

Low-cost Transmission, Storage, and Integration for Renewable-source Energy: Hydrogen and Ammonia C-free Fuel Systems via Underground Pipelines, with Storage in Salt Caverns and Liquid NH₃ Tanks

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ABSTRACT

Solar and wind are the lowest-cost renewable sources, but are intermittent. New, low-cost transmission and storage infrastructure will be needed as we convert the world's largest industry -- energy -- from fossil to renewable sources, as we progress to "run the world on renewables". We must now consider gaseous hydrogen (GH₂) and anhydrous ammonia (NH₃, "the other hydrogen") as complete renewables-source energy systems: renewable-source electricity is converted at the sources, both "centralized" (large, remote plants) and "distributed" (at point-of-use) to GH₂ and NH₃ fuels. ⁱ, ⁱⁱ, ⁱⁱⁱ, ^{iv} Underground pipelines gather, transmit, distribute, and store these C-free fuels, to supply CHP and transportation markets, and all other energy demand. We now need to form a collaborative to conceive, design, bid, build, and operate pilot plants by which we can test these cases and hypotheses.

Keywords: transmission, storage, integration, systems, dispatchable, renewable, hydrogen, ammonia, pipelines

STRATEGY

The energy output of most renewables varies greatly, at time scales of seconds to seasons: the energy capture assets thus operate at inherently low capacity factor (CF); energy delivery to end-users is not "firm". New electric transmission systems, or fractions thereof, dedicated to renewables, will suffer the same low CF, and represent substantial stranded capital assets, which increases the cost of delivered renewable-source energy.

Electricity from diverse renewable energy (RE) resources may be converted to GH₂ and NH₃ carbon-free fuels and stored at < \$1.00 / KWh capital cost in large, solution-mined salt caverns for GH₂ and in NH₃ in steel surface tanks, both pressurized and refrigerated. This stored chemical energy is gathered and transmitted and distributed via continental-scale underground pipeline systems and converted to useful work, at residential to

industrial scales, via combined-heat-and-power (CHP) plants, via direct space heating and cooling, and as transportation fuels. We thus solve RE's severe transmission, storage, and integration problems via complete, optimized, systems design -- from photons and moving air and water molecules to delivered energy services. We need to supply all energy, not just electricity, from diverse RE resources, both distributed and centralized, where the world's richest RE resources -- of large geographic extent and high intensity -- are stranded: far from end-users with inadequate or nonexistent gathering and transmission systems to deliver the energy. Electricity systems may be suboptimal, technically and economically, at such large scale. Electricity energy storage cannot affordably firm large, intermittent renewables at annual scale, while carbon-free GH₂ and liquid NH₃ fuels can. See Figures 1 - 4.

Underground transmission pipelines, as would be required for GH₂ and NH₃, are typically easier to site and permit than electric lines, and each may have multi-GW capacity.

Relieving RE generation / conversion equipment of the requirement to deliver "grid quality" AC (V, f, PF, and harmonics) as well as "low voltage ride through" (LVRT), because RE electricity is entirely delivered to electrolyzers and NH₃ synthesis systems, may significantly reduce the capital and O&M costs of RE.

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 energy 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 because FERC has no authority for permitting interstate electric lines;

- Be difficult to site 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 generation curtailed;
- Provide no affordable “firming” (weekly-to-annual scale) energy storage, thus taxing the “system balancing” ability of the electricity grid;
- Be vulnerable to damage by acts of God and man.

TRANSMISSION AND STORAGE

GH2 transmission requires line pipe material and system components able to resist and control, or be immune to, hydrogen embrittlement (HE). In contrast, NH3 pipelines are moderate-strength, low-alloy, carbon steel. NH3 does not attack steel. Capacity of these pipelines, in GW-km of transmission service, and in capital cost, is comparable to the largest available electricity transmission systems. Energy storage cost at GWh scale is lower. Figures 1-7.

Without any expansion of the electricity transmission grid, all RE is converted at the windplant or other RE plant to GH2 fuel. High-pressure-output electrolyzers feed the pipeline directly at ~100 bar, from wind or other RE electricity sources. GH2 is stored at 100-150 bar in solution-mined salt caverns, typically 800,000 cubic meters physical volume, capable of storing ~ 2,500 net MT of GH2 in addition to ~2,000 MT of “cushion” GH2. The cavern top is typically ~800 m below ground level. The surface facility provides compression (if needed), GH2 gas drying upon withdrawal, and manifolding of multiple caverns in a storage array. Figures 3, 4.

In 2013, in Falkenhagen, Germany, Hydrogenics built a 2 MWe-input electrolyzer plant producing GH2 from otherwise-curtailed wind energy, for injection directly into the E.ON natural gas pipeline system, for “free” storage and transmission of otherwise-wasted wind energy. ^v

USA and Germany have several salt deposit realms with formations deep and tight enough to store GH2 in man-made caverns at 150 bar with negligible leakage. ^{vi} The wind or other RE would now be sold as GH2 or NH3 fuels for vehicles and DG of electricity in stationary CHP.

Figures 5-7. NH3 may be synthesized from RE-source electricity, water, and air. NH3 contains no carbon; has physical properties similar to propane; liquefies at ambient temperatures at about 10 bar or at -33 degrees C at 1 atmosphere. Liquid ammonia has over 50% more volumetric energy than liquid hydrogen; more than twice the volumetric energy of hydrogen gas at 700 bar. It is the second-largest-volume industrial chemical in global trade: ~130 MMT / year, mostly for N-fertilizer. USA consumes

~12 MMT / year, with a good safety record. NH3 is classified as an “inhalation hazard”.

NH3 is nearly 18% hydrogen by weight and has slightly over half the energy density of gasoline by volume. All of ammonia’s energy is derived from its hydrogen content; it can be easily reformed to hydrogen and nitrogen, with N2 returned to its source, Earth’s atmosphere. NH3 has the highest hydrogen content by volume of any liquid fuel, including gasoline, liquefied natural gas (LNG), liquefied petroleum gas (LPG, propane), ethanol, and even liquid hydrogen. Liquid anhydrous ammonia, NH3, has more atoms of hydrogen per liter than liquid hydrogen. This ability of NH3 to store hydrogen very compactly at ambient temperature and moderate pressure is a key advantage for NH3 over GH2.

Like hydrogen, ammonia can burn directly in spark-ignited internal combustion engines and may also be fed directly to medium temperature solid oxide, proton-conducting ceramic, and molten-salt direct-ammonia fuel cells.

Iowa State University and the NH3 Fuel Association have hosted ten annual Ammonia Fuel Conferences, which include NH3 as an RE transmission and storage medium, and as a transportation and distributed generation fuel. ^{vii}

Approximately 3,000 miles of carbon-steel ammonia pipeline is in service in America’s agricultural heartland, mainly in the Corn Belt. Almost a hundred large terminals for refrigerated ammonia storage are distributed along the pipeline. Barges, trains, and trucks round out the delivery system, which supplies the ammonia from the terminal to the farmer when he needs it for the growing season. The state of Iowa, alone, has over 800 retail outlets where farmers buy “anhydrous” or “nitrogen”, the vernacular for ammonia fertilizer, NH3.

About 20,000 MW of nameplate Great Plains wind generation would be needed to produce 6 MMT of NH3 per year, about one-half of the present USA demand for ammonia based fertilizer. This estimate is based on an overall 60% efficiency of converting wind power into energy stored as NH3. Several times as much wind, or other renewables generation, would be needed to produce all of the USA NH3 demand, especially if NH3 also becomes widely adopted as a transportation and CHP fuel.

CONCLUSION

We will need other transmission and storage media, systems, and strategies in addition to electricity. GH2 and NH3 are attractive alternatives, for which pilot plants should soon be built, in order to discover and demonstrate their technical and economic feasibility and their

acceptability to the public and to the business and finance communities. Both GH2 and NH3 provide affordable seasonal-to-annual-scale firming storage for diverse RE resources, as well as the transmission paths for bringing GW-scale, stranded RE to distant markets. End-users purchase their energy as GH2 and / or NH3 fuels, for CHP on-site generation, centralized generation, and for transportation fuels and for space-conditioning and industrial uses. Transmission pipelines for both GH2 and NH3 fuels have multi-GW capacity over hundreds of km. NH3 cryo tankers enable intercontinental trade. NH3 on-site farm use as machinery fuel and N-fertilizer, and for export, would eliminate costly electricity transmission.

We should assemble consortia to begin immediately to design and build pilot plants for RE-source GH2 and NH3 transmission and firming storage, by which to discover and demonstrate their technical and economic feasibility – or lack thereof. These RE systems, as alternatives to electricity, deserve more serious technical and economic consideration than the authors are able to provide; we believe we have set the stage.

We are trying to stuff a square peg into a round hole, as we urgently transform the world’s largest industry – energy – to “run the world on renewables” , plus some hard-to-predict degree of nuclear, via electricity: it is not well suited to gathering and delivering diverse, dispersed, diffuse, time-varying-output RE to distant markets as firm and dispatchable energy.

Only expanding, and making “smarter”, the electricity gathering-transmission-storage-distribution grid will not allow replacing fossil-source energy with RE-source energy quickly enough to meet humanity’s goal of preventing rapid and catastrophic climate change, ocean acidification, sea level rise, and species extinctions by quickly reducing GHG emissions.

“Electrification of transportation is the only way we can prevent further global climate change and get off foreign oil”.^{viii} If “electrification” means that the vehicle wheels or the boat propeller are turned by an electric motor, via a power electronics control system, it does not mean that the electric energy necessarily comes from on-board batteries, from the grid. Both GH2 and NH3 fuels can supply the electric energy via fuel cells, which may be a superior technical and economic strategy at continental scale, whereby these RE-source fuels are widely generated, transmitted, stored, and distributed.

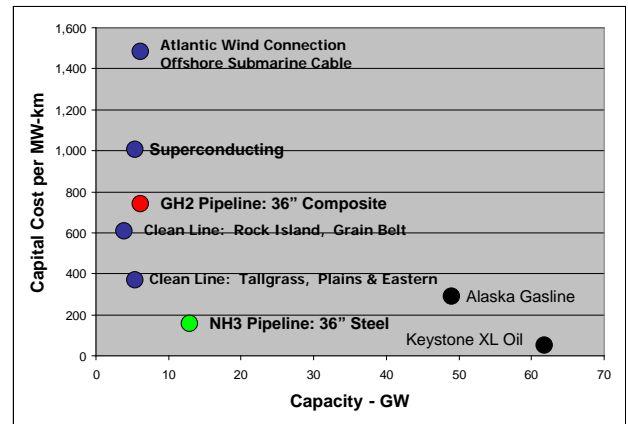


Figure 1. Capital cost and rated transmission capacity for hydrocarbon pipelines (blue), RE-source pipelines (red), and electricity. Pipelines are underground.

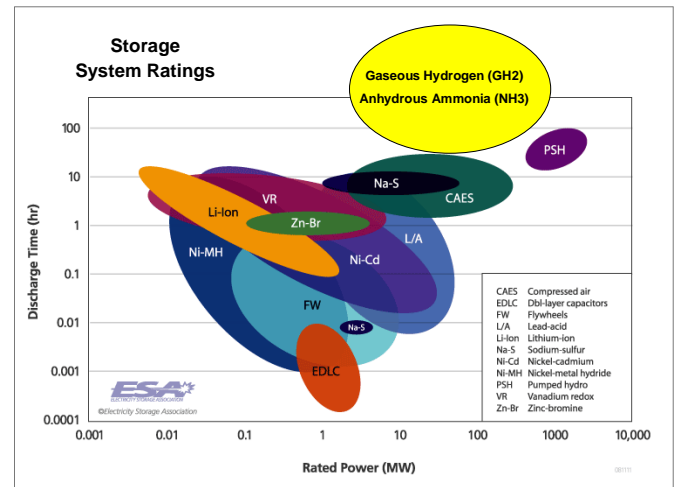


Figure 2. Both GH2 and NH3 provide very large capacity, low cost modular storage for annual-scale firming of diverse RE resources.

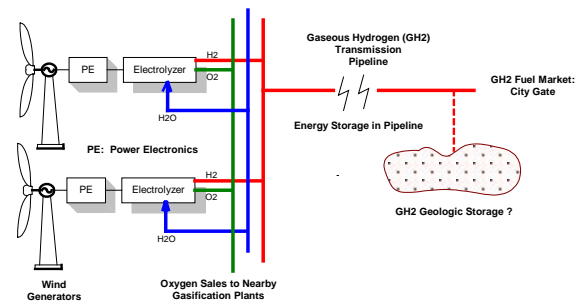


Figure 3. System topology options for wind-to-hydrogen energy conversion, gathering, and transmission. The hydrogen may be delivered to transmission pipelines or to nearby NH3 synthesis plants. Both GH2 and NH3 may be stored, affordably firming wind and diverse other RE resources.

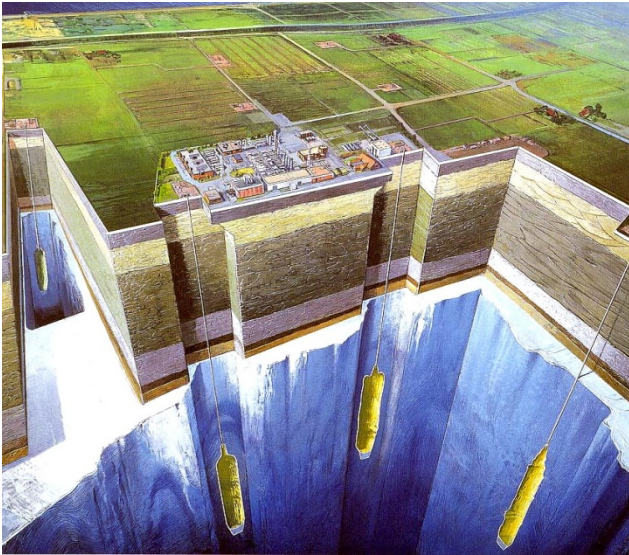


Figure 4. Multiple large, solution-mined salt caverns in “domal” salt, suitable for high-pressure storage of GH2. A typical cavern will store 90,000 MWh as 2,500 net MT of GH2 at 70-150 bar in ~800,000 cubic meters physical volume. Total capital cost of cavern, GH2 cushion gas, and shared surface facility is ~ \$ 15M; ~\$ 0.20 / kWh

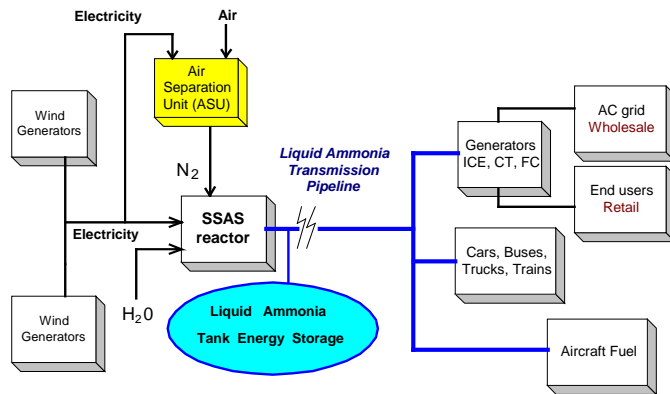


Figure 5. NH₃ energy system: production from RE, with large-scale, low-cost energy storage and transmission for fuel distribution at distant markets. SSAS is Solid State Ammonia Synthesis.



Figure 6. “Atmospheric” refrigerated liquid anhydrous ammonia (NH₃) tank stores 190,000 MWh as 30,000 MT of NH₃ fuel. Total capital cost ~\$ 15M; ~ \$ 0.10 / kWh

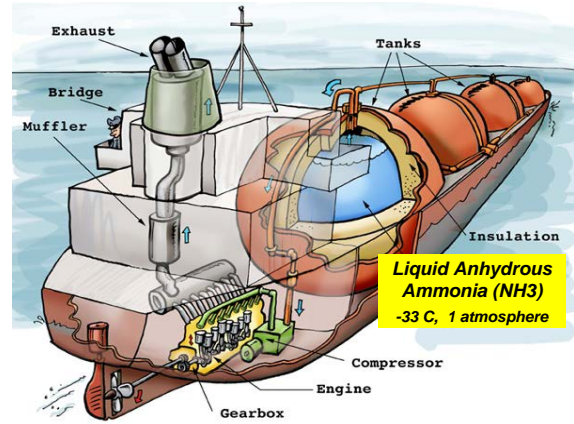


Figure 7. Bulk “green” NH₃ may be transported from diverse, large, stranded renewable energy resources via cryo tanker. NH₃ is the second-highest-volume chemical in world trade.

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