Hydrogen production and the role Infrastructure: mainly storage and transport related

Presented by

Thomas Jenkin

Adjunct Lecturer, Johns Hopkins University
Short Term Consultant, World Bank

February 22, 2024

Presentation intended for educational and discussion purposes. Large number of references used and cited at the end of main presentation. Material is primarily intended to synthesize existing knowledge and ideas for a wide variety of sources and make some related observations. Version 2.1

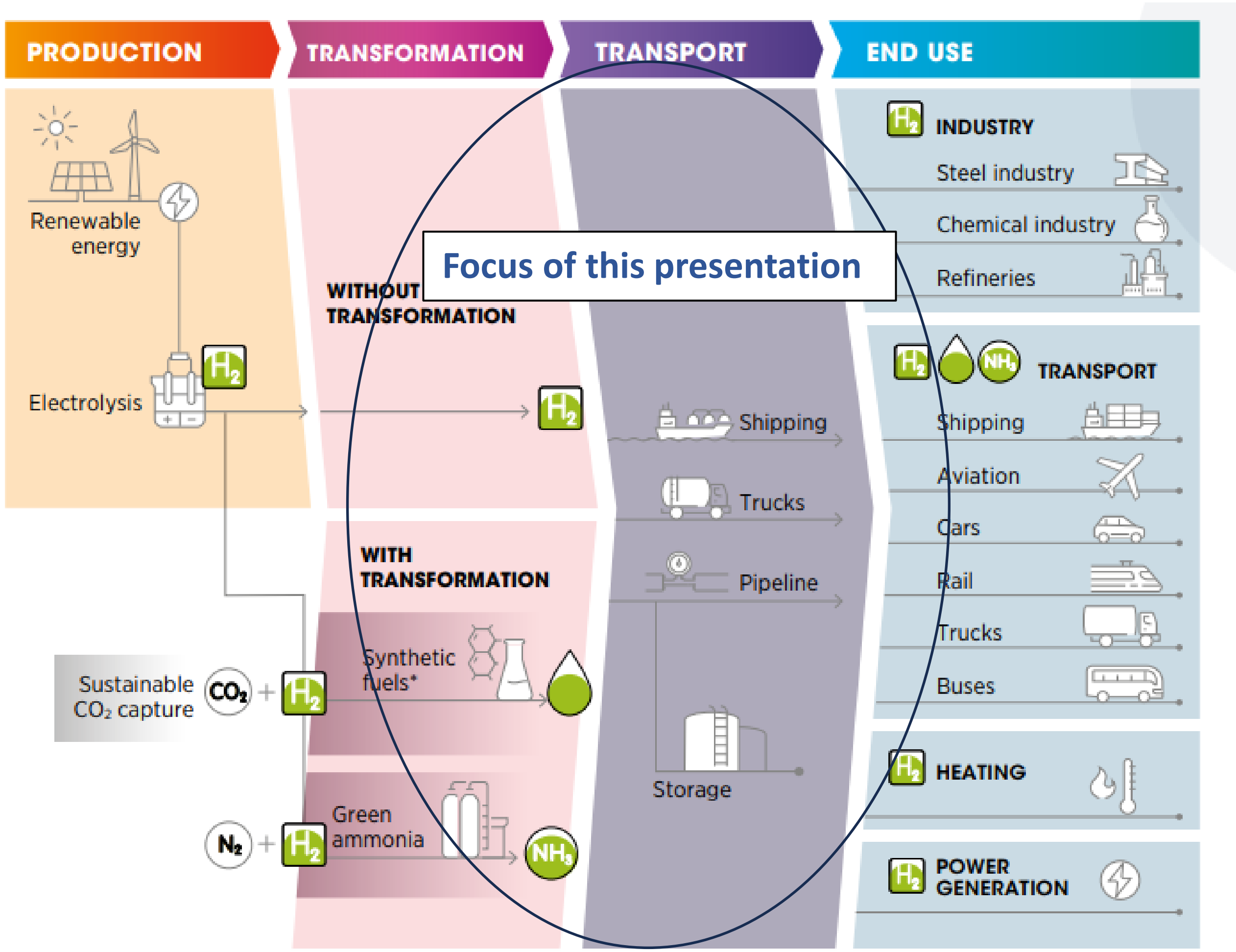
All estimates are draft and intended to be illustrative

Hydrogen production and the role of storage and transportation related infrastructure

1. **Difference between levelized cost of hydrogen (LCOH) production and delivered hydrogen (LOCDH)**; and why it matters, including distance moved and benefits of reliable/firm supply [use of storage]. For:
   I. **Shorter distances** (on-site/<10 km to 200 km+): includes historical production and use of hydrogen in regional networks (e.g., on Gulf Coast; Northern Europe)
   II. **Longer distances** (<2,000 km to 10,000 km+): to connect regions with large differences in levelized cost for green and/or blue production
2. **Infrastructure** "building blocks" to bridge production to hydrogen delivery at lowest the levelized cost including:
   I. **Hydrogen storage** and/or
   II. **Hydrogen pipelines** and/or
   III. **Ports/shipping/ports**
   IV. **Distribution** [Not covered in this presentation]
3. **Comparing delivery cost of infrastructure alternatives e.g., pipeline vs. shipping,** including any relevant carrier conversions
4. **Infrastructure investment significant**; though estimates out to 2050 (and how they vary with time ($ overall and $/kg H_2)) highly uncertain

Wide variety of storage and transportation infrastructure assets to store and move hydrogen to end use

DRAFT



- **Infrastructure requirements and levelized cost adder ($/kg H_2) can vary widely*.** Factors include:
  - Distance moved
  - Scale
  - Types and relative sizing of infrastructure assets
  - CAPEX
  - Asset utilization
- **Considerable interest in reusing existing infrastructure assets to lower investment requirements**

Source: Figure from: IRENA (2021), Making the breakthrough: Green hydrogen policies and technology costs.
Note: As Figure suggests hydrogen infrastructure is a large topic, and this presentation focuses on a of number of key areas, but coverage in not intended to be comprehensive
*Levelized cost for infrastructure may range from ~$0.3/kg H_2 (or less) to over $2.5/kg H_2. Equivalent to range of ~$10/MWh or $75/MWh based on LHV of hydrogen of 33.3kWh/kg H_2

Hydrogen storage plays a crucial role in linking the production of hydrogen through to end use

DRAFT

Some examples of the use of hydrogen storage include to:

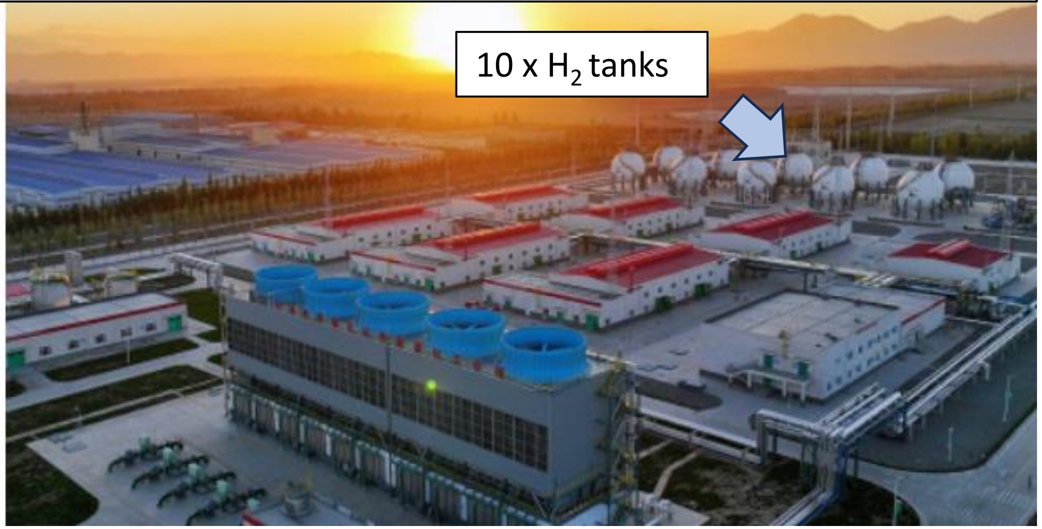
- **Balance variable production of green hydrogen with demand on shorter timescales: hourly to a few days** (using above ground storage typically up to ~20 to ~100 bar)
- **Provide hydrogen storage over longer timescales, including use of underground storage for monthly or even for large scale seasonal storage** (~up to 100 to 200 bar)
- **Increase the energy density** (MJ/m^3), **store and then deliver compressed hydrogen gas at ~350 or 700 bar for use in vehicle storage tanks for transportation**
- **Move hydrogen as compressed gas or liquid hydrogen** (LH_2) (~20K and a few bar)**, or as alternative carrier, such as liquid ammonia (**at -33C and 1 bar, or 20C and ~ 20 bar**)**

Hydrogen storage can act as buffer to balance variable output of green hydrogen production to next stage/demand

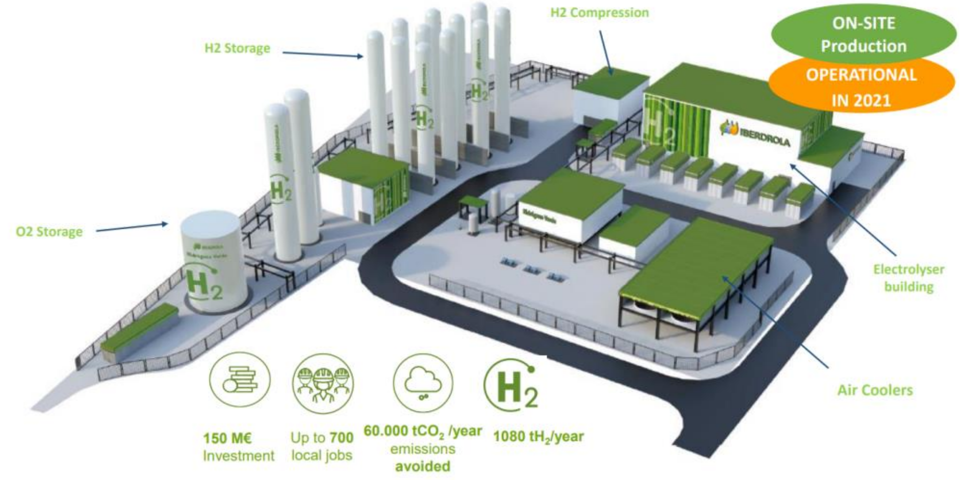
DRAFT

- **Spherical steel tanks or cylinders:** up to ~20 to 60 bar depending on design
- **Multiple closed steel pipes:** up to ~90 to 100 bar; above ground or underground

Example: 260 MW electrolysis plant: Hydrogen to feed pipeline for refinery: ~1/3rd day storage* acts as buffer to increase capacity factor of pipeline to nearby plant



Example: 20 MW electrolysis plant: Hydrogen for use in ammonia production: 1 to 2 days storage. 11 cylinders (~24m x ~3m) can each hold ~ 0.55 MT of hydrogen at 60 bar



Without hydrogen storage, the levelized cost of the next stage(s) may increase due larger sizing and/or lower utilization

Source: Figure on left from Sinopec Xinjiang Kuqa green hydrogen pilot project enters operation - Green Car Congress and on right from Iberdrola.com; see also Puertollano green hydrogen plant – Iberdrola
*Based on average target production, with 10 x 2 MT H_2 storage tanks [est.] . For educational purposes

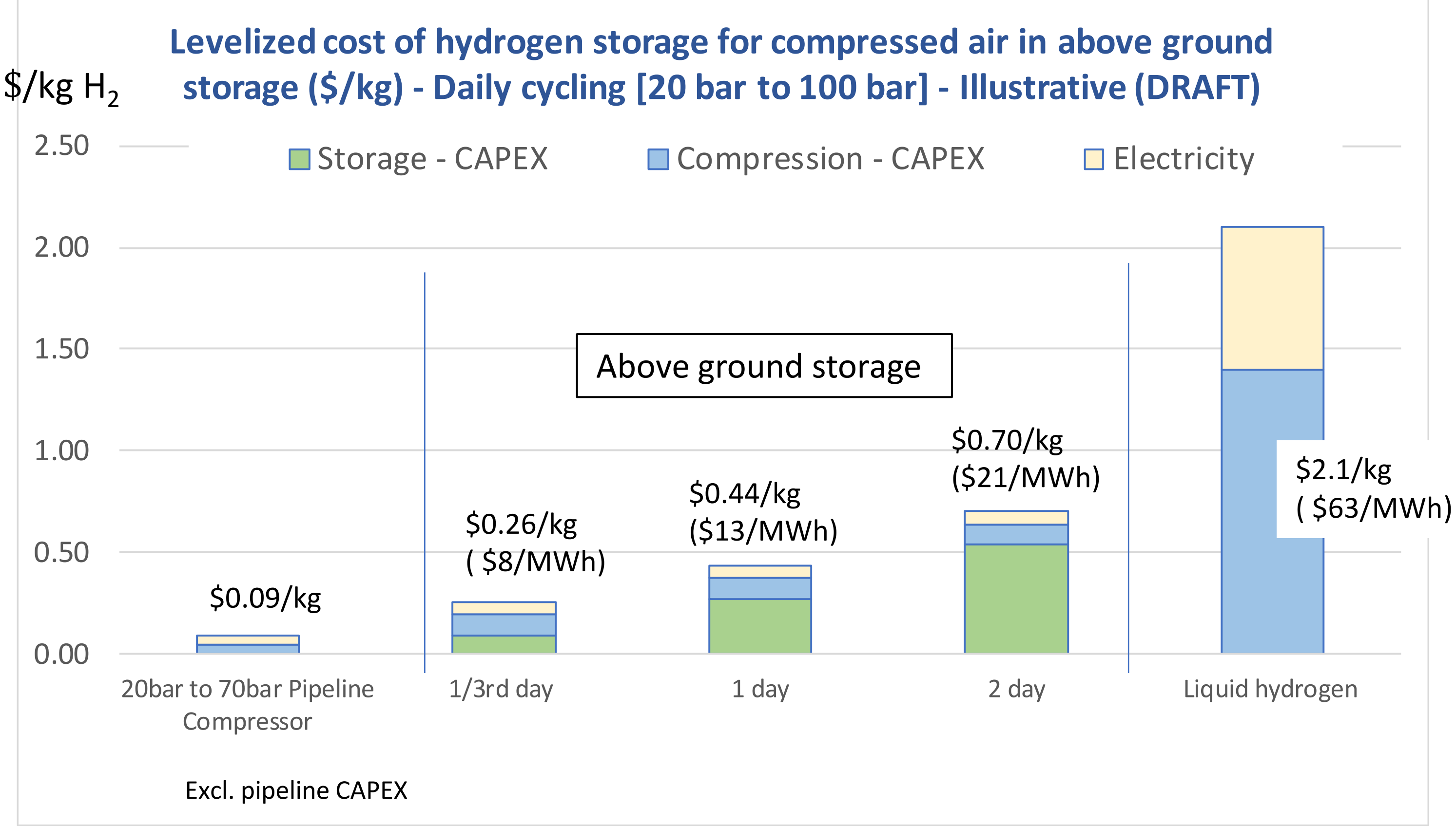
Levelized cost of hydrogen storage adder to balance hourly variable green hydrogen production to demand depends on size of storage, frequency of cycling and throughput

Illustrative example of daily cycling

Storage sized at 1/3, 1, and 2-days; where 60 MT of hydrogen equals '1 day'

Assumptions*:

- Installed CAPEX: Storage ~$700/kg H_2 and compressor at ~ $4m/MW
- Average H_2 production ~55 MT H_2/day (or 92% of '1 day' storage capacity):
- Daily cycling: 365 days year; where all hydrogen passes through storage



Storage requirements for balancing **for blue hydrogen may be much less** due to **reliable supply of natural gas**

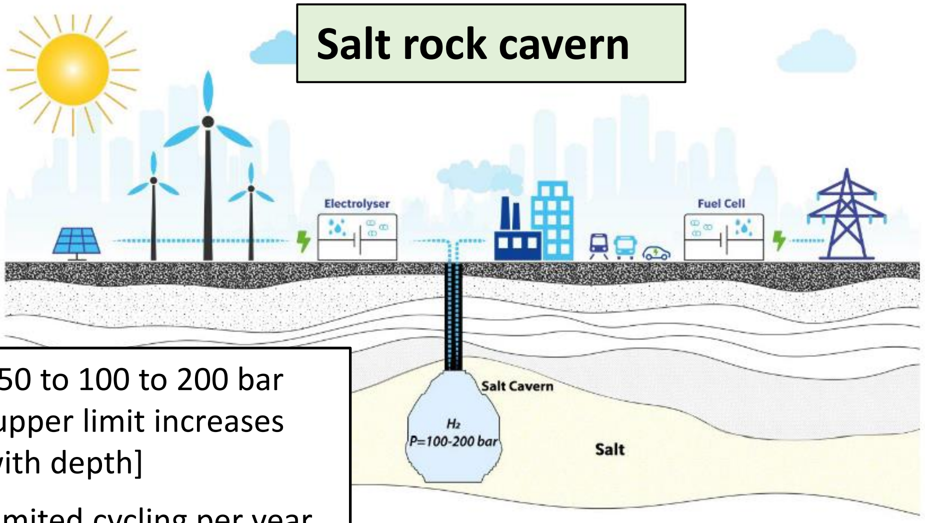
Note: *Other assumptions include 10% discount rate, 20-year life, and compressor sized to fill storage in 12 hours, and $70/MWh for [firm] electricity

$0.26/kg =>$7.8/MWh [=$0.26/kg H_2 x /(33.3kWh/kg H_2)]x1000kWh/MWh]

Underground caverns have potential for much larger storage capacity* (<500 to 2,000+ MT H_2) and lower CAPEX (\$kg H_2/m^3), though come with cycling restrictions

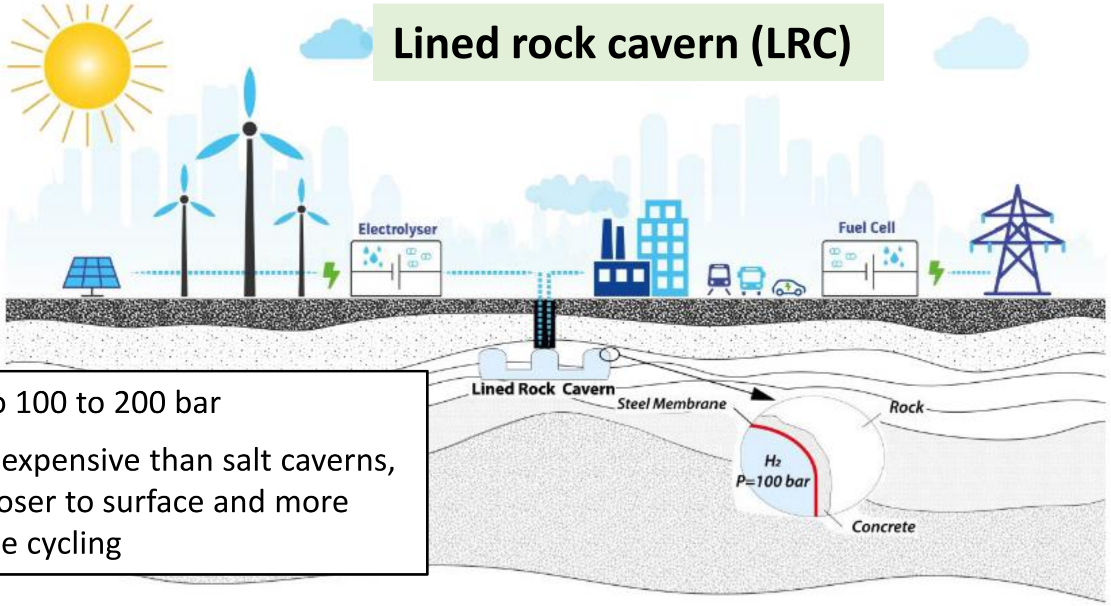
DRAFT

Salt rock cavern



- <50 to 100 to 200 bar [upper limit increases with depth]
- Limited cycling per year

Lined rock cavern (LRC)



- <50 to 100 to 200 bar
- More expensive than salt caverns, but closer to surface and more flexible cycling

- **Working volume may be 70% or less of actual physical volume:** cushion gas needed to prevent pressure falling too low
- **Underground storage for hydrogen inherently ~x3 more expensive than natural gas** [on a \$/MJ basis] since energy density (MJ/m^3) for hydrogen gas – for a given pressure – ~3x less than NG

Source: Figures from Louis Londe, Geostock, Four ways to store large quantities of hydrogen, March 3, 2023, https://www.geostockgroup.com/en/four-ways-to-store-large-quantities-of-hydrogen/. Two other important cavern types not shown but in article; includes porous rock oil and gas reservoirs and aquifers. For educational purposes

Installed cost of underground storage may be x10+ less than above ground hydrogen storage ($500+/kg H_2+ vs. $50/kg H_2 or less ($15+/kWh* vs. $2/kWh or less)

For underground salt caverns

1) CAPEX declines with scale/usable storage

=> Much lower levelized cost if cycled daily (vs above ground)

2) However, size of caverns, structural limitations and intended purpose means may be :

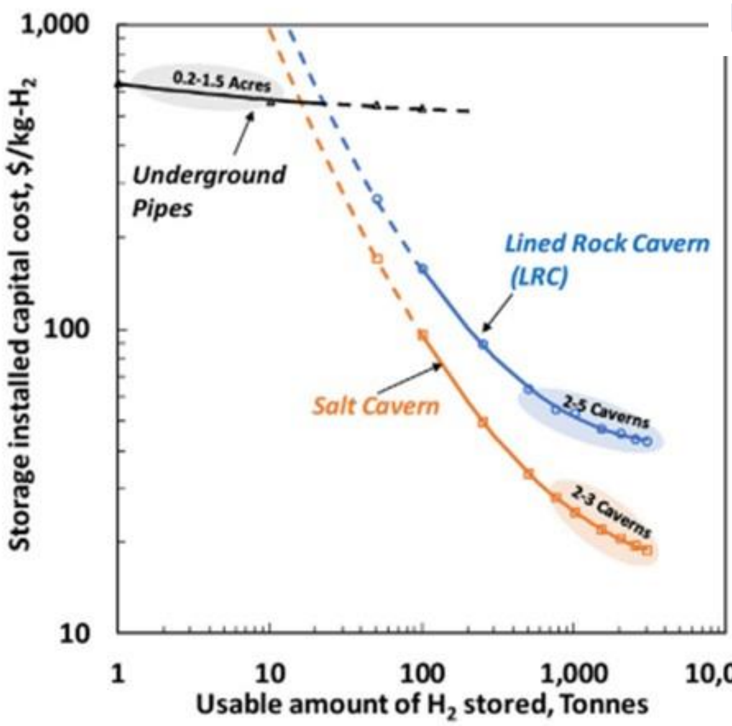
- Much larger e.g., 20 'days' storage, and
- Cycled less frequently, [e.g., Seasonal or few times a year]

3) LCOH storage depends on whether calculated based on

- Hydrogen stored and recovered, or
- Total annual production

Dividing by the total production - leads to lower levelized cost – would reflect benefit of storage 'shaping' all production

DRAFT



Source: Figure from Papadias andAhluwalia. "Bulk storage of hydrogen." *International Journal of Hydrogen Energy* (2021). Draft https://www.osti.gov/servlets/purl/1840539. For educational purposes

CAPEX for underground bulk hydrogen storage much cheaper than electricity storage for long duration [$2/kWh or less vs. $100/kWh+)**

Note: Papadias et al 2021 study considers hybrid approach where daily cycling may take place over smaller pressure range (10% of working gas) to be $0.21/kg H_2 (or $6/MWh)). Levelized cost needs to includes cost of cushion gas. *For example, $50/kg H_2 => $1.5./kWh = ($50/kg H_2 /33.3kWh/kg H_2)]. **Excludes compressor cost

Liquefaction of hydrogen to store as a liquid at -253C is expensive compared to compressing hydrogen gas in storage tanks: typically, \$2+/kg H_2 with targets of order of \$1/kg H_2 or less at scale

DRAFT

Advantage of LH2 for storage vs compressed gas

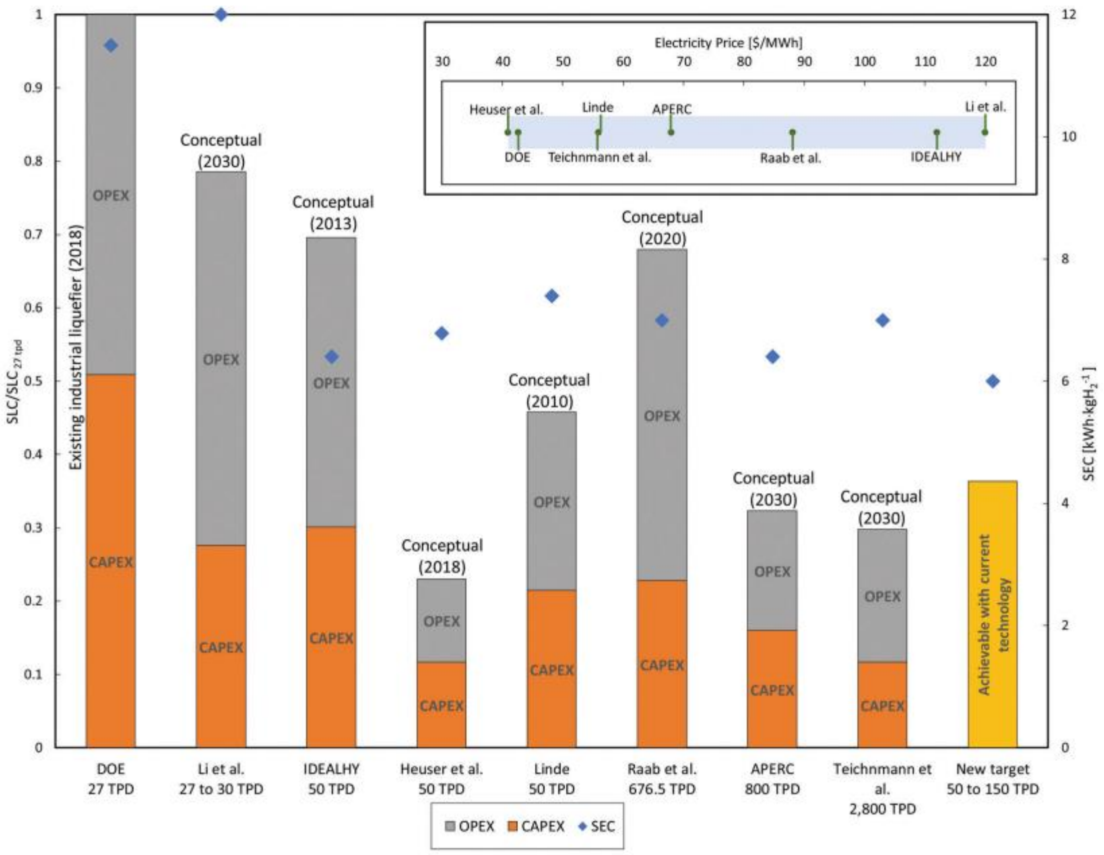
Energy density of LH_2 at 20K (-273C) about x10 hydrogen gas compressed to 100 bar 20 C

~71 kg LH_2/m^3 vs. ~ 8 kg H_2 (gas)/m^3 (100 bar)

Key disadvantage is storage of liquid hydrogen is expensive

Why is cryogenic liquid hydrogen so expensive?

- Liquefaction is energy intensive at 10kWh+/kg H_2, or ~1/3 the LHV of hydrogen
- CAPEX for liquefaction much greater than for compressor



Cost projections for the levelized cost of liquefaction of hydrogen; left hand bar for \$2.75/kg normalized to 1.0 [where \$1/kg H_2 corresponds to 0.37]

Sources: Figure is from: Al Ghafri et al 2022 "Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities." *Energy & environmental science*[Open access]. *Evaporation is another potential disadvantage

Hydrogen pipelines for transport are similar to steel pipelines used for natural gas (NG)

DRAFT

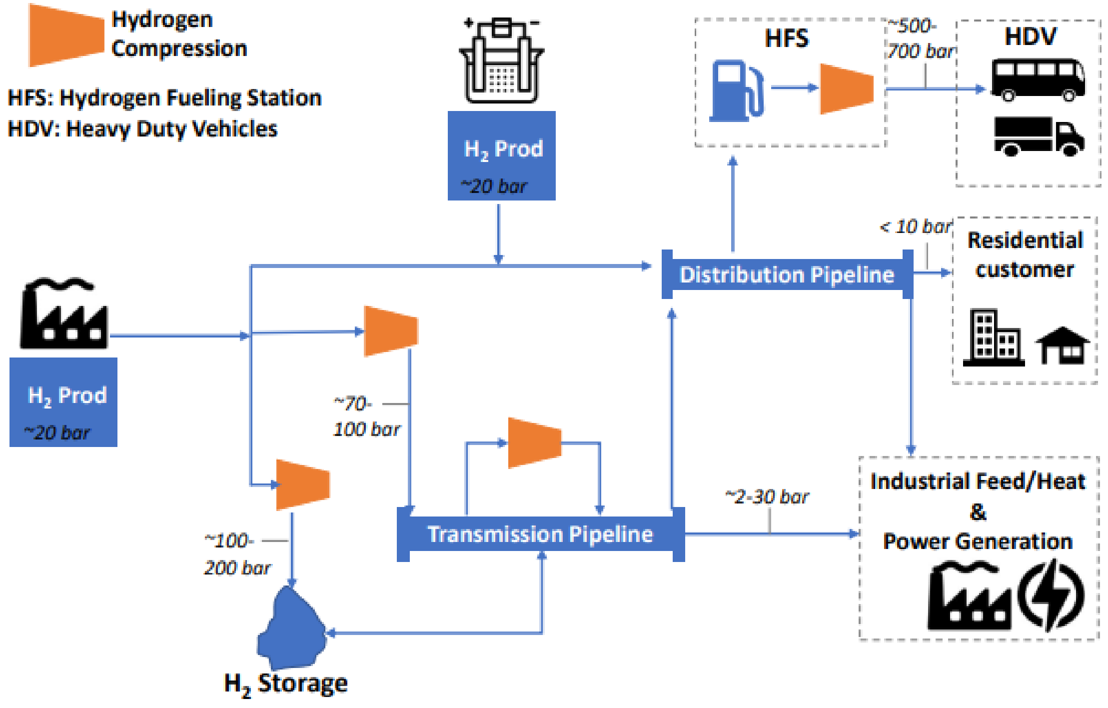
Some similarities for hydrogen and NG pipelines

- Use of steel pipelines, with similar operating pressures
- May use underground storage, such as salt caverns
- Flow rate (Q) (Sm^3/day) increases with pressure (*P*) difference gradient

$$Q = 1.1494 \times 10^{-3} \left(\frac{T_b}{P_b}\right) \left[\frac{(P_1^2 - e^s P_2^2)}{G T_f L_e Z f}\right]^{0.5} D^{2.5}$$

Some differences*

- Hydrogen energy density (MJ/m^3) ~1/3rd NG - for a given pressure => ~1/3 energy flow (MW) for <u>given gas speed</u>
- Decline in energy flow rate can be mostly off-set [to ~88% NG MW] by use of larger compressors <u>to increase gas speed</u>**
- Smaller size of H_2 molecules: embrittlement may lead to higher thickness requirements and greater tolerance for fittings

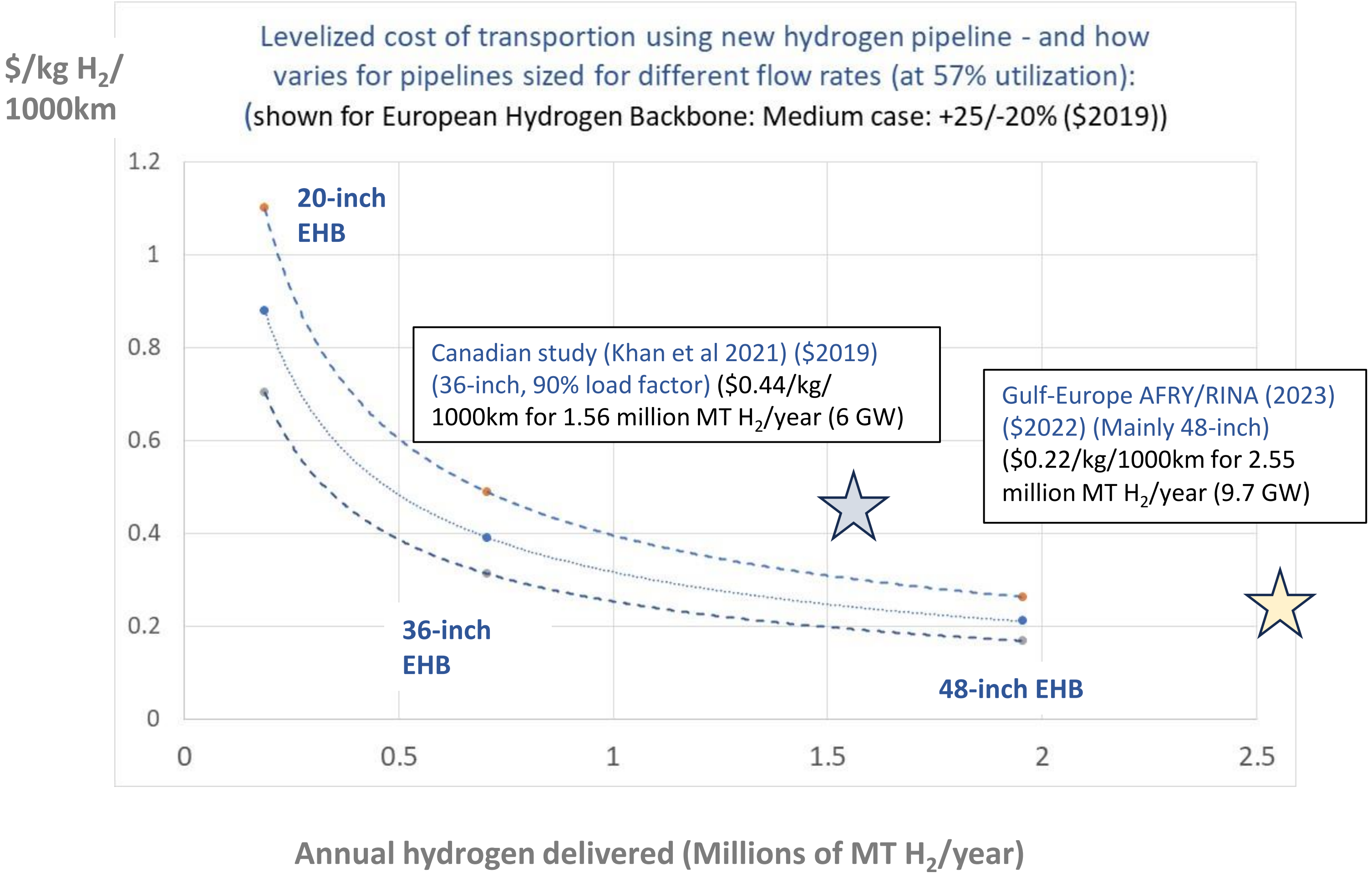


Source: Figure, main ideas and flow rate formula in box from: Khan, Young, and Layzell. "The Techno-economics of hydrogen pipelines." (2021):*Use of some types of storage reservoirs may be limited due to interaction of hydrogen with micro-organisms. **Where speed is capped by erosion limits. For educational purposes

Significant interest in repurposing in some existing NG pipelines to reduce investment requirements

Levelized cost estimate of ~\$0.2 to \$0.3+/kg H_2/1,000km for transport in new hydrogen pipelines relies on the use of high-capacity pipelines and flow rates [e.g., 48-inch, 2 million+ MT/year [7+GW*]]

DRAFT

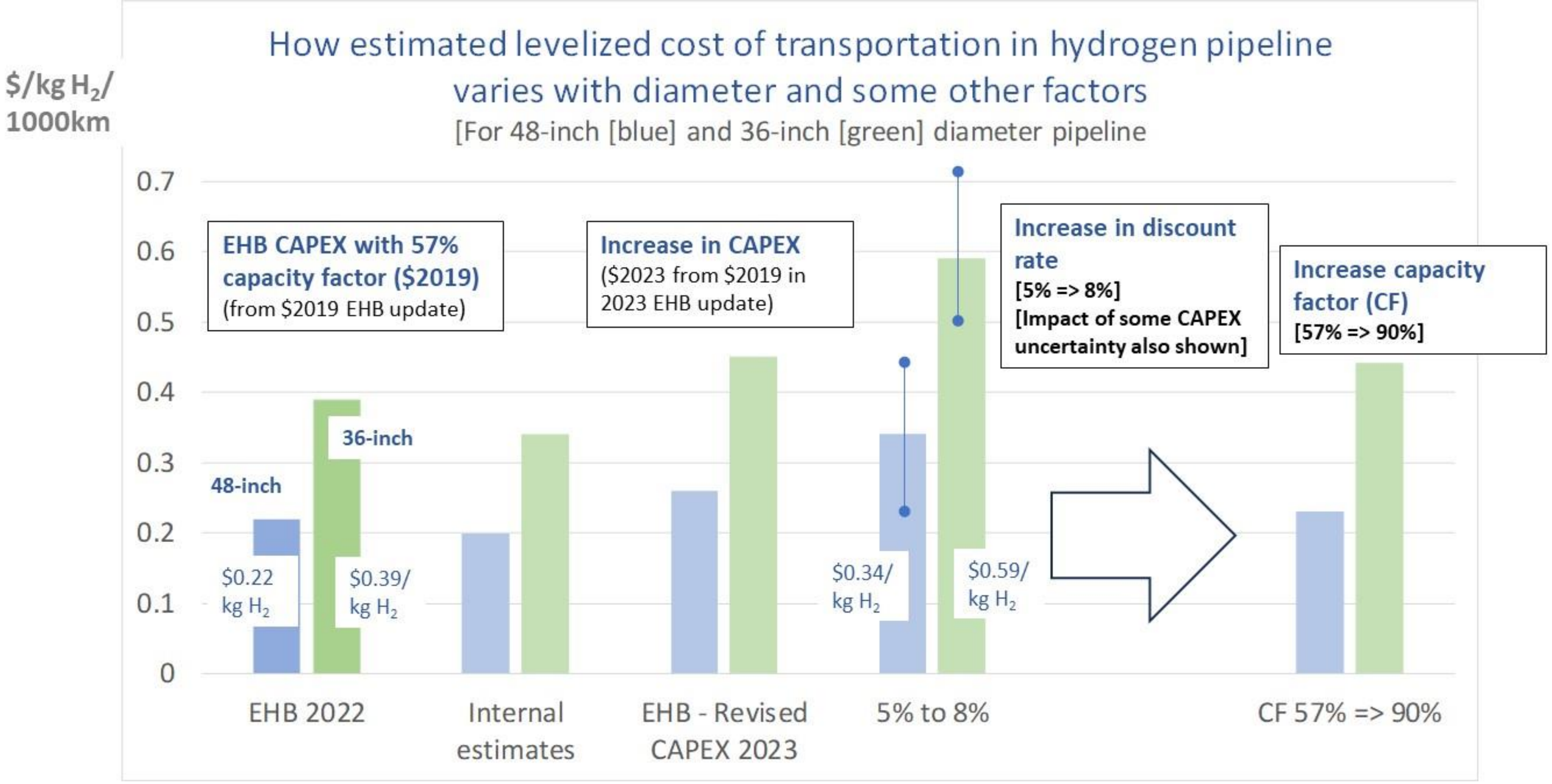


High flow rate may assume/require aggregation of supply from multiple green and blue hydrogen production sites

*2 million metric tons pe year is average energy flow rate of 7,610 MW = 2m MT x 33.3/MWh/MT/(8760), or 7.6 GW.

Many factors may impact the levelized cost of transportation ($/kg H_2/1,000km) using a hydrogen pipeline, including CAPEX/capacity (GW)*, utilization and discount rate**

DRAFT



Use of refurbished pipelines reduces investment needs, though impact on levelized cost depends on other factors [given owner may want a return on existing assets]

Note: *where CAPEX/GW is determined by pipeline diameter [D] and compressor sizing and separation. **Uncertainly is understated

Estimate levelized cost of shipping liquid ammonia using an **illustrative example of a port exporting of 1.2 million metric tons of green ammonia annually that is shipped 8,700km**

DRAFT

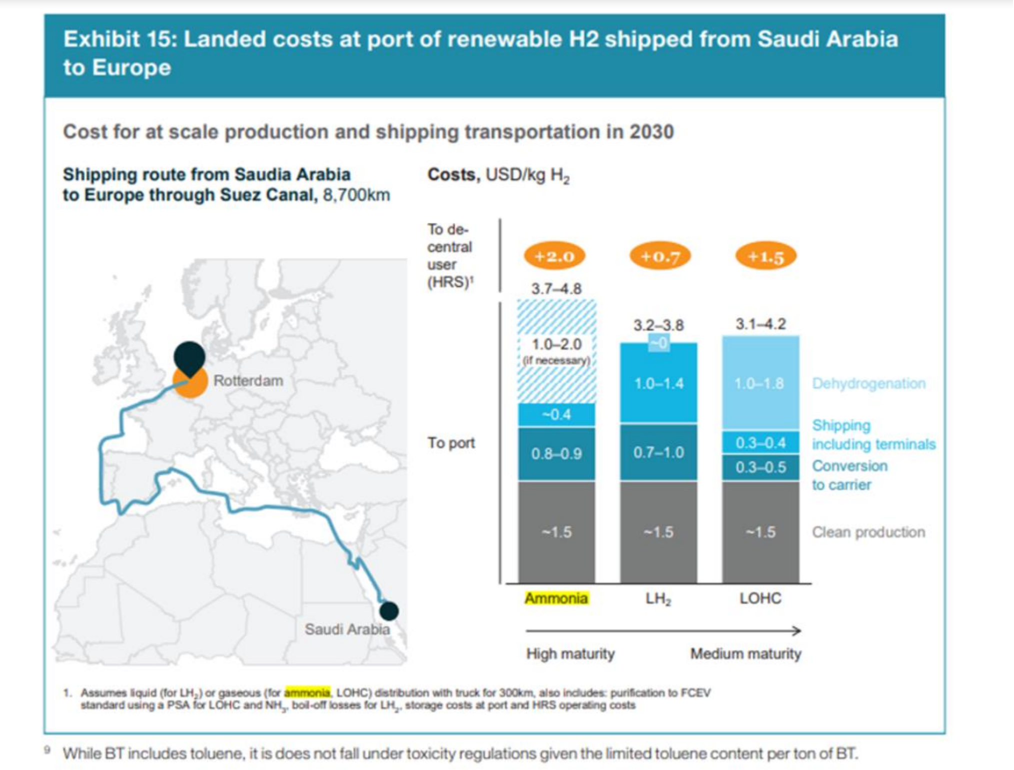
Maritime distance of 8,700km chosen for several reasons:

[1] Representative distance for some shipping routes; falls between shorter and longer routes

[2] Allows for comparison with different studies such as:

- 2021 Hydrogen Council 2030 estimate of ~ $0.4/kg hydrogen for shipping liquid ammonia [including port costs], and to:
- Compare the cost of use of liquid ammonia vs. liquid hydrogen or other carriers for shipping [including conversion costs]

[3] Methodology can be extended to estimate how costs changes with distance



Source: Figure from Hydrogen Insights 2021, Hydrogen Council

Allows comparison of **delivered cost of shipping vs. use of hydrogen pipelines over long distances – and how depends on scale**

Illustrative design layout for large green ammonia facility and export port (closely based on figure by Black & Veatch) to which illustrative CAPEX estimates have been added.

DRAFT

Ammonia Plant
(2,600 MT NH_3/day)
0.95 million MT/year

Ammonia Plant
(2,600 MT NH_3/day)
0.95 million MT/year

Ammonia Plant
(2,600 MT NH_3/day)
0.95 million MT/year

~$2 to $2.5bn
($750 to $1,000 per ton NH_3 /year*
[excluding hydrogen production)

Ammonia pump
(1.2MW)

~$4 to $5m

Ambient ammonia pipeline
2.6 million metric tons NH_3/year
(at 90% capacity factor)

~$2 to $4m, to ~$100m
(2km to 100km)

Refrigerated liquid ammonia tanks + pumps
2 x 60,000 MT NH_3

~$180m
(2x ~$90m)

~$100m
For new berth if needed
(but it may be shared)

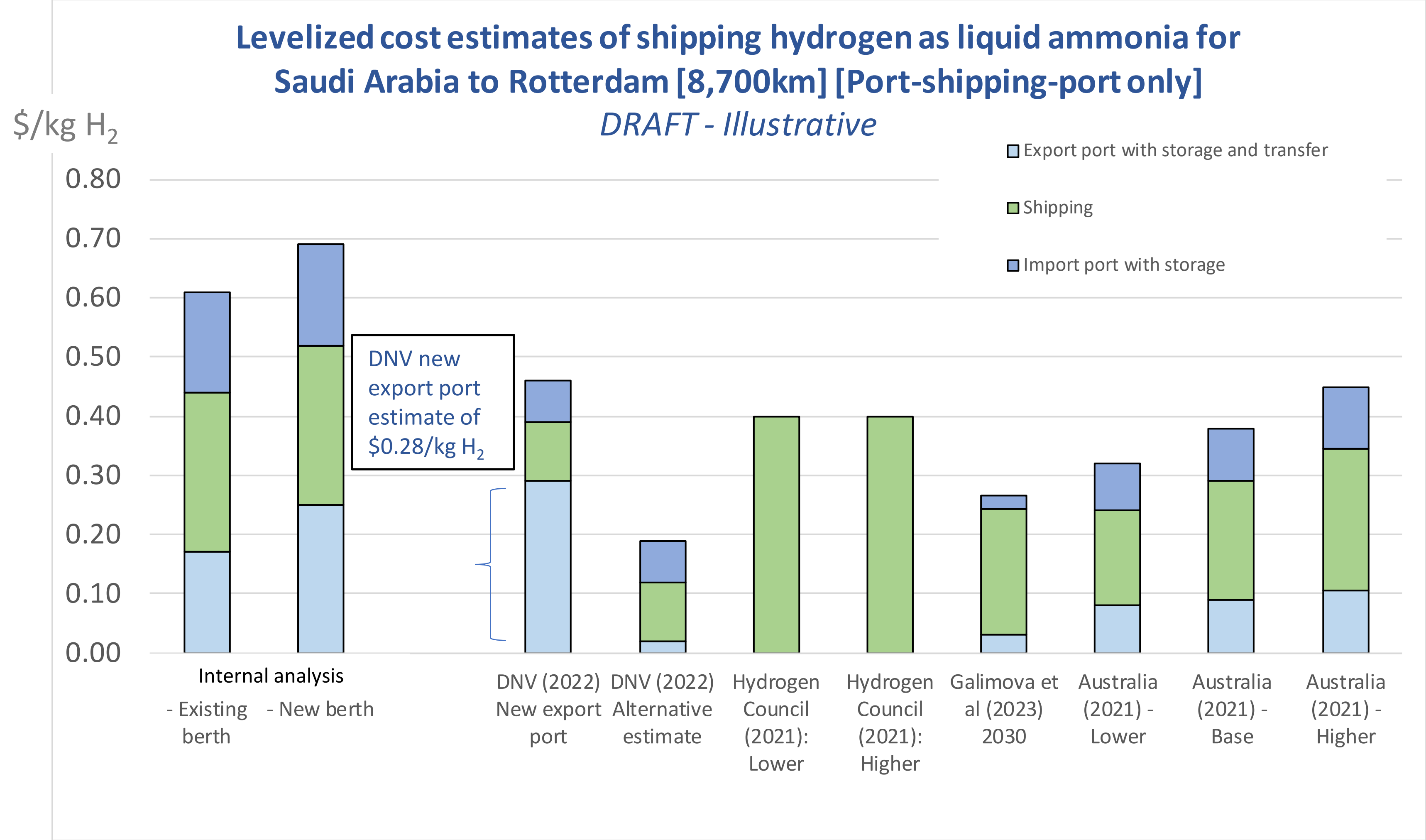
Liquid ammonia carrier
80,000 m3 (55,000 MT NH_3)

~$480m (4 ships at ~$120m each);
(Assumes each vessel makes monthly return trips, with ships staggered one-week apart)

Source: Figure and sizing very closely based on slide in Black & Veatch presentation by Michael Goff (2020) https://www.ammoniaenergy.org/wp-content/uploads/2020/12/Michael-Goff.pdf. Cost estimates added various sources including Nayak-Luke et al [2020]. $100m cost estimate for new berth is based on DNV (2022) estimate of $102m.

For example, $750/MT ton NH_3 year at 10% CRF would be $75/MT ammonia, equal to $0.40/kg H2 = (75 x 5.7)/1,000kg/MT excluding variable costs

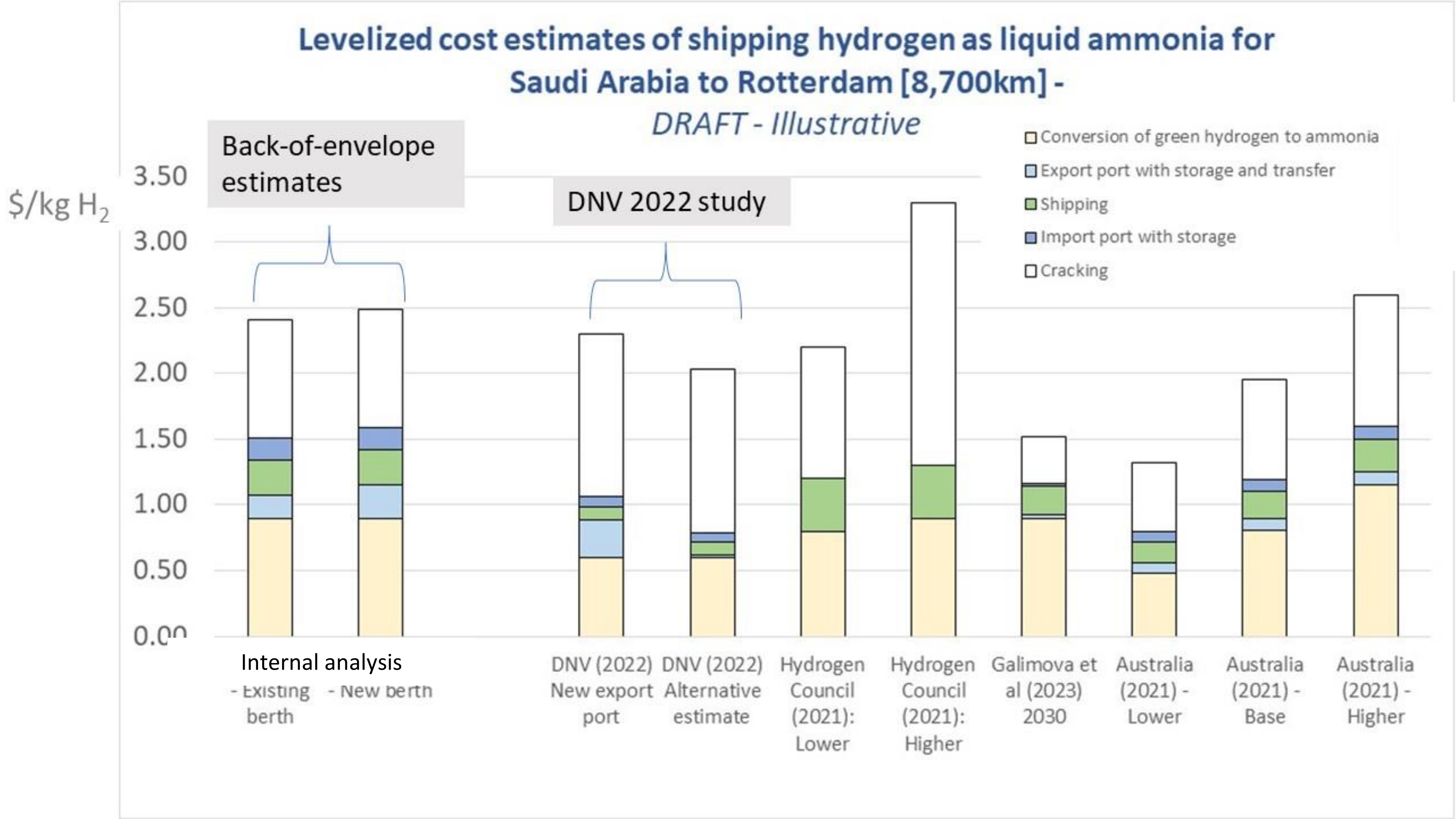
Different studies lead to a range of levelized cost for ammonia storage and loading at export ports: often from ~$0.10 (or less) to ~$0.30/kg hydrogen* (~$15 to $45/metric ton ammonia**)



Source: Australian study refers to analysis in Wang et al (2023) "Shipping Australian sunshine: Liquid renewable green fuel export"*Levelized cost may be lower for existing ports and/or where port and/or berth used for multiple goods/commodities **For example, $15.5/MT ammonia = $0.10/kg H_2 x (18.6MJ/kg NH_3)/(120MJ/kg H_2) x 1,000kg/MT

Estimated levelized cost of 'port-ship-port delivery' of liquid ammonia 8,700km mostly in the range ~$1 to $1.60/kg hydrogen, though with **significant uncertainty** both for **overall cost** and **breakdown***

DRAFT



Shipping costs for ammonia (~$0.02 to $0.03/kg H_2/1,000km) **are much less than pipelines** (~x10 even for 48-inch at ~$0.2 to $0.3 kg H_2/1,000km)
=>
Comparative advantage of shipping vs. pipelines increases with distance

Key barrier for shipping are conversion costs [and energy losses] at beginning and end of the process

Largest cost for conversion of hydrogen to ammonia (~$0.5 to $1.1/kg H_2 (yellow), and (where appropriate) for cracking ammonia back to hydrogen

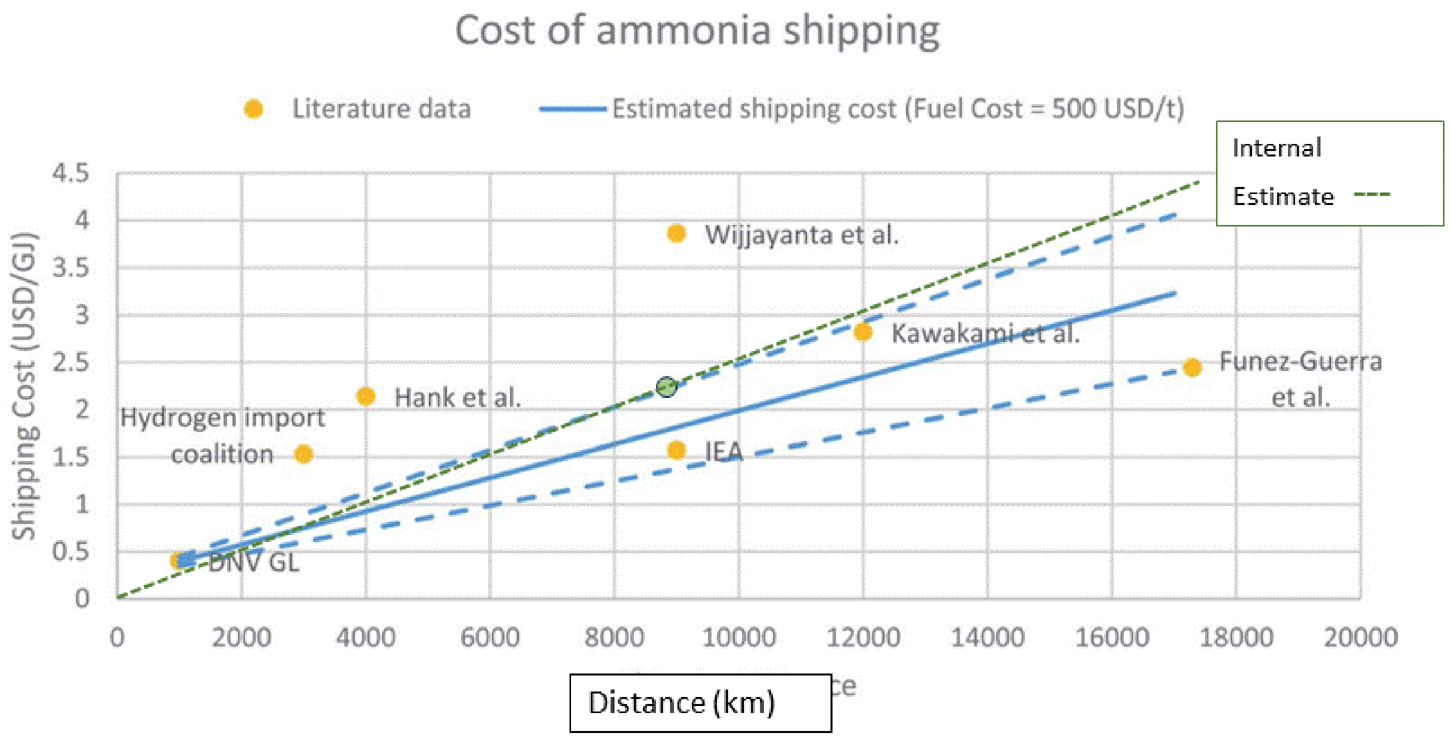
*Adjusted for common distance. Some studies higher estimates (e.g., Ishimoto 2020) and some have lower estimates (e.g., EHB 2021)

Differences in methodologies and/or input assumptions can lead to large differences in estimates for infrastructure costs

DRAFT

Wide variation in literature for infrastructure cost estimates

- Example: Cost of ammonia shipping as a function of distance (from Salmon et al 2021)
- Much larger differences and uncertainty (on $/kg H_2 basis) for more costly parts of value chain e.g., conversion, reconversion, transportation in lower volumes



For preliminary analysis of least cost infrastructure options =>

[1]: Need for care when using estimates from multiple sources

[2]: Useful to be able to replicate analysis independently and/or do sensitivity analysis

Source: Figure from Salmon and Bañares-Alcántara. "Green ammonia as a spatial energy vector: a review." *Sustainable Energy & Fuels* 5, no. 11 (2021): 2814-2839 (Open-access) Omits some examples with higher and lower costs Internal analysis estimate of LCOT [added to figure] ~$0.27/kg for 8,700km excluding ports is $2.25/GJ (=$0.27/120MJ/kg H_2 x 1GJ/1000MJ)

Levelized cost of shipping in liquid hydrogen (LH_2) vessel may be **~x1.5 to 2+ higher than use of liquid ammonia carrier** - due to differences in energy density and refrigeration requirements

DRAFT

1) Three hydrogen vessels are needed to transport the same amount of energy for every two similarly sized liquid ammonia vessels

- Energy density (per unit mass) of hydrogen is x 6.45 liquid ammonia [120MJ/kg H_2 vs. 18.6MJ/kg NH_3]
- However, the mass density of liquid ammonia per unit volume at -33C is x9.6 liquid hydrogen at -20K (683kg NH_3/m^3 vs. 71.1kg H_2/m^3);

Combined effect liquid ammonia (at -33C) has ~x1.5* the energy density per unit volume than liquid hydrogen (at 20K)

2) Capital cost of a vessel for liquid hydrogen for the same volume capacity may be [by some estimates] ~x1.33 greater than for an ammonia carrier*.

3) Makes liquid ammonia more attractive carrier than liquid hydrogen even if cost of liquefaction of hydrogen fell so that levelized costs at berth/point of loading were comparable.

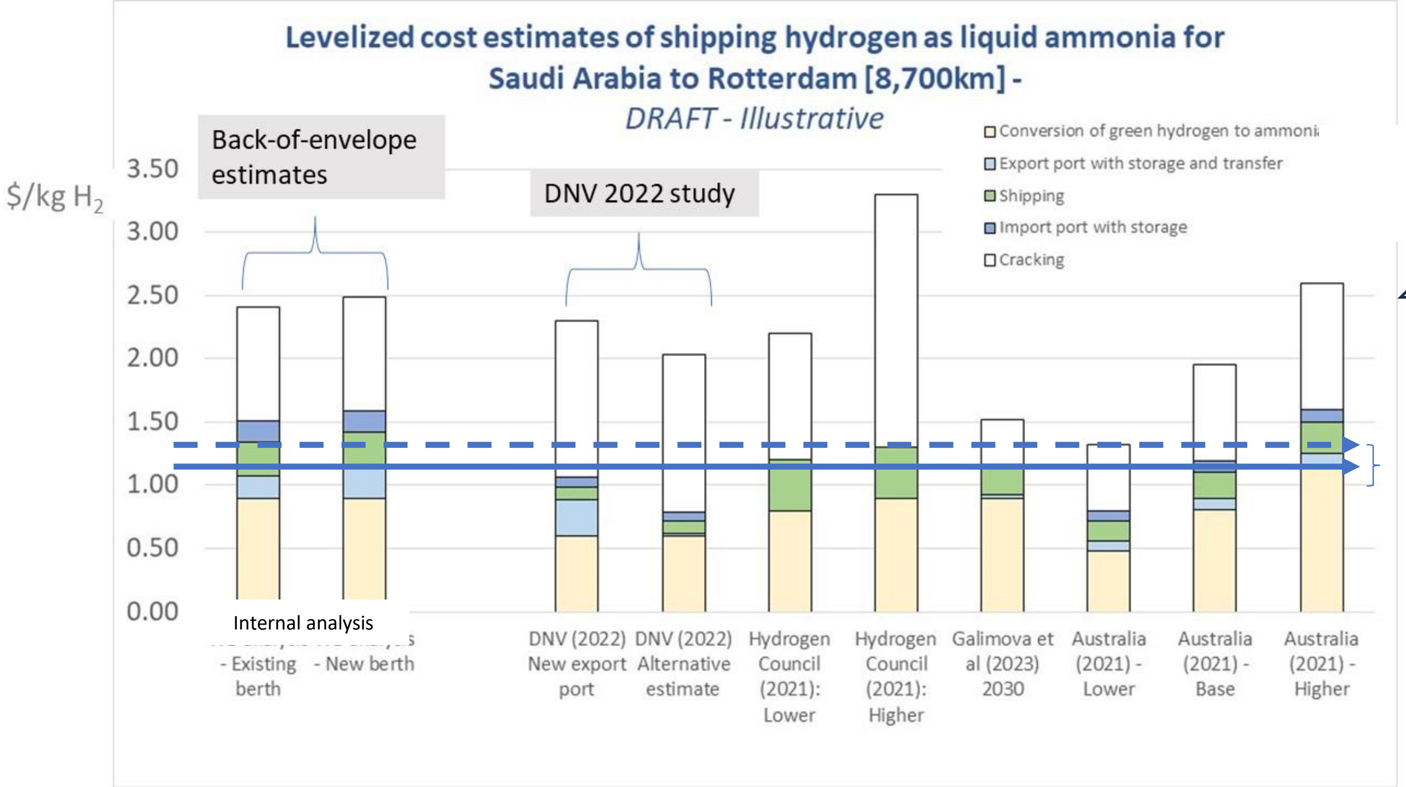
Key caveat – which is important - is that assume liquid ammonia used "as is" and not cracked by to hydrogen. If ammonia is cracked back to hydrogen there will be substantial incremental costs

Note: Additional levelized for hydrogen shipping due to greater boil-off losses vs. ammonia, particularly over longer voyages and during transfer process not included. *1.49 = 9.6/6.45)

Sources: **Various including Al-Breiki and Bicer (2020) which includes boil-off in some detail, Recent contract price for two mid-size LPG/Ammonia gas carriers with 40,000 m^3 storage (duel -fuel engine) was $61.5m each: (Global News Wire (2023). *1.49 = 9.6/6.45

Levelized cost of shipping can be compared to the use of hydrogen pipelines to Northern Europe from same point of origin (e.g., for 8,700km shipping vs. 5,000km or 5,900km via pipeline**)**

DRAFT



Levelized cost of use of pipeline increases for smaller pipeline and/or lower capacity factor

Illustrative example
$1.32/kg H_2 for 5,900 km; may be reduced to $1.10/kg H_2 for 5,000 km*

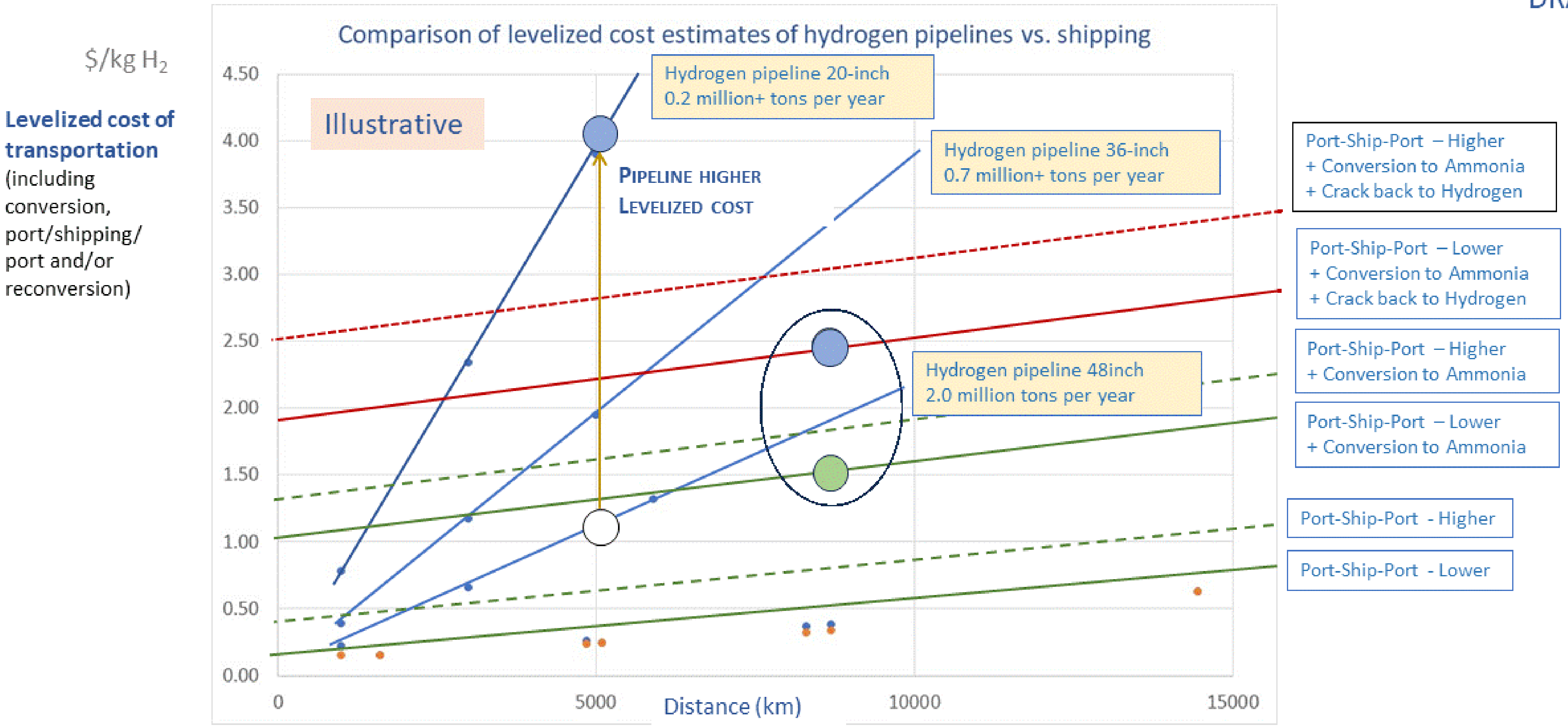
- Recent feasibility study (AFRY/RINA 2023) outlines potential **~5,900km hydrogen pipeline linking the Gulf Coast Countries to Europe;** sized at **2.55 million metric tons H_2/year** for estimated **investment cost of 28 billion Euro**

Relative economics for use of hydrogen pipeline gets worse for smaller diameter pipelines – or lower capacity factor

*This assumes pro-rated cost based on distance is a reasonable assumption. **For example, <0.02-0.03kg H_2/1,000km shipping vs.~ $0.22/kg H_2/1,000 km for large diameter pipeline

In contrast, for the same route, the **use of a smaller 20-inch hydrogen pipeline sized for~ x10 lower volume than 48-inch pipeline increases the pipeline levelized cost by a factor x4+**

DRAFT



Significant uncertainty in both the slope and intercept for both pipeline and shipping

And in this **illustrative case the use of hydrogen pipeline is more expensive than shipping even after cracking**

Note: Illustrative in the sense that cracking and other costs may be higher than shown above. For example, lower and upper case for cracking ammonia shown range from $0.9 to $1.20/kg hydrogen, whereas Hydrogen Insights 2021 study gives range of $1 to $2/kg hydrogen.

Some summary observations

DRAFT

- Infrastructure needed to provide reliable hydrogen supply to [1] end users and/or applications, and [2] to do so at the lowest cost
- Future hydrogen related infrastructure investment costs - while uncertain - are expected to be significant ($ trillions by 2050 according to World Bank internal estimate)
- At a project, regional or even multi-country level the levelized cost of hydrogen infrastructure adder ($/kg H_2) will vary widely depending on:
  - Distance moved Storage used Scale Asset/s utilization
  - Types and relative sizing of infrastructure assets CAPEX End use
  - Electricity/fuel costs Conversion and use of energy carriers
  - Discount rates and financing

  There is no one least cost solution for transportation – and Scale matters
- Considerable interest in reusing existing infrastructure assets to lower investment requirements
- Important not to overlook need for - and cost of infrastructure when considering low-cost green or blue hydrogen production and delivered hydrogen cost targets

Annex: Some reasons for wide range of estimates for the levelized cost of infrastructure adders include*

DRAFT

1) Installed CAPEX estimates for conversion, storage, transportation and/or re-conversion assets depend on assumptions about:

- How far CAPEX has fallen for a given types of infrastructure asset in future build year, and how CAPEX varies with scale; such estimates may be highly uncertain for some technologies/assets
- Relative sizing – and hence utilization - of 'connected' infrastructure blocks bridging production to end user. A systems optimization problem, though may be some useful rules of thumb for preliminary estimates e.g., VRE to electrolysis plant nameplate capacity, and electrolysis plant utilization

2) Ability to reuse or partly reuse existing assets [e.g., new ports vs. higher capacity factor at existing berth]

3) Different modeling approaches and input assumptions

- Discount rate – including recent changes in lending rates
- Feedstock and fuel cost, including firm electricity
- Asset lives (e.g., for pipelines, storage, compressor and pumps, port berths, ammonia plants)
- Energy efficiency assumptions [for storage, transportation and energy conversion]]
- Country-specific material, labor and land cost
- When to use to tariff rather than cost information

Some observations

- Even when normalize across such differences to tentatively identify preferred infrastructure option(s) – need to recognize many future cost and performance inputs are highly uncertain
- Useful to review sizing and design decisions for existing planned projects

*Note: This slide is intended to list some relevant factors, and is not intended to be complete

*Some references used in this presentation and Annex [in blue if publicly available or open-access]. *If used in main presentation*

DRAFT

- *AFRY/RINA (2023), Hydrogen pipeline from the Gulf to Europe: Use case and feasibility considerations, AFRY and RINA joint discussion paper, June 2023. https://afry.com/sites/default/files/2023-06/3355_afry_and_rina_joint_discussion_paper_hydrogen_pipeline_from_the_gulf_to_europe_use_case_and_feasibility_considerations_june_2023.pdf
- *Abdin, Zainul, Chunguang Tang, Yun Liu, and Kylie Catchpole. "Large-scale stationary hydrogen storage via liquid organic hydrogen carriers." *Iscience* 24, no. 9 (2021) [Open-Access].
- Adam, Peter, Frank Heunemann, Christoph von dem Bussche, Stefan Engelshove, and Thomas Thiemann. "Hydrogen infrastructure–the pillar of energy transition." *Munich: Siemens Energy, Gascade Gastransport GmbH, Nowega GmbH* (2020)
- *Al-Breiki, Mohammed, and Yusuf Bicer. "Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon." *Energy Reports* 6 (2020): 1897-1909. [Open-Access].
- *Al Ghafri, Saif ZS, Stephanie Munro, Umberto Cardella, Thomas Funke, William Notardonato, JP Martin Trusler, Jacob Leachman et al. "Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities." *Energy & environmental science* 15, no. 7 (2022): 2690-2731[Open access]
- Alamoudi, Rami, Osman Taylan, Mehmet Azmi Aktacir, and Enrique Herrera-Viedma. "Designing a solar photovoltaic system for generating renewable energy of a hospital: Performance analysis and adjustment based on RSM and ANFIS approaches." *Mathematics* 9, no. 22 (2021): 2929.) [Open-Access].
- Aldridge, Jamie, Argus, Weight of freight; can the ammonia fleet match growing demand, February 9, 2023, Weight of Freight: Can the ammonia fleet match growing demand? | Argus Media
- *Bolinger, Mark, Joachim Seel, Cody Warner, Julie Mulvaney-Kemp, Dana Robson, and Anjali Katta. *Utility-Scale Solar, 2023 Edition: Analysis of Empirical Plant-level Data from US Ground-mounted PV, PV+ battery, and CSP Plants (exceeding 5 MWAC)*. No. 5963. DOE Open Energy Data Initiative (OEDI); Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA (United States), 2023.
- Chen, Peggy Shu-Ling, Hongjun Fan, Hossein Enshaei, Wei Zhang, Wenming Shi, Nagi Abdussamie, Takashi Miwa, Zhuohua Qu, and Zaili Yang. "A review on ports' readiness to facilitate international hydrogen trade." *international journal of hydrogen energy* (2023). [Open access]
- Cockerill, Rob, PEM vs. Alkaline electrolysis, H2View, November 2020: https://nelhydrogen.com/wp-content/uploads/2021/07/Alk-vs-PEM.pdf
- *DNV, Pre-feasibility for a hydrogen export project, final report, Inter-American Development Bank May 9, 2022
- DeSantis, Daniel, Brian D. James, Cassidy Houchins, Genevieve Saur, and Maxim Lyubovsky. "Cost of long-distance energy transmission by different carriers." *IScience* 24, no. 12 (2021). [Open-access]
- *European Hydrogen Backbone, report (2021) "Analysing future demand, supply and transport of the hydrogen"; June 2021

DRAFT

- *European Hydrogen Backbone (2022), European Hydrogen Backbone: A European hydrogen infrastructure vision covering 28 countries, April 2022. https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf
- *European Hydrogen Backbone (2023), European Hydrogen Backbone: Implementation roadmap - Cross border projects and costs update, November 2023.
- EPA, Ammonia plant, Burrup Peninsula, Report and recommendations of the Environmental Protection Agency, December 2001 [This is the Yara Pilbara plant]
- *Elishav, O., B. Mosevitzky Lis, A. Valera-Medina, and G. S. Grader. "Storage and distribution of ammonia." *Techno-Economic Challenges of Green Ammonia as an Energy Vector. Elsevier* (2021): 85-103.
- GCMD-DNV, April 2023, Ammonia bunkering pilot safety study; https://www.gcformd.org/ammonia-bunkering-safety-study
- GIZ, July 2023, Study findings report: Green hydrogen transport scenarios: From Kazakhstan to Europe
- GO-Biz (California Governor's Office of Business and Economic Development, Hydrogen Station Permitting Guidebook, September 2020
- Global newswire (2023), https://www.globenewswire.com/en/news-release/2023/08/21/2728375/0/en/Avance-Gas-declared-the-option-of-newbuilding-contracts-for-two-Medium-Sized-LPG-Ammonia-Carriers.html
- *Goff, Michael, Presentation: Distribution of ammonia as an energy carrier, Black and Veatch, November 2020. https://www.ammoniaenergy.org/paper/distribution-of-ammonia-as-an-energy-carrier/
- Guerra, Omar J. "Beyond short-duration energy storage." *Nature Energy* 6, no. 5 (2021): 460-461.
- Hatfield,.Oliver, Argus, Country traded ammonia logistics and storage, present and future, 2021. https://www.ammoniaenergy.org/wp-content/uploads/2021/11/AEA-presentation-Oliver-Hatfield.pdf.
- Hank, Christoph, André Sternberg, Nikolas Köppel, Marius Holst, Tom Smolinka, Achim Schaadt, Christopher Hebling, and Hans-Martin Henning. "Energy efficiency and economic assessment of imported energy carriers based on renewable electricity." *Sustainable Energy & Fuels* 4, no. 5 (2020): 2256-2273
- Hjelmeland, Martin, and Jonas Kristiansen Nøland. "Correlation challenges for North Sea offshore wind power: a Norwegian case study." *Scientific Reports* 13, no. 1 (2023): 18670. [Open-Access].
- *Hydrogen Council, Path to hydrogen competitiveness: A cost perspective, 2020; Path to Hydrogen Competitiveness: A Cost Perspective | Hydrogen Council
- *Hydrogen Council/McKinsey, Hydrogen Insights 2021; Hydrogen-Insights-2021.pdf (hydrogencouncil.com)
- *IRENA (2021), Making the breakthrough: Green hydrogen policies and technology costs, International Renewable Energy Agency, Abu Dhabi
- *Ishimoto, Yuki, Mari Voldsund, Petter Nekså, Simon Roussanaly, David Berstad, and Stefania Osk Gardarsdottir. "Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers." *International Journal of Hydrogen Energy* 45, no. 58 (2020): 32865-32883.

REFERENCES: Continued

DRAFT

- *Khan, Mohd Adnan, Cameron Young, and David B. Layzell. "The Techno-economics of hydrogen pipelines." *Transition Accelerator Technical Briefs* 1, no. 2 (2021): 1-40
- *Lazard (2023), LCOE+ Lazard, April 2023,
- Leigh Collins, Auction results reveal that Chinese hydrogen electrolysers are two to five times cheaper to buy than Western machines, Hydrogen Insights, 13 December 2023 [updated 14, December 2023]
- Leigh Collins and Xu Yihe, World's largest green hydrogen project — China's 260MW Kuqa facility — to be commissioned at the end of May; 26 May 2023: https://www.hydrogeninsight.com/production/world-s-largest-green-hydrogen-project-chinas-260mw-kuqa-facility-to-be-commissioned-at-the-end-of-may/2-1-1457242
- *Louis Londe, Geostock, Four ways to storage large quantities of hydrogen, March 3, 2023, https://www.geostockgroup.com/en/four-ways-to-store-large-quantities-of-hydrogen/.
- *Nayak-Luke, R. M., C. Forbes, Zac Cesaro, R. Bañares-Alcántara, and Kevin Hendrik Reindert Rouwenhorst. "Techno-economic aspects of production, storage and distribution of ammonia." *Techno-Economic Challenges of Green Ammonia as Energy Vector; Bañares-Alcántara, R., Valera-Medina, A., Eds* (2020): 191-208
- Patonia, Aliaksei, Veronika Lenivova, Rahmatallah Poudineh, and Christoph Nolden. *Hydrogen pipelines vs. HVDC lines: Should we transfer green molecules or electrons?*. No. 27. OIES Paper: ET, 2023. [Open access]
- *Papadias, Dionissios D., and Rajesh K. Ahluwalia. "Bulk storage of hydrogen." *International Journal of Hydrogen Energy* 46, no. 70 (2021): 34527-34541.
- *Salmon, Nicholas, and René Bañares-Alcántara. "Green ammonia as a spatial energy vector: a review." *Sustainable Energy & Fuels* 5, no. 11 (2021): 2814-2839 [Open-Access].
- *Satyapal, Sunita, US Department of Energy, US DOE Hydrogen program annual metric review (AMR) plenary remarks, June 5, 2023
- Tzimas, Evangelos, C. Filiou, Stathis Dimitris Peteves, and Jean-Bernard Veyret. "Hydrogen storage: state-of-the-art and future perspective." *EU Commission, JRC Petten, EUR 20995EN* (2003).
- US Department of Energy, HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines (energy.gov)
- *Wang, Feng, Ross Swinbourn, and Chao'en Li. "Shipping Australian sunshine: Liquid renewable green fuel export." *International Journal of Hydrogen Energy* (2023). [Open access]

ACKNOWLEDGEMENTS

The content of this presentation reflects a subset of recent research on hydrogen infrastructure with input and guidance from Dolf Jean Gielen, Rafael Ben and Priyank Lathwal. Any errors, however, are the responsibility of the presenter. The estimates are deliberately noted to be draft and illustrative for several reasons, including the literature shows a wide range of estimates for similar metrics. The reasons for such differences are touched on in the presentation and include (but are not limited to) differences in assumptions about CAPEX for different technologies and assets, and how change over time [particularly how far the CAPEX for a particular asset for production, storage or transport has fallen by certain year, and impact of scale], discount rates, utilization and related relative sizing assumptions for connected assets [e.g., ,PV + wind (MW) to electrolysis plant (MW) to pipeline and/or storage (MWh)], input prices, and modeling approach. For modeling, while some studies, including this one use relatively simple spreadsheets to estimate levelized costs, there are a number more detailed hydrogen system models.

Supporting Slides

These slides support the main presentation and were removed to reduce length of main presentation

Annex [DRAFT] to these slides – Not included in this version

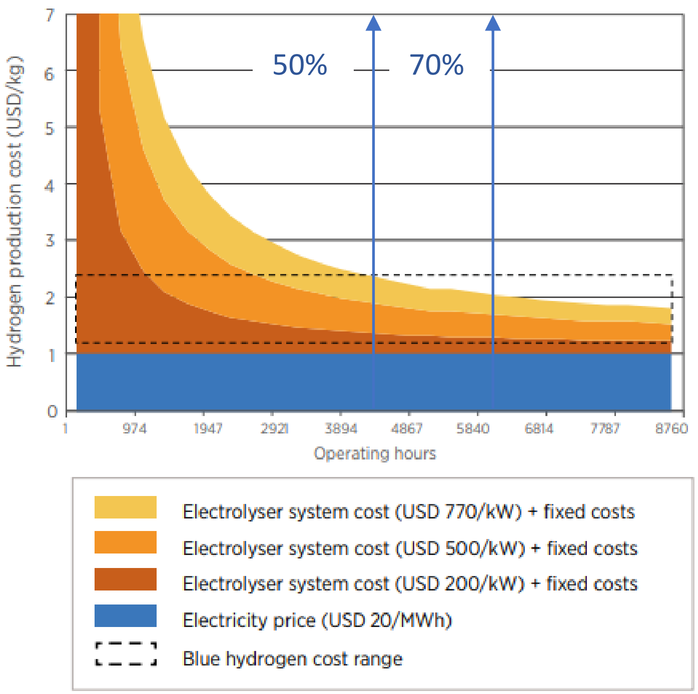
A low levelized production cost of green hydrogen (~$2 to $2.5/kg H_2 (or less)) requires low CAPEX for electrolysis plant, excellent PV and wind resources, <u>and high utilization of the electrolysis plant</u>

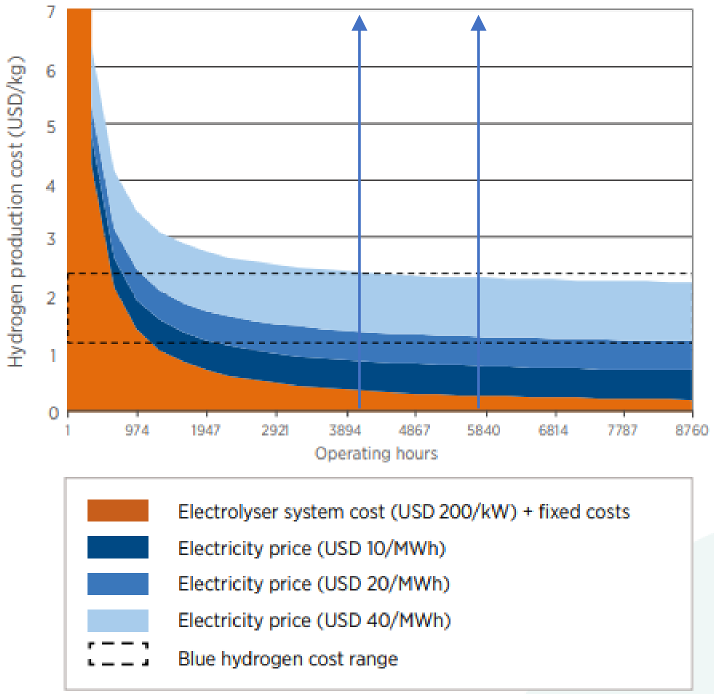
DRAFT

Utilization targets for electrolysis plant ~50% to 60%+ for non-grid connected VRE typically based on having:

- Excellent solar <u>and</u> wind resources, and;
- Combining Wind + PV, and oversizing capacity (MW); may be e.g., ~<x1.5 to x2+ electrolysis plant capacity

Note: Under very good resources PV capacity factor would only be 30%* if same capacity (MW) as electrolysis plant





Source: Figure from: IRENA (2021) *"Efficiency at nominal capacity is 65%..., the discount rate is 8% and the stack lifetime is 80,000 hours"*

However, **higher utilization for electrolysis plant** comes at the **extra cost of oversizing PV and/or wind [MW] relative to the electrolysis plant [MW]** (and/or the potential use of limited intra-day [e.g., battery] storage).

Note:: $20/MWh (or $0.02/kWh) for electrolysis plant with 65% conversion efficiency is equal a cost of $1/kg H_2 ($1.03/kg = $0.02/MWh x (33.3kWh/kg)/(0.65) or $30/MWh on LHV basis

[ii]* Capacity factor for top half of top quartile in US for PV with tracking is between 30% and 35%, while median for all is 24% (tracking and non-tracking): Source: Bolinger, Seel et al 2023

Compressors are used to increase the pressure and energy density of hydrogen in storage tank or underground reservoir [and well as to increase pressure for hydrogen pipelines]

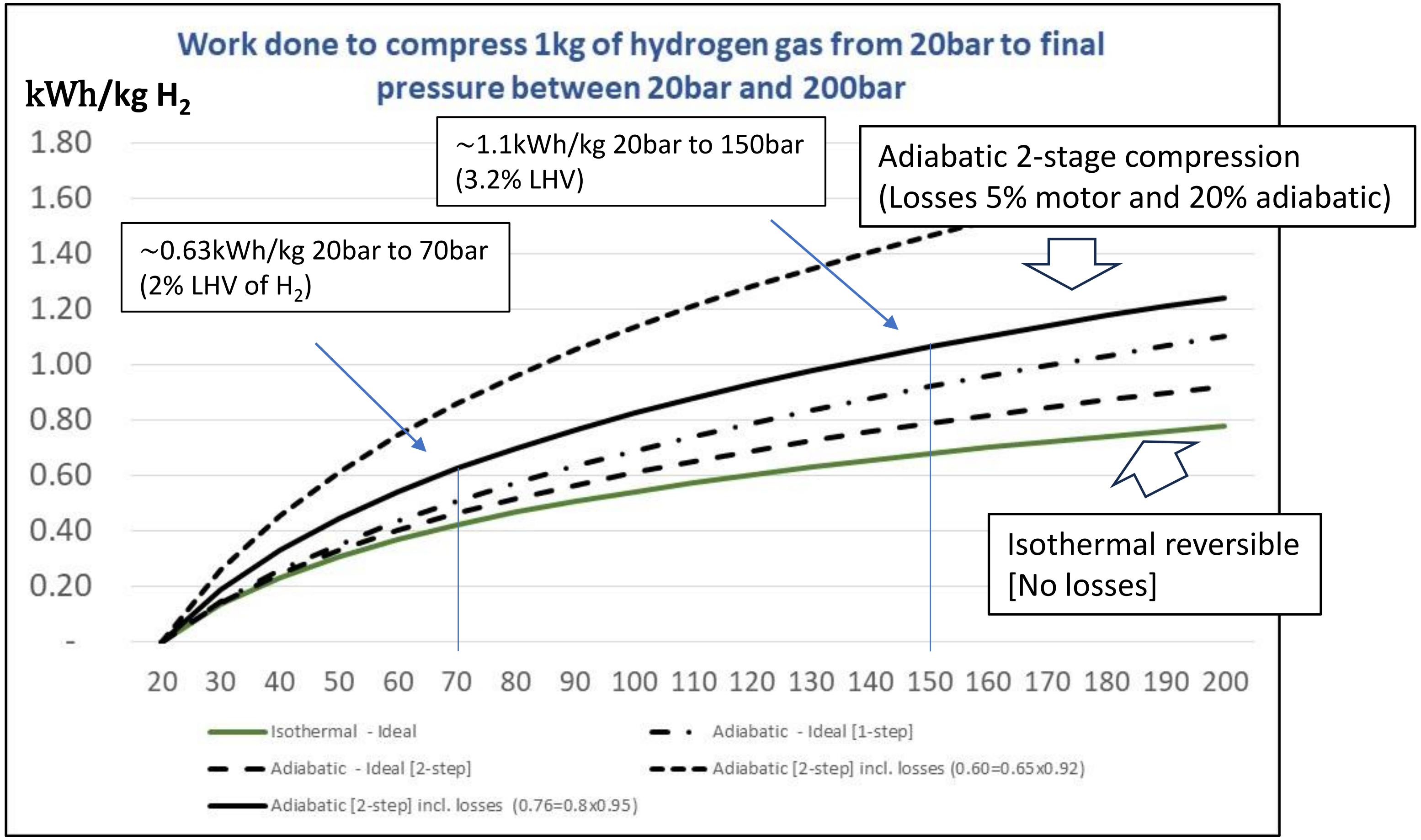
DRAFT

Electrical work done to compress hydrogen gas from 20 bar to 150 bar is ~1.1 kWh/kg H_2 (Est*)(or ~ 3.2% of LHV of H_2 (33.3kWh/kg H_2)

- 20 bar to 70 bar is ~0. 63kWh/kg H_2 or ~1.9% of LHV of hydrogen

In contrast, electrical work for liquefaction of hydrogen to liquid at 20K (-253C) may be over 1/3rd of LHV of hydrogen [or 10kWh+/kg H_2]

Note: Hydrogen may be produced from PEM electrolyzer at 20 bar. In contrast, hydrogen produced from ALK electrolyzer at lower bar will require higher compressor work. In fact, **the work done to compress from 2 bar to 20 bar is the same the work done to increase pressure from 20 bar to 200 bar** (see Annex)



Moving from 1 bar to 100 bar increases the energy (and mass) density of hydrogen from ~3kWh/m^3 (0.08kg/m^3) to ~273kWh/m^3 (and ~8kg/m^3) respectively [at 20C]]. In contrast, energy density for LH_2 is ~ 71kg/m^3 (or 2,360kWh/m^3)

Source: *Approach used in figure to estimate the work done to compress hydrogen consistent with 0.63kWh/kg H_2 estimate in Khan et al [Canadian study] [2021] [i] to compress from 20 bar to 70 bar with 2-step compressor under adiabatic assumption with inter-stage cooling based on [ii] compression and compressor efficiency losses of 0.8 and 0.95 respectively.

High CAPEX for storage using liquid hydrogen driven by cost of liquefaction process rather than the cost of storage

DRAFT

Recent study (Abdin et al 2021) **estimated installed CAPEX cost for 500 metric tons of hydrogen** :

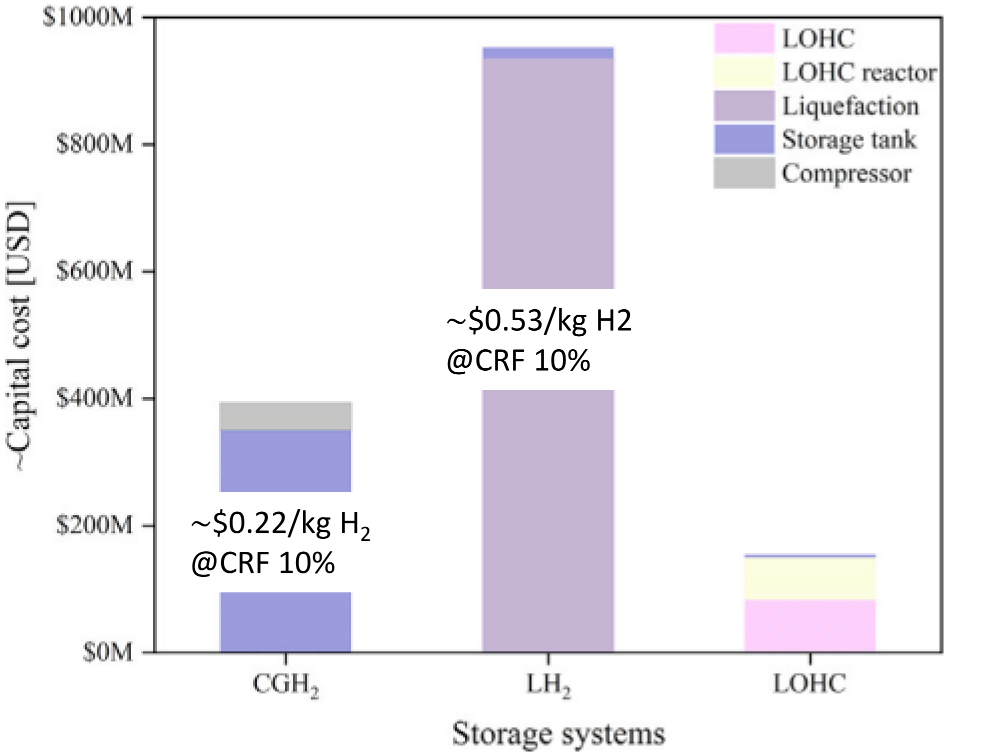
- Above ground hydrogen storage tank for compression to 200 bar at ~\$700/kg H_2 (in line with earlier ~ \$500 to 700/kg H_2 estimates); consistent with \$350m for 500 metric tons H_2)
- Liquid hydrogen storage is ~x20 less than for compressed hydrogen at \$35/kg H_2 (

Significantly lower CAPEX for storage of liquid hydrogen vs. compressed gas (on a kg/m³) may reflect

- Smaller volume needed to hold liquid (~71kg H_2 /m^3 for LH_2 compared to ~8kg H_2 /m^3 for compressed hydrogen at 100 bar)
- Less metal in container for liquid hydrogen at [few] bar as lower structural strength requirements may reduce thickness

CAPEX for liquefaction much greater than for compression on a \$/kg basis

- **Liquefaction**: ~ \$1,870/kg LH_2 => \$954m for liquefaction of 500 MT H2/day
- **Compressor**: \$86/kg H_2 for compressed gas => \$43m CAPEX



Capital cost of compressed hydrogen and liquefaction for storage and daily cycling of 500 metric tons of hydrogen. Figure from Abdin et al 2021 (Open Access) for \$m with implied levelized cost at 10% CRF added to original figure– Illustrative and excludes variable electricity costs.

Note: Compressor cost depends on flow rate, pressure increase and \$/MW assumptions. For 12hrs to fill 500MT using 3% LHV, estimated compressor size is 42MW = [500 MT x33.3MWh/MTx0.03/12hrs]. Using internal estimate \$4m/MW leads to cost of \$168m (42MW x \$4m/MW). Analysis suggests Abdin et al (2021) use lower MW and flow rate and/or lower estimated CAPEX. Alternative values increases estimate in figure of \$0.22/kg H_2 to \$0.29/kg H_2.

Relatively high levelized cost for a new port only exporting ammonia reflects low utilization: ~30 to 40 days berth occupancy (~8 to 12% utilization) for vessels arriving every two weeks with 36-hour turn

DRAFT

Example: Bulk liquid berth for Dampier port, Australia opened is 2005 and has two loading arms; one for liquid ammonia and one for diesel

2014 Annual report suggests in that year **55 ships in a year** [with total occupancy of **56.9 days] used bulk liquids berth to:**

- **Export 804,000 metric tons of liquid ammonia**
- **Import 445,300 metric tons of diesel oil**

"The jetty is 500m long jetty [15 x 32m spans] and a 20m… bridge connecting the approach trestle to the 37m x 34m loading platform.

Platform was ***constructed using precast concrete pile caps and beams****, with an in situ concrete deck.*

- *Supports two loading arms (diesel and ammonia)* *but has the capacity to accommodate up to* ***seven loading arms*** *in total."*

Source: Dampier Bulk Liquids Berth - Pritchard Francis (pfeng.com.au and
Lower figure from Pilbara ports annual report 2022/23; upper figure Google Earth; for educational purposes

Note: Dampier port is not a new port, but is only used to provide an illustrative example of berth utilization

Increasing berth/jetty utilization may reduce the levelized cost substantially. In this case level berth **has second loading arm used to import diesel**: increases utilization from ~8-12% to ~16% utilization [based on 57 days per year]

Example: Recent Gulf Region to Europe feasibility study (AFRY/RINA 2023) outlines potential **~5,900km hydrogen pipeline linking the Gulf Coast Countries to Europe;** sized at **2.55 million metric tons H_2/year** [~10GW]

DRAFT

Sized at 2.55 million metric tons of hydrogen per year (or on average 6,986 MT per day, or equivalently **~291 MT H_2/hour (~9.7GW))**

- 291 MT H_2/hour is ~10GW (9.7GW =291MT H_2/hour x33.3MWh/MT H_2/(1000MW/GW))
- Pipeline system would run from Qatar on Persian Gulf side, through and West across Saudi Arabia up via Egypt to Europe: pipeline is 48-inch for overland and 2x32-inch where underwater. Two potential routes in Europe shown in upper right figure

Estimated cost $31billion (split [est.] $26.6 bn pipeline and $4.4bn compressor**,*)

The study estimates the levelized cost of transportation to be $1.32/kg H_2**

- CAPEX 28 billion Euro, or $31 million, with annual revenue requirement recovery of $3.36bn (~ 10.8% of CAPEX based on 7% discount rate, and $1.10/Euro)
- $1.32/kg H_2 (= $3,360m/2,550 million kg H_2)) split ~70:30 pipeline: compressor]

  => 0.22/kg H_2/1,000km =$1.32/kg/5.9 x1000km]
- Estimated the levelized cost of transportation 4,500 to 5,000km from the Red Sea ~ $1.0 to $1.12/kg H_2 (if pro-rata approach were applicable)

Source: Data and figures from AFRI-RINA Gulf-Europe hydrogen pipeline study (2023). Study provides break down of costs for CAPEX, O&M and electricity for compressors. For educational purposes. *Cost split is only illustrative; based on total cost estimate of 28 billion Euro for system, and then using $4m/MW for the 1,100MW compressors (44x25MW)) so actual estimated split may be substantively different. **Using $1.1 = 1 Euro

This quantity of 2m+ metric tons of hydrogen per year and ~10GW flow rate assumes aggregation of supply multiple green and blue hydrogen production sites

The levelized estimate for **maritime shipping for different energy carriers shows differences that consistent with some other studies*** (for 8,700km, and on a $/kg H2/1,000m basis)

DRAFT

1) Levelized cost of shipping liquid ammonia estimate is ~$0.25/kg H_2 for 8,700km (for specific assumptions, and with significant uncertainty; illustrative)

2) Levelized cost of shipping liquid hydrogen is about x1.5 to 2+ higher than use of liquid ammonia (at ~$0.48/kg H2). Key reasons are the same sized LH_2 ship:

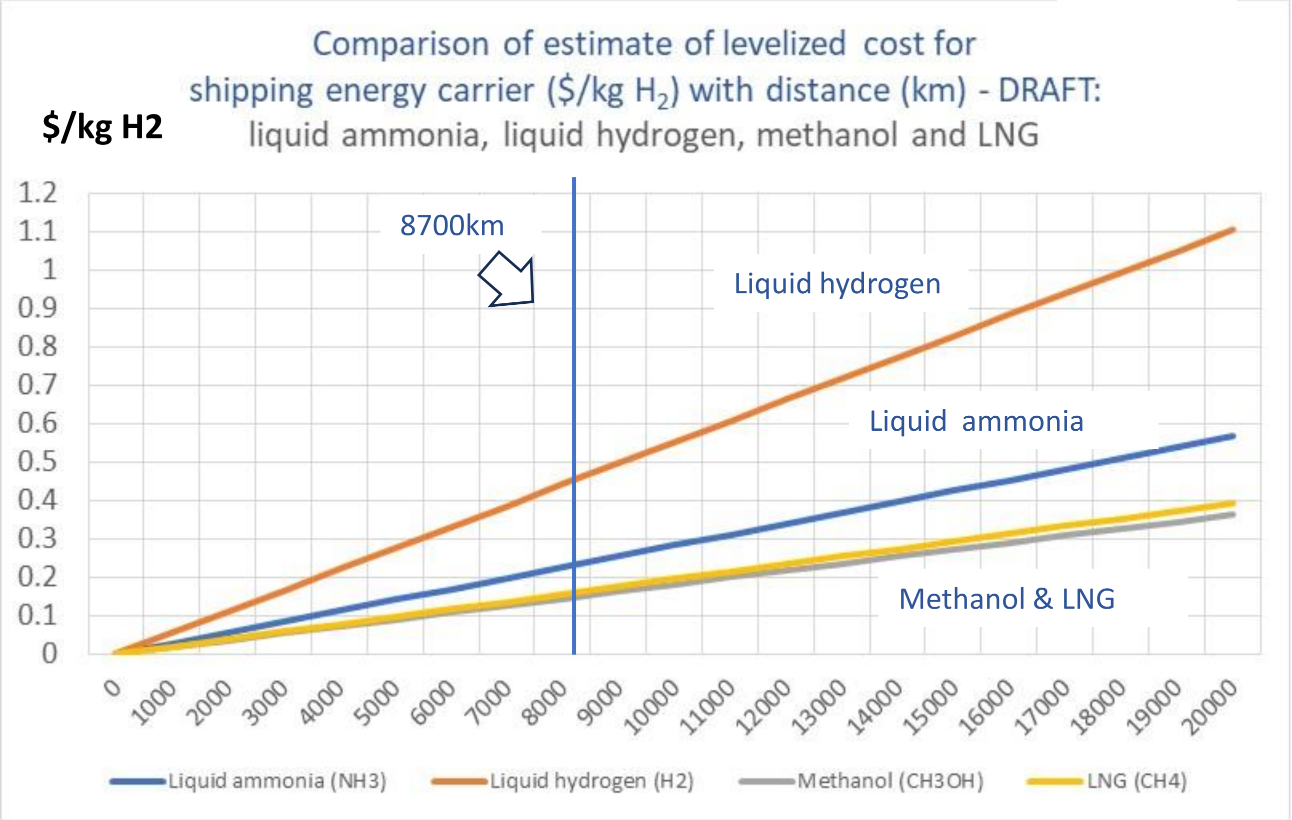
- **Carries only ~2/3rds of the energy** (12.7GJ/m^3 LNH_3 (at -33C) vs. 8.5GJ/m^3 LH_2 [at -253C]
- **May cost more per vessel given need for LH_2 to be stored at lower/cryogenic temperature**

Difference gets worse with increasing distance

3) Levelized cost of shipping liquid methanol may be lower than liquid ammonia (~$0.16/kg H_2 est.). Key reasons are for same sized methanol carrier ship:

- **Carries x1.25 more energy** [(16GJ/m^3 MeOH) vs. 12.7GJ/m^3 LNH_3 [at -33C]
- **May cost less per vessel given no need for refrigeration**

4) Levelized cost of LNG is similar to methanol, but lower than liquid ammonia. For LNG, the effect of higher CAPEX than ammonia [due lower storage temperature] may be more than offset by much higher energy density (20.5GJ/m^3 (>60%+))



Estimate for liquid ammonia is higher than some estimates and lower than others. **Uncertainty will be explored in more detail elsewhere and current estimates are DRAFT, and uncertainty is NOT shown above**

Note: Numbers may be high – compared to some studies – but relative effects would be expected to hold. *See e.g. ,Hank et al 2021 and Al-Breiki, Mohammed, and Yusuf Bicer (2020)

Note: Evaporation for hydrogen not included at this point, but could be added

Differences are **driven by science and engineering differences in energy density and refrigeration requirements**