Renewables-source Energy Storage for < $1.00 / kWh CAPEX as Hydrogen and Ammonia C-free Fuel Systems

Hydrogen and Ammonia Fuels via Underground Pipelines with Storage in Caverns and Tanks

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ABSTRACT Humanity's grand challenge now is converting the world's largest industry from ~ 85% fossil to 100% renewable energy (RE) sources as quickly as we prudently and profitably can, to "Run the World on Renewables" -- perhaps including some nuclear, now very hard to predict. Nothing less will allow us to escape these synergistic global consequences of large-scale fossil fuel combustion:

- Rapid climate change, generally warming
- Accelerating sea level rise
- Ocean acidification
- Species extinctions
- Violent human conflicts

Jacobson and Delucchi have demonstrated that we can run the world on wind, water, and solar (WWS). The wind energy of the twelve Great Plains states, if fully harvested on about 50% of these states' aggregate land area, transmitted to distant markets, and "firmed" at annual scale with storage, could supply the entire annual energy demand of the USA: about 10,000 terawatt-hours (TWh = billion kWh), or about 100 quads (quadrillion btu). However, existing Great Plains electric transmission export capacity is insignificant relative to this resource. Any large, new electric transmission systems, or fractions thereof dedicated to wind energy, will:

- Be very costly to build;
- Be difficult to site: FERC has no authority for permitting interstate electric lines;
- Be difficult to route and permit, because of public objection, as in NIMBY;
- Suffer the same low capacity factor (CF) (typically 40%) as the windplants and other RE plants they serve, unless RE gen curtailed;
- Provide no affordable "firming" (weekly-to-annual scale) energy storage, taxing "system balancing" ability of the electricity grid;
- Be vulnerable to damage by acts of God and man.

Relieving RE generation and conversion equipment of the requirement to deliver "grid quality" AC (Voltage, frequency, power factor, and harmonics) as well as "low voltage ride through" (LVRT), because RE electricity is instead entirely delivered to electrolyzers and NH_3 synthesis systems, may significantly reduce the capital and O&M costs of RE -- at the plant gate and at end-user.

Therefore, the RE industry needs to look beyond the electricity grid, which now supplies only about one-third of a modern country's total energy, to supply all energy, from all sources, for all purposes, without CO_2 emissions, as firm and dispatchable energy. Electricity systems are not well suited for delivering on-demand energy services from the time-varying output -- at scales of seconds to seasons -- of most renewables, while simultaneously and affordably providing:

1. Gathering and transmission, from both large, stranded, "centralized" RE plants and smaller "distributed" generation (DG)
2. Annual-scale firming storage, rendering RE dispatchable
3. Distribution, integration, CHP, and delivering energy services to end-users

A technically and economically superior strategy may be to:

1. Convert the wind or solar plant's entire energy output to the only two C-free fuels, hydrogen, H_2, and / or anhydrous ammonia, NH_3
2. Transport the fuels in underground pipelines as gaseous hydrogen (GH2) and / or liquid NH_3
3. Completely avoid the high capital and O&M costs of:

a. Electricity grid connection: gathering, field transformers, substation, and HV line links
b. Sophisticated generating systems required to deliver grid-quality AC with LVRT

4. Acquire, store, and deliver surplus energy from PV and other distributed RE generation.

Having left electricity at the RE sources, we would now deliver C-free fuel(s) to distant markets for stationary combined-heat-and-power (CHP), transportation fuel, and the complete other spectrum of residential, commercial, and industrial uses. We are thus emulating the natural gas industry's ubiquitous pipeline network and freedom from large, looming "Smart Grid" investments, enabled by their large and diverse array of low-cost energy storage and inherent long time constants.

The electricity grid, as we've known it, is rapidly transforming, perhaps atrophying, under pressure from DG, nascent demand for BEV charging, and new Smart Grid complexity, which together may make the grid more susceptible to cyberattack. While the Grid may always be with us, we need to look beyond it in our compulsion to run the world on renewables.

Figure 1 shows that GH2 and NH_3 underground pipeline transmission capital costs compare favorably with electricity, oil, and gas per MW-km, which should be the common measure of any transmission system's service. Underground pipelines are better protected; O&M costs per MWh-km are lower. New pipelines are generally easier to site and permit than new electric transmission lines. For example, these pipelines have 8 GW capacity:

- 1 m diameter, 800 km long, GH2 pipeline, at 100 bar input, 30 bar output, with no midline compression
- 50 cm diameter NH_3 pipeline, with midline pumping, of any length

Figure 2 shows the system simplicity and inherent low-cost energy transmission and storage when high-pressure-output electrolyzers input the GH2 pipeline; midline compression for < 1,000 km length is not needed. "Packing" the GH2 pipeline, as natural gas pipelines routinely are, provides "free" storage. If a national or continental GH2 pipeline "grid" can access a region of domal salt geology, very large and low-cost RE storage is available in large, deep, solution-mined, man-made, salt caverns, in Figure 3. Multiple caverns may be manifolded together, operating at the same pressure, sharing a surface facility, to reduce capital cost to well below \$ 1.00 / kWh at multi - 100 GWh scale. Two GH2 storage salt caverns, near Moss Bluff, TX, have operated well, with low O&M: Chevron-Phillips cavern for > 30 years; Praxair cavern for > 7 years.

Figure 3. USA has enough domal salt geology along the Gulf of Mexico coast to install ~ 15,000 large GH2 storage caverns, providing enough storage to firm the entire Great Plains wind resource, to provide all ~ 100 Quads of USA's total energy demand as annually firm and dispatchable. Northern Germany is also endowed with good salt geology for large storage caverns.

The large, nascent H_2 fuel market for fuel cell buses and light duty vehicles (LDV's) should motivate interest in integrated, optimized, RE-source systems. Toyota North America chief Jim Lentz recently told *Automotive News* that Toyota sees battery-electric vehicles (BEV's) only viable in "... a select way, in short range vehicles ..." Transportation fuel may be a larger market than the Grid, and may motivate turbine suppliers to offer equipment optimized for off-grid H_2 and NH_3 fuel production, with simpler, more robust, and less-costly electric generating systems, using variable-speed induction motors, as in Figure 5. Polymer-metal tubing and linepipe developed at ORNL may replace steel for high-pressure transmission pipelines, solving the hydrogen embrittlement and other corrosion problems.

NH_3, the "other hydrogen", is a higher-hydrogen-density energy carrier and storage medium than liquid hydrogen, LH2. A liter of NH_3 contains more H atoms than a liter of LH2. The modified internal combustion engine, combustion turbine, and fuel cell run well on NH_3, while RE transmission and storage costs are even lower than for GH2.

Figure 4 shows the Agrium terminal where twin mild steel tanks together hold 80,000 tons of refrigerated, liquid anhydrous ammonia, NH_3, which stores ~ 500,000 MWh as the energy content in NH_3, which may be directly used as fuel or may be easily reformed to H_2 fuel and harmless, vented N_2. At this scale, energy storage costs ~ \$ 0.10 / kWh capex. Over 4,000 km of NH_3 transmission pipeline is already in place in USA, where NH_3 is used primarily as N-fertilizer. These pipelines are low-cost, mild steel, operating at ~ 15 bar.

Figure 5: By any measure, the low cost and high capacity of GH2 and NH3 storage is "off the charts" vis-a-vis the several technologies considered for "electricity" storage, as adjuncts to the Grid.

Great Plains wind is very seasonally-variable: about 20% above average in Winter and Spring, 30% below average in Summer. Firming 1,000 MW (nameplate), to allow firm energy delivery every day of the year, would require ~ 300,000 MWh of storage: ~ 4 GH2 salt caverns or ~ 2 NH_3 tanks. In either case, the storage incremental capex is ~ 3 % of total windplant cost. Compressed air or reflow battery storage is many times higher. If we consider investing in the energy conversion equipment necessary to avail us of this low-cost storage, we should consider solving the transmission and integration problems as well, via complete, integrated, optimized, RE systems -- from sources to delivered energy services -- employing GH2 and NH_3 as the transmission and storage media. We should not allow ourselves to be limited to defining "storage" as an appurtenance to the electricity Grid.

Japan is researching three strategies for importing C-emissions-free H_2 from distant sources, as high-hydrogen-density liquids in ocean tankers, to build a significant "hydrogen sector" in their national energy system:

- Liquid hydrogen, LH2: Kawasaki Heavy Industry
- Anhydrous ammonia, NH_3: Sumitomo Chemic
- Toluene - Methylcyclohexane cycle: Chiyoda Chemical and Heavy Industry

Alaska's diverse, abundant, stranded RE resources are strategically close and convenient for export to Japan via any of these H_2 transmission schemes, and have been approximately surveyed.

For over a decade, researchers have been bravely and brilliantly engineering wind turbines and solar PV and CSP systems, and the Grid, to accommodate an increasing share of RE, attempting to deliver firm and dispatchable electricity with system stability while displacing fossil generation. This is ever more costly and technically difficult, at the margin, for both generation and transmission. This work is well reported by the IEEE Power and Energy Society in their journal, *Power and Energy*. But we have only begun to ask how RE may serve energy markets beyond the extant electricity sector, whether via an expanded electricity sector and Grid, or perhaps via alternatives to electricity. Do we imagine that we may supply all humanity's energy, for all purposes, from diverse RE sources, entirely, or even primarily, via electricity systems? The Grid, assaulted by PV systems large and small, connected to distribution circuits, may so evolve and atrophy as to be inadequate and unsuitable to "Running the World on Renewables"

Therefore, we now need to assemble a collaborative of private enterprise, academia, national labs, funders, and others to thoroughly and expertly model, technically and economically, complete RE systems -- from photons and moving air and water molecules to delivered energy services -- in the context of humanity's responsibility to expeditiously "Run the World on Renewables". Before we invest billions in a larger and smarter electricity Grid, we need to be sure we've considered alternatives, that we're not trying to stuff a square peg into a round hole. This serious consideration has never been done; our co-authors attempted analysis have been provocative, but inadequate and unpersuasive.

Please contact the author if you wish to consider participating. Conference presentations and papers on this and related RE topics are at: www.leightyfoundation.org/earth.php

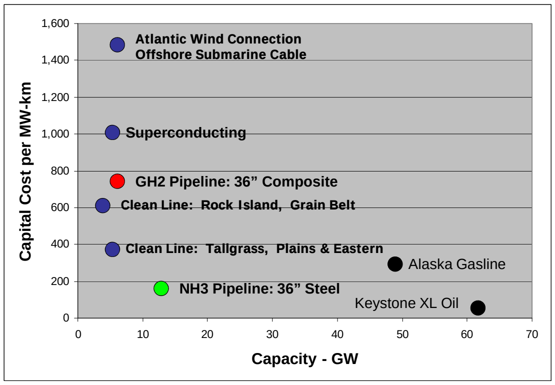

Figure 1. Approximate transmission capital costs per MW-km of service, $ US

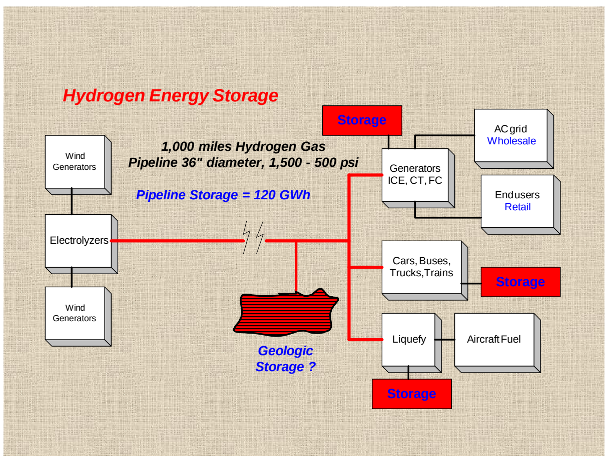

Figure 2. Complete Renewable Energy GH2 system: annual-scale firming, dispatchable storage

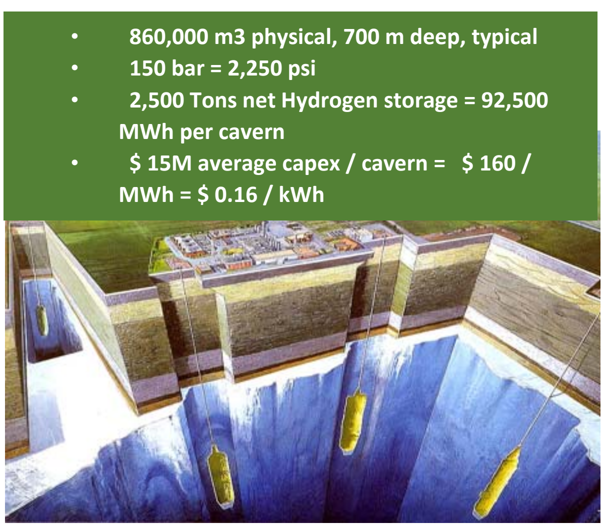

Figure 3. Solution-mined compressed Hydrogen storage caverns in deep domal salt. Multiple caverns manifolded together, share a common surface facility, for very large energy storage.

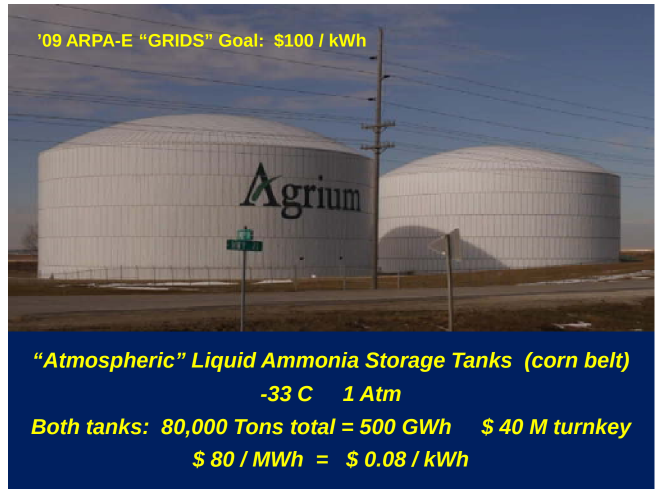

Figure 4. Agrium US, ammonia storage terminal at Early, Iowa, supplying N-fertilizer for corn ag.

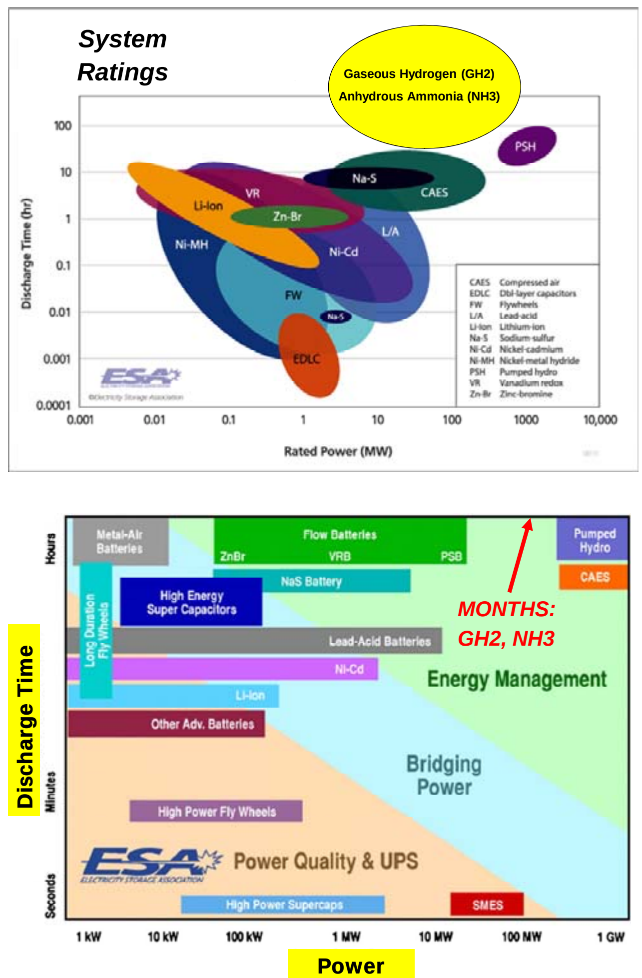

Figure 5. By any measure, the low cost and high capacity of GH2 and NH_3 storage is "off the charts" vis-a-vis the several technologies considered for bulk "electricity" storage as adjuncts to the Grid.

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