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

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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.

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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.

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

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

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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.

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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

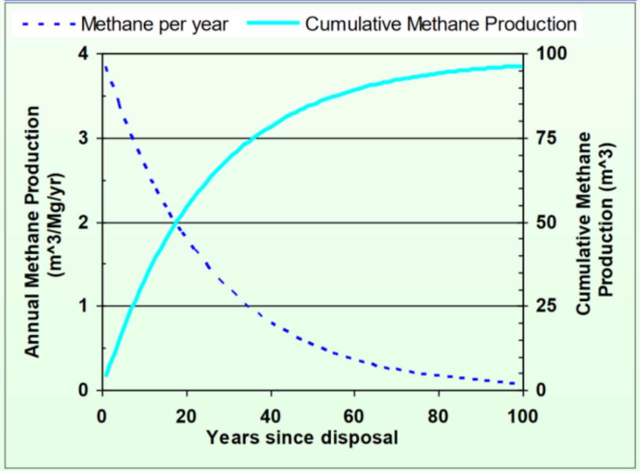
Adapt the preceding systems to take a stream of on-site LFG (post-siloxane removal), remove non-methane constituents (e.g., CO_2, N_2, O_2, sulfur, trace contaminants, etc.) and produce fuel cell purity hydrogen via SMR and PSA

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

biomass — Integrated Waste Management Board — UC 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 cost 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}).

Partial and complete landfill gas collection.

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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 company 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% CO2 and 50% CH4. 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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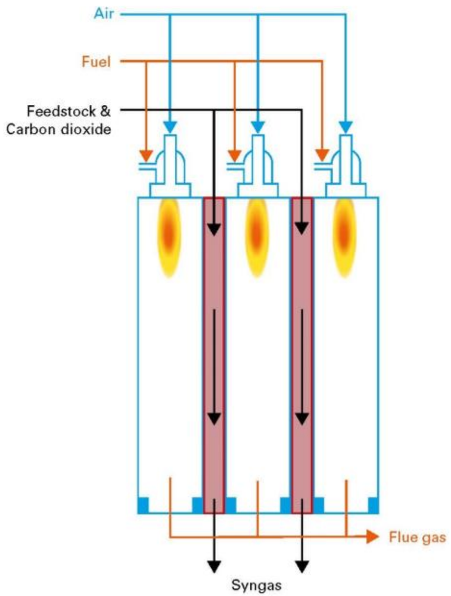

	Dry Methane Reforming – DMR (Carbon Dioxide Reforming)
Carbon feedstock	Natural gas plus carbon dioxide, or biogas
Oxygen feedstock	Air for fuel combustion to heat the process (not used for hydrogen generation in the SMR reactor tubes)
Steam feedstock	No
Catalyst required	Yes, Nickel, Nickel-Molybdenum, 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.

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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.

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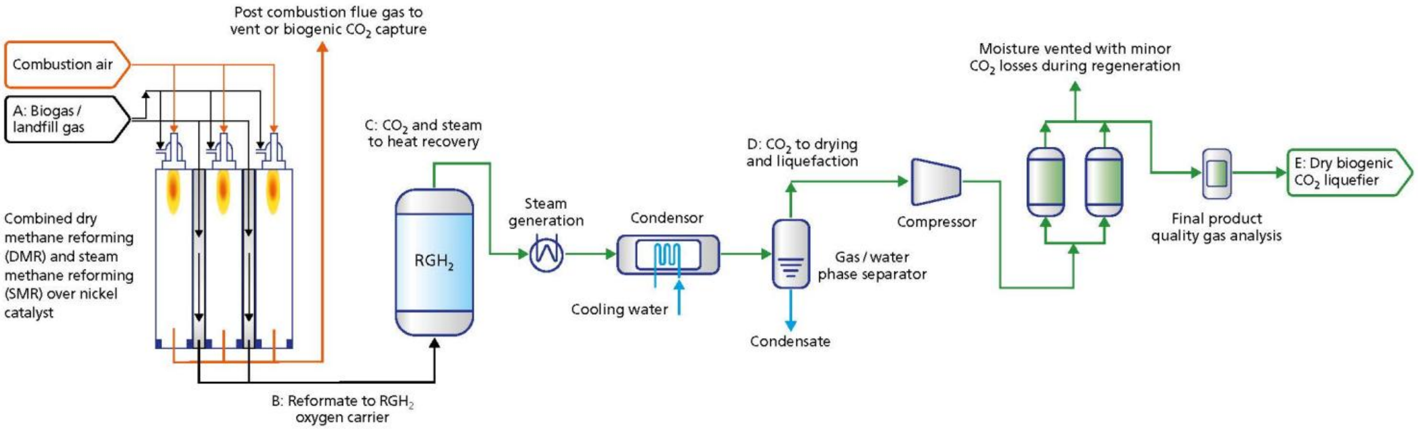

Stream	CH_4 Mol%	CO_2 Mol%	H_2 Mol%	CO Mol%	H_2O Mol%	Temp °C
A: Feed gas to reformer	45	45	0	0	10	Ambient
B: Reformate / syngas to RGH_2	3	6	45	39	7	650
C: CO_2 and steam from RGH_2	0	45	0	0	55	707
D: CO_2 to dryer	0	96	0	0	4	Ambient
E: CO_2 to liquefier	0	99.95	0	0	0.05	Ambient

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

$3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$*
$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$*

$2Fe_3O_4 + 2H_2 \leftrightarrow 6FeO + H_2O$**
$2Fe_3O_4 + 2CO \leftrightarrow 6FeO + 2CO_2$**

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

* 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.

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- 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.

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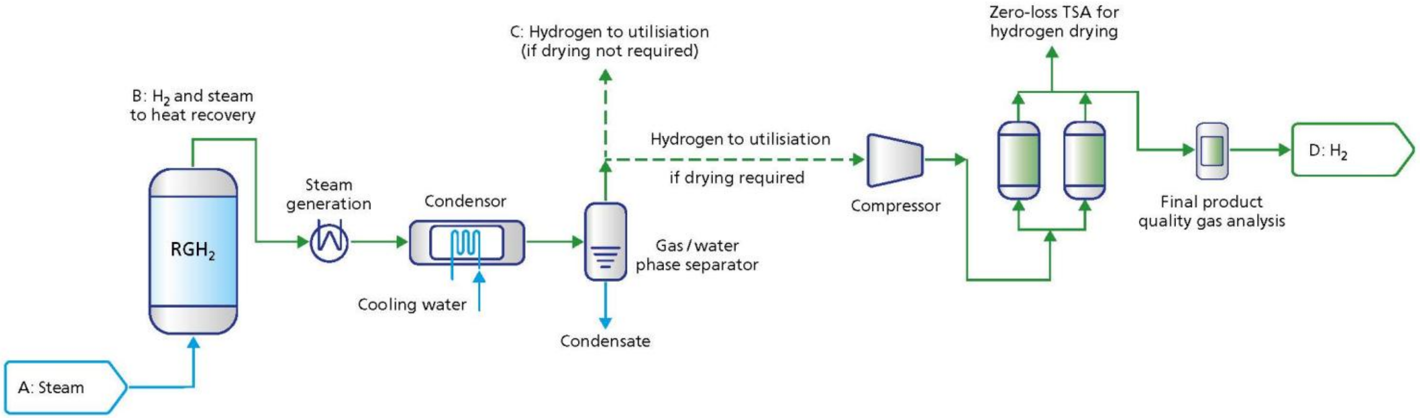

Biogas / Landfill gas feed Stream	H_2 Mol%	H_2O Mol%	Temp °C
A: Steam to RGH_2	0	100	185
B: H_2 and steam to heat recovery	44	56	806
C: H_2 to utilisation or dryer	96	4	Ambient
D: High purity, dry H_2 product	99.99	Trace	Ambient

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

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

$6Fe0 + 6H_2O \leftrightarrow 6Fe_3O_4 + 2H_2$

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- 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

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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.

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- 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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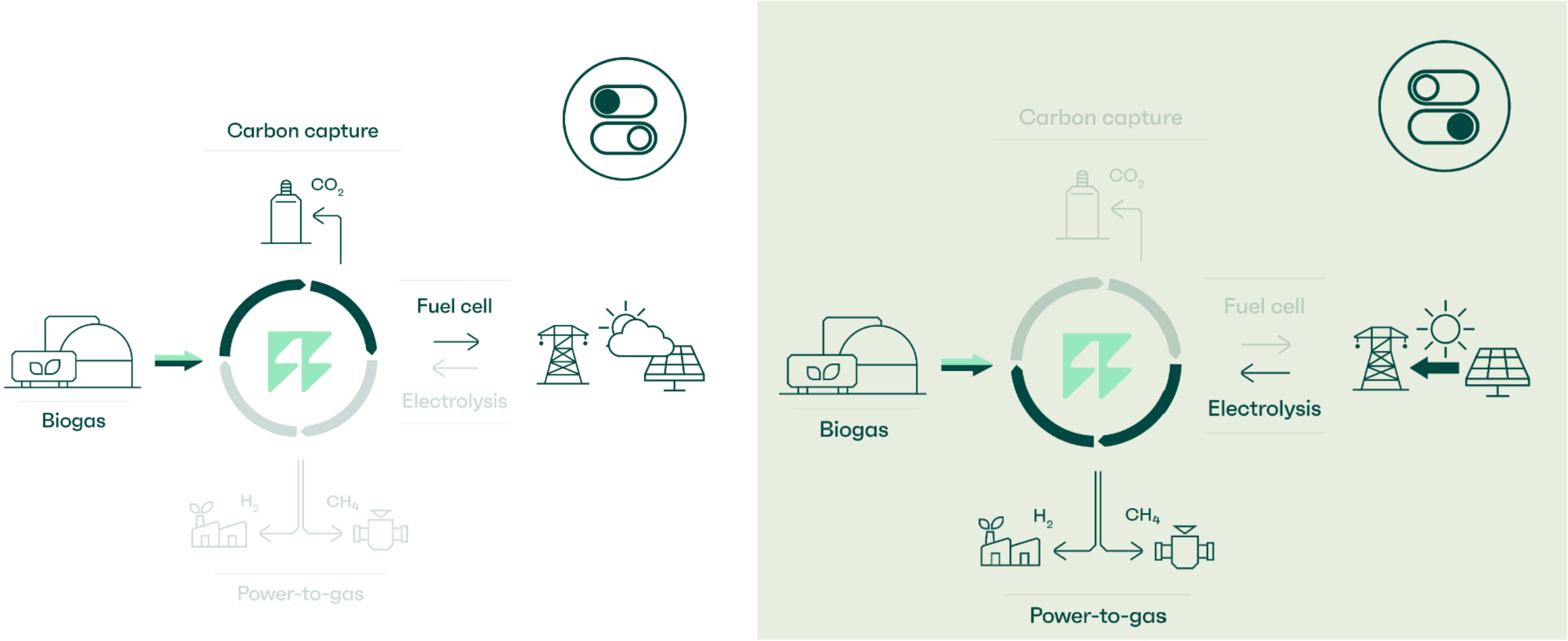

4) Carbon sequestration or utilisation

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

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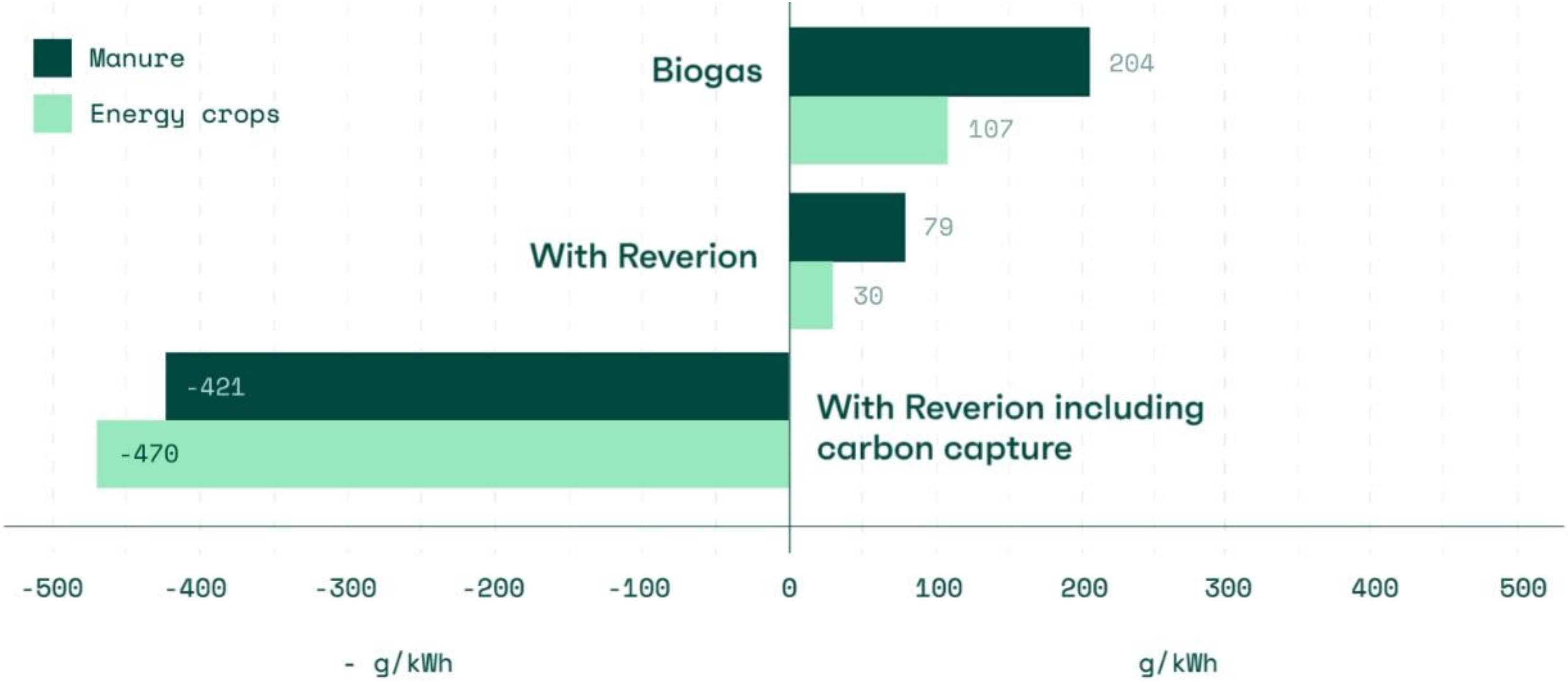

https://reverion.com/technology/

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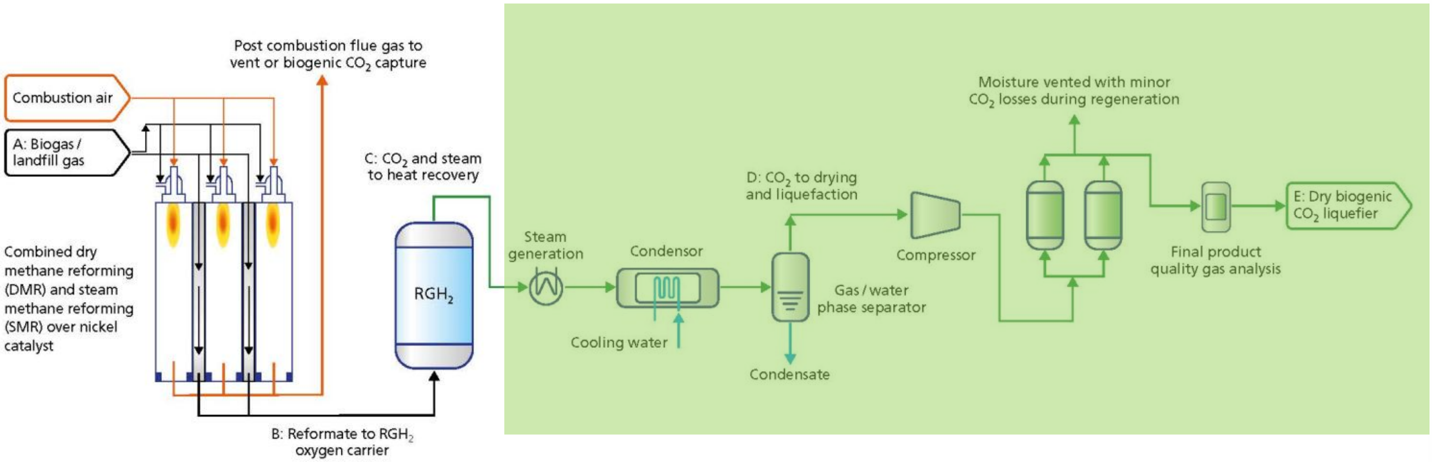

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- The RGH2 system can also integrate CO2 capture
- The question in these cases is what happens to the CO2?
  - Utilisation
  - Permanent sequestration

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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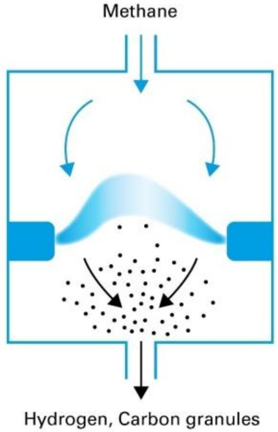
Notes:

- 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 gene-rate 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.

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- 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.

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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				

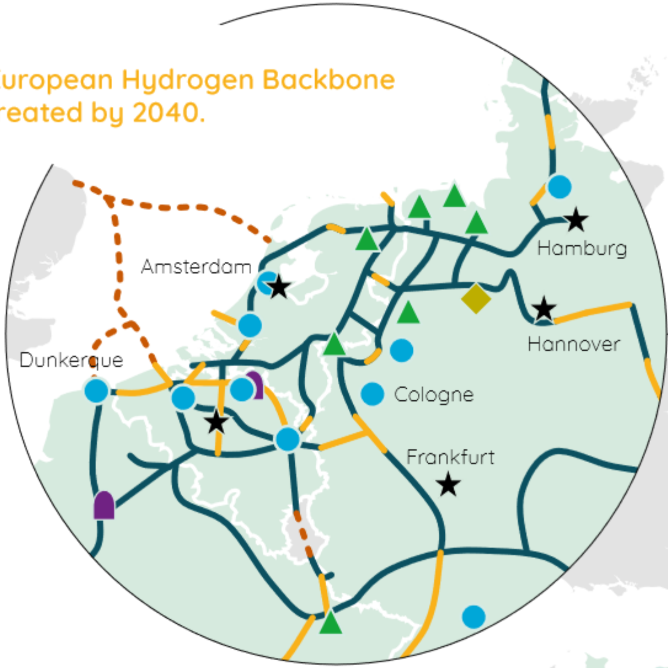
Color coding: Very likely (green) · Possible (yellow) · Less likely (red)

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.

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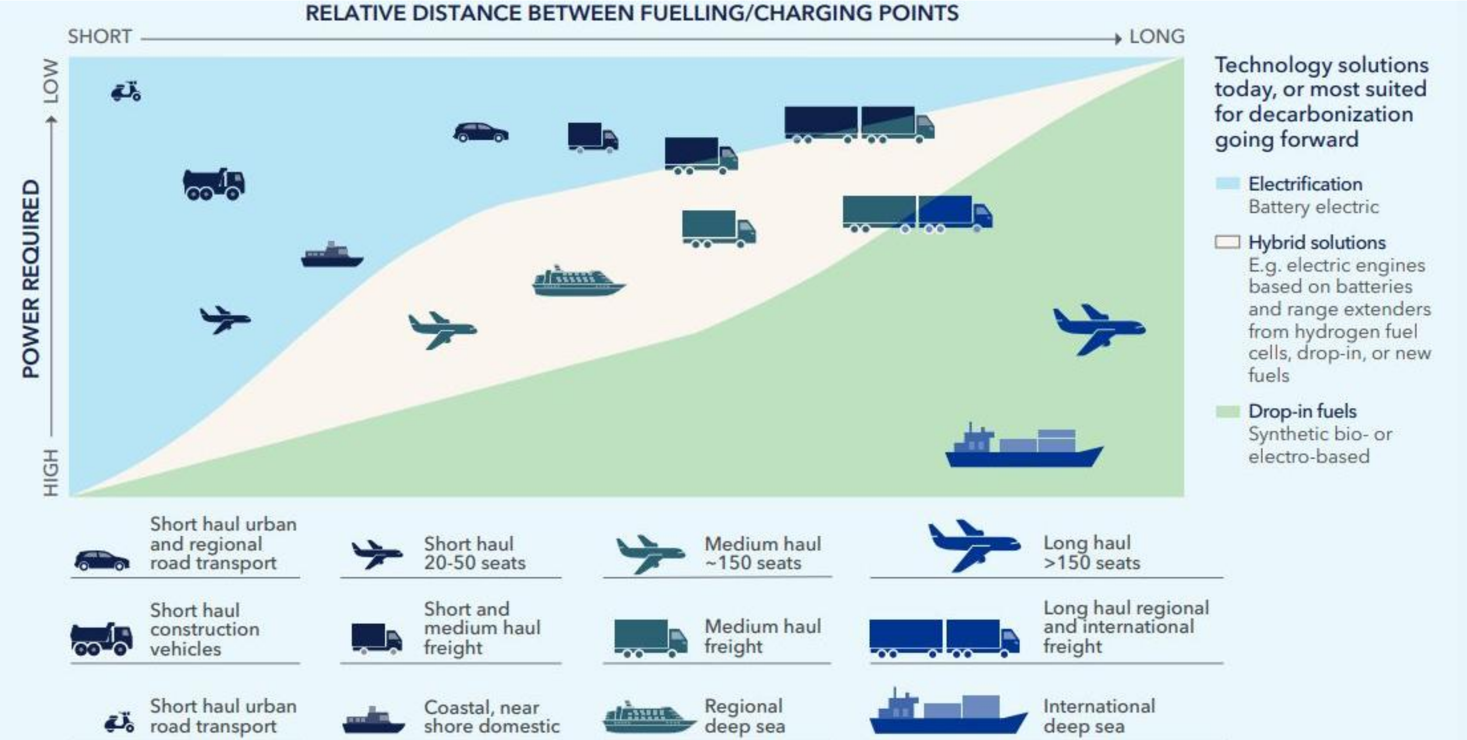

https://www.dnv.com/Publications/transport-in-transition-242808?utm_source=googleCPC&utm_medium=search&utm_campaign=Transport_in_Transition_PDF_EU&gad=1&gclid=Cj0KCQjwslejBhDOARIsANYqkD0xLAv_ScyD-glbLBLswROkgbssgJLmZ3lna5vun0zk8LzbbEnwNMMaAr5qEALw_wcB

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

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.

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

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


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

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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.

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Hydrogen production close to the community 2: municipal solid waste gasification and waste to energy.

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

Wednesday 15th May 2024, 11:05-11:45

Agenda from yesterday and for today

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1) How ‘green’ is hydrogen from MSW or biomass?

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Hydrogen – a rainbow of colours

Black – coal gasification

Brown – brown coal gasification

Purple – coal or petcoke gasification with CCS

Grey – natural gas reforming

Blue – natural gas reforming with CCS

Turquoise – methane pyrolysis with solid carbon

Pink – electrolysis using nuclear power

Green – electrolysis using renewable power

Green – from renewable biogenic sources

White – recovered from industrial processes

White – natural hydrogen

Gold – natural hydrogen

Colour? – waste to hydrogen

Note – colours are not internationally defined and do not specify CO_2 emissions values
The colours presented here are indicative examples selected for the purposes of this training

Waste to hydrogen is ‘orange’ in the 2023 update of the German national hydrogen strategy. Could it ever have been anything else?

Um einen schnellen Aufbau und Hochlauf des Wasserstoffmarktes sicherzustellen und die erwarteten Bedarfe, insbesondere in der Transformationsphase, zu decken und so die technologische Umstellung auf Wasserstoff zu ermöglichen, werden, zumindest bis ausreichend grüner Wasserstoff zur Verfügung steht, auch andere Farben von Wasserstoff genutzt werden, insbesondere kohlenstoffarmer Wasserstoff aus Abfällen oder Erdgas in Verbindung mit CCS. Die Nutzung von grünem und, soweit in der Markthochlaufphase notwendig, kohlenstoffarmem blauem[3], türkisem[4] und orangem[5] Wasserstoff wollen wir auf der Anwendungsseite in begrenztem Umfang unter Berücksichtigung von ambitionierten THG-Grenzwerten, einschließlich der Emissionen der Vorkette sowie der Erhaltung des gesetzlichen Ziels der Klimaneutralität, auch fördern.[6]

3 Aus Erdgas in Verbindung mit CCS erzeugter Wasserstoff.

4 Durch Methanpyrolyse erzeugter Wasserstoff.

5 Auf Basis von Abfall- und Reststoffen erzeugter Wasserstoff.

https://www.bmbf.de/SharedDocs/Downloads/de/2023/230726-fortschreibung-nws.pdf?__blob=publicationFile&v=1

MSW has a high biogenic fraction which is regarded as a ‘green‘ energy source.

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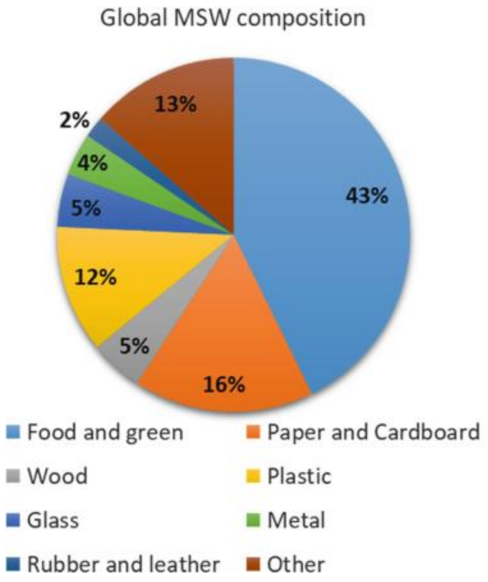

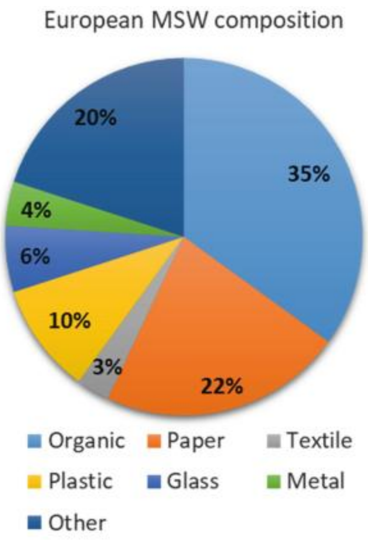

- The biogenic fraction of MSW can be 35 to 45% by mass after sorting out additional biogenic materials such as paper.
  - An equivalent percentage of the hydrogen derived from waste will be green (biogenic).
- Power from waste to energy (incineration) can be used for electrolysis of water to hydrogen and an equivalent percentage of the power will be green (biogenic).
- Waste to energy has recently been included in the EU ETS and waste incineration operators are closely measuring their biogenic vs fossil CO2 emissions.
- US IRA has CO2 emissions limits for H2 production.
- Non-fossil CO2 intensity of hydrogen production is a key measure.

https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-74406-9_23/MediaObjects/505005_1_En_23_Fig1_HTML.png

2) Chemcycling and its role in waste management

In US and Europe, more than 380 million tonnes of MSW could be diverted from landfill to yield circa 13 million tonnes of hydrogen each year, circa 18% of current global hydrogen demand.

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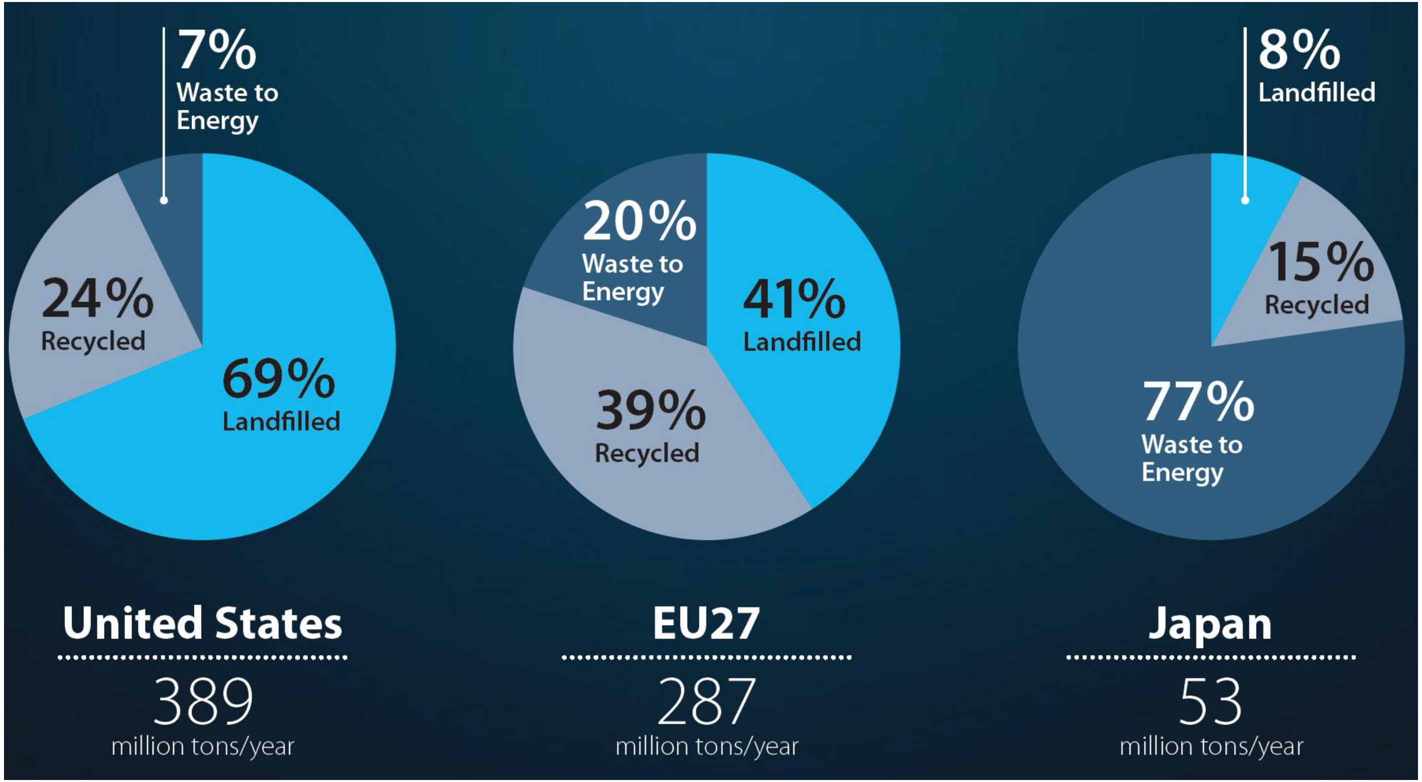

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwijuKTkveP1AhU0gf0HHVcABiAQFnoECAcQAQ&url=http%3A%2F%2Fwww.findera.fi%2Ffiles%2FCBR%252 0Presentation.pdf&usg=AOvVaw0SMM8AO38Q8ai_Fp0fCdip

EU Taxonomy of sustainable investment: Article 13 refers to waste incineration or landfill minimisation, for example through chemcycling of waste to hydrogen or hydrogen derivatives.

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Substantial contribution to the transition to a circular economy

1. An economic activity shall qualify as contributing substantially to the transition to a circular economy, including waste prevention, re-use and recycling, where that activity:

(a) uses natural resources, including sustainably sourced bio-based and other raw materials, in production more efficiently, including by:

(i) reducing the use of primary raw materials or increasing the use of by-products and secondary raw materials; or

(ii) resource and energy efficiency measures;

(j) minimises the incineration of waste and avoids the disposal of waste, including landfilling, in accordance with the principles of the waste hierarchy;

REGULATION (EU) 2020/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 18 June 2020

on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 19 November 2008

on waste and repealing certain Directives

Article 4

Waste hierarchy

1. The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy:

(a) prevention;

(b) preparing for re-use;

(c) recycling;

(d) other recovery, e.g. energy recovery; and

(e) disposal.

Plastic wastes are mostly made up of Carbon, Hydrogen and Oxygen. Refuse Derived Fuel, RDF (also called Solid Recovered Fuel, SRF) from non-recyclable plastics is an ideal gasification feedstock.

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Waste plastic	Ultimate analysis, wt.%				
	C	H	O	N	S
HDPE	78.18	12.84	3.61	0.06	0.08
PP	83.74	13.71	0.98	0.02	0.08
PS	90.40	8.56	0.18	0.07	0.08

https://www.researchgate.net/figure/Ultimate-and-proximate-analysis-of-different-waste-plastics_tbl1_326681146

RDF / SRF – ISO 21640 Standard defines source and quality (EN 15359 is an alternative).

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INTERNATIONAL STANDARD

ISO 21640

First edition
2021-05

Solid recovered fuels — Specifications and classes

Combustibles solides de récupération — Spécifications et classes

Reference number
ISO 21640:2021(E)

Table 2 — Classification for solid recovered fuels

Classification characteristic	Statistical measure	Unit	Classes 1	2	3	4	5
Net calorific value (NCV)	Mean	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	Mean	% in mass (d)	≤ 0,2	≤ 0,6	≤ 1,0	≤ 1,5	≤ 3
Mercury (Hg)	Median 80th percentile	mg/MJ (ar) mg/MJ (ar)	≤ 0,02 ≤ 0,04	≤ 0,03 ≤ 0,06	≤ 0,05 ≤ 0,10	≤ 0,10 ≤ 0,20	≤ 0,15 ≤ 0,30

Table 3 (continued)

3. Non-hazardous waste from waste management facilities	3.4 wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising)	3.4.1 paper and cardboard waste
		3.4.2 textile waste
		3.4.3 wood waste
		3.4.4 plastic and rubber waste
		3.4.5 other non-hazardous wastes (including mixtures of materials) from mechanical treatment of wastes
	3.5 end-of-life vehicles from different means of transport (including off-road machinery) and wastes from dismantling of end-of-life vehicles and vehicle maintenance	3.5.1 end of life tyres
		3.5.2 plastic waste (except packaging)
		3.5.3 other non-hazardous waste from end-of-life vehicles
4 Non-hazardous waste from material recycling facilities	4.1 reject fractions from material recycling facilities, not otherwise mentioned	4.1.1 paper and cardboard waste
		4.1.2 textile waste
		4.1.3 wood waste
		4.1.4 plastic waste
		4.1.5 other non-hazardous waste from material recycling facilities

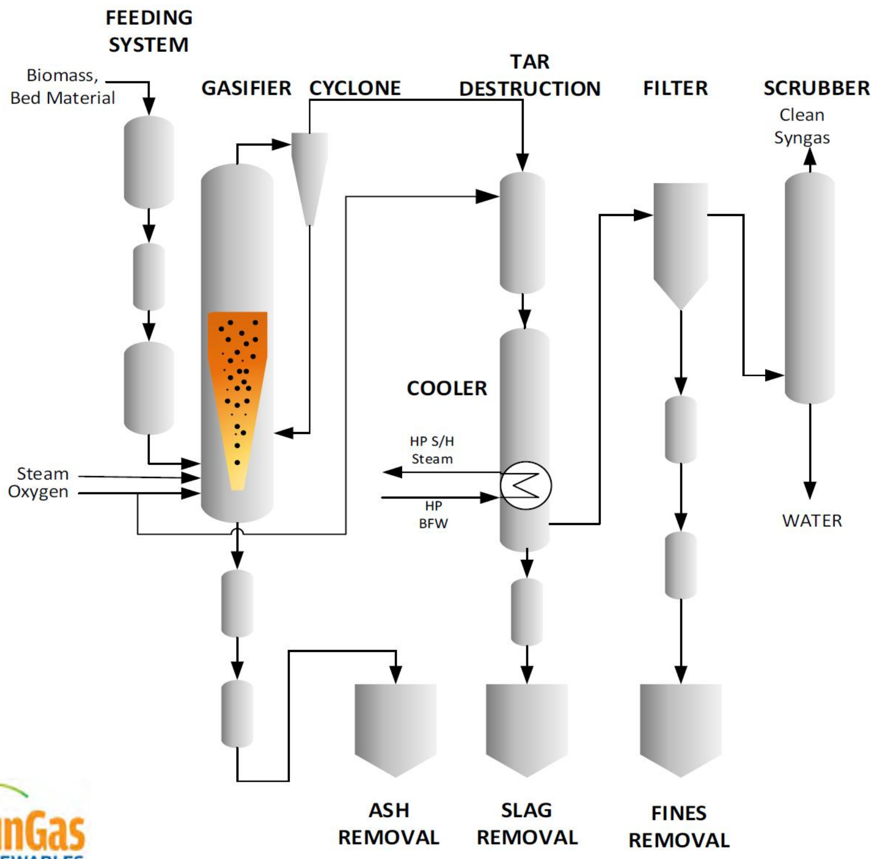
3) Technologies and projects for biomass and waste to hydrogen

3a) Bubbling fluidised bed gasification

GTI U-Gas, SunGas, Andritz

SunGas bubbling fluidised bed biomass gasification to syngas. Based on GTI U-Gas® technology.

- Fluidised bed gasifier reactor with separate tar reformer
- Lock hoppers and screw feeder to the gasifier enable batchwise solid feed introduction whilst maintaining continuous operation of the gasifier
- Lock hoppers remove ash from the base of the gasifier



https://sungasrenewables.com/wp-content/uploads/2022/04/SunGasBrochure-Rev007-04-07-22_SunGas-Gasification-Island-Battery-Limits-Inputs-and-Outputs.pdf

ANDRITZ* Bubbling Fluidised Bed for wood pellets gasification to syngas, Skive, Denmark. Motivation in this case is heat and power. In other deployments, the syngas could be used for hydrogen production.

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*Technology acquired from Carbona in 2005

https://www.gti.energy/creating-combined-heat-and-power-from-biomass-gasification-in-skive-denmark/
https://www.andritz.com/products-en/group/pulp-and-paper/power-generation/gasification/bfb-gasifiers

3b) Plasma gasification

Plagazi, Sweden using INENTEC technology for MSW gasification

The technology used by Plagazi: InEnTec plasma gasification. InEnTec has 13 Reference plants operating on biomass and MSW.

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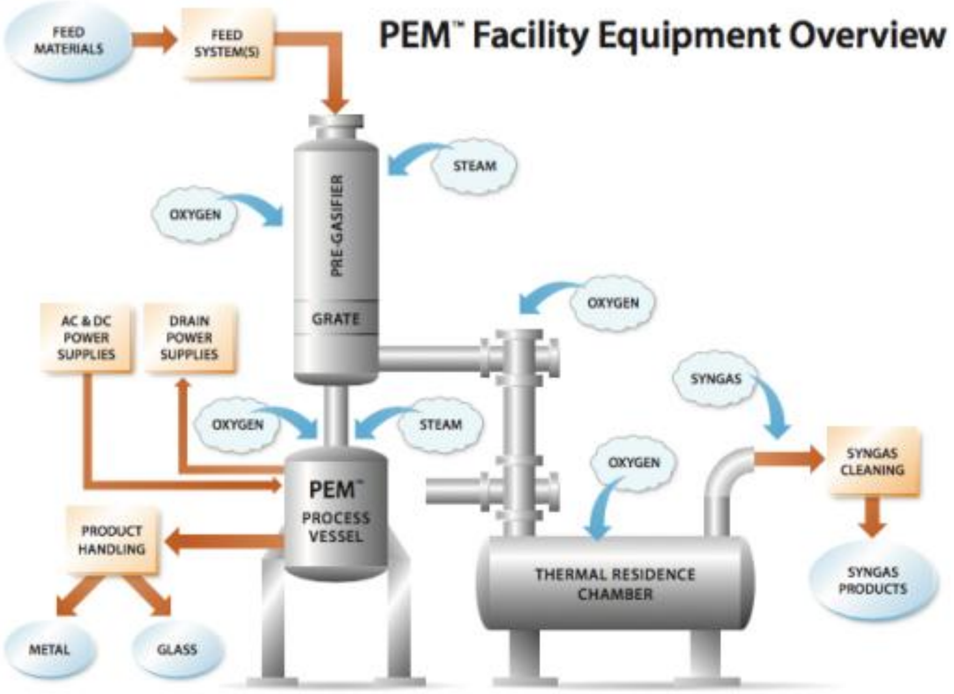
1. MSW delivered to system through an airlock into an airtight housing
2. Plasma torches at the bottom provide heat
   a) Plasma is an ionised gas where electrons flow freely
   b) Plasma is a highly efficient conductor of electricity and generator of heat
3. Controlled amounts of oxygen or air, steam may be injected above the torches (steam is a source of both oxygen and hydrogen).
4. Syngas is produced (H_2, CO, CO_2) which then passes to filtration and purification systems
5. Slag is also formed



Plagazi demonstration plant, Oregon

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Image courtesy of and copyright Plagazi.

Köping Hydrogen Park, Sweden. Planned to be operational in 2025. MSW to hydrogen and heat.

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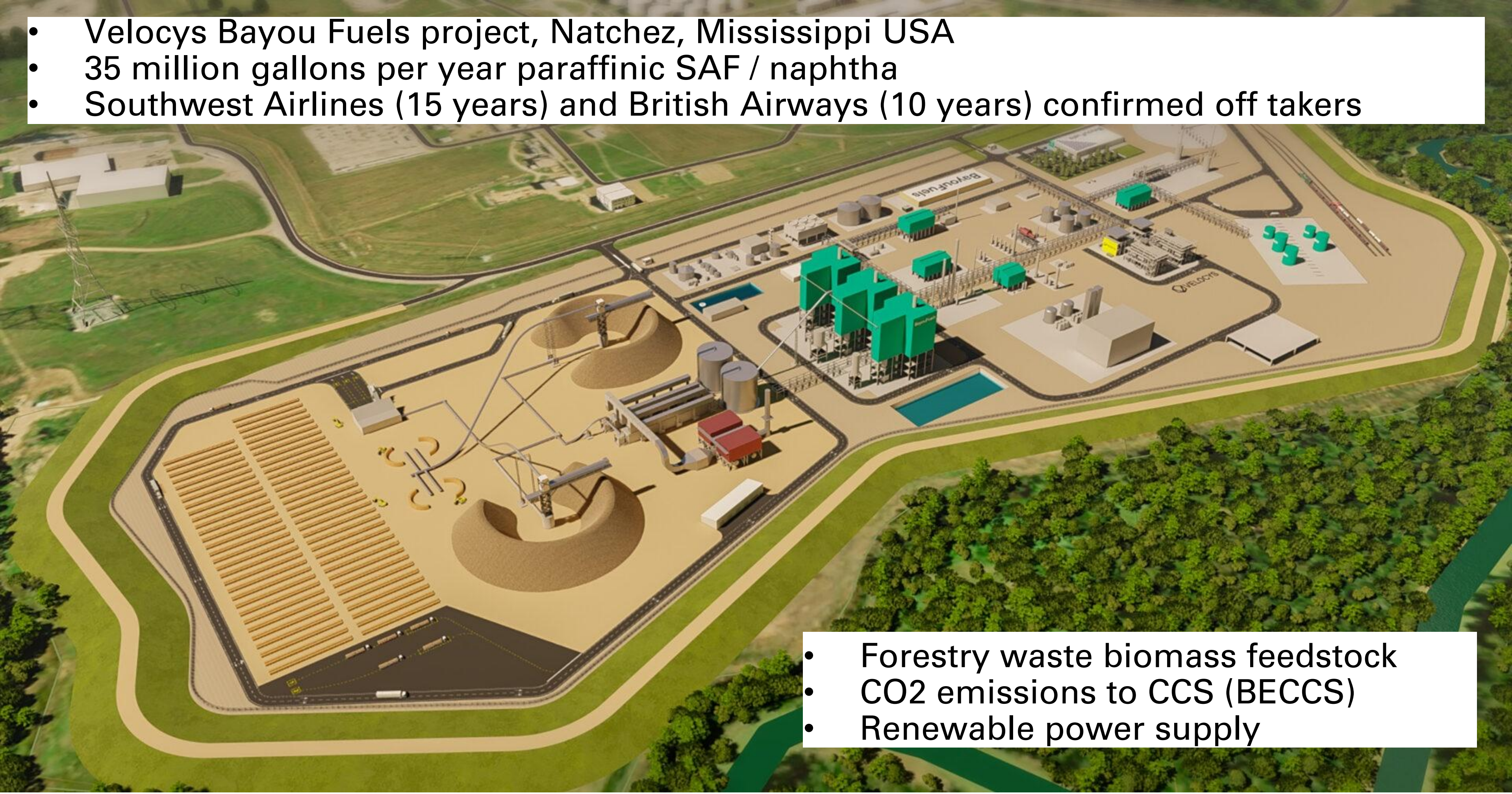
- 3x HE-2000 Plagazi plants
- Power consumption of 10 MW for the plasma and other BOP
- Feedstock: 66,000 tonnes of non-recyclable waste annually
- 12,000 tonnes per year of fuel-cell grade hydrogen produced
- 10MW of district heating
- 150,000 tonnes of liquid CO_2 per year produced for various industrial processes

https://en.plagazi.com/nyheter-press
https://www.plagazi.com/k%C3%B6ping-hydrogen-park

3c) Hydrogen derivatives from biomass and waste

- Velocys Bayou Fuels project, Natchez, Mississippi USA
- 35 million gallons per year paraffinic SAF / naphtha
- Southwest Airlines (15 years) and British Airways (10 years) confirmed off takers



- Forestry waste biomass feedstock
- CO_2 emissions to CCS (BECCS)
- Renewable power supply

GIDARA Amsterdam: pelletised waste wood and RDF gasification for methanol with CO2 offtake

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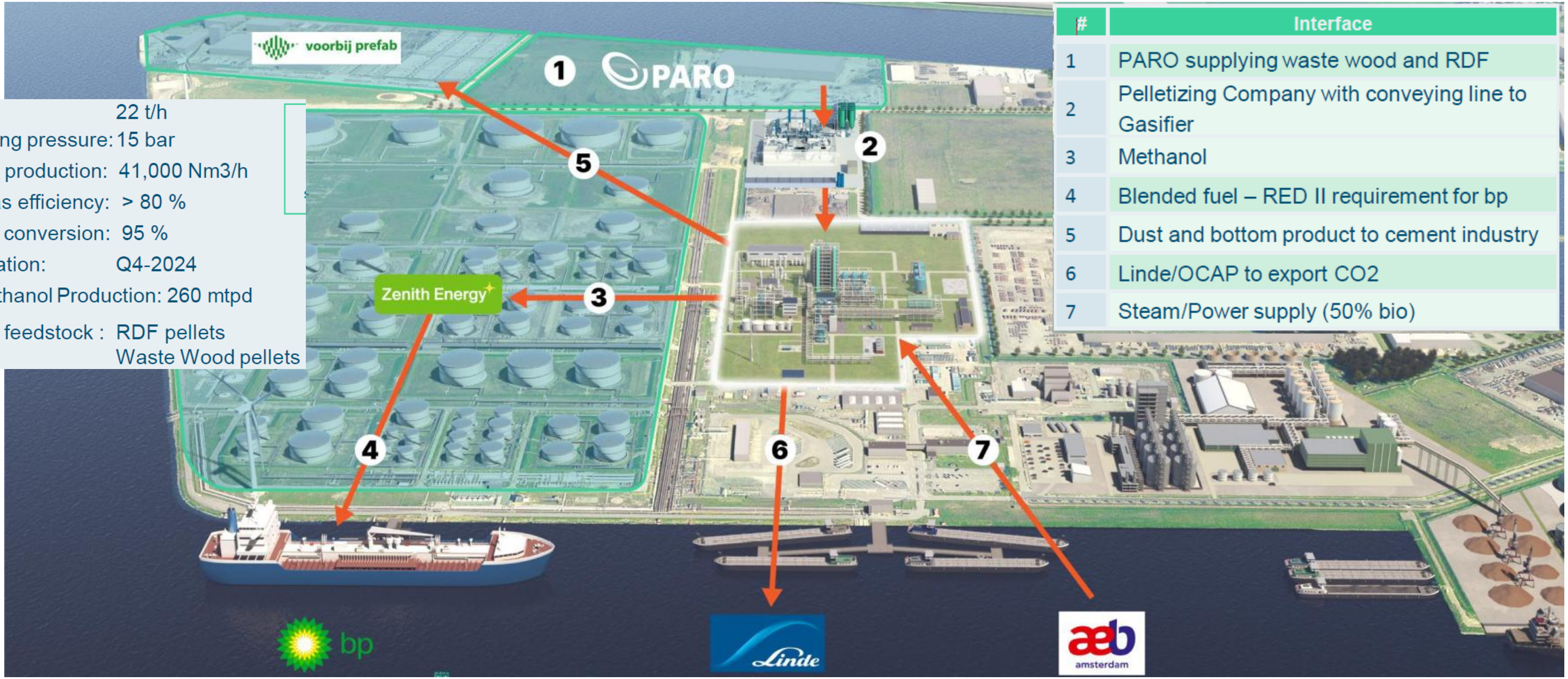
Feed:	22 t/h
Operating pressure:	15 bar
Syngas production:	41,000 Nm3/h
Cold gas efficiency:	> 80 %
Carbon conversion:	95 %
In operation:	Q4-2024
Bio-Methanol Production:	260 mtpd
Type of feedstock :	RDF pellets Waste Wood pellets



#	Interface
1	PARO supplying waste wood and RDF
2	Pelletizing Company with conveying line to Gasifier
3	Methanol
4	Blended fuel – RED II requirement for bp
5	Dust and bottom product to cement industry
6	Linde/OCAP to export CO2
7	Steam/Power supply (50% bio)

- ALTALTO, Velocys waste to fuels plant proposal for UK, start-up 2027
- In partnership with British Airways to make SAF
- 500,000 tonnes of MSW per year
- 60,000 tonnes of liquid fuels (kerosene, diesel and gasoline fractions)

https://www.altalto.com/wp-content/uploads/2019/08/plant_model_looking_east_at_height_regrade.jpg

4) Lessons from the past

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https://www.letsrecycle.com/news/worlds-largest-gasification-plant-nears-completion/

Alter NRG Corp (now Sunshine Kaidi), Westinghouse plasma gasifier for TV2. Fabricated by KNM Group, Malaysia. In 2016, during commissioning of TV1, both the TV1 & TV2 plants were abandoned due to difficulties with MSW flow properties in the gasifier, despite the technology being proven at smaller scale.

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https://www.modernpowersystems.com/features/featuresecond-plasma-unit-for-tees-valley-4302650/
https://www.endswasteandbioenergy.com/article/1330160/uk-second-tees-valley-plasma-gasifier-fabricated

Fulcrum's Nevada demonstration unit. TRI Gasification, Arvos (Schidtsche Schack) heat exchange technology and Linde POx. But problems with the MSW feed hopper led to low production and the project has defaulted on its bond payments.

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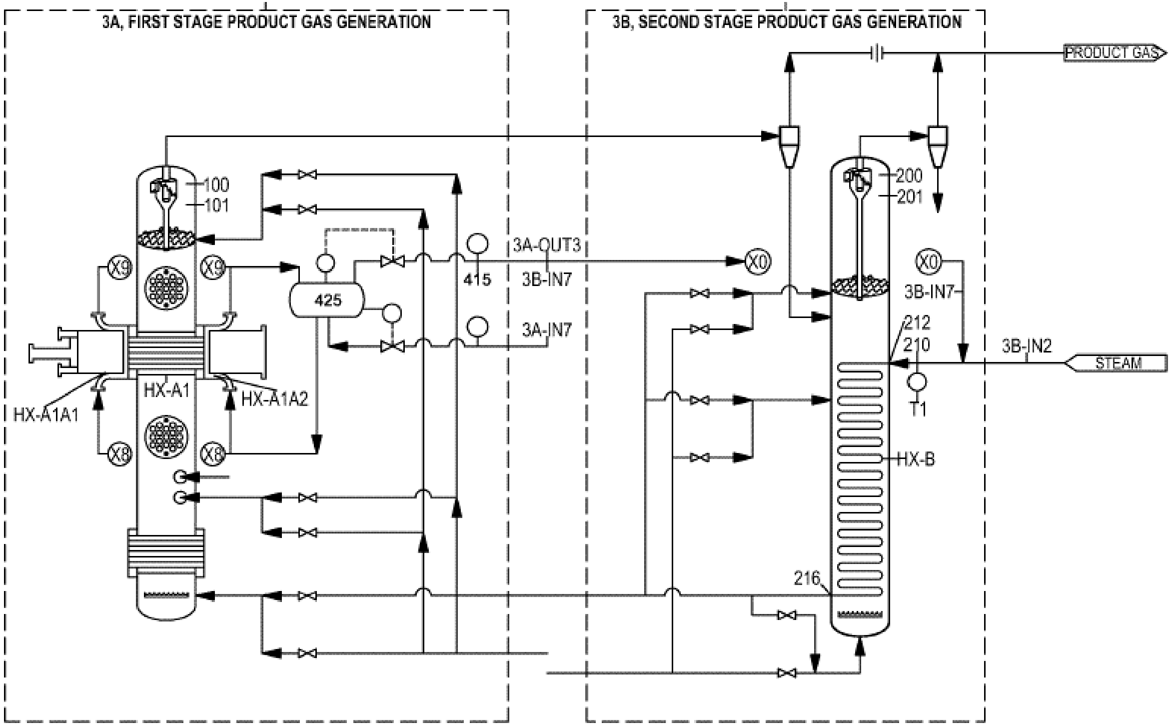

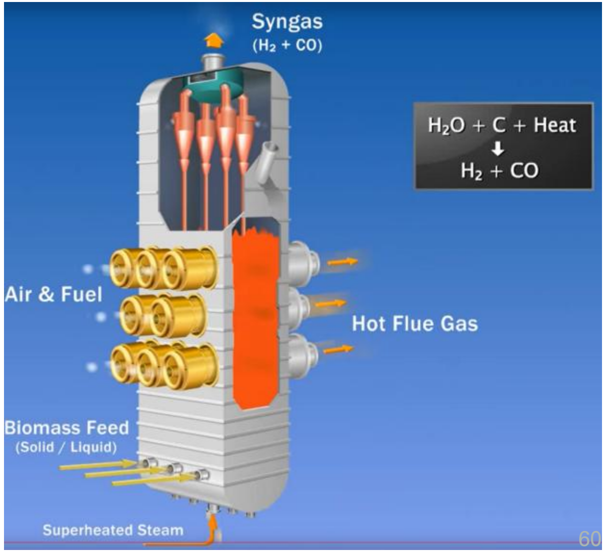

EP 3 416 757 B1
https://tri-inc.net/steam-reforming-gasification/
https://www.schmidtsche-schack.com/company/news-events/details/first-plant-to-turn-household-waste-into-jet-fuel

Fulcrum Bioenergy: will the issues at Sierra, Nevada derail expansion proposals to other facilities in USA and UK?

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- Sierra
  - Circa 150,000 MTPA of MSW per year
  - 11 million gallons per year of clean fuels
  - 80% CO_2 emissions reduction vs fossil fuel
  - Oxygen-fed gasifier (Linde HOT technology)
  - Wet gas scrubbing and CO enrichment of syngas
  - FTS conversion to syncrude on site
  - Syncrude refined to fuels by Marathon Petroleum
- Larger proposed projects now on hold!
  - Each at circa 100 million litres of synfuels per year
  - Trinity Fuels Plant, Gulf coast, 600,000 MTPA MSW, 2025
  - Gary, Indiana, 600,000 MTPA MSW, 2026
  - NorthPoint, Cheshire, UK, 600,000 MTPA MSW, 2027

https://www.fulcrum-bioenergy.com/sierra-biofuels

MSW to RDF preparation with pelletising and torrefaction can assist materials handling in the gasifier.

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https://www.kx-machinery.com/msw-isw-briquette-machine/
https://eqtec.com/the-case-for-converting-municipal-waste-into-energy-with-gasification/

5) Waste to energy and electrolysis as a pathway to hydrogen

Classical "waste to energy" using combustion / incineration vs gasification.

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	Combustion	Gasification
Air flow for stoichiometric conversion	High, due to combustion to CO_2 and H_2O and excess oxygen	Low (very low with pure oxygen)
Reactor capex cost / complexity	Low	High
Gas cleaning equipment size	Large, due to high air flow	Small
Partial pressure of impurities	Low, due to high air flow	High (very high with pure oxygen)
Able to operate at pressure	No, due to high cost of air compression	Yes, with air-tight fed hopper arrangement
CCS potential for CO_2 emissions reduction	Low, due to high nitrogen gas flow, low pressure and low partial pressure of CO_2	High when operated at pressure with oxygen feed
Dioxins, NO_x and SO_x	High, due to high air flow	Low
Tar formation	Low, oxidised during combustion	High – needs downstream mitigation
Halogens and heavy metals	Must be mitigated for environmental reasons	Must be mitigated for environmental and downstream gas processing reasons
Hydrogen production	None	Yes, in syngas / producer gas

Waste to energy, then power to hydrogen through electrolysis for bus fleet operation in Wuppertal, Germany.

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1) Incineration of unrecyclable, sorted residual municipal solid waste (MSW) “Restmüll“ (biogenic fraction close to 50%)
2) Power generation on 427,000 tonnes per year MSW to energy plant (2x 20MW electrical power turbines)
3) Excess power generation (during low electricity demand periods) to a 1.25MW Hydrogenics hydrogen electrolyser
4) Maximator integrated hydrogen storage of 425kg hydrogen capacity and Hydrogen Refuelling Station (HRS)
5) Certified “green“ hydrogen for local Van Hool A330 Fuel Cell Electric Bus fleet

https://commons.wikimedia.org/wiki/File:Luftbild_M%C3%BCllverbrennungsanlage_Wuppertal.jpg

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Introduction to Stephen B. Harrison and sbh4 consulting

sbh4 consulting

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.