Low Total Cost of Hydrogen by Exploiting Off-Shore Wind and PEM Electrolysis Synergies

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Hugo Groenemans, Michiel Damien (HYGRO)
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DOE Hydrogen Program
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Project Goals

▪ Develop a model to calculate the levelized cost of hydrogen produced using off-shore wind integrated with electrolyzers (OSWE) based on location (wind speed, intermittency, water depth and distance to shore).

▪ Determine impact of seawater impurities on electrolyzer performance and develop viable solutions for obtaining sufficiently pure water for electrolysis offshore.

▪ Build a 250 kW PEM water electrolyzer for wind turbine integration testing.

▪ Determine system process and instrumentation needs for OSWE and design power electronics and control systems for integration.

▪ Integrate PEM electrolyzer stack with wind turbine simulation to investigate OSWE operations.
Project Overview

Timeline
- Project start date: 8/23/2021
- Project End date: 8/22/2023

Budget
- Total Project Value: $1,100,000
  - DOE Share: $1,100,000
  - DOE Funds Spent: $196,000 by 4/22/2022

Barriers
- Economic viability of direct wind-electrolysis integration
- Hardware integration challenges

Project Team
- Giner Inc.: Prime
  - Overall project management; water quality impact; PEMWE stack design
- NREL: Subcontract
  - Wind turbine emulation; wind power and electrolyzer integration
- GE Research: Subcontract
  - Physical and electrical integration trades
- Hygro: Consultant
  - System economic analysis
- Plug Power: Vendor
  - PEMWE stack build
The project objective is to model and validate an integrated system to produce clean hydrogen directly using entirely offshore wind power at lower cost than traditional onshore electrolyzers or fossil fuel-derived hydrogen.

Pertaining to DOE H₂ Energy Shot goals

- Achieve the Hydrogen Shot goal of $1 for 1 kg hydrogen in 1 decade
- Lower greenhouse gas emissions and criteria pollutants
- Build clean energy infrastructure
- Provide pathways to private sector uptake

*2020 Baseline: PEM (Polymer Electrolyte Membrane) low volume capital cost ~$1,500/kW, electricity at $50/MWh. Pathways to targets include capital cost < $300/kW by 2025, < $150/kW by 2030 (at scale). Assumes $50/MWh in 2020, $30/MWh in 2025, $20/MWh in 2030
Approach

- Model OSWE under a variety of conditions to determine how those factors (wind speed, intermittency, water depth and distance to shore) affect hydrogen production cost.
- Study impact of seawater on PEM performance and determine limiting concentrations of impurities in water feed under various conditions.
- Integrate 250 kW electrolyzer stack with wind turbine at NREL.
  - Simulate wind turbine output and study effect on electrolyzer performance.
  - Determine how feedback from electrolyzer will affect wind turbine, develop mitigation strategies.
- Design power electronics and instrumentation needs for OSWE based on results of dynamic modeling and integrated electrolyzer testing.

<table>
<thead>
<tr>
<th>Major Milestones</th>
<th>Progress Made</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlate catalyst (Pt or Ir) loading to the tolerance of PEM electrolyzer</td>
<td>50% complete: Measured performance of baseline catalyst loading under various</td>
</tr>
<tr>
<td>performance on seawater ion concentrations</td>
<td>sea water ion concentrations</td>
</tr>
<tr>
<td>Receive all the components of 250 kW stack</td>
<td>25% complete: Stack design is selected and will be assembled at Plug Power</td>
</tr>
<tr>
<td>Design the layout of 5MW wind turbine-PEM electrolyzer integration</td>
<td>10% complete: modeling and preliminary electrolyzer tests are underway, will</td>
</tr>
<tr>
<td></td>
<td>form basis of design for integrated system.</td>
</tr>
</tbody>
</table>
Results and Accomplishments

Task 1: Modeling of H₂ price from two scenarios

Centralized H₂ Production
Off-shore Wind –Shore Electrolyzer (OSWSE)

- Electricity produced by off-shore wind turbine
- Inter array cables to substation
- Electricity export to shore by cable
- AC-DC-AC-DC transformation
- On-shore substation
- On-shore electrolysis facility on shore

H₂ Windfarm
Off-shore Wind and Electrolyzer (OSWE)

- Wind turbines directly integrated with PEM electrolysis and compression
- Off-shore electrolysis facility
- Subsea pipeline connection to export H₂
- Power conversion lines eliminated
- Power transmission costs reduced

HYGRO hydrogen as primary energy carrier
Model assumptions: Electrical Architecture of dedicated hydrogen production wind turbine

- The rotor converts the wind energy into mechanical energy
- The generator converts the mechanical energy into electrical energy
- The active front end converts the variable frequency alternating current into direct current
- The direct current is mainly fed into the electrolysis stack, where the energy is converted into hydrogen
- The remaining dc energy is converted into regulated AC for use in:
  - Balance of plant wind turbine
  - Balance of plant electrolysis
  - Compression system

Eliminated components

Power generator and transmission
- DC to AC converter
- Grid filter
- Transformer
- Infield cable
- Offshore substation
- Technical installation
- Foundation
- Installation
- Export cable
- Onshore substation

- Electrolysis system
  - Transformer
  - Grid filter
  - Rectifier

Added components

- Water purification system
- Electrolysis stacks
- Electrolysis gas treatment
- Compression system
- Safety switch off valves
- Infield pipeline for hydrogen
- Export pipeline for hydrogen
**H₂ Production Cost**

- Reference value of grey hydrogen is set at gas price of $32/MWh to break even green hydrogen production compared to grey hydrogen cost.

<table>
<thead>
<tr>
<th></th>
<th>Power production</th>
<th>Centralized hydrogen (OSWSE)</th>
<th>Hydrogen Windfarm (OSWE)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of turbines</td>
<td>49</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>Production of Energy (MWh)</td>
<td>76,816,713</td>
<td>59,984,232</td>
<td>78%</td>
</tr>
<tr>
<td>Cost of energy (MWh)</td>
<td>$52.84</td>
<td>$56.53</td>
<td>107%</td>
</tr>
<tr>
<td>H₂ Production (ton)</td>
<td>1,337,945</td>
<td>1,522,979</td>
<td>114%</td>
</tr>
<tr>
<td>Cost hydrogen ($ per kg)</td>
<td>$3.66</td>
<td>$2.27</td>
<td>62%</td>
</tr>
</tbody>
</table>
Seasonal Effect Analysis and Average Wind Speed Analysis

- Seasonal effect on the different years and the typical year effect. Seasonal storage is required. The order of magnitude is 1 salt cavern of 10 k ton H2 per 1.5 GW offshore wind farm.

- This curve for hydrogen production follows the same trendline as normal wind turbines have for electricity production.
Task 2: Impact of Seawater Ions on Electrolyzer Performance

- NaCl is the most abundant salt in seawater and its concentration in seawater is ~29 g/L. K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), SO\(^{2-}\) are lower in concentration, at around 0.5-2 g/L. 350ppm NaCl is a typical drinking water level concentration.
- The baseline catalyst loading for this test was 0.22 mg/cm\(^2\) Pt on the cathode and 1 mg/cm\(^2\) Pt/Ir on the anode.
- 3.5ppm salt does not significantly affect the cell performance and the HFR over a 2-3 h test.

<table>
<thead>
<tr>
<th>Solution Feed</th>
<th>Voltage at 1A/cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra Pure Water</td>
<td>1.632</td>
</tr>
<tr>
<td>3.5 ppm NaCl</td>
<td>1.638</td>
</tr>
<tr>
<td>3.5 ppm CaCl(_2)</td>
<td>1.641</td>
</tr>
<tr>
<td>3.5 ppm KCl</td>
<td>1.643</td>
</tr>
<tr>
<td>3.5 ppm Na(_2)SO(_4)</td>
<td>1.638</td>
</tr>
<tr>
<td>3.5 ppm MgSO(_4)</td>
<td>1.639</td>
</tr>
</tbody>
</table>
A 3.5ppm NaCl solution was fed to the cell for ~ 220 hours and voltage rose 41 mV, while HFR remained stable.

- Will characterize catalyst and membrane to assess any potential damage to the cell.

After 1 minute of 35 g/L NaCl intrusion, cell performance was nearly fully recovered in terms of voltage performance within 60 minutes of testing.

- Electrolyzer operations should be designed to respond to ion intrusion and mitigate impact on wind turbine.
Impact of Seawater Ions on Electrolyzer Performance (Cont’d)

- 35ppm salt has impact on performance starting around 0.8A/cm², with K⁺, Ca²⁺, and Mg²⁺ having more impact than to Na⁺, Cl⁻, and SO₄²⁻ at the same concentration level.
- The HFR also rose during testing, which is an indication of the impact of ions on the membrane.
- Most of the cells are recoverable after washing in ultra pure water for several days.

### Solution Feed | Voltage at 1A/cm²
---|---
Ultra Pure Water | 1.632
35 ppm NaCl | 1.659
35 ppm CaCl₂ | 1.690
35 ppm KCl | 1.678
35 ppm Na₂SO₄ | 1.657
35 ppm MgSO₄ | 1.819
Impact of Seawater Ions on Electrolyzer Performance (Cont’d)

350ppm Salt Concentration

- 350ppm salt caused the voltage to rise > 600mV at 1A/cm² while HFR also increased
- Only testing with NaCl was recoverable after several days of washing in ultra pure water. The other ions resulted in permanent cell damage at this concentration after only a few hours of exposure.

### Solution Feed

<table>
<thead>
<tr>
<th>Solution Feed</th>
<th>Voltage at 1A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra Pure Water</td>
<td>1.632</td>
</tr>
<tr>
<td>350 ppm NaCl</td>
<td>2.253</td>
</tr>
<tr>
<td>350 ppm KCl</td>
<td>2.255</td>
</tr>
<tr>
<td>350 ppm Na₂SO₄</td>
<td>2.258</td>
</tr>
<tr>
<td>350 ppm MgSO₄</td>
<td>2.212</td>
</tr>
</tbody>
</table>
Task 3: Build 250 kW Electrolyzer Stack

- Plug Power’s 1 MW PEMWE platform
- 1/4 number of cells to reach 250 kW
- Operating: 3600 A and 120 V
- To be ready in Fall 2022 and Installed at NREL

![Image of electrolyzer stack]

Input

<table>
<thead>
<tr>
<th>Stack Power Consumption</th>
<th>Up to 1 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage &amp; Frequency</td>
<td>480VAC, 60HZ (USA)</td>
</tr>
<tr>
<td></td>
<td>400VAC, 50HZ (EU)</td>
</tr>
<tr>
<td>Water Consumption</td>
<td>13 liters per kg of H2 produced</td>
</tr>
</tbody>
</table>

Output (Hydrogen Gas)

<table>
<thead>
<tr>
<th>Volume</th>
<th>2,000 Nm³ / hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>425 kg / day</td>
</tr>
<tr>
<td>Purity</td>
<td>Up to 99.999%</td>
</tr>
<tr>
<td>Pressure</td>
<td>40 barg / 580 psig (w/o compressor)</td>
</tr>
</tbody>
</table>

Operational

<table>
<thead>
<tr>
<th>Start Up Time</th>
<th>30 sec warm / &lt; 5 min cold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Stack Efficiency</td>
<td>49.9 kWh / kg</td>
</tr>
<tr>
<td>Load Following</td>
<td>Instantaneous</td>
</tr>
</tbody>
</table>

Physical / Environment

<table>
<thead>
<tr>
<th>Installed Footprint</th>
<th>29.3m² / 320 ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature</td>
<td>-20°C to +40°C (wider temperature range optional)</td>
</tr>
</tbody>
</table>

Tasks 4 and 5: Down select Electrolyzer Test Bed and Design of Integrated Power Electronics

Two potential Test Beds at NREL’s ESIF*

- **STB1:** 750 kW electrolyzer system
  - < 20 kg LP buffer tank
  - 2500 psi
  - 200 kg LP tanks
  - 20 kg/tank; 10 tanks
  - Dryer
  - Sized for 1-MW stack flow rate
  - Compressor
  - Sized for 1-MW stack flow rate (variable control: 0–100%)
  - Power supplies
  - 4,000 ADC and 250 VDC

- **STB2:** 250 kW System
  - Grid integration
  - *Planned construction in Summer 2022*

* Energy Systems Integration Facility, NREL
Small Scale Wind and 250 kW Electrolyzer Testing

- What is the effect of varying input power from a utility scale offshore wind turbine on the electrolyzer efficiency and degradation, when the combined system is operated in an islanded mode?

- Hardware-in-the-loop (HIL) testing
  - Open loop testing (10-100 ms) on 250 kW Giner stack
  - Use of Stack Test Bed for balance of system
  - Magna-Power MTD 1000-250 units configurable in series or parallel up to 1500 ADC or 4000 VDC

- Evaluating configurations for test results:
  - Validating variable operation
  - Identify effects of AC conditions on stack
  - Identify effects of DC conditions on stack
  - Test tailored power converter
### Details of Experimental Design for Integrated Power Electronics

<table>
<thead>
<tr>
<th>Boundary Conditions</th>
<th>Assumptions</th>
<th>Implications for Experiment Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small scale test with single stack of 250kW</td>
<td>▪ Power generated with IEA 15MW turbine</td>
<td>▪ The power output of a 15 MW wind turbine is simulated and then scaled to 250kW</td>
</tr>
<tr>
<td></td>
<td>▪ Equal distribution of power among multiple stacks</td>
<td></td>
</tr>
<tr>
<td>Islanded operation</td>
<td>▪ Power generated by WTG is 100% consumed by electrolyzer stacks</td>
<td>▪ Impact of (dynamic) electrolyzer I-V characteristic on WTG operability is ignored: turbine is emulated as a power source with no impedance</td>
</tr>
<tr>
<td>Focus on electrolyzer stacks</td>
<td>▪ Turbine produces 100% DC power</td>
<td>▪ System boundary is DC: grid simulator produces DC power for Electrolyzer stack</td>
</tr>
<tr>
<td></td>
<td>▪ Power consumption of BOP ignored</td>
<td>▪ BOP runs continuously using secondary AC power</td>
</tr>
<tr>
<td>Focus on production</td>
<td>▪ Electrolyzer is operational</td>
<td>▪ Operation strategy to start/stop BOP based on available power out of scope</td>
</tr>
<tr>
<td>Power variation from wind turbine is emulated</td>
<td>▪ Bandwidth of power variations is driven by turbulence of wind and dynamics of wind turbine</td>
<td>▪ Update cycle of power reference for emulator is 40ms</td>
</tr>
<tr>
<td></td>
<td>▪ No buffering / storage present</td>
<td>▪ Simulated power reference is directly used as reference for emulator, no smoothing involved</td>
</tr>
<tr>
<td></td>
<td>▪ Wind speed varies from cut-in to cut-out</td>
<td>▪ Power references for emulator are created with wind speeds from 4 to 25 m/s</td>
</tr>
<tr>
<td>Power conditioning</td>
<td>▪ Power conversion is done such that turbine acts like a DC current source, with zero losses, and non-floating ground</td>
<td>▪ Grid simulator integration done to match electrolyzer DC interface</td>
</tr>
</tbody>
</table>

- Islanded operation
- Focus on production
- Power variation from wind turbine is emulated
- Power conditioning
This project was not previously reviewed.
Collaboration and Coordination

- **Giner, Inc. (prime):** Hui Xu, Judith Lattimer, Shirley Zhong – Project Lead, management and coordination, small-scale electrolyzer building and testing, saltwater management and mitigation assessment.

- **NREL (sub):** Genevieve Saur, Kumaraguru Prabakar, Kazunori Nagasawa, Dan Leighton – Modeling of OSWE, coordinate electrolyzer installation and testing at NREL for integration with simulated wind turbine experiments.

- **GE (sub):** Rogier Blom, Arvind Tiwari – Perform trade off analysis for physical and electrical integration of wind turbine system with electrolysis system.

- **HYGRO (consultant):** Hugo Groenemans, Michiel Damien – Modeling of OSWE costs, development of dynamic modeling for integration of electrolyzer with wind turbine.

- **Plug Power (vendor):** Cortney Mittelsteadt and Zach Green – Build and ship 250 kW Electrolyzer stack to NREL for integration with simulated wind turbine system.
Remaining Challenges and Barriers

- On-site demonstration of this technology is the next logical step to validate the modeling
  - Designing the power electronics required for integration, the first step to physical integration of the two systems, is currently underway
  - Real-world testing of the integration will likely have to be done in steps, starting with on-shore small-scale turbines and electrolyzers
- Utilization of seawater directly for electrolysis would be ideal
  - Will require some kind of purification system that will need to be included in the electrolyzer BOP
  - Development of more tolerant catalysts/membrane components for saltwater intrusion would enable this technology to be more robust for offshore applications
Proposed Future Work

- Continue modeling of H2 pricing for OSWE system
  - Investigate impact of water depth: Monopile < 45 meter; Jacket < 55 meter; Floating > 55 meter
  - Impact of distance to shore
  - Energy (hydrogen) storage amount in pipelines to shore and other storage solutions
- Determination of catalyst loading vs. tolerance for saltwater ions
- Development of mitigation strategies for saltwater intrusion
  - This will fulfill Go/No-Go milestone for Task 2
- The 250 kW electrolyzer will be delivered to NREL for integration with deselected testbed infrastructure
  - This will fulfill Go/No-Go milestone for Task 3
- Integration and testing of electrolyzer stack at NREL with simulated wind turbine data
  - These results will be used to design fully integrated wind turbine electrolysis system for OSWE
  - This will fulfill major upcoming milestones for Tasks 4 & 5.
Summary

- Modeling of H₂ production cost for off-shore wind integrated with electrolysis has been performed that predicts to reach $2.2/kg H₂
- The tolerance of baseline Pt and Ir loading for the six most common seawater ions has been determined that may provide insights for electrolyzer-wind turbine operations
- Design for integrating 250 kW electrolyzer stack into down selected testbed with simulated wind turbine input is underway.
- Experimental design for integrated power electronics has been detailed.

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Description</th>
<th>Projected Completion</th>
<th>Actual Completion</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Determine the LCoH at 100%, 75%, 50% and 25% wind power output</td>
<td>2/22/22</td>
<td>12/15/21</td>
<td>100%</td>
</tr>
<tr>
<td>1.2</td>
<td>Determine the LCoH at variable water depth</td>
<td>5/23/22</td>
<td>TBD</td>
<td>75%</td>
</tr>
<tr>
<td>2.1</td>
<td>Determine sensitivity of membrane conductivity to a series of seawater ions</td>
<td>11/22/21</td>
<td>3/15/22</td>
<td>100%</td>
</tr>
<tr>
<td>2.2</td>
<td>Determine sensitivity of PEM electrolyzer performance to a series of seawater ions</td>
<td>2/22/22</td>
<td>3/15/22</td>
<td>100%</td>
</tr>
<tr>
<td>2.3</td>
<td>Correlate catalyst (Pt or Ir) loading to the tolerance of PEM electrolyzer performance on seawater ion concentrations</td>
<td>5/22/22</td>
<td>TBD</td>
<td>25%</td>
</tr>
<tr>
<td>3.1</td>
<td>Receive all the components of 250 kW stack</td>
<td>8/22/22</td>
<td>TBD</td>
<td>25%</td>
</tr>
<tr>
<td>4.1</td>
<td>Design the layout of 5MW wind turbine-PEM electrolyzer system integration</td>
<td>2/2/22</td>
<td>TBD</td>
<td>0%</td>
</tr>
<tr>
<td>4.2</td>
<td>Determine suitability of placing the electrolyzer inside or outside wind turbine</td>
<td>5/22/22</td>
<td>4/15/22</td>
<td>100%</td>
</tr>
<tr>
<td>5.1</td>
<td>Get the test bed ready at NREL</td>
<td>8/22/22</td>
<td>TBD</td>
<td>0%</td>
</tr>
</tbody>
</table>
Acknowledgements

- Financial support from DOE SBIR funding under award number: DE-SC0020786
- Hydrogen and Fuel Cell Technologies Office (HFTO) for additional supports
- Project Manager: Dr. Michael Hahn
Technical Backup and Additional Information
Technology Transfer Activities

- We are working with GE, Hygro, and Plug Power on a technology-to-market plan
Publications and Presentations

- Presented in Netherlands -US expert meeting “offshore wind to hydrogen” Webinar on Sept 10, 2021