Lower-cost Hydrogen (H2) Fuel Production from Distributed Wind via Paralleled Self-Excited Induction Generators (SEIG's) & Close-coupled Electrolysis at Multi-turbine Off-grid Windplants

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ABSTRACT

Achieving the California (CA) "80 x 50" (80% reduction in CO_2 emissions from transportation, below 1990 level, by 2050) and other statutory and regulatory goals will require ~ 7 million tons (MMT) per year of high-purity, zero-carbon-emissions, Hydrogen fuel for surface transportation (LDV, bus, goods movement), by Year 2050. This would require full output of ~ 250 GW of nameplate wind and/or solar. Freight trucking, in CA, would require ~ 1.6 million tons per year. [1] Aviation Hydrogen fuel, if that market develops, supports CA Gov Brown's ambition to reduce CA's petrol-source transportation fuel use. “80 x 50” cannot be achieved with BEV’s, displaced by FCV's except for short, light-duty travel; attempting to is technically and economically suboptimal. 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.

Keywords: Hydrogen, renewable, pipeline, electrolysis, self excited induction generator, off-grid

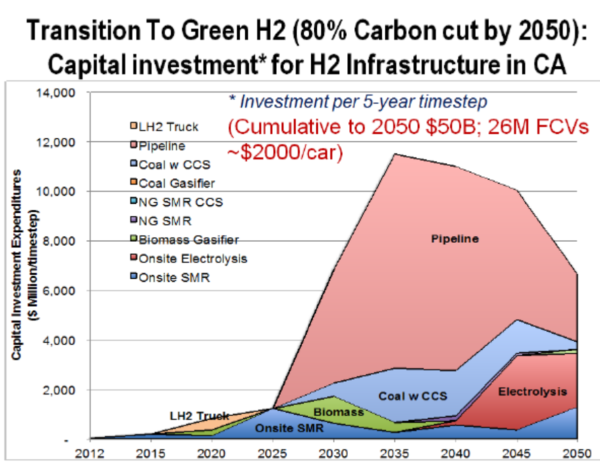

Figure 1. Year 2050 Hydrogen transport fuel demand in CA drives investment in new hydrogen pipelines.

1 SEIG + ELECTROLYSIS

SBV project success at NREL will achieve TRL 6-7 in both SEIG and close-coupled electrolysis stack technologies, to enable:

> Reducing wind turbine, windplant, and electrolysis complexity, capex, and O&M costs, reducing wind-source H2 cost ~ 20%

> Eliminating wind curtailment, via "free" storage in pipeline packing, salt cavern storage, and continental Hydrogen pipelines

> Greatly increasing "distributed" wind energy harvest area, delivering H2 fuel, without grid connection, to a new pipeline net

> Wind turbines and plants dedicated to delivering 100% of captured energy as H2 and/or NH_3 fuels, with or without grid tie

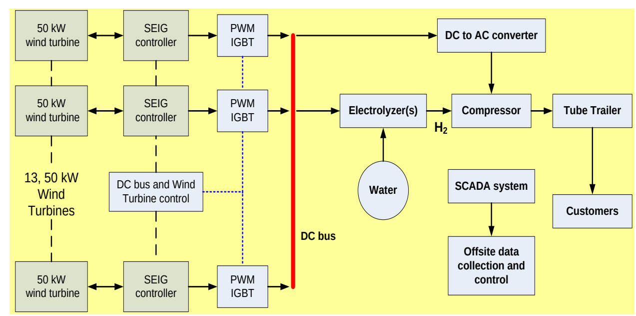

Figure 2. SEIG mode operation of wind turbines to DC bus, close-coupled to the electrolysis stacks.

Technology applications:

a. New wind turbines and windplants dedicated to Hydrogen and Anhydrous Ammonia (NH_3) fuel production, with no connection to the electricity grid, saving capex and O&M costs for the wind generation assets and for the grid, by avoiding the subsystems and infrastructure needed to deliver grid-quality AC.

b. Extant older windplants with turbines equipped with induction motors as generators; new windplants, with turbines of any size, dedicated to hydrogen fuel production, off-electricity-grid.

2 WINDPLANT R&D&D PROJECT

An existing 13-turbine windplant in San Gorgonio Pass, Palm Springs, CA, is stranded, off-grid, with no connection to the Southern California Edison (SCE) grid. The PPA has been retired, after the windplant delivered successfully to the SCE grid for over 20 years. These vintage-1985 turbines are simple, 50 kW nameplate, downwind, free-yaw, with centrifugal governor for overspeed protection, a "soft" rotor of flexible fiberglass blades, and 60 hp nameplate 3-phase induction motors as generators.

Figure 3. 13-turbine Palm Springs windplant test bed [4]

New solid-state controllers will be developed to operate the turbines in Self-Excited Induction Generator (SEIG) mode, as described in literature, by NREL and others, based on laboratory-scale operating models. Each turbine's "wild AC" output, from its variable-speed operation, is rectified to DC and delivered to one or more electrolyzers to produce hydrogen fuel and byproduct oxygen from feedstock water. The hydrogen fuel is compressed into a "tube trailer" of typically 500 kg capacity at 250 bar, for delivery to nearby customers, for fueling the nascent fleets of fuel cell buses and light duty vehicles (LDV's). The primary technical challenges are:

1. Achieving stable operation of the induction motor, as SEIG- mode generator, on each turbine, as windspeed varies;
2. Achieving high energy conversion efficiency, from kinetic wind energy impinging on the turbine to "wild DC" output at each turbine;
3. Achieving high energy conversion efficiency, from kinetic wind energy impinging on each turbine, and on the entire array of 13 turbines, to kg of hydrogen fuel;
4. Impedance matching the turbine DC outputs to the electrolyzer stack(s) for maximum power and energy transfer;
5. Minimizing the capital and O&M costs of the system power electronics, at wind turbine and electrolysis plant levels;
6. Automatically protecting the electrolysis plant from overload or other dangerous conditions;
7. Dispatch the 13 turbines to optimize system capacity factor (CF) and minimize long-term cost per kg of hydrogen fuel production.

AASI will design, via a new CRADA with NREL, at NREL, a unique, integrated, proof-of-concept, wind-to- H2 fuel system optimized for delivering all its captured wind energy as H2 fuel, with no connection to, nor energy delivery to, the Grid. We will package this pilot plant system in an insulated CONEX and test it on operating wind turbines at AASI's Palm Springs, CA windplant. We will collect operational data to:

a. Verify system design and refine system hardware and software designs to improve performance;
b. Predict system scalability and commercial potential;
c. Estimate the value of relieving the Grid of costly burdens of high-penetration, high-percentage, VG renewables transmission, storage, and integration;
d. Design and plan conversion of entire 13-turbine windplant to dedicated, off-Grid, Hydrogen fuel production.

The integrated system innovations include:

a. Self-Excited Induction Generator (SEIG), by which the common, economical, rugged induction motor is the autonomous generator, with no connection to, nor energy delivery to, the Grid:
b. Combining the "wild AC" outputs of several wind turbines on a common DC bus as "wild DC" feeding the electrolysis "stacks";
c. Close-coupling electrolysis stacks to windplant DC bus, to minimize power electronics, eliminating the "transformer-rectifier" subsystem in off-shelf commercial electrolysis plants;
d. Integrating all wind turbine, power electronics, and electrolysis controls in a single SCADA system.

AASI demonstrated SEIG mode operation on one of its Palm Springs turbines, delivering wind energy to a dummy load.

Now, we are ready to integrate and test the above complete system, via NREL CRADA, at an ideal site: the AASI Palm Springs windplant. [2], [3]

This unique, potentially-transformative, integrated system technology plan has been developed collaboratively with the NREL team and presented in our several partnered funding applications: 2015 ARPA-E "OPEN" and 2016 "REFUELS" FOA's; 2016 DOE Small Business Voucher; 2016 NSF STTR. This project will discover whether our technical success with this novel system technology enables:

a. Stable operation of complete SCADA system; adequate data collection;
b. Stable, safe operation of complete wind-to- H2 system with no connection to SCE Grid;
c. Electrolysis stacks operation limited to safe kWe input region, in all wind conditions;
d. Impedance matching of electrolysis stacks to wind turbines and windplant DC bus;
e. Lower long-term CAPEX and OPEX for generation of H2 fuel from wind; lower plant-gate cost;
f. Convenient delivery of H2 fuel, via PDC Machines compressor, to H2 gas tube trailer for local delivery, emulating H2 gas delivery to the new, CA-wide GH2 pipeline system .

The 13 small (50 kW) wind turbines at AASI's Palm Springs windplant are equipped with squirrel cage induction motors as generators. Each will be equipped with simple power electronics, of novel and proprietary design via CRADA with NREL, to achieve stable, controllable, efficient SEIG-mode operation, including impedance matching each turbine to the DC bus, and DC bus to electrolysis stacks. This windplant is the perfect size and location for this pilot plant R&D and Demo project.

3 COMMERCIALIZATION

In CA in year 2050, the energy market for renewables-source Hydrogen transportation fuel will exceed that for energy gathered, transmitted, and delivered as electricity, by the "grid". Hydrogen storage in deep, solution-mined caverns is < $1.00 per kWh capex, while batteries will remain > $100.00. [1]

Therefore CA, USDOE, and global research should begin now to encourage and fund R&D & Demonstration projects to discover and showcase paths to large-scale commercialization of high-purity Hydrogen fuel production from wind, solar, and other CO2-emissions-free energy sources to achieve:

• Lower-cost Hydrogen fuel, at the plant gate or other source terminals, and at the end-user's fueling station. At large scale, a 20 - 50 % cost reduction may be possible.

• Much larger geographic areas over which renewable energy (RE) can be harvested, without expansion of the electricity grid, assuming availability of new Gaseous Hydrogen (GH2) fuel pipeline systems.

Novel polymer-metal tubing linepipe material, developed at Oak Ridge National Lab, with IP owned by Hydrogen Discoveries Inc., and with potential manufacture by Smart Pipe, Houston, may solve the hydrogen embrittlement problem of steel Hydrogen transmission pipelines at 100 bar Maximum Allowed Operating Pressure (MAOP) and frequent pressure fluctuation characteristic of production from renewables.

• "Free" energy storage in the GH2 pipeline system by "packing" the pipelines to MAOP when RE-source Hydrogen is available and surplus to demand, then drawing down pipeline pressure as customers withdraw Hydrogen fuel when RE-source energy production is reduced; this emulates the natural gas industry's routine pipeline "packing" storage practice which adds great value to their product and service;

• Even more attractive economics with liquid ammonia (NH3) systems.

But, to satisfy this very large looming demand for "green" Hydrogen fuel, we probably do not want to:

• Build new electricity transmission, storage, and distribution infrastructure to gather, transmit, and deliver this large amount of energy from diverse, dispersed renewable resources.

• Inflict on those renewable energy sources the cost of generating and delivering grid-quality AC or DC to the electricity "grid", if it is to be converted back to Hydrogen fuel at point-of-use, at considerable capital and energy conversion loss cost.

Impact: SBV 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.

4. Use 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.

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. [3]

4 IP STATUS

AASI will use project success results to establish new IP, and to attract interest to, and investment in scaleup to commercializing, while respecting all extant IP. SEIG mode operation has long been in the public domain. NREL has published at least one paper, but SEIG mode has not been commercialized. [5]

5 CONCLUSION

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