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Hydrogen production close to the community 1: pathways from liquid wastes and biogas / landfill gas.

Stephen B. Harrison, Managing Director, sbh4 consulting, Germany

Tuesday 14th May 2024, 11:25-12:05

Agenda for today and tomorrow

1) Biogas from liquid wastes to hydrogen
2) Landfill gas to hydrogen
3) Biogas or landfill gas to power followed by electrolysis as a pathway to hydrogen
4) Carbon sequestration or utilisation
5) Distributed hydrogen production and utilisation in the community

1) How 'green' is hydrogen from MSW or biomass?
2) Chemcycling and its role in waste management
3) Technologies and projects for biomass and waste thermolysis to hydrogen
    a) Bubbling fluidised bed gasification
    b) Plasma gasification
    c) Hydrogen derivatives from biomass and waste
4) Lessons from the past
5) 'Waste to energy' and electrolysis as a pathway to hydrogen

1) Biogas from liquid wastes to hydrogen

Biogas from liquid wastes can be upgraded to biomethane and biogenic CO2. Biomethane can be purified and then reformed to make syngas, which can be conditioned to yield hydrogen.

Biogas is generated from biomass through anaerobic digestion

- Biogas consists predominantly of CH_4 and CO_2 with potential traces of H_2S, H_2O and other gases

Biomethane is produced from biogas through purification or ‘upgrading‘ of biogas

- CO_2 removal
- H_2S removal
- Drying

Small-scale steam methane reforming can convert biomethane to hydrogen.

https://hygear.com/news/kiwa-uk-starts-hydrogen-production-with-hygears-technology/

Biomethane steam methane reforming to hydrogen uses small-scale reformers.

1. Ventilation fan
2. Desulphurisation vessel
3. PSA-vessels
4. Off-gas storage
5. Hydrogen storage
6. Water separator for vacuum pump
7. Vacuum pump
8. Coolant heater
9. Reformate cooler
10. Electronics cabinet
11. Steam generator
12. Reformer unit
13. Low temperature shift
14. Coolant expansion vessel
15. Burner air blower
16. Water purification system

- Biomethane is stripped of sulphur and CO2 prior to entering the reformer.
- Pressure swing adsorption (PSA) for hydrogen purification, eg to fuel cell grade for mobility, if required.
- PSA off-gases used as reformer burner fuel.
- Heat from the burner is utilised to generate steam for the reforming reaction.
- Output: 47 Nm^3/hr H_2 (3.8kg/hr)
- Feedstocks
  - Biomethane feed: 23 Nm^3/hr (~16 kg/hr)
  - Electricity required: 14.5 kW
  - Water required: 100 – 300 litres/hr

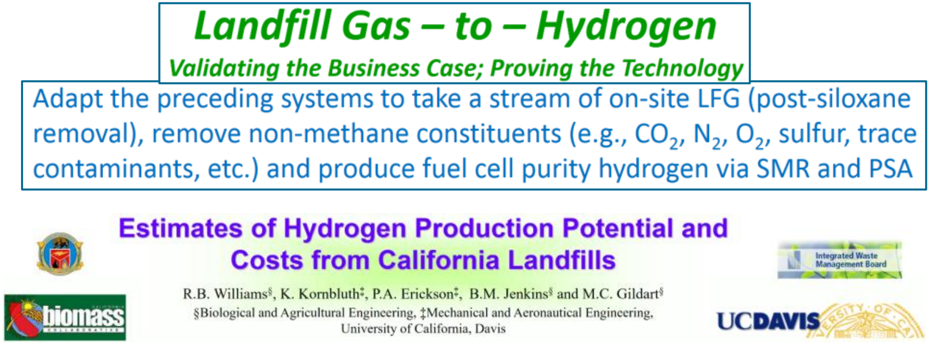
Image: HYGEAR

2) Landfill gas to hydrogen

Landfill gas – methane from landfills is a potent GHG and excellent energy resource. Landfill gas can be purified and then reformed to make syngas, which can yield hydrogen.

In California, for example, the collection of landfill gas (mostly methane and CO_2) is often required to comply with environmental regulations

- The cost of conversion to hydrogen is related to landfill gas preparation, reforming then storage and distribution
- The discretionary additional costs result in a LCOH that is comparable to small-scale natural gas reforming



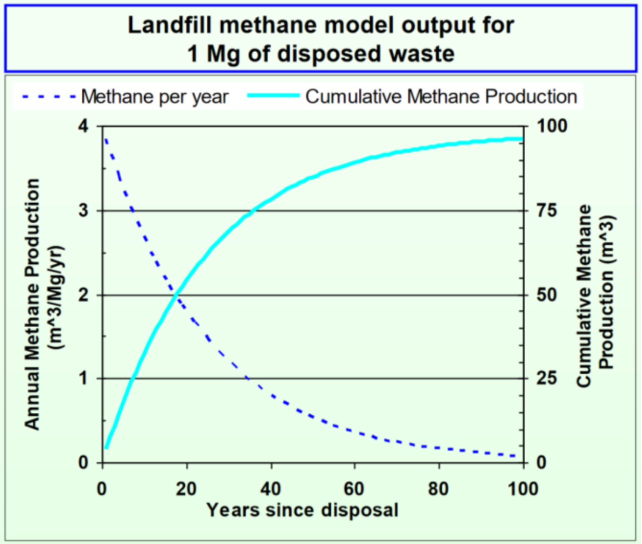
Landfill Gas – to – Hydrogen

Validating the Business Case; Proving the Technology

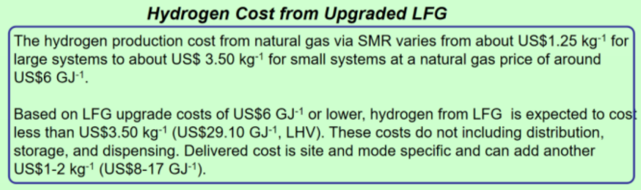
Adapt the preceding systems to take a stream of on-site LFG (post-siloxane removal), remove non-methane constituents (e.g., CO_2, N_2, O_2, sulfur, trace contaminants, etc.) and produce fuel cell purity hydrogen via SMR and PSA

Estimates of Hydrogen Production Potential and Costs from California Landfills

R.B. Williams§, K. Kornbluth‡, P.A. Erickson‡, B.M. Jenkins§ and M.C. Gildart§
§Biological and Agricultural Engineering, ‡Mechanical and Aeronautical Engineering,
University of California, Davis



Landfill methane model output for 1 Mg of disposed waste



Hydrogen Cost from Upgraded LFG

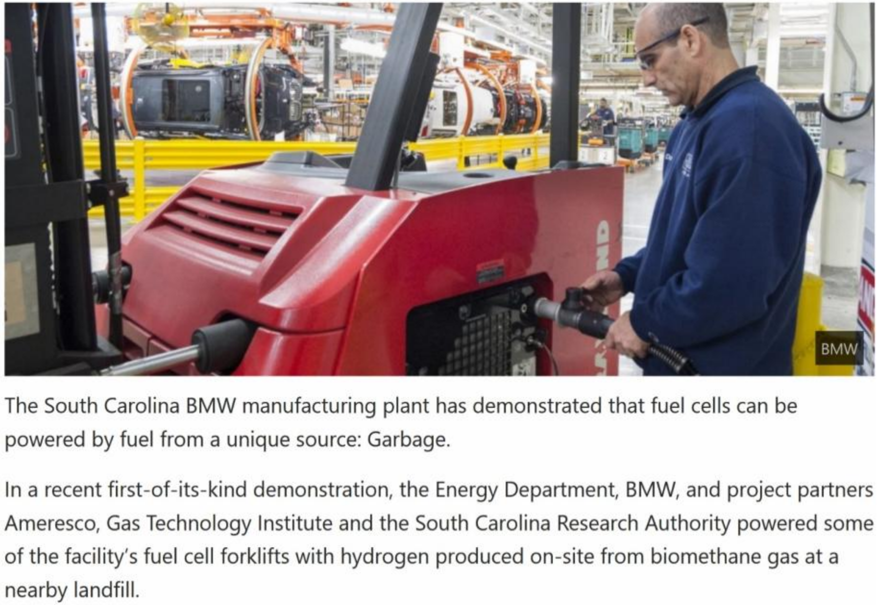
The hydrogen production cost from natural gas via SMR varies from about US\$1.25 kg^{-1} for large systems to about US\$ 3.50 kg^{-1} for small systems at a natural gas price of around US\$6 GJ^{-1}.

Based on LFG upgrade costs of US\$6 GJ^{-1} or lower, hydrogen from LFG is expected to cos less than US\$3.50 kg^{-1} (US\$29.10 GJ^{-1}, LHV). These costs do not including distribution, storage, and dispensing. Delivered cost is site and mode specific and can add another US\$1-2 kg^{-1} (US\$8-17 GJ^{-1}).

https://www.hydrogen.energy.gov/pdfs/review14/mt007_baxterclemmons_2014_o.pdf

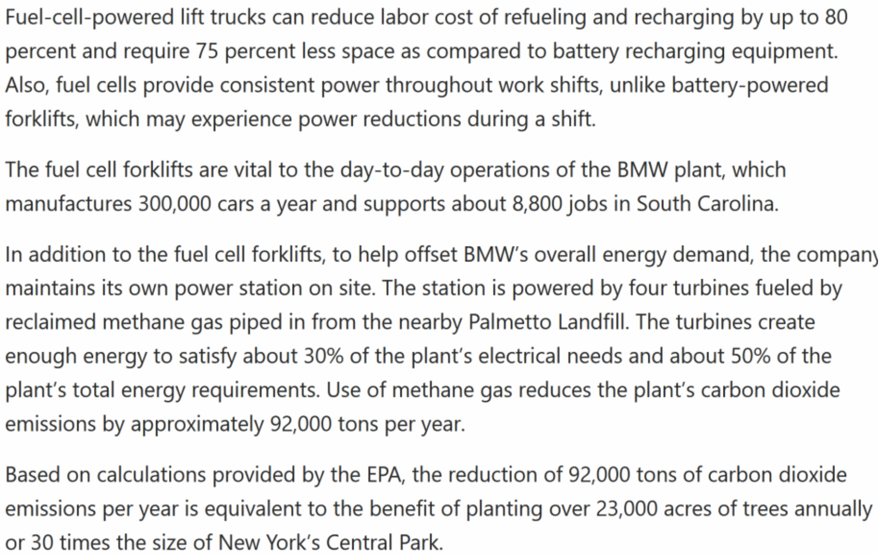
Partial and complete landfill gas collection.

Steam reforming of methane from landfill gas in South Carolina: hydrogen for forklift fuel in BMW car plant.



The South Carolina BMW manufacturing plant has demonstrated that fuel cells can be powered by fuel from a unique source: Garbage.

In a recent first-of-its-kind demonstration, the Energy Department, BMW, and project partners Ameresco, Gas Technology Institute and the South Carolina Research Authority powered some of the facility's fuel cell forklifts with hydrogen produced on-site from biomethane gas at a nearby landfill.



Fuel-cell-powered lift trucks can reduce labor cost of refueling and recharging by up to 80 percent and require 75 percent less space as compared to battery recharging equipment. Also, fuel cells provide consistent power throughout work shifts, unlike battery-powered forklifts, which may experience power reductions during a shift.

The fuel cell forklifts are vital to the day-to-day operations of the BMW plant, which manufactures 300,000 cars a year and supports about 8,800 jobs in South Carolina.

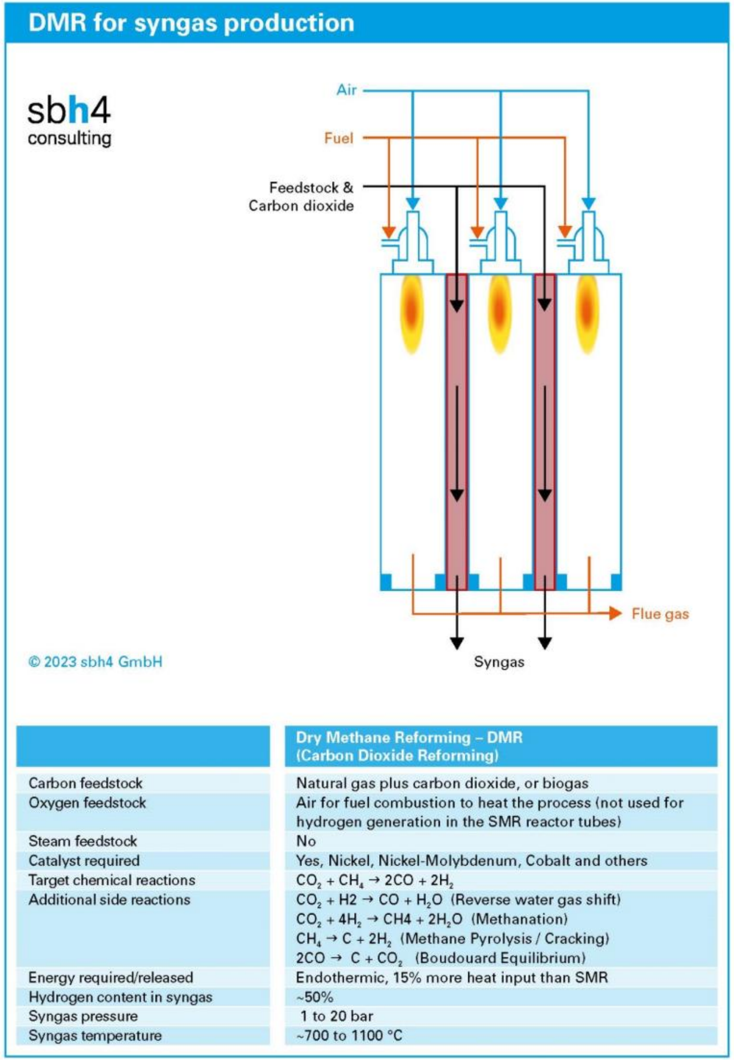
In addition to the fuel cell forklifts, to help offset BMW's overall energy demand, the compan maintains its own power station on site. The station is powered by four turbines fueled by reclaimed methane gas piped in from the nearby Palmetto Landfill. The turbines create enough energy to satisfy about 30% of the plant's electrical needs and about 50% of the plant's total energy requirements. Use of methane gas reduces the plant's carbon dioxide emissions by approximately 92,000 tons per year.

Based on calculations provided by the EPA, the reduction of 92,000 tons of carbon dioxide emissions per year is equivalent to the benefit of planting over 23,000 acres of trees annually or 30 times the size of New York's Central Park.

https://www.spartanburg.com/news/2019/07/garbage-in-power-out-south-carolina-bmw-plant-demonstrates-landfill-gas-to-hydrogen-fuel/

Landfill gas dry methane reforming and combined methane reforming.

- Landfill gas and biogas can contain about 50% CO_2 and 50% CH_4. This is an ideal feedstock to dry methane reforming (DMR).
- Catalyst coking is a common problem in DMR can be avoided if some steam is added so the process operates as combined DMR and SMR.
- Electrification of the energy input for the endothermic reforming (instead of a fired burner for reforming) can also support low-carbon hydrogen production, if renewable power is used.



DMR for syngas production

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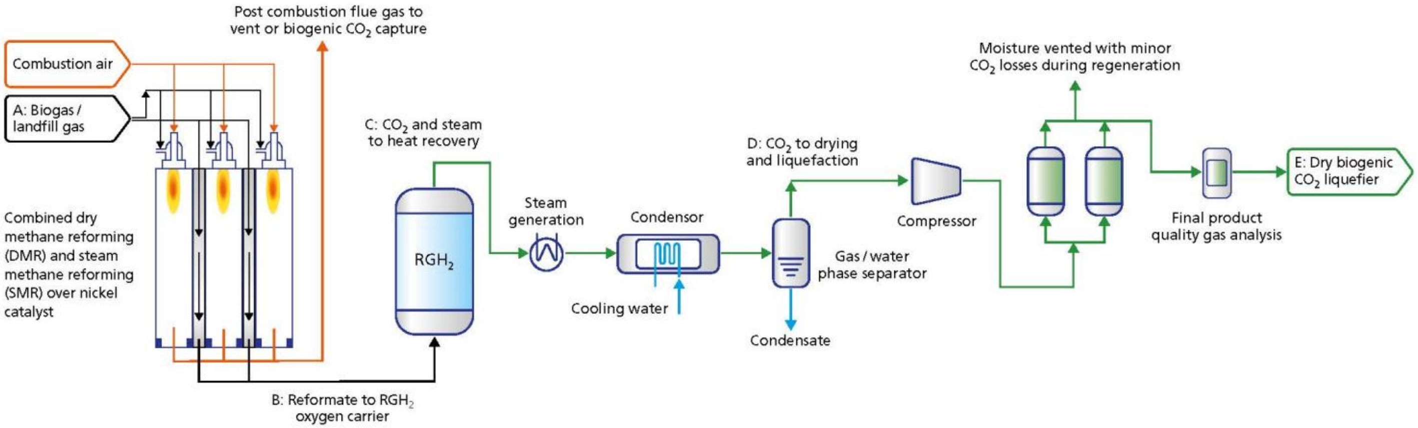
	Dry Methane Reforming – DMR (Carbon Dioxide Reforming)
Carbon feedstock	Natural gas plus carbon dioxide, or biogas
Oxygen feedstock	Air for fuel combustion to heat the process (not used for hydrogen generation in the SMR reactor tubes)
Steam feedstock	No
Catalyst required	Yes, Nickel, Nickel-Molybdenum, Cobalt and others
Target chemical reactions	$CO_2 + CH_4 \rightarrow 2CO + 2H_2$
Additional side reactions	$CO_2 + H2 \rightarrow CO + H_2O$ (Reverse water gas shift) $CO_2 + 4H_2 \rightarrow CH4 + 2H_2O$ (Methanation) $CH_4 \rightarrow C + 2H_2$ (Methane Pyrolysis / Cracking) $2CO \rightarrow C + CO_2$ (Boudouard Equilibrium)
Energy required/released	Endothermic, 15% more heat input than SMR
Hydrogen content in syngas	~50%
Syngas pressure	1 to 20 bar
Syngas temperature	~700 to 1100 °C

RGH2: landfill gas combined methane reforming, followed by conditioning to hydrogen with plug flow Iron Oxide chemical looping. Demonstration project in Leppe, Germany.

Images courtesy of RGH2, Austria

Stage 1 (landfill gas or biogas reformate feedstock): Reduction and biogenic CO_2 production. Reduction of the RGH_2 oxygen-carrier with CO, H_2 and CH_4 from biogenic syngas.



Stream	CH_4 Mol%	CO_2 Mol%	H_2 Mol%	CO Mol%	H_2O Mol%	Temp °C
A: Feed gas to reformer	45	45	0	0	10	Ambient
B: Reformate / syngas to RGH_2	3	6	45	39	7	650
C: CO_2 and steam from RGH_2	0	45	0	0	55	707
D: CO_2 to dryer	0	96	0	0	4	Ambient
E: CO_2 to liquefier	0	99.95	0	0	0.05	Ambient

Key reactions in the RGH_2 plug-flow, iron-oxide chemical looping reactor

$3Fe_20_3 + H_2 \rightarrow 2Fe_30_4 + H_2O$*
$3Fe_20_3 + CO \rightarrow 2Fe_30_4 + CO_2$*

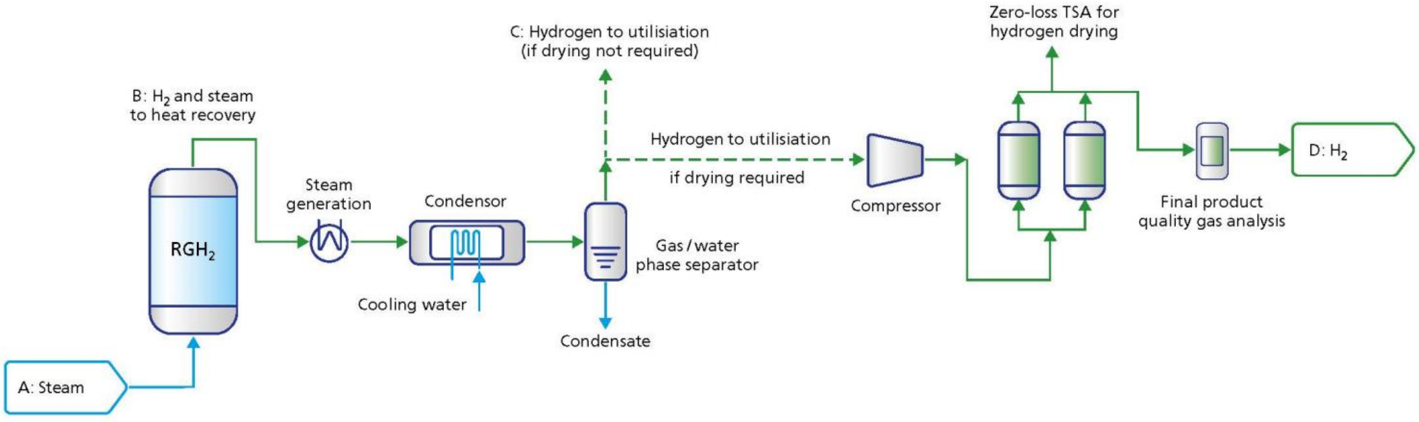
$2Fe_30_4 + 2H_2 \leftrightarrow 6Fe0 + H_2O$**
$2Fe_30_4 + 2CO \leftrightarrow 6Fe0 + 2CO_2$**

$6Fe0 + 6H_2 \leftrightarrow 6Fe + 6H_2O$***
$6Fe0 + 6CO \leftrightarrow 6Fe + 6CO_2$***

* This reaction non-reversible is required to ensure full conversion of H_2 and CO in the syngas feed to CO_2 and moisture.
** This reversible reaction converts 65 to 80% of hydrogen and CO in the syngas feed to CO_2 and moisture.
*** This reversible reaction converts 30 to 40% of hydrogen and CO in the syngas feed to CO_2 and moisture.

- Landfill gas or biomethane as a blend of CO2 and CH4 is reformed
- The reformate reduces an iron oxide plug flow, fixed reactor bed
- The bed is then fed with steam

Stage 2: Steam oxidation and hydrogen production.
Oxidation of the RGH_2 oxygen-carrier with steam generated from heat produced by the RGH_2 process.



Biogas / Landfill gas feed Stream	H_2 Mol%	H_2O Mol%	Temp °C
A: Steam to RGH_2	0	100	185
B: H_2 and steam to heat recovery	44	56	806
C: H_2 to utilisation or dryer	96	4	Ambient
D: High purity, dry H_2 product	99.99	Trace	Ambient

Key reactions in the RGH_2 plug-flow, iron-oxide chemical looping reactor

$6Fe + 6H_2O \leftrightarrow 6FeO + 6H_2$

$6FeO + 6H_2O \leftrightarrow 6Fe_3O_4 + 2H_2$

- As the bed is fed with steam, oxygen from the water molecules oxidises the iron oxide bed and hydrogen gas is produced
- The process can operate at high pressure to yield high pressure hydrogen
- **The chemistry is like the mechanism of natural / geological hydrogen generation**
- Steam is generated from a third phase of the process to ensure the system requires no steam import

3) Biogas or landfill gas to power followed by electrolysis as a pathway to hydrogen

Biogas or landfill gas combustion in a gas engine, followed by electrolysis.

California Energy Commission, SoHyCal in Fresno: biogas to power on a solid oxide fuel cell and green hydrogen production for local mobility applications.

- Biogas from Bar 20 Dairy farm
- Power generation using purified biomethane and Bloom Fuel cells
- Direct connection to 15 MW solar plant
- Phase 1 (shown) is 3MW electrolysis, 1,290 kg H2 per day for mobility applications
- Phase 2 additional 3MW, phase 3 completes to 9MW
- Plug Power 3x Allagash 1MW PEM stacks
- System integrated by H2B2

https://www.h2b2.es/h2b2s-sohycal-project-in-california-has-started-hydrogen-production/
https://www.h2b2.es/h2b2-electrolysis-technologies-unveils-sohycal-the-first-operational-green-hydrogen-plant-in-north-america/
https://www.caclimateinvestments.ca.gov/2022-profiles-1/ddrdpbar20

Reverion – biogas to power on a high temperature fuel cell, followed by power to methane or hydrogen gas. Integrated CO2 separation - no need for biogas to biomethane upgrade.

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https://25608455.fs1.hubspotusercontent-eu1.net/hubfs/25608455/Website-Materials/Reverion_Data_Sheet.pdf

Reverion – biogas to power with up to 80% efficiency, then power to methane or hydrogen gas. Reversible in less than 1 minute. Enables LDES.

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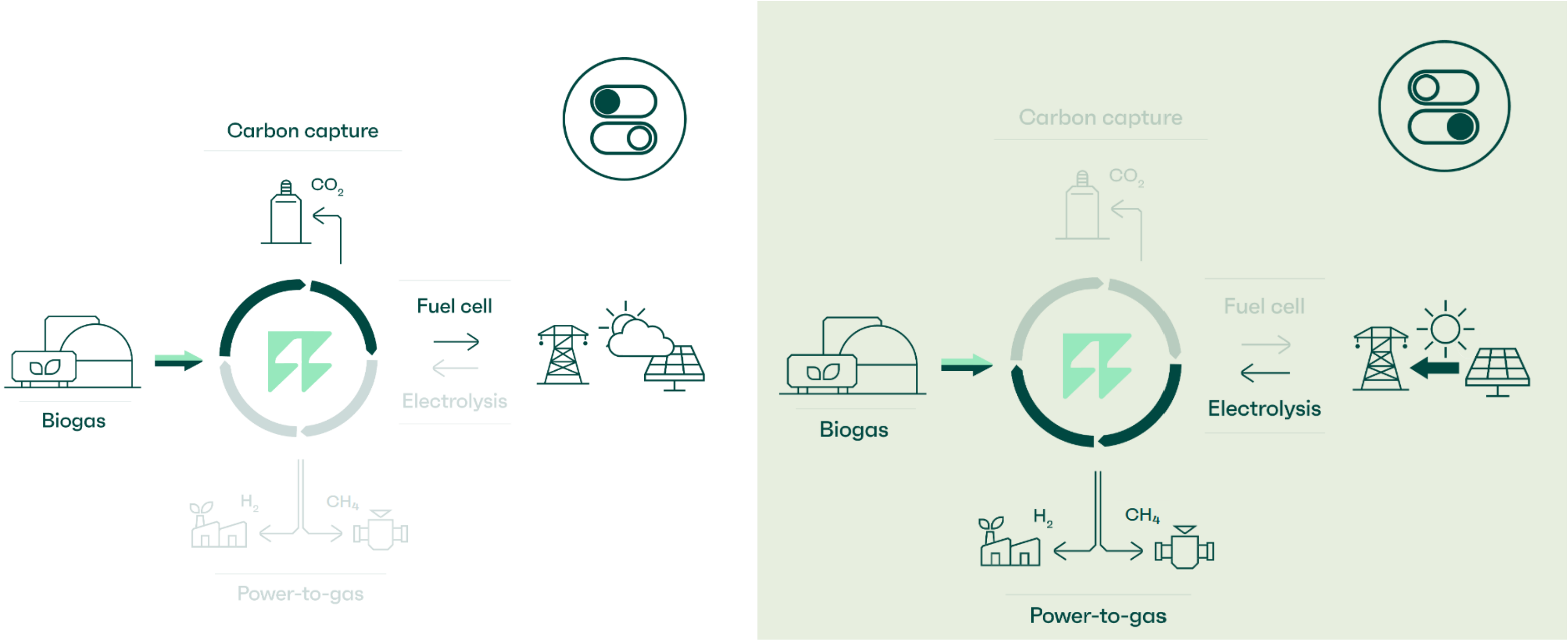


Carbon capture

CO_2

Fuel cell

Electrolysis

Biogas

H_2

CH_4

Power-to-gas

Carbon capture

CO_2

Fuel cell

Electrolysis

Biogas

H_2

CH_4

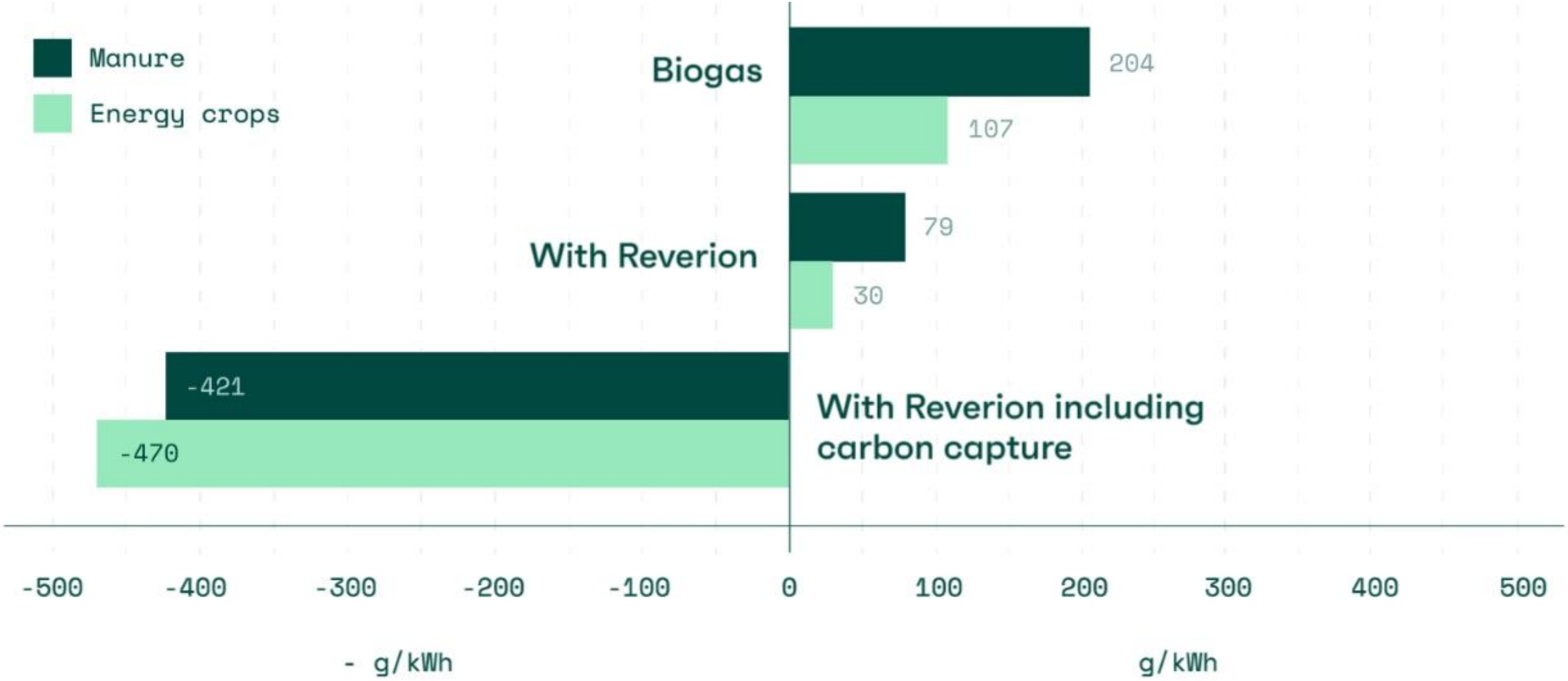
Power-to-gas

8 April 2024

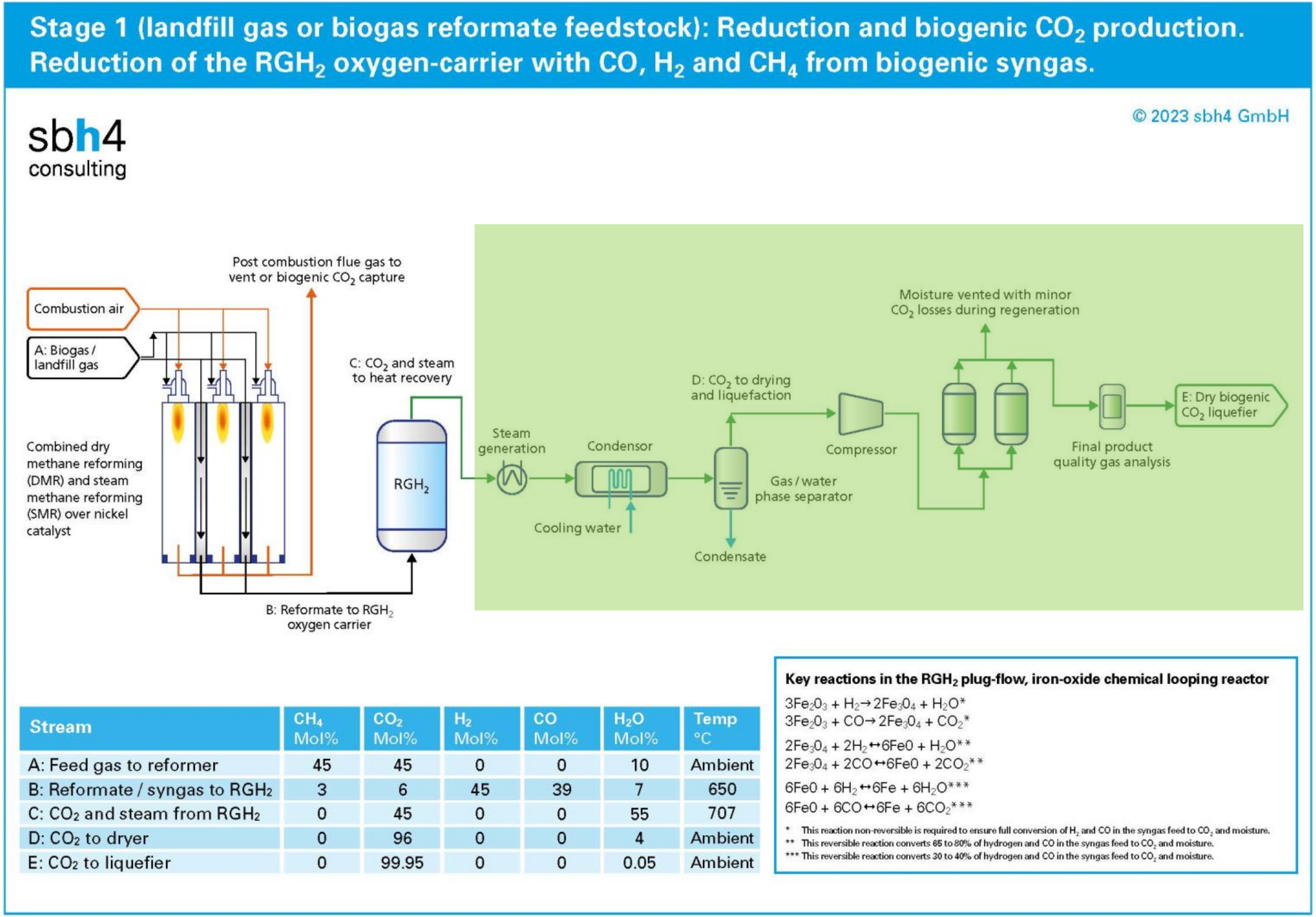
https://25608455.fs1.hubspotusercontent-eu1.net/hubfs/25608455/Website-Materials/Reverion_Sales_Deck_EN.pdf

4) Carbon sequestration or utilisation

With integrated CO2 capture, the Reverion system can yield carbon-negative power from biogas from liquid waste.



https://reverion.com/technology/



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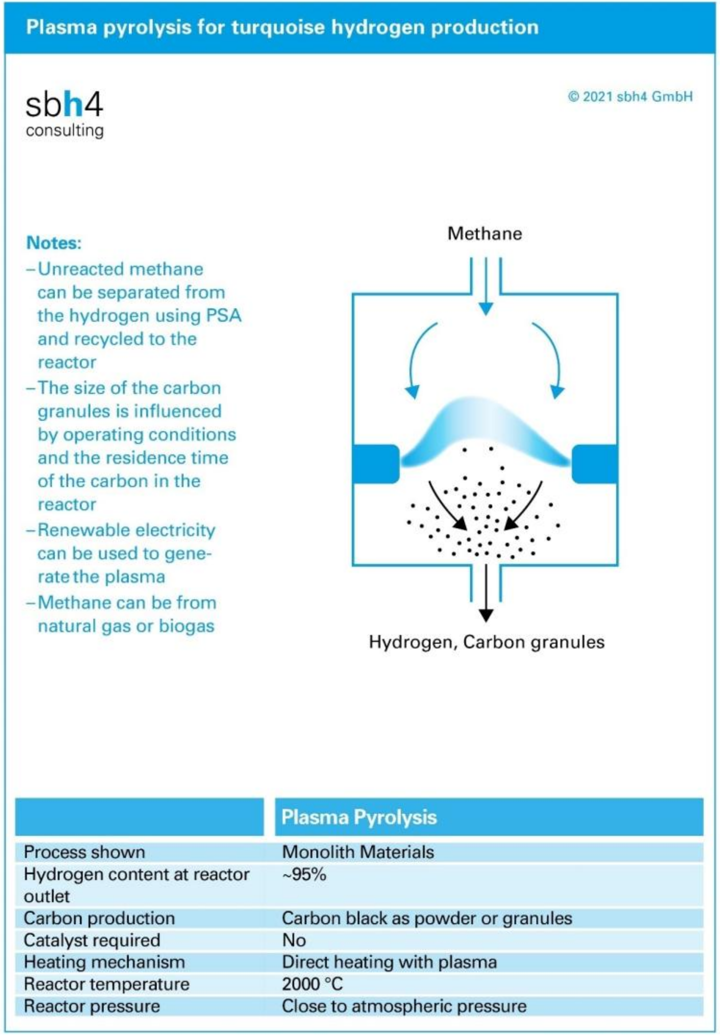
- The RGH2 system can also integrate CO2 capture
- The question in these cases is what happens to the CO2?
  - Utilisation
  - Permanent sequestration

Biomethane or landfill gas for turquoise hydrogen – carbon negative?

- Turquoise hydrogen from landfill gas or biogas can be carbon negative due to the carbon being locked into solid carbon and not released as CO_2.
- If renewable power is used for the DC, AC or microwave plasma (instead of a fired burner for reforming), the CO2 intensity of the hydrogen can be reduced.
- Levidian working with United Utilities biogas / biomethane plant in Manchester UK.

https://hydrogen-central.com/sewage-biogas-produced-manchester-become-sustainable-feed-source-graphene-and-hydrogen-production-thanks-to-a-pioneering-partnership-between-levidian-and-united-utilities/



Plasma pyrolysis for turquoise hydrogen production

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Notes:

- Unreacted methane can be separated from the hydrogen using PSA and recycled to the reactor
- The size of the carbon granules is influenced by operating conditions and the residence time of the carbon in the reactor
- Renewable electricity can be used to generate the plasma
- Methane can be from natural gas or biogas

	Plasma Pyrolysis
Process shown	Monolith Materials
Hydrogen content at reactor outlet	~95%
Carbon production	Carbon black as powder or granules
Catalyst required	No
Heating mechanism	Direct heating with plasma
Reactor temperature	2000 °C
Reactor pressure	Close to atmospheric pressure

5) Distributed hydrogen production and utilisation in the community

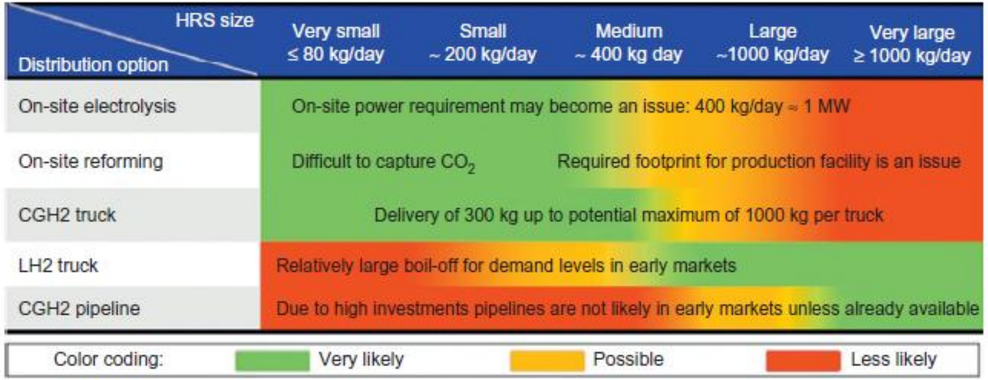
Compressed hydrogen gas distribution is very inefficient.

- Type 1 steel cylinders at 200 Bar
- Circa 300 kg H_2 / trailer
- Less than 1% of the vehicle weight is hydrogen

- Type 4 carbon-fibre cylinders at 500 bar
- Total payload of hydrogen circa 1 tonne
- Circa 2.5% of the vehicle weight is hydrogen

Images courtesy of Air Products and Chemicals, Inc

Decentralised waste to hydrogen creates circularity within communities and can bridge the years, or decades, between now and centralised hydrogen production and pipeline transmission.



Distribution option \ HRS size	Very small ≤ 80 kg/day	Small ~ 200 kg/day	Medium ~ 400 kg day	Large ~1000 kg/day	Very large ≥ 1000 kg/day
On-site electrolysis	On-site power requirement may become an issue: 400 kg/day ≈ 1 MW				
On-site reforming	Difficult to capture CO_2		Required footprint for production facility is an issue		
CGH2 truck	Delivery of 300 kg up to potential maximum of 1000 kg per truck				
LH2 truck	Relatively large boil-off for demand levels in early markets				
CGH2 pipeline	Due to high investments pipelines are not likely in early markets unless already available				

Color coding: 🟩 Very likely 🟨 Possible 🟥 Less likely

Figure 12.1 Overview of delivery options for a hydrogen infrastructure for road transport

IEA, 2013. Hydrogen refuelling stations and role of utilization rates: key messages and issues.

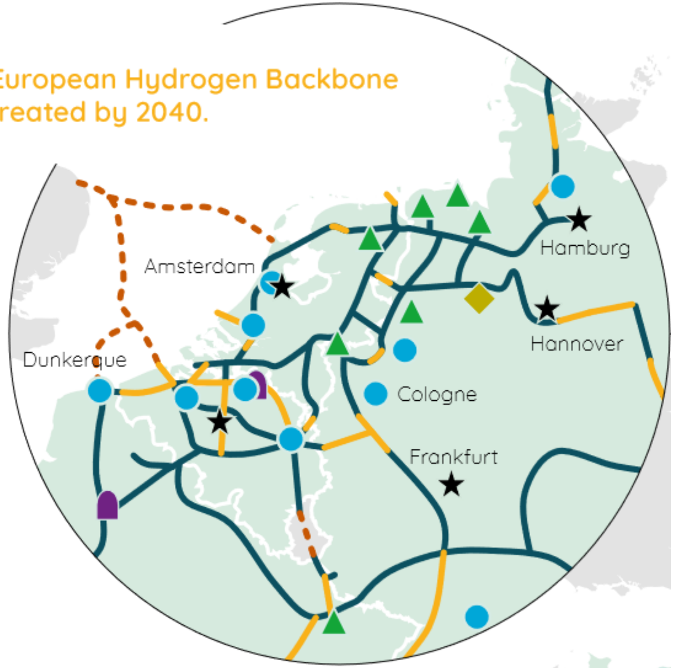
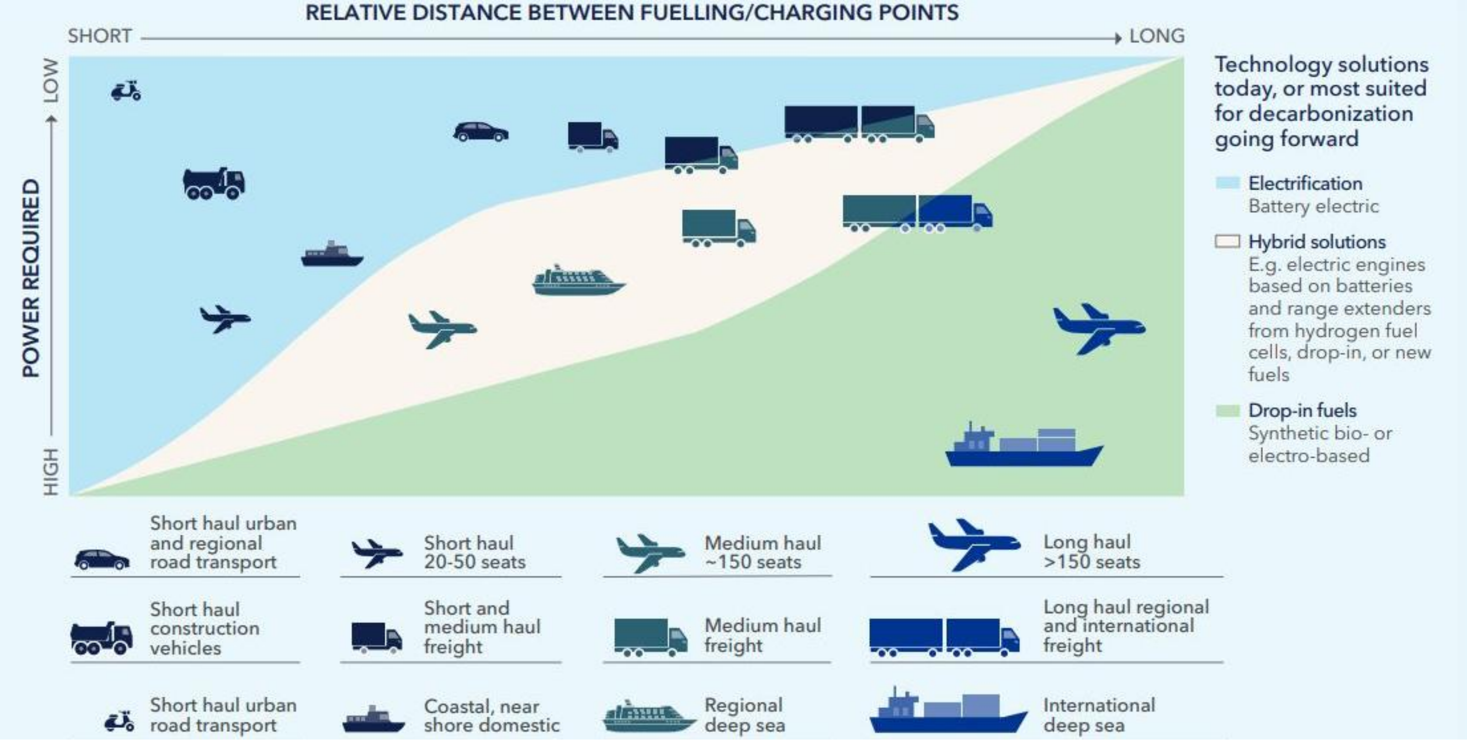


FIGURE 1

Mature European Hydrogen Backbone can be created by 2040.

https://gasforclimate2050.eu/wp-content/uploads/2020/07/2020_European-Hydrogen-Backbone_Report.pdf

Hydrogen is an alternative to biofuels, e-fuels and batteries in heavy duty mobility applications. Operational profile, fuelling time, power, fuel density and range are important factors.



https://www.dnv.com/Publications/transport-in-transition-242808?utm_source=googleCPC&utm_medium=search&utm_campaign=Transport_in_Transition_PDF_EU&gad=1&gclid=Cj0KCQjwslejBhDOARIsANYqkD0xLAv_ScyD-glbLBLswROkgbssgJLmZ3Ina5vun0zk8LzbbEnwNMMaAr5qEALw_wcB

Hydrogen fuel cell powered cars, forklifts, trucks, trains and buses. There is a healthy push and pull between batteries and fuel cells for mobility.

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- Hydrogen storage on trains and buses (mass transit passenger vehicles) is generally in large type 3 or type 4 compressed hydrogen gas cylinders
- Passenger car hydrogen storage is generally at 700 bar due to space restrictions
- Trucks are migrating to 700 bar
- Liquid storage on trucks has also been promoted by some OEMs, such as Daimler
- Hydrogen pressure is reduced to 10 bar and piped from the tank to the fuel cell

8 April 2024

https://fuelcellsworks.com/news/worlds-first-hydrogen-train-with-a-speed-of-160-kilometers-per-hour-rolled-out-in-china/

Gaseous and liquid hydrogen for zero-emissions electric maritime propulsion in US and Norway.

- Hydra stores liquid hydrogen on board
- Propulsion is from 2x Ballard Power 200 kW FCWave fuel cell modules

Hydra hydrogen powered ferry, Norway

Sea Change hydrogen powered ferry, California

- Sea Change stores compressed gaseous hydrogen on board
- 2-days of operation is enabled by the hydrogen storage
- Propulsion is from 3x 120 kW Cummins HyPM-R120 S fuel cell modules
- Power supply integrated with XALT 100 kWh lithium-ion battery

https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration-project
https://maritime-executive.com/article/video-norway-s-hydrogen-powered-ferry-begins-service

H2 Barge 1: operating between Rotterdam and Meerhout (Belgium) on behalf of Nike. ELEKTRA: hybrid battery and hydrogen fuel cell powered barge push-boat for use between Berlin and Hamburg in Germany.

https://www.est-floattech.com/projects/elektra-first-hydrogen-canal-tug/

Fendt, Germany - hydrogen fuel cell powered tractor. H2ARGAR, Austria ski piste grooming machine.

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Fendt, Germany - hydrogen fuel cell powered tractor, H2ARGAR research project

Ski piste grooming machine, Austria

https://www.fendt.com/int/geneva-assets/widget/37559/news-2-high.jpg sbh4

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Introduction to Stephen B. Harrison and sbh4 consulting

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Stephen B. Harrison founded sbh4 GmbH during 2017 in Germany. His work focuses on decarbonisation and greenhouse gas emissions control. Hydrogen and CCTUS are fundamental pillars of his consulting practice.

Stephen has supported the World Bank and IFC on green hydrogen projects in Namibia and Pakistan. He has also served as the international hydrogen expert for three Asian Development Bank projects related to renewable and low-carbon hydrogen deployment and CCS in Pakistan, Palau and Viet Nam. He also supported the European Commission's CINEA to evaluate e-fuels, hydrogen and CCS applications to the third innovation fund in 2023.

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 and carbon dioxide 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 energy and clean-tech sectors. Private Equity firms and investment fund managers and green-tech startup CEOs are regular clients. Helping operating companies to develop and deploy industrial decarbonisation strategies is an area where Stephen is also active.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for these international magazines. Working with Environmental Technology Publications, he served as a member of the scientific committee for CEM 2023 Barcelona and was session chair for the Power to X to Power clean energy emissions monitoring session.

Stephen was also session chair for the e-fuels and hydrogen propulsion track at the Hydrogen Technology Expo 2023 in Bremen. He also served on the advisory board for the International Power Summit, Munich in 2022. Stephen also runs a comprehensive range training courses and masterclasses for CLASS OF H2, World Hydrogen Leaders and Sustainable Aviation Futures.