HYDROGEN SYMPOSIUM, JUNE 12-14, 2022, ERICE, ITALY

EXECUTIVE SUMMARY

Overview

The EMFCSC Hydrogen Symposium was held 12-14 of June in Erice, Italy. The participants' backgrounds were diverse including business, academia, research, and politics. They were invited to spend three days to discuss and debate hydrogen topics from a variety of perspectives, including the challenges involved in scaling up hydrogen production and use, discovering new ways hydrogen could serve as a clean energy carrier and explore policies that could help build a sustainable hydrogen energy economy. The Symposium's 3-day format permitted ample discussion time where all participants engaged discussing many technical issues or expressing different points of view. The Erice venue, along with the Symposium's lunches and dinners, provided an opportunity for participants to discuss issues more informally and get to know each other. Overall, the collective experience led to an insightful discussion of hydrogen policy and energy security.

Organization of the Symposium

0) Welcome, Introductory Remarks and Keynote Address
1) Introduction and focus on the clean energy transition
2) Using hydrogen
3) Producing hydrogen
4) Hydrogen storage and transport
5) Financing hydrogen, developing a hydrogen market
6) Energy security panel
7) Policy panel

The Keynote Address

Cristian Galbiati, professor of physics, Princeton University and EMFCSC Board Member, explained why hydrogen's affinity to oxidize accounts for its unique role in providing modern energy since the industrial revolution. Hydrogen, embedded in coal and all other hydrocarbons, provides readably available, energy-dense, transportable, and easily stored primary energy. The goal now, Galbiati explained, is to keep using hydrogen, but in a better form, without the carbon atoms along with the pollution they produce. Galbiati referred to this form as "coal without carbon." Science, Galbiati maintained, will be the key to meeting this challenge and why Erice, with its distinguished scientific history, is the right place to discuss how to achieve "coal without carbon."

Highlights from Sessions 1, 2, and 3 (The Clean Energy Transition, Using Hydrogen and Producing Hydrogen)

- **Green hydrogen costs**: Green hydrogen costs, currently around \$5/kgH_2 to \$6/kgH_2, with typical renewable energy costs and current electrolysis technologies, can decline to \$3.50/kgH_2 with renewable costs of \$25/mWhr, to as low as \$1/kgH_2 with more efficient electrolyzers and lower renewable costs (\$10/mWhr). For example, Chile's renewable energy potential features unusually high-capacity factors and enough production capacity to produce 160 mtons/yr of green hydrogen at \$1/kgH_2.
- **Biomass**: Gasification of biomass provides an opportunity to produce hydrogen with the best environmental consequences. Gasification of biomass, with carbon capture and storage, produces hydrogen and negative carbon emissions.
- **Blue hydrogen costs:** Reforming hydrocarbons with carbon capture and storage can be produced for approximately \$2/kgH_2 depending on a variety of factors, especially feedstock costs and availability of carbon transport and storage. The geographic distribution of low-cost blue hydrogen is likely to be more widespread, and closer to industrial centers, than low-cost green hydrogen (typically associated with solar-rich regions that have low renewable energy costs). The environmental consequences of blue hydrogen can differ widely depending on feedstocks and production technologies. Consequently, "colors" should not be used to consider clean hydrogen benefits. Instead, the full-fuel-cycle greenhouse gas emissions of each hydrogen source should be estimated and used to motivate or evaluate progress towards a clean energy transition.
- **Nuclear reactors**: nuclear reactors have a waste heat that sufficient to drive the direct thermochemical conversion of water to hydrogen and oxygen. The process is not simple and the commercial outlook for building this type of nuclear reactor is not promising. Perhaps the emerging small modular nuclear reactors will include some high temperature designs that might be able to cogenerate hydrogen. The significant uptake of this technology does not appear to be promising at this time. However, if certain types of small modular reactors become commercially successful, they might be candidates for hydrogen cogeneration.
- **Early markets for clean hydrogen**: Several opportunities to use clean hydrogen where investment costs are relatively minor. These include:

- Low-carbon hydrogen can replace currently used grey hydrogen in the refining and chemical sectors.
- Low-carbon ammonia can be co-fired with coal, a clean hydrogen pathway with current power markets. Green ammonia can also be used to replace conventional ammonia, reducing emissions from the chemical and fertilizer industries.
- Low-carbon hydrogen can be mixed with natural gas by varying percentages depending on local regulations.

- **Emerging markets for clean hydrogen:** Several industries can replace fossil fuels with clean hydrogen for a variety of processes. These include processes requiring high temperature heat. Also, hydrogen can be used as the reducing agent instead of natural gas in electric arc furnaces (to reduce iron ore in the production of steel). A varying amount of investment is required to develop these new markets for hydrogen. They provide opportunities to consume a significant amount of clean hydrogen in a limited geographical area that would be close to sources of clean hydrogen. These opportunities are reflected in the hydrogen hub approach to develop the hydrogen economy.
- **Energy storage:** Intermittent renewables will require either electricity storage for short and long time periods or increased reliance on natural gas peaking plants and natural gas storage. Batteries can provide short term storage but conversion to green hydrogen may be the most practical approach to long term storage. We learned of a project that would use of hydrogen produced in green utilities in California to be transported via pipelines for massive storage in form of high pressure gaseous H_2 in a salt dome sited in Utah, serving as a battery for the entire city of Los Angeles. One point that emerged from the discussion was that storage projects cannot be easily financed in deregulated power systems. The customer for the California-Utah project is a municipal power provider, and the project is made possible by a loan guarantee from the U.S. DOE.
- **Hydrogen vehicles:** The very few hydrogen fuel cell vehicles (HFCVs) that have been produced are mostly restricted to government demonstration programs. Widespread HFCV use would require a massive development of fuel supply infrastructure (production, pipelines, local distribution) while the number of HFCV customers can only gradually increase. Before *any* HFCVs can be sold, consumers must know that they can find convenient refueling in a variety of circumstances and locations. This means that the supply investments must be made at a large scale well before they can possibly be profitable. The best opportunity for hydrogen, apart from centrally fueled fleets, are

over-the-road heavy trucks. At some point net-zero will require clean heavy trucking. HFCVs have a strong advantage over battery electric trucks due to the heavy batteries that would limit truck load capacity. Nonetheless, the government expenditures required to create heavy truck refueling infrastructure and HFCV tractor cost reduction are not among the top priorities to promote a hydrogen economy at this time.

- **The circular carbon economy**: The circular carbon economy provides an integrated strategy to employ all resources, along with carbon capture, to achieve net-zero emissions throughout the economy.

Highlights from Sessions 4 and 5 (Hydrogen Storage and Transport, Financing Hydrogen).

- **Overseas transport**: The least expensive and most abundant sources of green hydrogen may require overseas shipping to get green hydrogen to markets. Conversion to more easily transported green ammonia would make worldwide green hydrogen trade cost effective while connecting the world's green energy centers with the world's industrial consumers.
- **Shipping clean hydrogen:** If hydrogen pipelines are not available or practical to ship hydrogen as a gas, liquefaction is not likely to be a commercially successful approach as it has been for natural gas shipments. Hydrogen liquefaction requires cryogenic temperatures (20 K, i.e., minus 253 °C). This would consume 30-36% of the energy contained in the hydrogen itself. Apart from cost and thermodynamic losses of hydrogen liquefaction, a hydrogen tanker would carry half of the amount of hydrogen as an ammonia tanker.
- **Hydrogen corridors**: Regions with Europe have the potential to serve as green hydrogen corridors. Sicily, for example, plans to exploit its considerable renewable energy potential, local industry, and geography to transit hydrogen from North Africa. Similar activities, for example, in Spain, can establish the basis for a European green hydrogen pipeline network.
- **Superconducting electrical transmission**: Another option may be to send inexpensive green electricity from solar-rich regions to industrial consumers where the conversion to hydrogen could take place for local consumption. Superconducting cables would be cooled with liquid hydrogen to provide electricity transmission over long distances with minimal loss. While not necessarily a technology that is commercially viable at this time, it could shift the strategy of shipping hydrogen to transmitting electricity over long distances.

- **Outside the box:** An innovative method of storing hydrogen in water was proposed using bladders encased in light-weight structures that would be sunk to the seabed. The amount of hydrogen that could be stored in each bladder would be proportional to the depth. The energy required to pressurize the hydrogen into the bladders was shown to be much less than liquefaction. Formulas and calculations were provided suggesting that this would be a cost-effective way to store hydrogen.
- **Financing challenges:** A 10,000-fold increase in hydrogen production will be needed by 2050 to meet net-zero using clean technologies and value chains that are yet to be established. The challenges facing emerging project proposals include proof of technology, proof of accessible markets, value-adding innovations, relevance in the value-chain and third-party validation. The synchronized involvement of independent actors to create new hydrogen production and consumption hubs itself poses great risk to each participant. Consequently, hydrogen projects are not likely to be financed without a variety of government policies including:
    - Subsidies both for producers, market creation and offtake consumption
    - Fostering the transportation and distribution infrastructure.
    - Establishing a regulatory environment that fosters the hydrogen industry.
- **Hydrogen markets:** Several preconditions are needed for liquid community markets. Physical requirements include, for Europe for example, cross-border transport of hydrogen, several sources of supply and multiple users using common carriers. If, in Europe, the main source of hydrogen is imports from outside Europe, hydrogen trading hubs are less easily established. By inference, establishing hydrogen markets may be easier in the United States where traditional uses of hydrogen are not waning, and significant domestic supplies of clean hydrogen are more likely. In all regions, substantial changes in infrastructure (production, transport, and consumption) are needed before hydrogen can be traded in a transparent, liquid futures market. Consequently, it will be several years before hydrogen producers and users will enjoy the benefits transparent hub pricing and futures contracts similar to those we take for granted in the petroleum, petroleum products, and natural gas markets.
- **Enormous investment requirements:** Most estimates of the investment requirements to achieve the hydrogen economy estimated to be necessary to achieve net-zero emissions show that trillions of dollars need to be invested each year from now to 2050. For example, McKinsey puts that figure at $235 trillion, or $9.2 trillion per year.

Energy Security

Energy security and hydrogen policies were featured in separate policy panels. The energy security panel was added to the program at the last minute as so many comments were emerging about the importance of achieving stable energy markets during the transition to net-zero. Large swings in hydrocarbon prices were not viewed as positive incentives to adopt hydrogen or other clean energy technologies due to the economic damage these swings typically cause. Sharply higher prices, as we have seen during 2021 and 2022, are as likely to lead to backsliding rather than faster investment in clean alternatives, for example, relying more on coal generation to meet power demand when natural gas prices are extremely high. One panelist offered a reason why energy markets, like petroleum or natural gas, can be so volatile: a very low price-elasticity of demand and a robust income-elasticity of demand. Small imbalances of supply and demand cause sharp swings in price, up or down (due to the very low price-elasticity of oil demand, around -0.05). At the same time, rapid economic growth or recession has a more-or-less proportional impact on fuel demand (income elasticity of oil demand around +1.0). These price swings are avoided when there is ample spare production capacity, and this capacity is managed to increase or decrease supplies as required. Price swings are much higher when there is limited spare capacity and stocks are low. In the transition to net-zero there is a danger that hydrocarbon investments are being abandoned too quickly because of government policies, investment funds (ESG), or the reasonable fear that oil and natural gas investments would not yield long-term returns if we approach "peak-demand" (caused by electric vehicles, renewable power generation, etc.).

There was considerable discussion about how emerging markets could avoid transitional reliance on hydrocarbon fuels as they grow their economies. Some Middle Eastern and African countries are considering this approach. Panelists also emphasized that long-term energy security depended on a transition to a low-carbon future soon enough to avoid the worst consequences of climate change.

Hydrogen Policies

Many specific recommendations emerged from the policy panel as well as general themes or principles. These included:

- Hydrogen policies should provide general incentives as opposed to blueprints for specific outcomes. Examples of this approach were:
    - support for hydrogen hubs,
    - hydrogen production and investment tax credits,

- carbon capture and storage hydrogen production and investment tax credits,
- R&D to improve critical technologies, and,
- expedited permitting of hydrogen-related projects.

- Production and investment tax incentives have already been effective in developing renewable technologies such as wind or solar and can be expected to have similar results with clean hydrogen production.
- Clean hydrogen should not be supported by color, instead, reliable methodologies need to be established to estimate the upstream greenhouse gas emissions of particular hydrogen sources. For hydrogen produced from fossil fuels, this can be complicated as innovative technologies can significantly affect a plant's full fuel-cycle emissions. For example, advanced technologies to convert natural gas to syngas can reduce the conversions losses normally associated with methane steam reforming.
- While a cutoff point for minimum emission reduction will needed, along with a sliding scale for variable support, hydrogen produced from fossil fuels should not be excluded from government incentives. Both green and blue hydrogen developments will be needed to grow the hydrogen economy.
- Methane leakage in the production and transport of natural gas should be treated pretty much the same way that carbon emissions in national grids are treated *vis a vis* battery electric vehicle. BEVs receive public support even when their power is mostly derived from fossil fuels. There are expectations that electricity grids will get cleaner. Likewise, we should work to reduce fugitive methane emissions in the natural gas sector rather than counting them as an inherent consequence of producing hydrogen from natural gas.
- Certain hydrogen policies should be deferred until there is a better likelihood that they would be prudent investments, for example, establishing a national network of hydrogen refueling stations for hydrogen automobiles. Neutral government hydrogen incentives will let markets determine where hydrogen uptake will first occur. As hydrogen hubs and other activities emerge, there will be opportunities to devise hydrogen policies to promote particular outcomes, such as the emergence of a hydrogen commodity market.
- Take a neutral stance towards clean hydrogen and clean electricity. For example, replacing household natural gas use with hydrogen, might not be necessary if gas end-use equipment is converted to electric end-use equipment. Focus hydrogen uptake where electricity does not work.
- In the extreme, we should remember that policies cannot change the laws of nature. Even when the science is sound, we should carefully review policies that rely on the rapid commercial developments of new concepts. Processes that work at laboratory scale do not

automatically scale up to commercial production. For example, the 2007 U.S. renewable fuel standards anticipated the development of a new cellulosic ethanol industry. Fifteen years later, commercial cellulosic ethanol production is still elusive.

- Successful policies need to engage multiple stakeholders to ensure cooperation and community support. Attention to disadvantaged communities and environmental justice is particularly important.