EWM Green Liquid Hydrogen System™

www.envirowaterminerals.com

SUMMARY

EWM has developed a high efficiency Green Liquid Hydrogen System™ with the following benefits:

- Uses 100% renewable photovoltaic (PV) and wind power to produce and liquify hydrogen for energy storage, Electro-methanol (E-Methanol) production, and green ammonia production.

- 98% energy efficient Liquid Hydrogen (LH2) production, with byproduct heat captured and used for desalination, CO2 Direct Air Capture (DAC), and on-demand steam turbine power production.

- Co-production of Liquid Air (LAir) and liquified air based industrial gases (helium, neon, nitrogen, argon, krypton, and xenon) for additional energy storage.

- High efficiency (>95% H2 Low Heating Value (LHV) to power) conversion of stored LH2 and LAir to on demand peaking power

Overall Plant Concept

The EWM Green Liquid Hydrogen System™ creates green liquid hydrogen in conjunction with EWM's Full Recovery Processes. Figure 1 is a schematic of EWM's Full Recovery systems (Desalination, Agriculture, Green Glass – brown boxes) and associated third party industrial processes (blue box). The Green Liquid Hydrogen System™ (tan box) depicts the role this system plays in the overall plant concept. EWM's Green Liquid Hydrogen System™ provides consistent, baseload (24/7/365) supply of the following critical streams to the various processes:

- dispatchable steam turbine power and cogen heat
- low temperature heat to desalination and CO2 DAC
- export LH2
- export dispatchable peaking power based on LH2 and LAir
- high pressure hydrogen to E-Methanol and green ammonia
- high pressure nitrogen to green ammonia

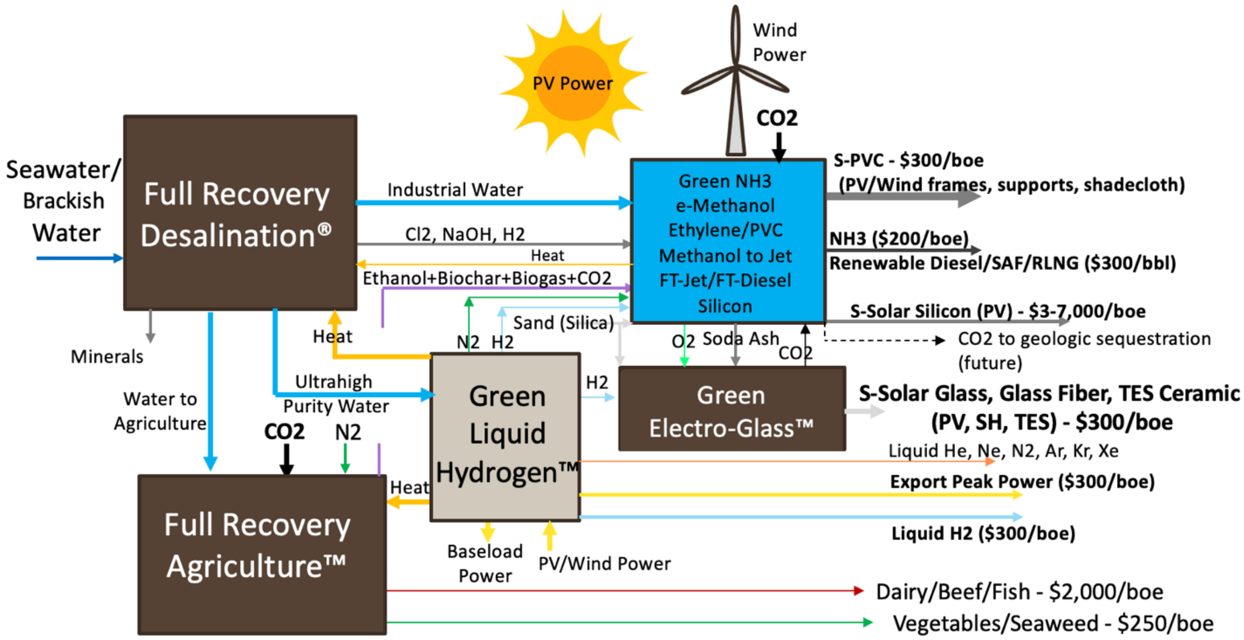


Figure 1 – EWM Green Liquid Hydrogen System™

LH2 production and liquefaction in EWM's Green Liquid Hydrogen System™ will occur intermittently whenever low-cost PV, wind, or short term (< 2 hour) battery power is available. LH2 byproduct heat will be stored in Thermal Energy Storage (TES) systems for use on demand. A dispatchable steam turbine uses high temperature TES heat along with liquid hydrogen (backup fuel) to supplement intermittent PV and wind power, ensuring a consistent supply of baseload power to the overall plant. Cogen heat from the steam turbine is to be used to supplement the LH2 and LAir byproduct heat, which provides for a reliable supply of heat to the various TES systems. A standby condensing steam turbine (airfan condenser) converts any excess heat to power during any startup, shutdown, or upset that occur in the overall system. As explained below, the overall plant's steam and power demands are designed in this process so there is normally no steam being condensed.

Water Supply and Heat Consumption

EWM's Green Liquid Hydrogen System™ uses its Full Recovery Desalination® process to supply irrigation water for agriculture, industrial water for the third-party industrial processes, and ultrapure water for electrolysis for green hydrogen production. The desalination process uses seawater, brackish groundwater, and stormwater capture with storage to produce minerals and the water required for the overall plant. The desalination energy consumption can be adjusted to use either more power and less low temperature heat (membranes and mechanical vapor recompression evaporators/crystallizers) or more low temperature heat and less power (multieffect steam powered evaporators/crystallizers) to balance the power and heat produced in the Green Liquid Hydrogen System.™

EWM's Full Recovery Agriculture™ process (discussed further in EWM's Full Recovery Agriculture™ for the Energy Transition paper) uses low temperature heat for the CO2 DAC system. The size of the agriculture system and the amount of CO2 capture is adjusted to match the low temperature heat available from the Green Liquid Hydrogen System.™ In an emergency winter scenario, with extremely cold nighttime ambient temperatures, all the TES heat and emergency heat from LH2 can be used to prevent low temperature crop damage. Having a large amount of emergency heat available is an important design requirement for the Full Recovery Agriculture™ process located in regions with infrequent, but severe low ambient temperature excursions.

LH2 Production

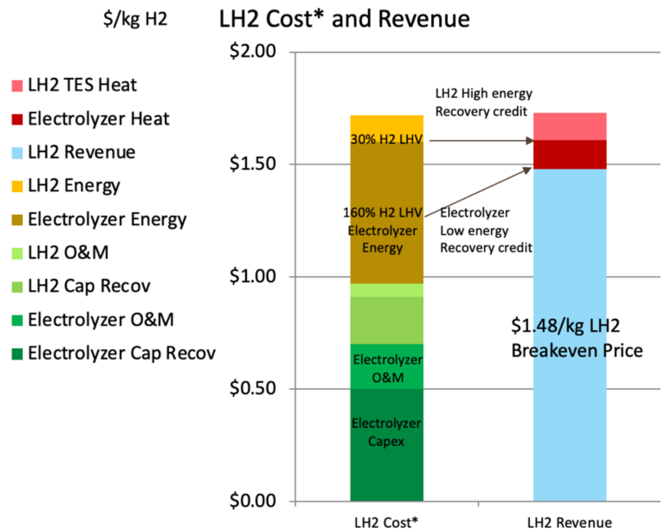
Commercial production of electrolyzers for green hydrogen production currently is increasing for many reasons, including: the availability of tax credits in the U.S. Inflation Reduction Act, financial incentives being given in the European Union (EU) for green hydrogen, strategic investments involving green hydrogen (e.g., NEOM), and planned strategic investments such as those in the UAE. There are several large-scale green hydrogen and green hydrogen based electro-fuel projects under construction or in development. The U.S. Department of Energy projects that electrolyzer prices will fall with higher volumes and increasing technical maturity similar to PVs. This will make it most profitable to operate electrolyzers using only low-cost, as available (intermittent) PV and wind power with a 2-hour battery storage - 40% estimated electrolyzer capital utilization.

Currently, in the typical system, hydrogen is compressed and stored in salt domes as a high pressure (up to 200 bar) gas and transported by intermediate pressure (60-80 bar) pipelines. There are currently four commercially operating salt dome hydrogen storage facilities, and several more are in development in the U.S. and EU. Gaseous hydrogen storage in salt domes, however, requires significant capital costs for compression, salt dome storage cavity construction, and pipeline infrastructure. In addition, there is high-power consumption for hydrogen compression for storage and pipeline transmission.

EWM's Green Liquid Hydrogen System™ stores intermittent electrolyzer hydrogen as a low temperature ambient pressure liquid, similar to liquid natural gas (LNG) but at a much lower temperature (-253° C vs -162° C). Commercial demonstration of LH2 production, storage, and marine transportation has occurred and is expected to be expanded to commercialize LH2, by developing larger LH2 marine tankers, following the LNG commercialization path.

Cost of LH2 Production

EWM's Green Liquid Hydrogen System™ uses the same LH2 infrastructure system for handling LH2 as the commercially demonstrated equipment (marine tankers, tanker trucks, ISO tanks, and rail cars), but uses an enhanced LH2 liquefaction system, tuned to meet the needs of EWM's overall plant concept. We believe this will result in a greater savings in the net cost of LH2 production.



* Based on 40% electrolyzer and LH2 dispatch (PV+wind+ 2 h onsite battery) and 2030 electrolyzer large scale production price

Figure 2 – EWM Net Cost of LH2 Sample Economics

EWM's process uses an advanced Liquid Air Energy Storage (LAES) system to produce both refrigeration for the LH2 system and heat for the TES systems. The EWM design reduces capital cost and maximizes heat recovery but requires a relatively high power consumption. Low-cost intermittent PV and wind power, therefore, is used to power the LH2 electrolyzer and liquefaction system. The byproduct heat credit is expected to offset the power cost for the LH2 system and a small portion of the cost of the electrolyzer power. The byproduct heat credit is important because the power required to liquify the hydrogen is very high - equivalent to 30% of the hydrogen's LHV. For comparison, the liquefaction power required for LNG is equivalent to only 10% of the natural gas LHV.

LAir Production

The current methods to produce LAir include compressor/expander based cryogenic air separation units. In this method, the LAir is distilled to produce oxygen and nitrogen for industrial use. Neon is currently produced as a byproduct of oxygen production. The oxygen is used mainly in coal-based steel and syngas (CO+H2) production.

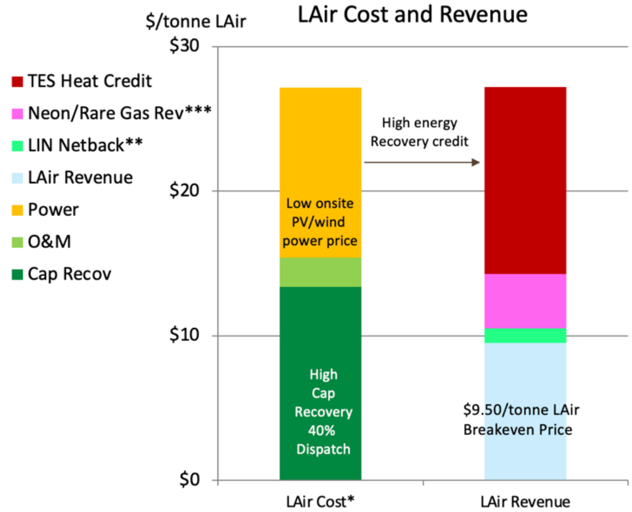
EWM uses a modified compressor/expander design optimized to produce liquid air and TES heat. EWM uses partial distillation of the LAir to produce high value rare industrial gases (helium, neon, argon, krypton, and xenon) and recover a small amount (10%) of high purity liquid nitrogen (LIN) for onsite ammonia production using LH2 and LIN.

Neon is an especially high value, high growth industrial gas used for electronics and cryogenic refrigeration. However, neon is present in air at low concentration (18 ppmv) and requires large volumes of liquid air production to be economically recovered. Coal based steel/syngas and the supporting oxygen production from air is being replaced with green hydrogen and green hydrogen-based steel. In addition, byproduct oxygen from water electrolysis (green hydrogen production) will be able to replace oxygen growth from air separation. Therefore, byproduct neon production from oxygen production will not be available to support the expected global demand growth in neon. Significant neon and oxygen air separation plants used for steel production in Ukraine also recently have been destroyed, adding to the need.

Cost of LAir Production

EWM's net cost of LAir is able to be low due to the following:

- large capacity plant with economy of scale advantage
- low-cost power from onsite intermittent PV/wind supply
- high TES energy credit to cover the cost of power (energy from both the power and the liquid air is recovered into the TES system – heat pump energy gain)
- high value neon and other rare gases are recovered from the large amount of air that is liquified (for LH2 and LAir production) and then ultimately vented (rich air containing neon and rare industrial gases is liquefied leaving only the lean air components (i.e., oxygen and nitrogen) to be vented)



*Based on 40% dispatch
** Based on netback from 10% N2 sale to onsite ammonia plant
*** Neon/Rare gas netback – excludes argon netback

Figure 3 -- EWM's Sample Economics for LAir Net Cost

The capital cost of liquid air production is minimized in EWM's design by using higher power consumption. The byproduct TES energy credit, however, offset the higher power consumption. The lower capital cost is an important factor in the cost of LAir production because the LAir capital utilization is low (40%).

LH2/LAir Storage and Consumption

LH2 has several advantages over gaseous hydrogen. These include:

- lower storage cost and co-location with low-cost PV/wind power and rail access (avoids salt dome geological location constraint)
- storage tank performance guarantee (avoids geological risk from leaks, over pressuring, no sulfur, or hydrocarbon contamination)
- LH2 can be transported in low-cost unit trains and by marine tanker (avoids difficult to permit and expensive new hydrogen pipelines and rights-of-way)
- low temperature, high pressure LH2 can be used as a refrigerant to produce liquid air for the LAES system, allowing full utilization of the refrigeration energy
- LH2 can be pumped to high pressures (300-500 bar) at low cost (avoids high-cost gaseous hydrogen compressors with high power and cooling requirements)

The last advantage mentioned above was demonstrated by the Space Shuttle and Artemis rocket engines, which pump LH2 to 400 bar for use in high pressure (330 bar) turbines (turbopump drives). Although the LH2 is pumped to over 400 bar, the temperature increases to only -222° C from -253^{o} C (NASA 1998), demonstrating very high pressurization efficiency (efficient cryogenic liquid pumping).

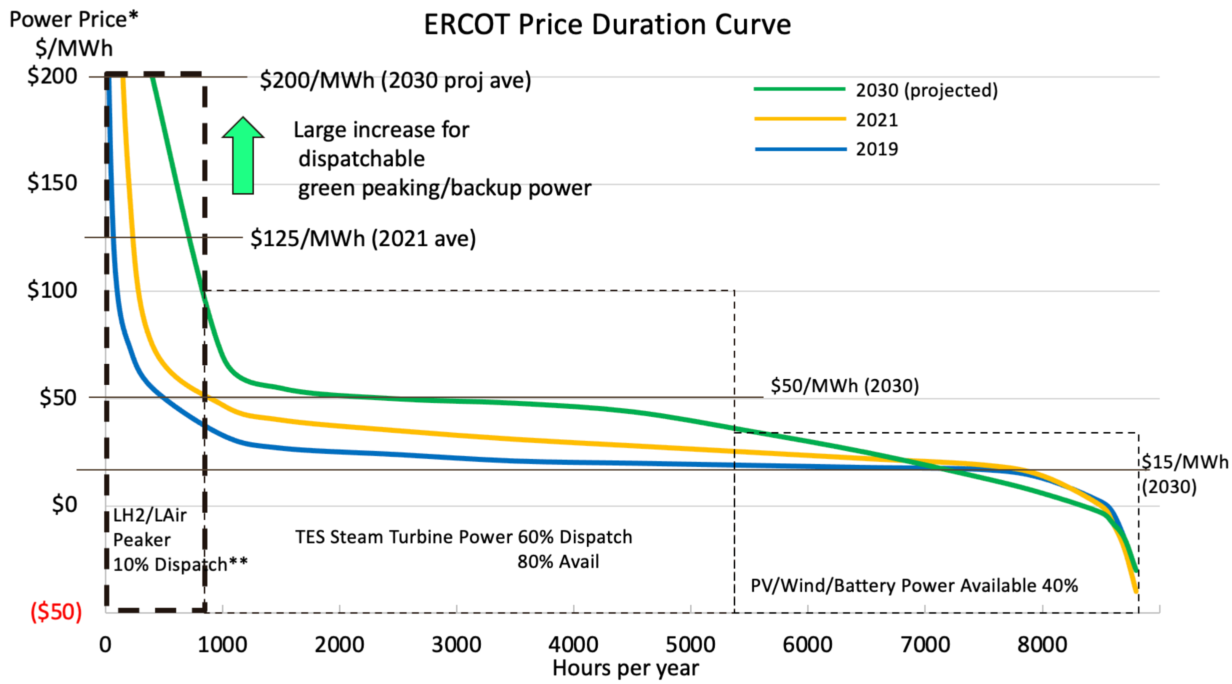
LH2 and LAir Storage

EWM's design stores LH2 and LAir in large cryogenic tanks similar in design to the largest LNG tanks (i.e., 270,000 m3). Larger scale tanks make LH2 storage more cost effective because both the capital cost and energy leakage are lower with larger tanks. EWM's LH2 and LAir tank designs use additional insulation, active cooling, solar and wind shielding, and boil off gas recompression using low-cost PV/wind power. The EWM LH2 tank uses a large height to diameter ratio and highly insulating composite (high strength to weight ratio) sidewall and bottom materials with a raised, micropile supported tank bottom taking advantage of LH2's low density (7% of water). This eliminates LH2 and LAir losses even with the low storage temperature of the hydrogen. The cryogenic tankage costs are the major component of the peaking power capital recovery cost.

The EWM design for the LH2 tank includes additional safety features addressing LH2's different combustion profile (as compared to LNG). These safety features include nitrogen and helium blanketing, emergency vaporization, emergency thermal radiation protection, and emergency external containment.

Peaking Power Production

On-demand green peaking power is increasing in demand due to the green energy transition currently occurring. PV and wind power are intermittent, and reliable green backup power options have not yet been commercialized. Currently, natural gas fueled turbines are used as low annual dispatch factor (10%) peakers. These are typically used in summer, 6 hours per day, for 120 days (720 h/y) and in winter for 7 days, for 24 hours per day (168 h/y). The Electric Reliability Council of Texas (ERCOT) price duration curve depicts typical power pricing for a public utility system with a high content of renewable PV and wind power generation.



*Prices exclude capacity charge for bulk transmission, includes CO2 offset for NGCC ($35/MWh) for 2030
** Backup LH2 and LAir is used to provide backup heat to the EWM TES system when byproduct LH2 and LAir heat is not available

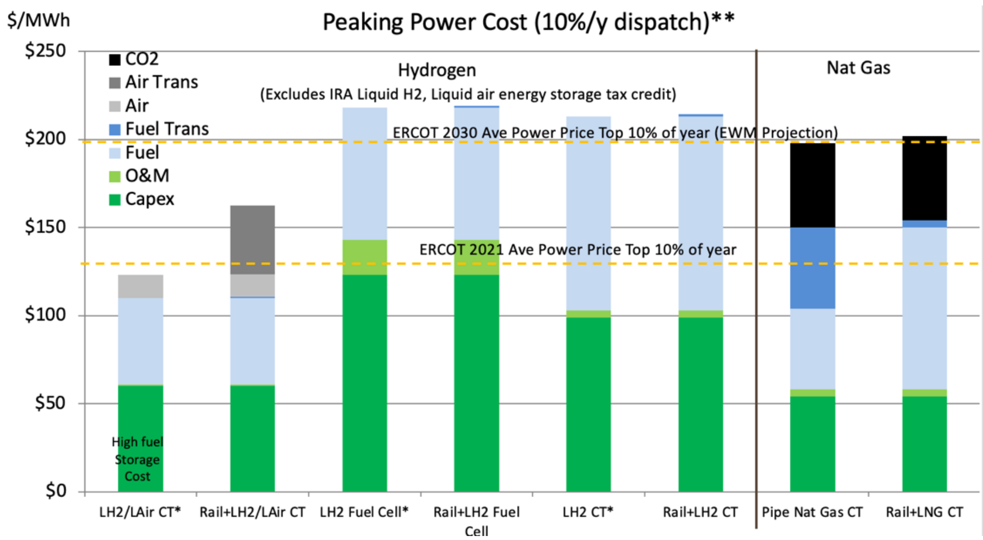
Figure 4 – ERCOT Power Price Duration

EWM's Green Liquid Hydrogen System™ uses a stationary version of the LH2 and liquid oxygen fueled two stage combustion rocket engine used for the Space Shuttle and Artemis. EWM's version uses LH2 and liquid air in the same two stage combustion system. This allows for a >95% hydrogen LHV efficiency because fuel and air compression is avoided. The fuel and air compression occurs during periods of low-cost PV/wind power to produce the LH2 and LAir feeds. Although turbine suppliers would need to assemble this engine, it would use a combination of:

- existing rocket engine technology (first stage combustion and expansion turbine); and
- existing combustion turbine technology (second stage combustion and expansion turbine).

The two-stage combustion design (high pressure and low pressure) used in the commercially proven LH2 fueled rocket engines solves the hydrogen combustibility and NOx issues currently encountered in the single stage, 100% hydrogen fueled, high efficiency combustion turbines.

As shown in Figure 4, EWM anticipates that 50% of the power generation required to meet the power demand for the overall plant shown in Figure 1 will be from the TES heat fueled cogen steam turbine. Therefore, there is a large amount of thermal energy required to meet the onsite power and heat requirements. This thermal energy is normally supplied by the byproduct heat from the production of LH2 and LAir. During times of low PV and wind power availability, backup LH2 and LAir is used in a two-stage combustion system to provide a source of backup heat when byproduct heat from the TES system is insufficient to meet onsite power and steam needs.



* Peaking system uses unused grid capacity combined with onsite intermittent PV/wind power generation when no PV/wind available

** Based on 2030 fuel prices $1.50/kg H2, $5/MMBTU nat gas, $10/MMBTU LNG, $100/tonne CO2. 10%/y dispatch based on 4 months/y, 6 h/d summer, and 7 days/y 24 h/d winter average emergency peaks.

Figure 5 – Dispatchable Peaking Power Options

The LH2/LAir combustion turbine is the lowest cost option for on demand peaking power. It produces power at a lower cost than existing natural gas peakers (when the cost of CO2 emissions is included), fuel cells, and gaseous hydrogen fueled turbines currently being developed. Therefore, instead of developing a new turbine design compatible with 100% gaseous hydrogen, a much more efficient and lower cost two stage LH2 and liquid air fed turbine would be developed instead.

The 100% gaseous hydrogen turbines currently under development include a high-cost compression section that consumes approximately 66% of the gross power produced by the turbine. In the EWM design the compressor is separated and operates at a 40% dispatch factor using low-cost off-peak power. The expansion turbine operates separately at 3 times the net power output at a 10% dispatch factor during peak power price periods.

During peaking power production, the refrigeration in the high-pressure liquid air in the EWM design is recovered as additional peaking power and chilled water for the plantwide TES chilling system. This creates more peaking power and reduces onsite peaking power consumption for cooling.

Ammonia Production

LH2 and LIN can enhance ammonia production. The ammonia process benefits from higher pressure supply of hydrogen and nitrogen, but existing plants use compressed gaseous hydrogen and nitrogen feed. Pressures up to 300 bar would increase ammonia reactor per pass yield and eliminate refrigeration needed to recover ammonia from unreacted hydrogen and nitrogen. The 300-bar ammonia reactor is only economically viable with pumped LH2 and LIN feeds.

Low-cost ammonia production is important because it is used as both a green fuel and a fertilizer. Onsite ammonia to nitric acid conversion can be used to produce high value potassium nitrate fertilizer for the onsite Full Recovery Agriculture™ system. The byproduct high pressure steam from ammonia to nitric acid conversion can be used to generate baseload green power in a steam turbine.

Methanol Production from CO2 and H2

LH2 also can enhance methanol production from liquid CO2 and LH2. Typically, methanol is produced from CO and H2 from natural gas reforming or coal gasification. In the energy transition, DAC or biogenic CO2 is combined with green hydrogen to produce E-Methanol. The methanol reactor and catalysts, however, have a lower yield when operated at the typical pressures (80-100 bar) used for CO and H2 feeds.

At higher pressures (360 bar) with excess hydrogen recycle, nearly a 100% single pass yield can be achieved with CO2 and H2. To economically achieve these conditions, the feed LH2 and liquid CO2 are pumped to 400 bar. The 400 bar H2 and CO2 feed is used in an eductor to recycle the excess hydrogen and mix it with the H2 and CO2 fresh feed to the 360 bar methanol reactor. Neither a feed gas compressor nor a recycle compressor would be required.

Low-cost E-Methanol production is important because it is used as a green intermediate in the production of green olefins (e.g., ethylene for PVC) and Sustainable Aviation Fuel (SAF). It also can be used directly as a green marine fuel and as a green fuel for existing combustion turbines.

LH2 Global Export

As currently being demonstrated by others, LH2 can be effectively used as a global energy commodity in the same manner as LNG. This allows renewable energy rich regions to cost effectively ship liquid “green power” to renewable energy poor regions. LH2 fueled hybrid fuel cell/battery unit trains can cost effectively and efficiently transport liquid hydrogen to inland markets and from inland producers to deep water ports.

In addition to peaking turbine fuel, LH2 can be used to fuel marine and aircraft turbine engines. EWM is developing modified two stage combustion turbine designs for marine and turbofan propulsion based on LH2 only fuel (no LAir). The two stage (high pressure and low pressure) combustion increases efficiency and effectively addresses the hydrogen combustibility and NOx issues.

Enviro Water Minerals Company, Inc.
9950 Cypresswood Dr., Suite 330
Houston, Texas 77070
www.envirowaterminerals.com
inquiries@envirowaterminerals.com