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California Floating Offshore Wind

Please see the attached PDF file "Hydrogen at Scale: Commercialization Plan for California Floating Offshore Wind".

Additional submitted attachment is included below.

Hydrogen at Scale: Commercialization Plan for California Floating Offshore Wind

Elias Greenbaum

GTA, Inc. recommends a bootstrap commercialization plan for early-stage monetization of the best wind resource in California: the north coast, from Mendocino County to the Oregon border, a region that includes the Humboldt Bay call area. The plan is unencumbered by the nominally problematic small load centers and limited electric transmission capacity that characterize the Humboldt Bay call area by advocating multi-gigawatt floating offshore wind farms that are **not** connected to a utility grid. Native electricity from each turbine is sent directly to the seafloor and conditioned to power a dedicated subsea electrolyzer system that is anchored at the seafloor, where renewable hydrogen is produced.[1] Each GTA electrolyzer communicates with a subsea hydrogen pipeline network and processing industry that prepares, stores and/or delivers the hydrogen to market. Please see the following page for a conceptual overview of the system.

Market examples are grid-balancing for renewable energy utilities and the California hydrogen fuel cell electric vehicle market. Another revenue stream is the production of 100% green ammonia. The U.S. produces about 10 million metric tons of hydrogen per year, about half of which is used for the agriculture industry for fertilizer. An air separation plant aboard a floating, production, storage and offloading (FPSO) vessel can extract nitrogen from the air and hydrogen from water to manufacture and deliver renewable ammonia. The proposed California intrastate commercialization plan is analogous to the newly established Japan–Australia joint venture wherein liquid hydrogen produced in Australia is delivered to Japan by Kawasaki Heavy Industries' liquid hydrogen tanker, the *Suiso Frontier*.[2] In the standard business model of offshore wind energy, the cost of power electronics, inter-array cables and high-voltage export cables connecting offshore wind farms to the onshore electricity grid is 25% or more (depending on distance from shore) of the system CAPEX. Also, insurance payments for the cables account for 30% of the system OPEX because 90% of the lawsuits and 70% of the actual cash settlements in the offshore wind electricity industry are associated with the cables. Overall electric energy cable losses between the offshore wind farm and utility consumers is in the range 8 – 15%. For subsea electrolyzers anchored at the seafloor, these expense categories and energy losses are eliminated. Energy transport by hydrogen in gas pipelines is eight times cheaper than energy transport by electricity in copper cables.[3]

Elias Greenbaum is President of GTA. Inc. and a member of the Board of Directors, California Hydrogen Business Council. The ideas and recommendations contained in the comments are those of the author, not the CHBC. Contact: greenbaum@gtaH2.com.

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[1] E. Greenbaum, "Scalable Subsea Electrolysis Arrays for Offshore Wind Energy Hydrogen Production", poster and talk presented at the AWEA Offshore Windpower Conference & Exhibition, October 22 – 23, 2019, Boston, MA. GTA TRL 4 prototype electrolyzers have been tested and validated at the National Renewable Energy Laboratory under Cooperative Research and Development Agreement CRD-18-747.

[2] *The Japan Times*, "Kawasaki Heavy Industries Launches World's First Liquid Hydrogen Ship in Quest to Establish Green Supply Chain", December 13, 2019.

[3] B. D. James, et al., "Analysis of Advanced H_2 Production & Delivery Pathways", presented at the DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting, April 30, 2019, Crystal City, VA.

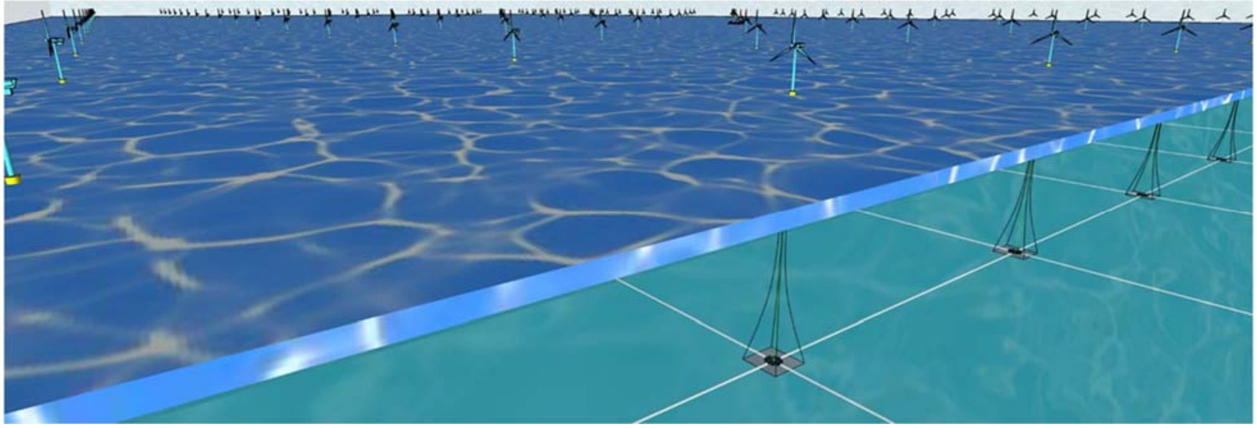

Figure 1 Subsea view of a 1 gigawatt offshore floating offshore hydrogen wind farm comprised of 100 ten-MW turbines. The floating wind turbines shown in the drawing are <u>not</u> connected to a utility grid. They are far from shore and out of sight from the coast line. Cold water and hydrostatic pressure at the sea floor are used for cooling the electrolyzers and compressing the hydrogen gas without mechanical compressors.

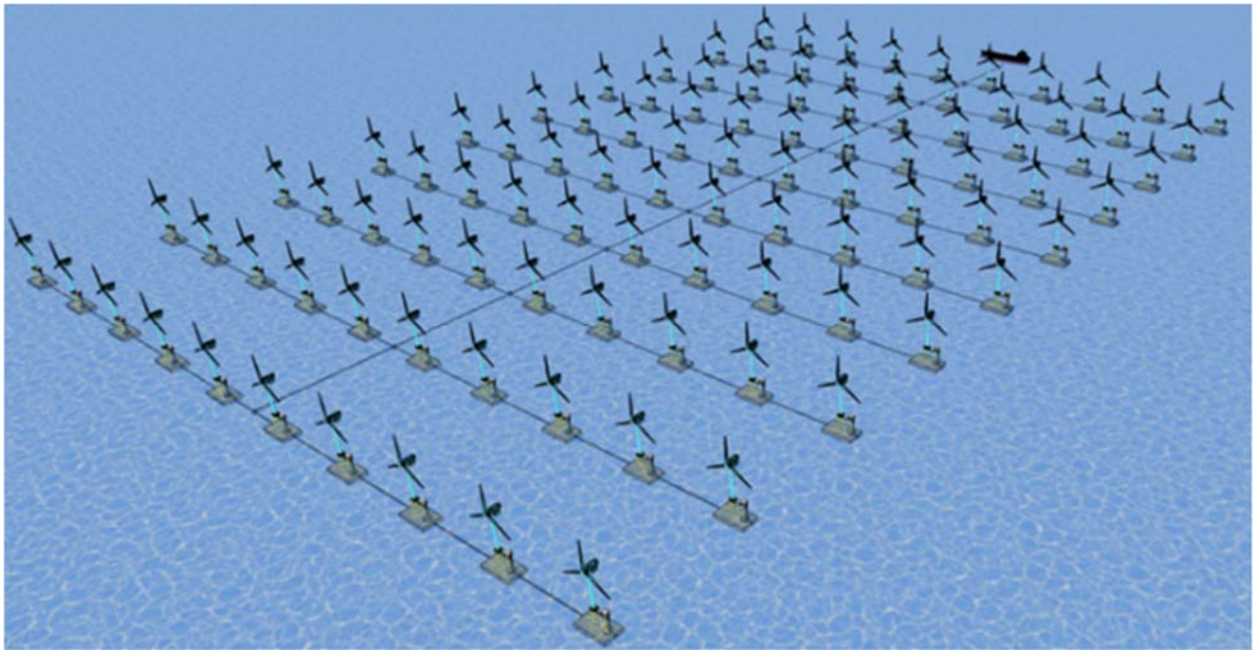

Figure 2 Aerial view of 1 gigawatt hydrogen wind farm showing a floating, production, storage and offloading (FPSO) vessel that is used for hydrogen processing at sea. Subsea technology developed for the offshore gas and oil industry can be readily adapted for subsea renewable hydrogen production powered by floating offshore wind turbines.

AWEA OFFSHORE WINDPOWER CONFERENCE & EXHIBITION
October 22 - 23, 2019 | Boston, MA

Scalable Subsea Electrolysis Arrays for Offshore Wind Energy Hydrogen Production

ELIAS GREENBAUM, GTA, INC., ATLANTA, GEORGIA USA

GTA MISSION

To design and develop subsea electrolyzers that will be used to expand the current business model of offshore wind energy by adding renewable hydrogen production at the sea floor.

STRATEGIC CONCEPT

Fig. 1 shows the strategic concept. A 1 GW offshore wind farm comprised of a 100 x 10 MW wind turbine array powers a 100 x 10 MW electrolyzer array anchored at the sea floor. Sea floor electrolyzers and their development are the subject of GTA's work. Fig. 2 is a close-up of a 10 MW electrolyzer system comprising an array of ten 1 MW electrolyzers drawn approximately to scale based on engineering data from the technology readiness level (TRL) 4 laboratory prototype shown in Figs 3 and 4. The strategic concept includes offshore wind farms that are not connected to the utility grid. They are connected to subsea electrolyzers that generate hydrogen, wherein the hydrogen is stored at the sea floor and distributed to shore or FPSOs in hydrogen pipelines.

METHODS

Figs. 3 – 6 show photographs of the laboratory prototypes that were constructed according to the method described in Ref. 1. The electrolyzer housings were machined from cast acrylic and provided with nickel ribbon wire cathode and anode electrode arrays. 25% w/w KOH in distilled water comprised the electrolyte. Testing and validation at the National Renewable Energy Laboratory (NREL) were done under Cooperative Research and Development Agreement (CRADA) CRD 18-747 with the TRL 4 prototype (proof of concept in the laboratory), shown in Figs. 3 and 4. The electrolyzer was shipped to NREL along with ancillary test equipment that included a Stanford Research Systems (Sunnyvale, CA) Model BGA244 Binary Gas Analyzer for native oxygen content of the hydrogen stream and an Advanced Micro Instruments Model 1000RS Trace O2 Analyzer for gas analysis that passed through an OxiGone 130 oxygen getter (Research Catalysts, Houston, TX). The electrolysis cells were operated at a gauge pressure of 5 psi, elevation 270 m and the voltage range 2.0 – 3.5 V. Fig. 3 shows the pressure regulators and electronic control equipment that was used to operate the system. Purity of the hydrogen was measured in two ways: (i) real-time analysis of the gas flow that emerged from the H2 compartment; and (ii) batch analysis using sample collection cylinders shown in the foreground of Fig. 3. The cylinders were shipped to SmartChemistry, Sacramento CA for purity analysis.

RESULTS

H2 Purity The electrolysis cell shown in Figs. 3 and 4 was used for the tests conducted at GTA and NREL and for the samples that were sent to SmartChemistry, Inc. for fuel cell grade analysis according to the SAE J2719 standard. SmartChemistry's report is shown in the following table.

SAE J2719 Fuel Cell Grade Hydrogen		**GTA Electrolyzer H_2**
	SAE J2719 Limits µmole/mole	GTA Sample µmole/mole
H_2O (ASTM D7649)	5	279*
Total Hydrocarbons (Methane) -C_1 Basis (ASTM D7892)	2	0.48
O_2 (ASTM D7649) with O_2 getter	5	9.4
O_2 (ASTM D7649) native O_2 content	5	3472
He (ASTM D1946)	300	10
N_2 & Ar (ASTM D7649)	100	40
CO_2 (ASTM D7649)	2	2.3
CO (ASTM D5466)	0.2	0.023
Total Sulfur	0.004	0.00082
Formaldehyde (ASTM D7892)	0.01	0.0012
Formic Acid (ASTM D5466)	0.2	<0.003
Ammonia (ASTM D5466)	0.1	<0.02
Total Halogenates	0.05	0.015

*No attempt was made to remove water vapor or CO_2.

The SmartChemistry report shows that the native purity of the hydrogen is ~99.65%, a value that is sufficient for all the industrial markets shown in the upper left corner of Fig. 3, except hydrogen vehicles. The table suggests that fuel cell grade hydrogen can be achieved by adding standard chemical engineering unit operation purification steps.

Subsea Hydrogen Production Fig. 5 shows an operational GTA electrolyzer submerged in Atlantic Ocean seawater. This is a TRL 5 prototype: proof of concept in a relevant environment. Fig. 5 potentially demonstrates the feasibility of producing hydrogen at high pressure without the use of mechanical compressors by leveraging deep-water hydrostatic pressure. Since the differential pressure between the inside and outside of the electrolyzer is close to zero, seawater-stable plastic such as marine grade polyethylene can be used for subsea production of hydrogen (and oxygen) at high absolute pressure.

GTA Electrolyzers Connected in Series (Fig. 6) Electrolysis of water is a low-voltage, high-current process. Fig. 6 shows a bipolar electrolysis cell consisting of two cells connected in series, a configuration with technical and economic benefits for the DC power supply that drives the electrolysis reaction. The U-shaped bipolar electrodes are in the center of the cell. Each arm of the U is at the same potential, but serves as a cathode or anode depending on compartment location.

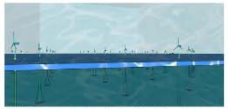

Fig. 1 Conceptual view of a 1 GW offshore hydrogen wind farm powered by 100 × 10 MW offshore wind turbines. Electrolyzers are anchored at the sea floor.

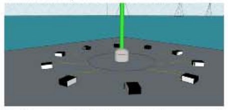

Fig. 2 Drawing of 10 MW subsea electrolyzer anchored the sea floor and comprised of 10 one MW electrolyzers. Subsea installation of the electrolyzers will build on best practices of subsea construction in the offshore gas and oil industry.

Experimental Setup at NREL Successfully completed all task items of the CRADA including installation, testing and sample collection.

Fig. 3 TRL 4 GTA electrolyzer that was used for testing and validation at the National Renewable Energy Laboratory. In addition to the electrolysis cell, the pressure regulators and electronic control equipment that were used to operate the system are also shown. The sample collection cylinder is in the foreground. Gas samples with and without an oxygen scrubbing step were collected and sent to SmartChemistry, Sacramento, CA for purity analysis. As discussed in the Results section, the native hydrogen purity was sufficient for almost all the hydrogen industrial operations shown in the upper left graphic.

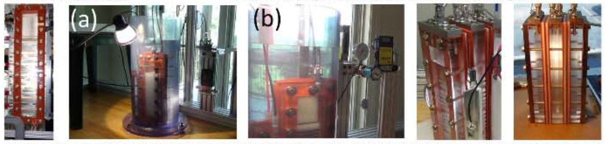

Fig. 4 (left) is a close-up view of the GTA electrolyzer in Fig. 3. The 2 foot-tall unit was used for purity analysis at GTA, NREL and sample collection for analysis by SmartChemistry. Fig. 5(a) shows an operational electrolyzer fully-submerged in Atlantic Ocean seawater. Fig. 5(b) is a close-up view showing the wires and hermetic feed-throughs that were used for submerged electrical power (black and red wires (left) plus polyethylene connecters) and hydrogen and oxygen product removal (stainless steel connectors). Fig. 6 (right, two panels) shows front and back views of a stack of two electrolyzers connected in series. Electric power is applied to the monopolar electrodes and the ends of the stack.

DISCUSSION

The significance of the Results section can be summarized as follows: First, GTA electrolyzers contain no moving parts and are constructed from relatively inexpensive and robust commodity materials that exclude platinum group metals. Second, native GTA hydrogen purity is sufficient for most of the industrial applications that use the ten million metric tons of hydrogen produced annually in the United States from fossil feedstocks, primarily natural gas. Third, the emerging markets for high-purity fuel cell grade hydrogen for electric utility grid balancing and hydrogen fuel cell cars and trucks, currently on sale in Japan, Europe, California, and elsewhere can be achieved with GTA electrolyzers plus standard chemical engineering unit operations. Fourth, hydrogen gas pipelines will not compete for onshore access to the grid. Fifth, six important parameters for large-scale production of renewable hydrogen are safety, purity, pressure, CAPEX, OPEX and system efficiency. Subsea hydrogen production powered by offshore wind and marine hydrokinetic devices are the most advantageous renewable power sources for optimizing the parameters because: (i) Deep-water hydrostatic pressure can be leveraged for equipment cooling and producing high pressure hydrogen at the sea floor without mechanical compressors or high strength materials. (ii) Subsea storage of hydrogen is inherently safe because it excludes ambient oxygen and is far from population centers. (iii) A simple and scalable design for rapid manufacturing is used. (iv) Export and inter-array cables and associated substations are eliminated and replaced with plastic hydrogen pipelines and gas valves. Cables and substations account for ~27% of an offshore wind farm's CAPEX.[2] About 30% of the OPEX of an offshore wind farm is associated with insurance premiums for law suits that are associated with the cables.[3] The amortized transmission cost of energy for hydrogen in pipelines is 8.4 times less than electrical cables.[4] Sixth, optimizing the first five parameters confers a degree of latitude with respect to electrolytic cell efficiency.

CONCLUSIONS

GTA has designed, tested and validated a prototype electrolyzer that is uniquely tailored for offshore wind and ocean energy conversion. The new electrolyzer has the potential to expand the offshore wind energy industry. Early stage technical risk has been eliminated by proof of concept in a relevant environment (TRL 5, Fig. 5). Advanced wind farms may add a second category of offshore wind turbines that are not connected to the utility grid. They are connected to subsea electrolyzers that are anchored at the sea floor beneath the turbines, away from inclement weather, and are dedicated to large-scale renewable hydrogen production. The advanced wind farms eliminate export and inter-array cables and their associated substations. Energy transport via hydrogen gas pipelines is cheaper and more efficient than transporting electricity via high-voltage export cables. The new approach may help fulfil the large-scale multinational renewable hydrogen at scale production goals that are currently underway.[5] The new business opportunities include the ~USD 150 x 10^9 per year hydrogen merchant and commodities markets. Fuel cell grade hydrogen will be used for utility-scale electric grid balancing and emerging vehicular hydrogen fuel markets.

ACKNOWLEDGEMENTS

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