Scalable Electrolytic Systems for Renewable Hydrogen Production

Cooperative Research and Development Final Report

CRADA Number: CRD-18-747

NREL Technical Contact: Guido Bender

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5900-76136
February 2020

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: 2/13/20

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: GTA, Inc.

CRADA Number: CRD-18-747

CRADA Title: Scalable Electrolytic Systems for Renewable Hydrogen Production

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$25,000.00
TOTALS	$25,000.00

Abstract of CRADA Work:

The project focuses on offshore wind energy which is an emergent renewable energy source in the United States. Onsite hydrogen production for this sector is not available. The overall goal of GTA's work is development of scalable multi-megawatt water electrolysis systems that exclude platinum group metals, are constructed from readily available commodity materials and are mass produced using advanced manufacturing and robotics. They fabricated and successfully tested a scalable TRL 4 laboratory prototype that demonstrated promising results for achieving the goal. They further performed calculations and prepared scale drawings for an envisioned onsite TRL 8 electrolytic hydrogen production system at an offshore 8 MW wind turbine. The work plan of the CRADA proposal between NREL and GTA focuses on validation of the current TRL 4 prototype with potential development and refinement for advancement to a TRL 5 system. GTA, Inc. proposes joining the H2@Scale consortium to leverage DOE funds, benefit from and contribute to the common knowledge-base and work with NREL as a CRADA partner.

Summary of Research Results:

The work plan for this project was structured around GTA's need to characterize hydrogen purity as delivered by the system. For this purpose, gas samples were to be collected using a proto-type GTA system operated at NREL.

Task 1. GTA will send to NREL prototype electrolysis cells of less than 700W total power. To facilitate the collaboration and optimize resources, GTA will also send to NREL ancillary equipment such as pumps, dryers, programmable DC 750 W power supply, and catalytic O2 cleanup of the hydrogen. NREL will prepare the KOH electrolyte solution in distilled water.

Task 2. NREL will run a series of steady-state hydrogen and oxygen producing polarization (IV) tests on the stack and measure the output quantity and quality of the hydrogen. Oxygen will be vented. NREL will run a trace gas analysis on the product hydrogen. Once the system is set up, NREL may run an initial ~100 hour durability test to look for early signs of degradation.

Task 3. NREL will prepare a report for GTA and return all GTA equipment at the end of the project.

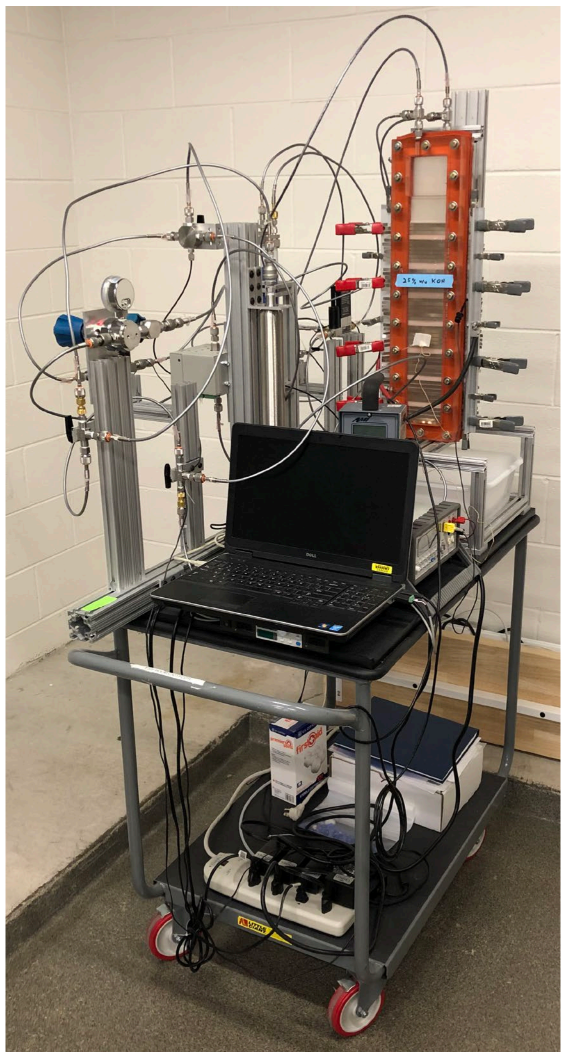


Figure 1: GTA test equipment with TRL4 test stack installed at NREL after electrical safety inspections.

Task 1:

As planned, NREL received the test equipment and hardware from GTA early in the project. NREL conducted electrical safety inspections and then assembled and commissioned the test equipment on a cart as shown in Figure 1. The equipment was validated, and some improvements were implemented with respect to the ability to automate the data collection, add temperature measurements and enable the ability to collect pressure data. The test equipment was installed on a cart for straight forward integration into NREL's fuel cell and electrolysis laboratories.

Task 2:

As planned, NREL verified operation of the electrolyzer system and conducted gas sampling and trace gas analysis. *Figure 2* shows performance comparison between NREL and GTA. The performance varied, which was expected due to the high elevation of 5,500 ft at NREL and the limitation that the system could only be operated up to 5 psig operating pressure due to equipment limitations. The different pressures resulted in an interesting observation of the effects of bubble size. At lower elevation and overall higher operating pressure the kinetics of the electrochemical reactions are accelerated. In addition, bubble formation is less extensive and transport losses may be lowered. In any case, NREL could confirm the operation of the system resulting in the production of oxygen and hydrogen. NREL subsequently expanded the experimental setup to include gas collection of the anode exhaust gas as shown in *Figure 3* with and without activation of the system's oxygen scrubber.

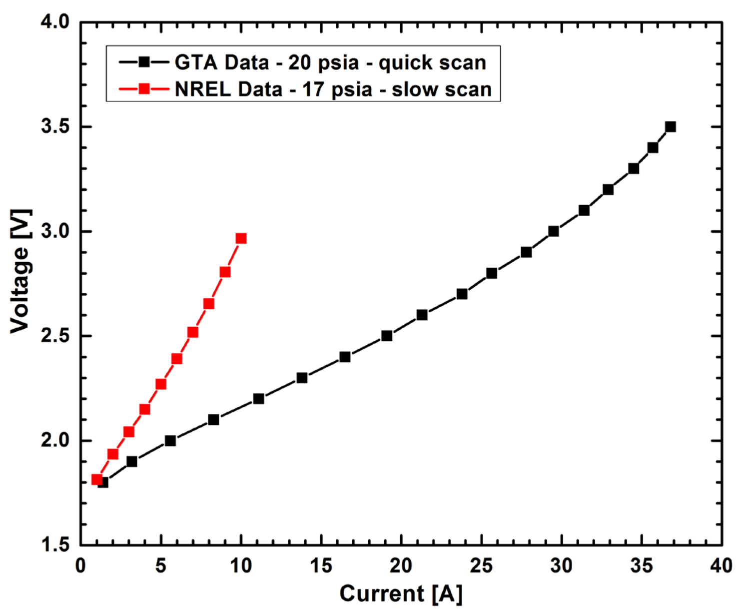


Figure 2: Performance measurement of GTA stack conducted at NREL.

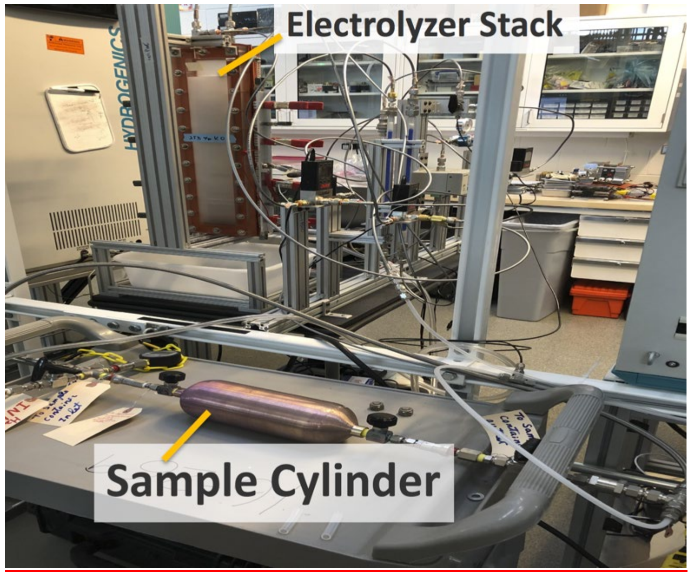


Figure 3: Operating GTA electrolyzer with integrated anode exhaust gas sampling setup.

Figure 4 shows the results of the gas analysis which was outsourced to Smart Chemistry, a well-established and renown company specializing in fuels purity analysis. The report quantifies the individual compounds that are called out in the SAE J2719 fuels purity recommendations for fuel cell vehicles. In summary, the Hydrogen purity measured was 99.97%. H_2O, O_2, and CO_2 content was above the stringent fuels purity standard. The gas purity met the expectations and is sufficient for many hydrogen applications for H2@scale objectives. Simple upgrades could be envisioned to further improve the hydrogen fuels purity.

Task 3:

After completion of the measurements, the equipment was dismantled and shipped back to GTA. In addition to several conversations, a report in form of a power point slide deck was delivered to GTA listing and discussing the experiments and the findings. Furthermore, the project was presented through joint presentations of NREL and GTA at the H2@scale webinar series as well as the DOE Hydrogen and Fuel Cells Program Annual Merit Review 2019.

SmartChemistry

SAE J2719 — Sample Receipt Date 11/30/2018 — NREL Electrolyzer H_2

SUMMARY	SAE J2719 Limits (µmol/mol)	SmartChemistry Detection Limits (µmol/mol)	Concentration (µmol/mol)
H_2O	[illegible]	[illegible]	279
Total Hydrocarbons -C_1 Basis	[illegible]		0.48
Methane			0.15
Acetone			0.039
Benzene			0.008
Ethane			0.21
Ethanol			0.022
Isopropyl Alcohol			0.011
Toluene			0.025
Hexanal			0.010
Octane			0.009
O_2 NREL Electrolyzer H_2	[illegible]	[illegible]	9.4
O_2 NREL Electrolyzer H_2 **WITHOUT OXYGEN TRAP**			**3472**
He	[illegible]	[illegible]	< 10
N_2 & Ar	[illegible]		
N_2		[illegible]	40
Ar		[illegible]	1.4
CO_2	[illegible]	[illegible]	2.3
CO	[illegible]	[illegible]	0.023
Total S	[illegible]		0.00082
Hydrogen Sulfide		[illegible]	0.000015
Carbonyl Sulfide		[illegible]	0.00060
Methyl Mercaptan		[illegible]	< 0.00001
Ethyl Mercaptan		[illegible]	< 0.00001
Dimethyl Sulfide		[illegible]	0.0000085
Carbon Disulfide		[illegible]	0.000066
Isopropyl Mercaptan		[illegible]	< 0.00001
Tert-Butyl Mercaptan		[illegible]	< 0.00001
n-Propyl Mercaptan		[illegible]	< 0.00001
Thiophene		[illegible]	0.0000098
Diethyl Sulfide		[illegible]	< 0.00001
n-Butyl Mercaptan		[illegible]	< 0.00001
Dimethyl Disulfide		[illegible]	0.000056
Tetrahydrothiophene		[illegible]	0.000056
Formaldehyde	[illegible]	[illegible]	0.0012
Formic Acid	[illegible]	[illegible]	< 0.003
Ammonia	[illegible]	[illegible]	< 0.03
Total Halogenates	[illegible]		0.015
Cl_2		[illegible]	< 0.003
HCl		[illegible]	< 0.014
HBr		[illegible]	< 0.008
Total Organic Halides (32 compounds in red and bold listed in "Non-Methane Hydrocarbons") (ASTM D7892, Smart Chemistry limit is for each individual organic halide)		[illegible]	0.015
Ethene, chlorotrifluoro-			0.0026
Hexane, 1,1,1,2,2,3,3,4,4,5,5,6,6-tridecafluoro-			0.0012
1-Butene, 4,4-dichloro-1,1,2,3,3,4-hexafluoro-			0.0064
1-Propene, 3-chloro-1,1,2,3,3-pentafluoro-			0.0048
Particulate Concentration	[illegible]		Not Required
Particulates Found & Size			Not Required
Hydrogen Fuel Index	[illegible]		99.96681%

Figure 4: Operating GTA electrolyzer with integrated anode exhaust gas sampling setup.

Subject Inventions Listing:

None

ROI #:

None

Responsible Technical Contact at Alliance/NREL:

Guido Bender | guido.bender@nrel.gov

Name and Email Address of POC at Company:

Elias Greenbaum | greenbaum@comcast.net

DOE Program Office:

Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office (FCTO)

Supplemental Documents: 3 PowerPoint slide presentations

1. GTA-NREL H2@Scale Webex Make Working Group Meeting 18DEC2018
2. h2001_bender_2018_p_small
3. h2001_bender_2019_p

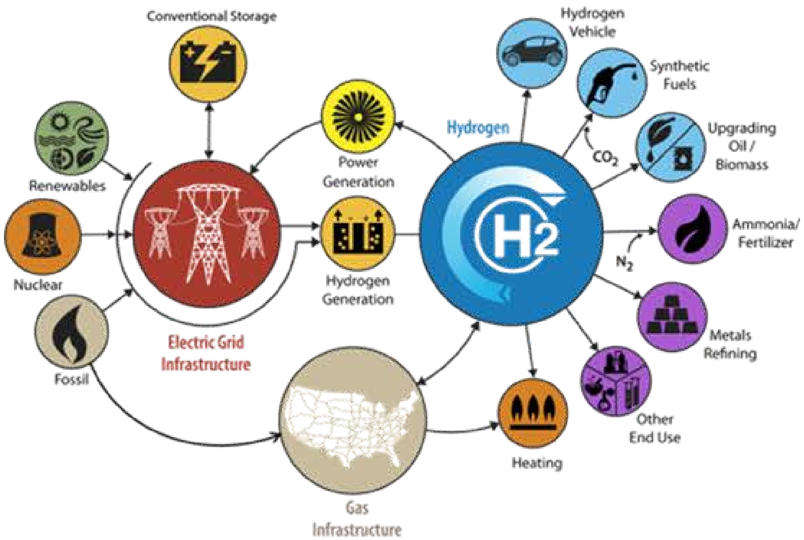
Scalable Electrolytic Systems for Renewable Hydrogen Production

The Parallels of Offshore Wind, Subsea Gas & Oil and Gigawatt Scale Renewable Hydrogen Production

H2@Scale Webex Make Working Group Meeting
December 18, 2018

Elias Greenbaum
GTA, Inc.
Fairview Technology Center
Knoxville, TN

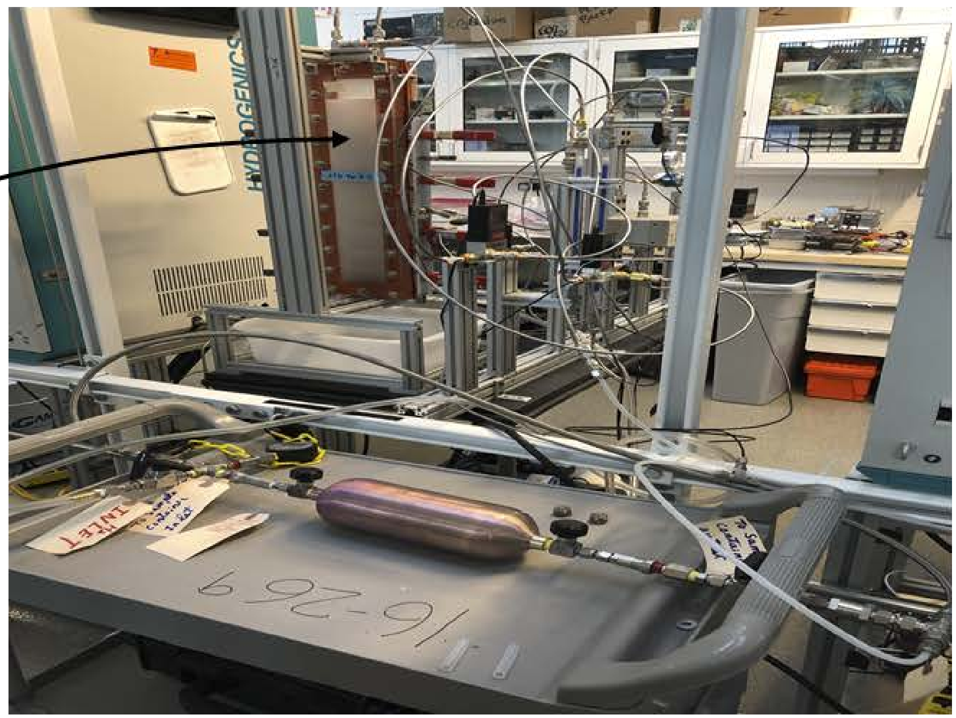
Guido Bender and Matthew Post
National Renewable Energy Laboratory
Golden, CO



H2@Scale
U.S. Department of Energy

GTA

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



~99.97% H2
~0.3%O_2
270 ppm H_2O
2.3 ppm CO_2

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

SmartChemistry

SAE J2719 NREL Electrolyzer H_2

Sample Receipt Date [illegible]

SUMMARY	SAE J2719 Limits [illegible]	Smart Chemistry Detection Limits [illegible]	Concentration (µmol/mol)
H_2O	[illegible]	[illegible]	279
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1-Butene, 4,4-dichloro-1,1,2,3,3,4-hexafluoro-			0.0064
1-Propene, 3-chloro-1,1,2,3,3-pentafluoro-			0.0046
Particulate Concentration	[illegible]		Not Required
Particulates Found & Size			Not Required
Hydrogen Fuel Index	[illegible]		99.96681%

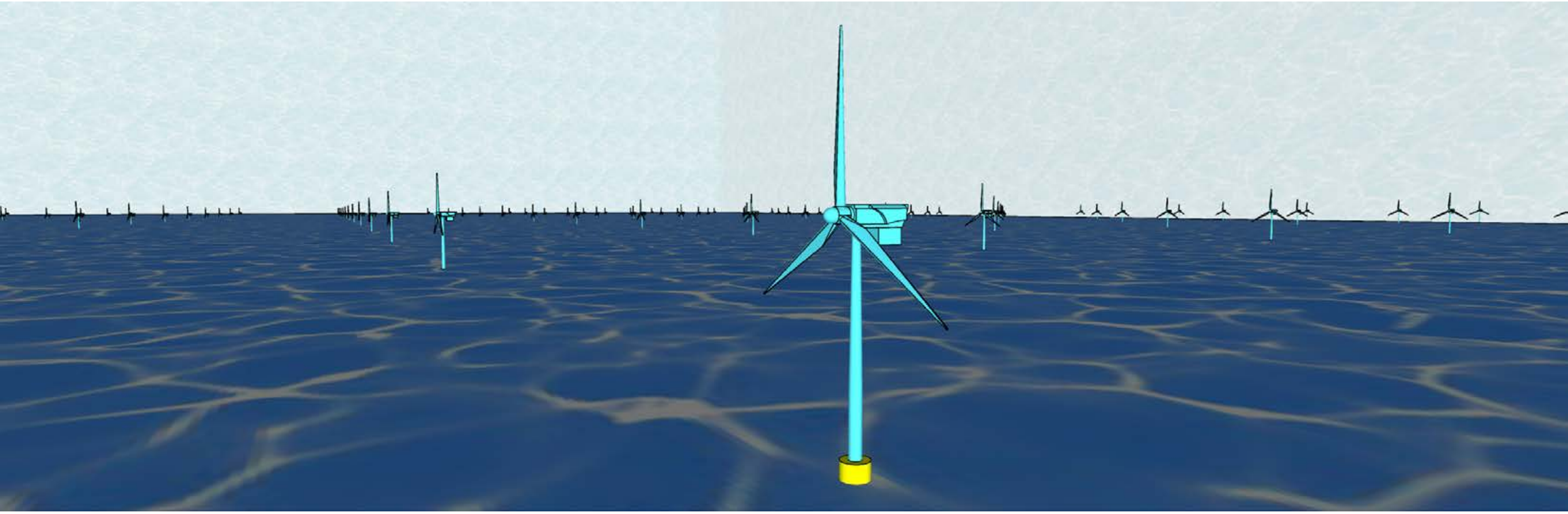
GTA Goals

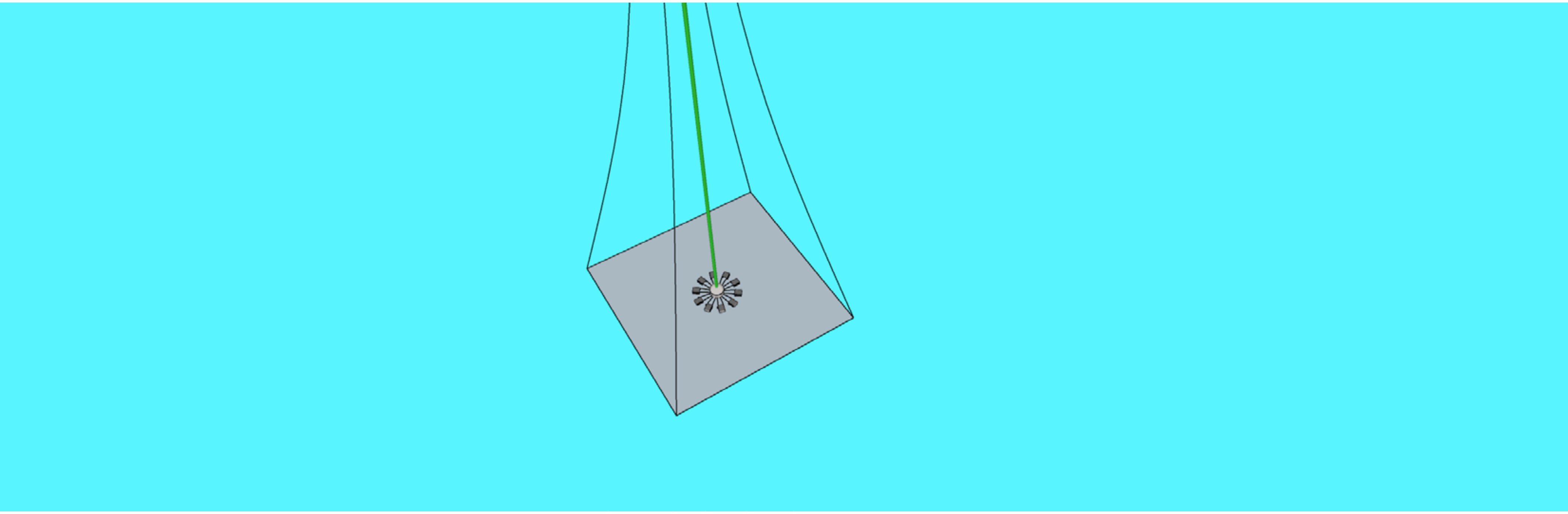
- Support U.S. Department of Energy's H2@Scale Program
- Expand Business Model for Offshore Wind Energy: Non-Grid Connected Wind Turbines
- Deep Water Subsea Electrolytic Hydrogen Production
- Adapt Subsea Offshore Oil and Gas Production Engineering
- "Free" Cooling
- Safe Production and Storage of Large Amounts of Hydrogen at High Pressure
- New value for depleted gas and oil fields
- Intense Solar Flare and EMP Resistant
- Offshore Ammonia Manufacturing, etc.

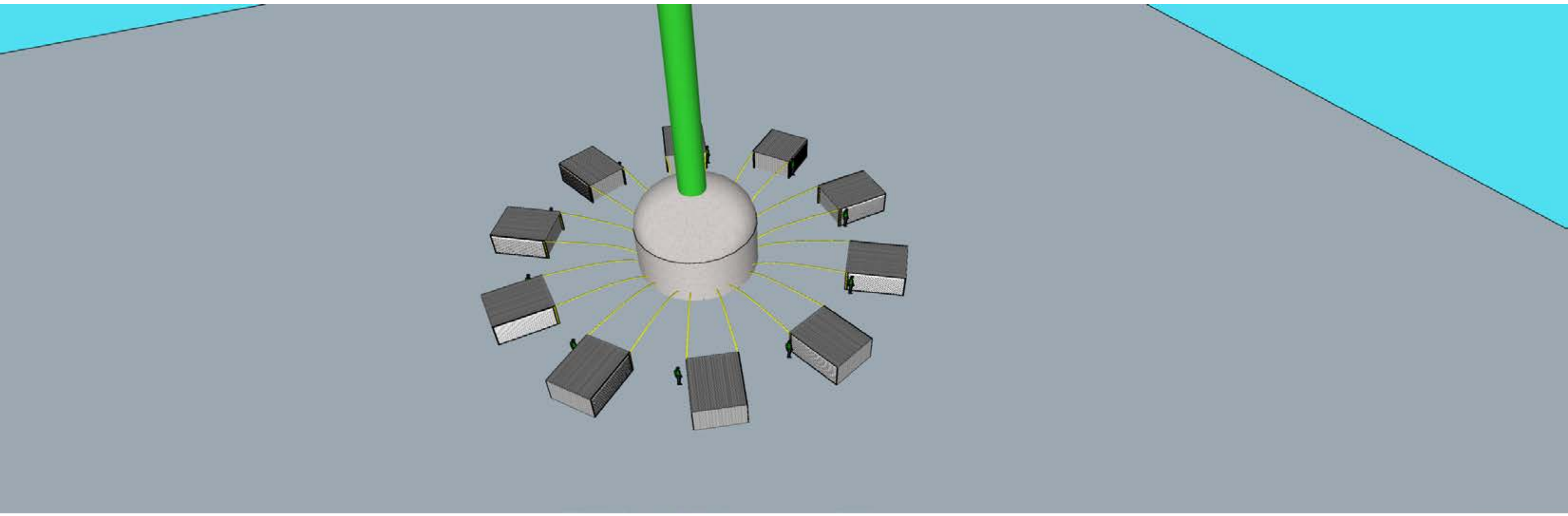
GTA Technical Approach

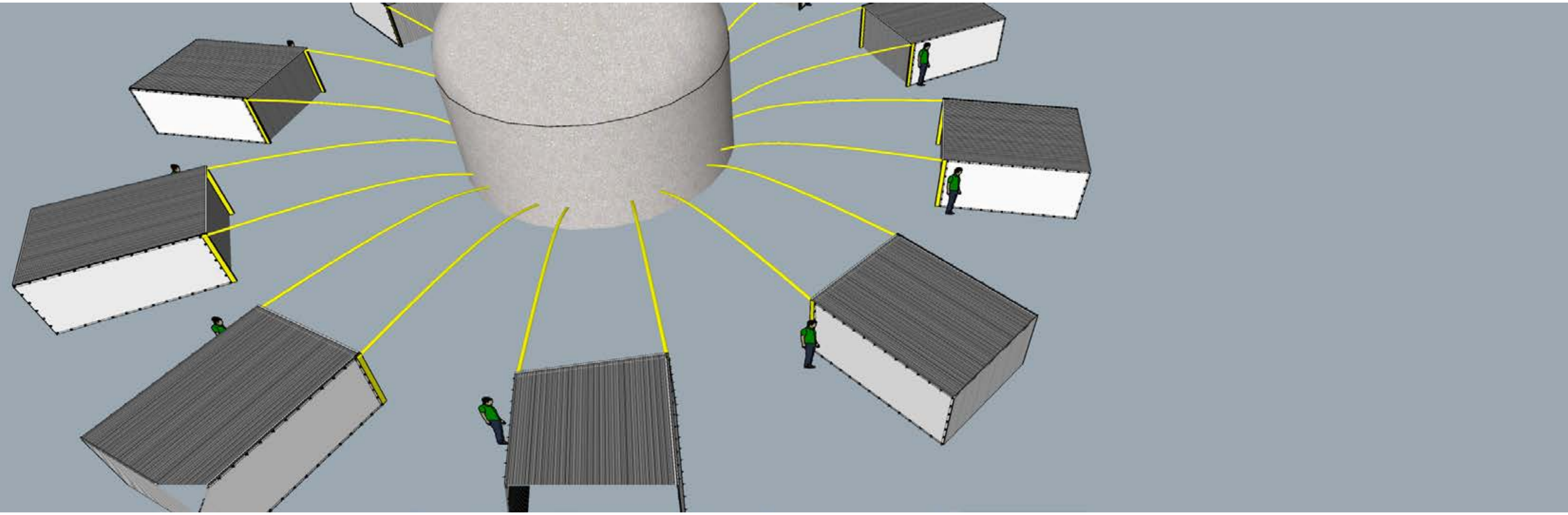
- **Non-grid connected wind turbines connected to adjacent electrolysis systems - No high voltage export cables**
- **Readily available commodity materials: polyethylene, aluminum, nickel, silicone rubber, structural steel**
- **High absolute pressure, Low differential pressure**
- **Polyethylene hydrogen pipelines to FPSOs or shore**
- **Leverage deep-water hydrostatic pressure for high-pressure hydrogen production**
- **No moving parts: passive cooling by immersion in sea water**
- **Simple mechanical design for rapid high volume manufacturing**

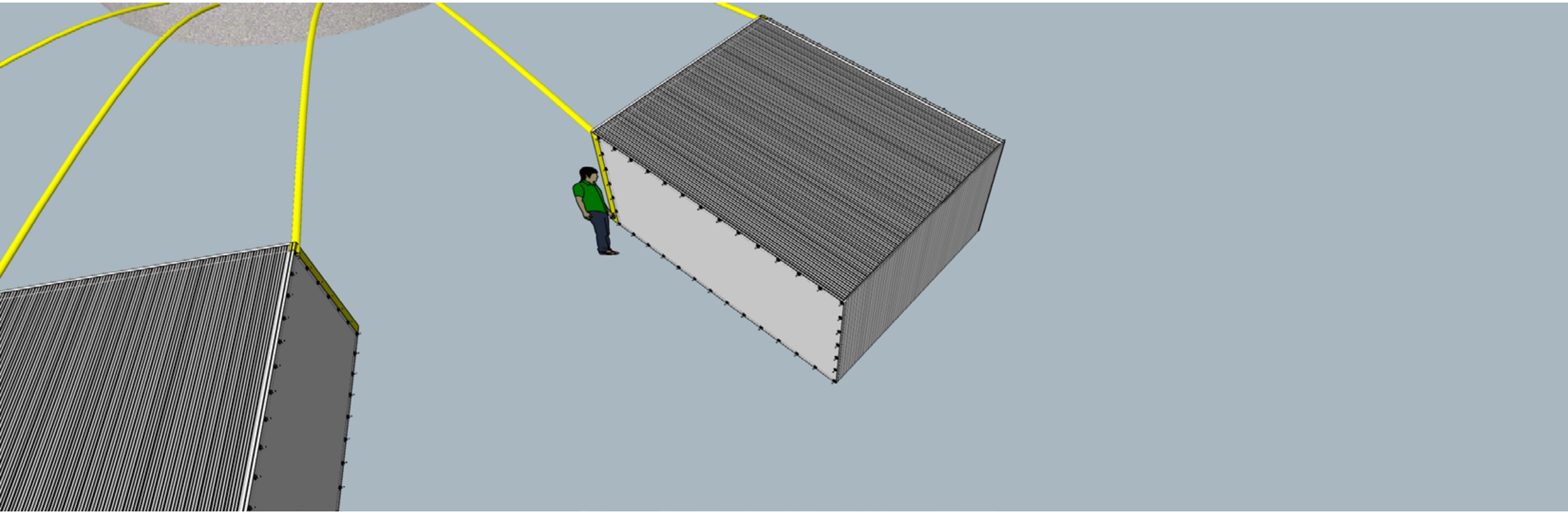
Offshore Hydrogen Farm
Deep Water Floating Wind Turbines







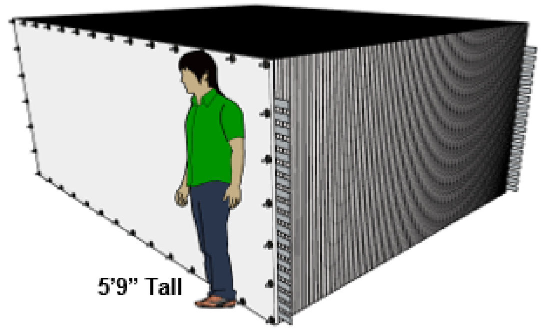




Elements of Materials Cost

Non-Fuel Cell Grade Hydrogen

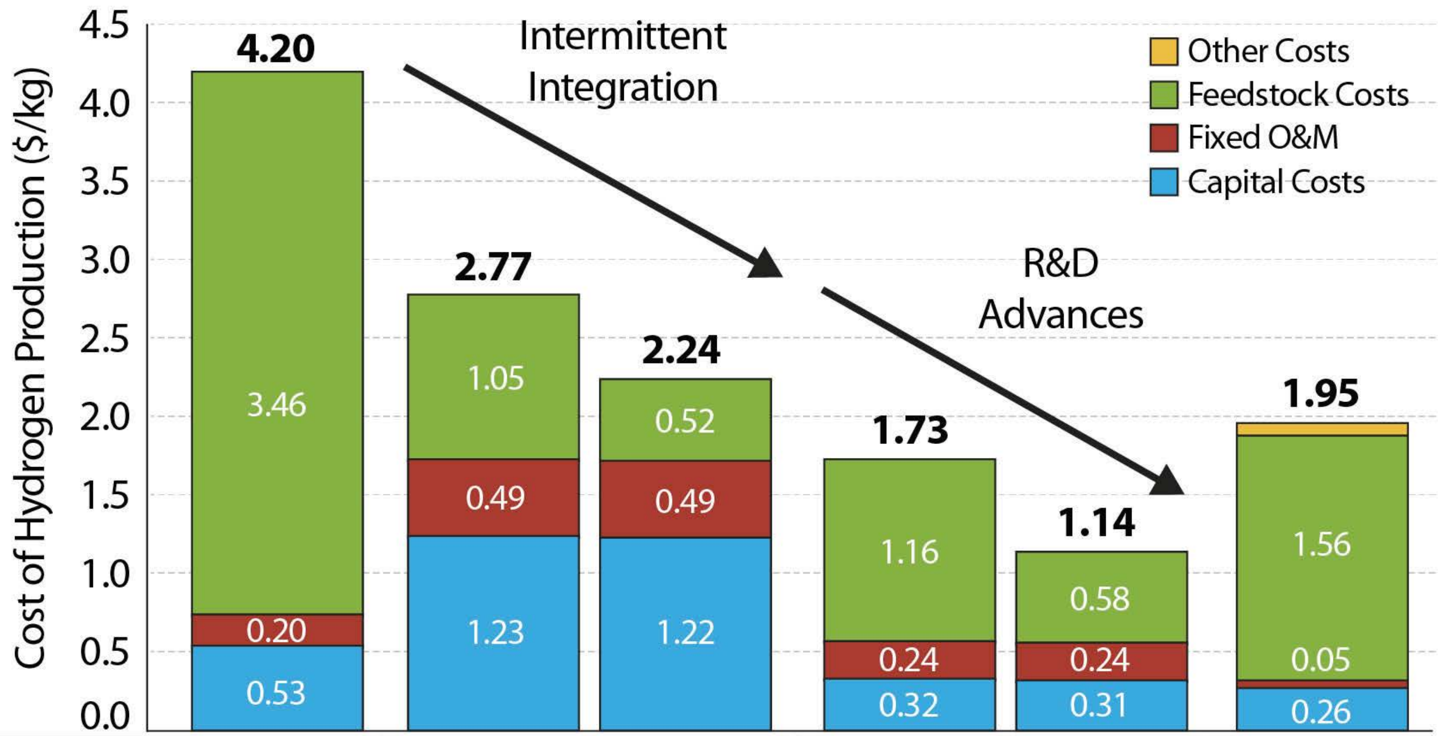
1 MW GTA Subsea Electrolyzer
Parts List: Components and Materials



Component	Material	Weight (kg)	Unit Cost Range* ($)/kg	Price Range ($)	
				Low	High
End Caps, 2 pcs.	Marine Grade PE	117	uhmw-pe dock boat bumper fender pe1000 sheet for marine US $1.50-$4.00 / Kilogram 500 Kilograms (Min. Order) Size: Custom Size Thickness: 1-30mm Color: Customized Material: PE Certificate: ISO9001:2008 Certification: SGS	173	462
Spacers 112 pcs.	"	1577	"	2,366	6,309
Frames 57 pcs.	"	328	"	328	1313
Diaphragms 57 pcs.	Porous PE	1531	The factory of porous polyethylene sheet US $3.00-$5.00 / Kilogram 200 Kilograms Min. Order Size: 1200mm*4000mm Thickness: 6mm-200mm color: white,black & others Material: PE type: porous polyethylene sheet Density: 0.94-0.96 g/cm^3	4,593	7,655
Gasket 228 pcs.	Silicone Rubber	144	High Elastic Heat Resistant Silicone Rubber Sheet Roll US $4.30-$4.90 / Kilogram 30 Kilograms Min. Order Thickness: 0.3 - 50mm Color: transparent, translucent...etc Material: Silicone Certification: SGS, RoHS, ISO9001...etc Hardness: 50 - 70 shore A Width: 0.5/1.0/1.2/1.5m...etc	617	703
Electr. Arr. 39 pcs.	Ni200	9.2	High quality pure nickle material pure nickel strip US $25.00-$35.00 / Kilogram 10 Kilograms Min. Order Grade: Pure Nickel,Nickel 200 Application: Industry Type: Nickel Strip Powder Or Not: Not Powder Delivery Time: 7 to 20 Days M.O.Q: 10kg	230	323
Bipol. Elec., 56 pcs.	Ni200	920	High quality ASTM B162 N4 N6 Ni200 Ni201 99.6% 99.9% Pure Nickel Sheet / Nickel Plate Inconel 625 US $23.00-$68.00 / Kilogram 1 Kilogram Min. Order Grade: Pure Nickel Application: Chemical Industry / Batteries Type: Nickel Plate Powder Or Not: Not Powder Place of Origin: Tianjin,China (Mainland) Ni (Min): 99.6%	21,171	62,593
Tie Rods 38 pcs	310 SS	135	Cold Drawn/Hot Rolled/Forged AISI 310S 310 Stainless Steel Round Bar/Rod/Shaft US $1000.00-$4000.00 / Ton 1 Ton Min. Order	149	595
			Materials Cost per MW	**$29,627**	**$79,953**
				Low	High

*Prices are quoted from the Alibaba website which generate pro and con discussions on Internet chat groups. The in-stock retail price listed by United States Plastics Corp.® is $5.14/kg for UHMW-PE sheet (Catalog Page 302). The commodity contract price for UHMW-PE resin quoted on The Plastics Exchange.com, http://www.theplasticsexchange.com/, is $1.19/kg. The commodity price for nickel is $10.71/kg, http://www.infomine.com/investment/metal-prices/nickel/.

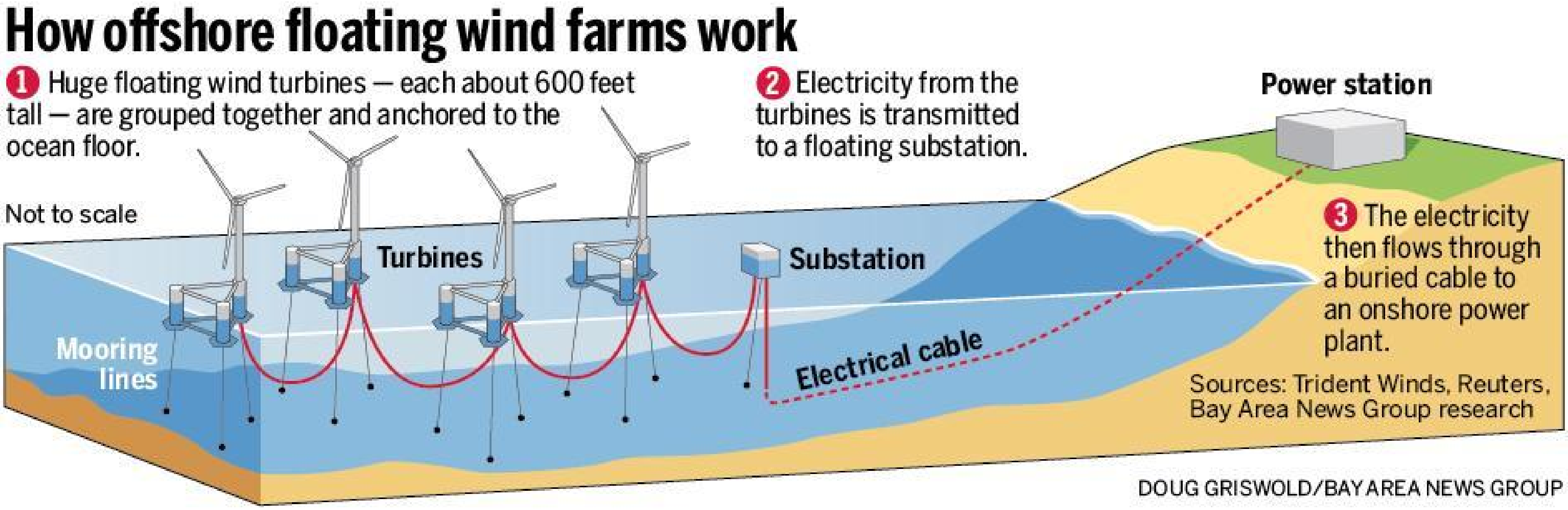
Analysis of Electrolyzer-Based Hydrogen Production Costs



Capacity Factor	97%	40%	40%	0.9
Cost of Electricity	¢6.6/kWh	¢2/kWh | ¢1/kWh	¢2/kWh | ¢1/kWh	
Capital Cost	$400/kW	$400/kW	$100/kW	
Efficiency (LHV)	66%	66%	60%	
	Electrolyzer			**SMR**

B. Pivovar, N. Rustagi, and S. Satyapal, "Hydrogen at Scale (H2@Scale) Key to a Clean, Economic, and Sustainable Energy System", The Electrochemical Society *Interface,* Spring 2018, pp. 67 – 72.

$100/kW = $100,000/MW



ECOSSE Subsea Systems

Cost of Cable Damage

- Niels Kragelund - Head of Wind Energy at Danish Insurers Codan says…..

"cables account for 90% of the number of offshore wind claims"
"cables account for 70% of the actual cost of claims"

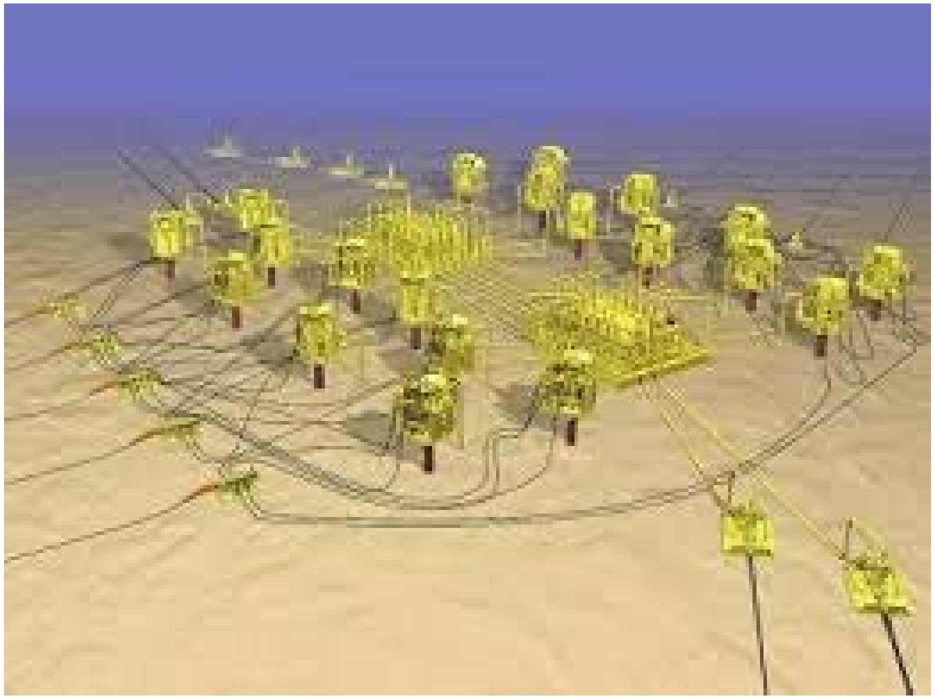
- Tim Halperin-Smith - Director at Global Insurance brokers Willis says …..

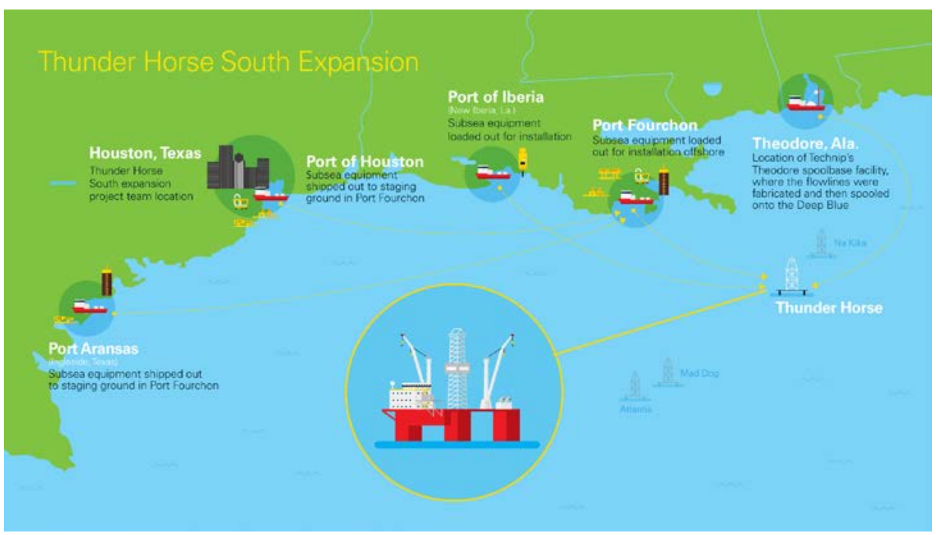
"of all of the offshore wind claims his firm receives, most incidents occur during installation, half of them due to human error'

High-Voltage Export Cables

- **25% CAPEX**
- **90% Legal Challenges**
- **70% Actual Settlements**
- **30% OPEX**
- **Electricity Only**
  - **Demand vs. Supply**
  - **One Customer**
  - **Needs Value-Added Expanded Market**

Thunder Horse Offshore Gas & Oil Production

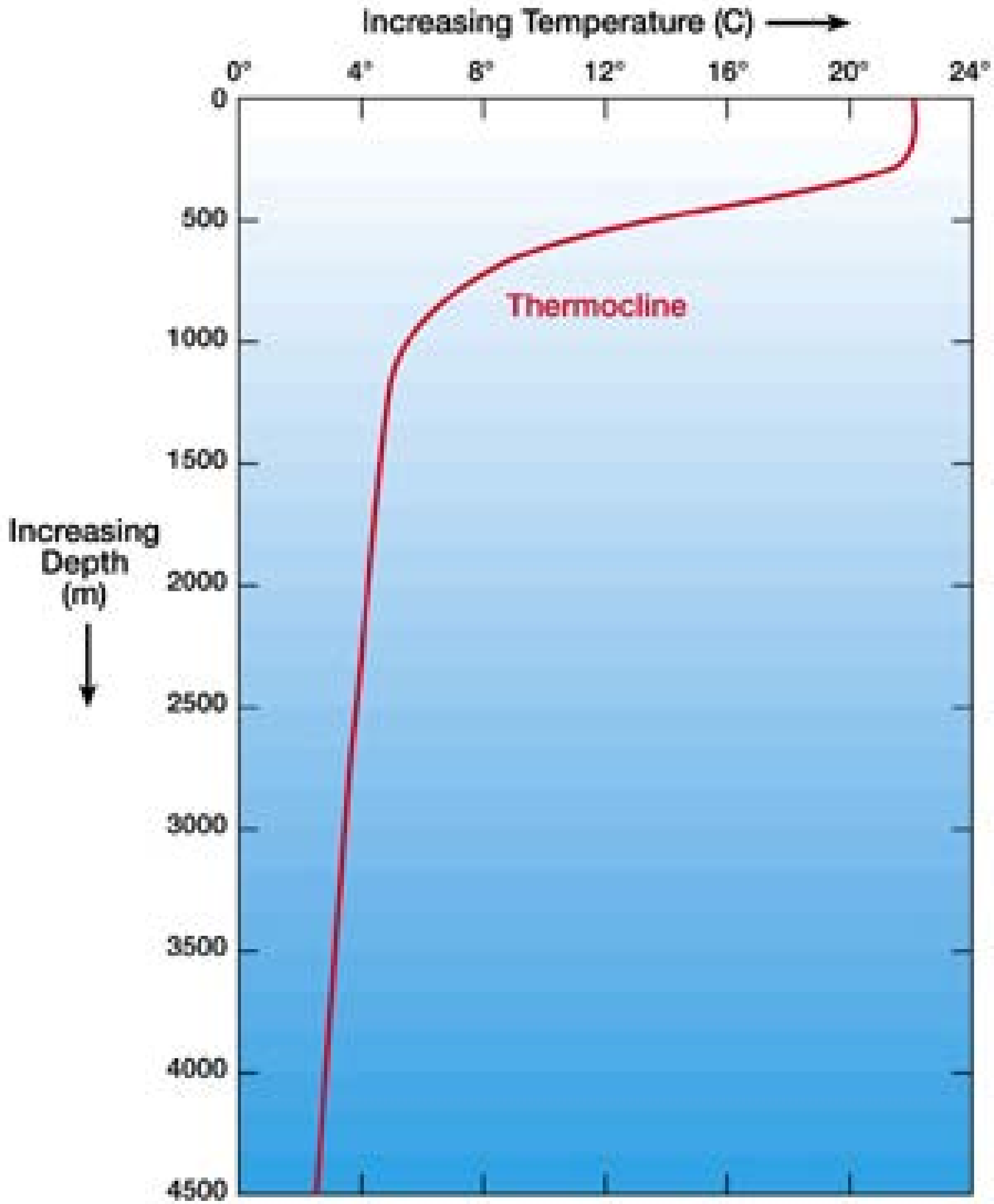




- 25,770 ft = 7,850 m
- 11,437 psi = 786 bar
- Labor intensive: 24/7/365 Operation
- 100 – 120 staff
- 2 twelve-hour shifts, 2 wks on/2 wks off
- 5–10 yr lifetime for deep water operations
- Unpredictability of product composition
- Deepwater Horizon; Torrey Canyon
- Flow assurance: methane hydrates, paraffin
- Injection wells

GTA thanks Guido Bender and Matthew Post for their help, cooperation, support and advice during the course of this CRADA project. We also thank the staff of NREL for their assistance during the early stages of the work.

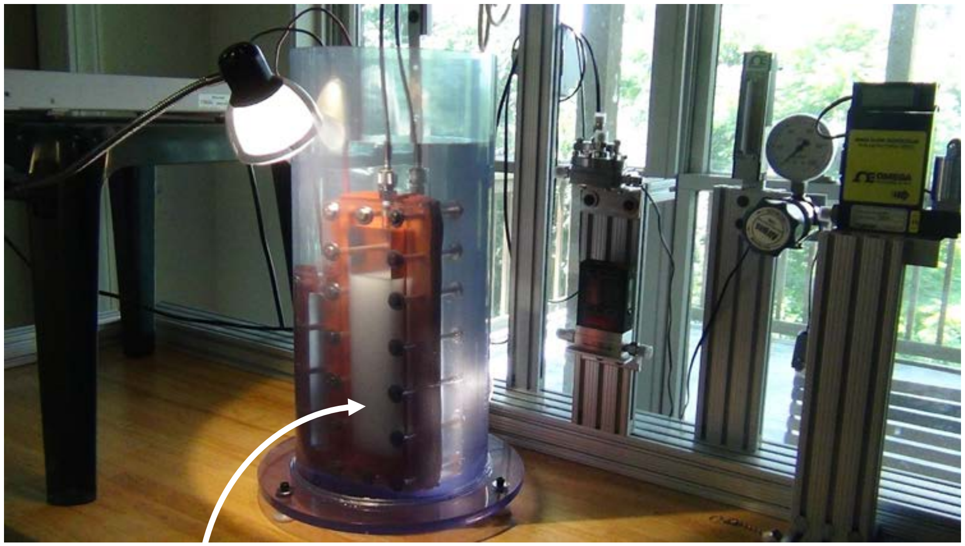
Supplemental Slides



https://www.windows2universe.org/earth/Water/temp.html

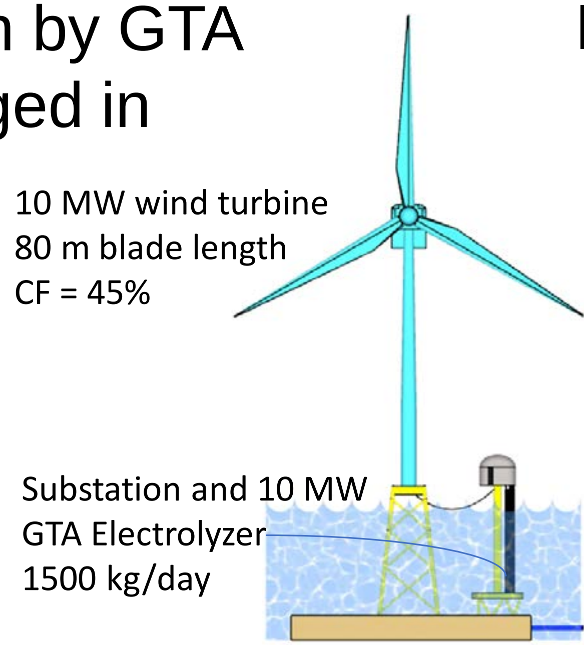
GTA TRL 5: Component validation in relevant environment

Relevant environment is seawater.



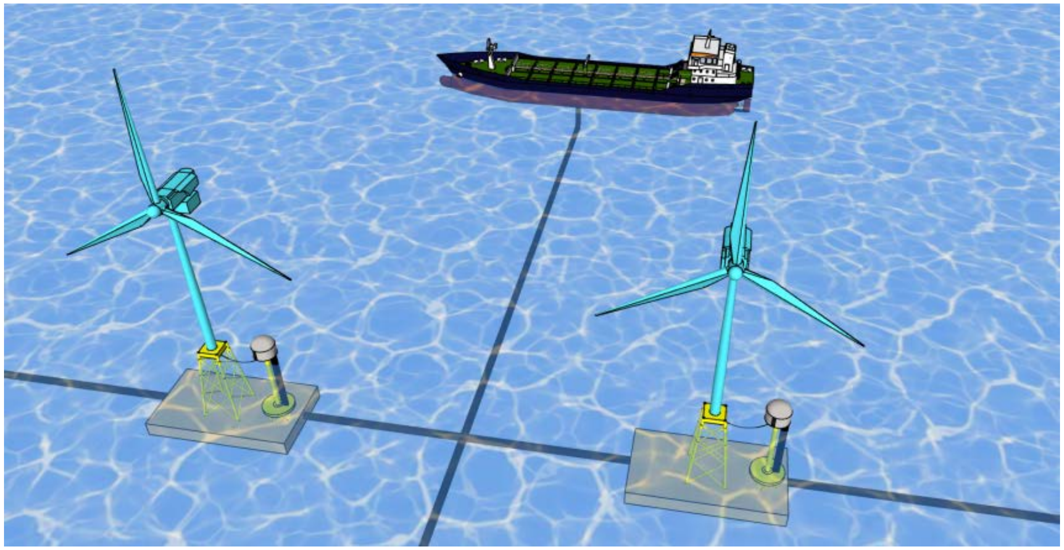
H_2 and O_2 production by GTA electrolyzer submerged in seawater.

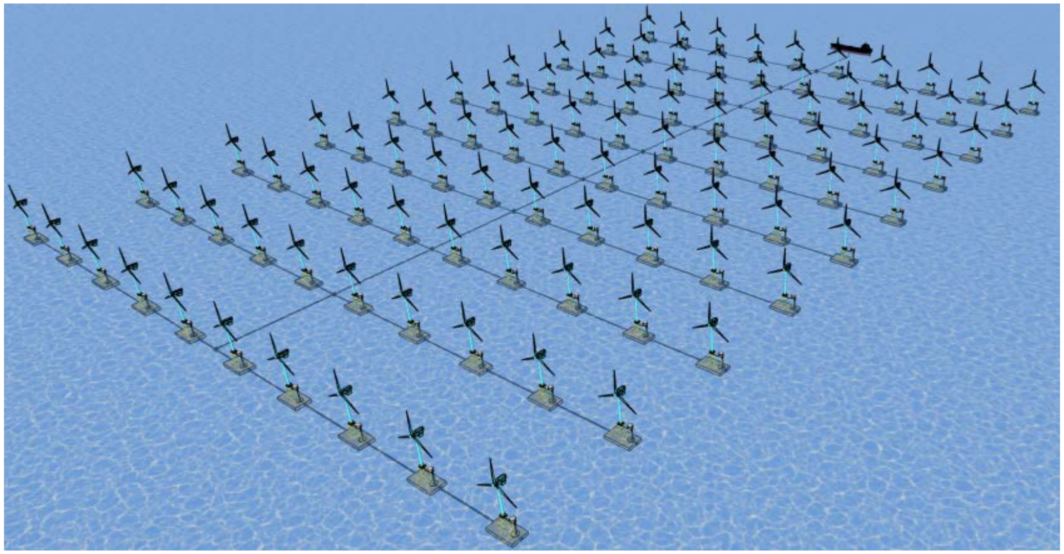
H_2 and O_2 gas feed-throughs submerged in seawater.



A One Gigawatt Offshore Windfarm

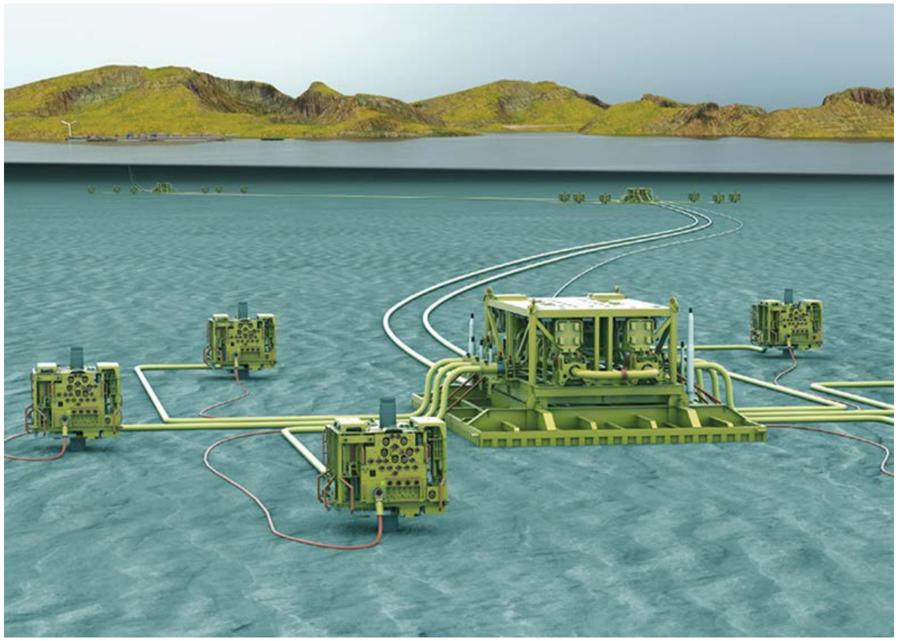
The Parallels with Offshore Gas & Oil





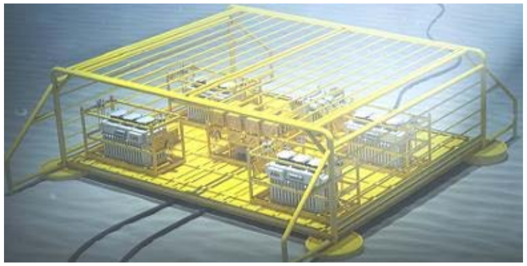
100 X 10 MW = 1 GW H2 Farm

Seabed Construction, Power and Data Transmission



Offshore "All Electric Subsea Systems Deliver Intelligence on Demand", June 2018.

ABB Group Subsea Power Substation

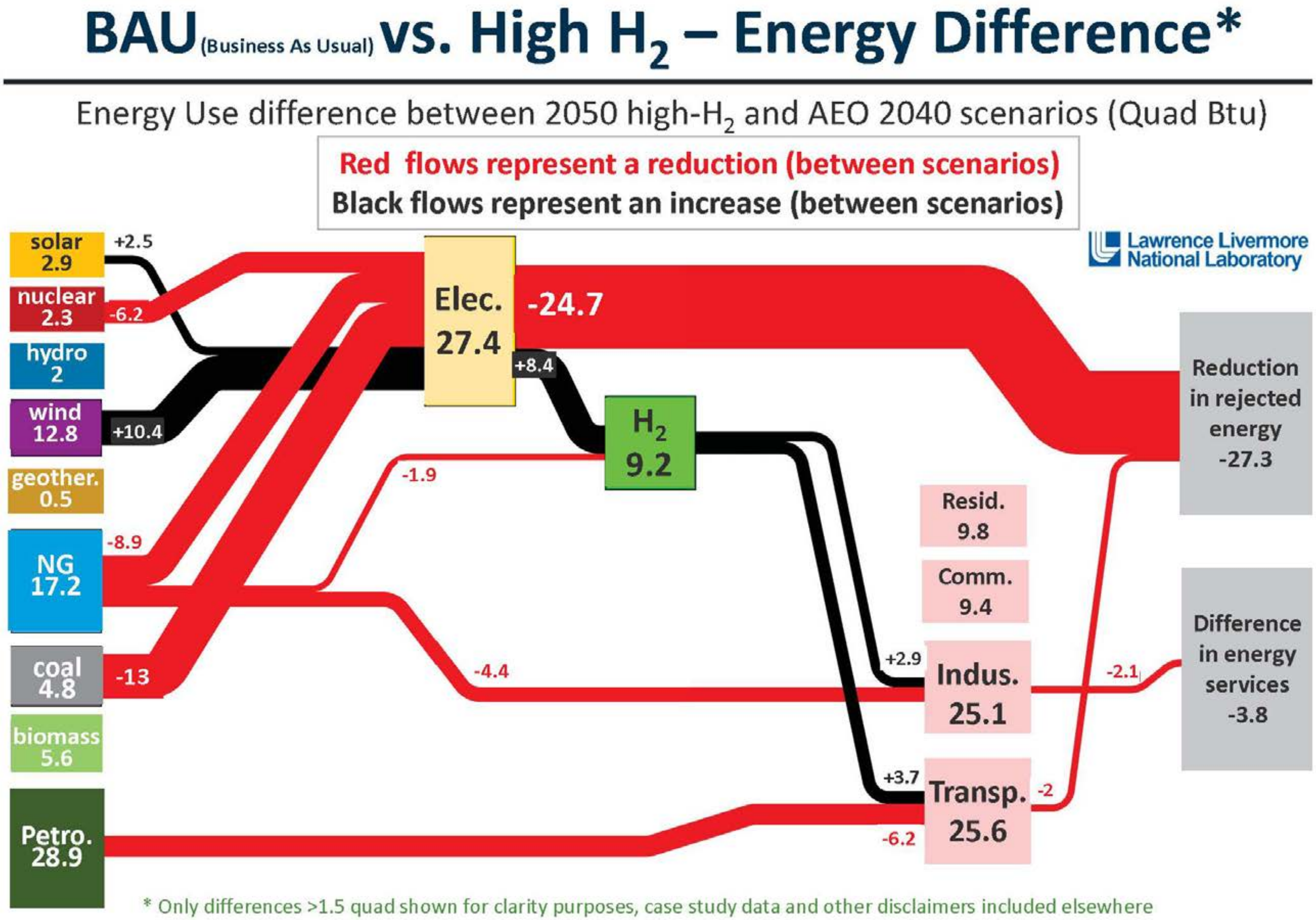


Siemens Subsea Lab Trondheim, Norway

Subsea power and information at 3000 m

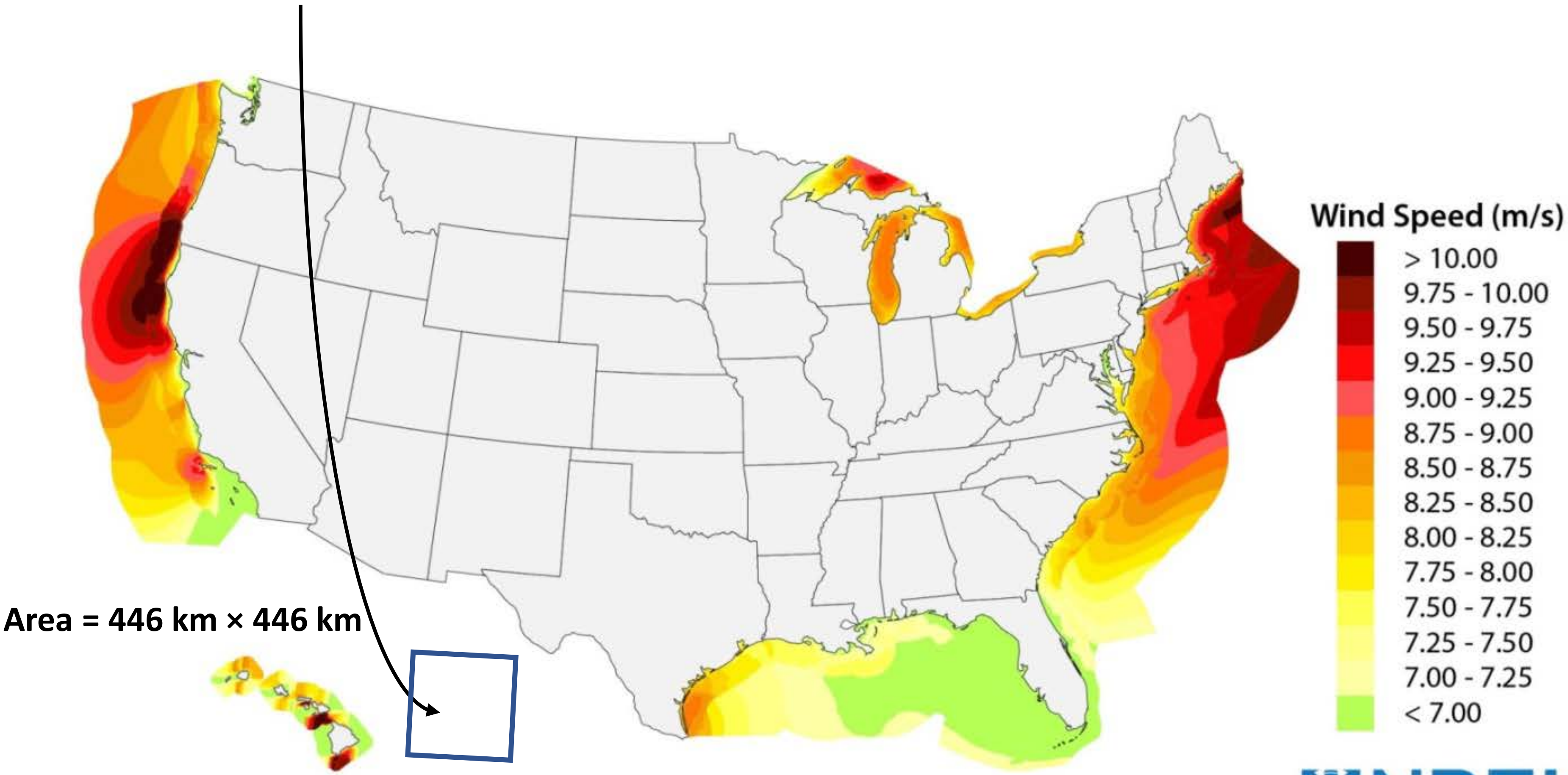
wind
12.8

2.8 Quad Btu Wind Energy Challenge



B. Pivovar, "H2@SCALE: Deeply Decarbonizing our Energy System", July 28, 2016, U.S. Department of Energy Fuel Cells Technology Office Webinar

Area for 12.8 Quad per Year Electrical Power Offshore Wind Energy
94,800 × 10 MW Wind Turbines; Capacity Factor = 0.45



= 58 million metric tons H2 per year @ 60% conv. eff.

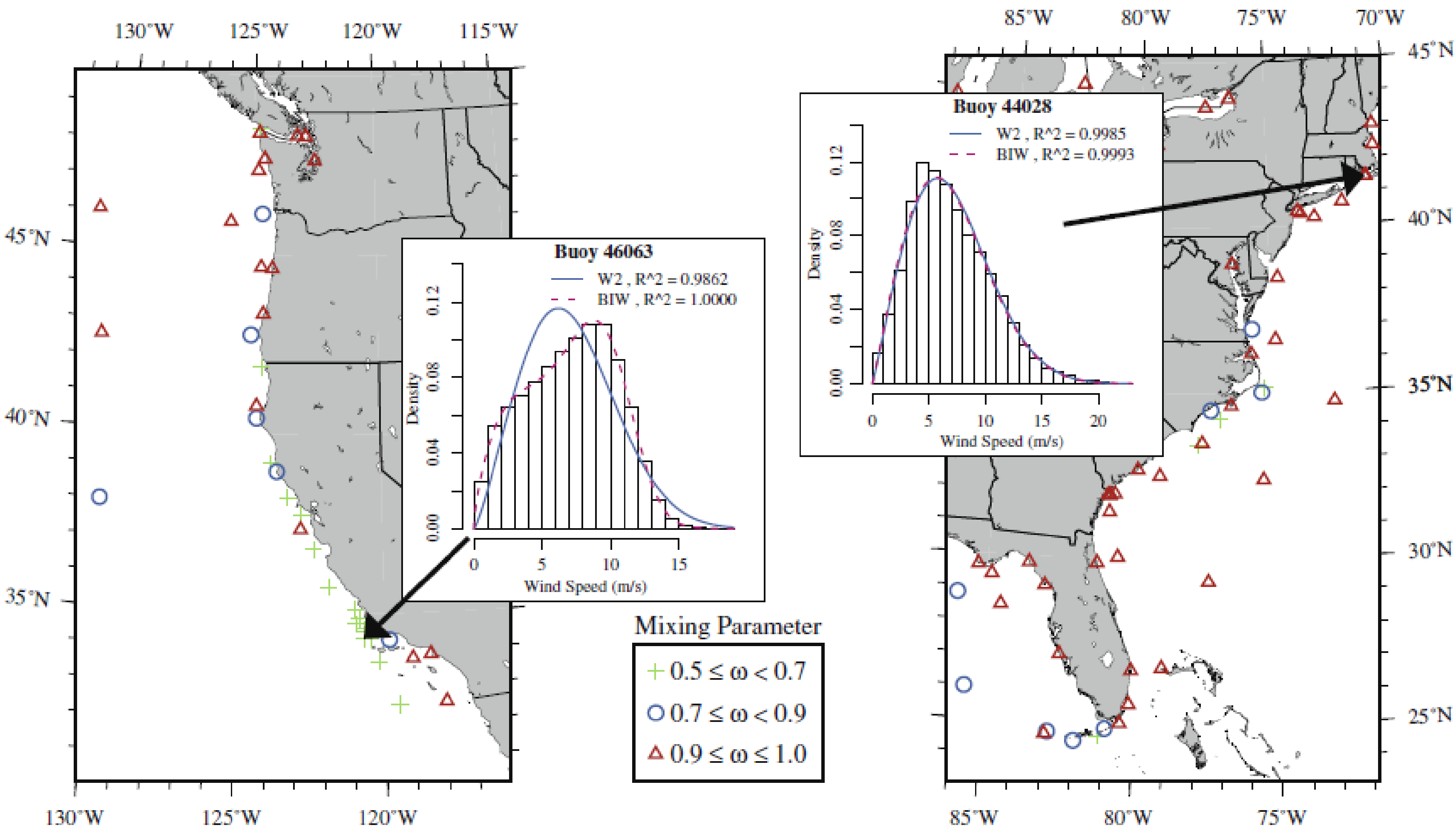
- **Adapted from W. Musial, D. Heimiller, P. Beiter, G. Scott, and C. Draxl, *2016 Offshore Wind Energy Resource Assessment for the United States*, Technical Report, NREL/TP-5000-66599, September 2016.**
- **341,000 wind turbines world-wide as of 2017. Anmar Frangoul Freelance Digital Reporter, CNBC.com, 8 September 2017.**

Energy Conversion and Management 52 (2011) 15–26

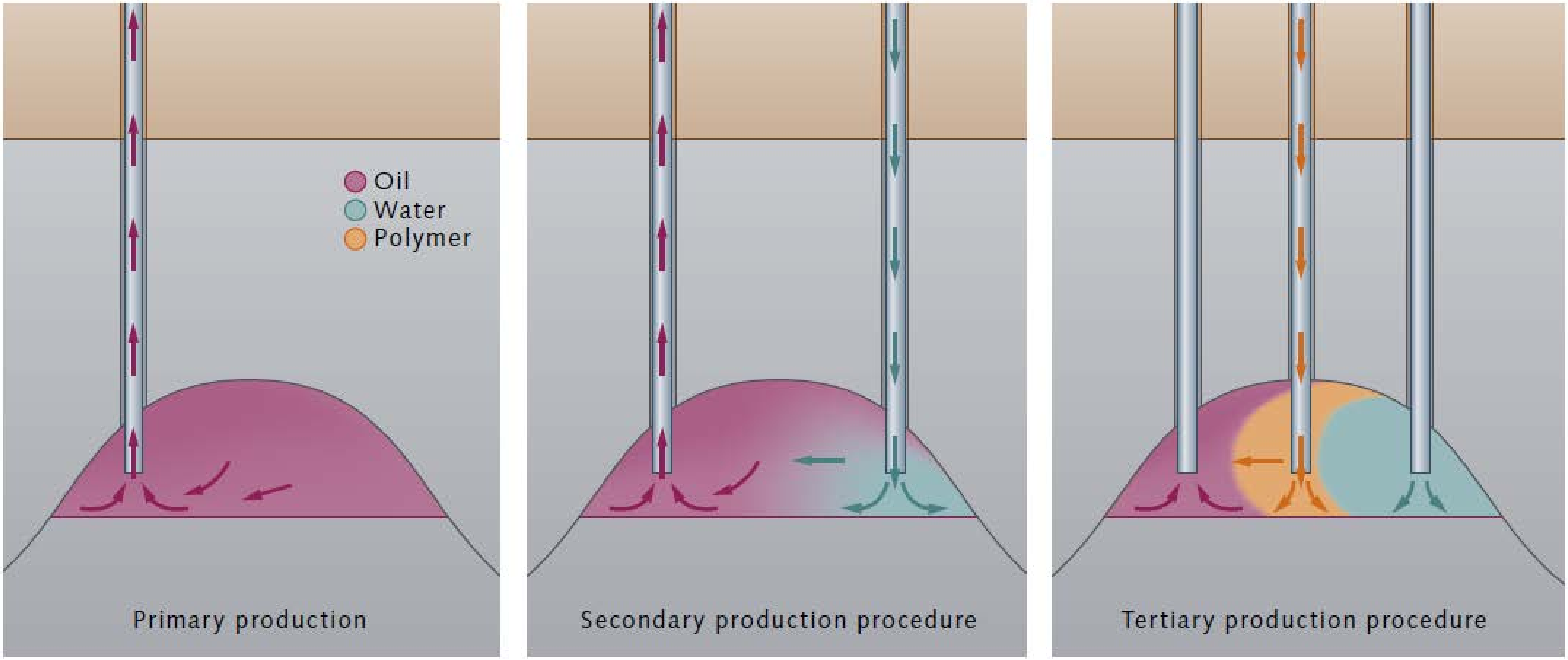
Probability distributions for offshore wind speeds

Eugene C. Morgan [a,*], Matthew Lackner [b], Richard M. Vogel [a], Laurie G. Baise [a]

[a] Dept. of Civil and Environmental Engineering, Tufts University, 200 College Ave., Medford, MA 02155, United States
[b] Wind Energy Center, University of Massachusetts, Amherst, United States

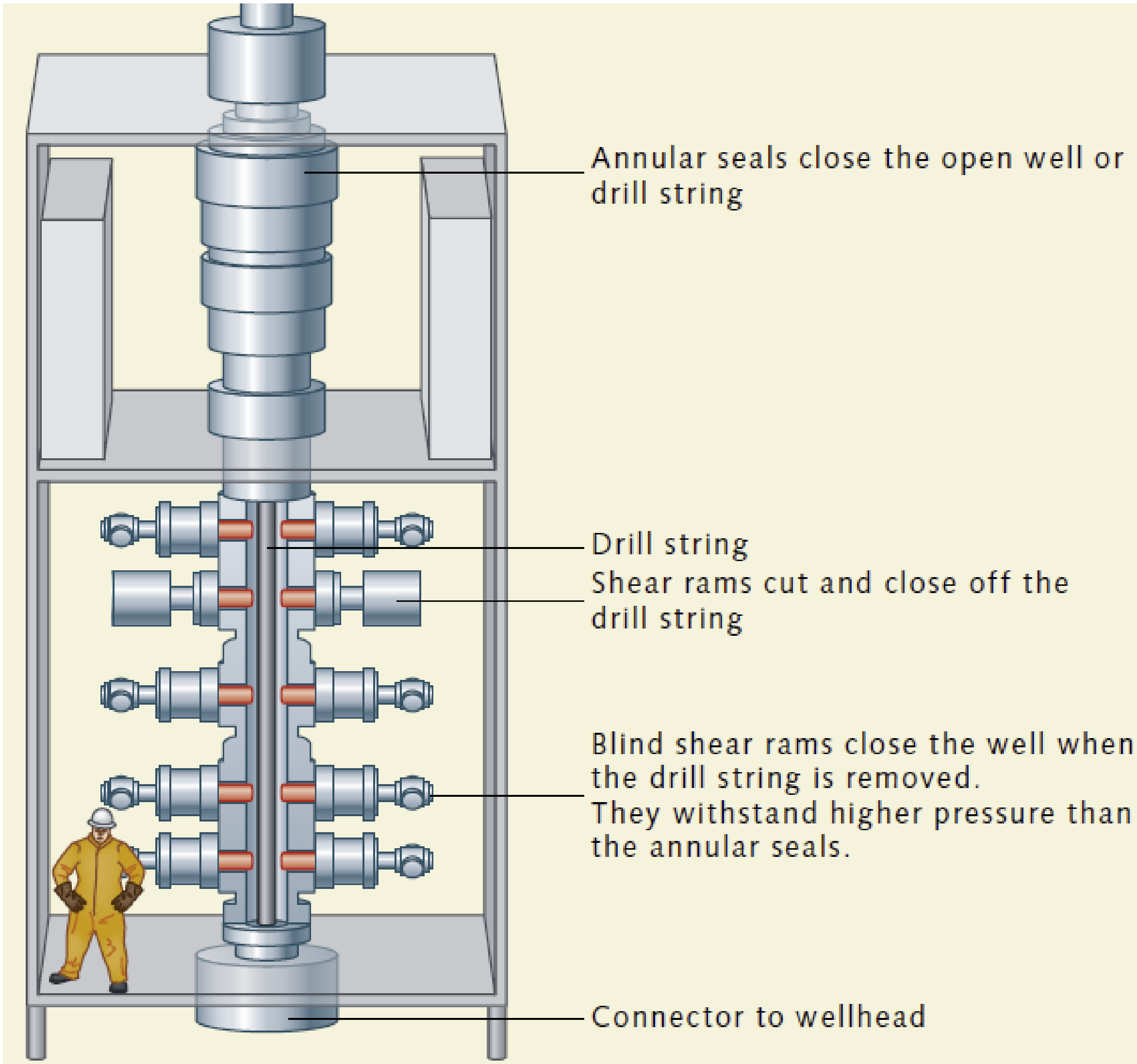


Three Phases of Subsea Oil Production



J. Lehmköster, et al., *Oil and Gas from the Sea,* p. 26, Maribus GmbH, Hamburg, Germany*, ISBN 978-3-86648-221-0,* www.maribus.com.

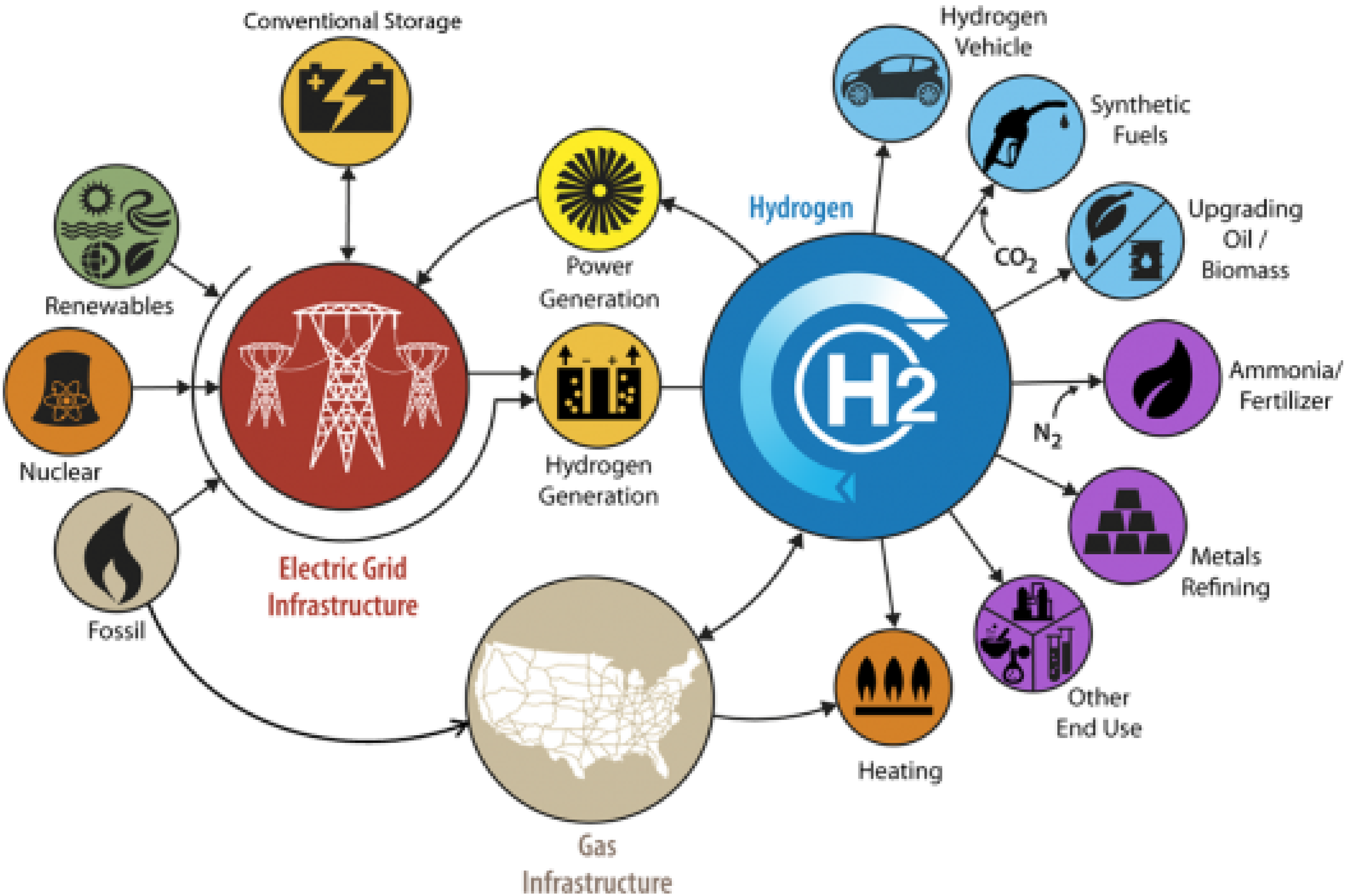
Scale of Subsea Equipment



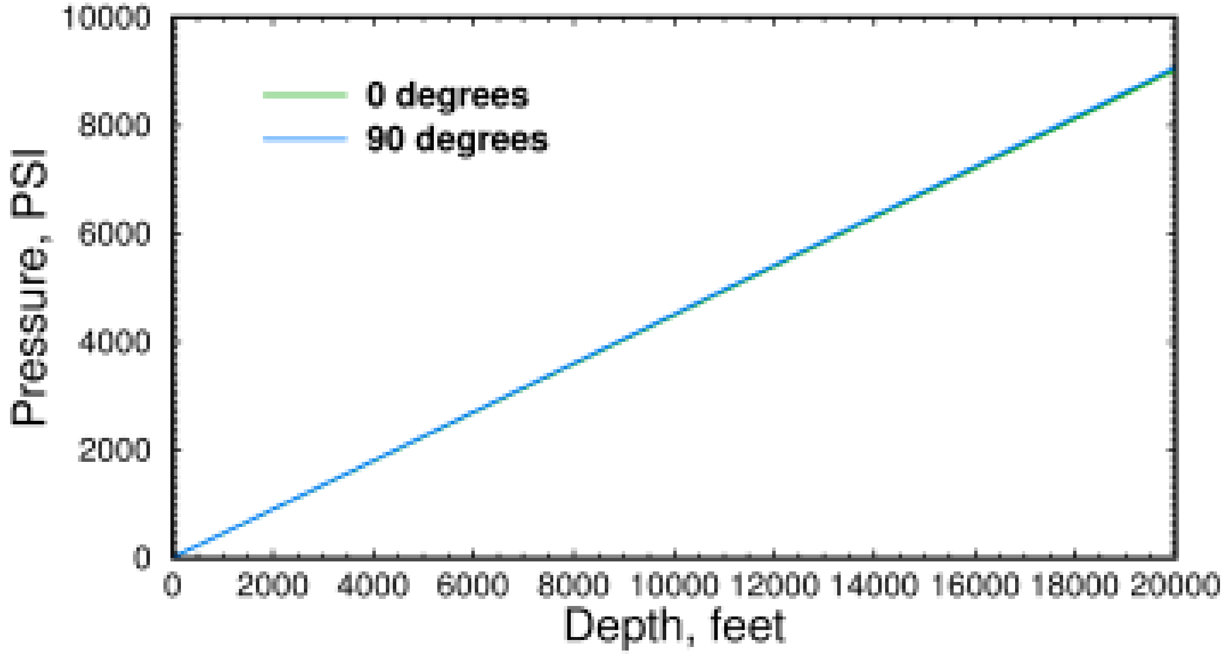
1.34 > A blowout preventer is a tower-like structure which acts as a large plug. Fitted with shut-off valves and shear rams, its purpose is to seal off wells on the sea floor. The *Deepwater Horizon* disaster occurred partly because the BOP technology failed.

J. Lehmköster, et al., *Oil and Gas from the Sea,* p. 38, Maribus GmbH, Hamburg, Germany, ISBN 978-3-86648-221-0, www.maribus.com.

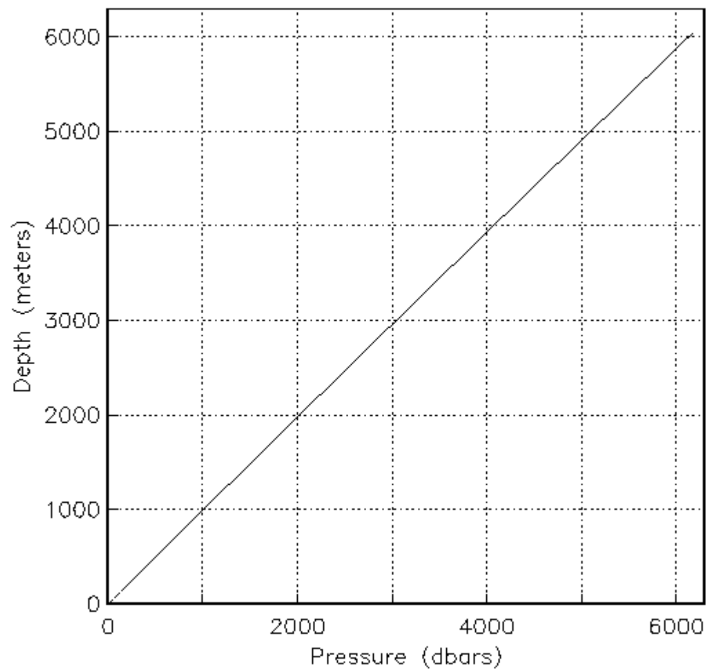
H2@Scale Concept



Source: U.S. Department of Energy



https://www.randombio.com/ocean-pressure.html



http://pordlabs.ucsd.edu/ltalley/sio210/PPSW/index.html

Scalable Electrolytic Systems for Renewable Hydrogen Production

Guido Bender
National Renewable Energy Laboratory
June 14, 2018

DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID: h2001

Overview

Timeline and Budget

- Project start date: 02/26/18
- Project end date: 01/01/19
- Total project budget: $150,000
  - Total partner share: $25,000
  - Total federal share: $25,000
  - Total partner in-kind: $100,000
  - Total DOE funds spent*: $0

* As of 3/31/18

Barriers

- Utilization of remote off-shore wind resources
- Capital cost reduction

Partners

- GTA
- NREL

Relevance

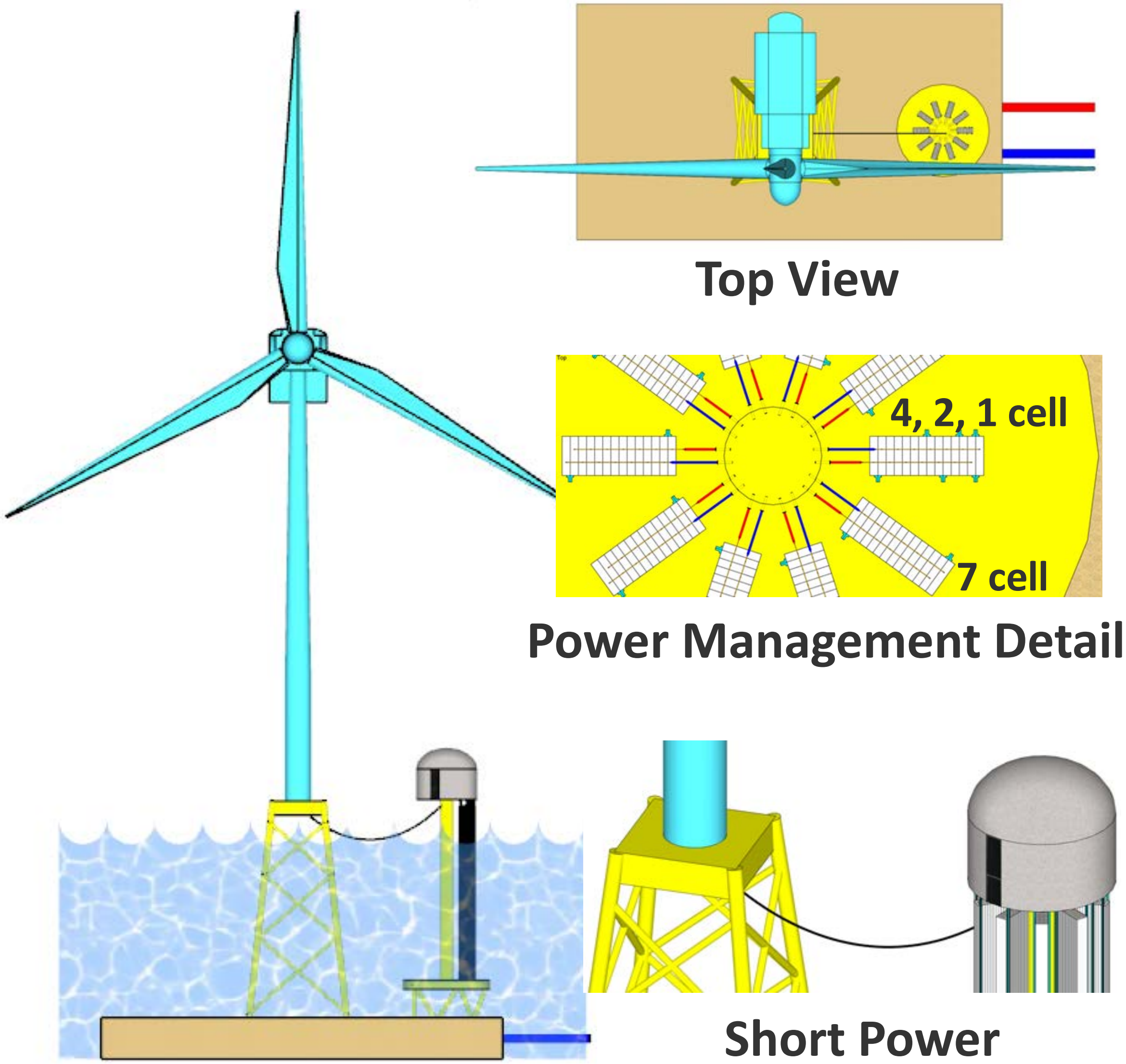
- Relevance (H2@Scale CRADA call)
  - Support development of multi-MW (typically 10-12 MW) low temperature water electrolysis system that integrates with off-shore wind farm
- Objectives:
  - Verify technology at TRL4 level
  - Create input for advancement to TRL5 level

Approach

- Approach
  - Project will leverage NREL in-situ testing capabilities
  - GTA will provide prototype electrolysis cell of ≤700W and other specific laboratory equipment as needed
  - NREL will integrate and commission test equipment
  - NREL will perform a series of VI tests and provide trace gas analysis on the product hydrogen
  - NREL may run ~100 hour durability tests as funding allows
  - GTA will utilize information from exchange into next development step

Approach

Schematic of Offshore System Installation



Top View

Power Management Detail

Front View

Short Power Transmission

- **Offshore system installation on fixed base**
- **Hydrogen production at wind site**
- **Negligible electrical power transfer loss**
- **Hydrogen delivery via gas lines**
- **70:1 turn down ratio**

Approach

Power Management Table

Exemplary Power Levels

Power Level [%]	Cells per Module			
	7	4	2	1
0	0	0	0	0
20	2	0	0	0
25.7	2	1	0	0
50	5	0	0	0
50.3	5	0	1	0
100	9	1	1	1


Energy Conversion and Management 52 (2011) 15–26

Probability distributions for offshore wind speeds

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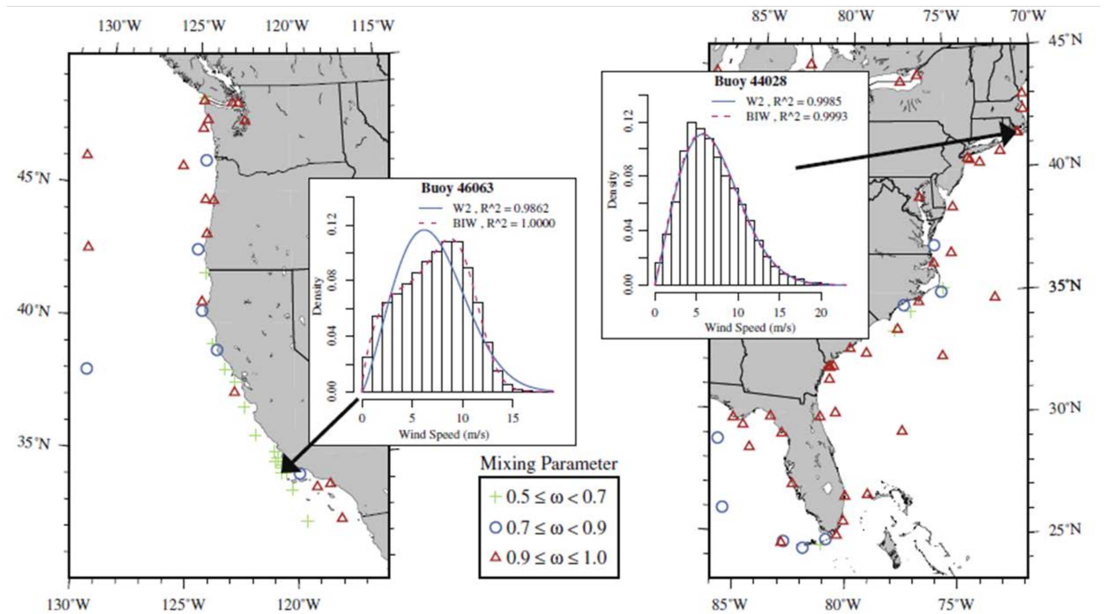
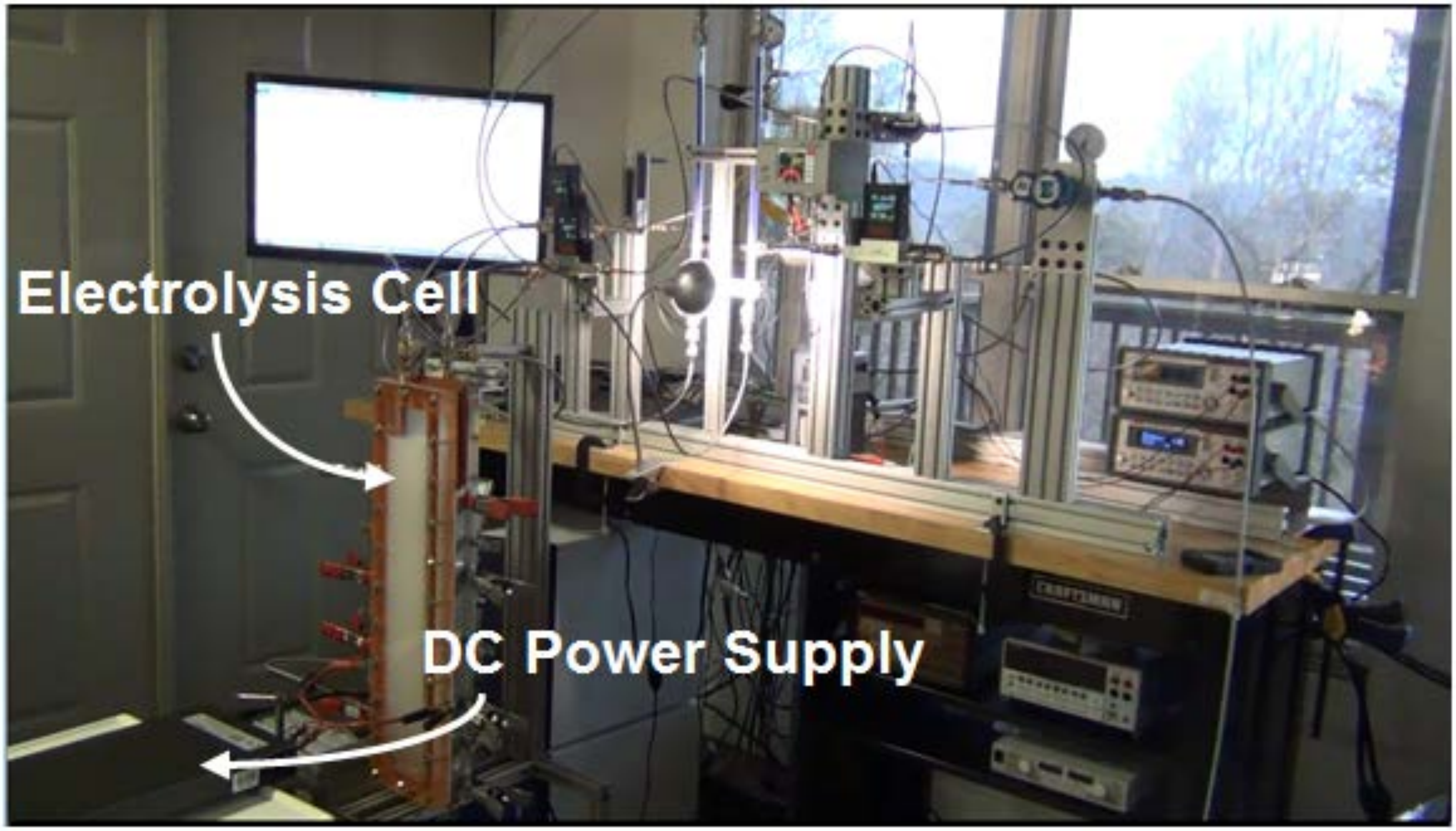


- **Online electrolyzer optimization with regards to wind speeds**
- **Modular configuration with respect to location and expected wind profiles**

Approach

Electrolysis Cell

Laboratory Scale System



Approach

NREL 3kW test system

- Integration of GTA electrolysis cell for off-shore wind platform into NREL's electrolysis test system
- GTA cell ≤700W
- NREL system 12V / 250A
- Integration with additional pumps and sensors to allow operation with KOH solution as needed for AEM technologies and non-PGM catalysts

Approach

- Milestones

Deliverable title	Description	Producer	Due date Month (M)
Equipment transfer	Deliver stack and required ancillary equipment to NREL.	GTA	M3
Verify cell performance	Conduct performance test and trace gas analysis of the product hydrogen.	NREL	M6
Report results	Complete report and return all equipment	NREL	M12

Accomplishments and Progress

- CRADA
- Funding has been received in 03/17/18
- Bailment list has been completed
- Timing for delivery of equipment has been set to end of April ‘18

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- This is a newly awarded project, and thus was not previously reviewed

Collaboration and Coordination

- Industry partner: GTA
  – Defines objectives
  – Defines operating conditions
  – Provides information about specific operating procedures
  – Provides specialized equipment
  – Provides data measured at GTA
- National lab partner: NREL
  – Performs system setup in NREL lab for ≤700W cell
  – Conducts VI experiments
  – Characterizes hydrogen quality via trace gas analysis
  – Depending on available time and funding conducts long term test of ~100 hr

Challenges and Barriers

- Integration of AEM technology, for example:
  - Flow stream with KOH solution into PEM technology test stand without contamination of equipment
  - Utilization of advanced diagnostics such as AC impedance spectroscopy

Proposed Future Work

- Potential expansion to TRL5 level
- Expansion of power levels >700W

Technology Transfer Activities

- This project is not expected to result in technology development
- NREL will assist GTA with the data interpretation which may influence TRL5 level design

Summary

- Project awarded under H2@Scale CRADA call
  - Industry partner: GTA
  - Lab partner: NREL
- Approach: leverage NREL in-situ testing capabilities developed for water electrolysis
- Relevance: verification of existing TRL4 level technology with respect to performance, hydrogen quality
- Accomplishments/Future Work: Project just initiated

Acknowledgements

GTA

- Elias Greenbaum, Industry Partner PI

NREL

- Matthew Post, system integration sub-lead

Thank You

www.nrel.gov

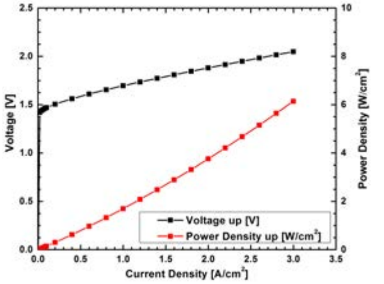
Publication Number

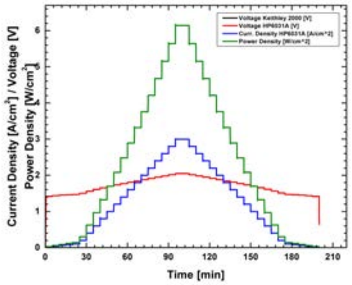
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Back-Up Slides

NREL Capabilities: In-Situ Electrolyzer Testing

- 5x NREL built electrolyzer system
  - 150 A power supply
  - Up to 1.5 bar operation
  - AC impedance
- 2x Greenlight G40 system
  - 12V/250A power supply
  - Up to 50 bar operation
  - individual cell voltage monitors
  - AC impedance up to 30A
  - Anode & cathode product gas analyzer
  - H2 pump option





Project Task Details

- **Task 1:**

  GTA will send to NREL prototype electrolysis cells of less than 700W total power. To facilitate the collaboration and optimize resources, GTA will also send to NREL ancillary equipment such as pumps, dryers, programmable DC 750 W power supply, and catalytic O2 cleanup of the hydrogen. NREL will prepare the KOH electrolyte solution in distilled water.
- **Task 2:**

  NREL will run a series of steady-state hydrogen and oxygen producing polarization (IV) tests on the stack, and measure the output quantity and quality of the hydrogen. Oxygen will be vented. NREL will run a trace gas analysis on the product hydrogen. Once the system is set up, NREL may run an initial ~100 hour durability test to look for early signs of degradation.
- **Task 3:**

  NREL will prepare a report for GTA, and return all GTA equipment at the end of the project.

Scalable Electrolytic Systems for Renewable Hydrogen Production

Guido Bender
National Renewable Energy Laboratory
April 30, 2019

DOE Hydrogen and Fuel Cells Program
2019 Annual Merit Review and Peer Evaluation Meeting

Project ID: H2001

Overview

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- Project end date: 05/01/19
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  - Total recipient share: $25k
  - Total federal share: $25k
  - Total DOE funds spent*: $25k

* As of 3/01/19

Barriers

- Utilization of remote off-shore wind resources
- Capital cost reduction

Partners

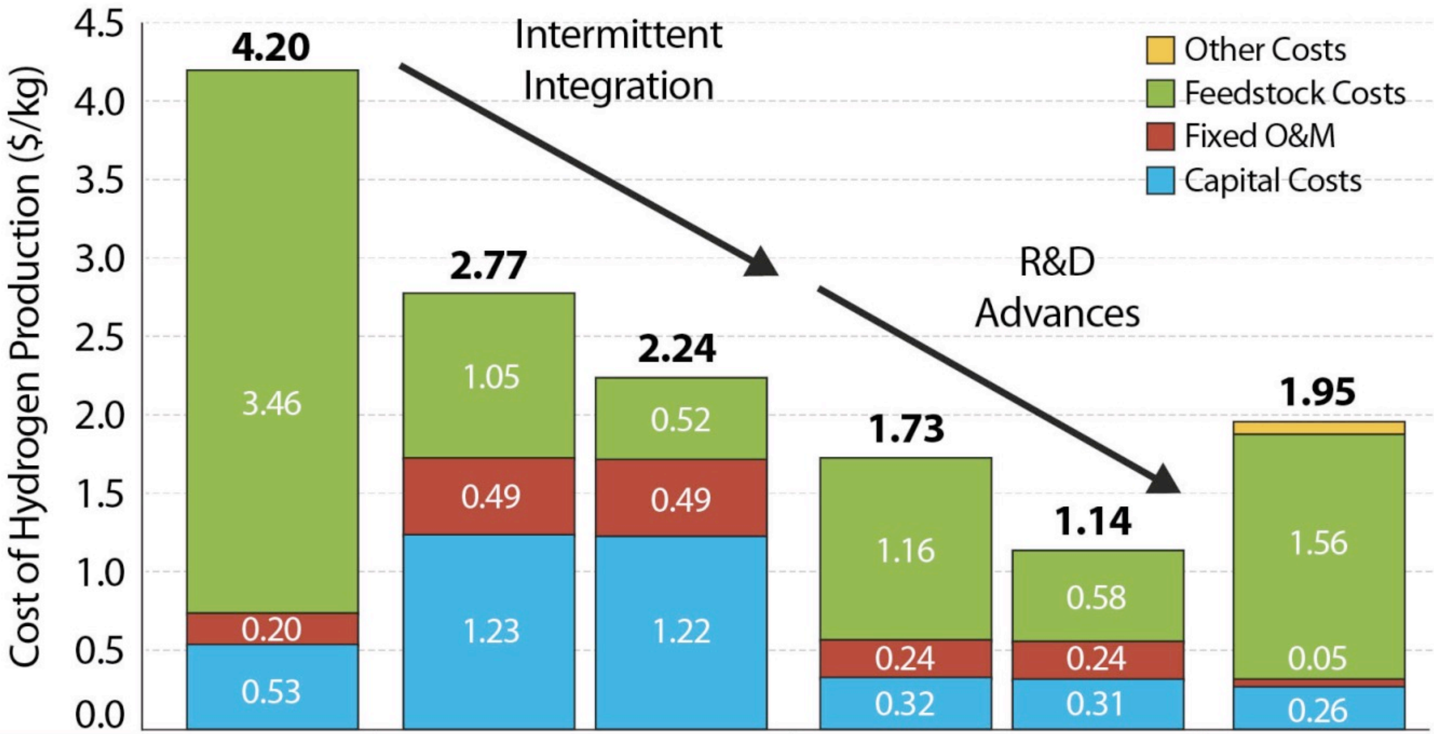
- GTA
- NREL

Relevance

- Relevance (H2@Scale CRADA call)
  - Support development of multi-MW (typically 10-12 MW) low temperature water electrolysis system that integrates with off-shore wind farm
- Objectives:
  - Verify technology at TRL4 level
  - Create input for advancement to TRL5 level

Relevance

Analysis of Electrolyzer-Based Hydrogen Production Costs



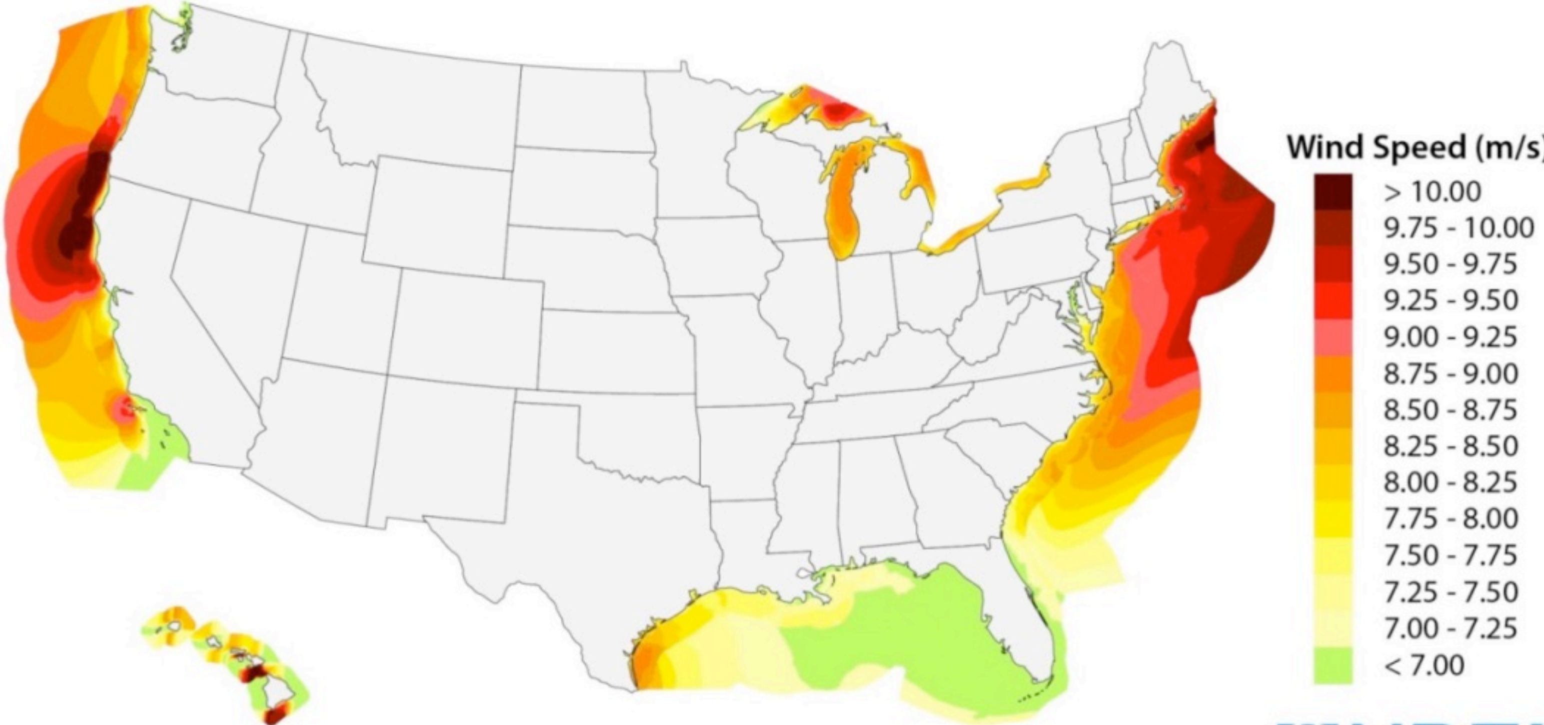
Capacity Factor	97%	40%		40%		0.9
Cost of Electricity	¢6.6/kWh	¢2/kWh	¢1/kWh	¢2/kWh	¢1/kWh	
Capital Cost	$400/kW	$400/kW		$100/kW		
Efficiency (LHV)	66%	66%		60%		
	Electrolyzer					SMR

$100/kW = $100,000/MW

B. Pivovar, N. Rustagi, and S. Satyapal, “Hydrogen at Scale (H2@Scale) Key to a Clean, Economic, and Sustainable Energy System”, The Electrochemical Society *Interface*, Spring 2018, pp. 67 – 72.

Relevance

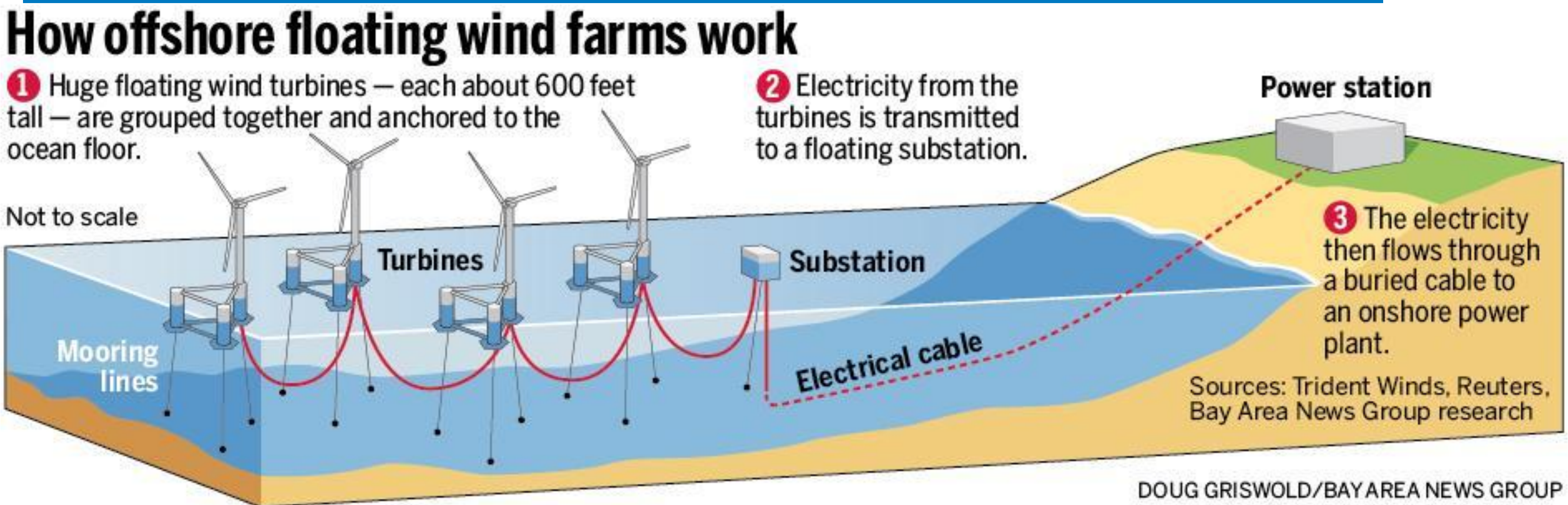
- **In one H2@scale future scenario 12.8 quad of wind electrical power is added**
  (B. Pivovar, DOE FCTO webinar, "H2@scale: Deeply Decarbonizing Our Energy System", July 28th 2016)
- **12.8 quad = 58 million metric tons H_2/year @ 60% conversion efficiency**
- **Red square area needed for 12.8 quad/year of electrical power offshore wind energy**
- **12.8 quad/year require for example 94,800 wind turbines at 10 MW each; capacity factor = 0.45**



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

- **Adapted from W. Musial, D. Heimiller, P. Beiter, G. Scott, and C. Draxl, *2016 Offshore Wind Energy Resource Assessment for the United States*, Technical Report, NREL/TP-5000-66599, September 2016.**
- **1 quad = 10^{15} BTU**
- **341,000 wind turbines world-wide as of 2017. Anmar Frangoul Freelance Digital Reporter, CNBC.com, 8 September 2017.**

Approach - Technology



ECOSSE Subsea Systems

Cost of Cable Damage

- Niels Kragelund - Head of Wind Energy at Danish Insurers Codan says…..

  "cables account for 90% of the number of offshore wind claims"
  "cables account for 70% of the actual cost of claims"

- Tim Halperin-Smith - Director at Global Insurance brokers Willis says …..

  "of all of the offshore wind claims his firm receives, most incidents occur during installation, half of them due to human error'

High-Voltage Export Cables Cost

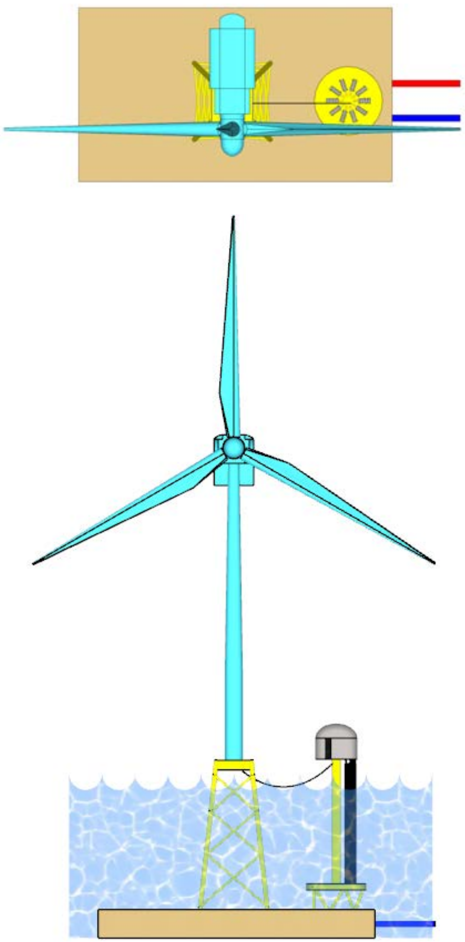
- **25% CAPEX**
- **30% of OPEX are cable related liability insurance premiums :**
  - **90% legal challenges**
  - **70% of those are actual cash settlements**

Wind turbine operating models

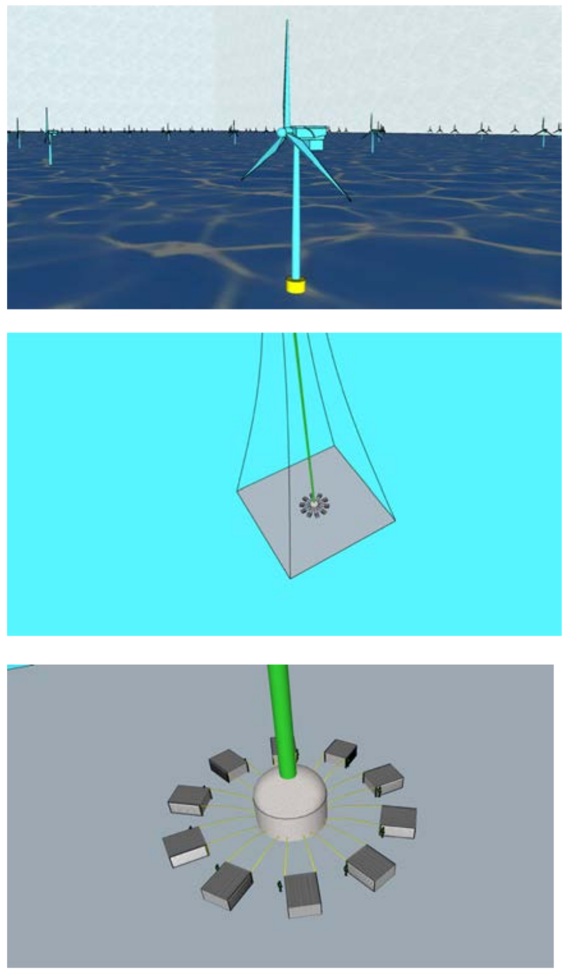
- **Electricity single product**
- **Demand vs. supply challenge**
- **Typically one customer**
- **Benefits from value-added H2**

Approach - Technology

Fixed Base Turbines



Floating Turbines



- **Offshore wind turbine options:**
  - **Fixed platform**
  - **Floating spar buoy**
- **Hydrogen production at wind turbine site**
- **Minimal electrical power transfer loss from turbine to electrolyzer**
- **Hydrogen delivery via gas pipelines**

Approach - Project

- **Project leveraged NREL in-situ testing capabilities**
- **GTA provided prototype electrolysis cell of ≤700W and other specific laboratory equipment as needed**
- **NREL integrated and commissioned test equipment**
- **NREL conducted a series of performance tests**
- **NREL conducted trace gas analysis on the product hydrogen**
- **GTA utilized information from exchange into next development step**

Accomplishments and Progress

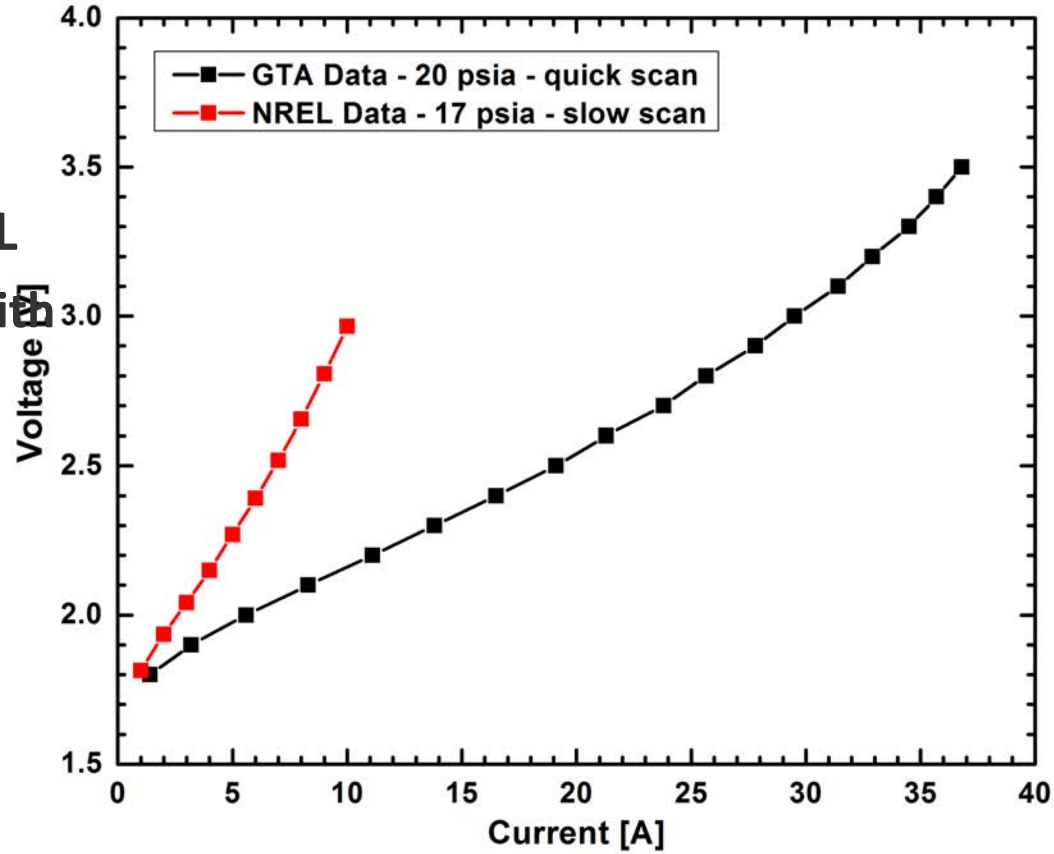
Test setup

- **Received, assembled and commissioned at NREL**
- **Integrated into NREL's laboratory environment**
- **Refined with**
  - **Thermocouple testing**
  - **Automated performance experiments**
  - **Automated data collection**
  - **Backpressure control**

Accomplishments and Progress

Verification of Operation

- Electrolyzer performance measured with and without oxygen scrubber
- Performance difference observed between GTA & NREL
  - Assigned to NREL elevation with ambient pressure of 12 psia
  - Bubble size effect expected
  - Only 5 psi gauge pressure operation was available with hardware
- Pressure adjusted to sea level ambient pressures and slightly elevated pressure for fuel quality experiments

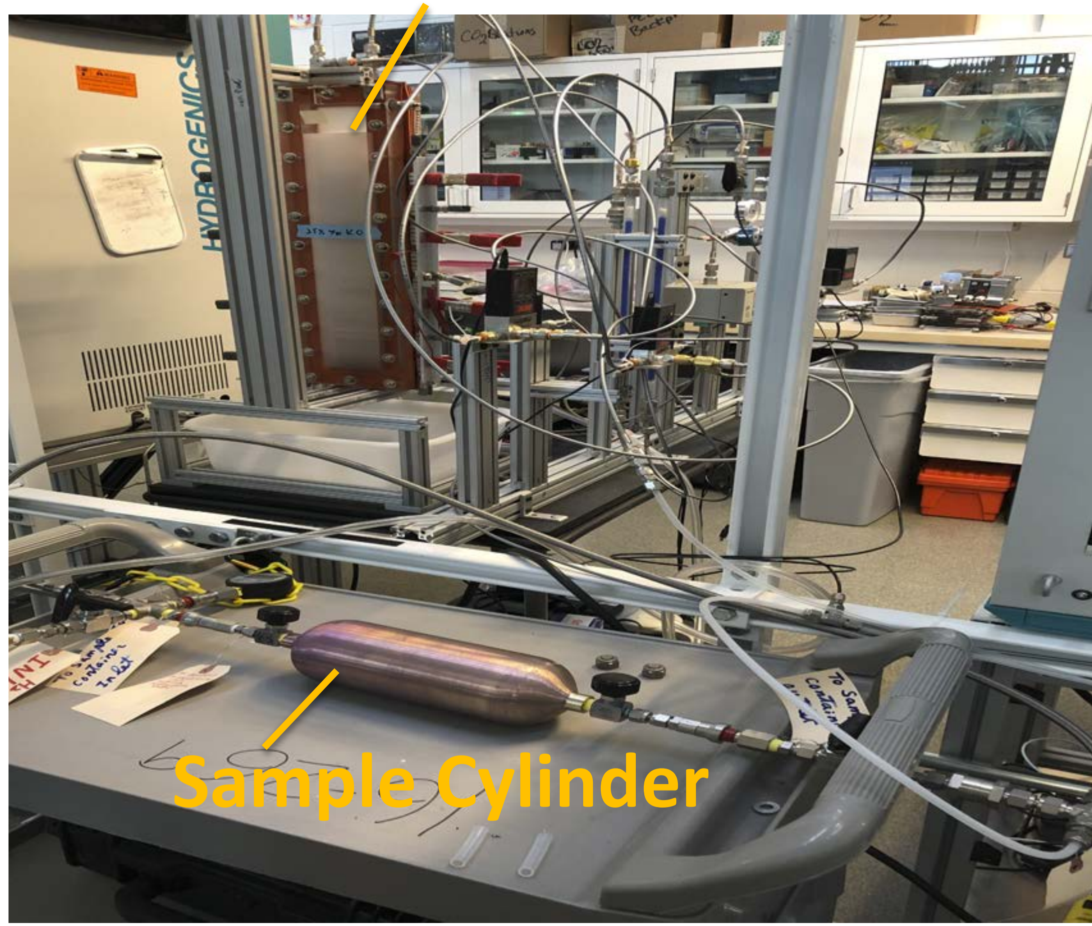


Accomplishments and Progress

Trace Gas Analysis

- Electrolyzer operated with sample cylinder collecting gas samples with and without oxygen scrubber
- Gas analyzed towards SAE J2719 fuels purity standard
- Hydrogen fuel purity reported by GTA verified at NREL

Electrolyzer Stack



Accomplishments & Progress

Characterization of H_2 purity

- Gas collection with custom containers for Hydrogen fuels purity characterization from Smart Chemistry
- Hydrogen purity as measured = 99.96681%
- H_2O, O_2, and CO_2 as measured are above the stringent SAE J2719 fueling standards
- Gas purity met the expectations and are sufficient for many hydrogen applications for H2@scale objectives
- Simple upgrades could be implemented to meet the SAE J2719 fueling standard
- Removing the H_2O, O_2, and N_2, the hydrogen purity would increase to be above 99.999%

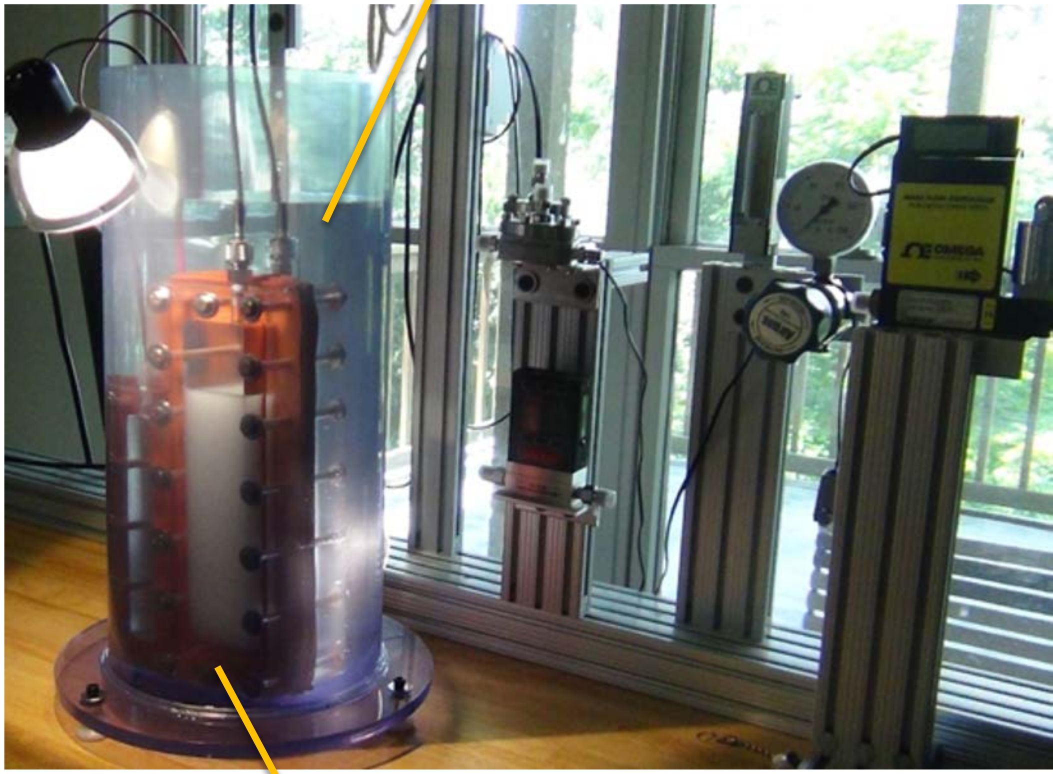
SmartChemistry

SAE J2719 — Sample Receipt Date 11/30/2018 — NREL Electrolyzer H_2

SUMMARY	SAE J2719 Limits (µmol/mol)	Smart Chemistry Detection Limits (µmol/mol)	Concentration (µmol/mol)
H_2O	[illegible]	[illegible]	279
Total Hydrocarbons -C_1 Basis	[illegible]		0.48
Methane			0.15
Acetone			0.039
Benzene			0.008
Ethane			0.21
Ethanol			0.022
Isopropyl Alcohol			0.011
Toluene			0.025
Hexanal			0.010
Octene			0.009
O_2 NREL Electrolyzer H_2	[illegible]	[illegible]	9.4
O_2 NREL Electrolyzer H_2 WITHOUT OXYGEN TRAP			3472
He	[illegible]	[illegible]	< 10
N_2 & Ar	[illegible]		
N_2		[illegible]	40
Ar		[illegible]	1.4
CO_2	[illegible]	[illegible]	2.3
CO	[illegible]	[illegible]	0.023
Total S	[illegible]		0.00082
Hydrogen Sulfide		[illegible]	0.000015
Carbonyl Sulfide		[illegible]	0.00060
Methyl Mercaptan		[illegible]	< 0.00001
Ethyl Mercaptan		[illegible]	< 0.00001
Dimethyl Sulfide		[illegible]	0.0000085
Carbon Disulfide		[illegible]	0.000066
Isopropyl Mercaptan		[illegible]	< 0.00001
Tert-Butyl Mercaptan		[illegible]	< 0.00001
n-Propyl Mercaptan		[illegible]	< 0.00001
Thiophene		[illegible]	0.0000098
Diethyl Sulfide		[illegible]	< 0.00001
n-Butyl Mercaptan		[illegible]	< 0.00001
Dimethyl Disulfide		[illegible]	0.000056
Tetrahydrothiophene		[illegible]	0.000056
Formaldehyde	[illegible]	[illegible]	0.0012
Formic Acid	[illegible]	[illegible]	< 0.003
Ammonia	[illegible]	[illegible]	< 0.03
Total Halogenates	[illegible]		0.015
Cl_2		[illegible]	< 0.003
HCl		[illegible]	< 0.014
HBr		[illegible]	< 0.008
Total Organic Halides (32 compounds in red and bold listed in "Non-Methane Hydrocarbons") (ASTM D7892; Smart Chemistry limit is for each individual organic halide)		[illegible]	0.015
Ethene, chlorotrifluoro-			0.0026
Hexane, 1,1,1,2,2,3,3,4,4,5,5,6,6-tridecafluoro-			0.0012
1-Butene, 4,4-dichloro-1,1,2,3,3,4-hexafluoro-			0.0064
1-Propene, 3-chloro-1,1,2,3,3-pentafluoro-			0.0048
Particulate Concentration	[illegible]		Not Required
Particulates Found & Size			Not Required
Hydrogen Fuel Index	[illegible]		99.96681%

TRL4 to TRL5 Transition

- Component validation in relevant environment
- Simulated off-shore operation by submersion of electrolysis stack in seawater
- Redesign of stack for TRL5 demonstration
- Successful operation of submerged system
- **Screening test of various diaphragm materials underway**



Collaboration and Coordination

- **Industry partner: GTA**
  - **Defined objectives**
  - **Defined operating conditions**
  - **Provided information about specific operating procedures**
  - **Provided specialized equipment**
  - **Provided data measured at GTA**
- **National lab partner: NREL**
  - **Performed system setup in NREL lab for ≤700W cell**
  - **Performed refinements to experimental setup**
  - **Confirmed GTA performance**
  - **Characterized hydrogen quality via trace gas analysis for GTA**

Remaining Challenges and Barriers

- **Scope of project completed**
- **No challenges remain within the scope of the project**

Proposed Future Work

- Project completed
- No future work planned within this project

- Future work outside this project
  - Demonstrate functionality in various scenarios:
    - Simulated ocean floor pressure submersed in seawater
    - Actual off-shore environment
  - Investigate performance improvement through
    - Pressure operation
    - Electrode optimization

Technology Transfer Activities

- **This project did not result in any technology transfer**

Responses to Previous Year Reviewer's Comments

- Project was not reviewed last year

Summary

- **NREL and GTA successfully collaborated on verification and characterization of GTA's submersible electrolyzer technology for off-shore operation**
- **Verification of performance data at NREL**
- **Successful characterization of hydrogen fuels purity**
  - **Hydrogen purity as measured = 99.97%**
  - **Theoretical purity above 99.999% after removal of H_2O, O_2, and N_2**

Acknowledgements

GTA

- **Elias Greenbaum, Industry Partner PI**

NREL

- **Matthew Post, system integration sub-lead**

Thank You

www.nrel.gov

Publication Number: 73493

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NREL

Transforming ENERGY

Reviewer-Only Slides

Project Task Details

- **Task 1:**

  GTA will send to NREL prototype electrolysis cells of less than 700W total power. To facilitate the collaboration and optimize resources, GTA will also send to NREL ancillary equipment such as pumps, dryers, programmable DC 750 W power supply, and catalytic O2 cleanup of the hydrogen. NREL will prepare the KOH electrolyte solution in distilled water.
- **Task 2:**

  NREL will run a series of steady-state hydrogen and oxygen producing polarization (IV) tests on the stack, and measure the output quantity and quality of the hydrogen. Oxygen will be vented. NREL will run a trace gas analysis on the product hydrogen. Once the system is set up, NREL may run an initial ~100 hour durability test to look for early signs of degradation.
- **Task 3:**

  NREL will prepare a report for GTA, and return all GTA equipment at the end of the project.