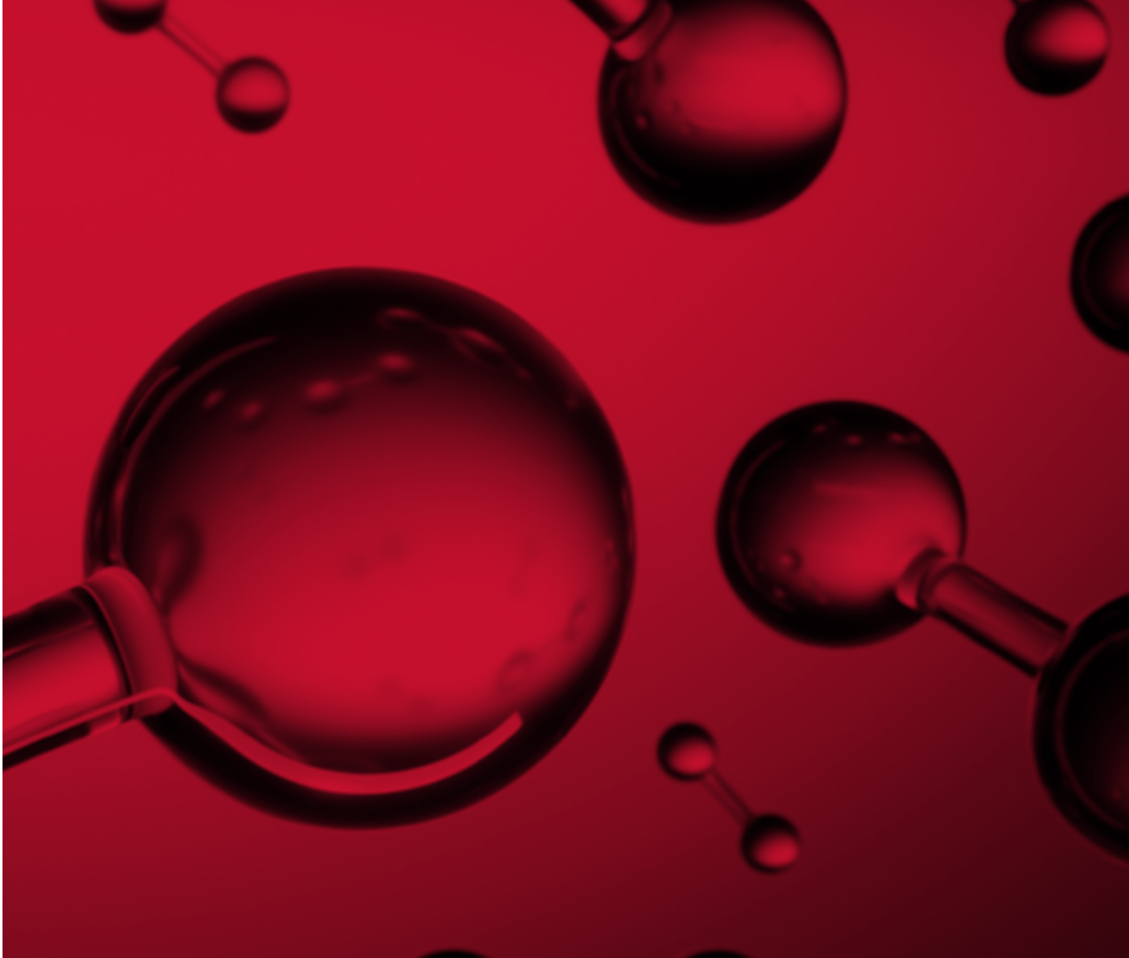


THE HYDROGEN ECONOMY

CAPSTONE PROJECTS
SUMMER 2021 - FALL 2023

UH Energy
UNIVERSITY OF HOUSTON

ABOUT THE CAPSTONE PROJECTS

The energy transition is in progress, and the world is grappling with the energy trilemma: How can we supply energy that is affordable, secure and reliable, and environmentally responsible, for everyone?

There is no single solution to this formidable challenge. But hydrogen is a key component of the most credible sustainable energy scenarios, with significant growth projected for the global energy system over the next 30 - 50 years.

Hydrogen is currently used heavily in the process industries, and it is seen as a significant future replacement option for the fossil fuels that are now used in power generation, transportation, and industry. However, most hydrogen today is produced from fossil energy sources. It will need to be decarbonized if it is to take its place as a dominant player in sustainable energy.

The Hydrogen Economy program is an interactive, online educational program that shares insights into the technology, economics, policy, and business drivers and barriers for hydrogen, both in the short term and in the long term. It examines hydrogen's production, transportation, safety, use, and commercial opportunities, and considers both onshore and offshore applications.

The Hydrogen Economy Program experience culminates with a capstone project. The project is based on developing and defending a business plan for a clean hydrogen start-up venture, demonstrating knowledge of the principles taught in the course.

This is augmented by additional independent research related to the specific type of business model, technology deployment, and location chosen. Students can either work individually or form teams to evaluate their ideas, and then present them to the class and the panel of judges (aka the shark tank). Past cohorts have shared some wonderful ideas and creative presentations, and the whole activity was great fun. This brochure features summaries of the winning projects, all of which have real-world potential as sustainable, reliable and environmentally responsible solutions that the energy transition will need in order to be fully realized.

Alan Rossiter, Ph.D., PE
Executive Director, External Relations & Educational Program Development, UH Energy
Hydrogen Economy Course Instructor

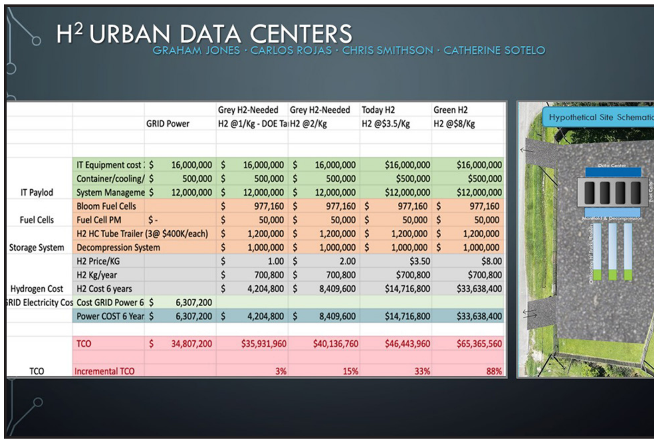

SUMMER
2021

H_2 Urban Data Centers (1st Place)

Group Members

- Graham Jones - Wind Development Manager, Tenaska
- Carlos Rojas - Datacemter Modeling Architect, NVIDIA
- Chris Smithson - Chief Technology Officer, Croft Production Systems
- Catherine Sotelo - Environmental Consultant, Resolute Compliance

Abstract



		GRID Power	Grey H2-Needed H2 @1/Kg - DOE Ta	Grey H2-Needed H2 @2/Kg	Today H2 H2 @$3.5/Kg	Green H2 H2 @$8/Kg
IT Paylod	IT Equipment cost :	$ 16,000,000	$ 16,000,000	$ 16,000,000	$16,000,000	$16,000,000
	Container/cooling/	$ 500,000	$ 500,000	$ 500,000	$500,000	$500,000
	System Manageme	$ 12,000,000	$ 12,000,000	$ 12,000,000	$12,000,000	$12,000,000
Fuel Cells	Bloom Fuel Cells		$ 977,160	$ 977,160	$ 977,160	$ 977,160
	Fuel Cell PM	$ -	$ 50,000	$ 50,000	$ 50,000	$ 50,000
Storage System	H2 HC Tube Trailer (3@ $400K/each)		$ 1,200,000	$ 1,200,000	$ 1,200,000	$ 1,200,000
	Decompression System		$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
Hydrogen Cost	H2 Price/KG		$ 1.00	$ 2.00	$3.50	$8.00
	H2 Kg/year		$ 700,800	$ 700,800	$700,800	$700,800
	H2 Cost 6 years		$ 4,204,800	$ 8,409,600	$14,716,800	$33,638,400
RID Electricity Cos	Cost GRID Power 6	$ 6,307,200				
	Power COST 6 Year	$ 6,307,200	$ 4,204,800	$ 8,409,600	$14,716,800	$33,638,400
TCO	TCO	$ 34,807,200	$35,931,960	$40,136,760	$46,443,960	$65,365,560
	Incremental TCO		3%	15%	33%	88%

Datacenters consume more than 1 % of global electricity and demand keeps increasing. As such, it is increasingly important to decarbonize this consumption vector. In this project we concentrated on mid-scale datacenters that for varying reasons: must be located in close proximity to the customer within urban locations, have inadequate land access for renewable energy generation on-site, and where powering with traditional energy sources (diesel generators) is not an option. Our project was based on a Total Cost of Ownership methodology considering a 1 MW datacenter footprint. Our baseline calculates the cost of such a datacenter powered by a traditional grid (majorly fossil-fuel energy) in addition to multiple scenarios where the datacenter is powered via clean energy (H_2). We explored three different topics for our project:

- H_2 Turbines and Fuel Cells as electricity generation options.
- H_2 Storage and supply strategy.
- Physical footprint and safety concerns.

All these considerations were included in our Total Cost of Ownership analysis. We concluded that there was not a current economical path for a fully H_2 powered datacenter; however, two tracks for future exploration were established:

- Sensitivity analysis to the cost of H_2 showed our project could be viable as the DOEtargets for H_2 cost ($1/kg) are met in the future.
- Potential for hybrid sites where a portion of the energy comes from a renewable source,is supplied via grid electricity, or the customer has staged emission reduction goals.

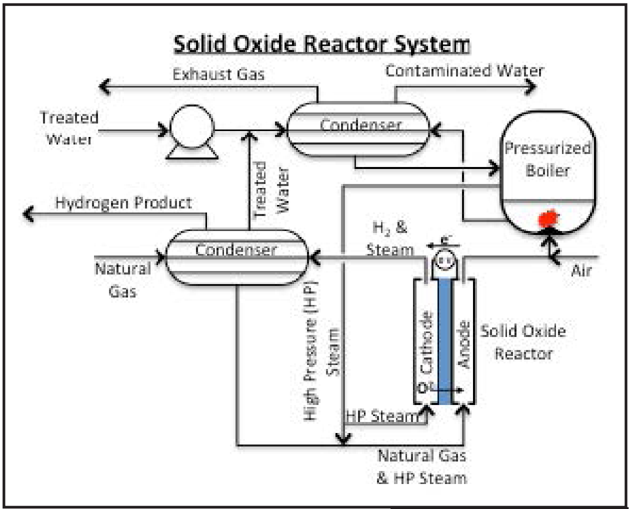
Solid Oxide Reactor System (T-2nd Place)

PROJECT LEAD

• Fritz Pierre Jr. - Texas Process/Research Engineer, ExxonMobil

Abstract

North America's inexpensive natural gas and its existing pipeline networks favor the use of natural gas to produce onsite hydrogen for non-industrial users. Investors do see a profitable business model in the distributed production of hydrogen. Indeed, the opportunity exists now to provide the hydrogen at low cost and low emissions. Bayotech is one of several companies offering onsite hydrogen to customers based on steam methane reforming (SMR) technologies. SMR has the advantage of being a mature technology. However, with the target of blue hydrogen production with minimal carbon dioxide emissions, the SMR technology has several inherent disadvantages.



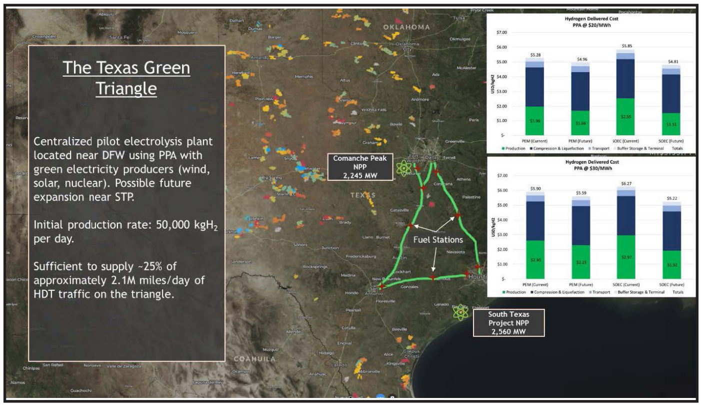
Haldor Topsoe (Denmark)

Solid oxide technology provides a different pathway to produce hydrogen using natural gas. In its case, the natural gas provides the molecules that are oxidized in the anodes of the solid oxide cells to drive the electrolysis of steam into hydrogen in the cathodes of the solid oxide cells. Low cost thermal energy is used to power the reactor rather than high cost electricity. The use of solid oxide technology to produce hydrogen with the aid of natural gas has several advantages over competing technologies. For example, the technology is thermally more efficient than SMR due to inherent heat integrations within the solid oxide reactor. The technology is more amenable to carbon capture for the production of blue hydrogen since the reactor system can be designed such that effluent containing carbon dioxide is only in mixture with steam. Another important advantage for the solid oxide technology using natural gas is the high utilization rate to better offset the high capital cost of the solid oxide cells. Solid oxide technology using renewable electricity in conventional electrolysis does not have this advantage. Thus, solid oxide technology using natural gas provides a pathway to commercialize this solid oxide technology at scale to drive down cost for all uses.

GROUP MEMBERS

- Aaron Totemeier -Founder, 1932 Advisors, LLC.
- Ali Oktay - Regional Sales Manager, Medtrade, Inc.
- Ricardo Chona - Petroleum Engineer, Bureau of Land Management

ABSTRACT



Texas is well-positioned to take a leadership role in the emerging clean hydrogen production value chain as we have both a stable zero-emission electricity supply (nuclear, wind, and solar) and a reliable demand side with over 2 million miles of heavy-duty truck (HDT) traffic around the Houston – San Antonio – DFW triangle each day. These HDTs represent an attractive early market for conversion to hydrogen fuel cell vehicles as many of them never leave the Texas region and an early stage refueling network around the triangle would be cheaper than deploying an interstate network for long-haul trucking. Our project hypothesized that a centralized electrolyzer plant for clean H_2 production in the DFW region could provide sufficient H_2 to convert approximately 25% of the regional HDTs to hydrogen fuel in the near term. The business model we considered was based on securing power purchase agreements with regional wind, solar, and nuclear suppliers to ensure round-the-clock production at a 50 tonH_2/day facility. Using the H_2A models developed by the National Renewable Energy Lab (ver. 3.2018), we evaluated centralized PEM and SOEC facilities with current and future scenarios, assuming PPA pricing of \$20 and \$30/MWh. Capital costs calculations for the facilities were lowest for the current PEM facility (\$70M) and the future SOEC facility (\$50M). The peak cost of hydrogen production (assuming \$30/MWh) varied from \$2.60/kgH_2 (current-PEM) to \$1.92 (future-SOEC). We estimate compression, staging, delivery, and storage costs of \$3.30/kgH_2 to supply a regional fuel station network around the triangle, for a total delivered cost in the range of \$5.28-\$5.90/kgH_2 depending on PPA pricing. This price is approaching the range where hydrogen fuel for HDT could make economic sense, and with the legislative support proposed in the Clean Energy for America Act, the delivered price could decrease to < \$2 kg/H_2, expanding the market opportunity a regional clean hydrogen project.

A Vision For A Houston Low-Carbon H_2 Hub (Hon. Mention)

GROUP MEMBERS

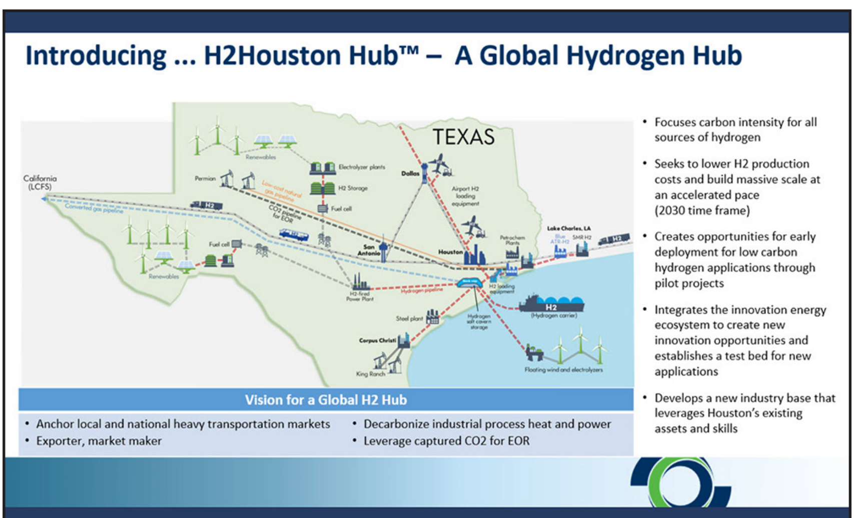
- Brett Perlman - CEO, The Center for Houston's Future
- Kay McCall - Executive Director, Renewable Energy Alliance – Houston
- Dana Wells - Principal, Dana Wells & Associates

Abstract

As an alternative to the standard Capstone Project, two of the program participants volunteered as mentors for the Center for Houston's Future summer research program. Below is a summary.

Houston, we have a problem. Houston is known as the oil and gas capital of the world. However, with alternative energy sources, changing customer demands, and goals to reach net-zero carbon emissions by 2050, Houston has charted a new mission to become the energy capital of the world. So how do we make this happen? We do it by exploring one opportunity at a time. Can Houston become a global hydrogen hub? We think so. This presentation showcases The Center for Houston's Future vision of transitioning Houston into a Global Hydrogen Hub. It:

- discusses major funding opportunities for Hydrogen Hubs;
- explains what positions Houston to be a global hydrogen hub – 'H_2Houston Hub™';
- assesses the feasibility of creating an H_2Houston Hub™ with a Transportation Application Study;
- describes energy transition action and inaction impacts on the Houston Economy; and
- ends with a call to action for how you can get involved to make H_2Houston Hub™ a reality.



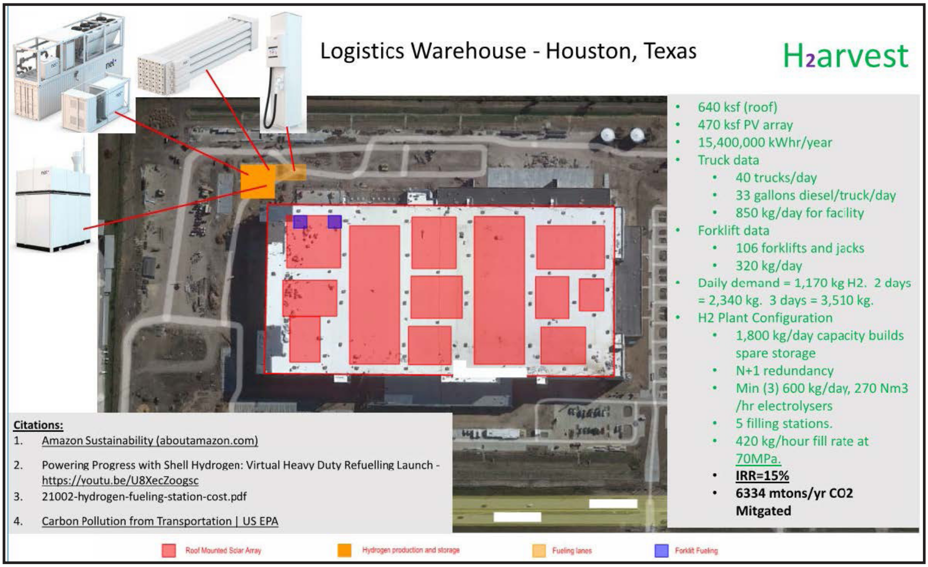
SPRING 2022

H_2ARVEST (T-1ST PLACE)

PROJECT LEAD

- Brian Peterson, Executive Vice President, Telios

ABSTRACT



Each year, in the United States, Class 8 semi-trucks burn over 38.4 billion gallons of diesel fuel, at a current fuel cost of approximately $195 billion, and emit over 55.3 million metric tons of CO_2e. This represents 7% of the yearly US greenhouse gas emissions. Hydrogen (H_2) fuel cell vehicles (FCEV) have zero emissions so they represent an impactful alternative to diesel trucks. Although battery electric vehicles (BEV) are also zero emissions, FCEV are advantaged in HD trucks due to their lighter weight, shorter fueling duration, longer vehicle range, and better driver comfort and decreased fatigue. Seven companies (Walmart, Amazon, Kroger, Costco, Walgreens, UPS, and FedEx) represent 80% of the class 8 delivery market. Currently each has a goal and strategy to get to zero emissions in their delivery operations. The federal government continues to apply pressure to corporate America to decrease emissions and is incentivizing adoption of zero emissions technologies. This project makes a business case for converting electrons to molecules by utilizing solar arrays on distribution warehouses to power PEM electrolysers, H_2 compressing, cooling and storage equipment, and filling equipment to fuel FCEV class 8 trucks delivering to/from the facility. A corresponding feasibility study found that a 640,000sf facility can produce enough solar power and H_2 to fuel 40 trucks and 106 forklifts per day. The economics of the project produced an internal rate of return of 15%. And, the amount of yearly emissions mitigated is approximately 6,334 metric tons per year of CO_2e.

Biogas to Hydrogen for Asphalt Heat (T-1st Place)

GROUP MEMBERS

- Ryan Davis - President, AMJ
- CJ Okafor - Senior Production Engineer, Dow
- Ozgur Ozen - Development Planner, ExxonMobil

Abstract

Biogas production at landfills, where economic reserves of biogas exist, has been an important pathway for the mitigation of methane released into the atmosphere from the natural decomposition of organic matter for some time now. The sale of this biogas upon removal of impurities as pipeline grade natural gas, and in some cases, flaring of the same where no pipeline exists, has been extensively developed at many landfill sites worldwide.

Landfill sites with adequate reserves for the economic development of biogas production are generally located around large cities. Roadway construction and repair is also concentrated around large cities. Most of the roadway construction and maintenance performed throughout the United States utilizes asphalt concrete as the paving material. Given the very high viscosity of asphalt binder (it remains solid even in extreme Texas heat), heating is required to maintain adequate flow of the binder for mixing with rock aggregates to form asphalt cement and for transportation of the final product. Stationary and portable hot mix asphalt plants are used in the industry to mix asphalt binder with aggregates for final delivery.

Where a roadway project location exceeds a certain distance from the location of a stationary plant, portable mixing plants are required. These plants utilize portable fuels such as diesel or, more recently, LNG, for fired heaters in mixing drums to maintain asphalt temperatures of approximately 350F.

Abstract (Cont'd)

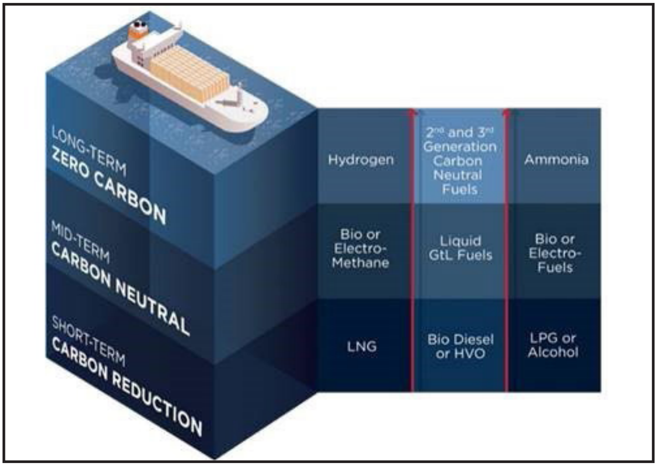
The quantity and proximity of available biogas production at landfill sites near cities throughout the USA matches well with the demand for asphalt, making the delivery of hydrogen at small scale plants viable for this application. Hydrogen as a substitute fuel for diesel has the environmental benefit of generating no CO_2 byproduct, and hydrogen burners have recently been optimized to eliminate or greatly reduce NOX associated with higher temperatures produced when burned. Our project involves the development of small-scale hydrogen production at landfill sites, the capture of CO_2 generated as a byproduct of the production of hydrogen from methane, and the sale of the hydrogen to a pre contracted network of asphalt producers for use in their respective supply chains. The concept harnesses the proximity of supply and demand centers and the synergies in the available volumes of biogas and asphalt heating demand to substantially reduce or eliminate emissions from both the burning of biogas, as well as the burning of diesel as a fuel for heat at portable hot mix plants.

GROUP MEMBERS

Team ABS:
- James Abrams - M&A Analyst, ABS Group
- Gareth Burton - Senior Vice President, Global Enginnering, ABS
- Joseph Rousseau - Director, Offshore Technology, ABS
- Derek Schmidt - Vice President, Commercial Services, LISCR

Abstract

For the offshore wind industry producing green energy, there is increased sensitivity for the support infrastructure to be part of the decarbonization effort as well. Are there future opportunities to use Hydrogen as fuel for offshore vessels supporting the offshore wind industry? This high-level use case explores the integration of hydrogen fuel cells on newbuild maritime assets with currently available technology in the marketplace.



There are many drivers for decarbonization in the maritime sector. However, the challenges in quickly adopting these new technologies are great. Critically, there are two major factors influencing this. First, the financial investment for large vessel adaptation of fuel cells as the primary source of energy adds a substantial premium compared to conventional vessel design. Second, there are still many practical engineering challenges to overcome; significantly, how to store hydrogen as fuel on board a vessel.

While this use case explores a singular application of hydrogen in the offshore industry, it is noted that future drop in hydrogen prices may make this a viable option. In the interim case, there are some options to consider; waste heat recovery from fuel cells, hybrid alternatives (combination of diesel fuel, battery & fuel cell), and ammonia or methanol as the energy vector.

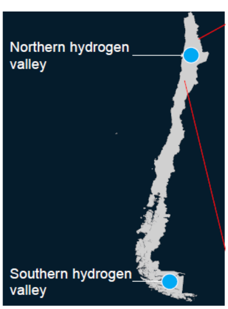
FALL 2022

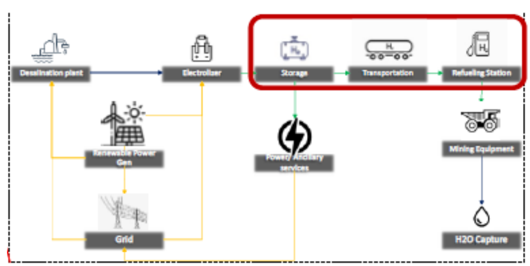
GROUP MEMBERS

H2Mining:
• Anna Gretchina - Power Solutions Manager, New Energy, Americas, Woodside Energy
• Rob Haun - Director, Anspanner

Abstract

Chile has known solar and wind power generation potential. Both are necessary resources for green hydrogen production. The country already has some 13.4 GW of renewable installed capacity, which supplies over 30% of the total national demand for electricity. Projects in the pipeline include an additional 52 GW of renewable generation. The maximum potential is estimated at 1,800 GW – equivalent to 70 times the total local demand. At the same time, Chile is the leading copper producing country. Major global mining groups have large copper operations, mostly in the northern region. Those groups have publicly announced aggressive GHG emissions reductions, targeting net zero in the next decades. Mining GHG emissions come mainly from their electricity consumption (off-set by renewable power purchases) and diesel consumption for large mining equipment. Over 1,500 mining trucks currently operate in the country, with about 950 gal of diesel consumption per day, per truck. We see as an opportunity the replacement of diesel by green hydrogen in the mining trucks operations. GHG emissions can be significantly reduced at a competitive cost. The electricity required for new, green hydrogen production will come from PV and wind projects. The source of water will have to be desalinated. This can be purchased from existing and planned projects in the area. The electrolizers will be located near the power generation facilities, reducing the transmission costs and curtailments effect. The main mining truck supplier, along with engineering groups and mining companies, is already developing workable alternatives to convert existing equipment to hydrogen. Dual diesel-H2 operation and H2 fuel cells are being considered. Our project will develop a robust storage and logistic chain for this new and fast-growing hydrogen demand. Storage at the production site, transportation to the mining operations and refueling stations to secure 24/7 operational needs and optimization will be included. Additionally, automatic refueling will be considered in order to reduce safety risks.



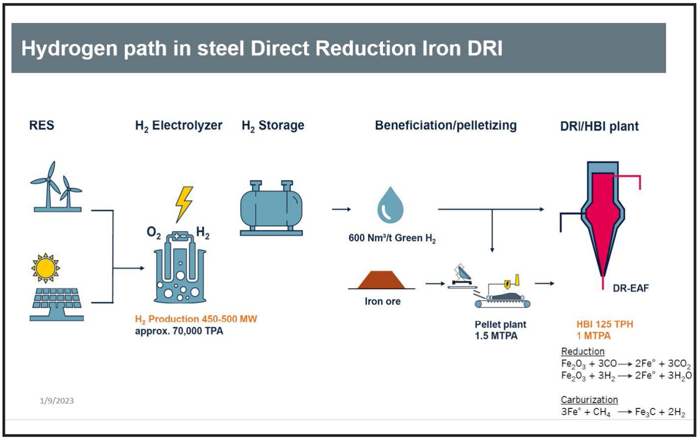


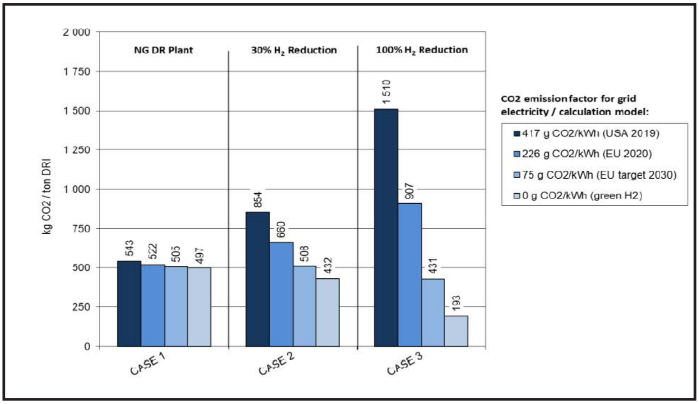
PROJECT LEAD

- Joao B. S. Gonzaga, Sr. - Director of Engineering, Gerdau Steel

Abstract

The iron and steel industry is responsible for a portion of 7-9 % of the global CO_2 emissions, it has to reduce its CO_2 emissions drastically during the next 30 years. Greater CO_2 reductions in steel industry can only be achieved by switching to different iron & steel production processes. This can be either the scrap-EAF route for certain quality grade steels or the utilization of H_2 in Iron direct reduction route. The use of hydrogen sources in the existing BF-BOF route can only contribute to a small reduction of CO_2 emissions, which it will not be sufficient to achieve the CO_2 reduction targets. In order to achieve the future targets, the direct reduction plant (DRI/EAF route) using H_2 is one of the alternatives for CO_2 reduction strategy. This study analyses the environmental benefits of the hydrogen based direct reduction process and its impact on operational cost based on average unit cost for a DRI.





PROJECT LEAD

- Shivaprakash C. Rao - Head of Consulting and Energy Transition, BMT Asia Pacific

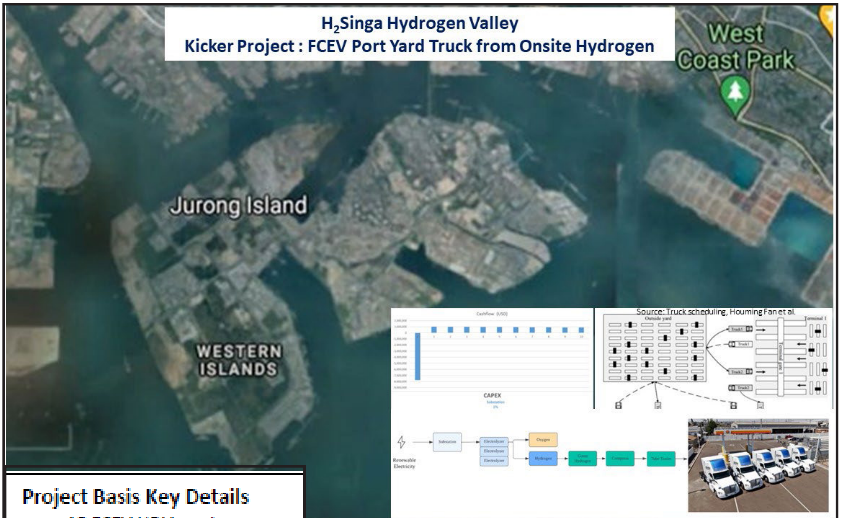
Abstract

Singapore has committed to achieving net zero emissions by 2050. Its national hydrogen strategy (2022, Oct) states that hydrogen is the preferred energy vector if technology advances, and international efforts remain strong. Singapore has assessed that hydrogen could contribute to 50% of Singapore's projected electricity demand by 2050. For a city-state like Singapore with minimal access to in-situ renewable energy, importing green electricity from the neighborhood and producing green hydrogen provides a "boot-up strategy" towards hydrogen adaptation since it presents a scalable way to participate in the emerging worldwide hydrogen economy and be in step with international efforts.

An excellent place to foster a hydrogen economy is Jurong Island. The island has more than 100 world-class energy and chemical companies that have invested more than $100b of investment, making it the 8th largest exporter of chemicals globally, generating 24,000 direct jobs and 3% of Singapore's GDP. While the economic importance of Jurong Island to Singapore and the world's energy and chemical sectors is evident, the island will have to transform by weaning itself away from its current fossil fuel dependency as feedstock. Its already established sectoral couplings and concentration of off-takers perfectly positions Jurong Island to capture hydrogen economy opportunities, leveraging its world-class infrastructure (storage, pipelines etc.) to transform to a hydrogen valley and a new energy trading hub of the future. The risk of not transforming Jurong Island would be having stranded assets of declining economic value to the nation as economies worldwide decarbonize. Since the Singapore government has a long-term low emissions strategy, a calibrated approach can be formulated to transform Jurong Island into Hydrogen Valley.

The proposed H_2Singa masterplan project takes a phased approach to transform the existing fossil fuel-based Jurong Island cluster into a hydrogen-based chemical cluster. H_2Singa masterplan proposes starting with the "kicker project" to kick start the hydrogen valley: Hydrogen FCEVs for the port's yard trucks for the new and futuristic Tuas mega port. The project is based on generating onsite hydrogen from imported renewable electricity (Laos/Sarawak etc.) to produce hydrogen for yard truck operations to haul containers between the various ports in Singapore and within the ports. This concept would offer higher asset utilization and productivity compared to battery operated trucks, improves port productivity, enables green port positioning, and kick-starts hydrogen economy in Jurong Island for larger regional and international play.

H_2Singa Hydrogen Valley Jurong Island, Singapore (3rd Place)



Project Basis Key Details

- 15 FCEV HDV trucks
- 60 km/hr. while covering 800 km covered in 24 hrs.
- Average emissions per truck 1.8 ton/day
- Refueling time 3 to 8 min (vs 60 min electric fast charger)
- Hydrogen FCEV trucks will provide higher asset utilization due to 24 hrs. duty before refueling.
- Electrolyzer USD 1000 per KW and Trucks 329,000 each
- Charter Rate USD 260 per truck per day for Period 10 years
- WACC 10% and Inflation of 3%
- Revenue model there is no escalation
- Payback 9th Year, this metric has been kept less aggressive as market penetration strategy
- Project is Financially Feasible

SPRING 2023

H_2 Airport Hub (T-1st Place)

GROUP MEMBERS

- Richard Henahan - Project Consultant, Baltic Innovation Agency
- Peter Diakow - Hydrogen Lead/Senior II Consultant, BakerRisk
- Lloyd Rude - Texas United Management Corporation
- Gregory Bohn - Project Development Assosicate, Tecnicas Reunidas

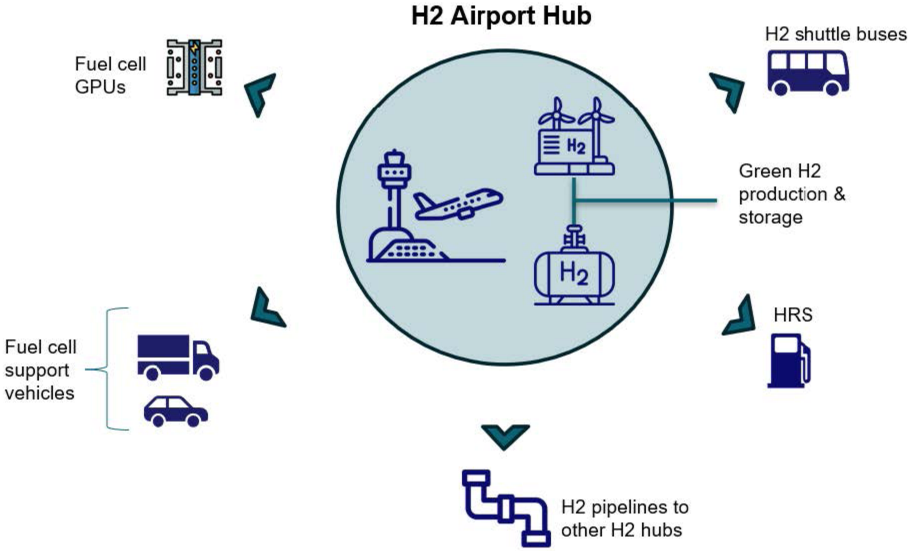
Abstract

The concept of a hydrogen airport hub represents a visionary step towards achieving sustainable air travel. With the urgent need to reduce carbon emissions and mitigate the environmental impact of aviation, this innovative concept offers a comprehensive solution by utilizing hydrogen as a clean and renewable energy source. A hydrogen airport hub would serve as a key infrastructure element in transitoning the aviation industry toward a greener future.

The proposed Hydrogen airport will be developed in 3 stages, where Stage 1 has a narrow focus, establishing the key technologies and identifying low hanging fruit opportunities to integrate market available H_2 technologies. Stage 2 and Stage 3 become progressively more integrated, where Stage 2 will establish onsite H_2 production and storage and Stage 3 will integrate infrastructure for H_2 aviation fuel and connect H_2 production with other logistic hubs, such as ports or ground transportation hubs, to create an integrated H_2 network. The current model focuses on Stage 1 activities.

Key Elements for Stage 1:
1. Hydrogen storage and compressors: The hub would include on-site facilities for hydrogen storage and compressors to supply fuel cell applications.
2. Hydrogen Refueling Stations: The airport hub would feature multiple hydrogen refueling stations strategically placed to serve a fleet of hydrogen-powered support vehicles.
3. Hydrogen fuel cell applications: Market available fuel cell vehicles and ground power units will replace existing fossil fuel powered vehicles. For example, shutle buses, baggage tuggers, ground power units, cars, forklifts, etc. Further, emergency back-up stations will be transitioned to fuel cell emergency back-up stations.
Benefits:
1. GHG reduction: Stage 1 will immediately decarbonise a significant amount of ground airport operations.
2. Energy Security and Independence: In Stage 2, by producing hydrogen on-site using renewable energy sources, airports can achieve greater energy security and reduce reliance on fossil fuels.
3. Integration with other logistic hubs: The envisioned hydrogen airport hub can be integrated with other logistics centers, such as ports and ground transportation hubs, and improve economies of scale which can increase H_2 integration into hard to decarbonise transportation sectors and decrease the price for green H_2.

H_2 Airport Hub (T-1st Place)



CAPITAL EXPENDITURE

Storage	32,205,600
Transition Vehicles	148,750,000
Ground Power Units	10867500
Compressor	5,000,000
Dispensing Stations	3,000,000
Pre-tax Capex	199,823,100
Sales Tax	1,873,341.56
Total Capex	201,696,442

Integrated Energy Systems for Nuclear Produced Hydrogen (T-1st Place)

GROUP MEMBERS

• Mike Curtis - Carbon and Energy Technology Principal, Dow
• Mikaela Dressendorfer - Project II Consultant, BakerRisk

Abstract

By 2050, the demand for low carbon electricity and hydrogen in the US is expected to increase from 4,000 to 7,000 TWh and from 10 to 41 million MT per year, respectively. A substantial portion of electricity will come from variable renewable energy (VRE). Electricity transmission and demand balancing with hydrogen production will be a challenge.

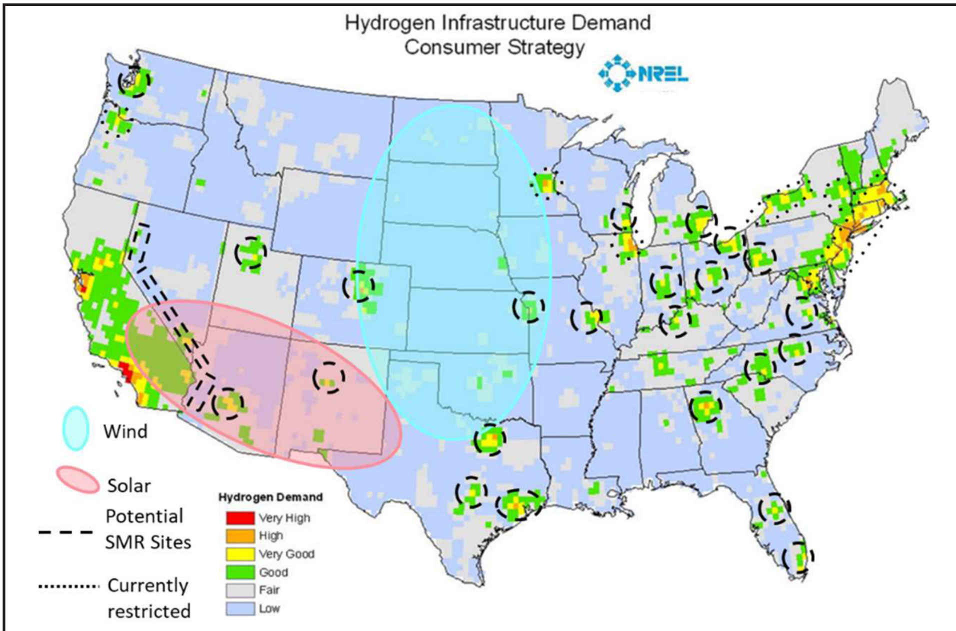
Steam methane reformation is a low carbon option for hydrogen production that avoids VRE capacity and transmission limitations. However, the need for geological storage of hydrogen, the sequestration of CO_2, and the challenge of long distance hydrogen delivery will limit the selection of practical and economic locations.

A viable option that addresses both VRE and steam methane reformation limitations is deployable hydrogen production via nuclear energy. The DOE predicts 200 GW of nuclear small modular reactor (SMR) capacity by 2050. This translates to ~2,000 SMRs with each having the ability to produce heat, electricity, and hydrogen. Small modular reactors will begin to come online in 2030 and Nu-H2 will be the first Integrated Energy System (IES) company to facilitate safe and efficient hydrogen production from nuclear energy.

Nu-H2 is a design, automation and safety company that provides:

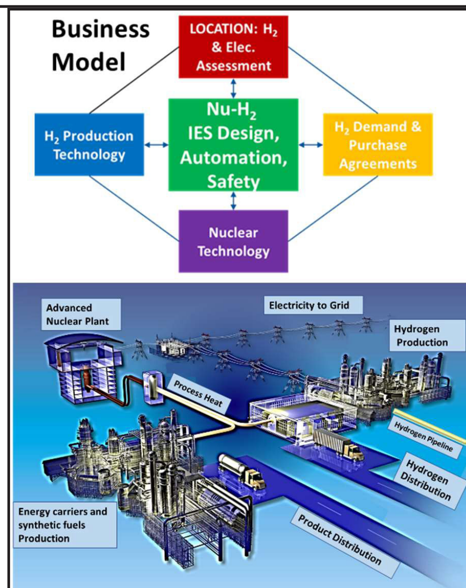
• Location demand assessments for co-generation of H_2 and electricity via nuclear SMRs near end users
• Acquisition of hydrogen purchase agreements (HPAs)
• Selection and synergy between different nuclear and H_2 production technologies
• Design including automation and safety systems for the integration of a H_2 plant with the nuclear facility

Integrated Energy Systems for Nuclear Produced Hydrogen (T-1st Place)



The ability to deploy nuclear SMRs across the US along with the Nu-H_2 approach will facilitate:

- Low transport costs and minimal pipeline length due to locating near hydrogen end users
- Minimal storage requirements due to continuous H_2 production based on HPAs
- Consistent behind the meter hydrogen production at steam methane reforming costs
- Ability to add electrochemical or thermochemical capacity, another nuclear SMR, or create gigafactories for
production of energy carriers and synthetic fuels with nuclear trigeneration of H_2, steam and electricity



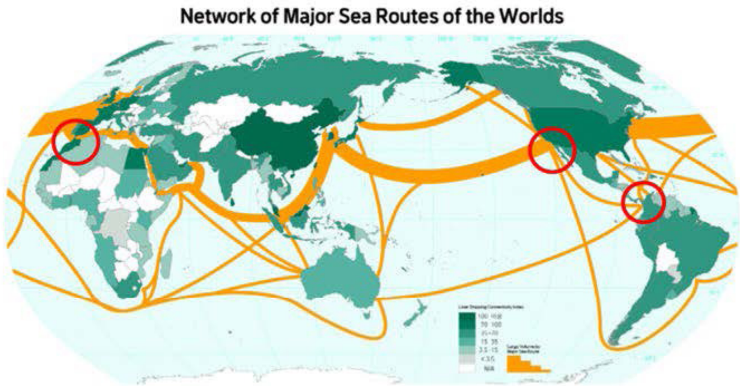
PROJECT LEAD

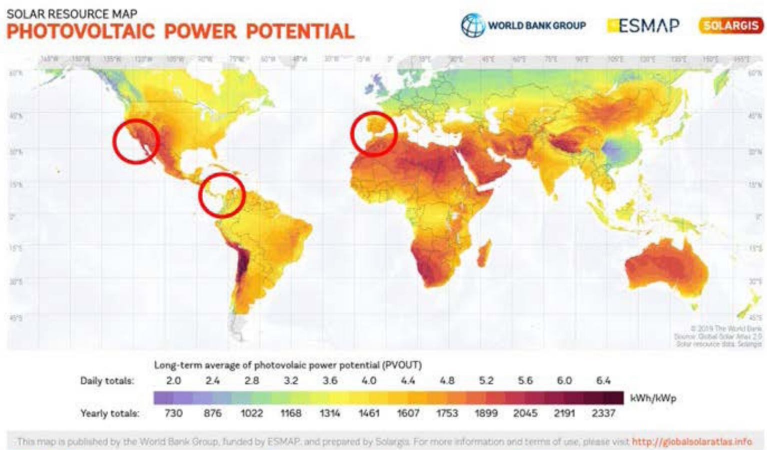
• Marc Schneider - Senior Project Manager. Hunt Guillot & Associates

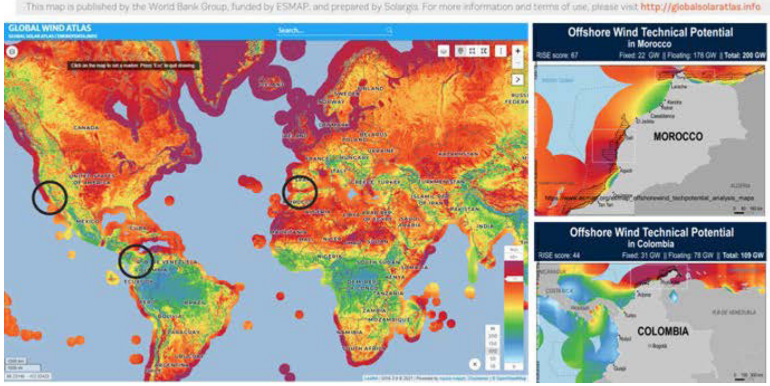
Abstract

There is currently a great effort to decarbonize the shipping sector implementing the use of alternative fuels. Major fleet operators such as Maersk, Southern Devall, NYK, and GSC are either focusing on ammonia or methanol as the potential low carbon shipping fuel of the future. While maritime engines or other solutions for the use of these alternative fuels are far along in development, the greatest challenge for the decarbonization of the shipping industry is that nearly all of today's ammonia and methanol supplies are produced using fossil fuels in highly energy- and carbon-intensive processes. This capstone project focuses on an opportunity to support the maritime decarbonization goals by evaluating the installation of green ammonia refueling stations along major shipping routes. First, three ideal locations positioned along some of the busiest shipping routes and with significant access to renewable energy are selected in the project. The three locations considered in the capstone project are Southern California, a location along the Panama Channel (in Columbia or Panama), and a location along the Strait of Gibraltar (Southern Spain or Morocco). Then, the capstone project evaluates the business case of building a green ammonia facility with SOEC electrolyzers, which benefit from the excess steam of the ammonia process. A financial model calculates the minimum price of green ammonia that provides attractive economics for the project.

The capstone project assumes a 100MW, 300 MTPD green ammonia facility at each of the locations, with TIC of $230 MM each. It also assumes SOEC electrolyzers, with electricity consumption of 39.6kWh/kg of hydrogen, and a renewable electricity price of $0.04/kWh. This system could economically produce green ammonia at an over the fence price of $750/MT. While at times, $750/MT of green ammonia would require a premium for the low carbon ammonia produced by the capstone project, in recent years we have seen prices of conventional ammonia well above the determined $750/MT. Thus, the capstone project, in conjunction with the alternative fuel efforts of the shipping industry, signifies a great step to reduce carbon emissions while keeping in mind the economics of these efforts.


Network of Major Sea Routes of the Worlds


SOLAR RESOURCE MAP
PHOTOVOLTAIC POWER POTENTIAL
WORLD BANK GROUP
ESMAP
SOLARGIS
Long-term average of photovolaic power potential (PVOUT)
Daily totals: 2.0 2.4 2.8 3.2 3.6 4.0 4.4 4.8 5.2 5.6 6.0 6.4
kWh/kWp
Yearly totals: 730 876 1022 1168 1314 1461 1607 1753 1899 2045 2191 2337
This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info


GLOBAL WIND ATLAS
Offshore Wind Technical Potential in Morocco
MOROCCO
Offshore Wind Technical Potential in Colombia
COLOMBIA

Slush H_2 for long-distance shipping

GROUP MEMBERS

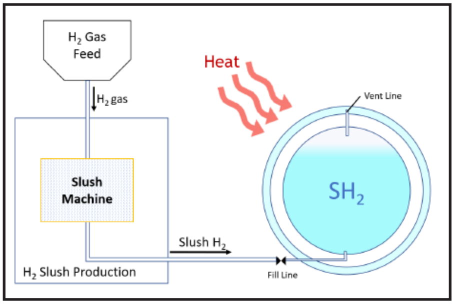
- Miguel Gonzalez - Research Scientist, Aramco
- Vijay Ramakrishnan - Engineering Specialist, Aramco

Abstract

In a future global energy economy led by renewable sources, such as solar/wind, hydrogen will have a key role as an energy vector, requiring efficient methods to transport it over long distances – from production to utilization. It is estimated that about 50 percent of internationally traded hydrogen will be through maritime transport [1]. However, shipping hydrogen across long distances remains a challenging problem – e.g., long-distance hydrogen transport in the form of chemical carriers (ammonia and liquid organic hydrogen carriers—LOHC) may incur in high reconversion costs, as well as potential toxicity and larger CO_2 intensities [2]; pure hydrogen transported by means of liquefied hydrogen incurs in losses from boil-off during loading/transportation/unloading.

Slush hydrogen, a mixture of liquid and solid hydrogen, can potentially achieve all the benefits of using liquid hydrogen (low CO_2 intensity, high-purity, easy to gasify) while reducing boil-off, hence lower net energy costs. At mixtures of approximately 50% solid, a 15% increase in density and an 18% increase in refrigeration capacities can be obtained. Losses from boil-off can be significantly reduced by minimizing fluid sloshing and improving transfer characteristics (reduced fluid friction losses through pipes, valves, etc.). These improvements can be achieved at relatively moderate costs of production [3]. A specific energy of consumption (SEC) of 4.5 kWh/Kg was estimated for slush produced via the Auger method, accounting for the thermodynamically reversible energy [4]. Adding liquefaction, an SEC lower bound of ~18 kWh/Kg can be obtained, which is comparable to that of ammonia production via the Haber-Bosch process [5].

Our studies found that, assuming a cost of carrier synthesis proportional to the SEC of the process, and the resulting boil-offs being comparable to those of other chemical carriers, the projected resulting costs of slush synthesis/loading/transportation/unloading can be estimated in the range of 2-2.5 USD/kg. This is in the same range as the comparable costs for ammonia and LOHC, but without the drawbacks of the chemical carriers, and with more favorable economics overall than liquefied hydrogen. Further exergy analysis could improve our understanding of the scalability of hydrogen slush production.



[1] IRENA (2021), Making the breakthrough: Green hydrogen policies and technology costs, International Renewable Energy Agency, Abu Dhabi.

[2] Ishimoto, Yuki, Mari Voldsund, Petter Nekså, Simon Roussanaly, David Berstad, and Stefania Osk Gardarsdottir. "Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers." International journal of hydrogen energy 45, no. 58 (2020): 32865-32883.

[3] Voth, R. O. "Producing liquid-solid mixtures (slushes) of oxygen or hydrogen using an auger." *Cryogenics* 25, no. 9 (1985): 511-517.

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FALL 2023

Coastal Corsairs Summary

GROUP MEMBERS

• Amy Warren - Project Manager, Fluor
• Xinlei (LeiLei) Liu - Fluor
• Rick Cunningham - Engineering Manager, Fluor

Abstract

The Coastal Corsairs, LLC mission statement is to identify and facilitate the development of business opportunities for the application of clean hydrogen fuel in maritime projects. The inaugural project focuses on a ferry service between France and the UK. This project supports maritime transport decarbonization goals in Europe. Phase 1 of our proposal is the development of a hydrogen facility, which will utilize 2 MW of PEM electrolyzers to produce hydrogen for supply to 3 passenger ferries. The hydrogen production facility will be located at the port and access power from the nearby Gravesline Nuclear Power Station. Due to the ongoing nation-wide nuclear expansion program in France, by winter of 2025/2026, it is expected that the national system will produce extra power capacity, including from Gravesline.

Each ferry will be powered by 2 fuel cells and hold 7 storage tanks of compressed hydrogen. This allows each ferry to operate for approximately 100 nautical miles, which is one roundtrip from Dunkirk to Dover and back. The ferry can operate for 4 hours before needing to be refueled. The fueling schedule is such that two ferries can be simultaneously fueled overnight during off-peak hours of the power plant and one ferry can be fueled during the day during peak hours of the power plant. Ferry operation and refueling is staggered so that the electrolyzers operate continuously, ramping down during the peak hours and ramping up during off-peak hours between 60 to 95 percent nameplate capacity. In support of France's nation-wide recycling initatives for wastewater, recycled municipal water is being considered as the source of water to produce the hydrogen. Desalinated seawater is being considered as the source for the cooling system. As with our business case for future projects, this inaugural project takes advantage of end-user adjacent available or stranded clean power and is based on a flexible production schedule. This physical location allows us to reduce or eliminate the cost for storage and transportation of compressed or refrigerated hydrogen. The physical location and the flexible production schedule allow us to use lower-cost power sources to feed the electrolysis process. The Corporation's partnership with Maersk will be predicated on the scalability of the ferry service into a European maritime shipping strategy in deploying this technology for the transportation of freight and goods.

3	**300**	**2 MW**
Ferries	Nautical miles per day	PEM electrolyzer
• 2 fuel cells / ferry • 7 storage tanks of 164 kg compressed H2 / ferry	• 2 hours / trip • 3 roundtrips / day • 4 hours at sea / ferry	• 8 hours refuel / ferry during off-peak hours • 12 hours refuel / ferry during peak hours

GROUP MEMBERS

- Betsy Cole - Commercial Operations Manager, Rigaku
- Jesse Johnson - Senior Policy Analyst, U.S. Dept. of Labor
- Mitesh Joshi - Senior Process Engineer, Amec Foster Wheeler
- Shannon McAvoy - Technical Sales Manager, ReNu Technologies

Abstract

Chicago O'Hare Baggage Vehicles:

•Through partnership with United Airlines, United would transition baggage cart ground support vehicles from diesel to hydrogen fuel cell vehicles. The initial phase would require 66 new baggage carts ($50,900 each).

•Utilize solar power from O'Hare rooftops. Initial demand is 1.25 MW. Assume $1.75/kW (capex $2.19M).

•Utilize a PEM electrolyzer to generate hydrogen. Utilize Nel hydrogen's MC250 which produces 531 kg hydrogen per day (capex $5.1 million – includes compression, storage, and distribution systems).

•The benefit to United is in fuel costs. Assume hydrogen at $7.53/kg and diesel at $4.36/gallon. This generates savings of $2.4 million/year, yielding an ROI between years 4 and 5. ROI could be further improved if credit is taken for Green H2 credit.

Expansion:

•Total hydrogen demand at O'Hare is estimated to be 28 MW = 11,294 kg hydrogen/day. Additional electrolyzers, compression/storage/distribution facilities, and solar capacity would be added incrementally.

•There's potential to leverage energy harvested from plane movement via JetWind's technology.

•Additional solar capacity may be available through the Double Black Diamond solar farm that is being constructed in central Illinois.

•Phase II expansion to various ground support vehicles (tugs, deicing vehicles, belt loaders, etc.) at the airport.

•Phase III expansion envisions O'Hare as H_2 Hub – supporting public transport system, logistics transport, etc.

Abstract (cont'd)

Why Chicago O'Hare?

•The Midwest was awarded a hydrogen hub through the DOE, announced in Fall 2023.
•Chicago O'Hare Airport is a hub for United Airlines with ample opportunity for renewable power.
•Illinois also offers favorable public policy such as the Climate and Equitable Jobs Act (2021), Solare Renewable Energy Credits, Illinois Energy Transition Act, and HB 2204 that creates a $10M/year tax credit in 2026 and 2027 for users of clean hydrogen.

Challenges:

•Lack of existing hydrogen infrastructure today.
•Permitting/perceived hydrogen safety concerns.
•Unknown future regulatory guidance: timing and legislation.

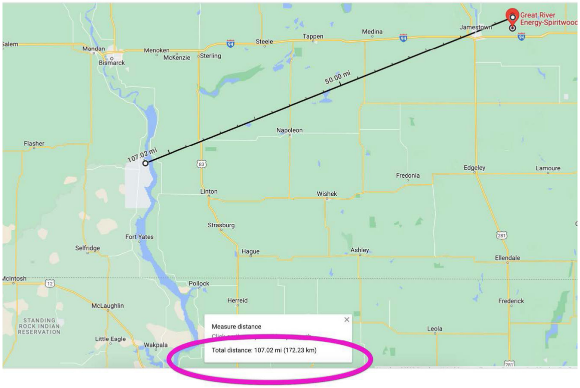
Transitioning to hydrogen as a fuel at O'Hare Airport offers a range of benefits, encompassing environmental, economic, and operational aspects and opens the door to future growth opportunities in the net zero transition.

GROUP MEMBERS

The Hydro-Gems:
- Adam Rose - Director of Partnerships & Growth, Travois
- Audrey Hooper - Power Process Engineer, Wood
- Christopher Brooks - Lens Valuation Product Owner, Wood
- Shuyun Li - Chemical Engineer, Pacific Northwest National Laboratory

ABSTRACT

As Native American communities continue to strengthen sovereignty through economic diversification, clean energy development continues to provide a viable path help to achieve many objectives. All Tribes, including the Standing Rock Sioux Tribe, continue to find ways to strengthen and enhance sovereignty, the inherent right to govern itself and make laws for its members. This includes small scale clean energy development all the way to massive utility scale energy development requiring investment in the billions.



Tribes also have unique regulatory ability to adopt and implement Tribal Energy Resource Agreements (TERAs). TERAs are agreements between a Native American tribe and the U.S. Department of the Interior (DOI), specifically the Bureau of Indian Affairs (BIA). They provide a framework for Tribes to assume greater control over the regulation and management of their energy resources on tribal lands. This combination of sovereignty and TERAs potentially enables a strategic advantage for Standing Rock to take the lead in managing their energy resources, fostering economic development, and exercising greater control over their energy futures. Without question, this could provide important differentiating factors to help leverage opportunities for green hydrogen as a long-term strategy for economic growth and prosperity where clean wind is abundant but connecting to the grid has many challenges. These opportunities have only increased with recent awards by the Dept. of Energy to H_2 Hub teams which now includes the Heartland HUB Team in North Dakota. This award proposes to support the expansion of green hydrogen to produce ammonia to serve the fertile agriculture sectors of the upper Midwest. A strong business case can be made for the Standing Rock Sioux Tribe to leverage its strategic position geographically to be the green hydrogen producer for this process, leveraging valuable hydrogen production tax credits in the process now part of the Inflation Reduction Act.

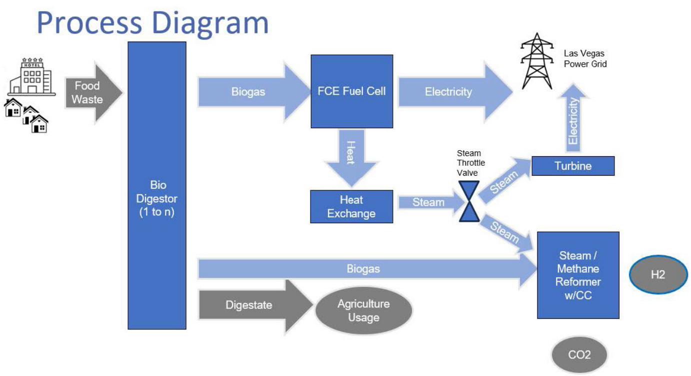
H_2 Production A Safe and Reliable Solution for Las Vegas

GROUP MEMBERS

- Noel Skwiot - Principal Engineer, Hartford Steam Boiler
- Mary Edwards - Sustainability Product Manager, LyondellBasell
- Lynn Lyon - Renewable Energy and Sustainable Transportation Executive, U.S. Energy
- Monica Davis - Client Engagement Manager, INF Associates
- Jerson Wattie - Health and Safety Manager, National Gas Company of Trinidad & Tobago
- Katherine Aliste - Senior Engineer, Business Planning, BHP

Abstract

Pilot scale plant with H_2 production based on biomass digestion and steam methane reforming, with the potential to be scaled or replicated in similar Island like locations. The 20 M USD Capex project was evaluated for 15 years, considering 1 $/Kg and 7 $/Kg of Hydrogen selling price, resulting in positive NPV evaluation for both scenarios.



This pilot project is to rely on a 2% portion of the 5 billion pounds of annual food waste generated by more than 1200 restaurants and 260,000 residential dwellings and several stadiums in the city of Las Vegas NV, USA. The food waste would act as feedstock in an anaerobic digester to produce biogas to be used as a fuel and feedstock for producing H_2, with a low carbon intensity score based on the GREET model. Tax credits and waste tipping charges were considered in the evaluation as well as potential clients for energy feed in the grid, CO_2 production and digestate for agricultural purposes.

The proposed location of the pilot is near the Union Pacific Intermodal Railyard in North Las Vegas, where there is close proximity to natural gas and electricity grid networks. This area would be ideal as the food waste feedstock is often transported on railcars and there is additional truck access. The finished products – H_2, Biomethane, and CO_2 – can then be readily transported via rail or heavy trucks in a "virtual" pipeline. To ensure the safe transfer of product, a risk analysis and hazop evaluation was prepared.

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