Paralleled Self-Excited Induction Generators (SEIG's) for Optimized Hydrogen Fuel Production from Stranded, Multi-turbine Windplants:

R&D and Demonstration at an Operating 13-turbine Palm Springs Windplant

This transformative project's success will reduce the cost of wind-generated hydrogen fuel and expand its geographic availability. It is a CRADA: all NSF funds will go to NREL for the team of three researchers who have partnered with the applicant on four unsuccessful applications: ARPA-E "OPEN" and "REFUEL", two SBV.

The NREL and AASI teams will design and build a unique off-grid wind-to-hydrogen system using an existing, stranded, 13-turbine windplant in Palm Springs, CA for testing and demonstration. Total windplant energy production will electrolyze water to produce hydrogen fuel for emerging nearby markets, for fuel cell buses and light duty vehicles, where large quantities of hydrogen fuel from diverse renewable energy resources will soon be required. This project is a fast path to production of hydrogen transportation fuel from a California windplant. It will develop and demonstrate two novel technologies for lowering the cost of wind-generated hydrogen fuel:

1. Self-Excited Induction Generator (SEIG) system controller at each wind turbine, simplifying the generator system, using generic, robust, low-cost induction motors as generators, thereby lowering wind turbine capital and O&M costs
2. Windplant and electrolysis plant integrated control for maximum wind energy capture and hydrogen fuel production; electrolysis stacks close-coupled to the turbine DC bus

PROBLEM AASI needs help from NREL's unique resources team to design and dyno-test this novel, simple system of power electronics and controls, close-coupling multi-turbine SEIG generators via a common DC bus to the electrolysis stacks, preparing a prototype system for deployment for field testing for 6 - 12 months of SCADA data collection and design improvement at AASI's Palm Springs windplant:

- Kevin Harrison: wind-to-H2 systems; windplant DC bus to electrolysis stacks drive PE; controls
- Robert Preus: distributed wind systems design and deployment; integration of H2 fuel systems
- Ed Muljadi: rotating machine systems, dyno test, SEIG controls integrate with electrolysis SCADA
- Woonki Na and Ping Hsu: (Fellows, Ed Muljadi) rotating machine systems, SEIG controls, dyno test

The above NREL team collaborated in this RFA preparation, partnered in AASI's unsuccessful $ 3 M Full Application for the 2015 ARPA-E "OPEN" FOA, and is ready to employ several used electrolysis plant components and a spare motor from AASI to commence NREL's SEIG-to-H2 design. Project success will be achieved, documented, and used for AASI's commercial purposes, to expand wind deployment, by:

a. Design, assembly, and dyno test of a pilot-scale SEIG-based wind-to- H2 system at NREL;
b. Packaging the system with SCADA and comm in a CONEX at NREL, for transport to Palm Springs;
c. 6 -12 months operation on 1- 3 AASI turbines; SCADA data analysis; system design improve; papers;
d. Enabling AASI's SCADA analysis for hardware + software advance on the SEIG-electrolysis system;
e. Long-term test and demo to attract customer interest, advancing system design to production-ready.

NREL's facilities and expertise are not globally elsewhere available and affordable to small business. The AASI Palm Springs windplant is the perfect test bed and demonstration site for the wind industry's first distributed wind-to- H2, SEIG-driven, close-coupled electrolysis system with plantwide integrated controls. AASI depends upon the NREL partners team from our 2015 ARPA-E "OPEN" Full Application to design the SBV protocol and scope of work and to estimate the RFA cost, to best address the Problem.

Figure 3. The novel technology to be developed at NREL by their wind-to-H2 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, system design improvements, H2 fuel delivery.

The best wind resources are often stranded, with neither costly electricity grid transmission to distant markets nor firming storage for their time-varying output. Wind generation often peaks at night, when demand and price are low, and is minimum in summer, when demand and price peak. An alternative to electricity systems is required for a dispatchable supply of transportation and Combined Heat and Power (CHP) fuel, potentially a larger aggregate energy market than the electricity grid, in California and nationwide, as both "power-to-fuel" and "power-to-gas".

Converting the entire windplant output to hydrogen fuel, with no electricity grid connection, enables low-cost transmission and distribution via underground pipelines, and low-cost annual-scale firming energy storage in deep salt caverns and packed pipelines, at large scale. SEIG-equipped wind turbines and windplants may be located in any good wind area, their hydrogen fuel delivered by trucks and pipelines. Project success should proliferate SEIG-equipped wind-to-hydrogen investments; scaleup should be feasible as hydrogen fuel demand expands.

This project's transformative technologies are novel, intelligent controllers for:

a. The SEIG on each wind turbine generator, and

b. Combining the "wild DC" output of the turbines on a DC bus directly feeding the electrolyzer(s), eliminating the costly "transformer-rectifier subsystem.

The complete system will be assembled and demonstrated at applicant's extant Palm Springs windplant, for at least two years. Figure 2. We have demonstrated stable SEIG-mode operation on one of the turbines at the Palm Springs windplant, with fixed shunt capacitance on the delta-connected generator stator. The NREL research team will advance this finding by:

1. Designing an SEIG controller for installation on each wind turbine, by which optimum self-excitation is maintained, at startup and shutdown, and under varying wind and load. Several topologies will be considered, featuring rectification of "wild AC" to "wild DC" at each wind turbine, for delivery to a common windplant DC bus, impedance-matching electrolysis stacks.
2. Designing a complete, integrated, wind-to-H2 plant controller to manage and dispatch turbine(s) and to optimize impedance matching to the electrolysis plant, for:
    a. Maximum wind energy harvest
    b. Efficiency in conversion to hydrogen fuel
    c. Electrolysis plant operation, protection, and safety
3. Customizing the electrolysis plant design by eliminating the "transformer-rectifier" subsystem and by integrating the electrolysis plant controls with the windplant controller
4. Analyzing data from the windplant SCADA system to improve the wind-to-hydrogen plant design and operation, at every level.

We expect that valuable IP will result from the successful project, in the form of control system hardware and software designs, which we intend to commercialize at multiple scales. We expect that project success will enable us to find funding by which to convert the entire 13-turbine windplant to Hydrogen fuel production of ~ 11,000 to 15,000 kg per year, with no connection to the Southern California Edison (SCE) Grid. We will buy our own tube trailer, for hydrogen fuel transport and delivery to customers: Sunline Transit, only 23 km away, operates many fuel cell buses and could use our full production.

Sunline partnered with us on the ARPA-E "OPEN" Full Application and wishes to buy the project's Hydrogen fuel if we can deliver it at an attractive pressure, purity, and price..

We intend to operate the wind-to-hydrogen plant profitably for several years after the project term, as a test bed, continuing to collect and publish operating data and improving system design.

Three NREL and two adjunct research staff teamed with AASI for this project. Contract help, as needed, will be from: UC Riverside (CE-CERT, Bourns Engrg); John Cornish, EPC, Lakewood, CO

BROADER IMPACTS Figures 5 - 10. Humanity needs to immediately accelerate its transformation of the world's largest industry from ~ 85% fossil to ~ 100% renewable energy sources. We cannot do that, and should not try, via electricity systems alone; they are probably technically and economically suboptimal for supplying all humanity's energy needs from renewable resources. We will also need carbon-emissions-free fuel systems to solve the three salient, chronic problems of time-varying renewable energy systems:

1. Gathering and transmission
2. Annual-scale firming storage, rendering renewables "dispatchable"
3. Distribution, integration, and end-use

The primary problem that SEIG, and multi-generator SEIG, may solve: Electricity systems can be adapted, at significant cost, with adjunct power electronics and energy storage and backup generation, to accommodate a large fraction of time-varying renewable energy input to the electricity sector. But electricity systems are probably a suboptimal technical and economic solution for the necessary transformation of the entire energy industry and its market segments, from fossil to renewable sources:

1. Overhead electric transmission lines are relatively expensive to build, per MW-km of transmission service, and are difficult to site.
2. O&M costs are high for overhead electric transmission and distribution lines vis-à-vis underground pipelines.
3. Without abundant storage and / or curtailment, electric line capacity factor is generally limited to the capacity factor of the sources.
4. Since the system operates in real time, at light speed, costly adjunct components and subsystems are required to maintain system stability and energy dispatchability.
5. Since annual-scale firming storage with "electricity" devices is not affordable, costly investment in backup generation, usually operating at low capacity factor, is required.

Thus, alternatives to electricity must be thoroughly considered, as complete renewable energy systems, from photons and moving air and water molecules to delivered energy services. Hydrogen, anhydrous ammonia (NH_3), and other "liquid hydrogen" fuels are attractive alternatives:

1. Generation, including conversion, may be less costly than for electricity systems
2. Transmission and storage are less costly than for electricity systems
3. Freedom from electricity grid connection greatly expands geographic harvest range
4. Complete renewables-source hydrogen and ammonia fuel systems may simultaneously solve renewable energy's three salient problems: transmission, storage, integration.

The best wind resources are often stranded, with neither costly electricity grid transmission to distant markets nor firming storage for their time-varying output. Wind generation often peaks at night, when demand and price are low, and is minimum in summer, when demand and price peak. This project's disruptive technologies are novel, intelligent controllers for (a) the SEIG on each wind turbine generator, and (b) combining the "wild DC" output of the turbines on a DC bus feeding the electrolyzer(s) to convert 100% of wind-generated electricity to hydrogen fuel, with no grid connection, for:

1. Transmission in underground pipelines

2. Storage in large, deep, salt caverns; in “packed” pipelines; in distributed vehicle tanks
3. Distribution for transportation and combined-heat-and-power (CHP) fuel

Wind and other turbines may consequently be equipped with simple, robust, low-cost, squirrel cage induction motors as generators, with minimal power electronics, and without field transformers and high voltage infrastructure, producing “wild AC” to “wild DC” to feed the electrolyzer stack(s). This results in:

1. Better mechanical load and electrical impedance matching between wind turbine and load
2. Lower cost of hydrogen fuel produced by wind and other variable-generation sources equipped with rotating-machine generators
3. The ability to combine the electric energy output of multiple wind turbines and other rotating renewable generation harvesters, on a common DC bus, to the electrolysis plant

Figure 25. The SEIG concept. SEIG-equipped wind turbines and windplants may consequently be located in any good wind area, their hydrogen fuel delivered by trucks and underground pipelines. Project success should proliferate profitable SEIG-equipped wind-to-hydrogen projects, especially in places with good wind resources and inadequate electricity transmission. In turn, this will hasten the adoption of hydrogen fuel for:

1. Transportation, in fuel cell cars, buses, and eventually, ships and aircraft
2. Stationary Combined Heat and Power (CHP) systems
3. Power-to-Gas, for direct injection into natural gas pipelines, to deliver mixed-gas fuel, with very low transmission and storage costs, to a hydrogen concentration limit

Project success will thus be disruptive:

1. Lowering the cost of hydrogen fuel produced by wind and other rotating-machine electricity generating systems; displacing DFIG and other more complex and costly systems on wind turbines
2. Expanding the geographic area over which wind energy may be profitably harvested

Figures 6 and 7. For an impact example, if 20% of California’s 45 million light duty vehicles (LDV’s) were hydrogen-fueled, fuel cell hybrid electric vehicles (FCHEV’s), driven 15,000 miles per year at 68 miles per kg hydrogen fuel, they would consume ~ 1.7 million tons of hydrogen fuel per year. That would require the full output of ~ 23,000 MW nameplate wind, at 40% capacity factor (CF). Importing that amount into California would require 3 hydrogen transmission pipelines, of 1 meter diameter, at 100 bar. Firming that fuel supply at annual scale, rendering it “dispatchable”, would require ~ 90 deep, solution-mined, salt storage caverns.

Example: In CA in 2050, transport H_2 fuel alone will require ~20 times today's installed wind capacity or ~ 25 times today's installed solar capacity, or equivalent combinations with other CEF sources:

INNOVATION TECHNOLOGY TO MARKET

Figure 2,3. This project’s SEIG application and system integration and optimization has not been attempted on an operating multi-turbine windplant. For decades engineering literature has recommended the SEIG for wind generation, but only in the past decade has power and control electronics advanced enough to enable its stable, efficient, and economical variable-output operation. But, SEIG has not been deployed with commercial success, anywhere.

Value: The H2 fueling stations now being installed with State of California funding are required to acquire one-third of their dispensed H2 from CEF sources. As fuel cell light duty vehicles (LDV's), buses, and trucks proliferate, the demand for CEF H2 will rapidly increase. This SBV project success will enable proliferation of off-grid windplants equipped with the simpler SEIG-driven H2 generation systems, producing high-purity H2 fuel, over a large geographic area, feeding the new, dedicated, underground, high-purity gaseous H2 (GH2) pipeline network in Fig. 4, dispensing H2 fuel at > 20 % lower cost than H2 made from grid electricity sourced from windplants burdened by the generating systems and infrastructure required to deliver grid-quality AC or DC. This H2 will bestow large beneficial impacts on CA's energy economy, and beyond, as the US and the world emulate the CA "lighthouse" transportation fuel and electricity systems, and the total CA energy system, pipelining in Great Plains wind and solar.

In CA in 2050, transport H2 fuel alone will require ~20 times today's installed wind capacity or ~ 25 times today's installed solar capacity, or equivalent combinations with other CEF sources:

NSF project proof-of-concept success will enable AASI to attract subsequent funding toward market readiness from one or several federal, State of California, and / or private enterprise sources to:

a. Advance the SEIG-based electrolysis design and integrated SCADA, to improve stability, wind-to-H2 energy conversion efficiency, and windplant energy capture: a major new energy capture innovation;

b. Improve baseline: the SCADA system will calculate the power curve for the windplant-to-H2 system in Palm Springs windplant operation, i.e. kg H2 production as a function of windspeed, with appropriate sample time averaging. NREL lab testing will determine the kWhe per kg H2 power curve for optimized electrolysis and dyno-driven SEIG subsystems. SCADA analysis will guide SEIG-close-coupled-electrolysis hardware and software design advances to improve windplant power curve vis-a-vis baseline.

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 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.

d. Acquire a MW-scale, custom-engineered, electrolysis plant to embrace all 13 turbines, to produce ~ 11,000 kg H2 fuel per year, improve the accuracy of (b), and prepare for system commercialization. Three electrolysis plant suppliers will propose a custom-engineered solution, collaborating with NREL research;

e. Operate the full windplant for years, collecting data for NREL and others to establish the commercial value of this novel wind-to-H2 generation technology, refine system hardware and software for preparing technical papers, and for commercialization. Long-term economic impact will be (a) lowering the cost of wind-source H2 fuel; (b) eliminating curtailment; (c) greatly expanding wind's geographic harvest area, without costly expansion of the electricity grid, but assuming an extensive new, dedicated, high-purity, underground H2 pipeline network of lower capex per MW-km than electricity lines as ITS proposed in Fig. 4; (d) enabling "H2@SCALE", deep decarbonization of the complete US and global energy system.

USE OF PROJECT RESULTS The IP established by this SBV and sequentially-funded projects will enable AASI to promptly redesign, manufacture, and eventually license this technology, at small and large scales. The immediate market is hundreds of small, old, still-operating wind turbines in CA that could easily be retrofitted for SEIG-mode H2 fuel production. The next market is new distributed wind turbines and MW windplants. Major wind OEM's will independently develop and adopt this technology, motivated by:

- Lower capex and O&M costs of dedicated H2 and Ammonia energy production, transmission, and storage systems vis-a-vis electricity systems, at both distributed and continental scales;
- Higher value per wind-generated kWh for H2 and NH3 fuel production than for the grid;
- Eliminating curtailment by total output delivery as H2 and NH3 fuels to storage-backed pipelines;

- Wind deployment over far wider geographic areas, serving the H2 fuel market via pipelines.

In CA in year 2050 the demand for CEF transportation fuel will probably exceed the demand for CEF grid electricity by > 30 %, a major new market for wind and other CEF energy sources. Fuel cell transportation will succeed only to the extent that abundant H2 fuel is ubiquitously available at competitive prices. Distributed wind-source H2 fuel production and a new pipeline network helps the EERE fuel cell program, and may motivate WWPTO to consider H2 and Ammonia systems as alternatives to electricity systems, including for offshore wind. This could launch a very large impact, emulating Japan's interest in importing tanker loads of H2-rich liquids from CEF sources worldwide -- perhaps especially from Alaska. Japan's NEDO assignments: Kawasaki, LH2. Sumitomo, NH3. Chiyoda, Methylcyclohexane (C_7H_{14}) < > Toluene. Thus, we build a global energy "hydrogen sector".

Hydrogen fuel demand, CA, year 2050, **Million metric tons per 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 several 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

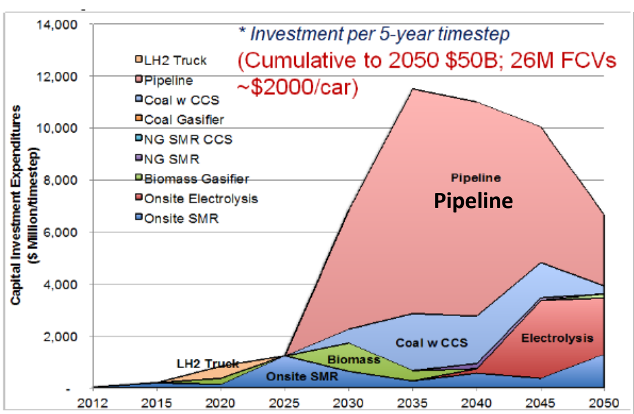

Figure 1.   Large, new, dedicated, high-purity Hydrogen pipeline systems in CA will accelerate distributed wind deployment, providing lower- cost transmission, storage, and distribution alternative to electricity systems, opening large windy land areas now without electricity transmission, as in DOE "H2@SCALE".   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 CEF transportation fuel energy will exceed the market for CEF grid electric energy. Source: ITS-STEPS, UC Davis

Figure 1. Broad Impact: If California achieves both its RPS and "80 in 50" transportation sector goals, by year 2050, it will need more CO_2-emissions-free energy for Hydrogen transportation fuel than for the electricity grid. Total electricity plus Hydrogen production in 2050 will require over 400,000 MW of nameplate generation, probably a mix of wind and solar. That will require building a new, dedicated, high-purity, underground, Hydrogen pipeline infrastructure between 2025 and 2050: area under the "Pipeline" curve is ~ $ 50 - 60 billion. However, this may be less capex investment than expanding and upgrading the electricity grid will require.

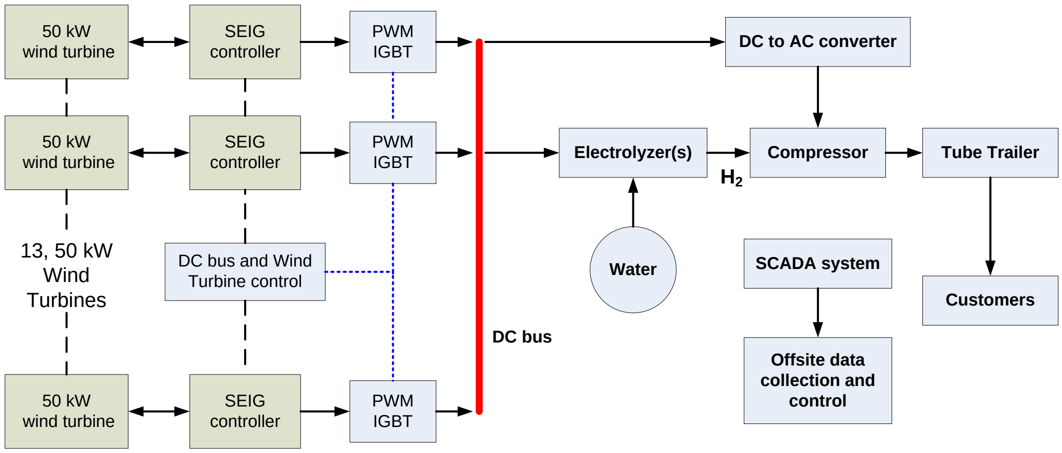

Figure 2. This project will develop novel Self Excited Induction Generator (SEIG) power electronics and controls allowing close-coupling of the electrolysis stacks to the windplant DC bus, eliminating the costly "transformer-rectifier" subsystem in off-shelf electrolysis plants.

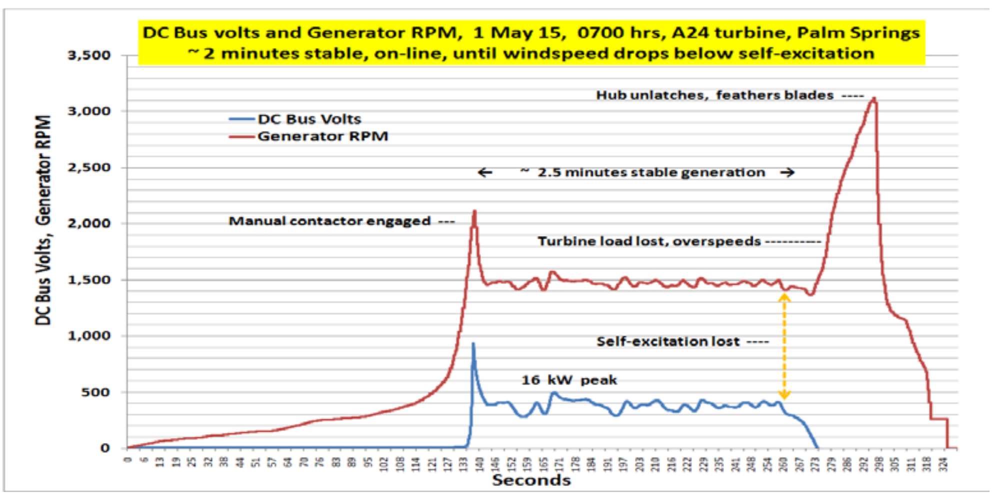

Figure 2. SEIG mode test on one of AASI's 13 Palm Springs 50 kW wind turbines, variable speed, "wild AC" to "wild DC" to resistive load. Self-excitation lost at low windspeed at 260 sec. No grid connection. Video: https://vimeo.com/160472532

Figure 3. AASI has demonstrated SEIG mode operation on one of its Palm Springs windplant turbines, under short-term manual control. Thus, prospects for project success are good, if a reliable autonomous control system may be developed by the NREL and AASI team for stable operation, close-coupled to the electrolysis stacks.

For a decade, engineering literature has reported wind-to-hydrogen systems research. However, few – if any – wind-to-hydrogen fuel plants have been built anywhere to supply merchant fuel, none in the USA, and none with:

1. SEIG rotating generation systems
2. Multiple turbines via optimization control, feeding a common DC bus, driving an electrolysis plant with electrolysis stacks close-coupled to the DC bus

Therefore, the project's disruptive innovation is the novel coupling of multiple SEIG-equipped wind turbines to an electrolysis plant with intelligent controls and minimum power electronics, resulting in:

1. Lower cost for hydrogen fuel than available from coupling off-the-shelf electrolyzers and wind turbines, of any size

2. Expanded geographic availability of wind-generated hydrogen fuel, by removing dependence on the electricity grid

Project performance goals:

1. Wind energy generation and energy conversion system capacity factor = 40%
2. Electricity-to-hydrogen energy conversion efficiency = 55 kWh / kg H_2
3. Hydrogen fuel cost < $ 3.50 / kg at the project windplant gate
4. Average annual production of 11,000 kg H_2 , all sold at plant gate for > $5.00 / kg
5. Demonstrated probable MW-scale, wind-to-hydrogen system economics, assuming no connection to the electricity grid, with total energy production delivered as hydrogen fuel at the plant gate:
   a. Capital cost savings of ~ $ 130,000 / MW vis-à-vis electricity grid delivery
   b. Capital cost for electricity-to-hydrogen conversion system of ~ $ 1 M / MW

These performance goals are derived from industry experience and practice, from literature and industry and engineering conferences:

1. Wind turbine manufacturing
2. Windplant construction
3. Electrolysis plant manufacturing, although at low series-production volume
4. Electrolysis plant energy conversion efficiency
5. The nascent retail market for hydrogen fuel in Los Angeles: estimated at ~ $ 9.00 / kg; the wholesale market is estimated at $ 5.00 – 6.00 per kg

Figure 4. Land-based windplant capital cost components: 3 charts. Source: NREL, RESCO We estimate the hydrogen fuel production cost reduction from the SEIG-equipped multi-turbine windplant in Figures 1 and 2, when scaled to a 100 MW windplant of modern MW-class turbines, based on Figure 4 and total installed turbine cost of $ 2 M per MW nameplate:

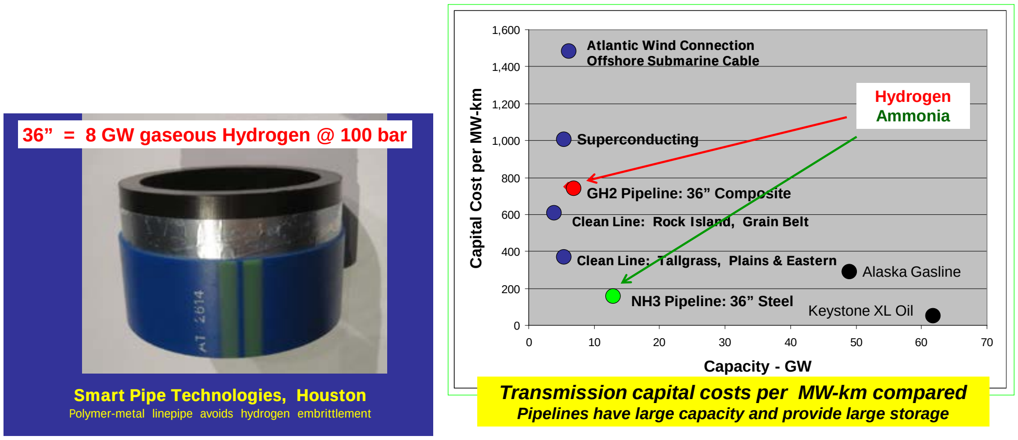

Figure 5. Transmission and distribution pipe: a thin Al or Cu foil provides the hydrogen permeation barrier, avoiding the hydrogen embrittlement danger inherent in steel linepipe. Hydrogen transmission pipelines are comparable in capex, and lower in O&M cost, than electricity transmission lines.

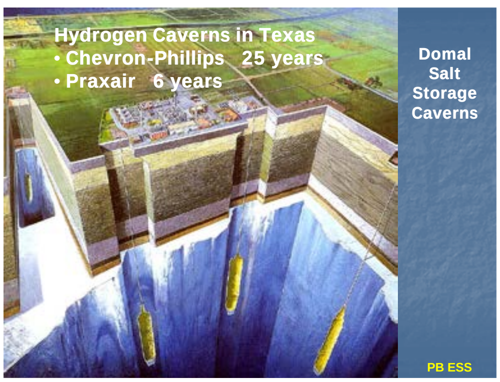

Figure 6. GH2 storage in large, deep caverns in domal salt geology. Each cavern stores ~ 2,500 metric tons (Mt) hydrogen at 150 bar: ~ 92,000 MWh. Caverns capital cost is ~ $ 5 M plus ~ $10 M "cushion gas" GH2, for total ~ $ 0.16 / kWh. Caverns may be manifolded at common pressure, to share surface facility for compression, gas drying, metering, monitoring.

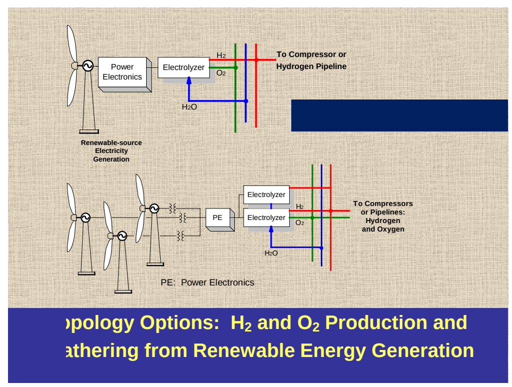

Figure 7. Windplants dedicated to Hydrogen fuel production, with no grid connection, eliminate the costly capex and O&M costs of electricity subsystems and infrastructure needed to deliver grid-quality power: miles of buried copper wire, substation and transmission feeder line, and often the transformer at the base of each turbine.

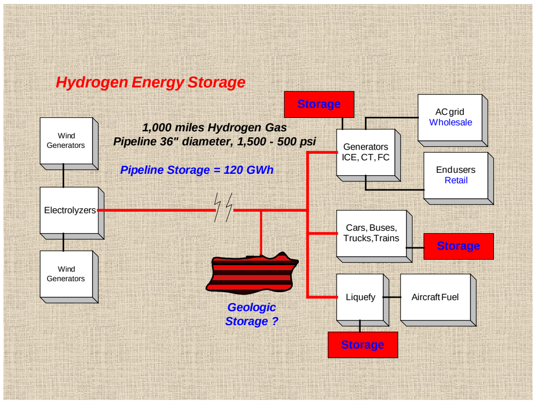

Figure 8. Gaseous Hydrogen (GH2) storage is very low cost at large scale. "Packing" the pipelines, as the natural gas industry does, costs only the compressor energy. Salt cavern storage capex is < $ 1.00 / kWh.

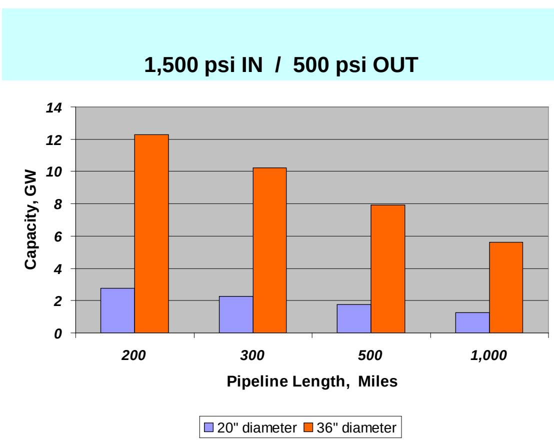

Figure 9.   GH2 pipeline capacity, without midline compression, is large, enabled by the low viscosity of GH2. High-pressure-output electrolyzers directly feed the transmission pipeline at 100 bar. Pipeline friction losses reduce city-gate delivery pressure to a convenient ~ 30 bar.

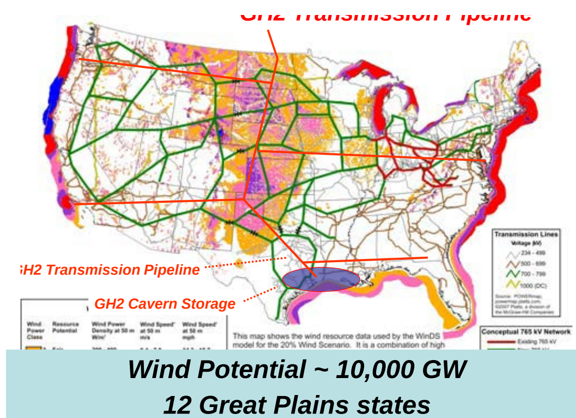

Figure 10.   A continental network of gaseous hydrogen (GH2) transmission pipelines enables low-cost gathering, annual-scale firming storage, distribution, and end-use of diverse renewables.

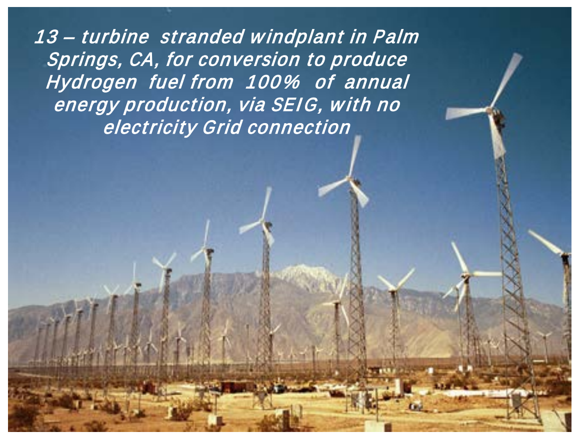

Figure 11. AASI's 13-turbine Palm Springs windplant which will be dedicated to the project.

Figure 12. Two used Proton Onsite model H6m electrolysis plants are owned by AASI, stored in Golden, CO, and will be dedicated to the project.

TRANSFORMATION POTENTIAL SEIG-equipped wind turbines and windplants may consequently be located in any good wind area, their hydrogen fuel delivered by trucks and underground pipelines. Project success should proliferate profitable SEIG-equipped wind-to-hydrogen projects, especially in places with good wind resources and inadequate electricity transmission. In turn, this will hasten the adoption of hydrogen fuel for:

1. Transportation, in fuel cell cars, buses, and eventually, ships and aircraft
2. Stationary Combined Heat and Power (CHP) systems
3. Power-to-Gas, for direct injection into natural gas pipelines, to deliver mixed-gas fuel, with very low transmission and storage costs, to a hydrogen concentration limit

Project success will thus be disruptive:

1. Lowering the cost of hydrogen fuel produced by wind and other rotating-machine electricity generating systems; displacing DFIG and other more complex and costly systems on wind turbines
2. Expanding the geographic area over which wind energy may be profitably harvested

Figures 6 and 7. For an impact example, if 20% of California's 45 million light duty vehicles (LDV's) were hydrogen-fueled, fuel cell hybrid electric vehicles (FCHEV's), driven 15,000 miles per year at 68 miles per kg hydrogen fuel, they would consume ~ 1.7 million tons of hydrogen fuel per year. That would require the full output of ~ 23,000 MW nameplate wind, at 40% capacity factor (CF). Importing that amount into California would require 3 hydrogen transmission pipelines, of 1 meter diameter, at 100 bar. Firming that fuel supply at annual scale, rendering it "dispatchable", would require ~ 90 deep, solution-mined, salt storage caverns.

California recognizes that large investments in hydrogen pipeline systems will be needed. California cannot meet its goal of "80 x 50", an 80% reduction in Greenhouse Gas (GHG) emissions from transportation sources by Year 2050 with battery-electric vehicles, (BEV's) alone, without many FCHEV's operating on carbon-emissions-free hydrogen fuel.

Water feedstock consumption for electrolysis is an important impact in California. 9 kg of fresh water is required for each kg of hydrogen fuel. This project will therefore consume ~ 100,000 kg per year, about 26,300 gallons. The Palm Springs windplant site has municipal water supply, which will be available for this project. An equivalent amount of water will be generated at each hydrogen fuel point-of-use, but prospect for collection and re-use is unknown.

Figure 8. At USA national scale, this magnitude of hydrogen demand for transportation fuel alone, would justify a continental-scale infrastructure of pipelines and GH2 storage caverns dedicated to the gathering, transmission, firming storage, distribution, and end-use.

Figure 9. GH2 pipeline capacity, without midline compression, is large, enabled by the low viscosity of GH2. High-pressure-output electrolyzers may directly feed the transmission pipeline at 100 bar. Pipeline friction losses reduce city-gate delivery pressure to a convenient ~ 30 bar.

Figure 10. Project impact assessment must include SEIG propagation to complete wind-to-hydrogen systems. If low-cost salt cavern geologic storage is available, accessed by regional or continental GH2 transmission pipelines, wind-hydrogen systems are probably technically and

economically superior to wind-electricity systems in delivering dispatchable energy services to end-users. GH2 storage at end-users enhances dispatchability. High-pressure-output electrolyzers may directly feed pipeline at 100 bar. Pipeline friction losses reduce city-gate delivery pressure to a convenient ~ 30 bar.

"Today, for the first time ever, G7 leaders have rallied behind a long-term goal to decarbonize the global economy." [8 June 15] As we accelerate our transformation of the world's largest industry, from ~ 85% fossil to ~ 100% renewable sources, we will need renewable energy systems that supplement and transcend the electricity grid. We cannot, and should not try to, "decarbonizes the global economy" with electricity systems alone. We will need hydrogen, and perhaps other C-emissions-free fuel systems, to solve renewables' three primary challenges: transmission, storage, and integration.
Japan is researching three strategies for transporting hydrogen from CO2-emissions-free sources, to Japan, as several liquid fuels, at very large scale, in commodity ocean tankers:

1. Liquid Hydrogen (LH2) By: Kawasaki Heavy Industry (HI)
2. Liquid anhydrous ammonia (NH3) By: Sumitomo Chemical and HI
3. Methylcyclohexane (C7H14) (MCH) By: Chiyoda Chemical and HI

Therefore, we should expect increasing global demand for renewables-source hydrogen, and begin now to reduce the cost of producing it from wind and other rotating generators, in both distributed and centralized configurations, via this potentially transformative SEIG project. We should also now conceive, design, build, and operate proof-of-concept gaseous hydrogen pilot plants, whereby gaseous hydrogen (GH2) fuel is gathered from diverse sources in a generation corridor, transmitted to a destination community via underground pipeline at 100 bar, and distributed for transportation and CHP.

COMPANY HISTORY Alaska Applied Sciences, Inc. (AASI) was founded in Juneau, Alaska, in 1990 as a renewable energy R&D and science education company. AASI's delivered electric energy from its Palm Springs R&D windplant to the SCE grid for 21 years, until the PPA expired in 2012. We improved many aspects of the vintage-1985 turbine design to improve its durability, reliability, and energy capture. In 2005 AASI completed blade manufacturing R&D on DE-FG36-03GO13140
Final: www.osti.gov/servlets/purl/859303-oXetpM/

AASI is now ready to convert its Palm Springs windplant entirely to "distributed" H2 fuel output, with no connection to the SCE grid. SBV project success enables wind deployment in a large new market. AASI's Full Application for ARPA-E 2015 "OPEN" FOA, for this RD&D technology, was not selected.

See video of the Palm Springs windplant in 2005, delivering electricity to the SCE grid at constant turbine RPM, with turbines' induction motors-as-generators locked at 60 Hz: https://vimeo.com/86851009
These turbines are equipped with common, rugged, low-cost, three-phase, 60 hp induction motors as generators. This windplant is the perfect test bed and scale for R&D and demonstration of this novel, low-cost, high-efficiency technology system for producing high-purity H2 fuel from wind-generated electricity, from single or multiple "distributed" turbines, with or without

connection to the electricity grid. Modified for Self Excited Induction Generator (SEIG) mode, the turbines would be closely coupled, via simple, smart rectification on a DC bus, to the electrolyzer stacks, via a SCADA system integrating the complete wind-to-H2 plant, to reduce system complexity and capital and O&M costs. This increases system reliability and maintainability, and reduces kWhe per kg H2, thus reducing plant gate H2 fuel cost.

This has been AASI's mission and vision for fifteen years: urging the renewable energy (RE) industry to seriously consider alternatives to electricity systems for gathering and transmission, affordable annual-scale firming storage, and distribution and integration of CO2-emissions-free (CEF) energy at small or large scales. H2 and Anhydrous Ammonia (NH3) are the attractive alternatives. See AASI Principal Bill Leighty's research papers, presentations, "H2@SCALE" comment: www.leightyfoundation.org/earth.php

No other company has proposed demonstrating this technology of SEIG-equipped turbines, closely coupled to electrolysis stacks or Anhydrous Ammonia synthesis reactors, on an operating multi-turbine windplant. This project's success could be scaled to multi-MW turbines and windplants, to produce, for example, ~7 million tons per year of H2 fuel required for the California (CA) transportation sector in year 2050 -- a larger market for CEF energy than electricity for the CA grid: AASI's vision. The project's H2 fuel will be delivered to Sunline Transit, 15 miles east on I-10, and / or to other local markets.

AASI has demonstrated SEIG mode operation on one of its stranded Palm Springs turbines, delivering rectified "wild AC", at variable speed, to a DC resistive load bank: Fig 3. https://vimeo.com/160472532

PROTON
THE LEADER IN ON SITE GAS GENERATION

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Bill Leighty 3 April 2016
Principal, Alaska Applied Sciences, Inc. (AASI)
Box 20993, Juneau, AK 99802-0993

Dear Bill,

I am writing to support your Small Business Voucher Request for Assistance, for the Palm Springs wind-to-H2 project. The application of PEM electrolysis technology for renewable energy storage has always been a primary vision of Proton OnSite. We have made a major financial commitment to bring a product to market that will enable that vision. The kind of research described in this SBV RFA for the NREL-led team will provide an important cabilityfor a new SEIG-based technology path to optimize the design of our M-Series platform for off-grid wind applications. This SEIG-based wind-to-H2 research has never been done before, and could be a breakthrough approach for reducing both system capital cost and improving electrical efficiency. Although Proton OnSite would not be directly involved in the SBV effort, we would be pleased to provide technical input to NREL to enhance the value of the AASI project.

Sincerely,

Stephen Szymanski
Director – Business Development

ITM POWER
Energy Storage | Clean Fuel

ITM Power supports the proposed project. Many of the R&D activities around the world are focused on grid tied hydrogen energy storage and this project provides a potential to increase efficiency of the process and reduce cost. ITM has a number of projects where we are either injecting hydrogen directly into a natural gas grid or using the hydrogen to fuel vehicles; all are grid tied. The development of controller and power supplied to work with the SEIG technology within this project would be a very exciting addition to our product portfolio and allow of grid renewables to be integrated with ease.

Sincerely,
Stephen Jones, Managing Director, ITM Power Inc.

LISA MURKOWSKI
ALASKA

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April 5, 2016

Mr. Mark Higgins, Operations Supervisor
U.S. Department of Energy, Energy Efficiency & Renewable Energy
Office of Wind and Power Technologies Office
1000 Independence Ave., SW
Washington, DC 20585

Re. Solicitation for Small Business Voucher Grant for Wind-source Hydrogen Fuels

Dear Mr. Higgins:

I am writing to ask that the Department of Energy's National Renewable Energy Laboratory consider granting a Small Business Voucher for research and prototype design for using the technology developed by Alaska Applied Sciences Inc. (AASI), to reduce the cost of Hydrogen and Anhydrous Ammonia carbon-free fuels made from wind turbines using specific technologies.

I have known the principal of AASI, Bill Leighty for more than two decades. He has published more than 20 professional papers and is recognized as an expert in developing renewables-source Hydrogen and ammonia energy systems. I am particularly interested in seeing this technology advance because of its potential applications to reducing the high-cost of energy in rural Alaska. Alaska's small, isolated communities could benefit greatly by reducing the cost of using seasonally produced renewable energy to produce carbon-free fuels.

My understanding is that AASI is seeking a $300,000 Small Business Voucher to prove the economic feasibility of using wind power from a 13-turbine wind farm at Palm Springs, CA to produce Hydrogen fuel by using low-cost, three-phase induction motors as generators, operating in Self Excited Induction Generator (SEIG) mode. Proof of this process would lower the cost of hydrogen fuel made from electricity generated by rotating machines, could increase the geographical area in which wind energy can be harvested, and simplify wind turbine and wind-to Hydrogen fuel productions systems nationwide.

This process could prove extremely useful to reducing energy costs in rural Alaska, where much of coastal and rural Alaska enjoy Class 6 and 7 wind conditions, and at windy sites without electricity transmission access nationwide. Consistent with all relevant rules, laws, and regulations, I respectfully request that all due consideration be given to funding this feasibility study, an outgrowth of AASI's unsuccessful Full Application for a $3 million grant from the ARPA-E "OPEN" solicitation last year, for a more complete version of this SBV project. I thank you for your consideration of this request.

Sincerely,

Lisa Murkowski
United States Senator