Lower-cost Hydrogen (H2) Fuel Production from Distributed Wind via Paralleled Self-Excited Induction Generators (SEIG's) at Multi-turbine Off-grid Windplants: NREL R&D plus Demonstration at an Operating 13-turbine Windplant in Palm Springs, CA

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Technical subcategory:	1.3 Mechanical - Chemical
Funding request:	$ 350,000 Duration: 12 months

1. ABSTRACT **Concept:** We will discover and demonstrate whether **w**ind turbines and windplants may be dedicated to Hydrogen fuel production, with no connect to the electricity Grid, enjoying simpler design for lower capex and O&M costs, and lower transmission and energy storage costs of Hydrogen, Ammonia and other C-free electrofuels, to serve the large nascent markets for Fuel Cell (FCEV) transport and CHP fuels, and for export, from Alaska to Japan, for example: SIP_energycarriers2016_en.pdf

Recent advances in power electronics and controls enable this novel, integrated wind-to-H2 system to be designed and field tested in this project, synergistically combining stable SEIG mode operation of: (1) the common, simple, rugged, low-cost, squirrel cage induction motor, producing "wild DC"; (2) close-coupling the electrolysis stacks array to a common DC bus integrating the output of multiple turbines; (3) a single SCADA system integrating and optimizing operation of turbine, electrolysis, water supply, and compression. Fig 1. The NREL team will design and build a 100 kW proof-of-concept pilot plant for installation at the Alaska Applied Sciences, Inc. (AASI) 13-turbine windplant in Palm Springs, CA for authentic testing, with data collection and design improvements guided thereby, to achieve proof-of-concept ~ TRL 4-5, to confirm expected > 20% reduction in plant-gate wind-to-H2 cost, for direct delivery as power-to-gas and / or via dedicated high-purity pipeline delivery. Fig 3. AASI has demonstrated manual SEIG mode operation on one of its Palm Springs turbines: Fig 2. Operating video: https://vimeo.com/160472532; //vimeo.com/86851009

Problem solved: Reduce the plant-gate and dispensed costs of wind-source H2 fuel by > 20 - 40 %. Motivation is the deep decarbonization of humanity's total energy economy, as quickly as we prudently and profitably can. H2 and other electrofuels in very large quantity will be required as FCEV's displace BEV's except for light-duty, short-distance transport. Large "distributed" (without Grid connection), low-cost, wind-source H2 fuel can be harvested over large land areas not served by electricity transmission, assuming pipeline gathering, transmission, and delivery. AASI windplant is the ideal testbed for this pilot project.

Impact: Accelerate displacement of fossil by CO2-emission-free energy sources. Discover, demonstrate, and improve upon this novel system's H2 cost reduction and scalability potential. Project's proof-of-concept success will enable AASI to attract subsequent funding from one or several federal, State of California, and / or private enterprise sources toward profitable commercial products, for older turbine retrofits and for OEM:

a. Advance the SEIG-based electrolysis design and integrated SCADA, to improve stability, wind-to-Hydrogen energy conversion efficiency, and windplant energy capture via major new process innovation;
b. Demonstrate how savings in capex and O&M costs for the simpler SEIG-driven windplant-to-H2 system will allow extrapolation to MW and multi-MW scale reduction in the plant-gate cost of wind-generated H2 fuel. We expect to demonstrate > 20% potential lower plant gate cost than H2 fuel from wind systems delivering grid-quality electricity to AC or DC grid systems for distant H2 conversion. Pipeline gathering, transmission, storage (by packing pipeline), distribution, integration should add > 20% cost reduction in dispensed price of wind-source H2 fuel vis-a-vis the electricity Grid. We compare complete RE systems;
c. Improve baseline: the SCADA system will calculate the power curve for the wind turbine and plant-to-Hydrogen system during Palm Springs windplant operation, i.e. kg H2 production as a function of windspeed. SCADA analysis will guide hardware and software design advances to improve the windplant power curve vis-a-vis the baseline, to confirm small- and multi-MW-scale potential for H2 cost reduction;

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c. Demonstrate how savings in capex and O&M costs for the simpler SEIG-driven windplant-to-H2 system will allow extrapolation to MW and multi-MW scale reduction in the plant-gate cost of wind-generated Hydrogen (H2) fuel. We expect to demonstrate > 20% potential lower cost than H2 fuel from wind systems delivering grid-quality electricity to AC or DC grid systems for distant H2 conversion. Pipeline gathering, transmission, storage (by packing pipeline), distribution, integration may add > 20% cost reduction in dispensed price of wind-source H2 fuel vis-a-vis electricity Grid, for total > 40% H2 fuel cost reduction;
d. Acquire a MW-scale, custom-engineered, electrolysis plant to embrace all 13 turbines, to produce ~ 11,000 kg H2 fuel per year, improving accuracy of (b), preparing for system commercialization. Three electrolysis plant suppliers will propose a custom-engineered solution, collaborating with NREL research;
e. Operate the full windplant, ideal testbed, for years, collecting data for NREL and others to establish the commercial value of this novel wind-to-H2 generation technology, to refine system hardware and software for commercialization, and for preparing technical papers. Long-term economic impact will be lowering the cost of wind-source hydrogen fuel and greatly expanding wind's geographic harvest area, without costly expansion of the electricity grid, but assuming an extensive new, dedicated, high-purity, underground Hydrogen pipeline network of lower capex per MW-km than electricity lines as ITS proposed in Fig. 4.

H2 and other electrofuels in very large quantity will be required as: (1) FCEV's displace BEV's except for light-duty, short-distance transport; (2) CA and other states achieve both their RPS and transport sector CO2 emission reduction goals; (3) accommodating larger penetration of wind and solar variable generation (VG) on the Grid becomes costly to electric utilities and their ratepayers; (3) large amounts of VG energy is lost, curtailed; (4) large investment in Grid expansion would be required to access new land areas for harvest of high-intensity wind and solar resources; (5) pipeline gathering, transmission, storage, and distribution of H2 becomes widespread, via a new high-purity H2 pipeline system or by extraction from power-to-gas mixes; (6) renewable energy (RE) transport and CHP fuels must compete with fossil sources, absent C-taxes, and (7) demand for C-free CHP fuel develops. Large "distributed" (without Grid connection), low-cost, wind-source H2 fuel can be harvested over large land areas not served by electricity transmission, assuming pipeline gathering, transmission, free storage -- by pipeline packing -- and delivery.

3. STATE Of ART Modern wind turbines > 100 kW are designed for delivery of all captured energy as Grid-quality electricity, to the Grid, requiring complex and costly generating systems, costly field wiring and transformers, substations and transmission lines, and extensive regulation. Wind turbines and plants dedicated to H2 production, with no connection nor energy delivery to the Grid, based on SEIG-mode developed here, will be free of these state-of-art constraints, reducing capex + O&M costs > 20% at plant gate plus > 20% dispensed cost saving by enjoying gathering, transmission, storage, distribution, and integration via pipeline at ~ 40% lower cost than via the Grid. Pipeline-packing storage is "free".

4. INNOVATION Figs. 1, 2. SEIG mode has been lab demonstrated for decades, but never commercialized in "distributed" wind turbines and windplants without Grid connection, nor in wind-to-H2 service. Close-coupling electrolysis stacks to a multi-turbine "wild DC bus", integrating and impedance-matching the output of several wind turbines, with a single SCADA system optimizing turbine, electrolysis, H2 compressor, and water supply, has never been done. Modern digital and power electronics should enable lower-cost, stable operation of wind-to-H2 systems than by Grid-connected systems. Only by NREL's design of the proof-of-concept pilot plant in Fig. 1, and by testing it at AASI's windplant, will we discover and demonstrate ~ 20 - 40% cost savings in H2 production.

5. RISKS AND CHALLENGES The NREL team is confident it can design, and deliver for windplant testing, the novel integrated system described above, although this high level of efficient system integration, with multiple SEIG-mode turbines feeding a single DC bus, close-coupled to the electrolysis stack array, plus turbine and compressor control, has never been attempted. NREL work:

> https://www.nrel.gov/docs/legosti/old/21436.pdf
> https://www.nrel.gov/hydrogen/wind-to-hydrogen.html

The primary challenges are system stability, good impedance matching, and efficient energy harvest of the impinging wind resource, across the range of windspeed and wind dynamics, as H2 fuel. The risk is technical failure to achieve stable, reliable, and efficient wind-to-H2 conversion in a scalable configuration, demonstrated on an operating multi-turbine, islanded, autonomous Palm Spgs windplant.

6. PROJECT PLAN AASI and NREL will define and evolve system design and specs. NREL will deliver in 12 months an integrated pilot plant, based on and incorporating turbine and electrolysis components provided by AASI. AASI will install this proof-of-concept plant at its Palm Springs windplant, connected to 2 or 3 turbines, for short-term test and SCADA data collection -- for design validation and improvement -- and for long-term test to estimate H2 cost reduction to be achieved by design maturation via AASI commercialization, and scaleup to multi-MW. Present technical papers.

7. TEAM AASI manages project. Wintec Energy Ltd donates site use and water. NREL designs and builds the proof-of-concept pilot plant, via team partnering with AASI on other applications:

> William C. Leighty, AASI, Principal: BSEE, MBA. 20 years experience in wind industry. Project manager; Palm Springs windplant prep, conversion, ops management; reporting + commercial
> Robert Preus, PE, NREL, Distributed Wind Manager: 30 years experience in wind industry. NREL POC, project oversight, SCADA architecture + software development, windplant install.
> Eduard Muljadi, PhD, NREL, Senior Engineer, Electric Systems: 30 years experience; 25 at NREL. SEIG development and test: custom power electronics + software; dyno test wind simulation.
> Kevin Harrison, PhD, NREL, Senior Engineer, H2 electrolysis: 20 years experience at NREL. Close-coupling windplant wild DC bus to electrolysis stack array; SCADA integration; test.
> Adjuncts, as funding allows: Mark Nelms, PhD, EE Dept head, Auburn Univ; Ping Hsu, PhD, EE Dept head, San Jose State Univ; Sadrul Ula, PhD, CE-CERT, UC Riverside; Woonki Na, PhD, Fresno State Univ. SCADA data review; estimate H2 cost reduction, commercial potential.

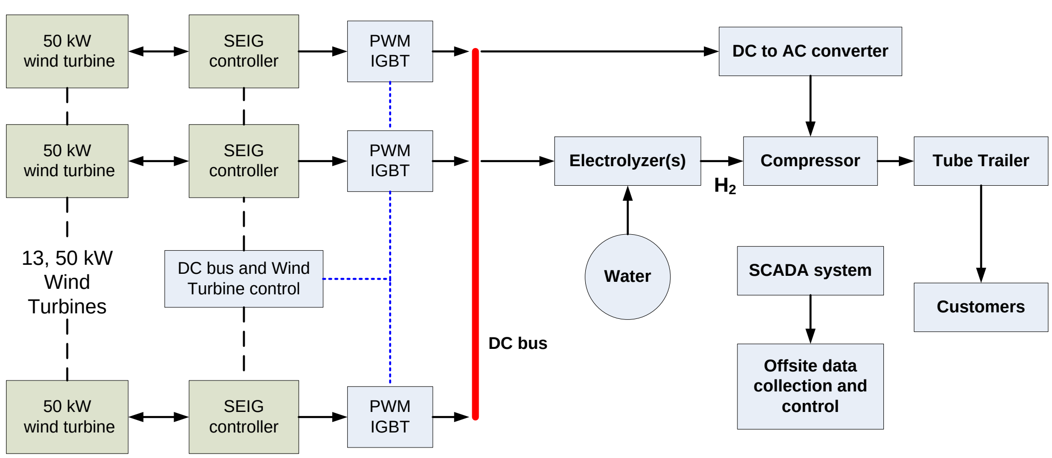

Figure1. The novel technology to be developed at NREL by their wind-to-Hydrogen team using the small dyno for power electronics and controls engineering verification. Prototype hardware capable of 2 or 3 turbines will be deployed at AASI's Palm Springs windplant for 6 months' data collection, software improvements, H2 fuel delivery.

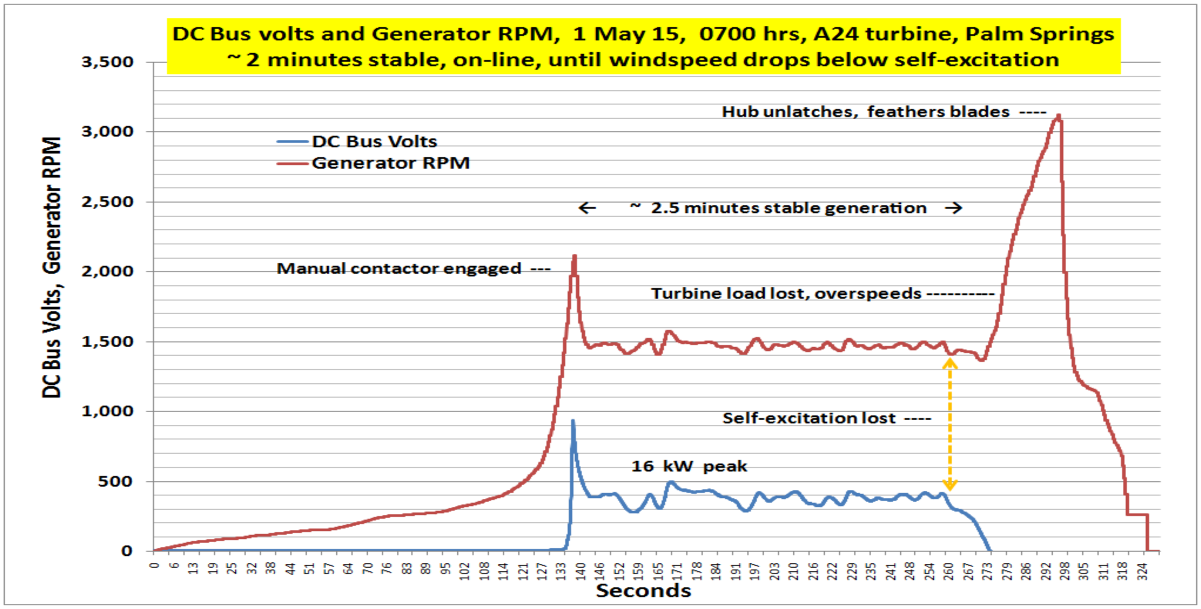

Figure 2. SEIG mode test on one of AASI's 13 Palm Springs 50 kW wind turbines, variable speed, "wild AC" to "wild DC" to resistive load. Self-excitation lost at low windspeed. No grid connection. https://vimeo.com/160472532

Figure 3. AASI's 13-turbine Palm Springs windplant, ready for conversion to dedicated "distributed" Hydrogen fuel production, with no connection to the SCE grid. "IDEAS" project will embrace 2 or 3 turbines; success will set the stage for attracting further funding to advance the SEIG-based electrolysis design and integrated controls. This will include acquisition of a MW-scale, custom-engineered electrolysis plant to embrace all 13 turbines, produce ~ 11,000 kg H2 fuel per year, and prepare for system optimization + commercialization. Three leading electrolysis plant vendors partnered with NREL, Sunline Transit, AASI, and others on AASI's ARPA-E "OPEN" Full Application, and will propose plant + in-kind custom engineering contributions in future projects.

Hydrogen fuel demand, CA, 2050, Million metric tons (MMt) / year:	
Light Duty Vehicles (LDV)	3.6
Trucking	1.6
Bus	1.4
Aviation and Other	0.8
Total	**7.4**

Source: interpret and extrapolate from papers by ITS-STEPS, UC Davis

Reference: Year 2015	**GW**
Total installed nameplate wind generation in California	6
Total installed nameplate solar generation in California	12
ELECTRICITY: California "Power Mix"	**GWh**
2014: Total electricity consumed	296,843
2050: Total electricity demand "Power Mix" is 130 % of 2014	385,896
ELECTRICITY in Year 2050	**GW**
Equivalent nameplate wind generation capacity @ 40 % CF	85
Equivalent nameplate solar generation capacity @ 35 % CF	97
TRANSPORTATION Hydrogen Fuel in Year 2050	**GW**
Equivalent nameplate wind generation capacity @ 40 % CF	126
Equivalent nameplate solar generation capacity @ 35 % CF	130

Figure 4. Large, new, dedicated, high-purity Hydrogen pipeline systems in CA will accelerate distributed wind deployment, providing a lower- cost transmission, storage, and distribution alternative to electricity systems, opening large windy land areas now without electricity transmission. Gaseous Hydrogen pipelines may be "packed" for "free" storage. Underground pipelines cost less per MW-km than electric lines. In CA in 2050 the market for CO2-emission-free (CEF) transportation fuel energy will exceed the market for CEF grid electric energy.