The Renewable Methanol Pathway to Green Hydrogen

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As the world moves toward decarbonizing the energy sector, two principal approaches are considered for clean transportation: battery-electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs). Presently, the global focus is to use renewable electricity to charge batteries for the BEV solution, or water electrolysis to produce hydrogen for the FCEV solution. It is generally assumed that renewable electricity is 100% carbon-free, economically viable, and available in sufficient quantities to support the transportation section. This paper reflects on these assumptions and offers an alternative to support emerging clean transportation solutions.

Availability of Renewable Electricity

Currently, the U.S. national grid is only 18% renewable power, comprised of 11% non-hydroelectric (wind, photovoltaic or PV, geothermal, tidal, etc.) and 7% hydroelectric. (1) The percentage of non-hydroelectric in the U.S. is similar to that of India and China. However, countries such as Germany and the U.K. have been more aggressive in "greening" the grid in the past decades (Figure 1).(2; 3; 4; 5)

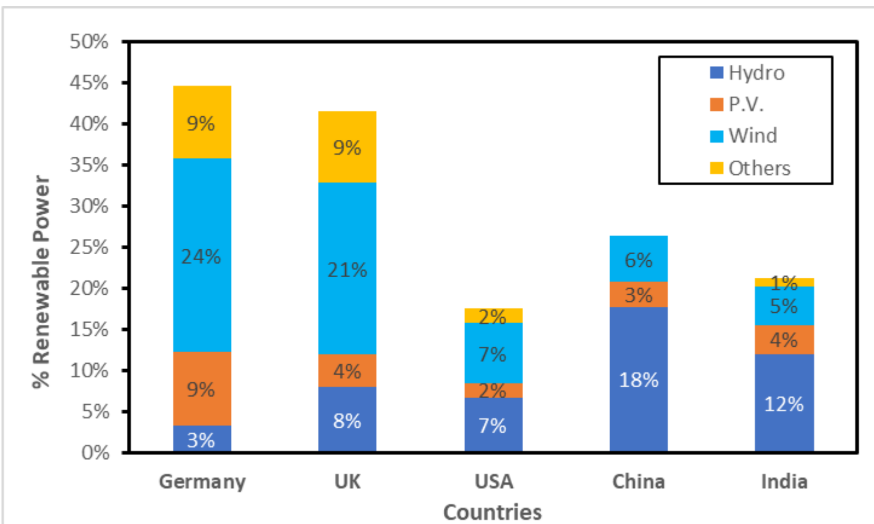

Figure 1: Percentage Renewable Electricity Generation in Selected Countries

The major source of growth of renewable electricity is non-hydroelectric solutions, primarily wind and solar. Due to the often-changing weather conditions, these production methods are only available during a limited timeframe (U.S. data): (6)

- Wind - ~35% of the day
- Solar - ~26% of the day

This limited window of renewable power requires alternative power generation from on-demand energy sources like coal, nuclear, and natural gas to keep the lights on, keep our homes heated, and keep our factories running.

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Cost of Renewable Electricity

This intermittency in power generation gives rise to three engineering and fiscal challenges.

- Renewable generation capacity would have to be overbuilt by at least 3x to 4x.
- Large-scale battery storage projects would have to be completed in parallel with the shift toward 100% renewable generation.
- Additional transmission and distribution systems to the point of use would be necessary to maintain stability and reliability. (7)

The cost of achieving the first two goals in the U.S. is conservatively estimated to be at least USD$4.5 to US$5.7 trillion. (8; 9; 10) Not included in this cost estimate is the value of land required to site the vast wind and PV farms, which has been estimated to be equivalent to ⅓ of the land area of the U.S. (10) Despite the significant progress in Europe, it will still cost about USD$3.6 trillion (EUR 3 trillion) to achieve 100% renewable energy, (11) and will cost at least USD$11 trillion for India. (12)

Similar to Europe, wind power and PV have in the U.S. captured an ever-increasing share of total power generation in the past 15 years (see Figure 2). During this time, the average industrial rate for electricity has been almost flat despite the addition of renewable generating capacity. However, the California average residential rates have increased from USD$0.13 to USD$0.17 per kWh from 2011 to 2019. (13) We consider the industrial rate because we assume that this is the rate most likely to apply to companies manufacturing hydrogen via electrolysis (rather than the residential rate or commercial rate, both of which are higher by about US$0.08 and US$0.04 per kWh, respectively).

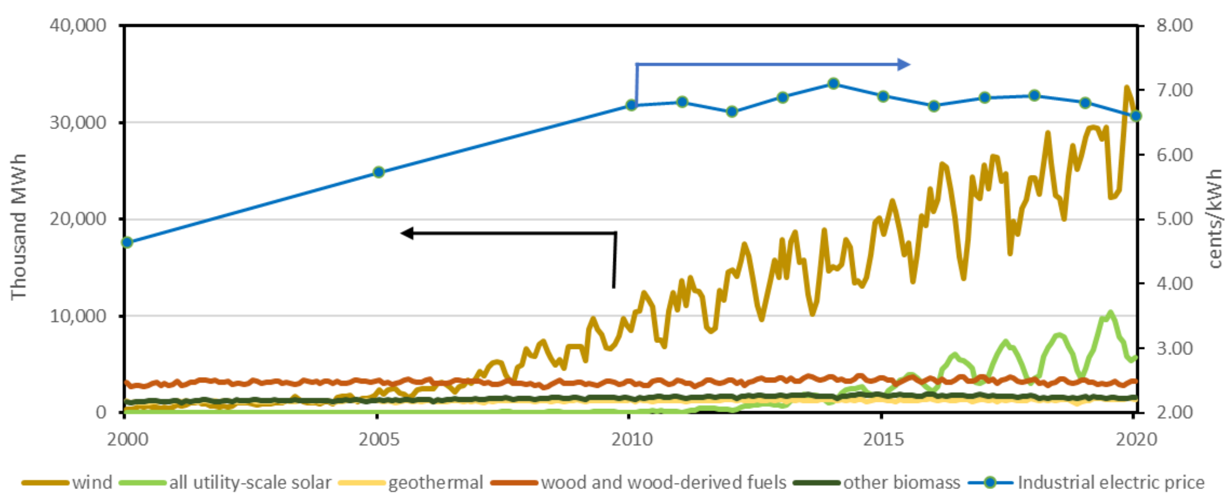

Figure 2. U.S. Net Electricity Generation vs. Average Industrial Price

Looking to the future, the average price of electricity (residential, commercial, and industrial) in the U.S. is forecast to be almost flat nationally over the next 30 years (14), but the price in states such as California is expected to go up while new renewable electricity rolls out. Likewise, the price of electricity is expected to increase in Germany (15; 16; 17) and the U.K. (18; 19) from 2020 to 2030, while that of China is forecast to remain almost flat. (20; 21) Some have suggested that adding renewable generation capacity to the national grid will drive down the cost of electricity—however, the data does not support this conclusion.

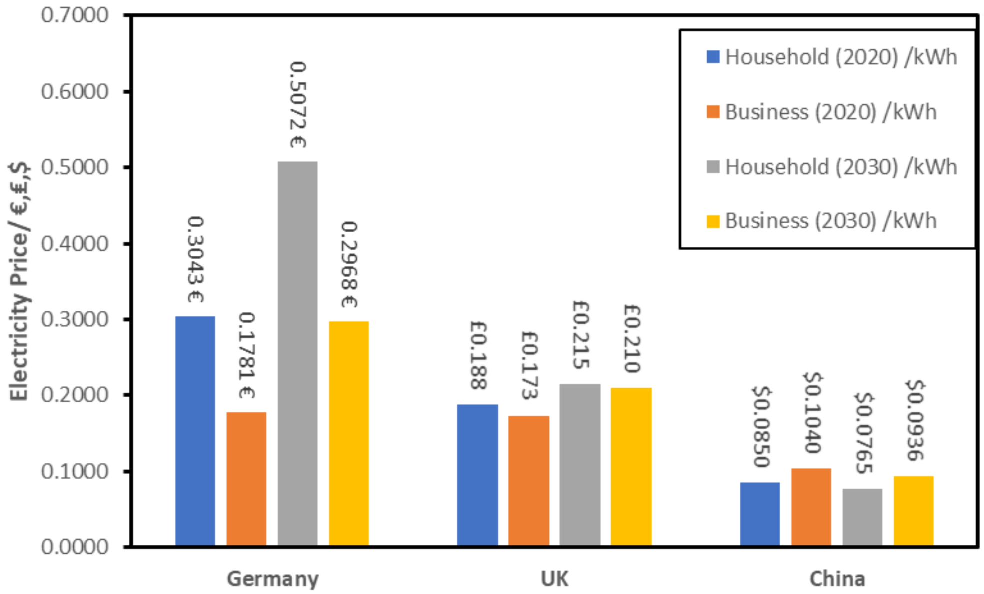

Figure 3: Current and Projected Electricity Price (per kWh) in Selected Countries.

The cost of electricity affects the economics of BEVs. In the U.S., the operating cost of BEVs will probably remain flat into the foreseeable future, not cheaper, and significant investment is still required for charging station infrastructure. An estimated cumulative 20 million chargers that cost at least US$10 billion will be needed in the U.S. alone by 2030. (11) The additional chargers also imply additional transmission and distribution systems will be required to support the electricity infrastructure.

Hydrogen is the only other zero-emission vehicle concept discussed. Increasing electricity rates also impact the cost of hydrogen produced via water electrolysis at gas stations for fuel cell vehicles (Nikola Model). If we use 50 kWh of electricity per kg of hydrogen produced and consider the U.S. industrial electric rate of US$0.07/kWh, the cost of electricity alone equals USD$3.5/kg hydrogen produced. The cost challenge is even more significant in regions with electricity rates higher than the U.S. average industrial rate.

Carbon Intensity of Electrolysis to Produce Hydrogen

Conventional thinking promotes water electrolysis as the preferred path to carbon-neutral hydrogen. However, the U.S. national grid (2019 data) has a carbon footprint of 0.453 kgCO_2e/kWh, (22) which comes from coal and natural gas power plants. This value is significant, but moderate among many industrialized countries. (23; 24; 25; 26)

Producing hydrogen by passing an electric current through water is energy-intensive, consuming 50 to 55 kWh/kg hydrogen produced and resulting in a high carbon intensity of more than 21 kgCO_2e/kg hydrogen. This would not be green hydrogen since the greenhouse gas (GHG) emissions attributed to grid power are substantial (see Table 1). To approach zero GHG emission and green hydrogen, the grid needs to be 100% renewable, or the hydrogen would need to be produced and used at the point of renewable electricity production. Green hydrogen produced at a dedicated renewable grid still needs to be transported to the point of use. The transportation process is energy-intensive, has a substantial carbon footprint, and is very costly.

Table 1: The Carbon Intensity of the Electricity Grid in Selected Countries and Corresponding Values in Hydrogen Production

	Germany	UK	USA	China	India
Carbon Intensity of Grid $kgCO_2e/kWh$	0.401	0.2	0.417305	> 0.7	0.697
Carbon Intensity for Producing 1 kg H_2 ($kgCO_2e$)	21.05	10.50	21.91	> 36.75	36.59

As we have discussed above, there are formidable challenges to decarbonizing the transportation sector with 100% renewable electricity due to renewable electricity's intermittency and cost of building out the infrastructure; challenges that are very unlikely to be overcome in the short- to medium-term.

Renewable Methanol to Support A Low Carbon Economy

To decarbonize the transportation sector, we need a pathway to green hydrogen that is not reliant on large amounts of electric energy, is scalable to support transportation, is cost-competitive with diesel fuel, and offers the near-term potential of being carbon neutral. That pathway is grey methanol produced from natural gas, with a near-future that is *renewable* methanol, which is made from sustainable feedstocks including:

- Municipal solid waste (MSW)
- Biomass
- Biogas from digesters
- CO_2 captured from industrial streams
- Direct air capture of CO_2

Methanol mixed with water is a dense hydrogen carrier that is readily converted to syngas (a mixture of hydrogen and carbon oxides). The process of separating purified hydrogen from syngas is also readily accomplished. Methanol is a top-10 globally produced chemical commodity that is available worldwide, and that can fill the gap between the high carbon-intensity fuels like diesel and the target goal of 100% renewable energy. Renewable methanol is commercially available, and many new plants are being constructed. There are excellent reviews on renewable methanol, including current commercial operations and cost projections. [27; 28] Renewable methanol at a transportation scale will take time, but global methanol manufacturers are investing to increase production as demand for renewable methanol increases.

The low carbon intensity of renewable methanol is very attractive. By using waste streams to make renewable methanol, the release of GHGs into the atmosphere is avoided. This avoided emission serves to drive the carbon intensity of the resulting renewable methanol to a negative value in select cases. A study published by Argonne National Labs indicates that renewable methanol feedstocks with significant avoided emissions include landfill gas, anaerobic digester gas, and biomass. [29] For example, the Enerkem plant in Edmonton, Alberta, converts 100,000 metric tons annually [30] of municipal solid waste (MSW) that would normally be destined for the landfill, producing renewable methanol instead. That solid waste, if buried in the landfill, would slowly decompose and release CO_2 and methane [31] into the environment.

Worldwide, there are currently about eight renewable plants in operation and at least 20 more coming online in the next 5-10 years. The production capacity is expected to reach 385 million metric tons per year by 2050. [28] The potential for renewable methanol as a feedstock to make green hydrogen is evident by the low (even negative) carbon intensities shown in Figure 4. To put this in perspective, methanol made from MSW has a carbon intensity of 0.014 kgCO_2e/MJ (LHV) (2.15 kgCO_2e/kg hydrogen), less than 10% of the GHG emissions from water electrolysis. [32] The well-to-wheel emissions of combining renewable methanol with FCEVs can result in negative emissions approaching -50 gCO_2e/MJ. [29]

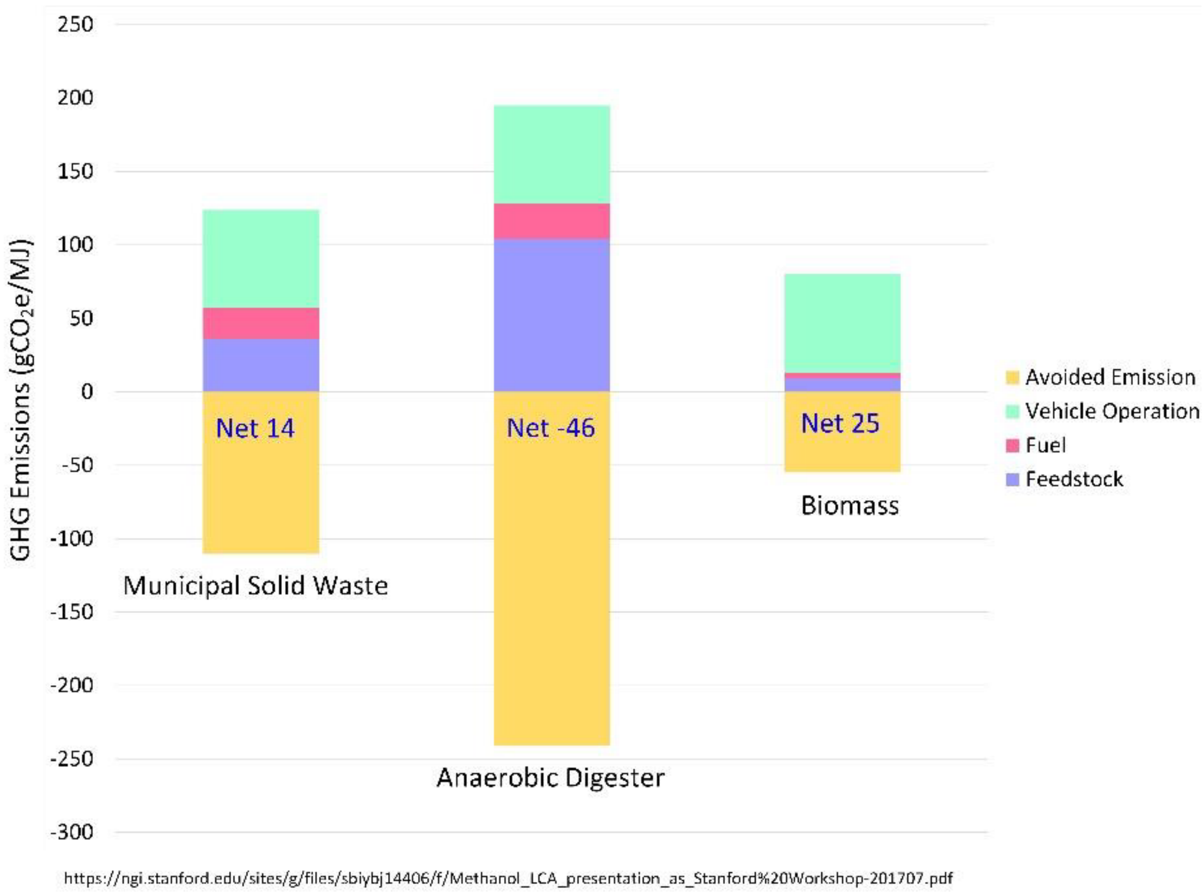

Figure 4. Well-to-Wheel Carbon Intensity for Renewable Methanol

Methanol to Hydrogen Generation Technology

In a recent study by Webber Research [33; 34; 35] (Figures 5 and 6), onboard methanol-reforming for hydrogen fuel cells compares favorably in range, fill time, and cost against other technologies in vehicular applications. Reforming methanol with water yields carbon oxides in addition to hydrogen, necessitating purification before the hydrogen may be used by a fuel cell. Compact and affordable processes are commercially available by Element 1 [36] to separate hydrogen from syngas and deliver high-purity hydrogen meeting ISO 14687 (2019) purity standards for fuel cell applications (both stationary and transportation).

The below comparison was done with a standard 300-gallon fuel tank, but Element 1 could expand this to a 600-gallon tank on a semi-truck.

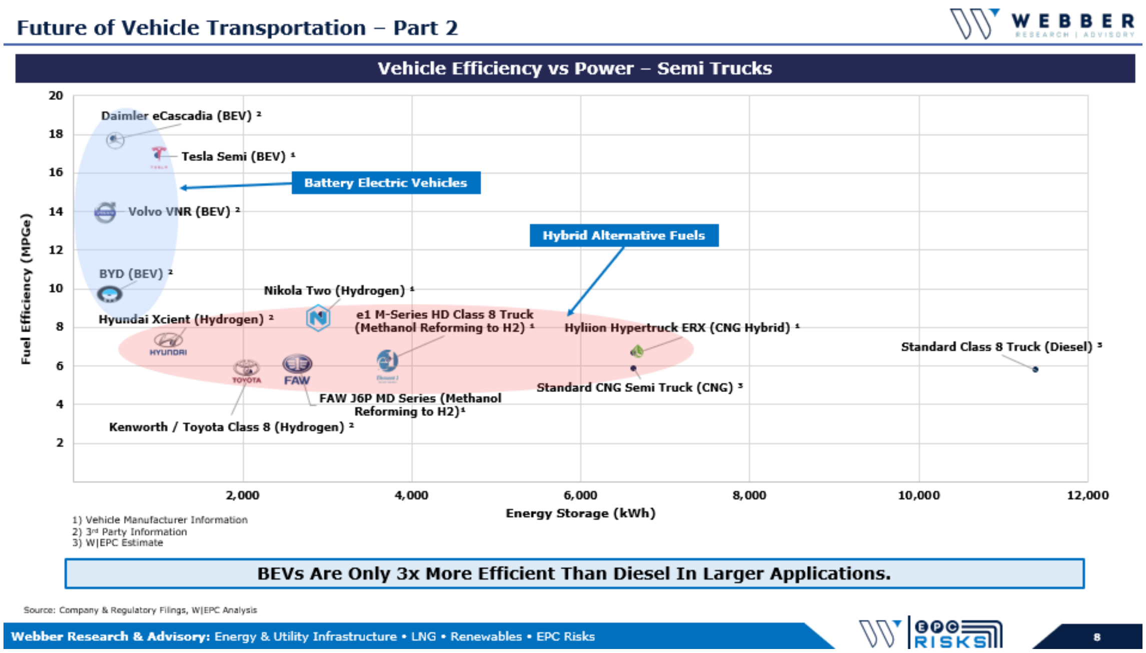

Figure 5: Comparison of Fuel Efficiency and On-Board Energy Storage

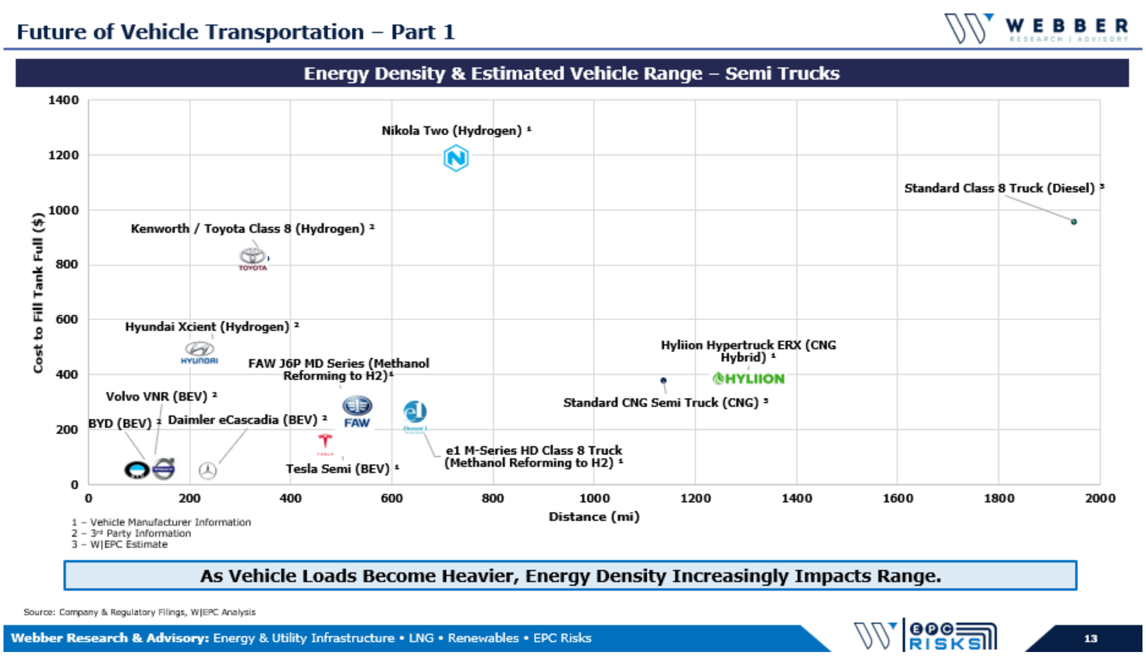

Figure 6: Comparison of Cost to Fill and Range

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Using an Element 1 methanol-to-hydrogen generator operating at 75% to 84% LHV energy efficiency, [37] hydrogen can be made at a cost of USD$2.56/kg H_2 (at USD$330/metric ton methanol). Based on the average cost of methanol in 2020, the cost of hydrogen in various regions is shown in Table 2 below.

Table 2: Cost of hydrogen using methanol-hydrogen technology in various regions

	EU	N America	APAC	China
Cost of methanol $/MT	$308.94	$332.25	$275.00	$275.85
Cost for producing 1 kg H2	$2.38	$2.56	$2.12	$2.12

Although the costs increase about 3x when using renewable methanol at current prices, the costs are still competitive against other approaches (see Figure 7). [35]

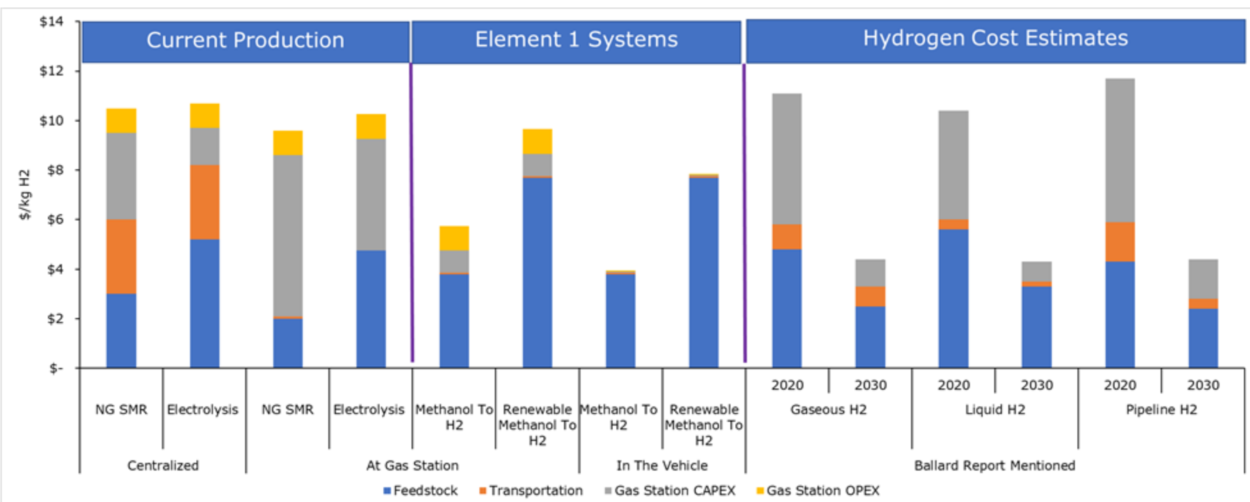

Figure 7: Comparison of Hydrogen Production Methods

The carbon intensity using Element 1 technology compares favorably against other current hydrogen-based technologies (see Figure 8) [35] and it is compliant with CA 2030 Carbon Intensity Goal, plus it meets Tier IV engine emission requirements. When using renewable methanol, the green hydrogen made using Element 1 technology has practically almost zero carbon footprint at a competitive cost.

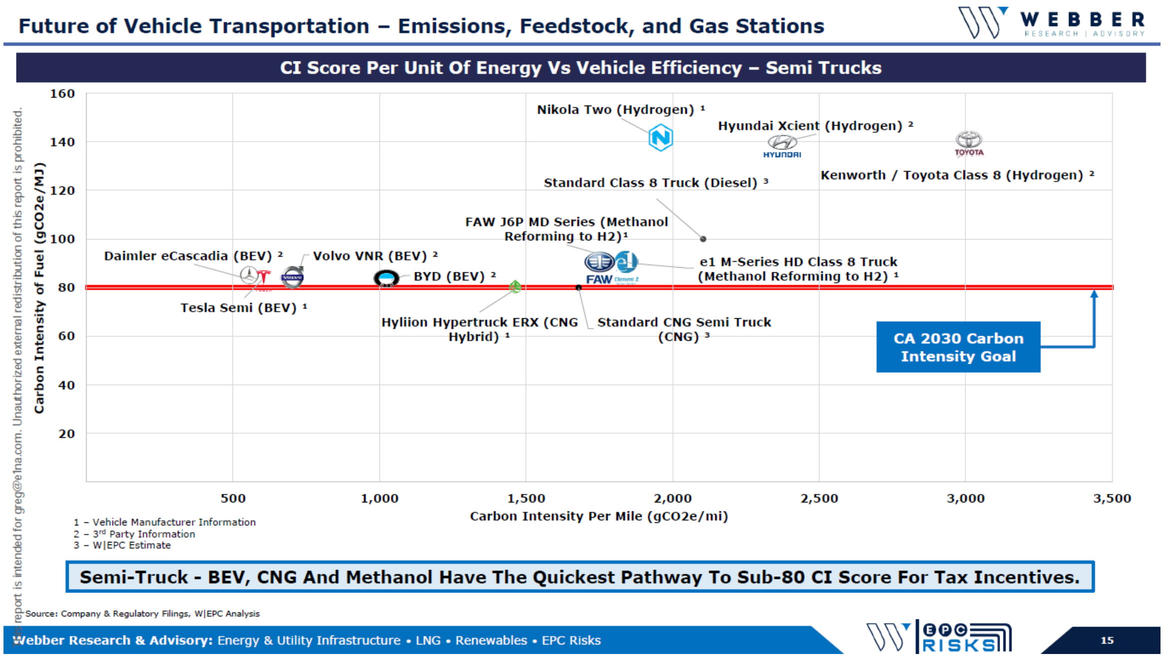

Figure 8: Comparison of Carbon Intensity

Conclusion

It is a formidable challenge to convert national grids to 100% renewable electricity. In contrast, methanol offers a low-carbon alternative pathway, independent of electrical input, to economically produce fuel-cell grade hydrogen. Methanol is already distributed globally and "is proven as a clean, efficient and safe marine fuel that offers immediate decarbonization benefits to vessel operators with substantial net GHG reductions, full compliance with IMO2020 and a pathway that leads to net carbon neutrality". [38] Of course, the goal is to use renewable methanol as the feedstock for green hydrogen production.

This goal is within our reach. Renewable methanol is available today in modest quantities, and investments are being made to produce transportation-scale quantities. Element 1 has the technology to produce green, carbon-neutral hydrogen affordably to decarbonize the transportation sector worldwide.

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