“Status of the Hydrogen Economy”

Panel Discussion with GCCSI

Mike Fowler
Clean Air Task Force

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Key Points/Takeaways

- **Hydrogen substitution/replacement of fossil fuels for end-users represents an enormous potential market**
- **Hydrogen is a manufactured energy carrier and production costs are currently high; beware "surplus" electricity at low CF as the fix**
- **Hydrogen is also difficult to store and move, but ammonia (NH_3) may be an attractive hydrogen-based fuel for some applications**
- **Innovation and international collaboration are key to reducing costs and speeding deployment of hydrogen and ammonia fuels**
- **However hydrogen fuels are produced, carried, and used, GHG accounting will be a key issue**

Hydrogen substitution/replacement of fossil fuels for end-users represents an enormous potential market

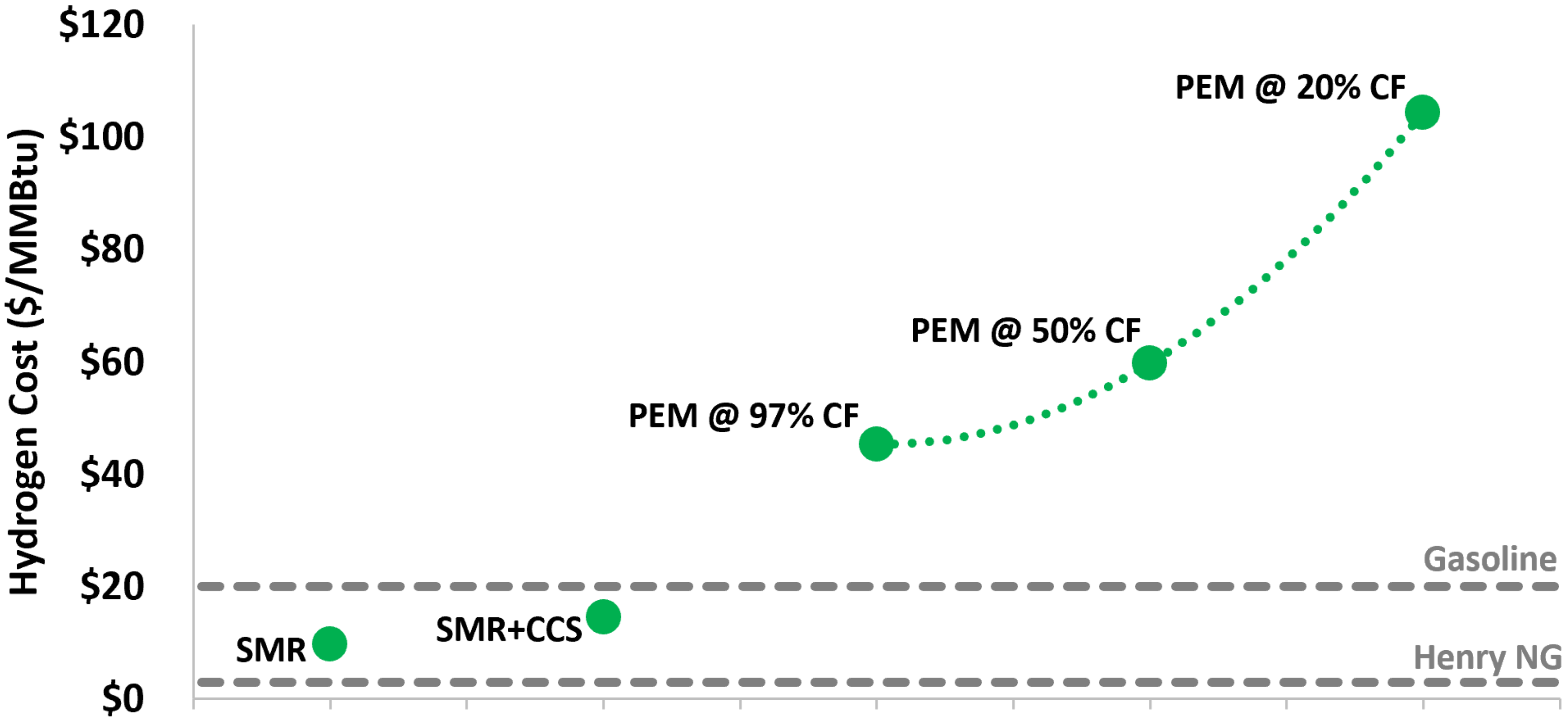
Current US fuels use in “difficult to decarbonize” sectors alone is significant. Examples:

- Medium- and heavy-duty trucking, aviation and marine, and off-highway vehicles: around **11 billion MMBtu/yr** fuel (per ORNL TEDB 37th ed.)
- Balancing electricity: close to **4 billion MMBtu/yr** fuel (CATF from EPA AMPD, as heat input to power plants operating at < 1/3 annual capacity factor)
- Industrial heat at > 600^{o}C: around **1.5 billion MMBtu/yr** fuel (per McMillan & Ruth, 2019; for industrial see also Friedmann, Fan, & Tang, Columbia U., forthcoming)

These fuels uses represent around **$250 billion** in sales and over **1 billion tons CO_2** emissions annually.

This does not include LDV, “baseload” power, etc. which would be considerably larger markets if hydrogen can compete

Hydrogen is a manufactured energy carrier and production costs are currently high; beware "surplus" electricity at low CF as the fix

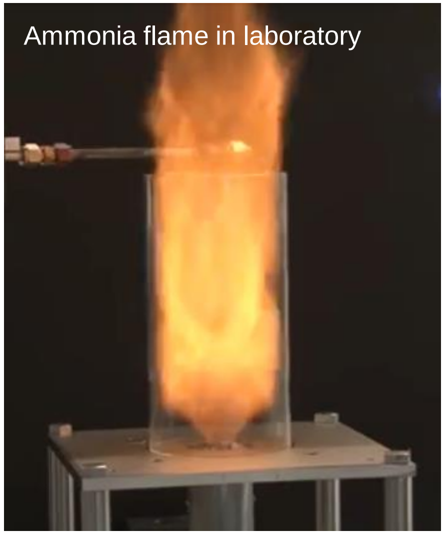


References: Hydrogen costs from SMR and SMR+CCS from Friedmann, Fan, and Tang (2019, in press); Hydrogen costs from PEM system (large centralized facility) at 97% capacity factor from DOE Hydrogen and Fuel Cells Program Record #14004, (2014), with other capacity factors adjusted by CATF; conversion to Btu basis in all cases by CATF.

Hydrogen is also difficult to store and move, but ammonia (NH_3) may be an attractive hydrogen carrier for some applications

Ammonia Fast Facts:

- Ammonia has physical properties similar to propane, but **burns without creating CO_2**, releasing about half the energy per liter (image at right)
- Ammonia is synthesized commercially from hydrogen and nitrogen (from air) at **scale similar to LNG** (~175m tpy) and transported like LPG (e.g., **tankers**)
- Liquid ammonia holds slightly more energy than liquid hydrogen, at much less extreme conditions (**almost 400ºF warmer)**
- Ammonia has been used as a fuel in the past, and **research and interest are expanding** (e.g., SIP “energy carriers” program and JERA in Japan)

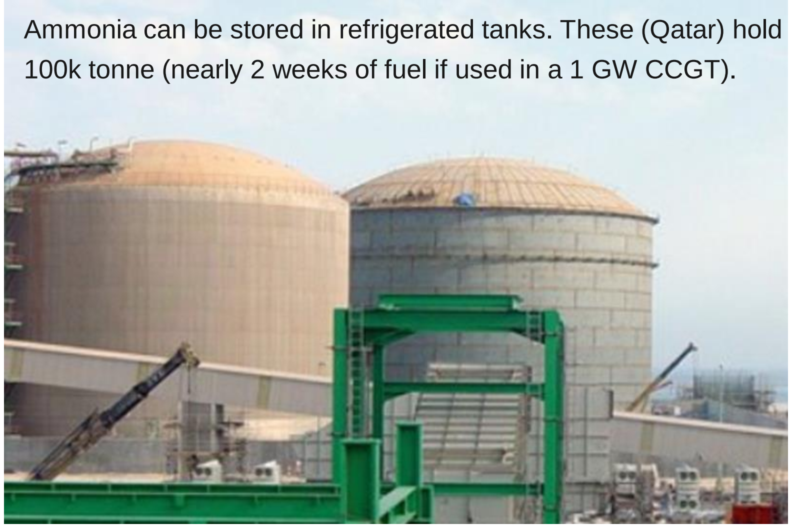


Ammonia flame in laboratory

Photo: Japan JST.

Refrigerated LPG tankers like the BW Hermes are used for ammonia. Yara’s dedicated fleet of 18 LPG carriers transport 4 to 5 million tons of ammonia annually.

Photo and data: gCaptain.com



Ammonia can be stored in refrigerated tanks. These (Qatar) hold 100k tonne (nearly 2 weeks of fuel if used in a 1 GW CCGT).

Photo: McDermott; CCGT calculations: CATF.

Innovation and international collaboration are key to reducing costs and speeding deployment of hydrogen and ammonia fuels

Research, Development, and Demonstration

- Improve efficiency and reduce cost of electrolysis
- Manage intermittent electricity at production facilities
- Improve conversion and utilization technologies
- Prove viability of multiple conversion technologies (ICEs, FCs, turbines, boilers) in multiple contexts (power generation, industrial heat production, heavy-duty transportation)

Deployment

- Build out distribution network (pipelines, ports, fueling infrastructure), with focus on high-impact hubs and corridors
- Reduce cost of and support full CCS at SMR facilities
- Manage hydrogen and ammonia safety/health risks

Cooperation

- Cooperate with Japan, Europe, Australia, others currently focused on hydrogen and ammonia technology and projects

Automotive Fuel Cell Cost Reductions per DOE

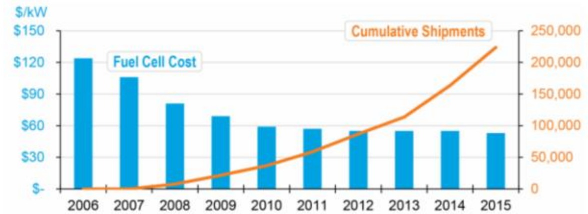


Figure 1. Fuel cell cost reductions based on modeled cost at high volume in nominal dollars and cumulative global fuel cell shipments for stationary, portable, and transportation applications.[6]

Vattenfall Magnum CCGT (Hydrogen Planned)

FREA Renewable Ammonia Synthesis

Image sources:
Fuel cell cost reductions - DOE FOA 0002022;
Magnum - https://www.equinor.com/en/news/evaluating-conversion-natural-gas-hydrogen.html;
AIST Japan renewable ammonia synthesis plant – Fowler/CATF.

However hydrogen fuels are produced, carried, and used, GHG accounting will be a key issue

Climate change is the driver for shifting to hydrogen fuels, so accounting for GHG in the final fuel is necessary for functioning markets.

Efforts are underway in the EU to certify the origin and GHG intensity of hydrogen for accounting purposes. Entities in Asia are also watching this space.

While the issue is important, CATF suggests that binary certification schemes (e.g., “green”) may not capture nuance of production and trade pathways and numerical metrics may be more appropriate. There may be an opportunity for the US to lead here.

However accounting is accomplished, upstream methane emissions from O&G should be included in this framework for SMR/CCS options.

CLEAN AIR TASK FORCE

114 State Street, 6th Floor
Boston, MA 02109

Phone: 617-624-0234
Email: info@catf.us

CATF.US