Looking back from 2050

The story of the Maritime Energy Transition: Klaas Visser – TU Delft

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2050: deadline year

- IMO greenhouse gas reduction
- EU
- Operational Energy Strategy NL MOD

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State of the Art 2050

- Extensive wind farms in the North Sea and floating solar islands in the Atlantic Ocean
- New artificial energy islands with maritime and airport facilities
- Broad portfolio of synthetic, alternative fuels produced by solar and wind energy

State of the art 2050

- 30.000+ TEU autonomous containerships with nuclear propulsion, transiting between artificial ports in the North Sea and East Asia
- A completely silent and emission free Inland fleet already in 2025, driven by PEM fuel cells and metal hydride hydrogen storage

State of the Art 2050

- A broad dispersal of synthetic methanol as a fuel for short sea shipping, combusted in ICE’s until 2030, after 2030 in SOFC’s.
- A completely zero environmental impact fishing fleet, with fish pumps as new fishing technology, following the ban on ‘pulse fishing’ in 2019.

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State of the art 2050

- The dredging fleet is transferred to sea bed control ships, autonomous and electrical
- The navy already had air independent propulsion in submarines, and transferred this technology towards surface ships to eliminate signatures and operate autonomous

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What was the strategy issue in 2020?

Alternative (mixes of) fuels

Synthetic, biological, carbon free or carbon neutral, nuclear

Alternative or modified energy converters

Fuel cells, evolved Internal Combustion Engines, Nuclear systems, Wind assist systems

Elimination at end of pipe

Scrubber, selective catalytic reduction, carbon capture

The fuel cell options 2020-2050

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications
Polymer Electrolyte Membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation

Source: *hydrogenandfuelcells.energy.gov, superscipts refer to publications*

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Emissions?

Which strategy?

Which converter?

Which fuel?

Which fuel storage on board?

Specific zero emission potential for the dredging market

A hint to solutions

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Converter: Fuel cells

Courtesy Nedstack.nl

- PEMFC: low temperatures, available, high power density, quick start-up, good dynamic performance, pure H_2 required, limited waste heat recovery, TRL: 7-9
- SOFC: high temperatures, high efficiency, high cost, low power density, higher tolerance to non H_2-fuels, useful waste heat recovery, TRL: 5-7
- Additional maritime aspects: low to zero noise, higher efficiency at part load (!), no single point of failure, solid state tech: low maintenance (cost), high reliability and graceful degradation when in modules and stacks. Promising technology for autonomous ships.
- Attention points: fuel selection (see above), cost (1000+ k€/kW for PEM, expected to decrease with start of serial production), lifetime (state of the art 20.000+ hours).

[1] Vora, S. D., Lundberg, W. L., & Pierre, J. F. (2017). Overview of U.S. Department of Energy Office of Fossil Energy's Solid Oxide Fuel Cell Program. *ECS Transactions*, *78*(1), 3–19. https://doi.org/10.1149/07801.0003ecst
[2] Mittermeier, T., Weiß, A., Hasché, F., Hübner, G., & Gasteiger, H. A. (2017). PEM Fuel Cell Start-up/Shut-down Losses vs Temperature for Non-Graphitized and Graphitized Cathode Carbon Supports. *Journal of The Electrochemical Society*, *164*(2), F127–F137. https://doi.org/10.1149/2.1061702jes
[3] van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources*, *327*(X), 345–364. https://doi.org/10.1016/j.jpowsour.2016.07.007

Converter: Internal Combustion Engines (until 2030)

- Gas Engines, Diesel Engines, Dual Fuel (pilot injected) engines
- Synthetic/bio fuels researched, 100% methanol/ammonia/hydrogen is challenge.
- Combustion timing adaption, gas recirculation, water injection, extreme valve timing (Miller), enhanced turbocharging (seq, 2stage).
- Lower efficiency level (incl partload) irt fuel cells.
- Attention point: remaining NOx emissions, even with synthetic fuels.
- Very mature TRL, cost level clear, although emission measures drive cost level and complicate efficiency
- Characteristics of emitted sound, single-point-of-failure and graceful degradation other than fuel cell.

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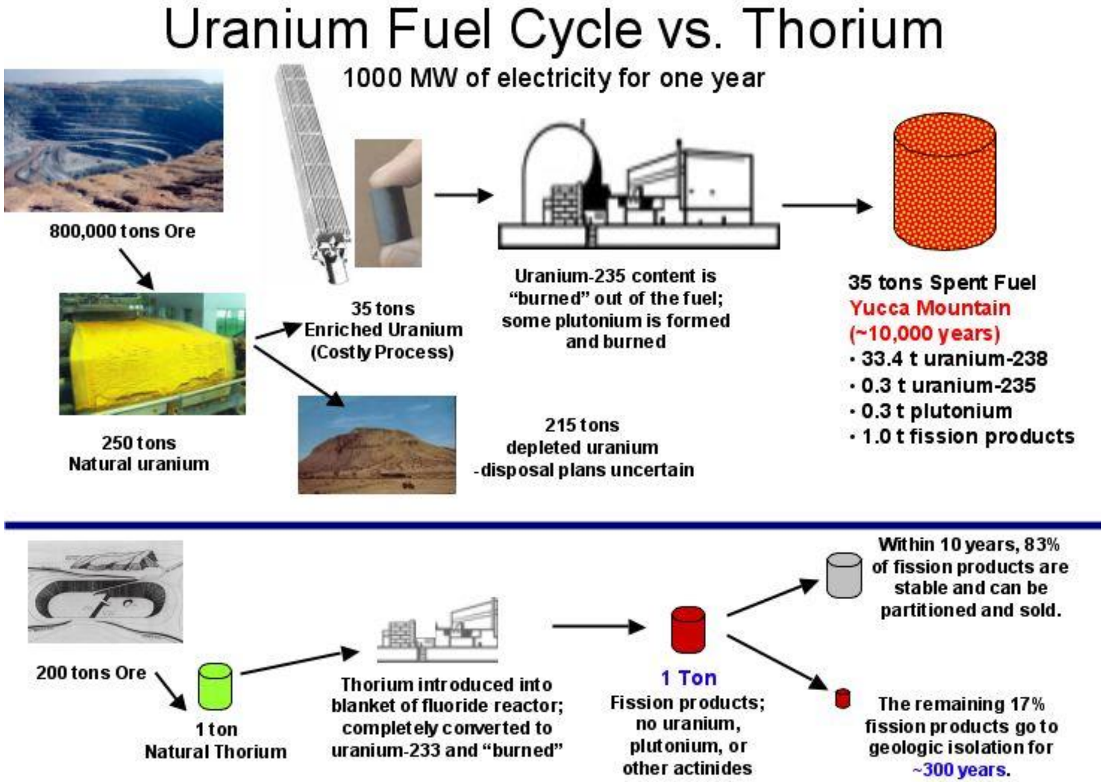
Nuclear conversion



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Which fuel? For PEM only H2!

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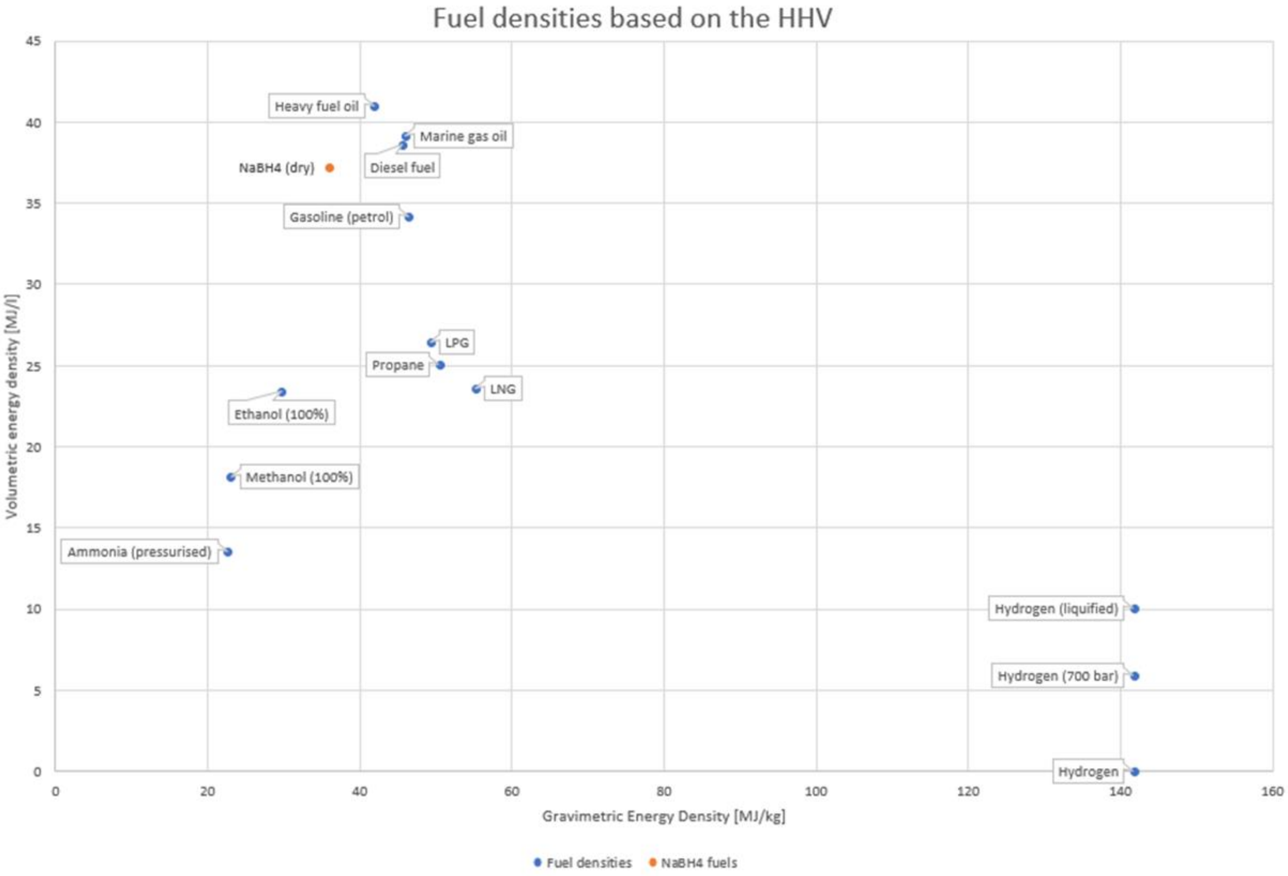
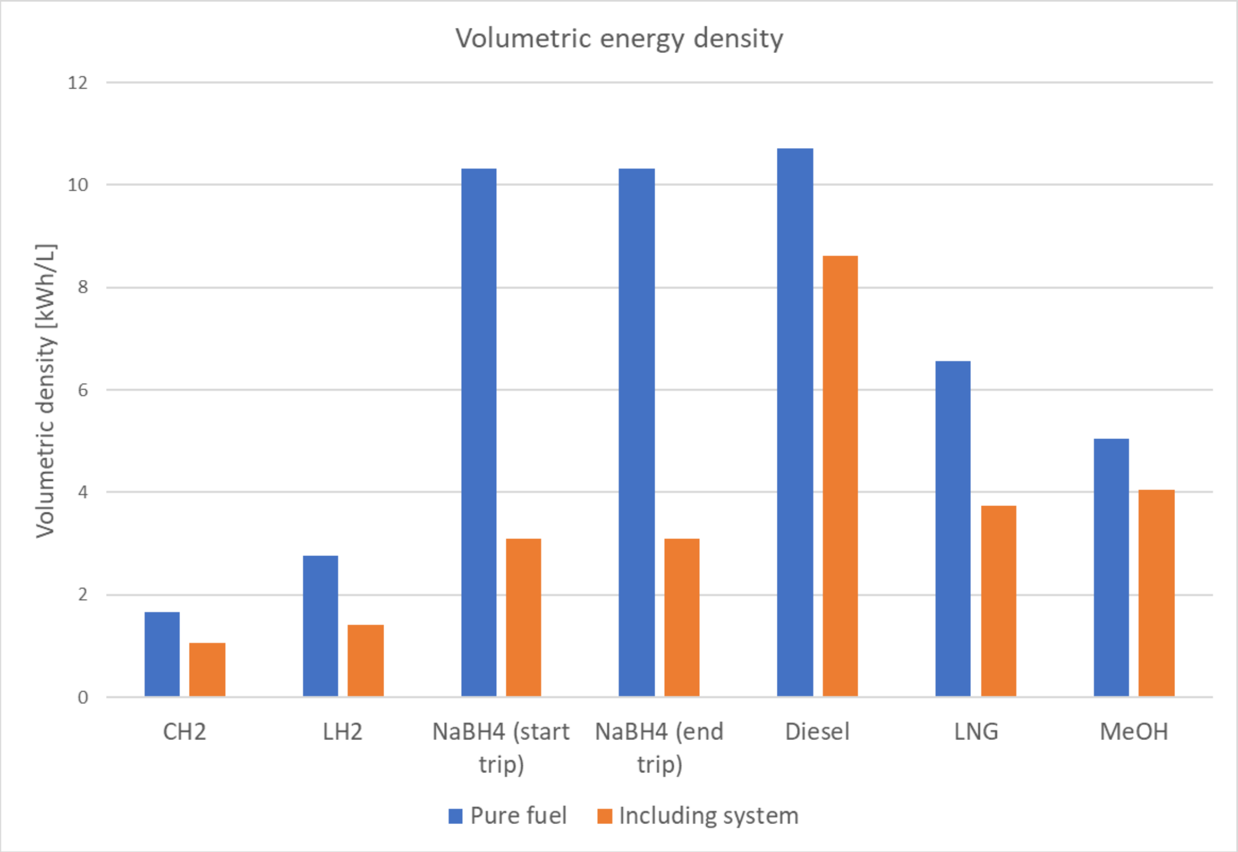


Which fuel? PEM H2, SOFC more



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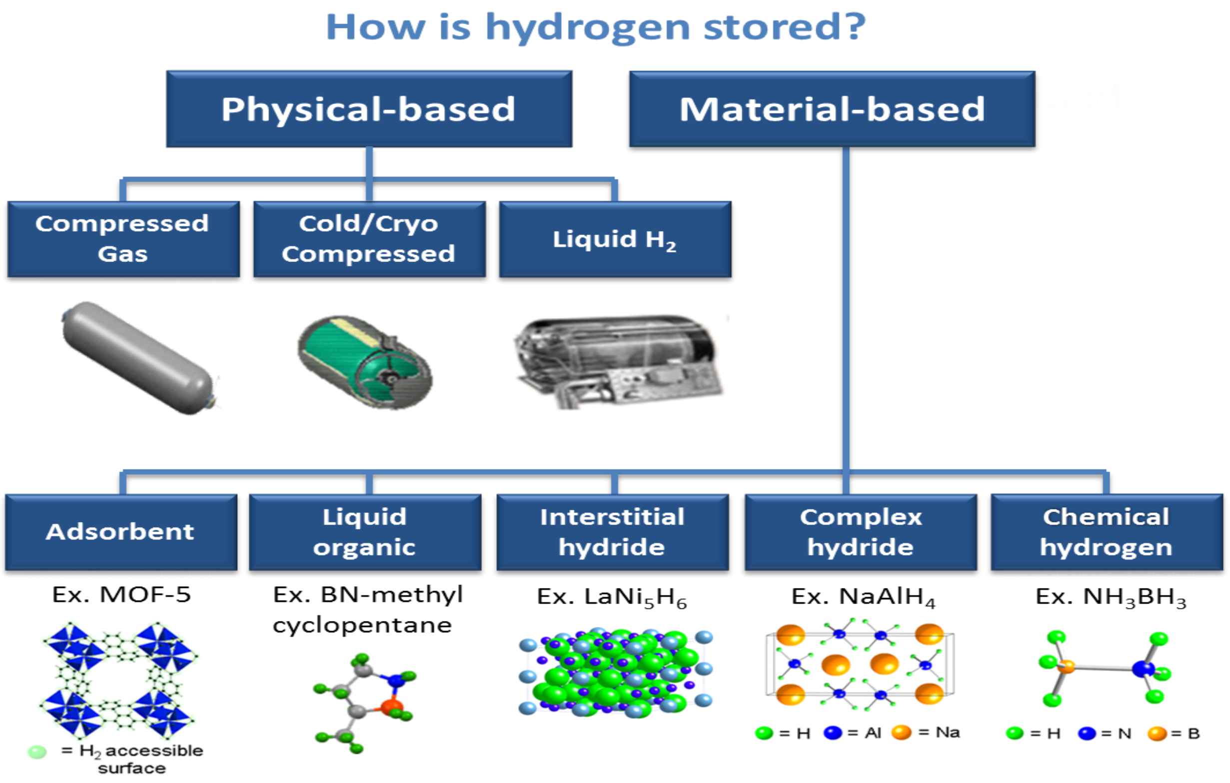

Source: *hydrogenandfuelcells.energy.gov*

The storage issues of 2020

a. hyperbaric 350-700 bar? Certification complex, lower density, high TRL, logistic availability, requirements for crew?
b. liquid (-253 degrees Celsius)? Certification very complex, high TRL, lesser support of captains?, logistic availability?, requirements for crew?
c. chemical storage in molecules: CH_3OH, CH_4, NH_3? Not directly applicable for PEMFC, logistic availability better, methanol liquid in ambient conditions, certification LNG complex, ammonia and methanol toxic, CO_2 as exhaust gas, potential for SOFC, although lower energy density.
d. chemical storage in chemical hydrides: $NaBH_4$? Experimental, proof of concept pending, certification process much less complicated, potential high storage density, new logistical process with solid states and spent fuel disposal/regeneration.

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What happened between 2020 and 2050?

- PEM solutions with metal hydrid storage for smaller ships
- SOFC’s became available for larger powers
- Power-to-x was dramatically enhanced by the development of solar and wind parks

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Key enablers were

- The business cases for fuel cells and alternative fuels
- Public and legal pressure to reduce CO2 production
- “Green” requirements of supply chain owners
- Investments of new energy companies for synthetic fuels and metal hydrides
- The availability of renewable fuels

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Insert a picture