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Production technology, market and regulatory framework for e-fuels

Stephen B. Harrison, Managing Director, sbh4 consulting

E-fuels Conference and Exhibition, Barcelona

Monday 6th February 2023

14:00pm to 14:40pm

Scope of the discussion and agenda

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Scope of the discussion

1) Production technology for E-Fuels, has been applied and provided by many companies in the EU and around the world
2) Creating a target market for E-Fuels
3) Enabling the industrialised uptake of E-Fuels
4) Forming a market design in the EU
5) What might an improved regulatory framework look like?

Agenda

1) E-fuels and electrolysis
2) Methanol synthesis
3) FTS, MTG, E-diesel, e-kerosene and e-gasoline
4) Technologies to generate syngas
5) Point source capture of CO2, liquefaction and transportation
6) Direct Air Capture of CO2
7) Markets and motivation
8) Concluding remarks

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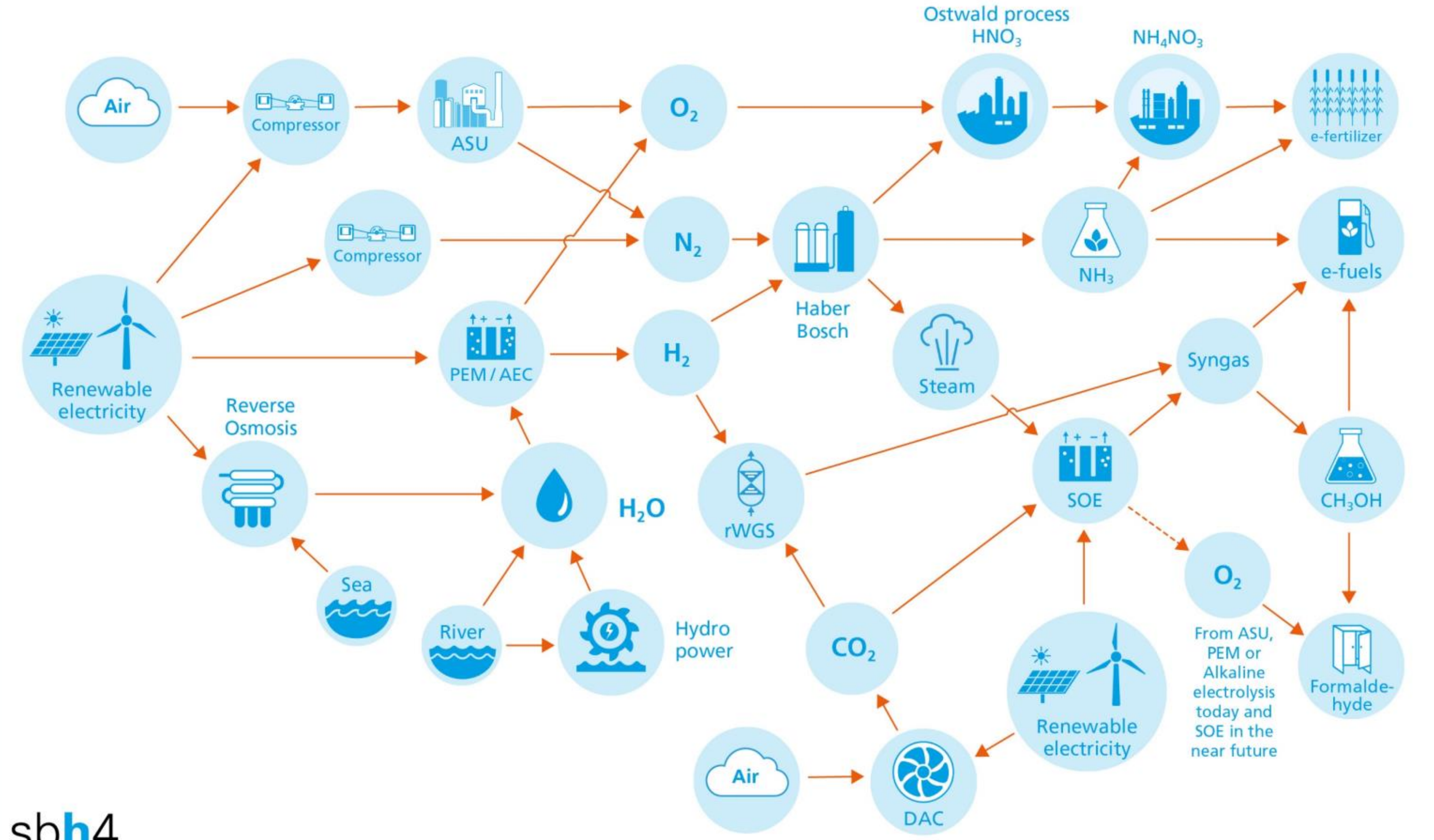
1) E-fuels and electrolysis

Air, water and renewable electricity for integrated e-fuels, e-fertilizers and e-chemicals production



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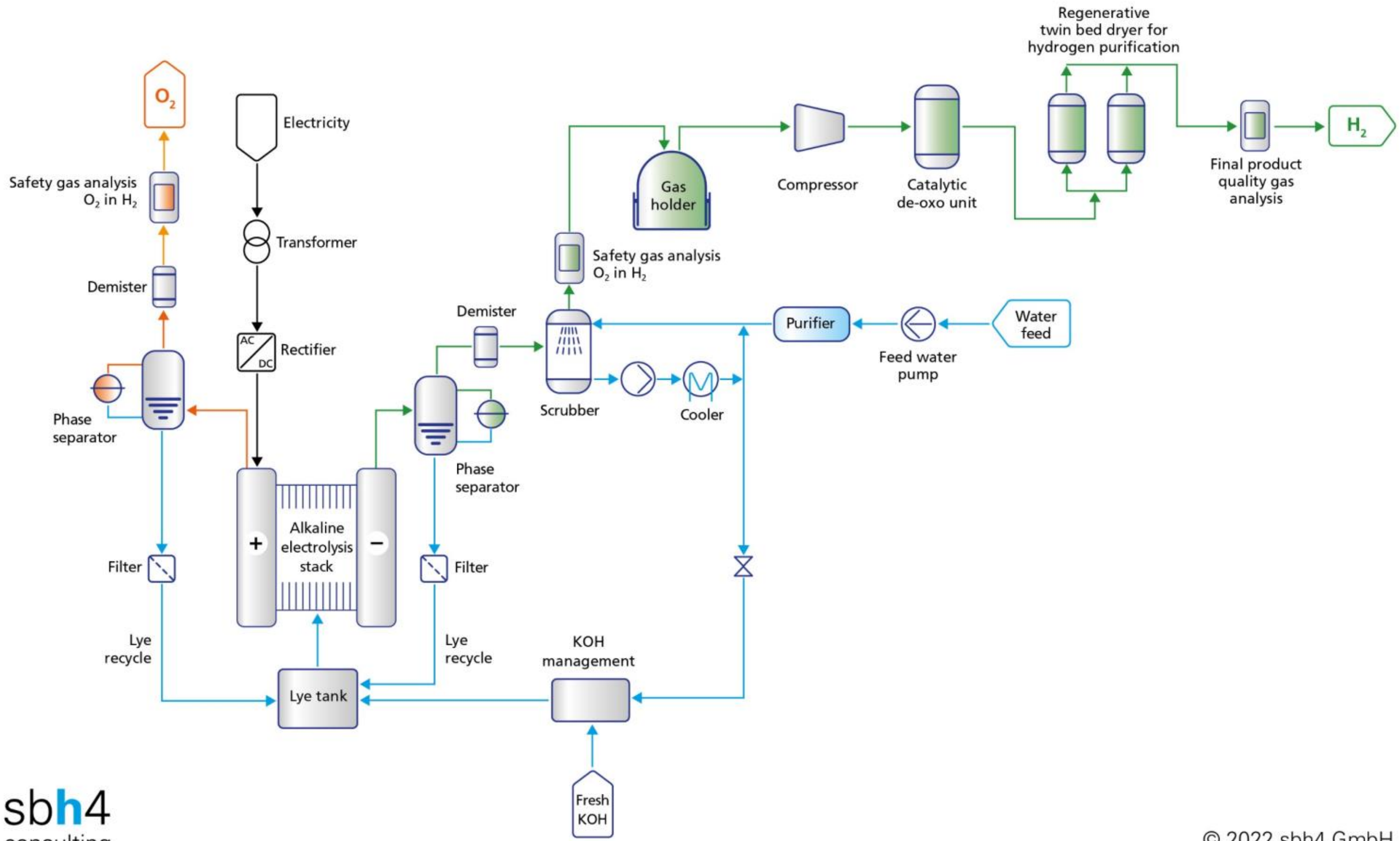
Low pressure alkaline water electrolysis process



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AsahiKASEI – Aqualyzer™ 10MW single-stack atmospheric pressure alkaline electrolyser for 2,000 Nm^3 per hour H2, Fukushima Hydrogen Energy Research Field in Namie, Japan

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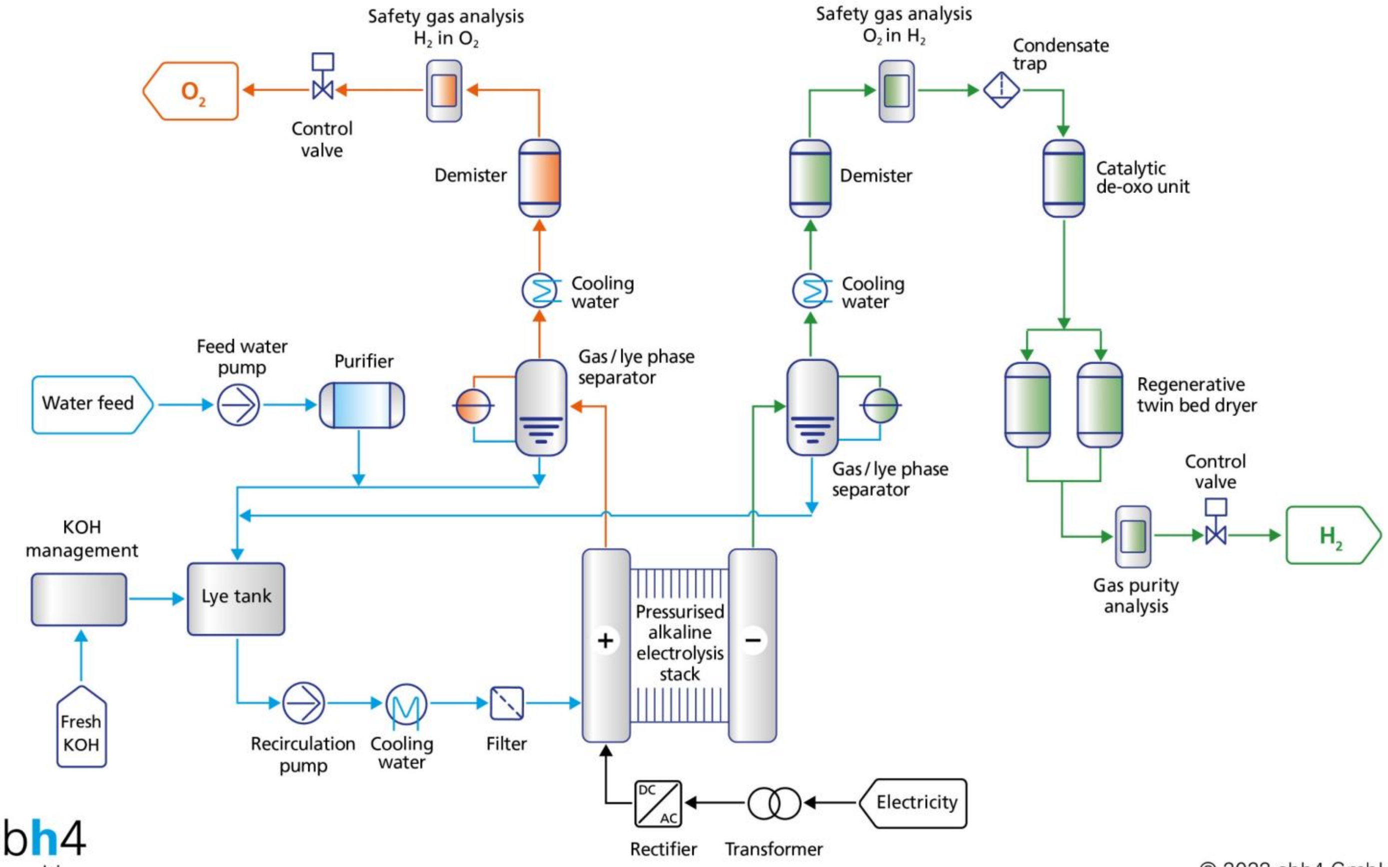
Pressurised alkaline electrolysis process



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Pressurised alkaline – stacks are getting bigger and cheaper. PA is in focus for the new generation of Chinese producers.

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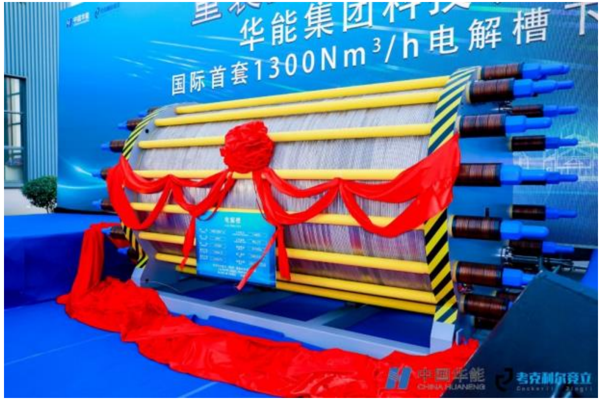

Cockerill Jingli DQ1300, largest single pressurised alkaline stack on the market

- 6.5MW, 480V, 13,100A
- 1,300 Nm³/hr H_2
- 650 Nm³/hr O_2
- Hydrogen pressure 16 bar
- Operating temperature 90 °C
- Weight 40.7 tonnes

HydrogenPro, Norway

- Test unit 10MW, 2m diameter, 80 tonne stack
- Standard stack 5.5MW, 2.4 tonnes per day hydrogen
- Made at THM JV in Tianjin, China
- Electrodes plated at legacy ASP, Denmark

https://hydrogen-central.com/john-cockerill-largest-single-hydrogen-electrolyzer-stack/

2) Methanol synthesis

Methanol synthesis is one of the most common chemical processes worldwide

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$$CO + 2H_2 \rightarrow CH_3OH$$

- Syngas from natural gas reforming – dominant today
- AEC / PEM pathway
  - Green hydrogen from water electrolysis using renewable power, plus…
  - Reverse water gas shift reaction to convert CO2 to CO
  - CO2 captured from industrial, geogenic or biogenic emissions or from direct air capture
- SOEC Co-electrolysis pathway
  - Syngas from co-electrolysis of steam and CO2 on a solid oxide electrolyser
  - CO2 captured from industrial, geogenic or biogenic emissions or from direct air capture

HyNL: green hydrogen to e-methanol with CO2 captured from local waste to energy facility

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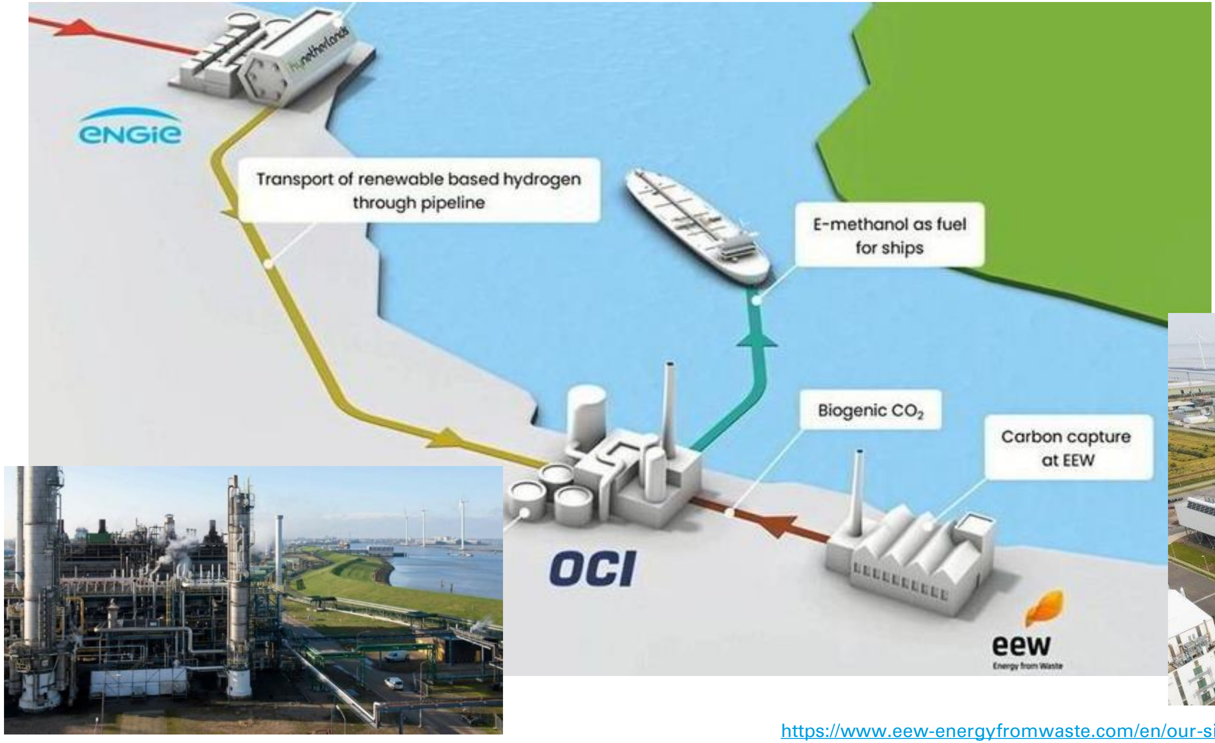

- Eemshaven, northeast NL
- 200MW offshore wind
- 100MW electrolysis at Engie facility
- CCU from EEW Delfzijl waste to energy
- Methanol production at OCI BioMCN
- E-methanol as bunker fuel for shipping

https://www.eew-energyfromwaste.com/en/our-sites/delfzijl/
https://www.tradewindsnews.com/gas/dutch-ammonia-and-methanol-producer-oci-targets-shipping/2-1-979148
https://www.rechargenews.com/energy-transition/offshore-wind-to-methanol-engie-and-partners-to-combine-1-85gw-of-green-hydrogen-with-captured-co2/2-1-1216569

Liquid wind: e-methanol production from green hydrogen and CO2 captured from local points source emissions, Sweden

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- Renewable wind power will make green hydrogen on a PEM electrolyser
- Captured CO_2, from flue gas emissions will be the CO_2 source
- CO_2 will be converted to CO using the reverse water gas shift reaction
- The CO and hydrogen are blended to form syngas
- E-methanol will be produced from the syngas using catalytic reactions
- E-methanol can be converted to synthetic fuels like gasoline using MTG or to diesel and jet using Fischer-Tropsch synthesis

Haru Oni: wind power, electrolysis and DAC to e-methanol and MTG, Chile

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https://www.siemens-energy.com/global/en/news/magazine/2022/haru-oni.html

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3) FTS, MTG, E-diesel, e-kerosene and e-gasoline

Fischer Tropsch Synthesis (FTS): chemistry and reactor types.

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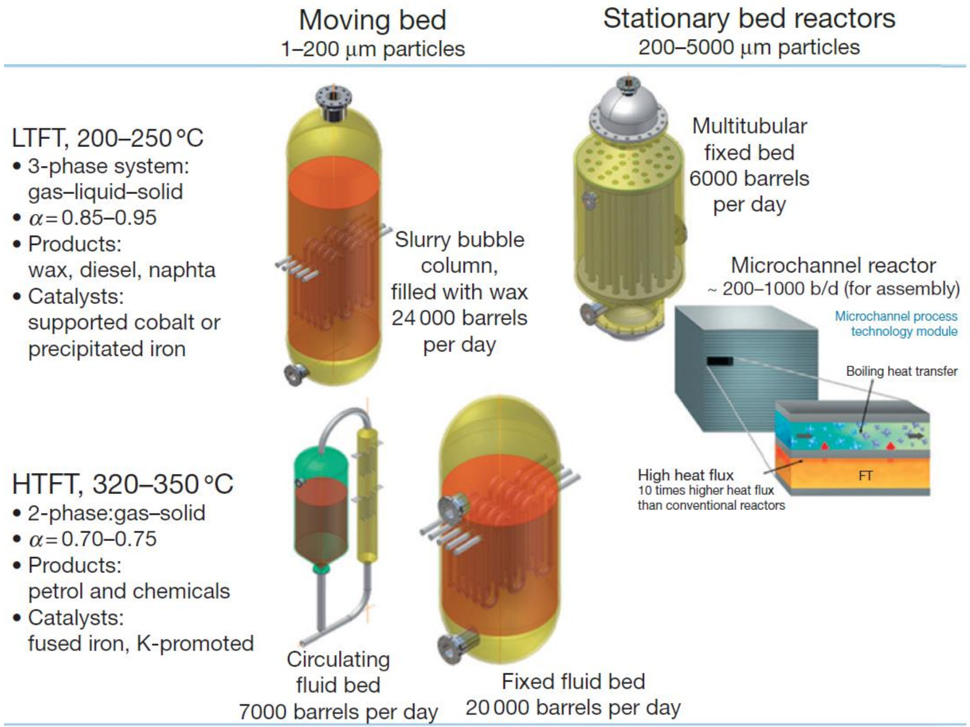
$$5CO + 11H_2 \rightarrow C_5H_{12} + 5H_2O$$

(and many other reactions)

- Produces e-crude: a mix of olefins, gasoline, diesel and jet fractions
  - Distillation is required to refine the e-crude
  - Specificity of the target molecules can be controlled by catalyst and reactor parameters (temperature, pressure, residence time)
- Has been used extensively in large-scale slurry bubble column reactors for gas to liquids and coal to liquids by Sasol, Shell and others for decades
- Heavily exothermic, can be integrated with RWGS for energy efficiency
- Is being implemented in small scale, modular or containerised systems using micro-channel reactors



https://www.researchgate.net/publication/258685985_Fischer-Tropsch_Synthesis_Catalysts_and_Chemistry

FTS is key to GTL, CTL, and PtL. It has been operated at scale in various reactor types.

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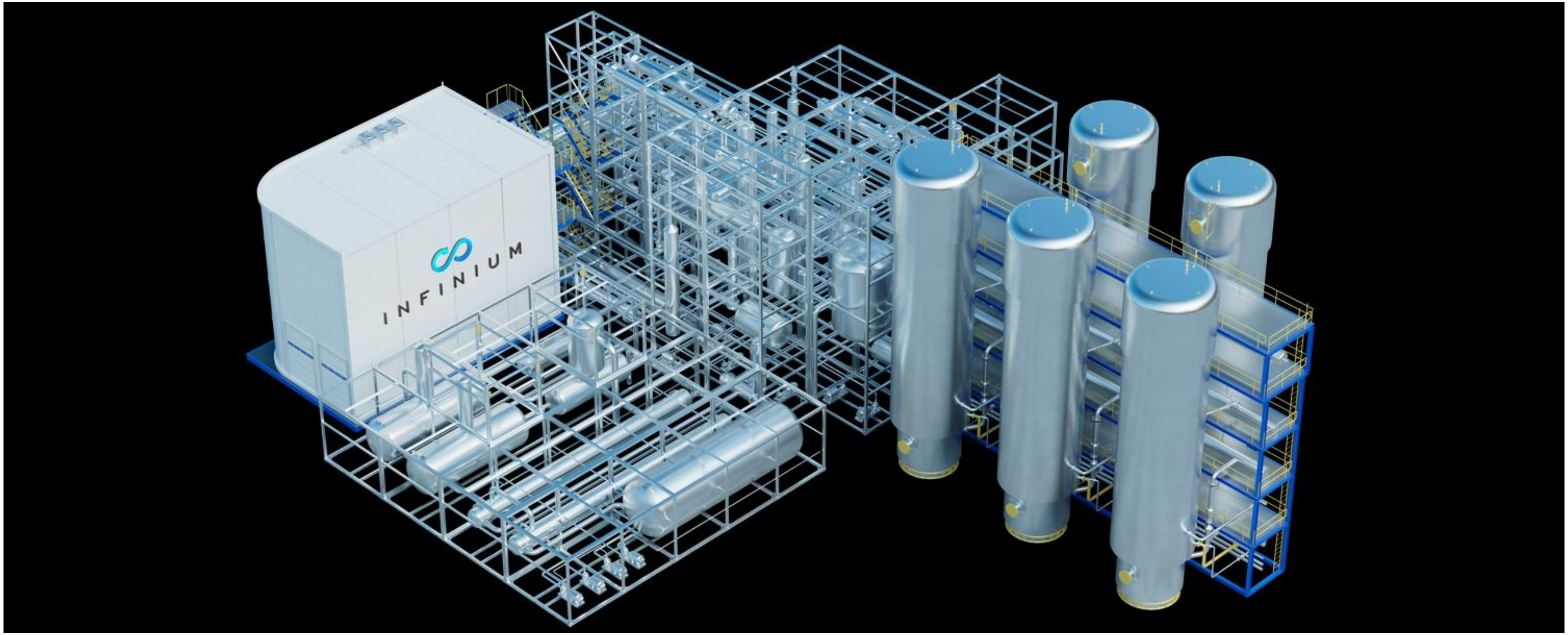
Sasol – positive actions - annual review and summarized financial statements 2009
https://www.sciencedirect.com/topics/engineering/fischer-tropsch-reactor

Infinium: integrated Power to Liquids with RWGS and FTS using in-house catalysts.



https://www.infiniumco.com/technology/

MTG: Methanol to Gasoline, via DME. HTAS Turkmengaz gas to gasoline (via methanol), Ashgabad. ExxonMobil New Zealand MTG Synthetic Fuels Project.

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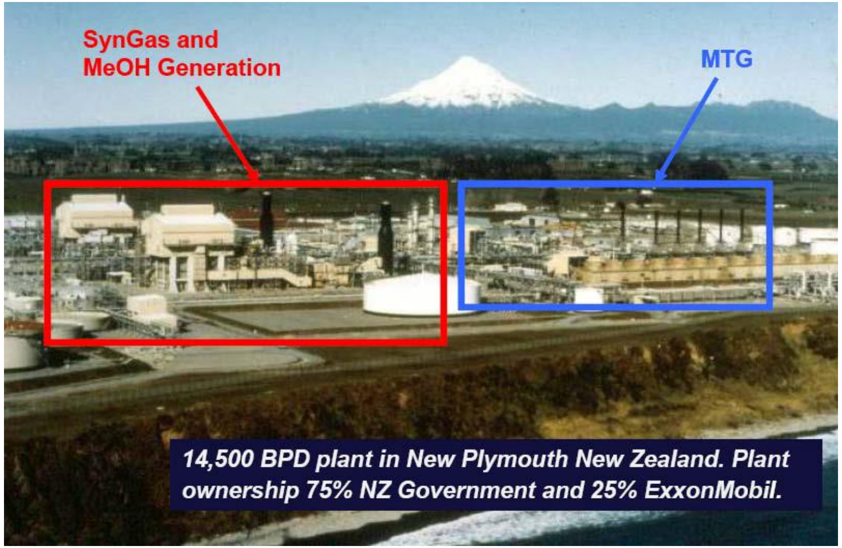
1. Natural gas reforming to make syngas
2. Methanol / DME production from syngas
3. Methanol / DME to Gasoline



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4) Technologies to generate syngas

Technologies to generate syngas for methanol, MTG or FTS

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1) Natural gas reforming (ATR) or partial oxidation (POx): GTL

2) Coal gasification: CTL

3) Waste gasification: WtL

4) H_2 from electrolysis on AEC, PEM, SOEC plus CO from RWGS: PtL

5) Co-electrolysis of steam and CO_2 on SEOC: PtL

Image courtest of Shell, Pearl GTL, Ras Laffan

Reverse water gas shift (RWGS) chemistry

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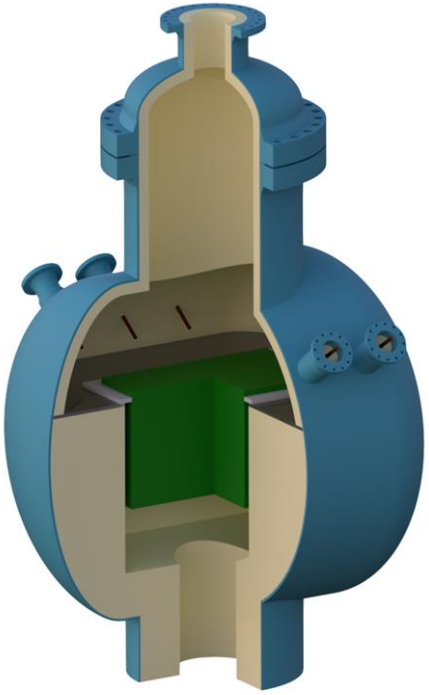
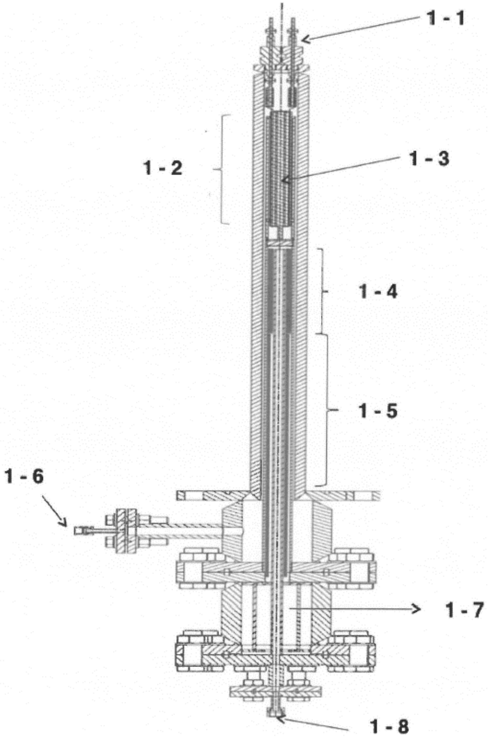
$$CO_2 + H_2 \rightarrow CO + H_2O$$

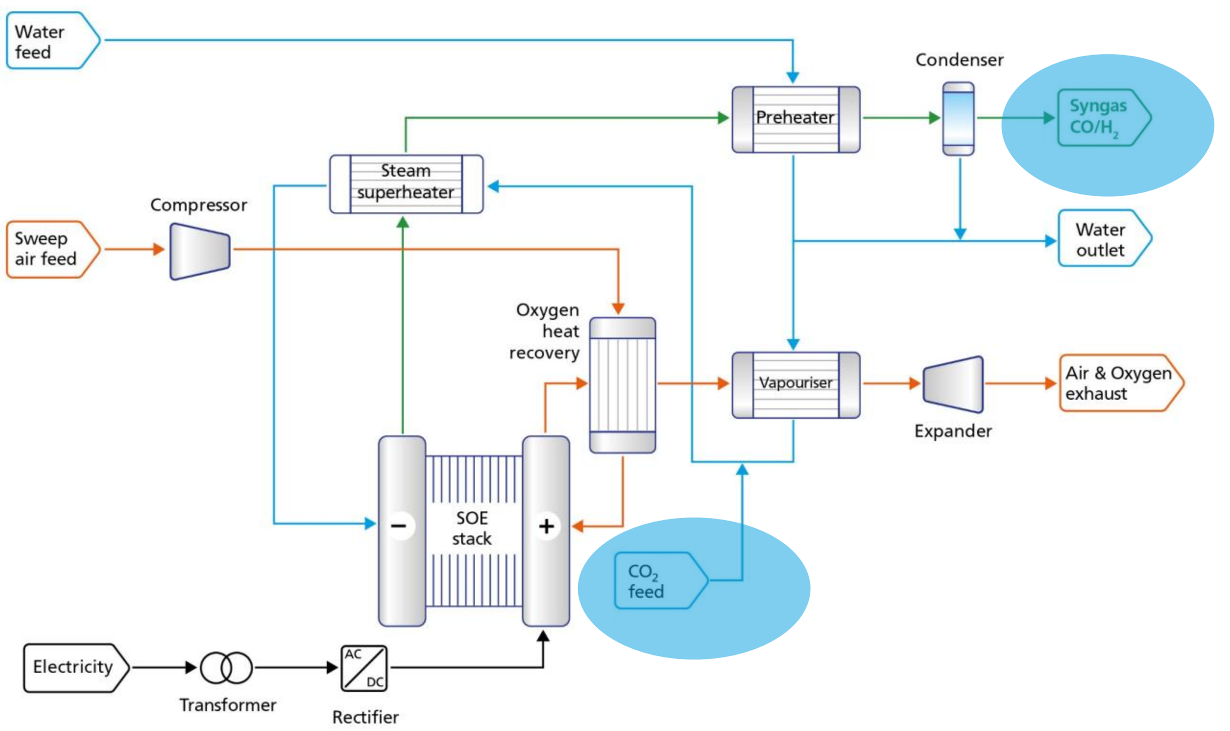
- The opposite of the water gas shift (WGS) that is used in reforming to upgrade the H2 content of syngas
- The RWGS reaction (in this direction) has not previously been used extensively
- Heavily endothermic, integration with exothermic FTS will be more efficient
- Electrical heating is possible to use green electrons
- The patented INERATEC RWGS reactor has heat exchange and heating directly prior to the catalytic reaction zone
- TOPSOE – eREACT™
  Electrically heated eRWGS also emerging





https://patents.google.com/patent/DE102017120814A1/de
https://www.topsoe.com/our-resources/knowledge/our-products/equipment/e-react-fuels?hsLang=en

Solid Oxide CO-Electrolysis process for syngas generation



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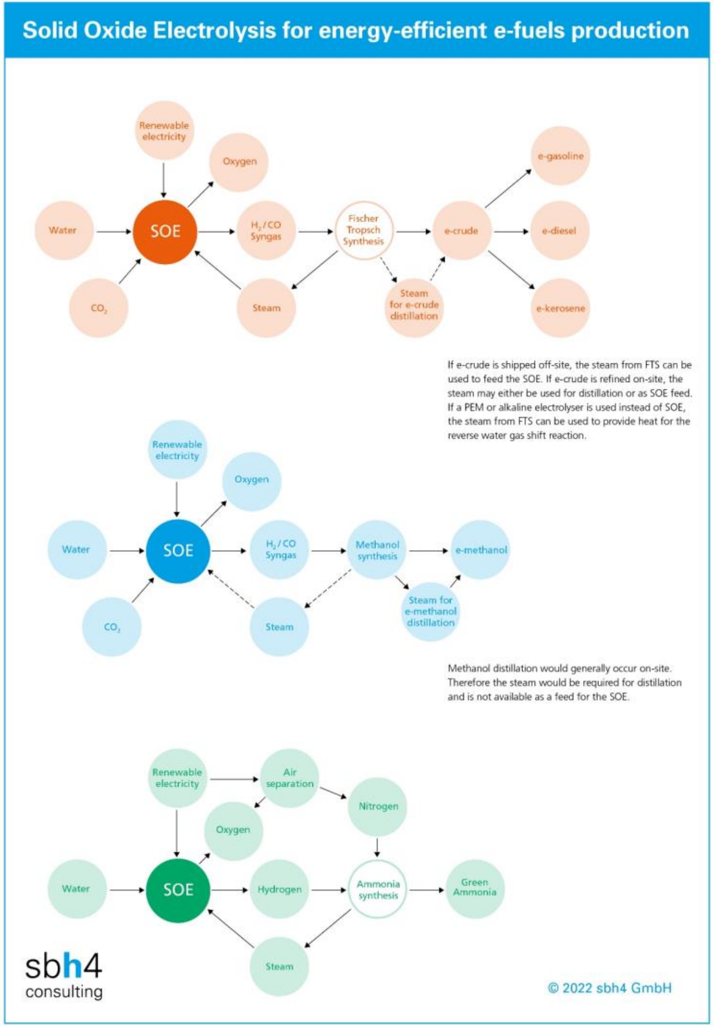
Steam-fed Solid Oxide Electrolysis can use excess heat for high efficiency.



Pure hydrogen from PEM and AEC electrolysers and CO from the reverse water gas shift reaction is dominating the first wave of e-fuels PtL projects. Will co-electrolysis on a SOEC be used later, to leverage its advantage?

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Images, BP Lingen refinery, Industriepark Höchst (INERATEC GmbH), Heide Refinery
e-Fuels are mandated to be 2% of the aviation fuels mix in Germany by 2030

5) Point source capture of CO_2, liquefaction and transportation

Established Carbon Capture Technology – VSA and Amine Solvent

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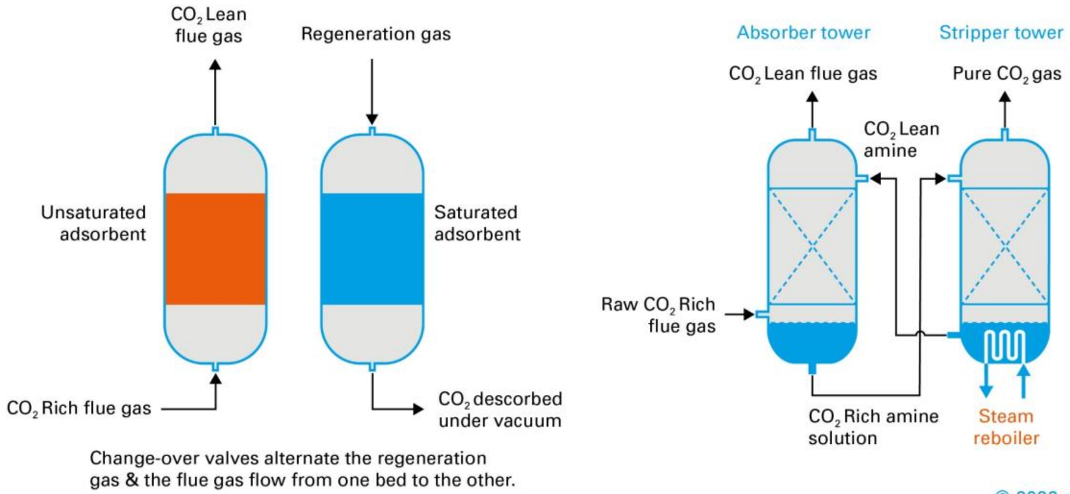

	VSA – vacuum swing adsorption	Amine Solvent with tower contactors
Separation principle	Adsorption	Absorption
Specific energy demand	1.7 GJ/t_{CO2} (mostly power)	3 GJ/t_{CO2} (mostly heat from steam)
Typical temperature	40°C	40 - 60°C in absorber, 120°C in stripper
Typical pressure	Cycling between moderate pressure and vacuum	Ambient to 30 bar
Typical CO_2 removal	< 90 %	>90 %
Typical CO_2 purity	< 95 %	>99 %
Typical plant size (tonnes per year CO_2 removal)	>1,000 - 500,000	40,000 - 4,000,000
Technology maturity level	Commercial with some demonstrations, eg Air Products Port Arthur SMRs, USA	Commercial from many suppliers

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- VSA carbon capture uses power as a major input and can therefore use green electrons
- Amine solvent carbon capture uses steam – which could potentially be from an electrical heater fed with green electrons

Amine-solvent CO_2 capture plant recovering CO_2 from SMR, Carburos Metálicos, Repsol Refinery, Spain

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Image courtesy of APCI Inc

CO2 adsorption is an alternative to absorption. VSA has been proven for carbon capture at 2x Air Products SMRs, in Port Arthur, USA.

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Image courtesy of APCI Inc

CO2 purification, liquefaction and storage equipment layout

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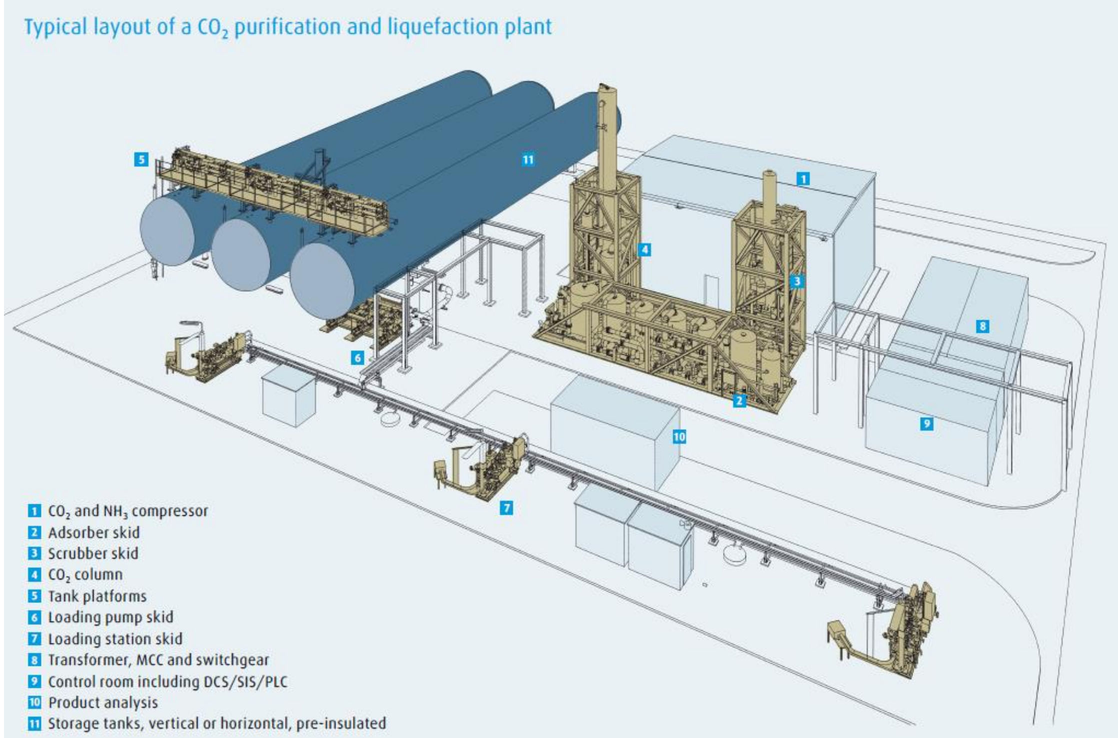

This process follows CO2 capture. The feed would be circa 98% CO2.

- CO2 cooling & water knock-down
- CO2 compression
- CO2 scrubbing / washing
- CO2 drying (moisture removal)
- Impurities adsorption (mercury etc removal)
- CO2 liquefaction and distillation (ammonia refrigerant on mechanical compression / expansion mechanical cycle)

Liquid CO2 distribution by road or ship

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Super-critical CO_2 pipelines operate at pressures of 80 bar and more, and require powerful CO2 compressors

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Difficult to decarbonise industries – CO_2 is released from within the process

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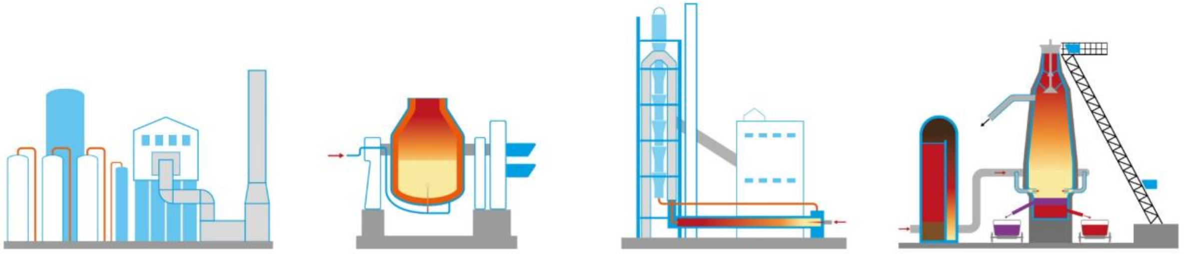
Notes:
- CO_2 emissions are also associated with the energy and power requirements for this industry sector
- These can potentially be decarbonised with renewable power and electrical heating or microwaves
- CCS to capture CO_2 from the process and / or the associated energy production is possible



Steam Methane Reformer | Aluminium smelting | Calciner tower & clinker kiln | Blast furnace

	Oil refining	Aluminium smelting	Cement making	Iron making
Application that releases CO_2	Hydrogen production from methane reforming for fuels desulphurisation	Reduction of alumina to aluminium using graphite electrodes	Reduction of limestone to calcium oxide	Reduction of iron ore to iron using coke
Chemical reaction producing CO_2	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow CO_2 + H_2$	$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$	$CaCO_3 \rightarrow CaO + CO_2$	$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$ $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
Decarbonisation approach for CO_2 generated by the process	Use turquoise hydrogen or green hydrogen to avoid the reforming reaction; or feed the reformer with biomethane instead of natural gas	Use carbon from turquoise hydrogen production instead of carbon from fossil fuels to make the electrodes	Replace a portion of the limestone with alternative materials such as calcined clay to make clinker for cement	Use hydrogen instead of coke; or substitute coke with carbon from turquoise hydrogen production
Reactions for the decarbonised process	As above using renewable methane	As above using renewable graphite electrodes	Above reaction can only partially be avoided	As above using renewable carbon, or use hydrogen: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$
Other industries with similar applications	Ammonia, Urea, Methanol, Gas-to-liquids	Gold and silver refining, electric arc furnace to melt scrap steel	– Lime making, as above – Refractory materials, $MgCO_3 \rightarrow MgO + CO_2$ – Glass making Na_2CO_3, $CaCO_3$, $MgCO_3$	None

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Biogenic CO2
- Carbon-neutral
- Biomass combustion
- Bioethanol fermentation

Geogenic CO2
- Unavoidable

CO2 from high temperature heat
- “Difficult to decarbonize”

CO2 from process chemistry
- “Difficult to decarbonize”

CO2 from fossil-fired power generation
- Decarbonise with renewable power and green electrons

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6) Direct Air Capture of CO2

DAC technologies for direct air capture of carbon dioxide

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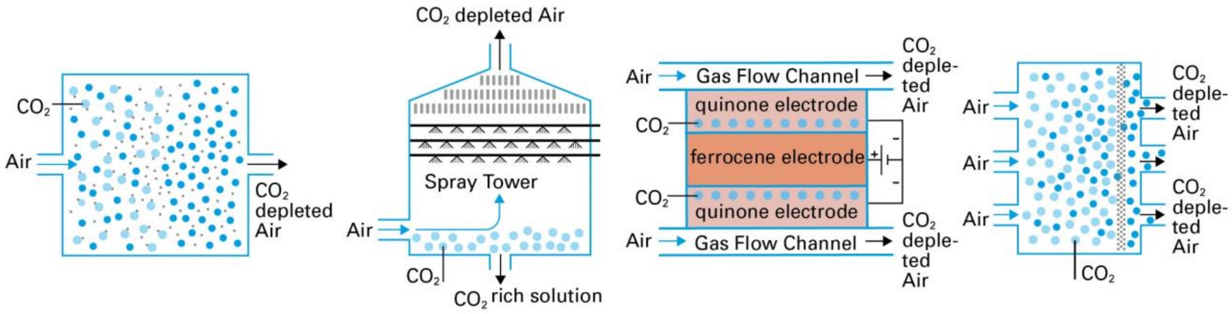
Notes:
Only the CO_2 separation aspect of each DAC process has been shown



	Climeworks	Carbon Engineering	Verdox	Carbyon
System type	Solid Sorbent	Liquid Absorbant	Solid Sorbent	Solid Sorbent
Technology	Amine-functionalised	Potassium Hydroxide solution / Calcium Carbonation	quinone–carbon nanotube composite	Thin film coated amine- and/or bicarbonate-based porous membrane
Regeneration	Temperature / Vacuum	Temperature	Electro-Swing	Temperature
Specific Energy Demand	Heat: 2,000 kWh / t_{CO2} Electricity: 650 kWh / t_{CO2}	NG: 2,777 kWh/t_{CO2} or Electricity: 1,500 kWh/t_{CO2}	Electricity (only cell, w/o BoP in particular ventilation): 568 kWh/t_{CO2}	TBD
Operating Temperature	80-100°C	900°C	Ambient	60-85°C
Technology maturity level	Commercial	Pilot	Laboratory	Theoretical

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- Some direct air capture technologies use a combination of heat and power
- Some use only power
- Green electrons can be used to make green CO2

Carbon Engineering, Squamish BC Canada. Climeworks, Hinwil Zurich Switzerland.

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https://climeworks.com/news/climeworks-ag-builds-first-commercial-scale-co2-capture

Namibia Green Hydrogen and Derivatives Strategy, Nov 2022. Vision is to upgrade green electrons and green hydrogen to e-kerosene using PtL technology to maximise export revenue.

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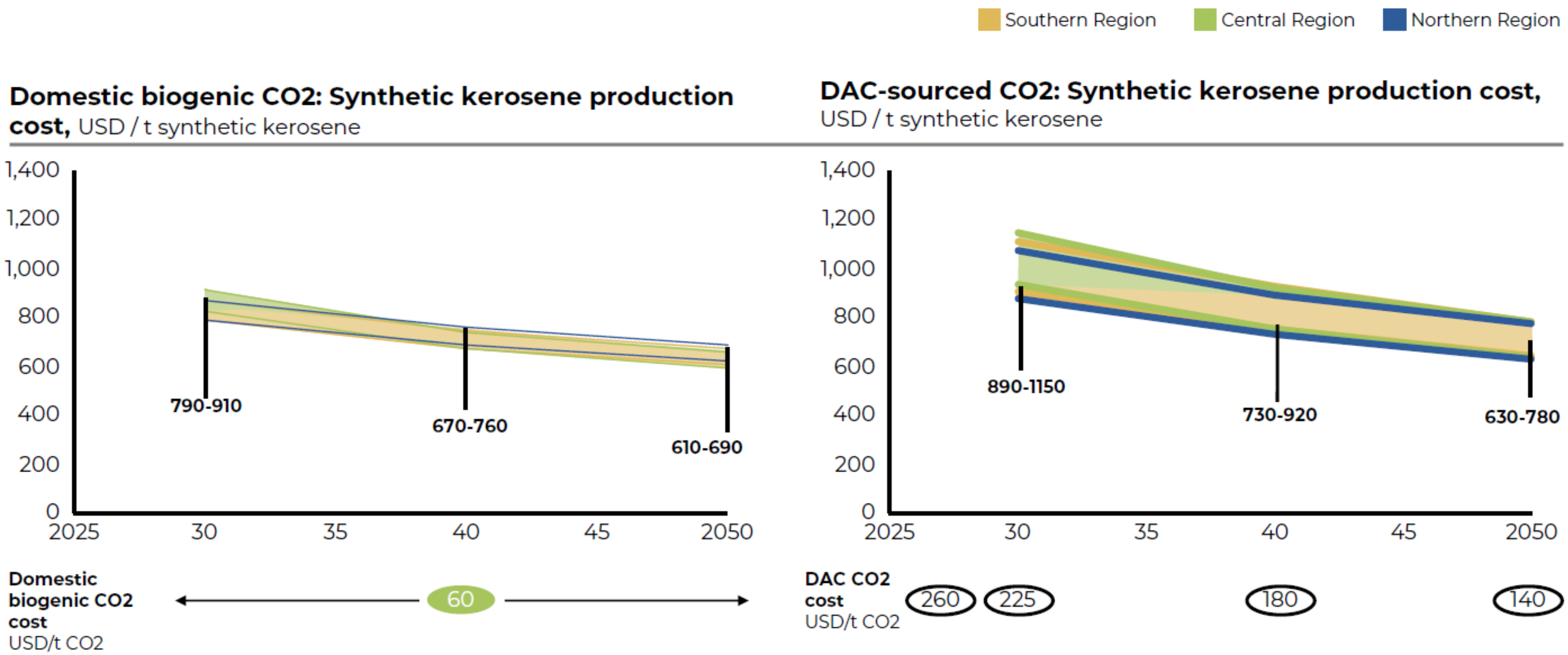

7) Markets and motivation

International shipping of hydrogen, hydrogen carriers and hydrogen derivatives

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	Compressed hydrogen gas	Liquid Hydrogen	Liquid Ammonia	Liquid Methanol	LOHC – Liquid Organic Hydrogen Carrier (MCH used as an example)	LNG, Liquefied Natural Gas
Temperature for trans-portation and storage	Ambient	-253 °C	-33.3 °C	Liquid at ambient temperature	Hydrogenation:150-200 °C; Transported at ambient temperature; Dehydrogenation: 250-320 °C	–162 °C
Pressure for trans-portation and storage	250 bar	Close to atmospheric pressure	Close to atmospheric pressure	Close to atmospheric pressure	Hydrogenation: above 20 bar; Transported at atmospheric pressure; Dehydrogenation: below 5 bar	Close to atmospheric pressure
Density	0.017 kg/L	0.071 kg/L	0.68 kg/L	0.79 kg/L	0.77 kg/L	0.46 kg/L
Toxicity	non toxic	non toxic	TWA 25 ppm	TWA 200 ppm	TWA 400 ppm	TWA 1,000 ppm
Flammability (% in air)	4-74 %	4-74 %	14.8-33.5 %	6.0-36.5 %	1.2-6.7 %	4 -15 %
Volumetric Lower Hea-ting Value (LHV)(MJ/L)	2.43	8,52	12.7	15.7	5.76-8.5	22.2
Gravimetric LHV (MJ/kg)	120	120	18.6	19.9	7.48-11	48.6
Infrastructure readiness for large scale deploy-ment in mid-term H/M/L	L	L	H	H	M	H
Commercialisation status and pilot projects	Global Energy Ventures, adapting CNG techno-logy for compressed hydrogen shipping	HySTRA-Hydrogen Energy Supply-chain Technology Research Association – Australia to Japan LH2 shipping	Many commercial liquid ammonia pro-duction, distribution and storage assets worldwide with 120 ports locations able to handle ammonia	Methanol is a widely traded commodity with tankers up to 50,000 tonnes	The HySTOC (Hydro-gen Supply and Trans-portation using Liquid Organic Hydrogen Carriers) project in Finland	Many commercial LNG production, dis-tribution, storage and regasification assets worldwide

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- Over long distances and at large scale, the additional costs of Power to liquids (versus the alternative of shipping pure hydrogen) can be recovered with shipping cost savings
- If reconversion to hydrogen is required, the economics of Power to Liquids suffers: direct use of the e-fuel is ideal
- E-gasoline (33 to 36 MJ/L) and e-diesel (43 to 49 MJ/kg) have even higher volumetric energy densities than the products shown in the table, and have the advantage of being "drop-in" replacements… but are more complex and more expensive to make

Hydrogen and CO2 conversion to e-fuels is an important value chain enabler that is a relatively small portion of the capex cost within a typical export-scale project investment.

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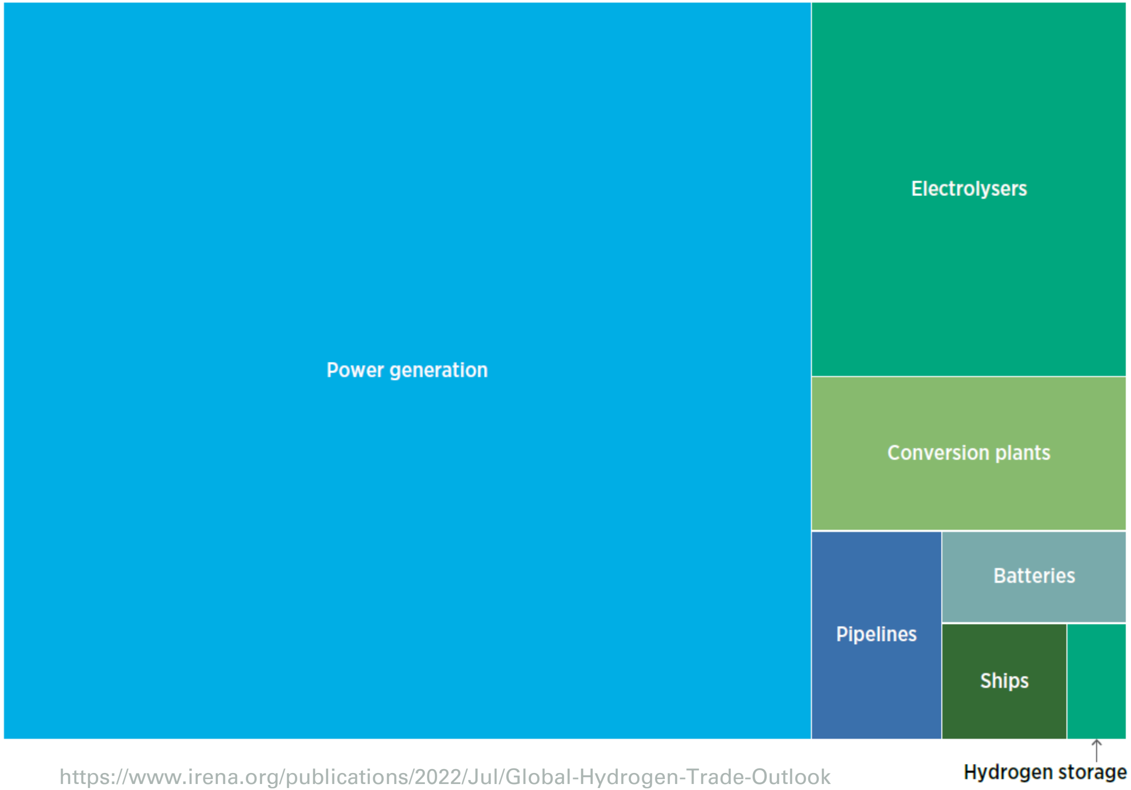

https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook

Waste to energy for green hydrogen mobility: €12 million project, 2019

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Hydrogen supply

- 1.25MW Hydrogenics PEM electrolyser
- MAXIMATOR 350 bar Hydrogen Refuelling Station (HRS)
- 425kg high pressure hydrogen buffer storage on the HRS

Hydrogen utilisation

- Fleet of 10 Van Hool A330 Fuel cell buses
- €6 million
- **50% of project cost**

https://www.cewep.eu/wuppteral-hydrogen-buses/

Liquid e-fuels are designed to be “drop-in” replacements for fossil fuels

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Avoided end-user costs

- Vehicle replacement
- Engine replacement / modification

Avoided infrastructure costs

- Fuel dispenser equipment
- Onsite fuel storage tanks
- Fuel distribution vehicles
- Tank / terminal assets

Avoided service network costs

- Re-tooling vehicle service garage network
- Re-training vehicle service personnel

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.shz.de%2Flokales%2Fflensburg%2Fartikel%2Feinfuehrung-von-e-fuel-diesel-an-team-tankstelle-verzoegert-sich-43315055&psig=AOvVaw1uqoCNhaHhznpDJOjVYj5B&ust=1671962734394000&source=images&cd=vfe&ved=0CBAQjRxqFwoTCNjX1NiAkvwCFQAAAAAdAAAAABAJ

8) Concluding remarks

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1) Many technologies for power to liquids (PtL) and e-fuels exist, others are emerging
   a) At GW-scale, leveraging GTL, CTL and MTG
   b) With emerging MW-scale micro-channel reactor technologies
   c) The SOEC Co-electrolysis pathway has advantages and support is required for demonstrations
2) Markets for e-fuels exist, but fossil fuels must be displaced with appropriate regulation
   a) ICE's in land-based mobility, maritime and aviation fuels are addressable markets
   b) The price advantage for fossil fuels must be eroded through appropriate regulation
   c) Carbon certification and blending can maximise leverage of existing supply chain infrastructure
3) Appropriate low-cost CO_2 inputs for e-fuel production must be encouraged through regulation
   a) Unavoidable, geogenic CO_2 could be given the same status as biogenic CO_2, eg from bioethanol fermentation
   b) Biomass combustion and BECCS for power generation should be challenged: it can lead to deforestation and can be replaced with renewable power generation
   c) DAC with renewable power is a utopian vision, but it is a high-cost technology pathway at present

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Introduction to Stephen B. Harrison and sbh4 consulting

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Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and greenhouse gas emissions control. Hydrogen, CCUS, e-fuels and e-fertilizers are fundamental pillars of his consulting practice.

Stephen has served as the international hydrogen expert and team leader for two ADB projects related to renewable hydrogen deployment in Pakistan and Palau. In 2021 Stephen specified more than 2GW of electrolysers for projects in Asia. In 2022, he supported the Word Bank and the Government of Namibia with the Southern Corridor Development Initiative for green hydrogen and other synthetic fuels. He also supported the IFC with a green hydrogen business case planning project in Pakistan.

With a background in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas, Stephen has intimate knowledge of hydrogen from commercial, technical, operational and safety perspectives. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

Stephen has extensive buy-side and sell-side M&A due diligence and investment advisory experience in the clean-tech sector. Private Equity firms, investment fund managers and green-tech start-ups are regular clients. Industrial corporations have often sought his guidance on their decarbonisation plans or growth strategies to offer products and services to the emerging hydrogen economy and energy transition.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for the leading hydrogen-focused international publications. He also served on the Technical Committee for the Green Hydrogen Summit in Oman in December 2022 and on the Advisory Board of the International Power Summit in Munich in September 2022.