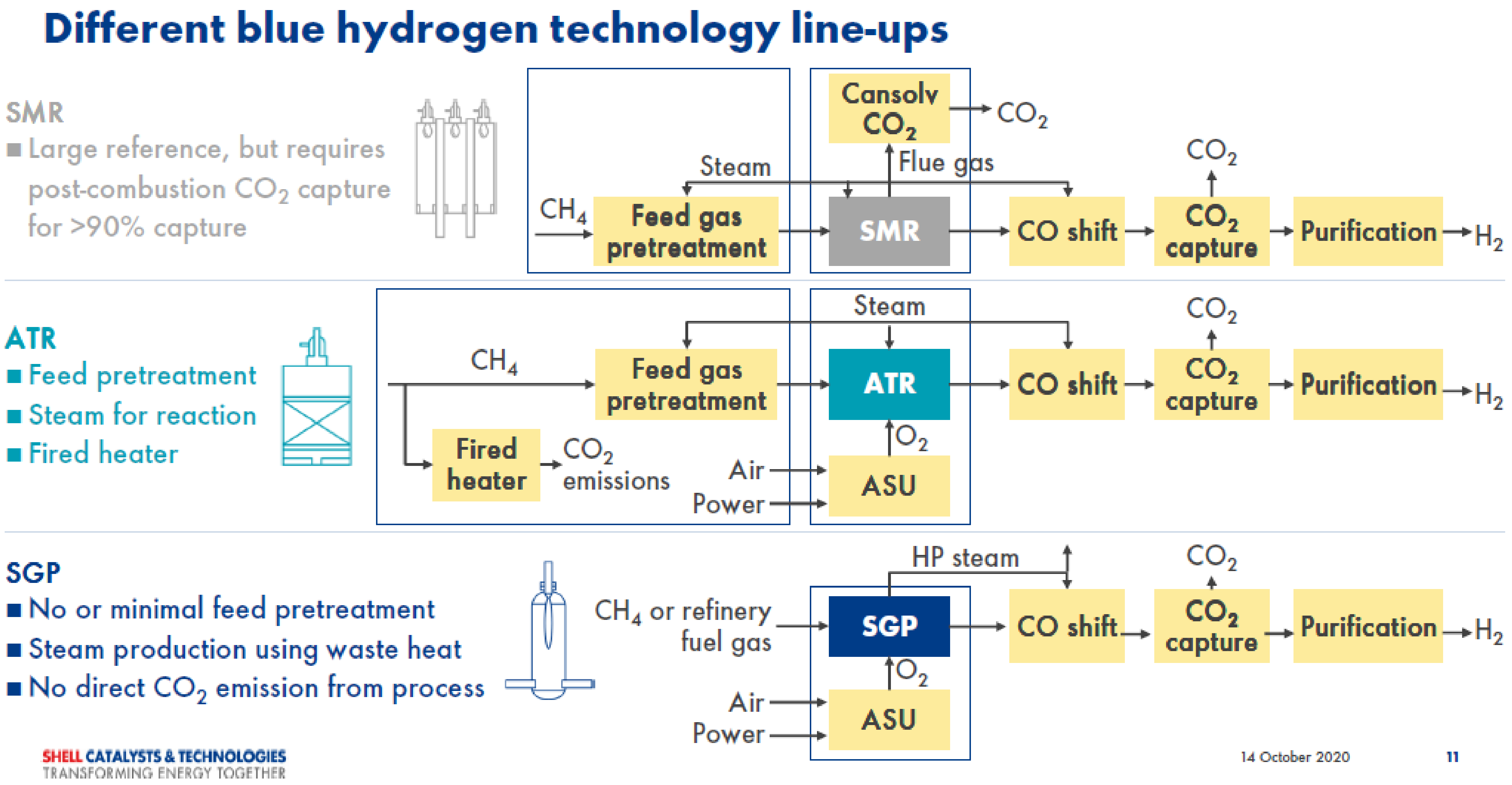


Storage: 65 km pipeline to:

- Deep saline aquifer
- High quality sandstone (~17% porosity) reservoir
- Excellent permeability (~1000mD)
- Multiple thick, continuous seals (>200m within the complex)



Blue Hydrogen Manufacture: SMR → ATR → POx



Shell Blue Hydrogen Technology, Hydrocarbon Processing Webcast Oct 2020

https://www.hydrocarbonprocessing.com/magazine/2021/june-2021/special-focus-process-optimization/increasing-blue-hydrogen-production-affordability

Hydrogen Manufacture: SMR → ATR → POx

SGP is proven for 500 t/d hydrogen equivalent production, and carbon capture and utilisation

PEARL GTL, QATAR

18 SGP trains, each with an equivalent pure hydrogen production capacity of 500 t/d[1] and in operation since 2011

PERNIS REFINERY, THE NETHERLANDS

1 million t/y CO_2 capture capacity from SGP to be used in greenhouses

The Guardian — Oil refinery gives greenhouses a boost with CO2 pipeline

https://www.theguardian.com/science/2006/aug/12/oilandpetrol.food

[1]Defined as pure H_2 production, i.e., not including any inerts, CH_4, CO_2, CO which will also be present depending on the final purification step.

SHELL CATALYSTS & TECHNOLOGIES
TRANSFORMING ENERGY TOGETHER

14 October 2020 18

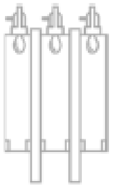
N. Liu, https://www.hydrocarbonprocessing.com/magazine/2021/june-2021/special-focus-process-optimization/increasing-blue-hydrogen-production-affordability; Shell Blue Hydrogen Technology, Hydrocarbon Processing Webcast Oct 2020

Hydrogen Manufacture: SMR → ATR → POx

Which technology is best for greenfield applications?

GOOD

Steam Methane Reforming (SMR)

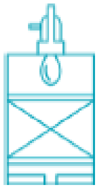


- Catalytic
- Indirect heating
- Non-oxygen based with steam
- Multi-tubular with external firing

Proven for grey hydrogen, but the alternatives may be better suited for blue hydrogen

BETTER

Auto-Thermal Reforming (ATR)

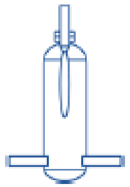


- Catalytic
- Direct heating
- Oxygen based with steam
- Refractory-lined reactor with catalyst bed

As an oxygen-based system, more cost-effective than SMR for blue hydrogen

BEST

Shell Gas POx (SGP)



- Non-catalytic
- Direct heating
- Oxygen based without steam
- Refractory-lined reactor

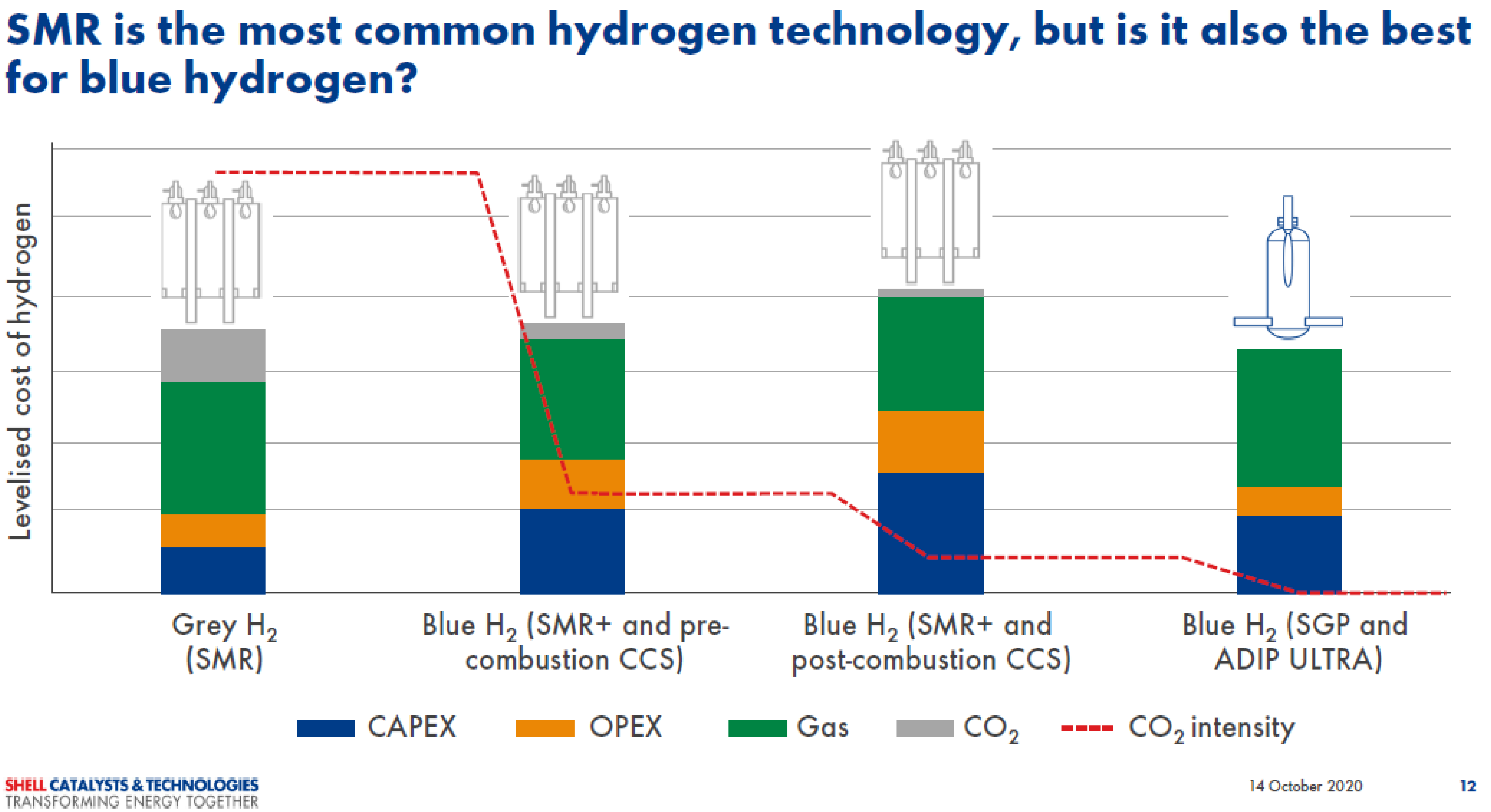
Offers key advantages over ATR, including, for 500 t/d hydrogen production:*

- $30 million/y lower OPEX
- 35% less power import
- 10–25% lower levelised cost of hydrogen (LCOH)

*Basis: 500 t/d of pure H_2 production (excluding inerts, CH_4, CO_2 and CO, which will also be present depending on the final purification step). Natural gas price = $396/t; demin. water = $8.4/t; power import = $86/MWh; solvent, TEG and catalyst costs based on internal quotations. H_2 discharge pressure of 72 bara; CO_2 discharge pressure of 150 bara. 95% plant availability.

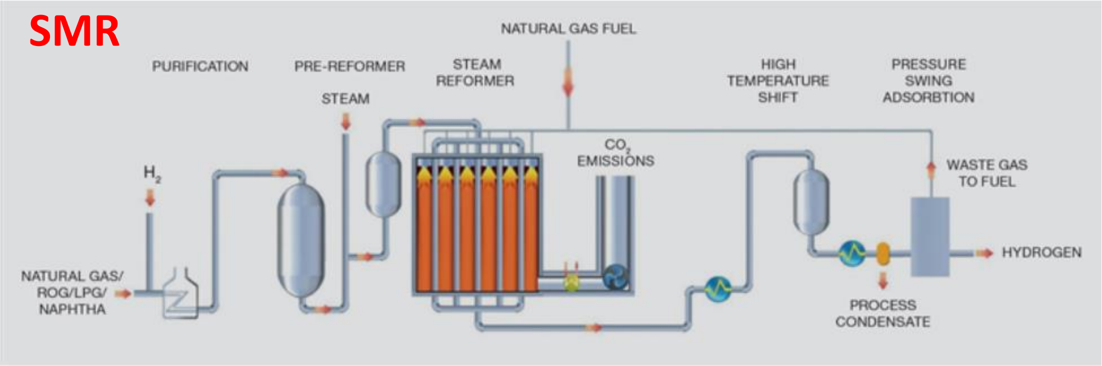
N. Liu, Increasing blue hydrogen production affordability, Hydrocarbon Processing, June (2021).
https://www.hydrocarbonprocessing.com/magazine/2021/june-2021/special-focus-process-optimization/increasing-blue-hydrogen-production-affordability; see Shell Blue Hydrogen Technology, Hydrocarbon Processing Webcast Oct 2020.

Hydrogen Manufacture: SMR → ATR → POx

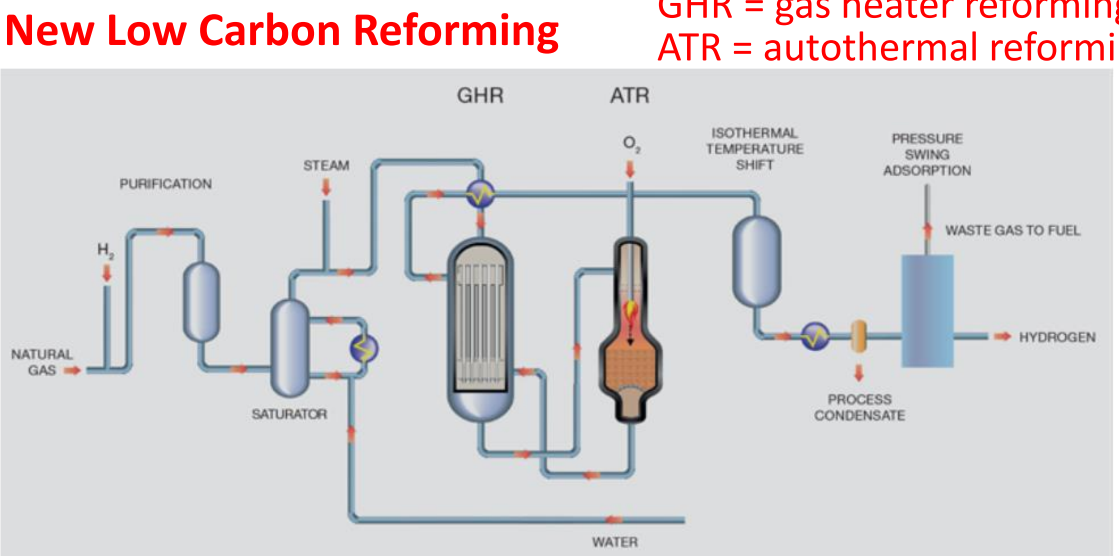


N. Liu, Increasing blue hydrogen production affordability, Hydrocarbon Processing, June (2021). https://www.hydrocarbonprocessing.com/magazine/2021/june-2021/special-focus-process-optimization/increasing-blue-hydrogen-production-affordability; see Shell Blue Hydrogen Technology, Hydrocarbon Processing Webcast Oct 2020.

Cleaner H2 from natural gas reforming



GHR = gas heater reforming
ATR = autothermal reforming



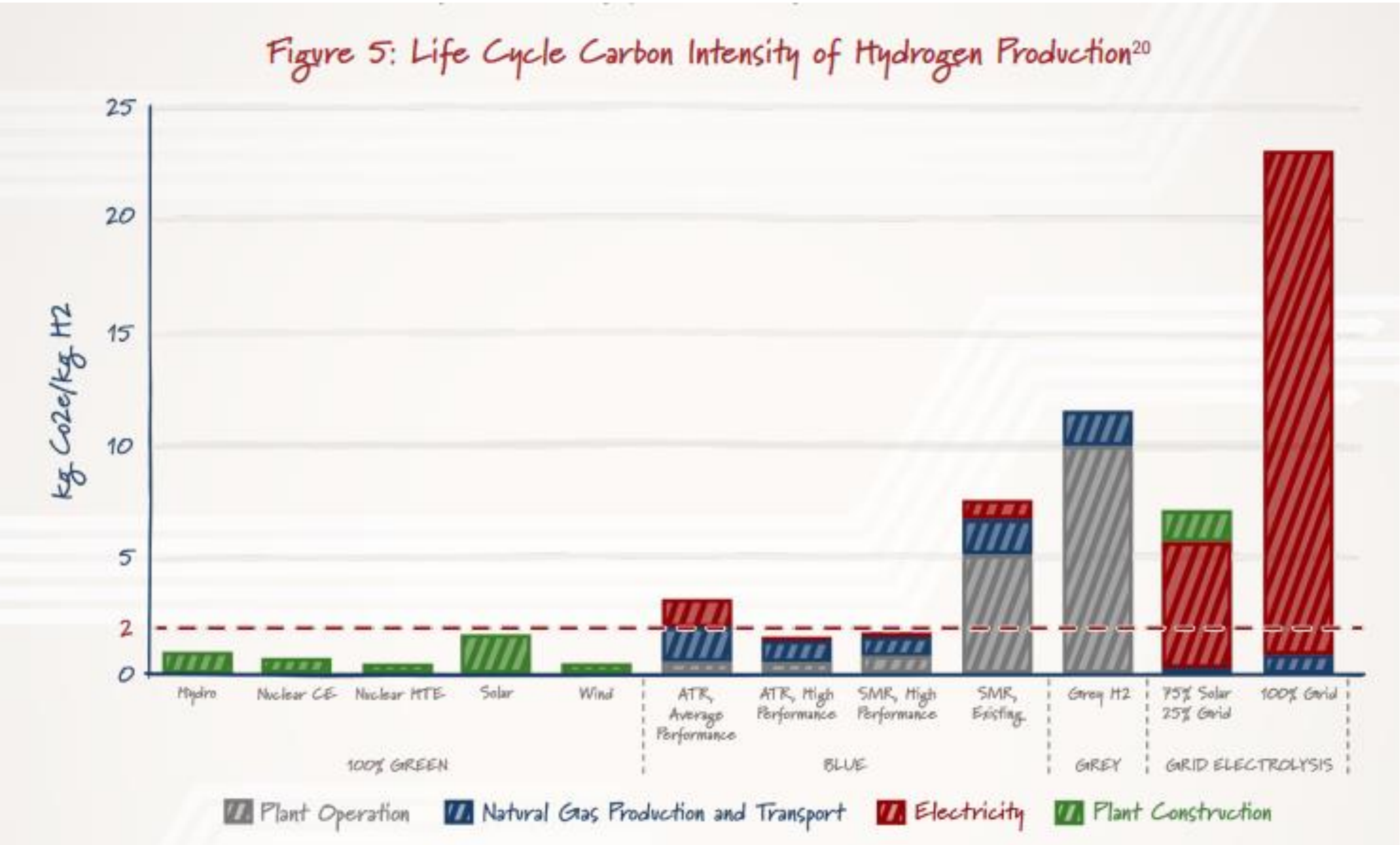
PARAMETER	UNITS	SMR FLOWSHEET	ATR FLOWSHEET	LCH FLOWSHEET
Natural Gas as Feed	kNm³/h	39.74	41.22	38.31
Natural Gas as Fuel	kNm³/h	5.36	0.19	0
Total Natural Gas	kNm³/h	45.10	41.41	38.31
Natural Gas Energy#	MW	439	432	400
Hydrogen Production	kNm³/h	107.4	107.4	107.4
Hydrogen Energy#	MW	322	322	322
Natural Gas Efficiency	%	73.3	74.5	80.6
CO_2 Captured	mt/h	83.7	83.6	76.3
CO_2 Emitted	mt/h	4.4	3.1	3.7
CO_2 Captured	%	95.0	96.4	95.4
ISBL + OSBL CAPEX	mGBP	261	195	159

 # Energy is stated on a lower calorific value basis

- Use O_2 vs. air to make CO_2 capture more efficient vs. SMR
- SMR here is higher cost high % capture

Bill Cotton: Clean Hydrogen. Part 1: Hydrogen from Natural Gas Through Cost Effective CO2 Capture, 15 March 2019
www.thechemicalengineer.com/features/clean-hydrogen-part-1-hydrogen-from-natural-gas-through-cost-effective-co2-capture/

Clean H2 definition



- https://static.clearpath.org/2021/10/american-clean-hydrogen.pdf

Global warming potential of Hydrogen (indirect)

Table 1 – Estimated global warming consequences of zero-carbon hydrogen distribution, supply and usage systems in the UK and US, making assumptions concerning the percentage leakage rate of the future hydrogen system.

	UK	US
Global warming, million tonnes CO_2 equivalent per year		
Minimum assumed leakage, 1%	0.26	1.26
Same leakage as respective natural gas network	0.6	0.6–2.7
Scale up natural gas leakage to account for H_2 energy content	1.5	1.6–6.8
Maximum assumed leakage, 100%	26	126
Current natural gas consequences	76	295–360

- Indirect Global Warming Potential due to atmospheric reactions with OH, NO
- GWP = 3.3 (<2022)
- GWP = 11 (2022)

Radical Reactions:

$OH + H_2 \rightarrow H + H2O$

$H + O2 \rightarrow HO_2$

$HO_2 + NO \rightarrow NO_2 + OH$

$NO_2 + hv \rightarrow NO + O$

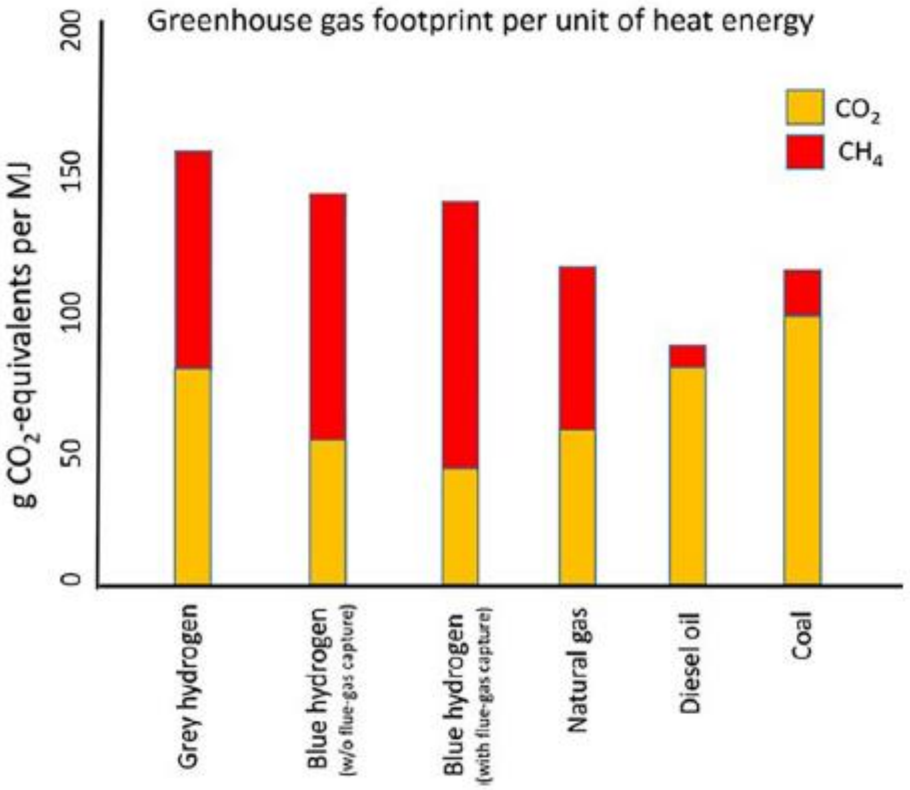
$O + O_2 \rightarrow O_3$

H2 leak rate	Tg CO2/yr	% of fossil
1%	417	1.81%
10%	4167	18.12%
Fossil economy	23000	100%

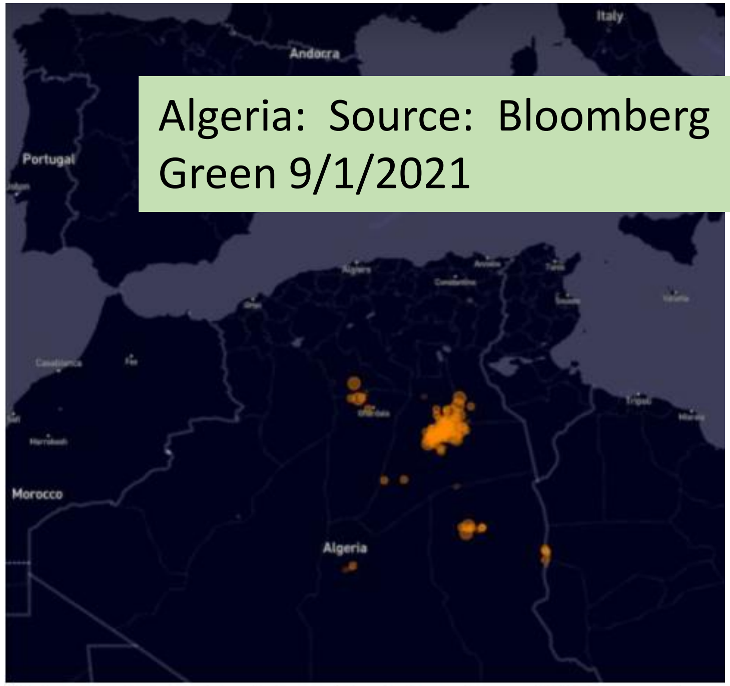
- Derwent, R. et al. (2006) "Global environmental impacts of the hydrogen economy", Int. J. Nuclear Hydrogen Production and Application 1(1): 57-67.
- R. G. Derwent, D. S. Stevenson, S. R. Utembe, M. E. Jenkin, A. H. Khan and D. E. Shallcross, Global modelling studies of hydrogen and its isotopomers using STOCHEM-CRI: Likely radiative forcing consequences of a future hydrogen economy, *International Journal of Hydrogen Energy*, 2020, **45**, 9211–9221.
- R. A. Field and R. G. Derwent, Global warming consequences of replacing natural gas with hydrogen in the domestic energy sectors of future low-carbon economies in the United Kingdom and the United States of America, *International Journal of Hydrogen Energy*, 2021, **46**, 30190–30203.
- N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle, University of Cambridge and NCAS and K. Shine, University of Reading, Atmospheric implications of increased Hydrogen use (2022) www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use

Methane Leakage

R. W. Howarth and M. Z. Jacobson, How green is blue hydrogen?, *Energy Sci Eng*, 2021, ese3.956.



Algeria: Source: Bloomberg Green 9/1/2021

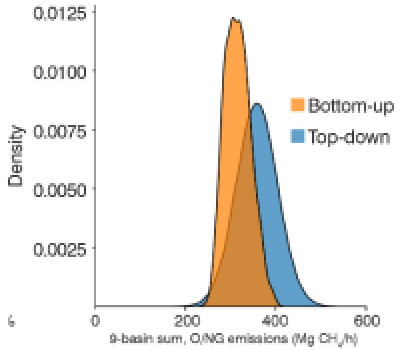


Methane emissions detected over Algeria from January 2019 to present including five observed this month. *Source: Kayrros SAS*

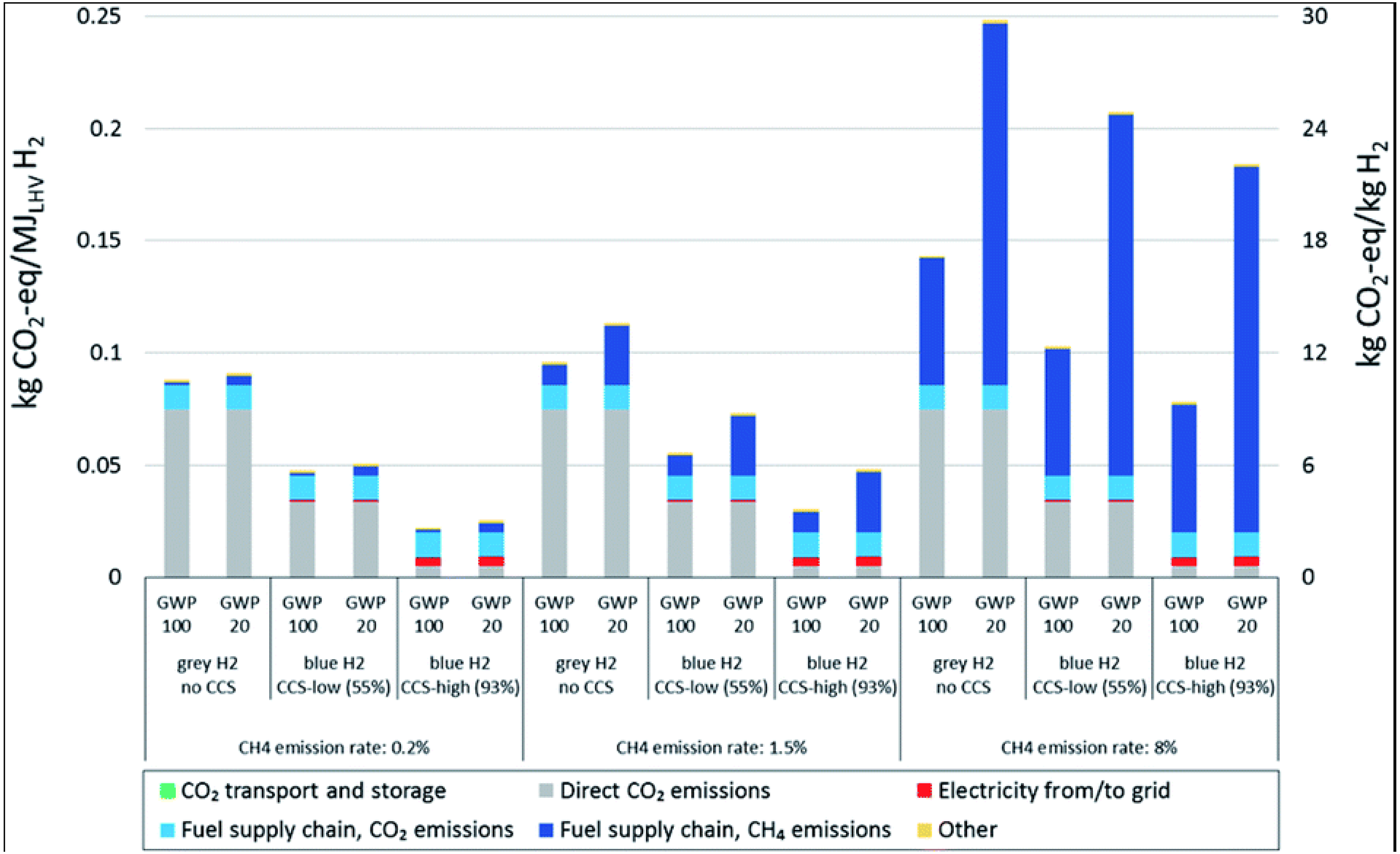
We're tackling methane on every front — with methane hunters Dr. David Lyon (EDF) and Dr. Anna Robertson (U. of Wyoming) in the [Permian Basin](), [MethaneSAT]() and with [Google Earth Outreach](). bottom right.

https://www.edf.org/climate/methane-crucial-opportunity-climate-fight

R. A. Alvarez, D. T. Allen et al., Assessment of methane emissions from the U.S. oil and gas supply chain, *Science*, 2018, eaar7204. https://www.science.org/lookup/doi/10.1126/science.aar7204



2022 Methane emissions update



- C. Bauer, K. Treyer, C. Antonini, J. Bergerson, M. Gazzani, E. Gencer, J. Gibbins, M. Mazzotti, S. T. McCoy, R. McKenna, R. Pietzcker, A. P. Ravikumar, M. C. Romano, F. Ueckerdt, J. Vente and M. van der Spek, On the climate impacts of blue hydrogen production, Sustainable Energy Fuels, 2022, 6, 66–75.https://pubs.rsc.org/en/content/articlepdf/2022/se/d1se01508g

Responsibly sourced gas (RSG)

Responsibly sourced gas: cleaner, greener, and here to stay — woodmac.com

Each certification program has a unique approach for recognizing performance

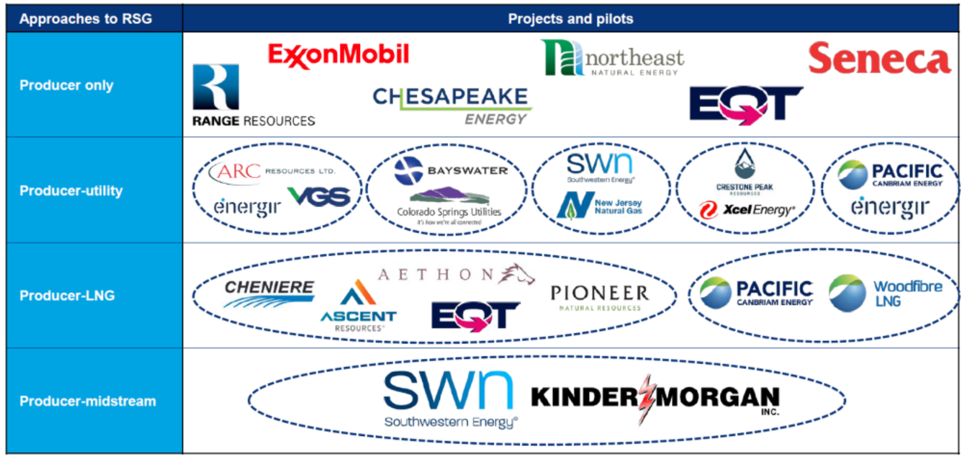
Certification is differentiated from other voluntary initiatives and commitments because it provides an explicit declaration of achievement by an administering organization to the participant

	Standard name	Continuous monitoring required?	Specific technology required?	Independent third-party assessment	Performance rating (low to high)	Funding model
Project Canary	TrustWell Responsible Gas	✓	✓	✗	Three scoring levels: Silver, Gold, Platinum	For-profit
MiQ	MiQ Standard	✗	✗	✓	Six grades from A-F	Not-for-profit
Equitable Origin	EO100™ for Responsible Energy Development	✗	✗	✓	Three levels of performance targets (PTs): PT1, PT2 and PT3	Not-for-profit
ISO	ISO 14001:2015	✗	✗	✓	Not applicable	Not-for-profit

- https://www.woodmac.com/news/opinion/responsibly-sourced-gas-rsg-a-primer/

Responsibly sourced gas: cleaner, greener, and here to stay — woodmac.com

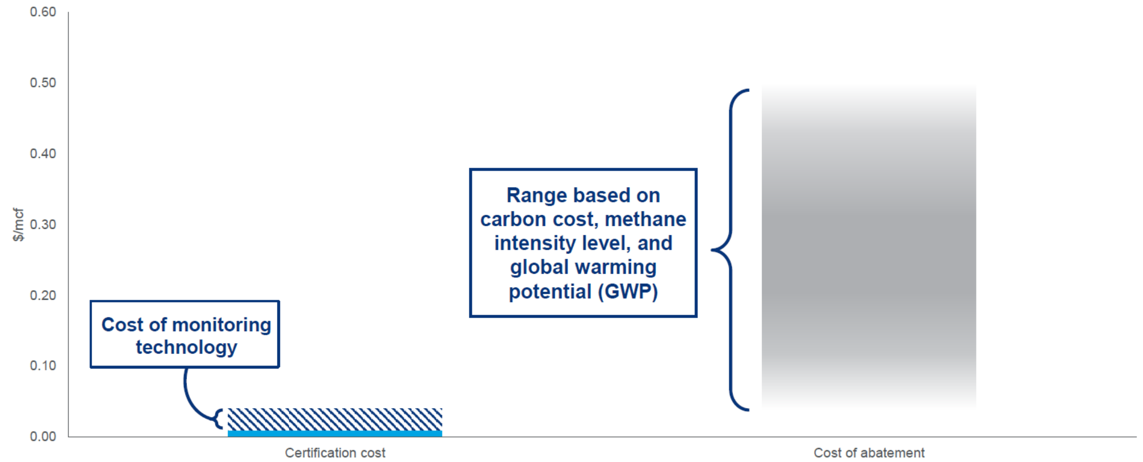
Multiple RSG partnerships form across different stakeholders in the gas industry



Responsibly sourced gas: cleaner, greener, and here to stay — woodmac.com

Potential cost of RSG certification versus cost of abatement under carbon tax

The value of RSG becomes the abatement cost, which is the difference of carbon cost of non-RSG certified gas at the higher methane intensity and RSG certified gas at lower methane intensity



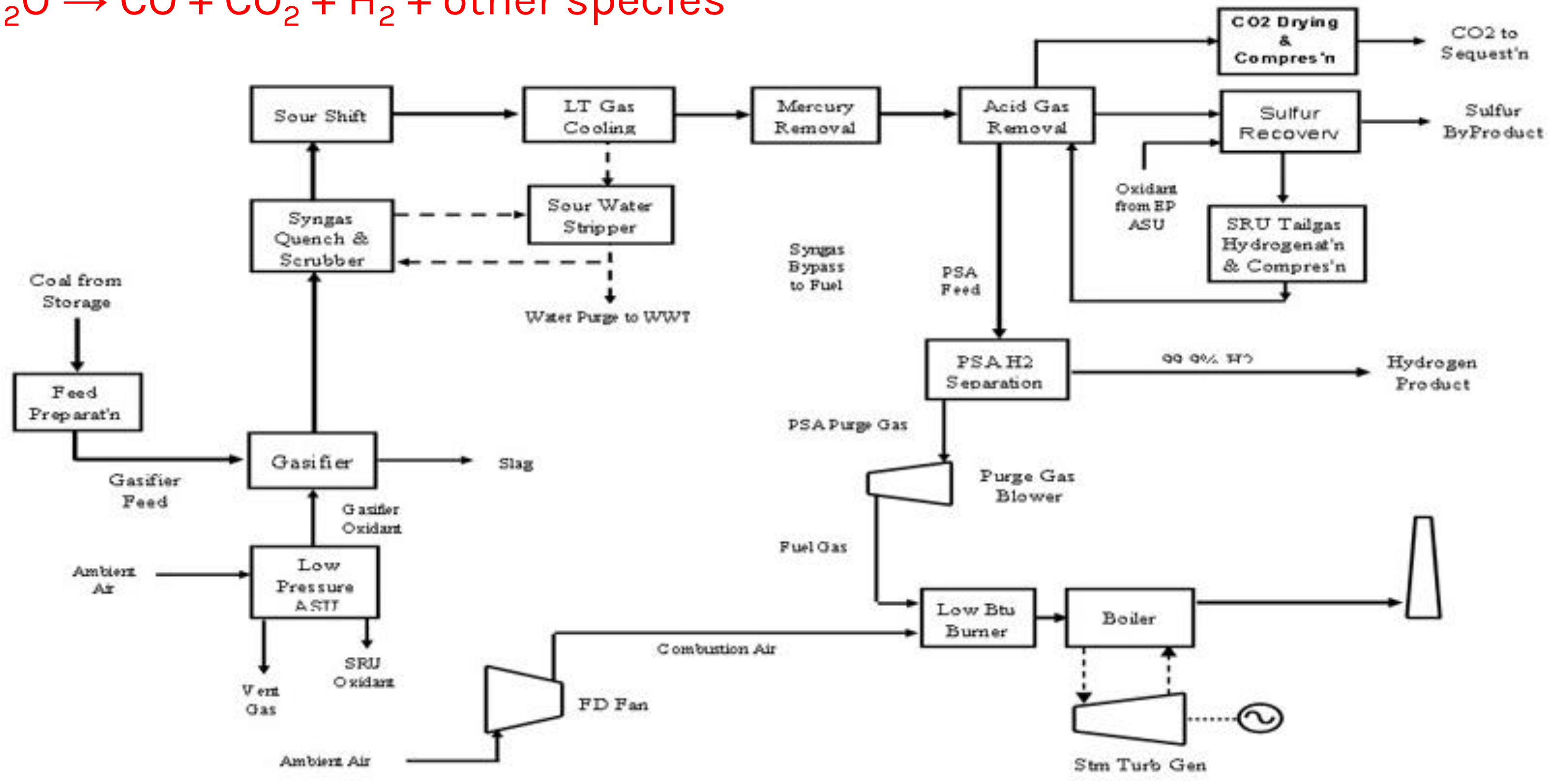
Sources: California emission price from August 2021 settlement (CARB); Europe ETS Price September 2021 settlement (ICE)

Hydrogen production from coal

Cheapest in China!

Coal gasification reaction (unbalanced):

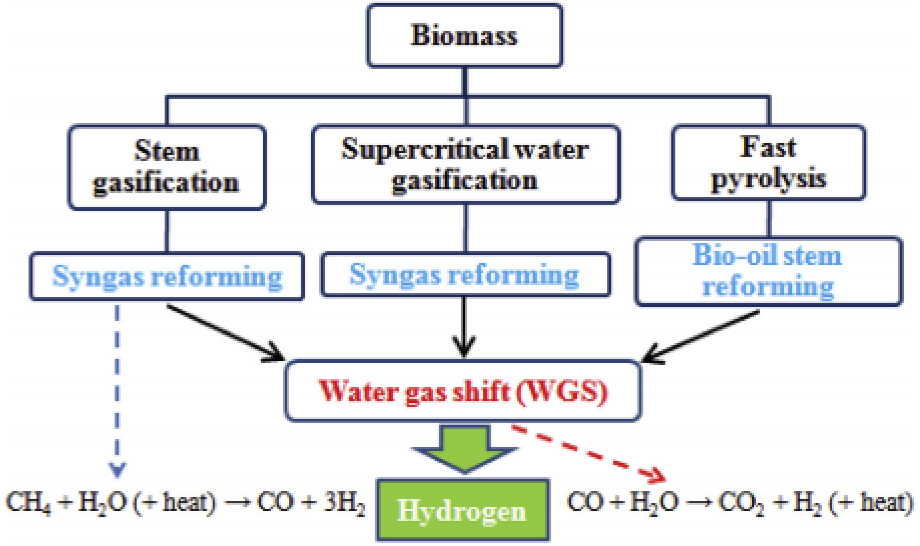
$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$

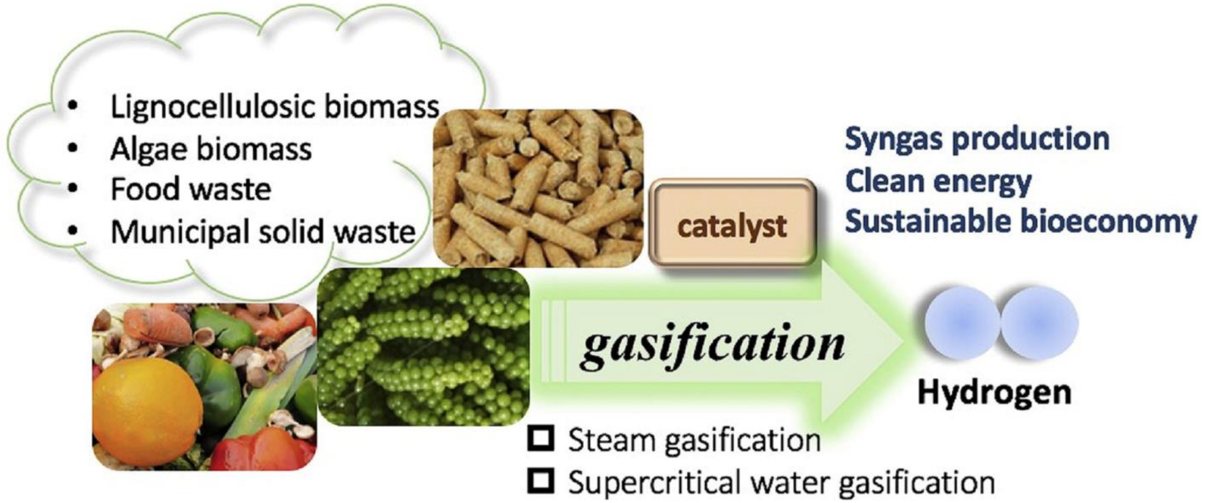


https://www.energy.gov/eere/fuelcells/hydrogen-production-coal-gasification;

https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/coal-to-hydrogen-without-power-export

2020 Review: Biomass gasification





- High temperatures and pressures
- Materials issues
- Tar formation
- Biomass feed at pressure
- Scale and collection radius

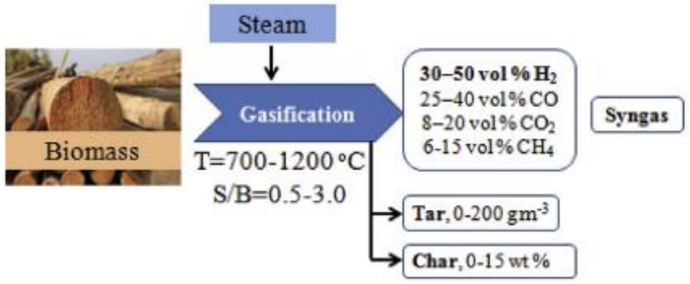
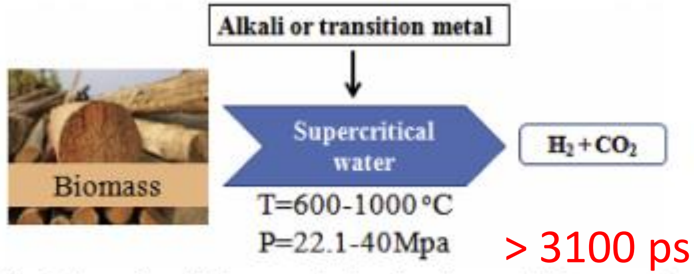


Fig. 3. Biomass-based hydrogen production through steam gasification process.

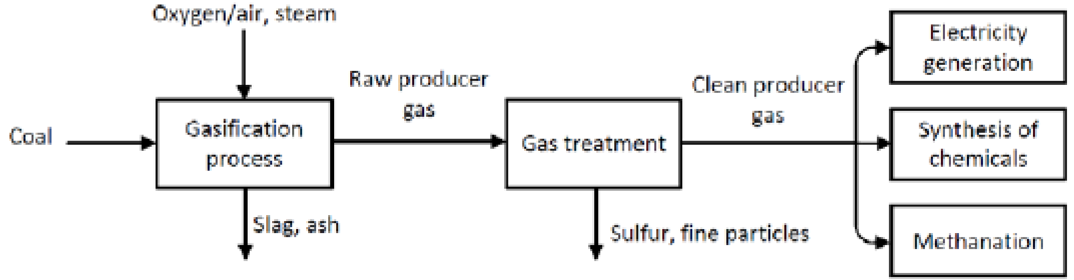


> 3100 psi

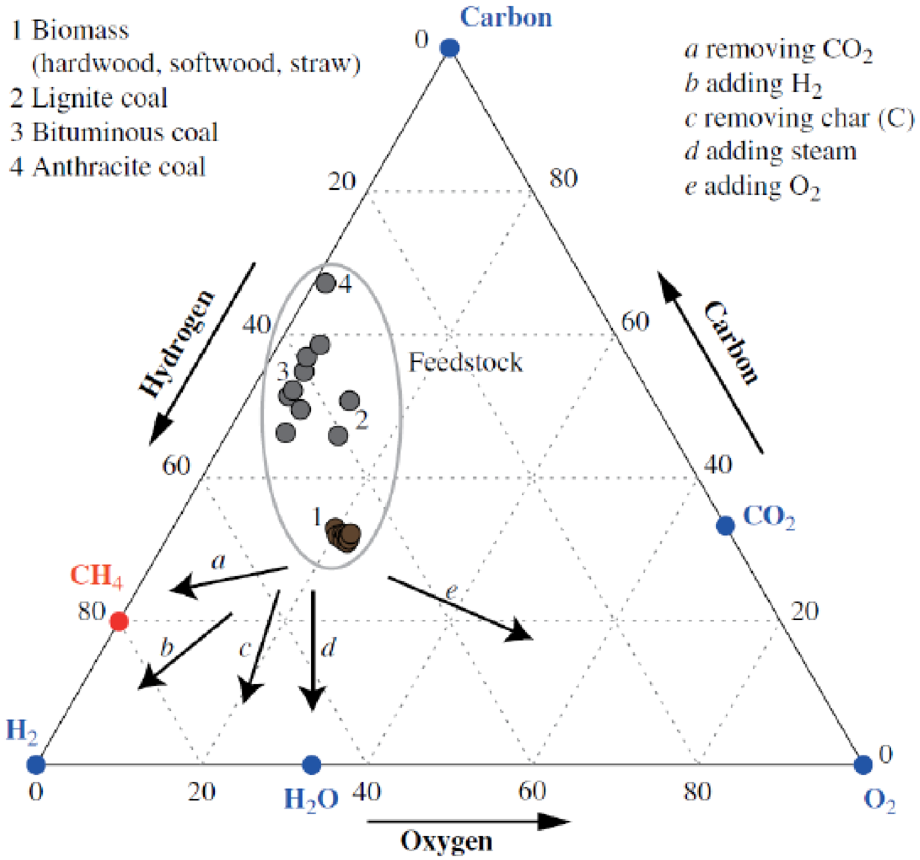
Fig. 4. Biomass-based hydrogen production through supercritical water gasification process.

L. Cao, I. K. M. Yu, X. Xiong, D. C. W. Tsang, S. Zhang, J. H. Clark, C. Hu, Y. H. Ng, J. Shang and Y. S. Ok, Biorenewable hydrogen production through biomass gasification: A review and future prospects, *Environmental Research*, 2020, **186**, 109547.

H_2 via biomass gasification



Similar to coal?

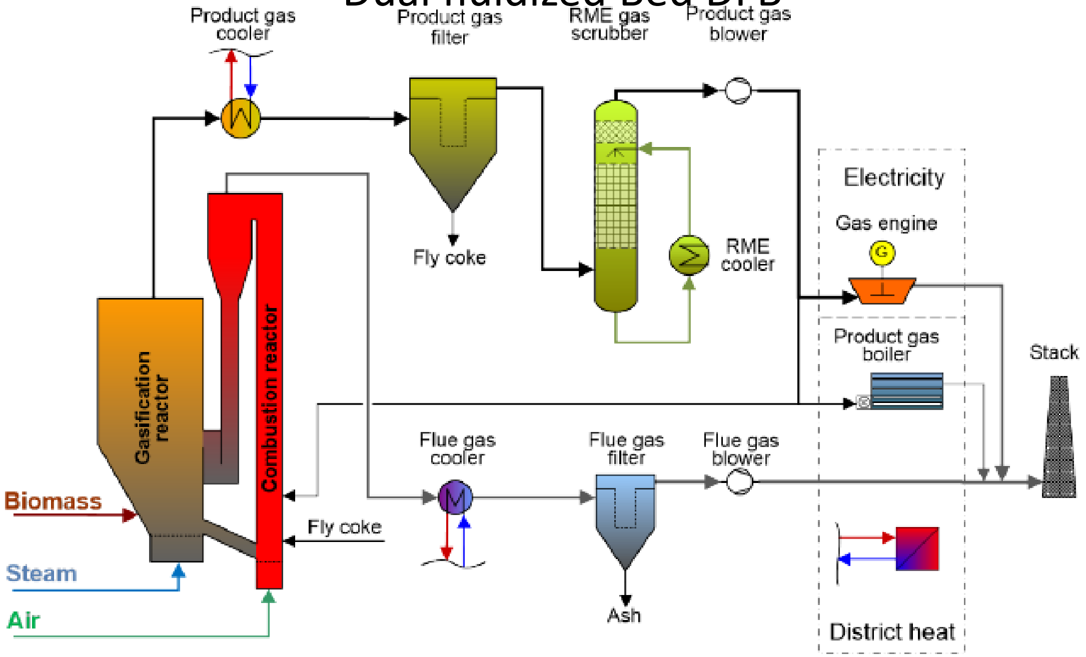


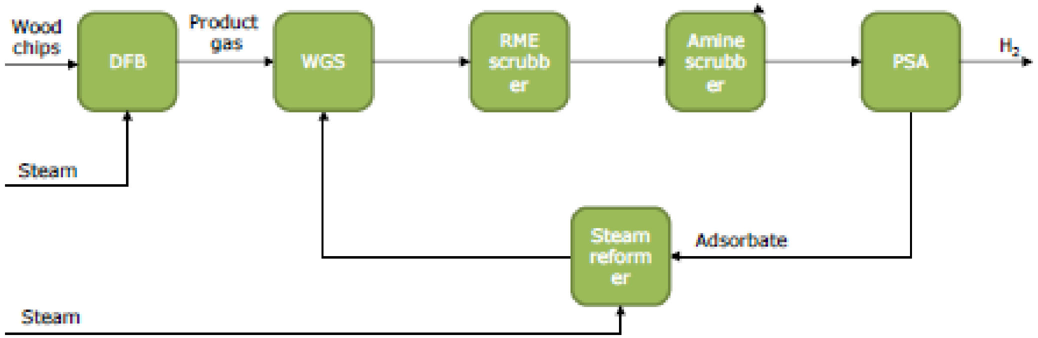
IEA Bioenergy, Hydrogen from biomass gasification (2018)

H_2 via biomass gasification

Sorption enhanced reactor (SER) = chemical looping

Dual fluidized Bed DFB





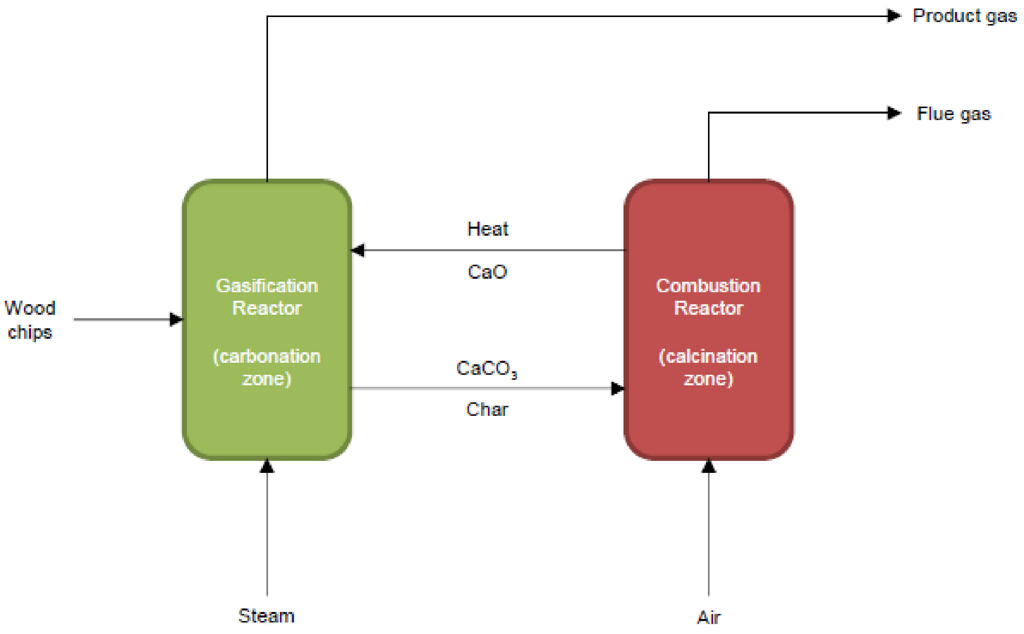
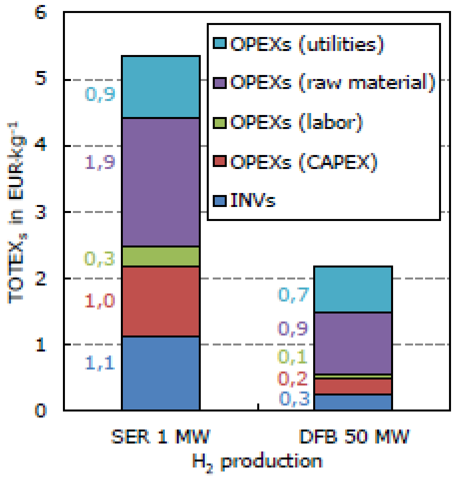


Figure 26: Principle of SER process based on biomass.



IEA Bioenergy, Hydrogen from biomass gasification (2018)

Biomass gasification:

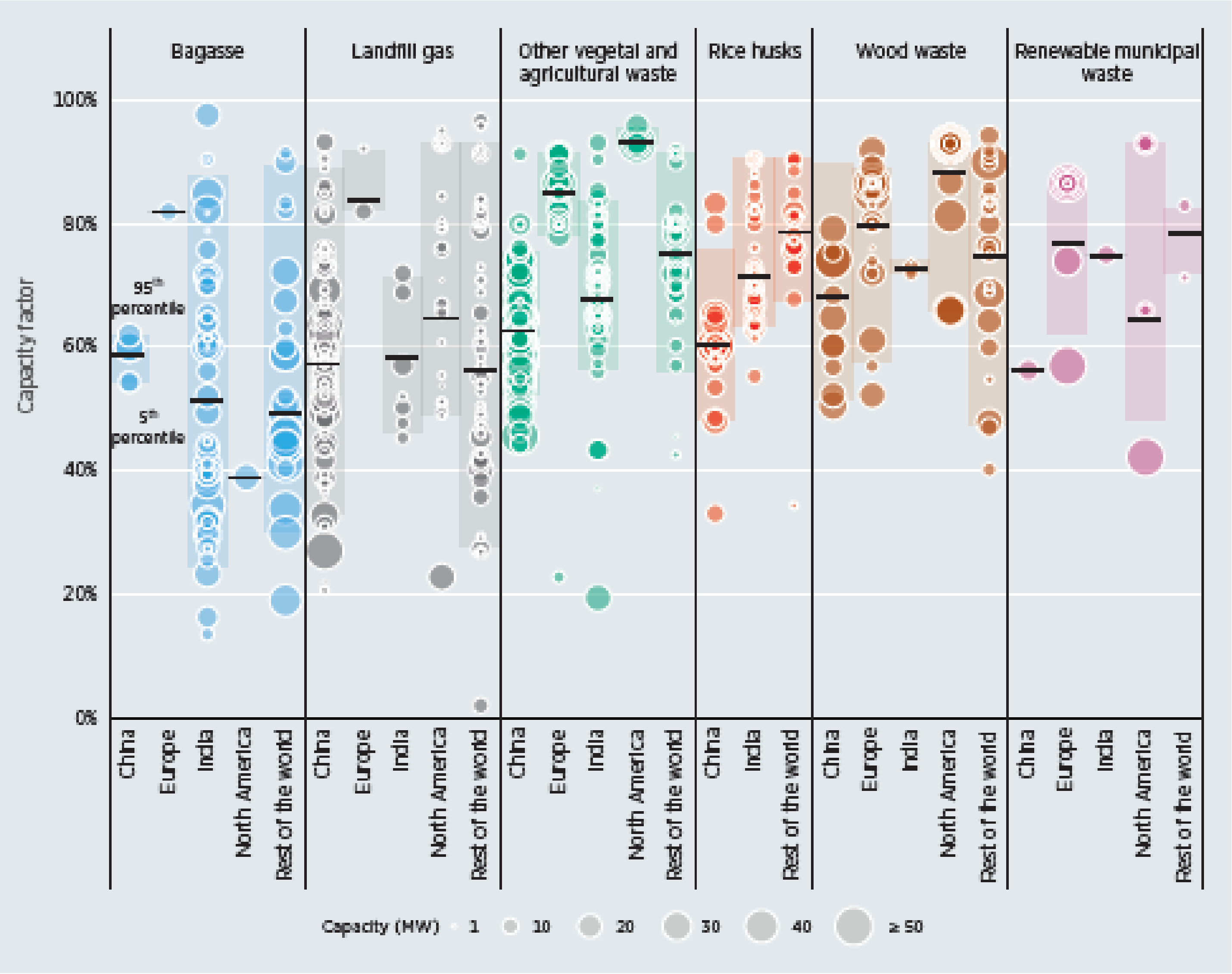
Municipal public waste as feedstock

- https://www.fchea.org/in-transition/2019/7/8/hydrogen-production-from-biomass-and-organic-waste
- https://www.forbes.com/sites/pikeresearch/2020/04/22/dont-forget-about-biomass-gasification-for-hydrogen/?sh=114eeda2724f

IRENA: Capacity factors for biomass

IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019

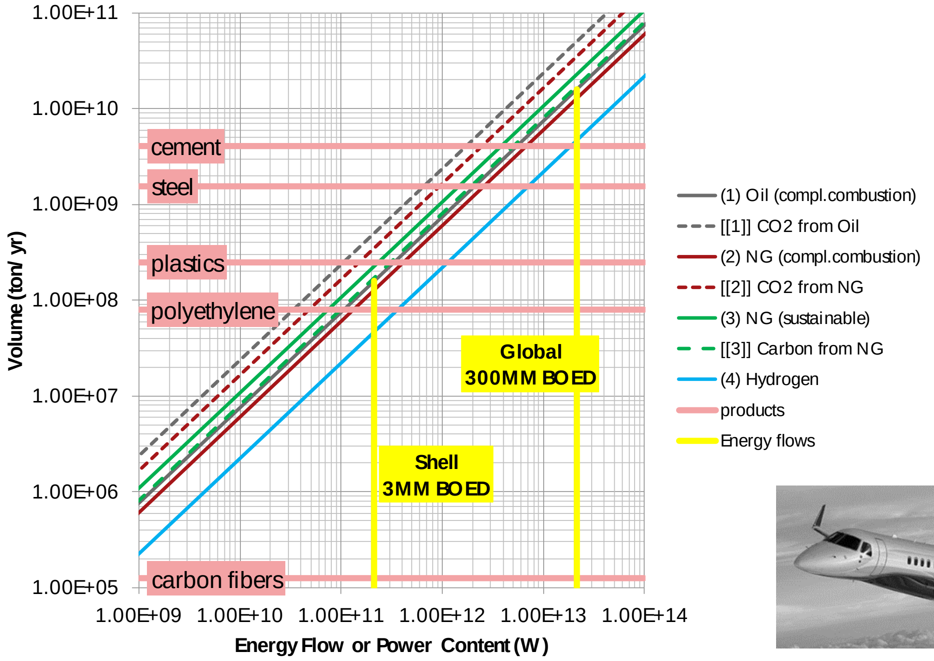
Figure 7.5 Project capacity factors and weighted averages of selected feedstocks for bioenergy power generation projects by country and region, 2000-2019

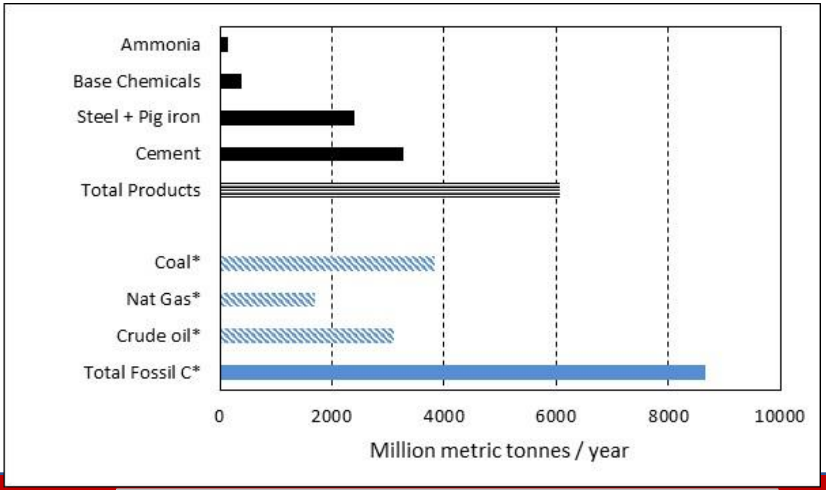


Source: IRENA Renewable Cost Database.

Energy Systems Analysis: Targets for Carbon Utilization

- **Scientific Challenge**
  - Develop new building techniques and products for carbon utilization to allow offset of a significant portion of fossil energy demand.
  - Develop and optimize pathways for clean H_2 production with co-production of carbon products
  - Develop additive manufacturing, polymeric and composite products with functionality (flame retardancy, strength) to serve in build industry
  - Advanced process concepts including renewable energy incorporation for coproduction of hydrogen and C-products suitable for build industry and advanced manufacturing methods
- **Impact:**
  - Large carbon sink via carbon utilization to build industry products.
  - H2 is freed for clean energy systems use (fuel cell)



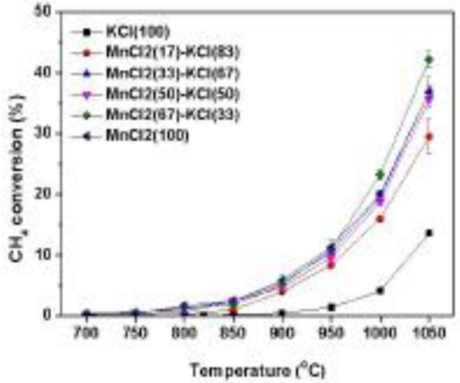


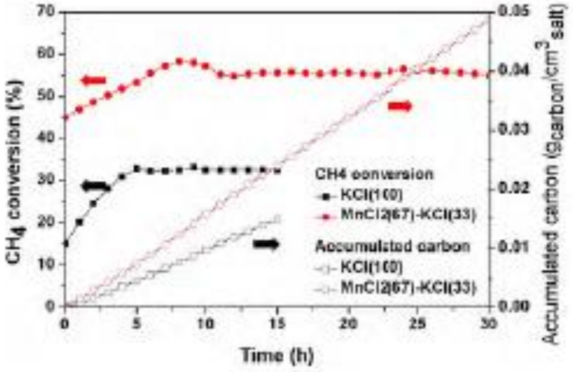
3D printed advanced composite Shelby Cobra (ORNL)

Low cost advanced manufacturing composite building (Mark Goulthorpe MIT)

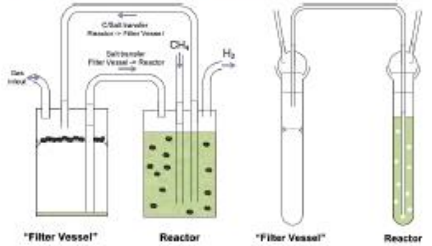
*C from CO2 emissions (2012)

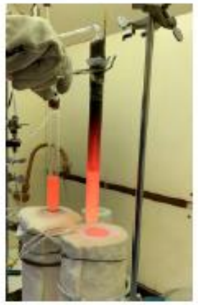
Methane Pyrolysis: CZero





High Temperature Carbon Transfer (Task 2)





- Analyzed a semi-batch process to separate the solid carbon from the molten salt
- Allows for isolation of the filter cake and subjecting the filter cake to normal or reduced pressure evaporative drying
- Accomplishment: Successfully demonstrated in a high temperature molten salt system

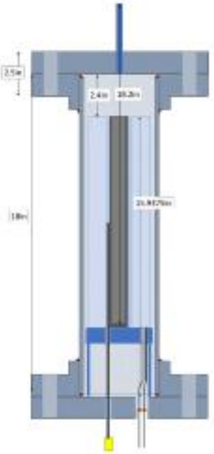
C||ZERO 12

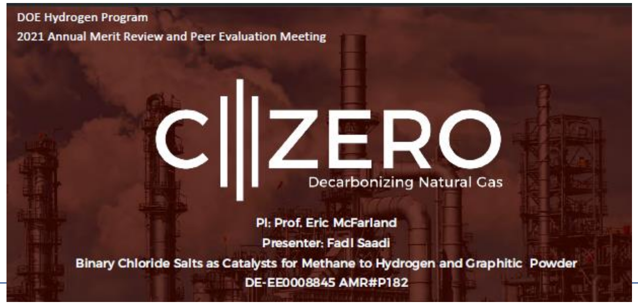
Carbon Removal via Screw Auger (Task 2)

- Tested several different solid removal processes in room temperature aqueous systems
- Screw auger systems are used in waste management to remove solids from liquid media
- Accomplishment: Successfully removed carbon analog from aqueous system (~500 g/hr)

Fabrication and Testing of High Pressure Reactors (Task 1)

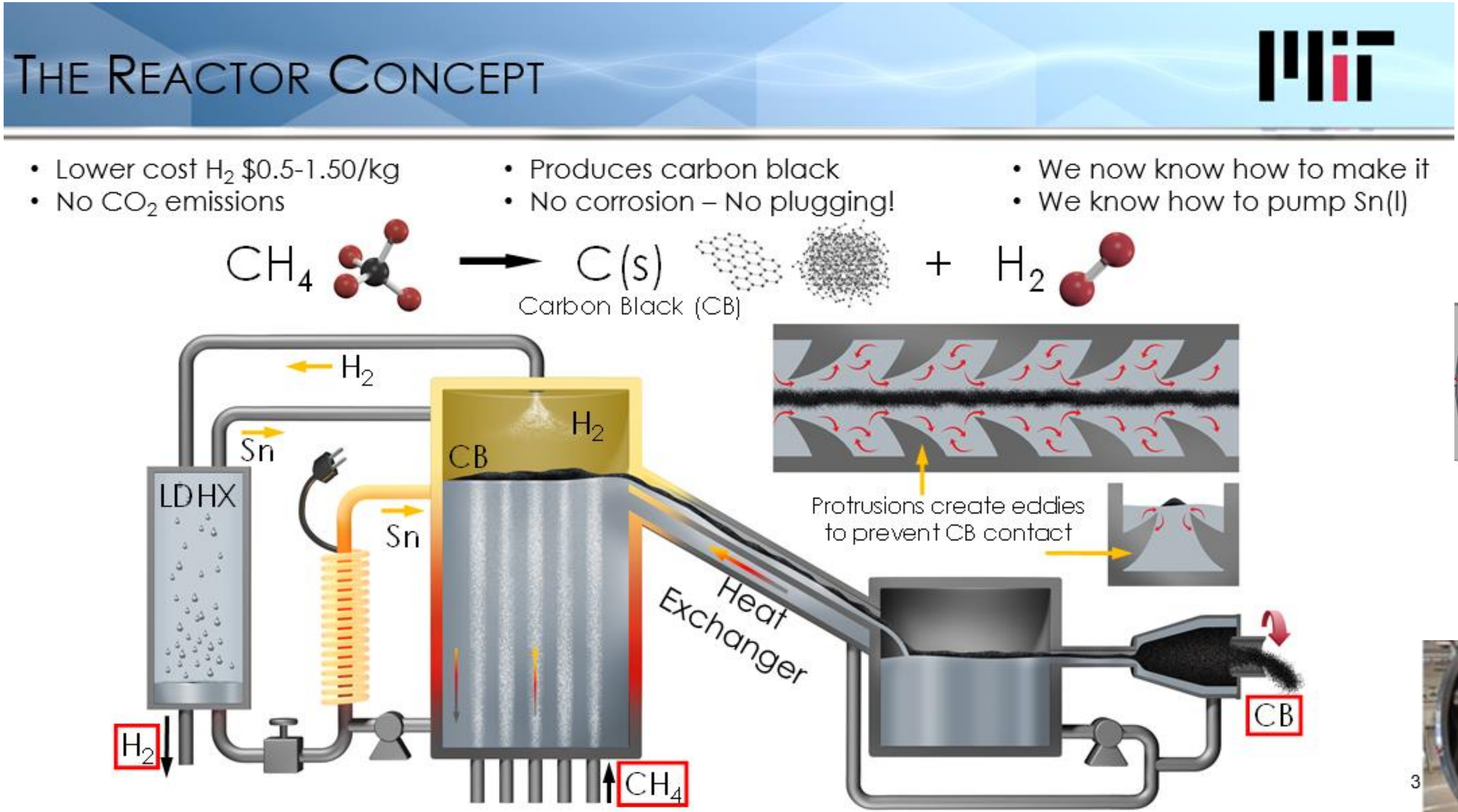
- Internally heated metal reactor fabricated in order to test systems at high pressure
- 1" dia fused quartz crucible with molten salt
- Vacuum/purge and pressurization with Ar gas
- Reactor was operated at 100-200 mL/min CH_4 flow at 17.7 bar (256 psig) and 1050-1100 C.
- The reactor functions as intended; wall temperature remains low enough under forced air cooling (<200 C) to allow for safe operation at >1100 C, 20 bar.
- Accomplishment: Operate molten salt system at High Temperature and Pressure

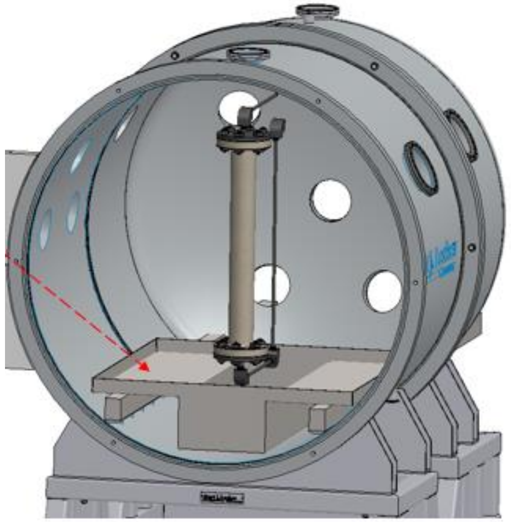




- AMR DOE 2021
- https://www.czero.energy/

Molten metal methane pyrolysis





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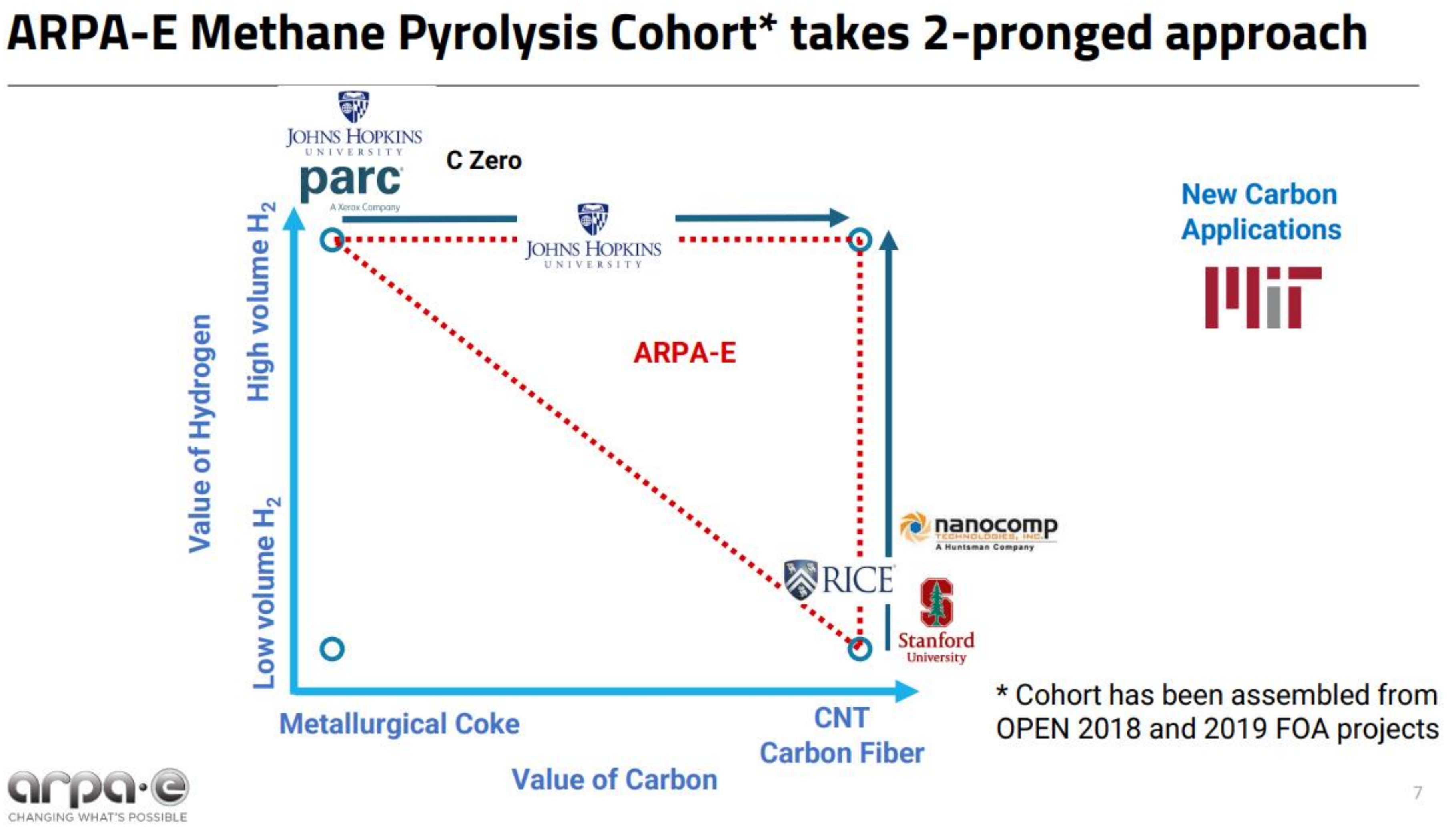
Aseguin Henry, et al., MIT (2021)

DOE Methane Pyrolysis Cohort

Marc von Keitz Program Director @ ARPA-E



https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-panel2-methane-pyrolysis.pdf

DOE Methane Pyrolysis Players (2021)

Marc von Keitz Program Director @ ARPA-E

Commercial docs database: https://docs.google.com/spreadsheets/d/1IcMP7WlmhntRz3hKvVjvr2IwrFprgCe-1bYAtY56eOk/edit?usp=sharing

https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-panel2-methane-pyrolysis.pdf

Monolith Receives Conditional Approval for a One Billion-Dollar U.S. Department of Energy Loan

- Title XVII of the Energy Policy Act of 2005 (42 U.S.C. Sec. 16511, et. seq.) provides authority for the D.O.E. to guarantee loans for projects that "avoid, reduce, or sequester air pollutants or anthropogenic emissions of greenhouse gases; and employ new or significantly improved technologies as compared to commercial technologies in service in the United States at the time the guarantee is issued." Current conventional processes to create carbon black release large amounts of greenhouse gases into the atmosphere. Through Monolith's methane pyrolysis technology, the company is able to prevent an estimated 2.3 tons of CO2 from being released for every ton of carbon black produced. With its production of cleanly made hydrogen, carbon black and ammonia, Monolith expects that its Olive Creek expansion will prevent one million tons of greenhouse gas emissions from entering the atmosphere each year compared to traditional manufacturing processes. While this conditional commitment demonstrates DOE's intent to finance the project, several steps remain, and certain conditions must be satisfied before a final loan guarantee is issued.

As the only U.S.-headquartered tire manufacturer, it's especially rewarding to be at the connection point of significant U.S. innovation with Monolith and the commitment of the Department of Energy to sustainable outcomes," said Richard J. Kramer, chairman, chief executive officer and president, The Goodyear Tire & Rubber Company. "We are excited to work with Monolith to reduce our carbon footprint and further our use of alternative materials as we continue to deliver industry-leading products."

https://www.prnewswire.com/news-releases/monolith-receives-conditional-approval-for-a-one-billion-dollar-us-department-of-energy-loan-301450496.html

Hydrogen via hydrocarbon reforming

- High Capacity factor
- Lowest production costs today (consider subsidies)
- Consider methane pyrolysis if CO2 storage is challenged
- Under pressure for reducing costs of future green electrolysis

Thank you!

Joe Powell Joseph B. Powell, PhD
NAE, Fellow AIChE, retired Shell Chief Scientist – Chemical Engineering
University of Houston Energy Institute
JBPowel5@central.UH.edu; JBPChE@outlook.com;

Energy Transition Institute
UH ENERGY
Shell FOUNDING PARTNER

Agenda

- I would appreciate it if you can cover:
- Dr. Joe Powell (15 minutes)
  - Blue hydrogen production metho: SMR, ATR, POX, methane pyrolysis, gasification, w CCS, costs of production,..
- Dr. Olga Marina
  - Green hydrogen production options: electrolyzes tech overview, costs, limitations, benefits
- Prof. Jorge Gascon:
  - Hydrogen production R&D: Current and future developments, investments, technology targets, etc..