Alternative fuels in detail: Fuels under development

Hydrogen

Overview

- Background and key characteristics
- Hydrogen fuel production value chain
- Feedstocks and energy sources
- Production technologies
- Onshore requirements
- Onboard requirements
- Regulations, standards and guidance
- Environmental impact
- Cost overview
- Barriers and risks
- Summary

Background and key characteristics

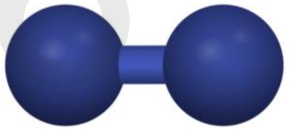
HFO

- Energy density: 42 MJ/kg = 35 MJ/dm^3.
- Flashpoint: 60°C.
- Water solubility: None.
- Most widely-used fuel.

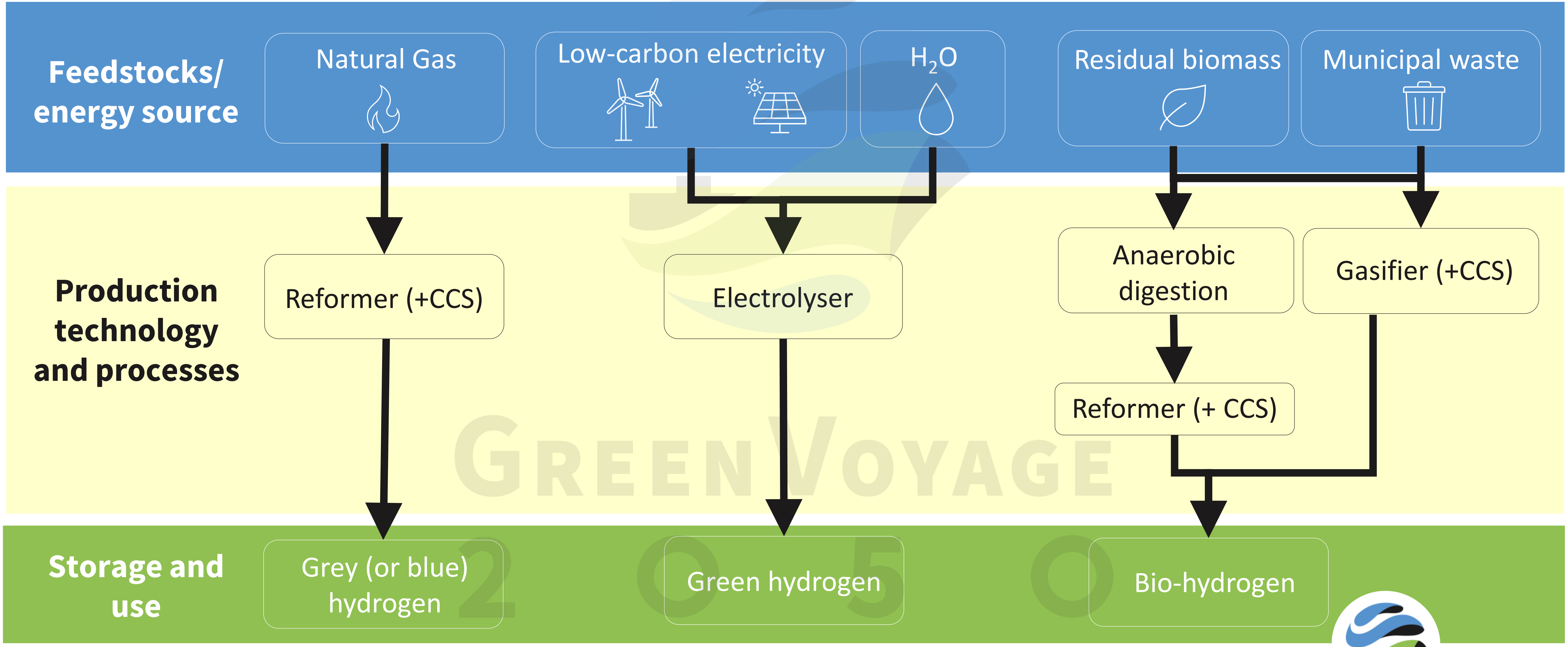
Hydrogen (H_2)

- Stored as compressed gas (GH_2 up to 700 bar) or as a liquid (LH_2 below -240°C) or chemically bound
- H_2 is already considered as a fuel for land-based transport in fuel cell vehicles (cars, buses, trucks and trains)
- Highly flammable (explosion range 4-75 vol %)
- In 2019 global hydrogen demand was 74 Mt
- Commonly used in refineries, ammonia and methanol synthesis

	Gravimetric energy density MJ/kg	Volumetric energy density MJ/dm^3
HFO	42	35
LH_2 −240°C	120 (LHV) **3 x greater than HFO**	8.5 **4 x less than HFO**
GH_2 700 bar rt.		4.5 **~8 x less than HFO**
GH_2 350 bar rt.		2.8 **~12.5 x less than HFO**



Hydrogen fuel production value chains



#Syngas = mixture of $H_2/CO/CO_2/CH_4$

*CCS can be added which makes these biomass routes produce carbon negative hydrogen

Feedstocks and energy sources

Current availability

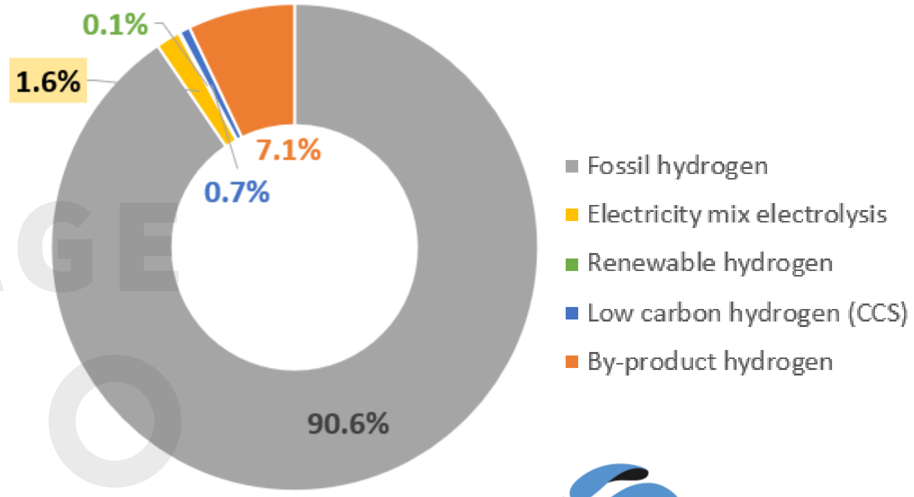
- Natural Gas
- Low-Carbon Electricity
- H_2O
- Residual Biomass
- Municipal Waste

Widely Available | Availability Constrained | Availability Very Restricted

Key Points

- Nearly all hydrogen (95%) is currently produced using fossil feedstocks (natural gas and coal).
- Electrolysis of water has no feedstock limitation, but some regions have higher renewable energy potential and lower costs than others
- Choice of low carbon production route is likely to be determined by local availability of energy e.g. natural gas plus CCS, renewable power or sustainable biomass as well as the economics of transporting hydrogen

European hydrogen generation capacity by technology



Source: Clean Hydrogen Europe (2019)

Production technologies

Production technology and processes	Reformer (+ CCS)	Electrolyser	Anaerobic digestion → Reformer (+ CCS)	Gasifier (+ CCS)
Readiness	TRL 9 (CCS TRL 7)	TRL 7-8	TRL 6-7 (CCS TRL 5)	TRL 6-7 (CCS TRL 5)

*DAC = Direct air capture / PSC = Point source capture
#Syngas = mixture of $H_2/CO/CO_2/CH_4$

Production technologies

Steam methane reforming *Source: Air Liquide*

Biomass gasifier: *Source: www.haiqimachinery.com*

PEM electrolyser: *Source: Nel Hydrogen (PEM electrolyser)*

Onshore requirements

Storage and use | Hydrogen

Storage

- Finding volume-efficient ways to store H_2 is challenging and in its elemental form these are limited to compressed gaseous (GH_2) or cryogenic liquid hydrogen (LH_2)
- GH_2 is stored in high pressure tanks (<700 bar) but safety issues from high pressures
- LH_2 at −253°C in cryogenic tanks but high energy requirements and boil off losses
- Hydrogen can also be chemically stored in carrier molecules e.g. LOHC/NH_3/PtX fuels

Transportation

- If a network is in place, pipelines are the most attractive method for GH_2 distribution
- If trucked, distance to be travelled determines if GH_2 (<300km) or LH_2 is preferred
- Ships have been designed to transport both LH_2 (Kawasaki) and GH_2 as cargo

Onshore requirements

Storage and use | Hydrogen

Bunkering

- No current hydrogen bunkering or regulations due to such low level of use as fuel.
- Bunkering method will be dependent on method of fuel storage (GH_2 or LH_2)
- GH_2 likely to be transferred to ship by direct compression or via a pressure differential
- LH_2 will be bunkered using cryogenic pumps drawing analogies with LNG
- Bunkering could also occur via the direct exchange of container racks

Onboard requirements

Storage

- Compression and liquefaction are expensive and energy intensive.
- Liquefaction at $-253\ ^{\circ}C$ is problematic because of boil-off losses; heavily insulated reservoirs with thick or double-walled vacuum-insulated containers are needed.
- Cold/cryo compression is a hybrid method (40-80K and 300 bar) with no boil off loss.
- 4-13 times larger tanks required for equivalent energy content of HFO.
- GH_2 and LH_2 tanks have fixed cylindrical shapes so cannot pack into void spaces.

Storage and use Hydrogen

Handling

- General safety consideration around the storage of a high-pressure flammable gas on vessels as high-pressure tanks carry the risk of explosion.
- No regulatory requirements available today for hydrogen as a marine fuel
- Crew should be trained on how to maintain a hydrogen system on board a ship and how to handle fire safety.

Onboard requirements

Propulsion

- Hydrogen can be burnt in a specialized internal combustion engine or gas turbine
- Retrofit engine conversions are possible e.g. by modifying the fuel injection system but H_2 is blended with conventional fuels (diesel/LNG) in ICE to aid combustion.
- Hydrogen can be used to generate electricity in fuel cells (PEMFC or SOFC), which can then drive electric motors
- FCs have higher powertrain efficiencies than ICEs, no GHG or air pollutants
- H_2 ICE conversions exist, but FCs at present are only at demonstration level as currently only have 1-2MW power output

Storage and use | Hydrogen

Hydrogen propulsion options

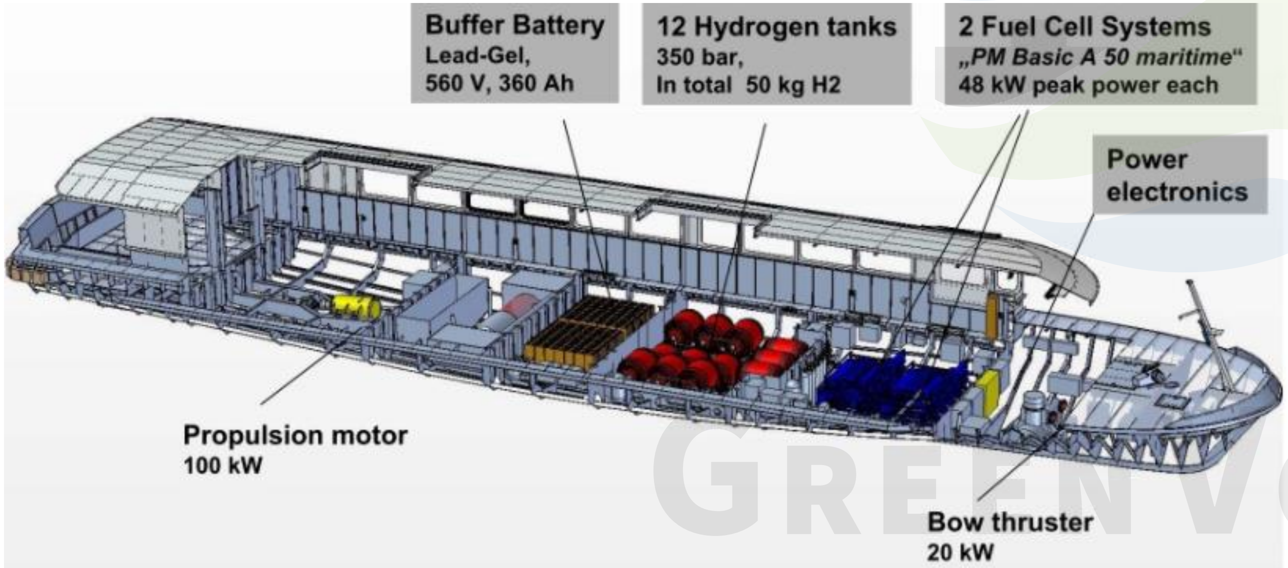
Option	Internal combustion engine (new or retrofit)	PEM fuel cell	Solid Oxide fuel cell
Readiness	TRL 7 (current examples in service)	TRL 7 (current examples in service)	TRL 6
Capital cost	Highly project specific	137 USD/kW[1]	Highly project specific
Efficiency (at shaft)	<55% (project specific)	40-50%	50-65% but <85% if waste heat used

[1] Estimated cost value for mobile applications based on current technologies under development. Royal Society Policy Briefing, 2020, £1=$1.37

Hydrogen engine example

Hybrid PEMFC-Battery engine

- 2x50 kW PEMFC system with a lead gel battery
- 50 kg of GH_2 stored onboard in 350 bar pressurized tanks



Fuel Cell Ship "FCS Alsterwasser" Source: www.blue-growth.org

PEMFC developed by Proton Motors for FCS Alsterwasser

Regulations, standards and guidance

Body/ Organisation	Documentation	Status/Comment
IMO	IGF Code	Current edition doesn't cover H_2 storage or H_2 as a fuel. H_2 storage and use must follow the alternative design approach in accordance with SOLAS Regulation II-1/55. IGC and IGF Codes cover the storage of liquefied gas on board ships, and the C-tank rules in principle cover LH_2
ISO	ISO/TR 15916:2015	Guidelines for the use and storage of GH_2/LH_2. Identifies basic safety concerns, hazards and risks, describes properties of H_2 relevant to safety.
ISO	ISO 20519 - "Ships and marine technology - Specification for bunkering of gas fueled ships"	Under preparation for its final publication. Bunkering and port regulations for bunkering H_2 fuel do not currently exist The bunkering of hydrogen-fuelled ships is subject to national regulations and therefore needs to be evaluated on a case-by-case basis.
ISO	ISO 14687	H_2 purity regulation
DNVGL Rules for Classification	Ships – Part 6 Chapter 2 Section 3 – Fuel Cell Installations	There is no binding international regulatory framework for maritime FC applications but this can be used to classify ships with FCs as FC(Power) or FC(Safety).

Examples of hydrogen vessels and related infrastructure

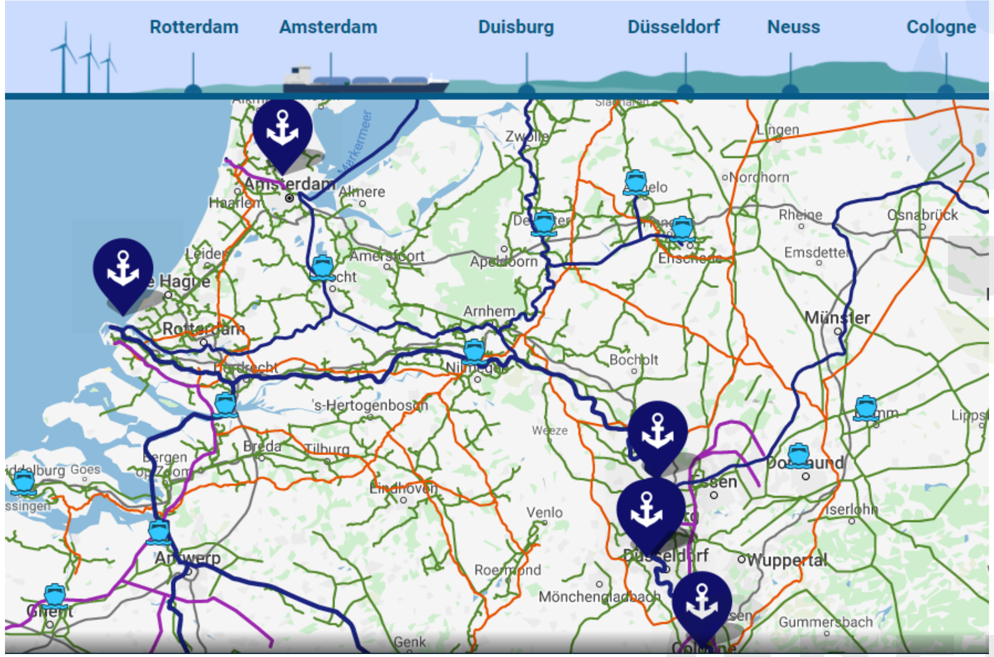
Vessels

- Relatively few (~20) hydrogen boats/ferries are in operation or under construction worldwide.
- The most advanced projects on future commercial application are part of the e4ships lighthouse project in Germany.
- Only small maritime FC applications with an electrical power output of <1MW are currently in operation.
- Hydroville is the first passenger shuttle that uses hydrogen to power a diesel engine (Germany).
- HyDIME project has a green H_2/diesel dual fuel conversion system in a RoPax ferry (Orkney Islands).
- Norled has developed two H_2 powered ferries with 400 kW fuel cells, one powered by LH_2 and one by GH_2 (Norway).
- HySeas III: Developed first vessel powered by green H_2 and FC.

Hydroville vessel, Passenger Shuttle

Source: http://www.hydroville.be/en/hydroville/

Examples of hydrogen bunkering and related infrastructure



RH2INE project inland waterway bunkering

Bunkering and infrastructure

- The RH2INE partnership will develop 3 hydrogen bunkering stations for inland shipping between Rotterdam and Cologne to power at least 10 hydrogen powered vessels by 2024.
- As part of the MARANDA project, hydrogen-storage containers and a fuel-cell system have been designed that are currently being tested and improved before their integration on-board the ship.
- The FLAGSHIPS project has meant vessel operators have started to discuss safety aspects of hydrogen applications on push boats for inland waterways.
- In December 2019, the ‘Hellesylt Hydrogen Hub’ was awarded NOK 37.6m (US$3.4m) from ENOVA for a H_2 supply facility to ships in the Geirangerfjord, 200 km NE of Bergen

Environmental impacts

	Grey/blue H_2	Green H_2	Bio H_2
Emission reduction drivers	• Choice of feedstock • CH_4 production method (SMR vs ATR) • CCS efficiency	• Electricity carbon intensity • Renewable sources vs. grid • Electrolyser efficiency	• Choice of feedstock • CH_4 production method (SMR vs ATR) • CCS efficiency
Well-to-wake GHG emissions vs HFO	**22% reduction (blue) [1] 70% increase (grey)**	**87% reduction [1]**	**Highly feedstock dependent**

Key Points

- **Well-to-Wake emissions also depend on the propulsion method, and phase of fuel (GH2 vs LH2).**
- If a pilot fuel is used alongside H_2 (e.g. MGO) this will lead to CO_2 emissions.
- NO_X cannot be eliminated from ICE but FCs do not produce CO_2, NO_X, SO_X or particulate matter emissions.
- ICE burning H_2 is more difficult to control NO_x, but have the potential to comply with the Tier III NO_x limits without requiring exhaust gas treatment in Otto-cycle engines.
- Compression and liquefaction have different (and significant) energy requirements so WtW emissions will depend whether GH_2 (and its pressure) or LH_2 is used as the fuel.
- Storage and transportation of hydrogen are energy intensive, contributing to overall WtW emissions.

[1] E4tech analysis: Excludes downstream transport, distribution and refueling. Values for liquid hydrogen. MGO pilot fuel used (4.8% on energy basis).

Fuel cost overview

Production route	Grey/Blue H_2	Green H_2	Bio H_2	
Key drivers (Expected trend: positive/negative/either)	• Natural gas price • CCS Capex and OPEX • Cost of carbon	• Green power cost • Electrolyser Capex, utilisation, efficiency	• Biomass feedstock cost and supply • Gasifier capex	
Current cost (per GJ fuel)	11 – 26 USD (unabated) 13 – 27 USD (+ CCS*)	16 – 33 USD	20 – 54 USD	**2020 hydrogen market price vs HFO market price**
Current cost vs. HFO market price (per GJ fuel)[1]	Additional 5 – 14 USD[1]	Additional 10 – 21 USD[1]	Additional 14 – 42 USD[1]	+5 to +42 USD
Potential for cost reduction vs current cost	High for CCS	High	High for gasification	

*high cost uncertainty associated with CCS technology

Source: E4tech analysis

[1]: Based on HFO market price of 250 – 500 USD/tonne.

Barriers and risks

Category	Barrier / Risk	Comment
Commercial	High hydrogen **production costs**, especially green but also blue	High - Excessive fuel cost is strong barrier to widespread adoption. However, significant cost reductions are expected across production pathways and policy action may make economics more favourable.
	Cost of engine **replacement/conversion**.	Medium - Increasing offerings in terms of hydrogen engines/replacements
	Low **volumetric energy density** leads to large tank volume requirements (in fixed shape containers)	Medium - Loss of cargo/passenger space has varying degree of concern depending on the intended application of the vessel
	Currently **no bunkering infrastructure**	Medium – in short-term this is a large barrier to commercial operation

Barriers and risks

Category	Barrier / Risk	Comment
Policy	Lack of **regulations** for bunkering and storage onboard and offboard	High – Hydrogen as fuel is not included in the IGF Code, bunkering procedures, storage and fuel cell standards need identifying.
Sustainability	Variable **sustainability impacts** of biomass and waste feedstocks	Medium – Important to have agreed sustainability criteria for fuel value chains
	Dominance of **fossil fuels** in hydrogen production	High – Hydrogen is almost entirely supplied from natural gas and coal today, which would not meet reduction targets
Technical	**Industrialization and scale up** of electrolyser and fuel cell components	Medium - Lifetime of stacks and reformer units need to be proven
	Safety challenge from high flammability range and low ignition temperature	Medium – Increased ventilation, gas detection, tighter control on sources of ignition
	Infrastructure requirements in the development of suitable transport, and storage technology	Medium – Insufficiencies of current methods for safely and effectively storing and transporting large quantities of high density hydrogen. Hydrogen causes embrittlement for hydride forming metals and hydrogen-assisted cracking for steels, which will affect pipeline and trucking materials and compressor designs.

Hydrogen summary

Key points

- There has been extremely limited deployment as a marine fuel to-date, but promising results achieved by early adopters.
- Production routes use generally well understood processes.
- Decarbonisation success will depend on electrolysis from renewable electricity (green H_2) and CCS (blue H_2)
- Costs are dominated by cost of underlying primary energy source
- Distribution (storage and transportation) – Compressed GH2 is less complex, cheaper and less energy intensive than liquefaction to cryogenic temperatures. LH2 also suffers boil off losses but has a higher volumetric energy density.
- Bunkering infrastructure for ships and its regulation does not currently exist and the bunkering method will be highly dependent on the method of fuel storage
- Combustion engines offer proven robustness, reliability and durability as well as lower costs. Conventional internal combustion engines can be modified to run on hydrogen blends which can be done for new engines or as a retrofit. However, further development is still required
- Fuel cells have higher efficiencies, can be zero emission, do not emit NOx and create less noise and vibrations.