Green Hydrogen and Industrial Policy Development Dialogue

Trade and Industrial Policy Strategies (TIPS)

African Energy Leadership Centre

Wits Business School

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13 March 2024

GROW TRANSFORM LEAD

Industry hype and ambitious forecasts have a chequered history in the energy industry – You need to dig deeper (1/2)

1. Industry hype and ambitious forecasts have a chequered history in the energy industry – You need to dig deeper (2/2)

- There is a developing consensus from COP 26[1] and the oil and gas industry[2] that green hydrogen[3] will play a pivotal role in the Just Energy Transition.
- But consensus can be overrated. *"The fast breeder reactor, is an example of a prolonged and costly innovation failure. In 1974, General Electric predicted that by 2000 about 90 percent of the United States' electricity would come from fast breeders"* [4]
- The current global wave of interest in green hydrogen is the third wave, with earlier waves having occurred in the 1970s and early 2000s [5]
- Not everyone agrees that hydrogen is the answer, and it has even been accused of being greenwashing and that it is a cult[6]. It can be argued that by and large the energy future is likely to be electrical rather than hydrogen except, perhaps, for some niche hard to decarbonise areas.
- The EU has recently announced it intends to produce 10 million tons per annum (tpa) of green hydrogen and import a further 10 million tpa by 2030[7]
- The South African and German governments together with Sasol have launched a collaboration to make sustainable aviation fuel which is based on green hydrogen[8]

1. https://rmi.org/cop26-made-clear-that-the-world-is-ready-for-green-hydrogen/
2. https://www.thenationalnews.com/business/energy/2021/11/22/why-green-hydrogen-is-shaping-the-future-of-oil-and-gas-majors/
3. Green hydrogen is defined as hydrogen produced by splitting water into hydrogen and oxygen using renewable electricity.
4. Vaclav Smil, Numbers don't lie. https://www.amazon.com/Numbers-Dont-Lie-Things-About-ebook/dp/B084DKCQHG
5. https://www.resilience.org/stories/2021-05-21/a-concise-history-of-the-concept-of-hydrogen-economy/
6. . https://www-forbes-com.cdn.ampproject.org/c/s/www.forbes.com/sites/jamesmorris/2021/12/11/hydrogen-is-not-a-fuel-its-a-cult/amp/
7. https://www.rechargenews.com/energy-transition/eu-plan-to-import-vast-amounts-of-green-hydrogen-from-north-africa-makes-little-sense-study/2-1-1220081
8. https://www.energyvoice.com/oilandgas/africa/lng-africa/414033/german-scholz-senegal-kerosene/

Who is right? The answer matters

Executive Summary

Green hydrogen is enjoying a resurgence of interest as a potential central pillar in the renewable energy transition

The production of green hydrogen at the multi-GW scale required is technologically challenging and capital intensive

The current levelised delivered cost for green hydrogen is ±8$/kg which is roughly equivalent to an oil price of $400/bbl

The forecasts for dramatic decreases in both the costs of producing and transporting hydrogen are uncertain

There are several competing options to green hydrogen with the direct use of green electricity being the most prominent.

The use of green hydrogen as a complete solution in the renewable energy transition is potentially over hyped

There are very significant megaproject business and execution risks for pioneers in multi-GW green hydrogen

There is a role for green hydrogen in hard to decarbonize areas such as nitrogenous fertiliser

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9. https://en.wikipedia.org/wiki/Energy_density

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2. Why is hydrogen a potentially good fuel?

Energy density is crucial

Energy density[9] is the amount of energy that can be stored in a given system, substance, or region of space. Energy density can be measured in energy per volume or per mass.

Fuel Type	Mass Energy Density MJ/kg	Volume Energy Density MJ/ℓ
Antimatter	90,000,000,000	It depends
Diesel	46	39
Petrol	46	34
Liquified natural gas (LNG -160 °C)	54	22
Liquid Ammonia	18.6	11.5
Hydrogen Liquid (-253 °C)	120	8.5
Zinc Air Battery	1.6	6.0
Hydrogen at 700 bar	120	5.0
Lithium Ion Battery	0.36-0.88	0.9-2.6
Water at 100m dam height	0.00098	0.00098

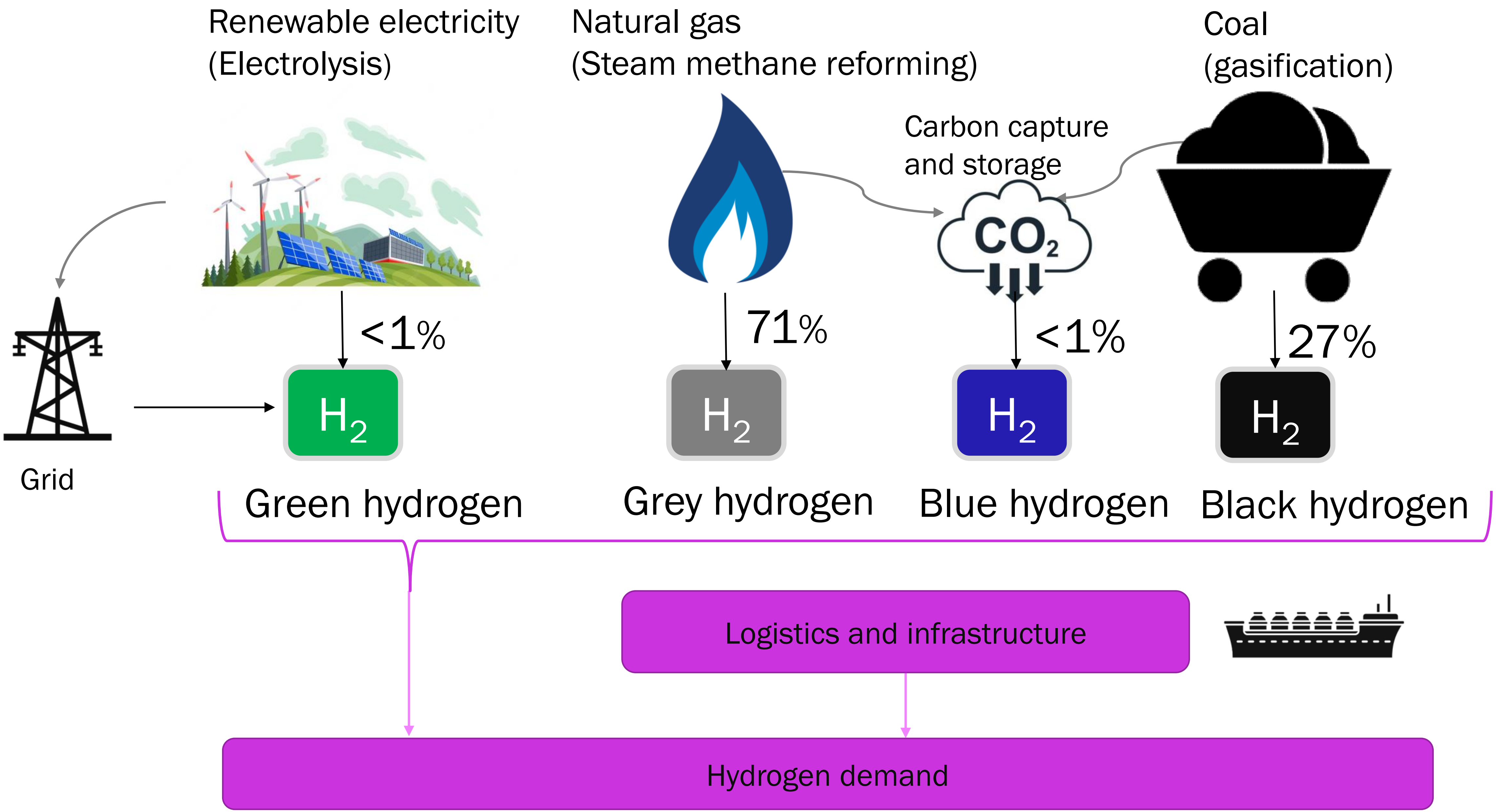
Decreasing volume energy density

Hydrogen has a good mass energy density but a relatively poor volume energy density and requires extreme storage conditions making it expensive to store

Hydrogen's other party trick is that it burns cleanly producing only water and no greenhouse gases

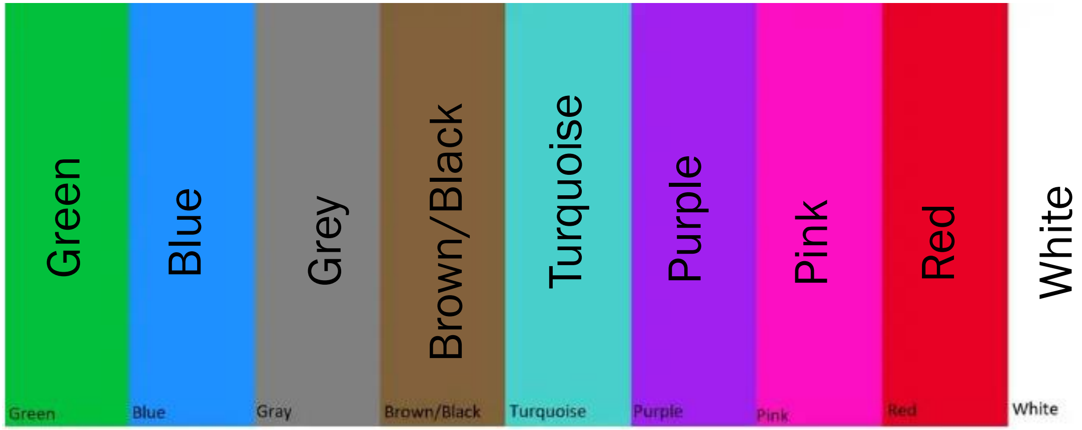
9. https://en.wikipedia.org/wiki/Energy_density

3. The hydrogen rainbow and green hydrogen (1/2)



3. The hydrogen rainbow and green hydrogen (2/2)

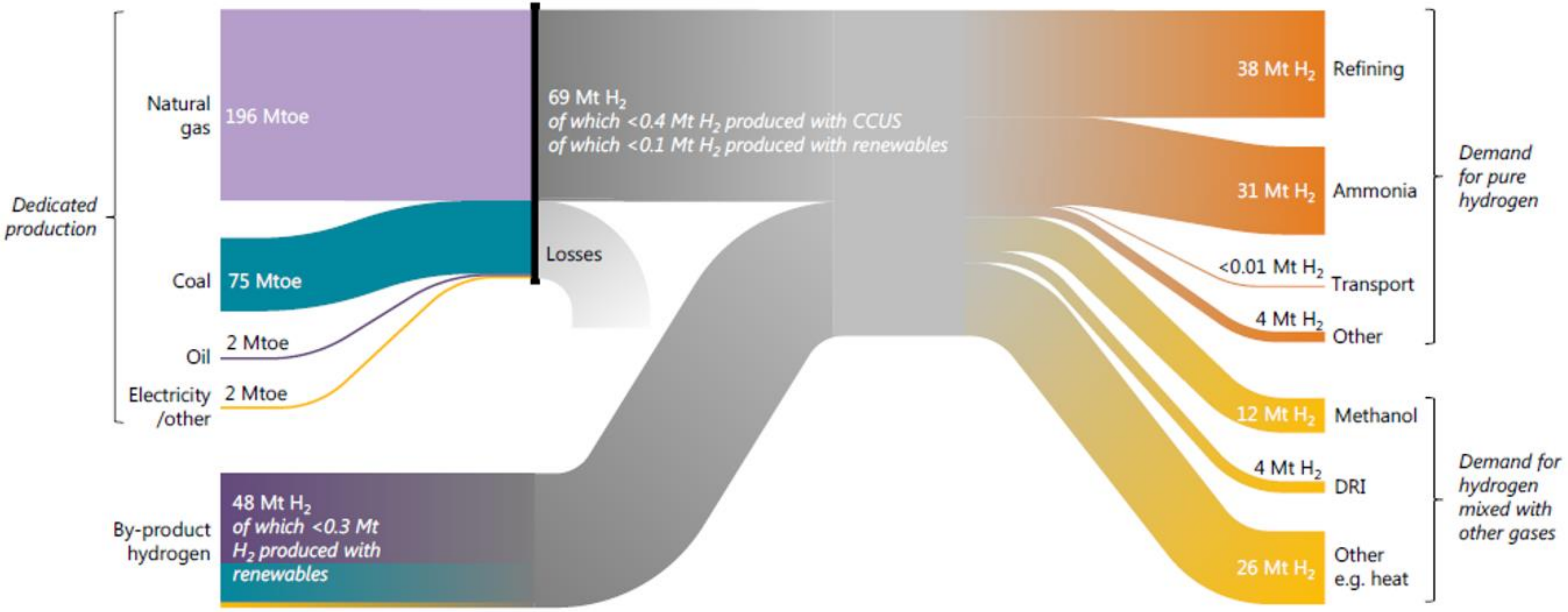
The colour codes of hydrogen refer to the source or the process used to make hydrogen. These codes are: green, blue, grey, brown or black, turquoise, purple, pink, red and white.



- Green hydrogen is produced through a water electrolysis process using renewable electricity
- Blue hydrogen is sourced from fossil fuel. However, the CO_2 is captured and stored underground
- Grey hydrogen is produced from fossil fuel and commonly uses steam methane reforming (SMR).
- Black or brown hydrogen is produced from coal.
- Turquoise hydrogen can be extracted by using the thermal splitting of methane via methane pyrolysis. Carbon is stored as a solid.
- Purple, pink and red hydrogen use nuclear energy and are speculative
- White hydrogen refers to naturally occurring hydrogen

Almost all hydrogen produced today is grey or black and is produced from fossil fuels. Green hydrogen production is very small

4. Why does the oil and gas industry like hydrogen? (1/2)



Todays (2019) Hydrogen Value Chains[10]

Source IEA 2019[10]

10. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

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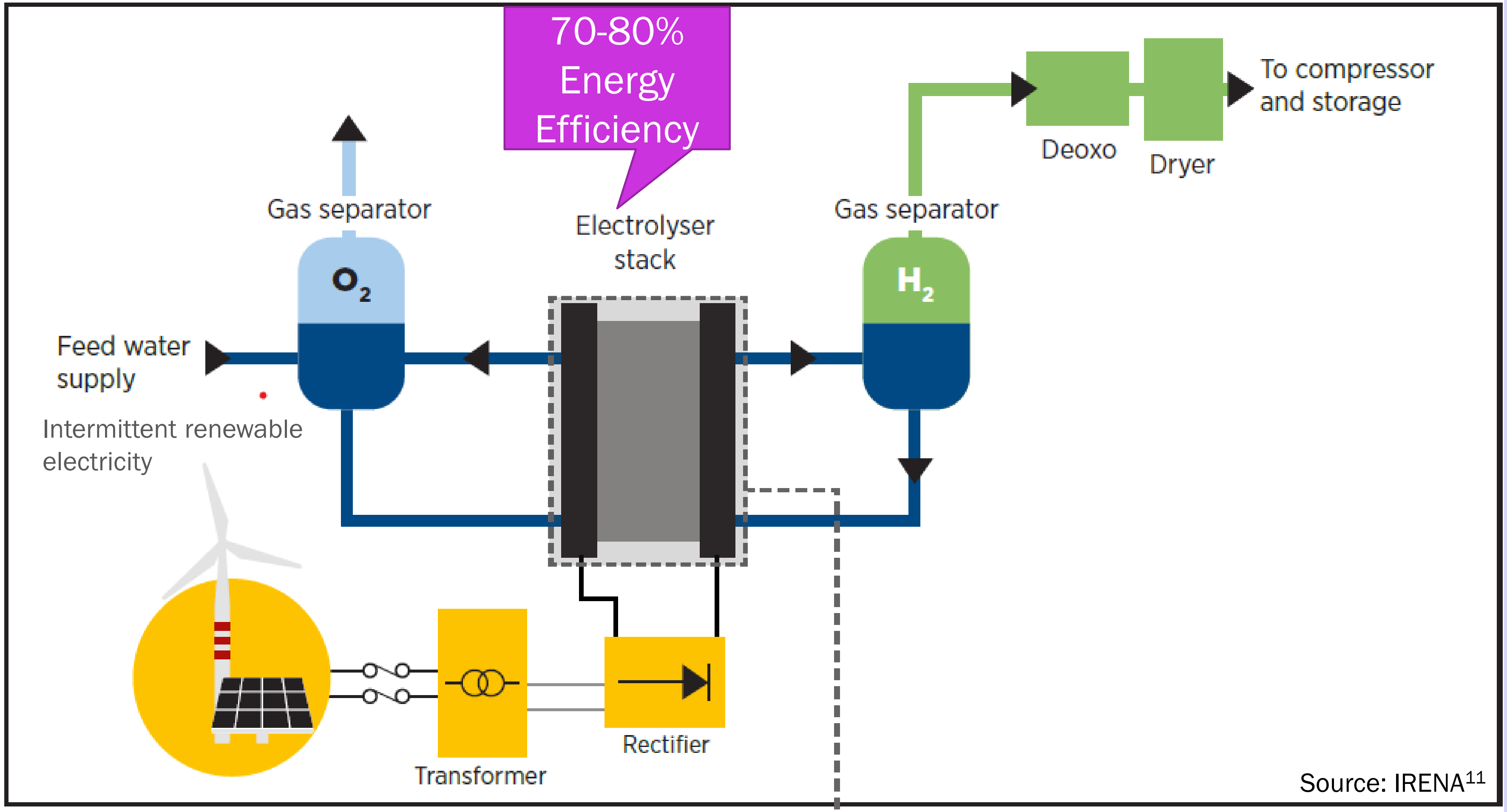
4. Why does the oil and gas industry like hydrogen? (2/2)

- Almost all of today's hydrogen is produced from fossil fuels emitting CO_2
- Use of hydrogen as a fuel fits with the oil major's current business model. They control the fuel production, supply and the wholesale and retail distribution of hydrogen fuel
- The oil majors can supply grey (or blue) hydrogen to transition to green hydrogen
- The direct use of electricity for battery electric vehicles and trucks represents an existential risk for the oil majors. Their wholesale and retail business model could break down
- The oil & gas industry has a strong vested interest in promoting green hydrogen to try and ensure their survival
- The referenced IEA report did not capture the fact that Sasol Secunda is a major producer of black hydrogen which could be used for process development and market seeding for later green hydrogen

The oil and gas industry has a vested interest in promoting hydrogen

5. Green hydrogen production[11,12,13] (1/2)



Source: IRENA[11]

- Largest commercially available electrolyser stack is 2-5 MW with plans for 20 MW
- Electrolyser technology is not mature and there are different technology options under development with no clear winner at this stage
- Efficiency, durability and cost for GW scale electrolysers are a significant challenge
- Pioneers of GW scale projects face significant technology risks

11. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf
12. https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II
13. https://www.iea.org/reports/the-future-of-hydrogen

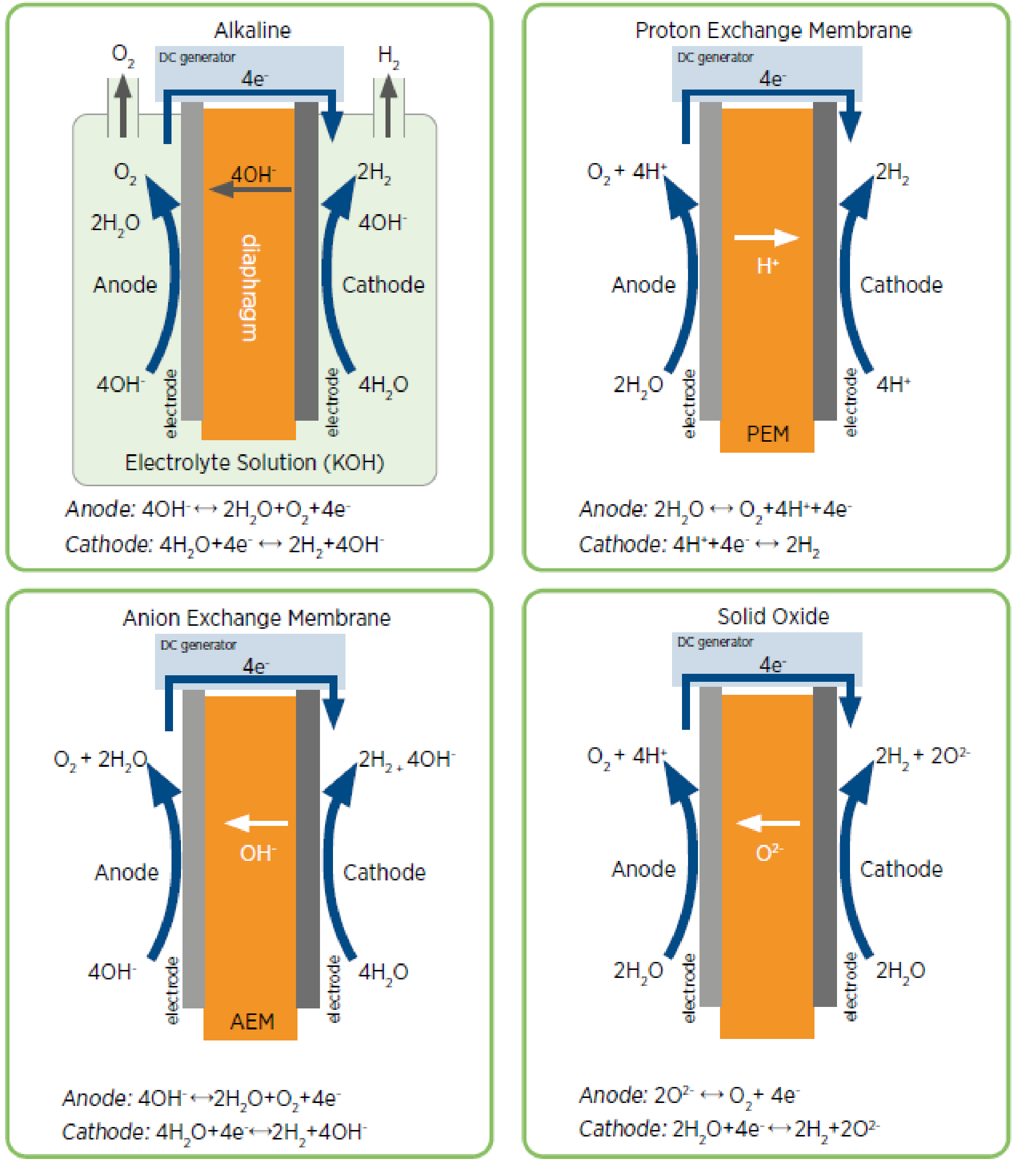
5. Green hydrogen production (2/2)

Different types of commercially available electrolysis technologies.

Most Mature

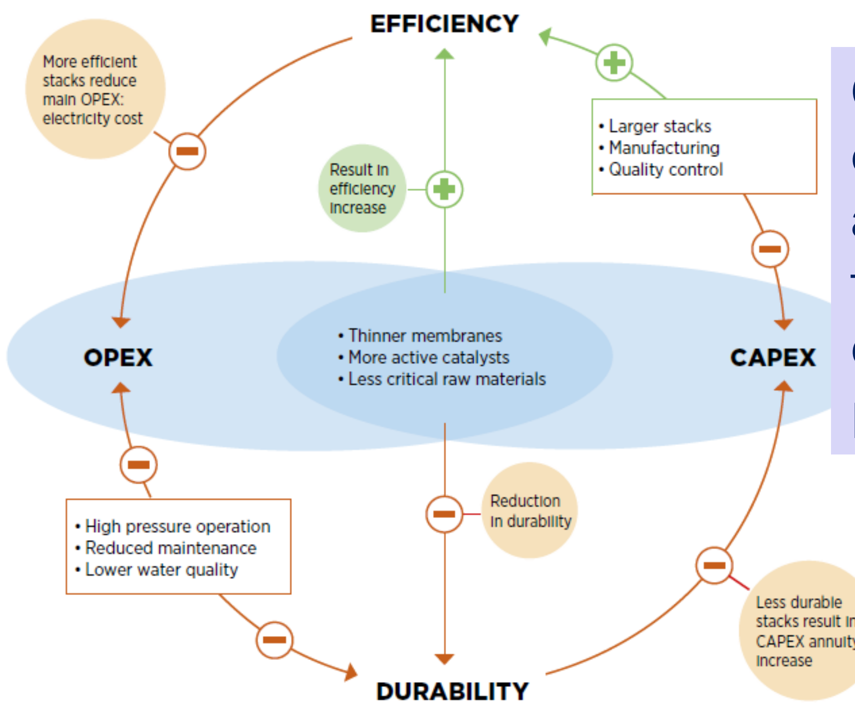
Not commercially proven at scale

In development phase



"Each technology has its own challenges, from critical materials to performance, durability and maturity; there is no clear winner across all applications[11]"

Trade-offs between efficiency, durability and cost for electrolysers.

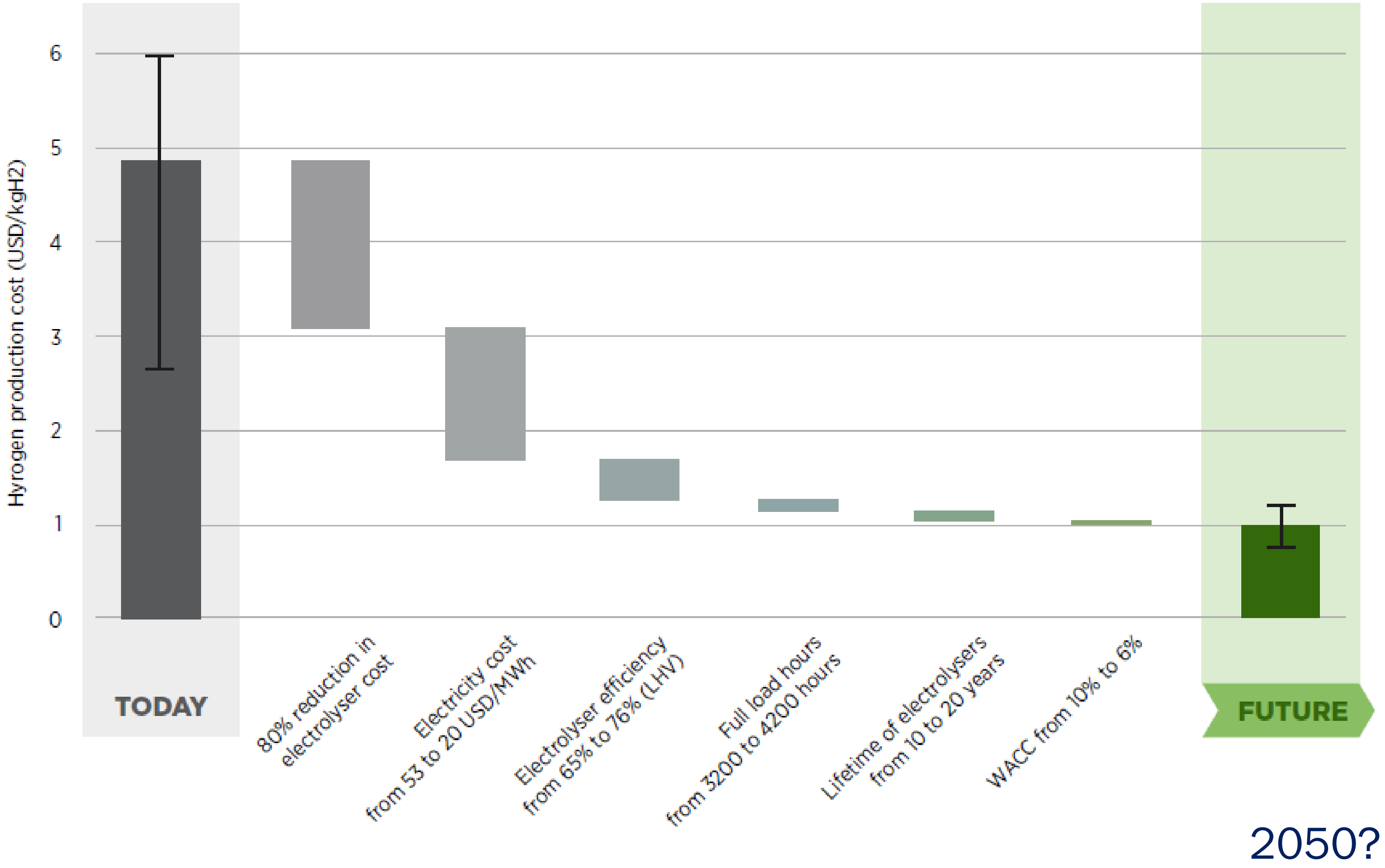


Note: The arrows represent a direct impact or effect from the R&D of a given material or component over each relevant dimension. CAPEX = capital expenditure; OPEX = operational expenditure.

GW scale electrolysers are still in the development phase

It will take decades to refine, optimise and perfect these technologies and some of them may be discarded

6. What does green hydrogen cost and can its cost be reduced? (1/2)



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

Source Irena[11]

- Current green hydrogen costs (at the factory gate) are ±5$/kg
- Based on a set of highly optimistic assumptions it is hoped hydrogen prices can reduce to 1 $/kg over decades
- 5 $/kg is equivalent to an oil price of about **250 $/bbl**
- The USA is proposing government subsidies of up to $3/kg to kick start the green hydrogen industry and enable competition with grey hydrogen[14]

14. https://www.rechargenews.com/energy-transition/us-green-h2-would-become-worlds-cheapest-under-tax-credit-plan-in-new-manchin-approved-bill/2-1-1268259

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6. Green hydrogen capital costs[15] (2/2)

	Alkaline Technology	PEM Technology
Hydrogen production capacity (tpa)	165000	150000
Capital Cost (€ billion)	1.4	1.8
Capital intensity (€/kW)	1400	1800
Capital Intensity (€/kg/day) hydrogen)	3100	4400

Capital cost estimates for total installed costs for a 1 GW green hydrogen plant [15] (-25%, +40% accuracy range)

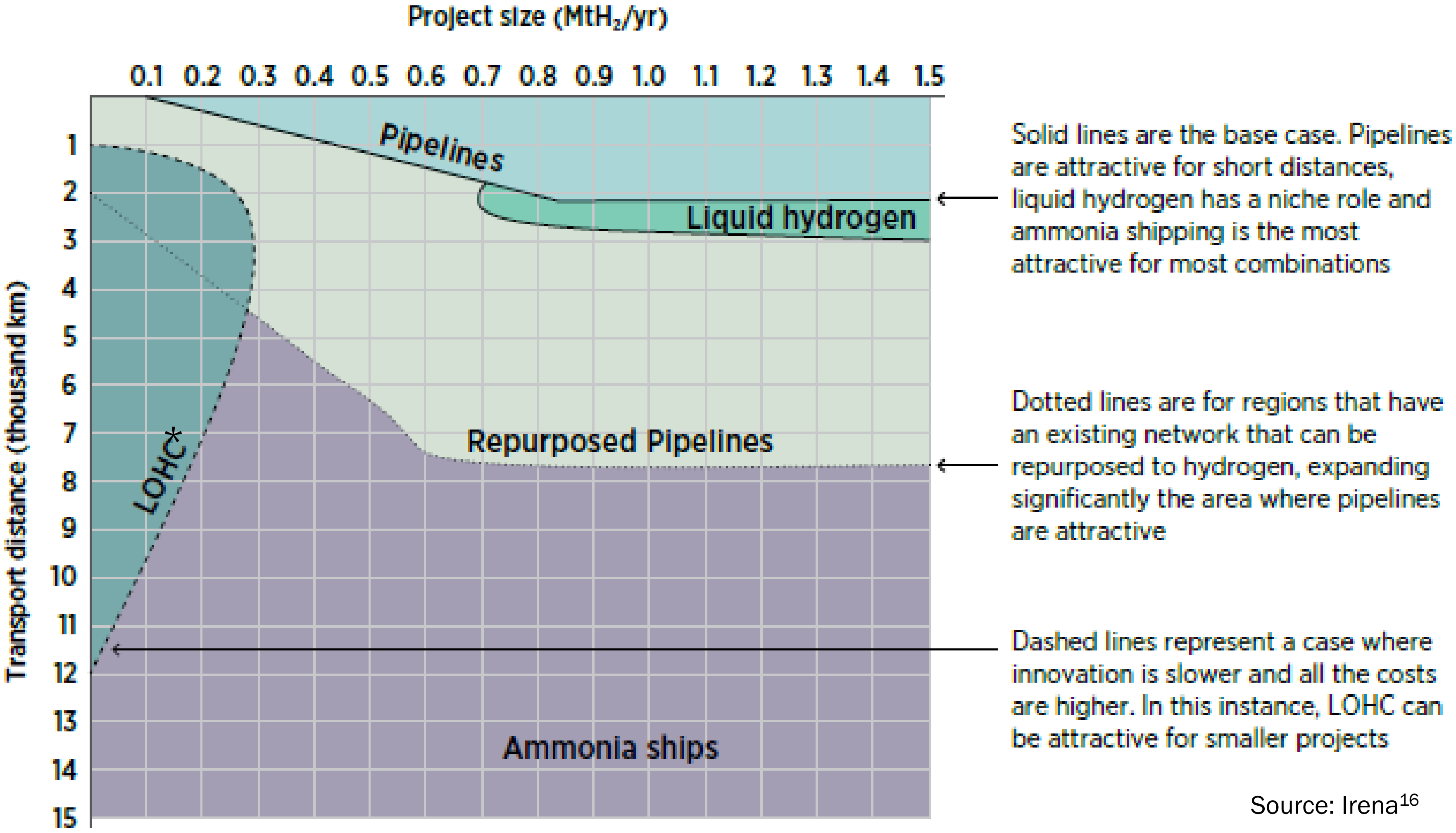
- European Union (EU) ambition for 20 million tpa of green hydrogen by 2030 implies:
  - 20-40 pioneering megaprojects (capital >$1 billion) of size 1-5 GW
  - Capital costs in the range of €170-240 billion.
  - Potential subsidies of up to $60 billion per year

Given the timescale to design, finance, approve, commission and run energy megaprojects the first wave of projects constructed before 2030 will all be first generation pioneering projects

Second generation projects where lessons learned, and technology improvements have been made will follow post 2030

15. https://ispt.eu/media/ISPT-public-report-gigawatt-green-hydrogen-plant.pdf

7. How do you transport hydrogen and what does it cost? (1/3)



Source: Irena[16]

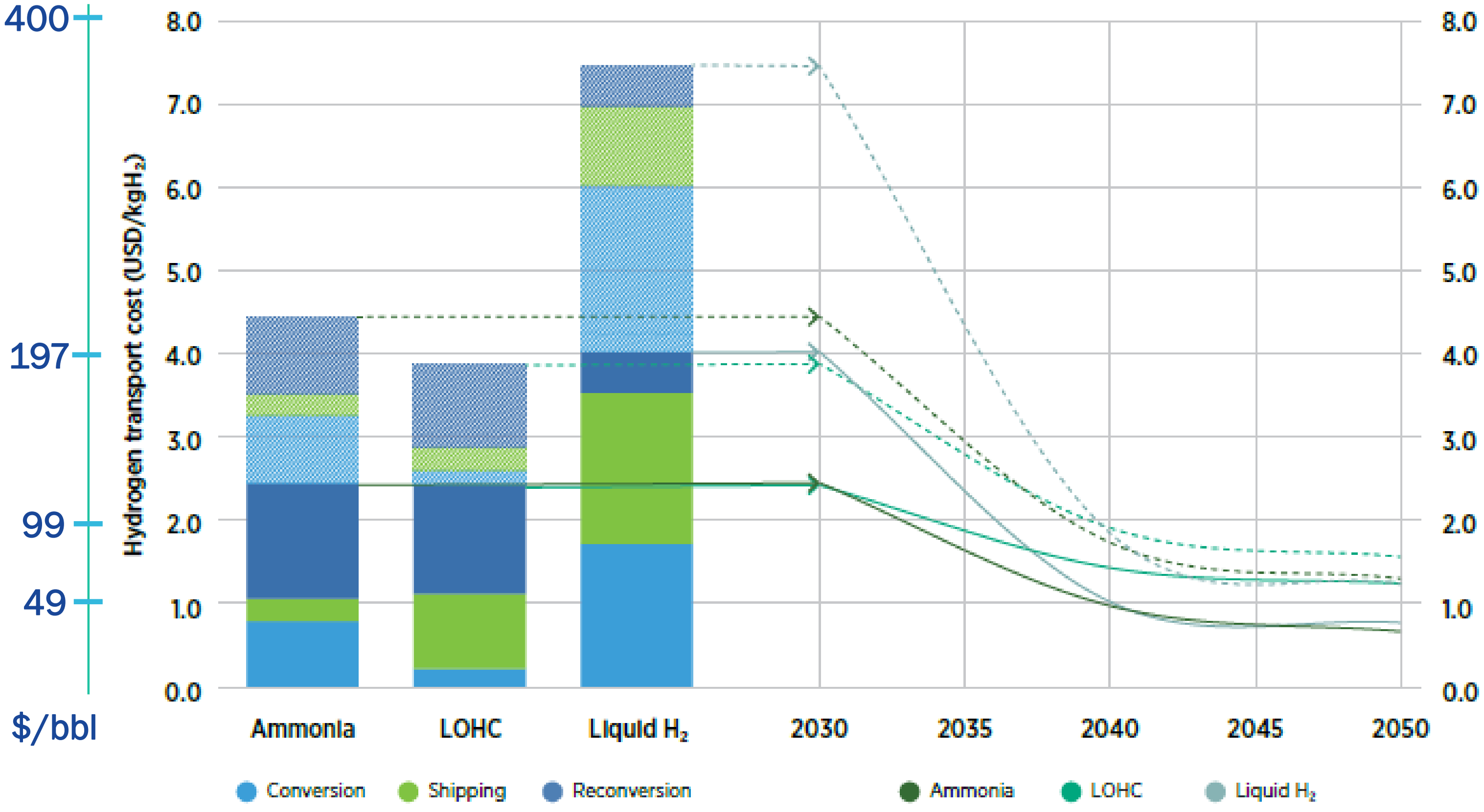
Export of green hydrogen from Southern Africa requires converting the hydrogen to ammonia, shipping the ammonia and cracking the ammonia back to hydrogen at the destination. This is costly and causes efficiency losses

* Liquid organic hydrogen carriers (LOHC)

16. https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

7. How do you transport hydrogen and what does it cost? (2/3)

Transport cost breakdown by carrier and stage for 2030 (left) and evolution towards 2050 (right)



Notes: Solid areas (left) and solid lines (right) represent the most optimistic technology conditions assuming innovation and economies of scale are the most favourable. In contrast, shaded areas (left) and dashed lines (right) represent a pessimistic scenario with lower global co-ordination, less learning and slower innovation. Distance of 10 000 km. Scale of 0.5 MtH_2/yr in 2030 increasing to 1.5 MtH_2/yr by 2050.

Source: Irena[16]

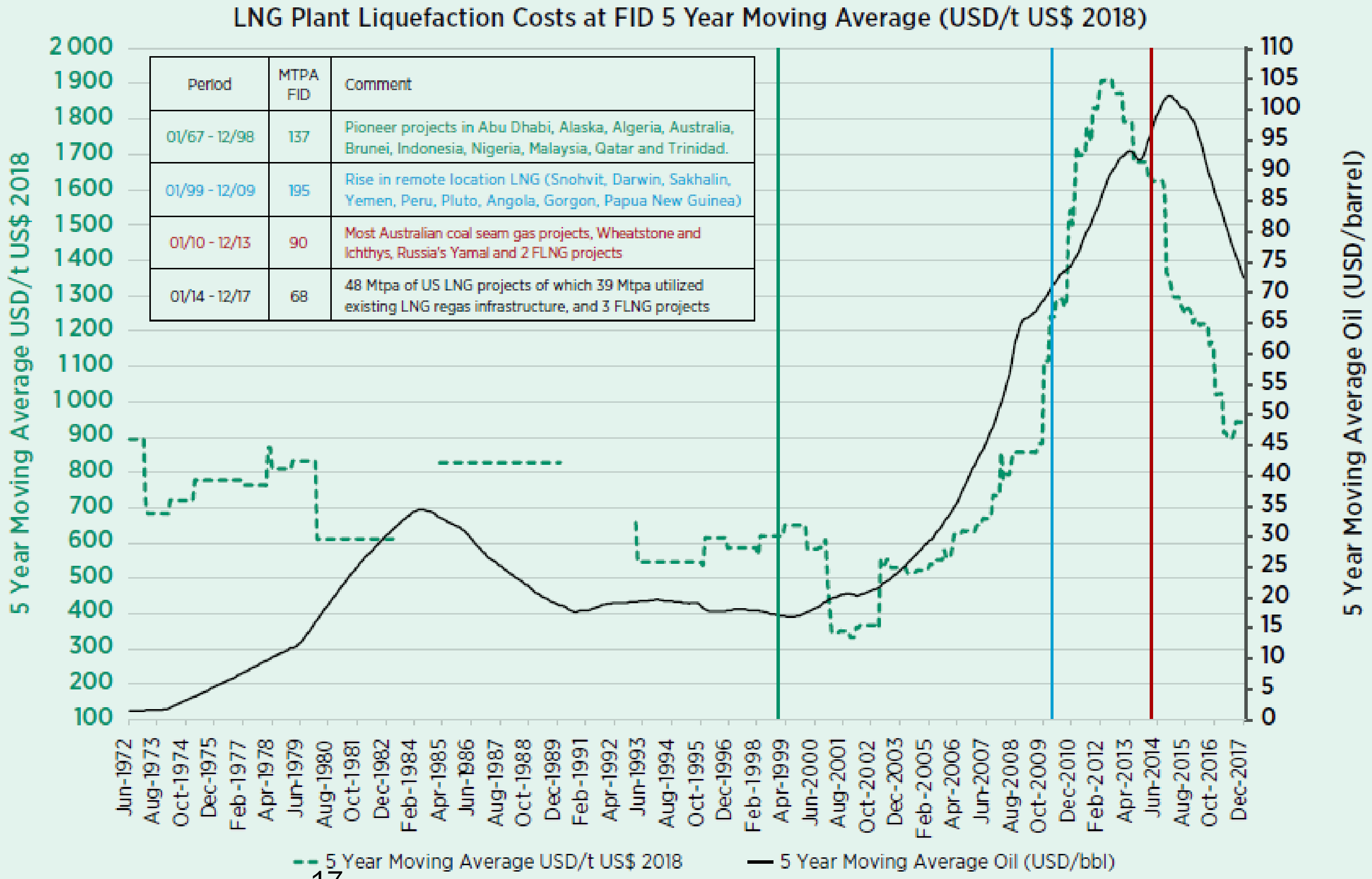
- In addition to the levelised cost of production of hydrogen of ± 5 $/kg you need to add an additional cost of ± 3 $/kg to ship the hydrogen as ammonia. The delivered cost to the customer is thus ± 8 $/kg. This is equivalent to an oil price of **$400/bbl**
- Dramatic reductions in costs are required for this to be feasible
- Ammonia production by the Haber Bosch process is more than 100 years old and is highly optimised and very mature. Dramatic cost reductions are unlikely
- Subsidies are required to allow green hydrogen to compete

16. https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

7. How do you transport hydrogen and what does it cost? (3/3)

Will hydrogen capital costs reduce dramatically?

LNG provides an interesting case study



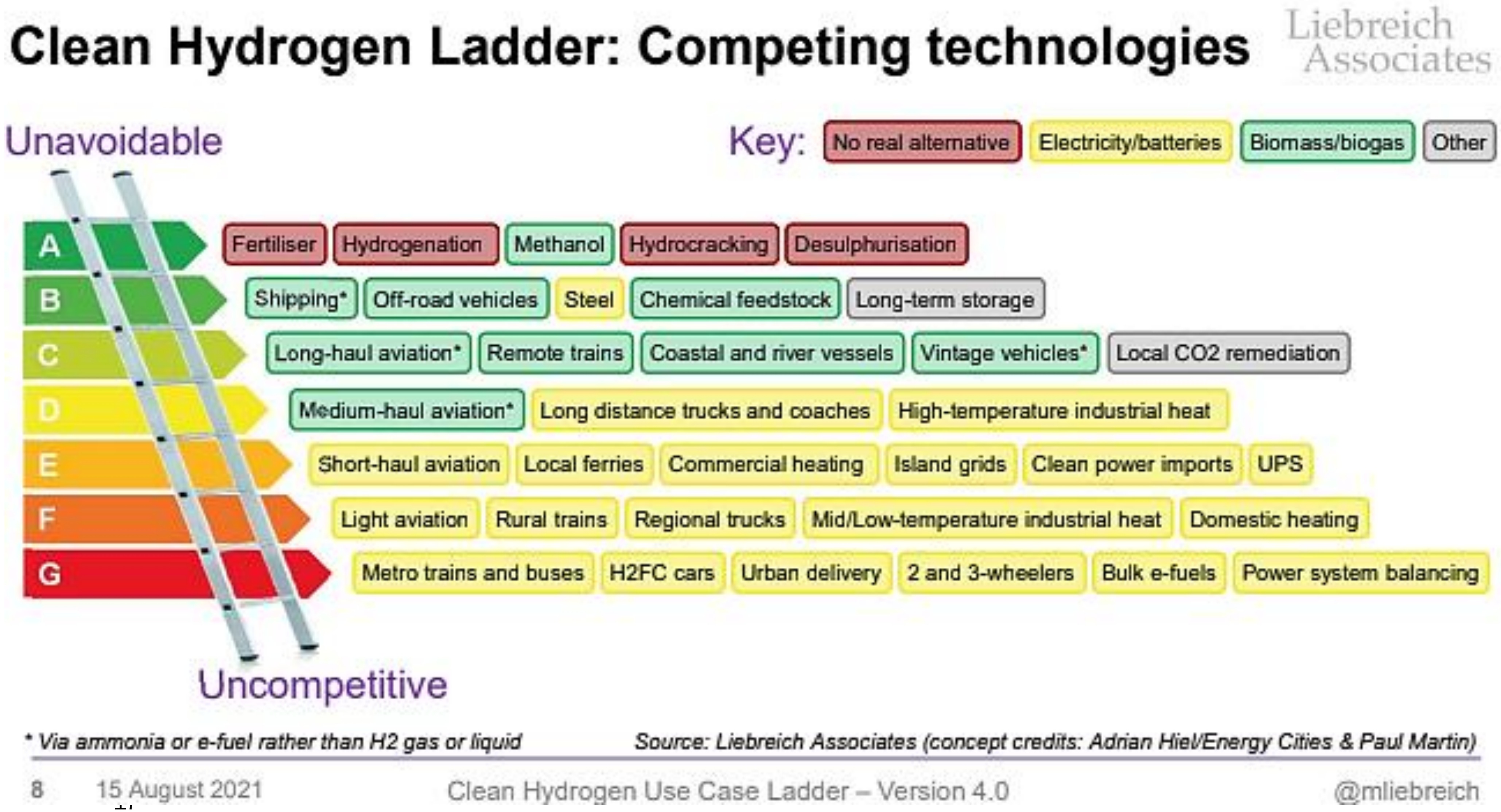
17

Source: Steuer (2019).

- LNG is a business which is 50 years old
- The green dotted line shows the capital cost evolution of LNG liquefaction plants over the decades
- No dramatic reduction in costs has been observed
- Capital costs of LNG liquefaction have been observed to be correlated to oil prices. When oil prices are high scarce resources and skills for project resources bid up prices
- It is not a given that the dramatic cost reductions for green hydrogen production and transport forecast by IRENA will transpire in practice

17. Steuer, C. (2019), *Outlook for Competitive LNG Supply*, Oxford Institute for Energy Studies, www.oxfordenergy.org/publications/outlook-competitive-lng-supply/.

8. What should green hydrogen be used for and Liebrich's[18] ladder (1/8)



Hydrogen is not necessarily competitive for all the applications it is being considered for

18 https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

8. What should green hydrogen be used for and Liebrich's ladder (2/8)

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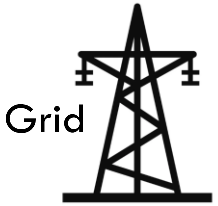
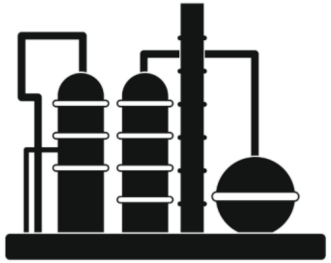
Hydrogen demand



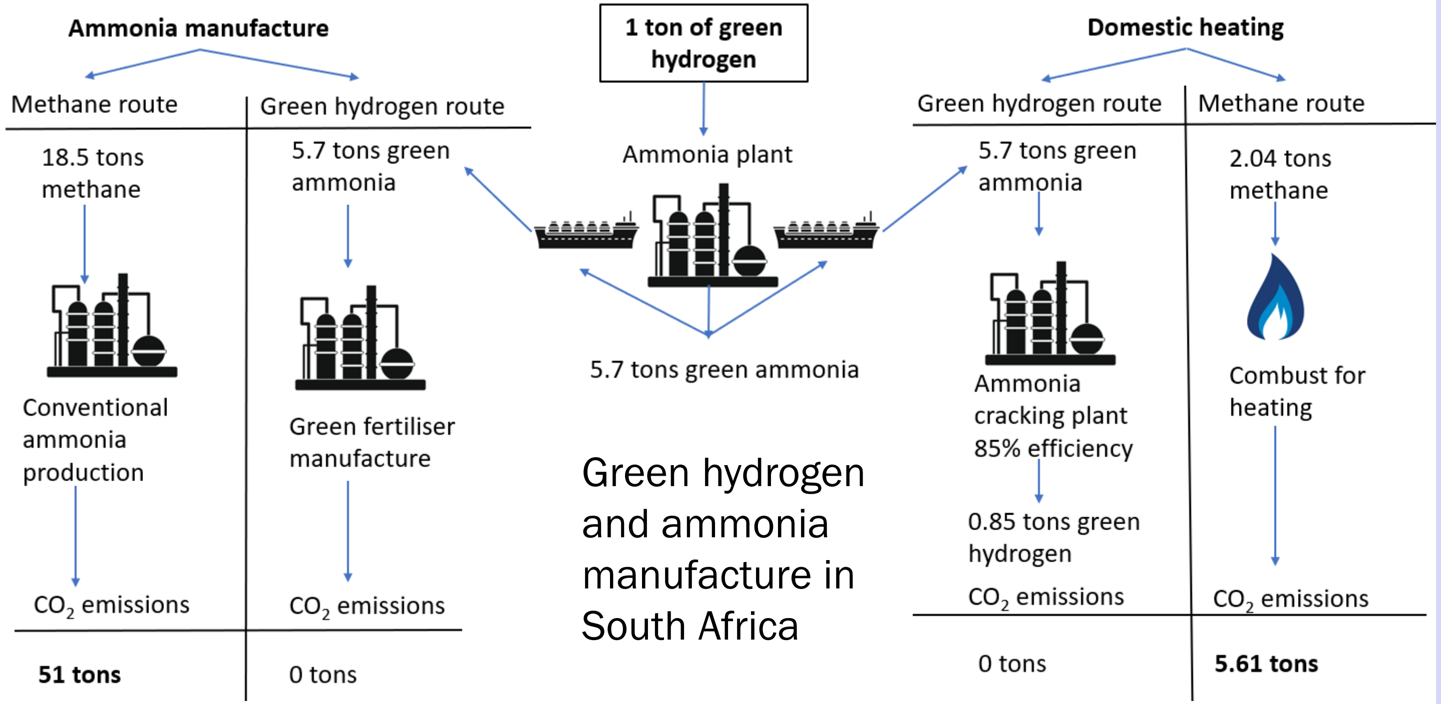


Electricity generation	Energy Storage and electricity	Buildings and heating	Transport	Industry and chemicals	Oil refining
CO_2 emissions billion tons per annum (2016)		8.7	8.0	12	1.3
	1. Long term storage 2. Island grids 3. Clean power imports 4. Uninterruptible power supply 5. Power system balancing	6. Commercial heating 7. Domestic heating	8. Shipping 9. Off road vehicles 10. Long haul aviation 11. Medium haul aviation 12. Light aviation 13. Coastal and river vessels 14. Remote trains 15. Fuel cell vehicles 16. Long distance trucks and busses 17. Local ferries 18. Rural trains 19. Regional trucks 20. Metro trains and busses 21. Urban delivery 22. 2 and 3 wheelers 23. Bulk e-fuels	24. Nitrogen fertiliser (0.45) 25. Methanol 26. Steel 27. Chemical feedstock 28. High temperature industrial heat 29. Mid/low temperature industrial heat 30. Local CO_2 remediation	31. Hydrogenation Hydrocracking 32. Desulphurisation

The potential applications are complex, and each of the 32 applications merits its own investigation into the relative merits of green hydrogen in terms of competing options, carbon dioxide emission reductions, cost, and safety considerations, amongst others.

8. What should green hydrogen be used for and Liebrich's[18] ladder (3/8)

A comparison of the use of green hydrogen for ammonia use as a fertiliser or its use for domestic heating

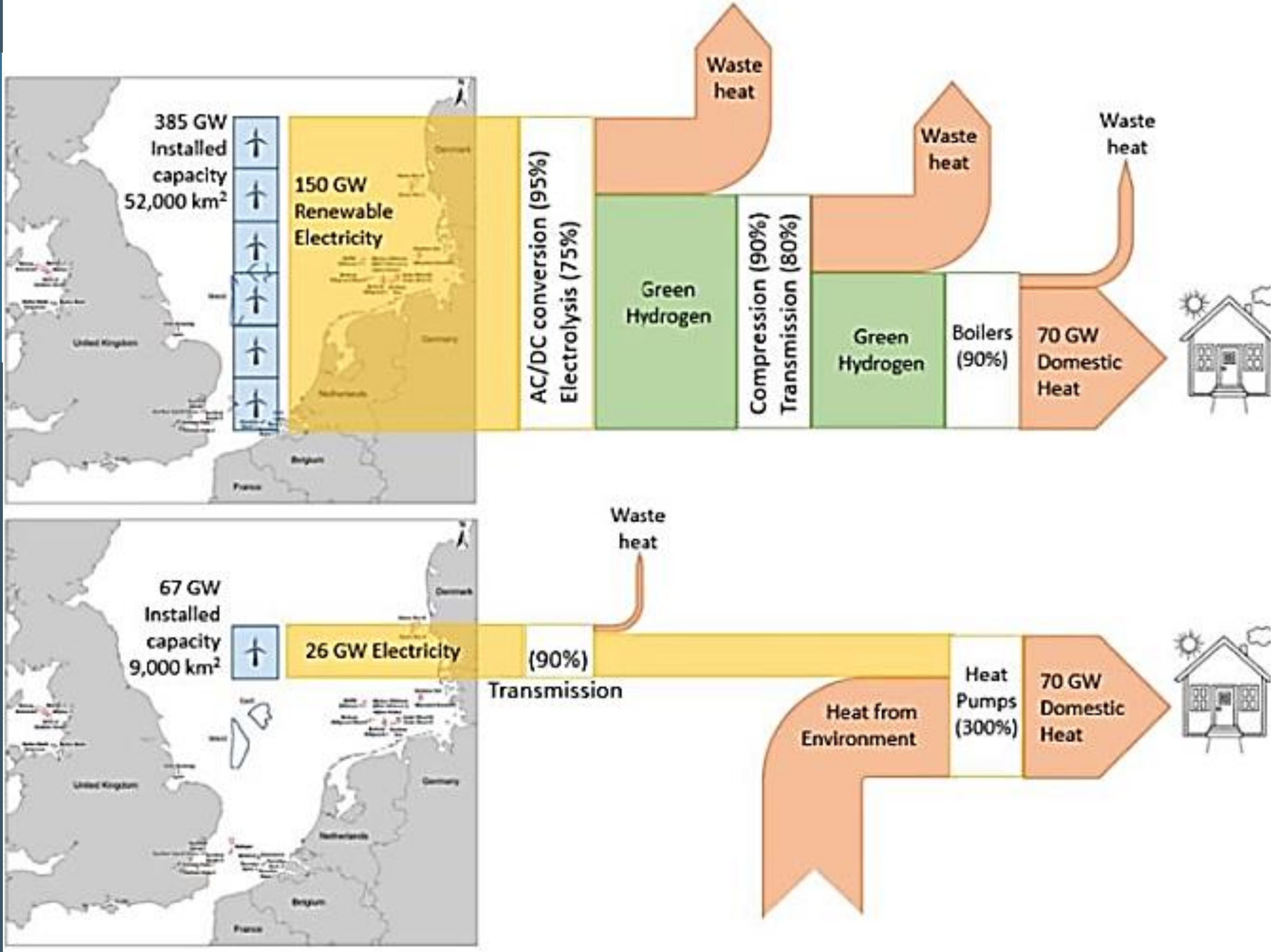


- One ton of green hydrogen used for ammonia fertiliser avoids 51 tons of CO_2 emissions
- One ton of hydrogen used as a domestic heating fuel avoids 5.61 tons of CO_2 emissions
- **From a decarbonisation perspective it is much more efficient to use green hydrogen for fertiliser production**

- Natural gas is the dominant and preferred feedstock for ammonia production, and steam methane reforming is the most practiced commercial technology employed.
- About 9 tons of CO_2 is emitted to the atmosphere for every ton of hydrogen produced when using natural gas as a feed.
- The ammonia can be used directly for fertiliser production or transported to Europe where it can be cracked back to hydrogen
- 0.85 tons of green hydrogen can replace 2.04 tons of natural gas for domestic heatng

8. What should green hydrogen be used for and Liebrich's[18] ladder (4/8)

A comparison of the use of green hydrogen for domestic heating or heat pumps using renewable electricity for the UK [1]



Providing domestic heating in the UK using either green hydrogen or heat pumps. The colour of the arrows indicate the type of energy: electricity, green hydrogen or heat. The width of the arrows are proportional to the power flows (in units of GW). The blue boxes show scaled areas of wind turbine farms on the maps.

- Green hydrogen needs 6 times more renewable energy provision (385 GW) than a heat pump
- Multiple independent studies conclude that hydrogen is not preferred from a life cycle cost standpoint[2]

1 https://www.linkedin.com/posts/tom-baxter-a141a1b_hydrogen-for-domestic-heating-does-anything-activity-7034423493286879232-05S4/?originalSubdomain=ng
2. http://www.janrosenow.com/uploads/4/7/1/2/4712328/is_heating_homes_with_hydrogen_all_but_a_pipe_dream_final.pdf

8. What should green hydrogen be used for and Liebrich's[18] ladder (5/8)

Efficiency of carbon dioxide reduction potential for selected green hydrogen applications[1]

Application	Carbon dioxide emissions avoided tons of CO_2/ton of hydrogen
Green ammonia for use as fertiliser	51
Fuel Cell Electric Vehicle	12.3
Fuel Cell Electric Truck	7.9
Hydrogen as heating fuel	5.6
E-kerosene for aviation	3.5

If the objective of implementing green hydrogen is to decarbonise in the most efficient manner, then different applications for green hydrogen show a wide range of carbon dioxide reduction potentials. Currently, a scattershot approach to green hydrogen applications is being pursued even where more efficient, cost-effective alternatives exist, as if green hydrogen is abundant and cheap, which it is not.

1 Own calculations by authors. Assumptions and calculations available upon request.

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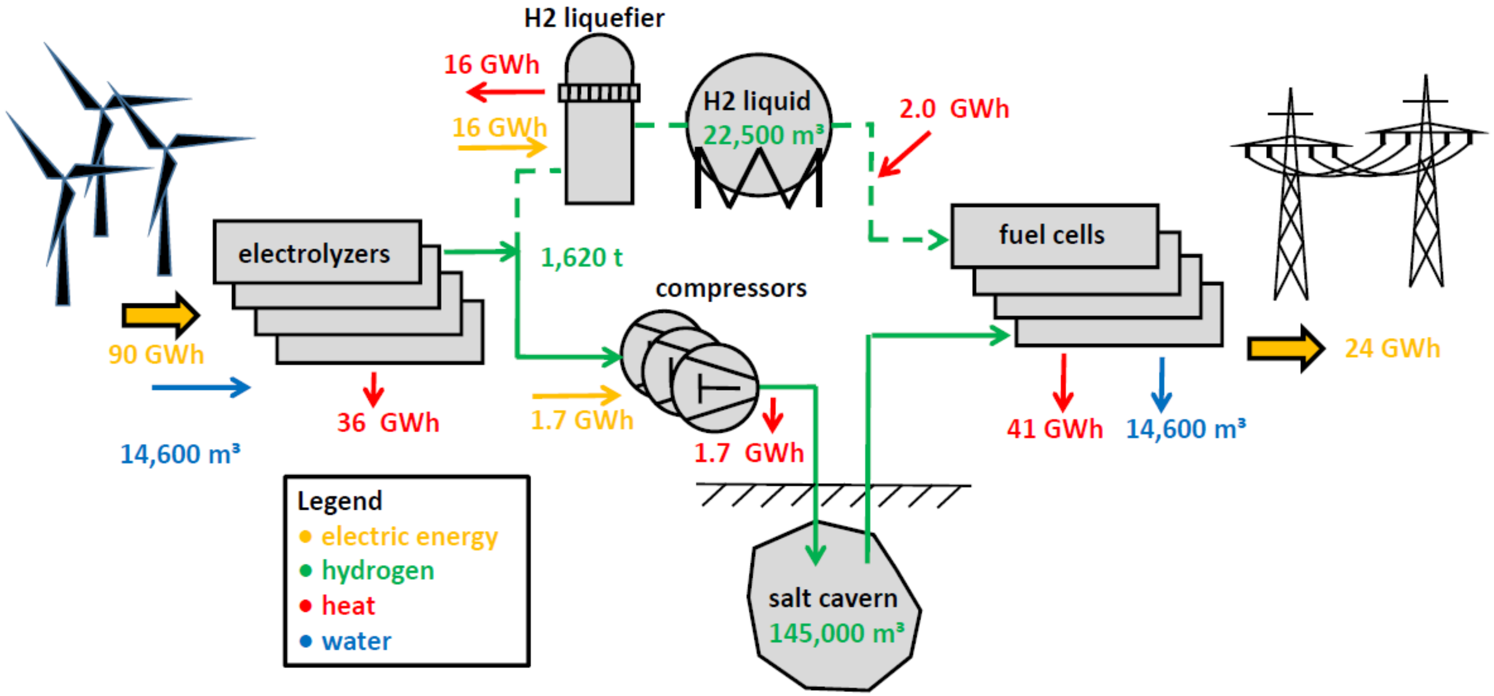
8. What should green hydrogen be used for and Liebrich's[18] ladder (6/8)

An analysis of using green hydrogen as an electricity storage option in Germany[1]



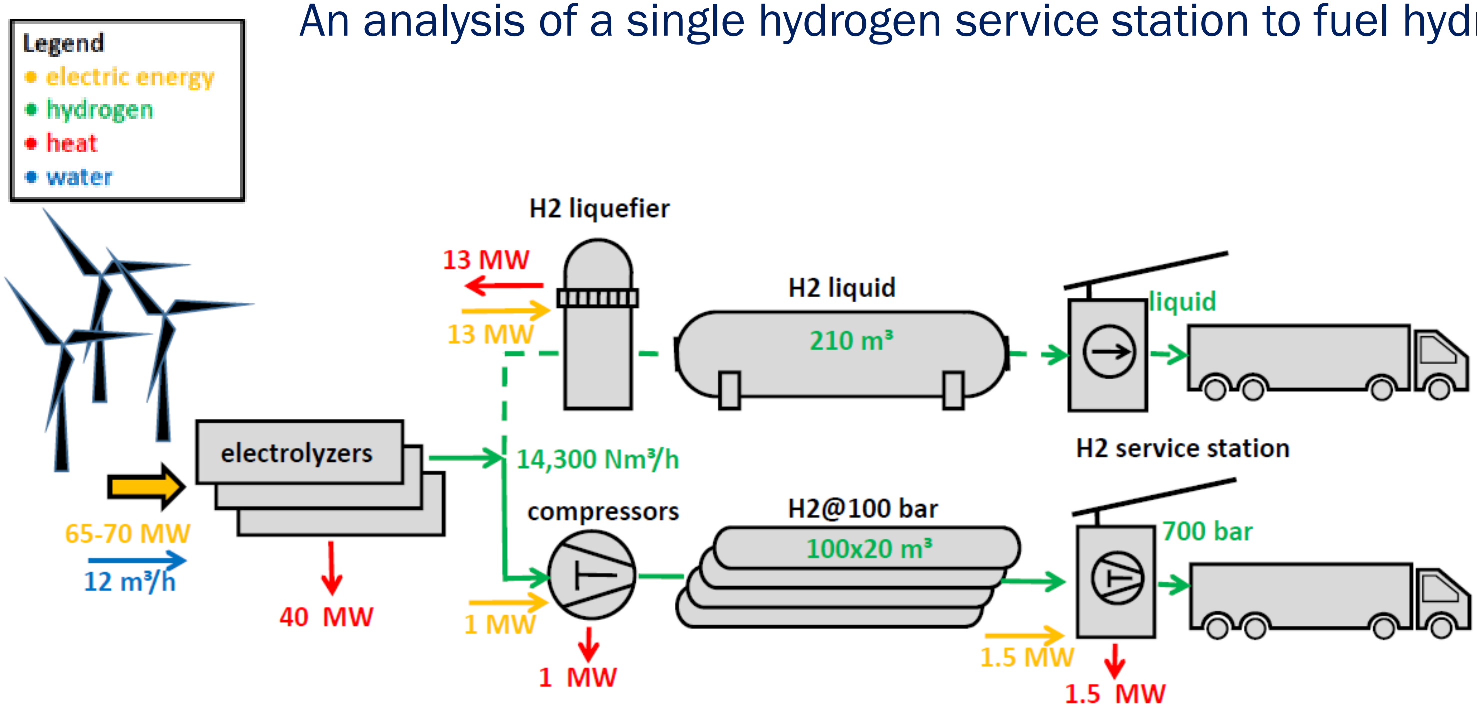
Schematic process chain, indicating the flow of electrical energy, hydrogen, heat, and water for liquid or high pressure underground storage of hydrogen for underground storage of hydrogen[1].

- The use of hydrogen as an electricity storage option to generate 1 GW of power for 24 hours to allow for an emergency electricity supply for a lull in intermittent renewable electricity supply is considered.
- This would either require a large cryogenic storage vessel of 22 500 m^3 or storage of 145 000 m^3 in a salt cavern at 150 bar.
- The author[1] questions the technical feasibility of this.
- Irrespective of whether this is technically or economically viable, if a market for 20 million tpa of hydrogen is to be created by 2030, decisions will soon need to be made regarding what applications the hydrogen will be used for and projects initiated to construct the infrastructure so that it is ready in time.

1 https://www.researchgate.net/publication/351951460_Transformation_of_electrical_energy_into_hydrogen_and_its_storage

8. What should green hydrogen be used for and Liebrich's[18] ladder (7/8)

An analysis of a single hydrogen service station to fuel hydrogen fuel cell trucks in Germany[1]



Process chain of a single (large) hydrogen service station[1].

- The question of whether sufficient demand from fuel cell electric trucks will be available by 2030 to match the supply and the infrastructure built is still an open one.
- If the trucks are available, it is still not clear whether freight companies will choose fuel cell trucks or battery electric trucks

- If the hydrogen is sold as a liquid, a liquefaction plant consuming 13 MW of electricity will be required together with a cryogenic storage vessel of 210 m^3.
- Alternatively, two stage compression to 700 bar is considered consuming 2.5 MW of electricity and 2027 m^3 of high-pressure storage vessels.
- The operation of the hydrogen filling station will resemble the operation of a chemical plant rather than a conventional service station.
- To reach net zero Germany will require 140 such service stations each consuming about 10 000 tpa of hydrogen
- The question of whether sufficient demand from fuel cell electric trucks will be available by 2030 to match the supply and the infrastructure built is still an open one.

1 https://www.researchgate.net/publication/351951460_Transformation_of_electrical_energy_into_hydrogen_and_its_storage

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8. What should green hydrogen be used for and Liebrich's[18] ladder (8/8)

- Given the high cost of producing and transporting green hydrogen alternative technologies also need to be considered
- Some applications like nitrogenous fertiliser production have no known real alternative but it will be expensive and the implications for food costs will be significant
- Direct use of electricity for many applications is cheaper and more efficient
- Domestic heating is cheaper and more efficient using heat pumps but requires replacement of existing boilers which is costly
- Aviation is likely to become significantly more expensive
- Use of green hydrogen as a chemical feedstock implies significant increases in the cost of chemicals

A key unresolved problem is how to move renewable energy to densely populated countries like Japan and parts of Europe

9. The iron law of megaprojects will apply to pioneering green hydrogen

Pioneering megaproject risks and the iron law of megaprojects

Megaprojects are large-scale, complex ventures that typically cost more than 1 billion US Dollars[19]
The iron law of megaprojects states: **Over budget, over time, under benefits, over and over again**[20].
Nine out ten megaprojects have significant cost and schedule overruns

Research has shown that megaprojects are driven by the four sublimes:

- The **"technological sublime"** describes the excitement engineers and technologists get in pushing the envelope
- The **"political sublime"** describes the tendency politicians have for constructing monumental infrastructure
- The **"economic sublime"** describes the delight businesspeople and trade unions get from making lots of money and jobs from megaprojects.
- The **"aesthetic sublime"**

Additional Risk Factors

- Pioneering Technology
- Remote locations (West coast of Southern Africa)
- Lack of skills to execute a megaproject

Size and Reputation Does Not Help

Chevron's Gorgon LNG project in remote Western Australia original budget was $34 billion; by 2014, costs had risen to $54 billion.

Pioneering GW scale green hydrogen projects in Southern Africa are virtually guaranteed to have significant cost and schedule overruns

19. https://www.pmi.org/-/media/pmi/documents/public/pdf/research/research-summaries/flyvbjerg_megaprojects.pdf
20.. https://www.researchgate.net/publication/299393235_Introduction_The_Iron_Law_of_Megaproject_Management

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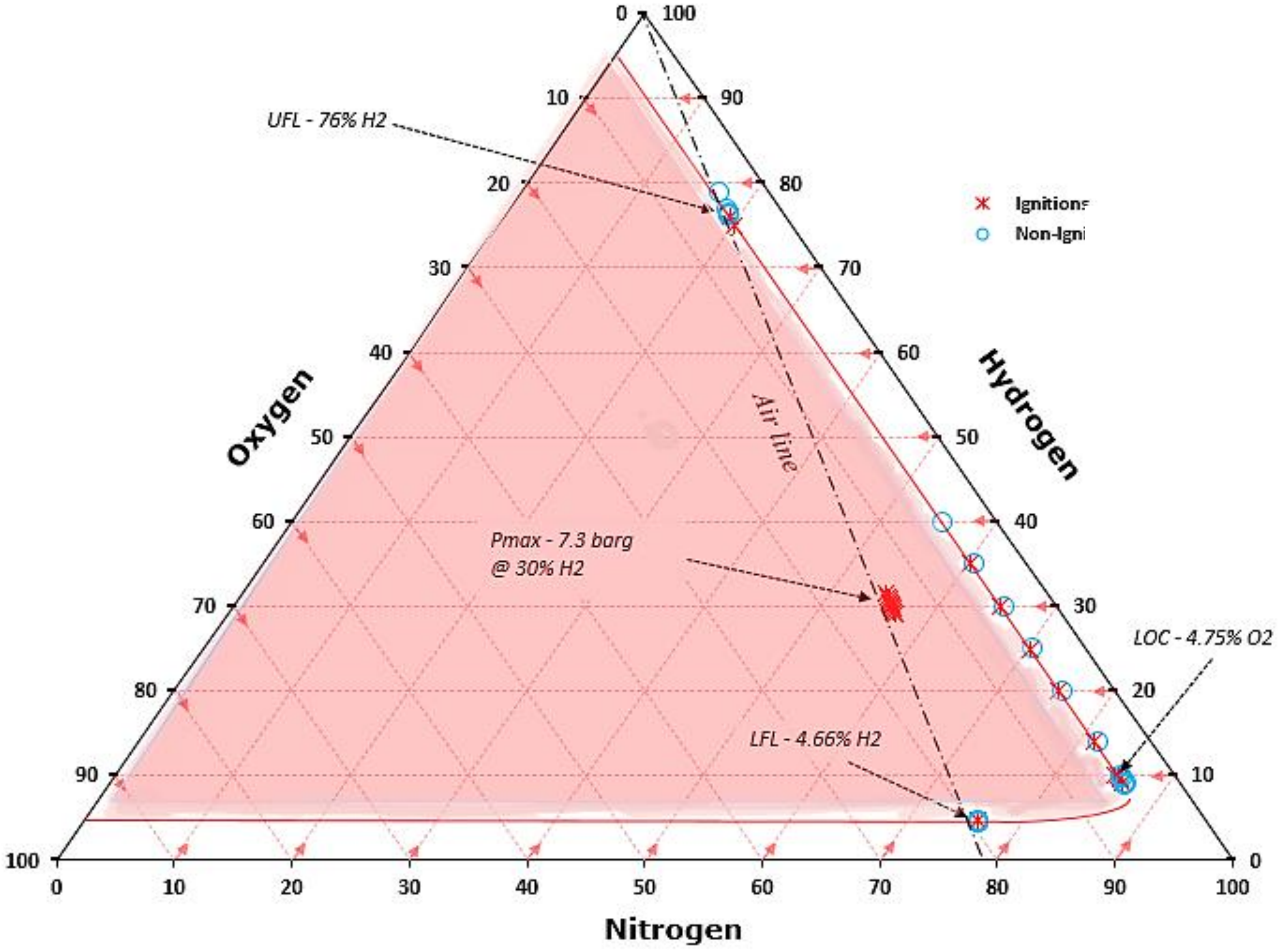
10. Other factors to consider (1/2)

How safe is hydrogen?



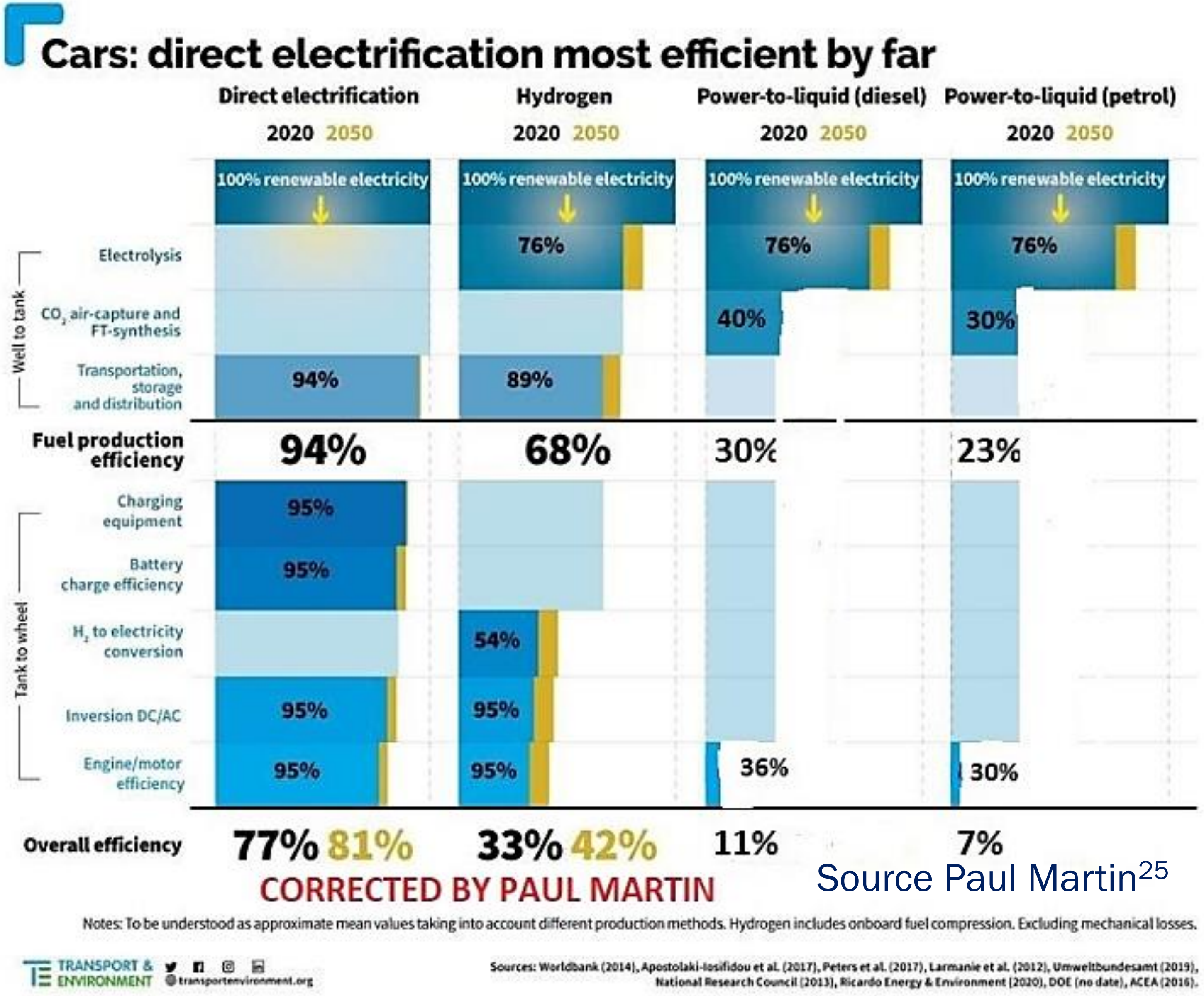
Flammability diagram for hydrogen at atmospheric pressure [21]

21 https://www.fauske.com/blog/safety-in-a-green-hydrogen-economy
22. https://www.aiche.org/chs
23. https://www.eenews.net/articles/hydrogen-could-fuel-u-s-energy-transition-but-is-it-safe/
24. https://www.rechargenews.com/energy-transition/hydrogen-in-the-home-would-be-four-times-more-dangerous-than-natural-gas-government-report/2-1-1047218

- Hydrogen has a very broad flammability range from 4 percent to 74 percent concentration in air
- Hydrogen has been used as an industrial gas for decades and although 400 incidents have been recorded by the Centre for Hydrogen Safety (CHS)[22] industry has absorbed lessons learnt and risks have been mitigated.
- The codes and standards for operating wholesale and retail infrastructure are still being developed[23]
- Safety incidents and explosions at the retail and wholesale level remain a concern[23]
- The use of hydrogen in a domestic setting is significantly more dangerous than natural gas[24]

10. Other factors to consider (2/2)

Fuel Cell Electric Vehicles (FCEVs) vs Battery Electric Vehicles (BEVs) vs Power to Liquids (PTL)



Source Paul Martin[25]

- The energy efficiency of BEVs is significantly better than FCEVs
- The poorer efficiency of FCEVs contributes to FCEVs being a worse economic proposition for passenger cars than BEVs
- Power to liquid for both petrol and diesel have a very low energy efficiency which contribute to a very high cost

25. https://www.linkedin.com/pulse/distilled-thoughts-hydrogen-paul-martin/

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Sasol Boegoebaai green hydrogen project[1]

Boegoebaai is 20 km south of the Namibian border and is remote with no infrastructure[2]
Closest town is Alexander Bay with a population < 2000

- Scale
  - 9 GW of renewable sun and wind energy
  - 400 000 tpa of green hydrogen
  - 5 GW of PEM electrolysers
- Project at pre-feasibility study stage planned first production 2030
- Capital cost estimate ± $4.8 billion with no allowance for remote location (61% of Sasol's market capitalisation)
- Sasol has struggled with megaproject execution in the recent past[3].
- Port and other infrastructure to be provided by (overindebted) South African government

1. https://www.miningweekly.com/article/northern-capes-proposed-green-hydrogen-hub-can-help-open-regions-full-energy-potential-2022-09-22
2. https://publishedetenders.blob.core.windows.net/publishedetenderscontainer/9083/Annexure%20Q%20-%20BOEGOEBAAI%20PORT%20Summary%20of%20available%20site%20information.pdf
3. https://cen.acs.org/business/investment/Sasol-CEOs-step-down-wake/97/i43

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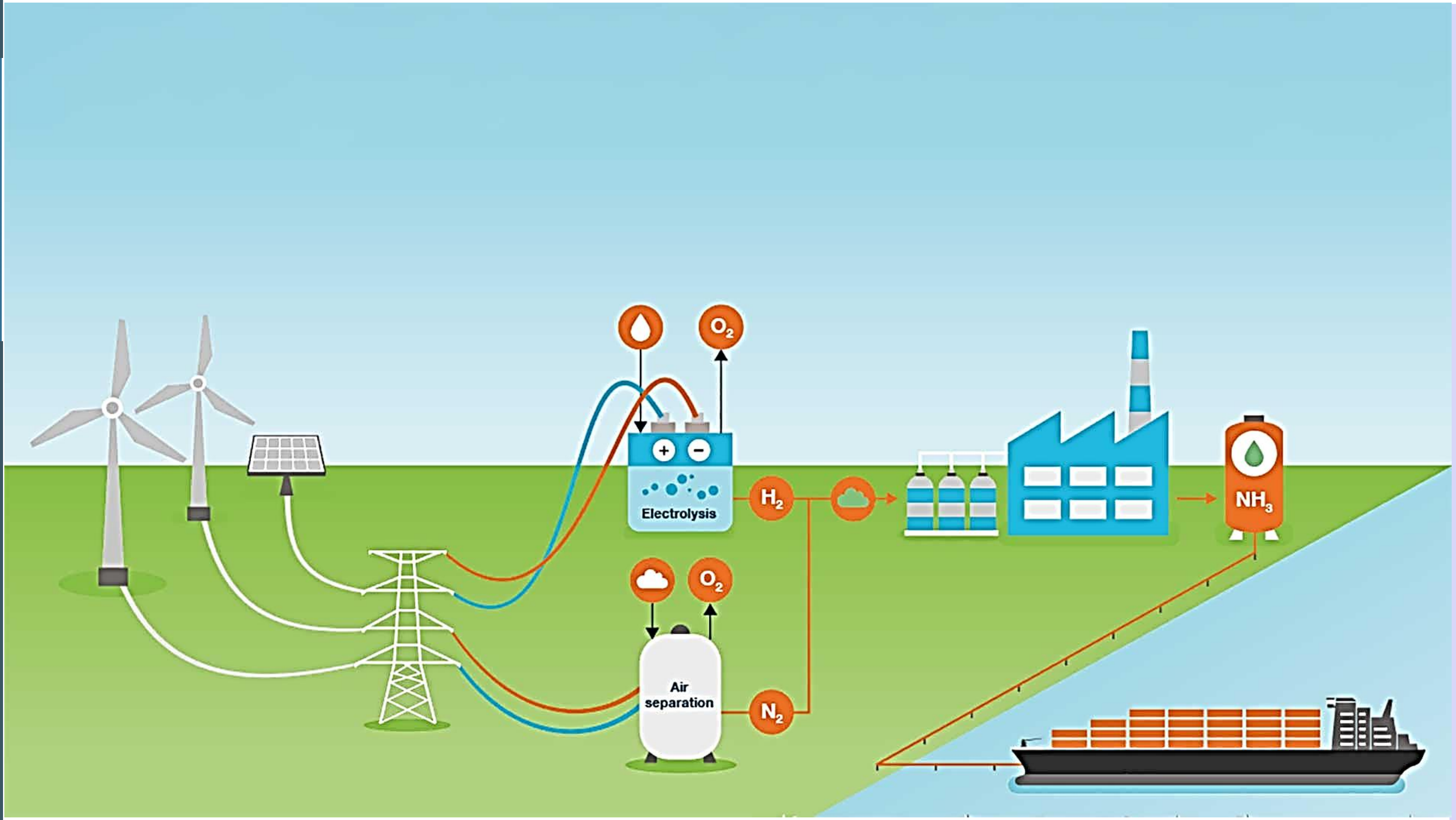
R100 billion Coega green ammonia project study announced by Hive Energy[1]



- In December 2022 the Hive Hydrogen project had been registered as a special integrated project (SIP) to expedite implementation and regulatory approvals
- Plan is to produce 950 kilo tons per annum (ktpa) of green ammonia[2]
- First production claimed to be in 2026

1. https://www.miningweekly.com/article/northern-capes-proposed-green-hydrogen-hub-can-help-open-regions-full-energy-potential-2022-09-22
2. https://edition.cnn.com/2022/10/18/africa/green-ammonia-hive-energy-scn-climate-spc-intl/index.html

Syndicate questions

1. How likely is it that green hydrogen will be used for all the applications it is envisaged for? Explain.
2. Discuss whether green hydrogen or ammonia should be exported from South Africa given South Africa's electricity crisis.