

## **Transmission and Firming of GW-Scale Wind Energy by Ammonia Pipelines and Tanks**

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### **Abstract**

This is a conceptual study; ammonia has not been proposed as a transmission and firming storage medium for GW-scale wind energy; no pilot plan exists for confirming the system capital costs and efficiencies we estimate. We analyze producing anhydrous ammonia (NH<sub>3</sub>), from wind, storing it in large-scale tanks, and delivering it to vehicles and fuel cells, via pipeline and truck, consistent with well-established global industry practice. Economical liquid NH<sub>3</sub> tank storage could firm Great Plains wind at annual scale, adding great strategic and market value. We compare energy transmission and delivery by NH<sub>3</sub> with gaseous hydrogen and high-voltage DC. Hydrogen holds great promise as a clean-burning energy carrier, and modern, efficient electrolyzers can produce large volumes of high-pressure hydrogen, ready for pipeline transmission and /or ammonia synthesis, from renewable energy sources, including wind, solar, and hydroelectric. However, because of hydrogen's extremely low volumetric energy density, compression or liquefaction of the hydrogen is required to increase energy density. These approaches consume a sizeable fraction of the energy contained in the hydrogen, still fall short of volumetric storage targets, and, except for large-scale geologic storage, require expensive storage devices. On the other hand, renewable-source hydrogen can be stored and transported effectively as NH<sub>3</sub>, which can be readily produced in a synthesis step following electrolysis using nitrogen from the air, and which consumes energy in synthesis comparable to compression of gaseous hydrogen to high pressure. Ammonia contains no carbon; has physical properties similar to propane; liquefies at ambient temperatures at about 125 psi or at -10 degrees F at 1 atmosphere. Liquid ammonia has over 50% more volumetric energy than liquid hydrogen; more than twice the volumetric energy of hydrogen gas at 10,000 psi. We reference three annual conferences dedicated to anhydrous ammonia as energy carrier, storage medium, and fuel.

### **Introduction**

The wind energy of the twelve Great Plains states, if fully harvested on about 50% of these states' 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).<sup>1</sup> However, extant Great Plains electric transmission export capacity is insignificant relative to this

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<sup>1</sup> Elliott, D., Wendell, L., Gower, G. Pacific Northwest Laboratory (1991). An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States. Pacific Northwest Laboratory, PNL-7789 / NTIS no. DE91018887, September, 1991.

resource. Any large, new electric transmission systems, or fractions thereof dedicated to wind energy, will:

1. Be very costly to build;
2. Be difficult to site and permit, because of public objection;
3. Suffer the same capacity factor (CF) as the windplants they serve, unless wind generation is curtailed;
4. Provide no affordable “firming” energy storage; taxing the “system balancing” ability of the electricity grid;
5. Be vulnerable to damage by acts of God and man.

Only two transmission and annual-scale, firming storage schemes seem technically and economically attractive for wind and other time-varying-output renewable electric energy sources at GW (nameplate) scale:

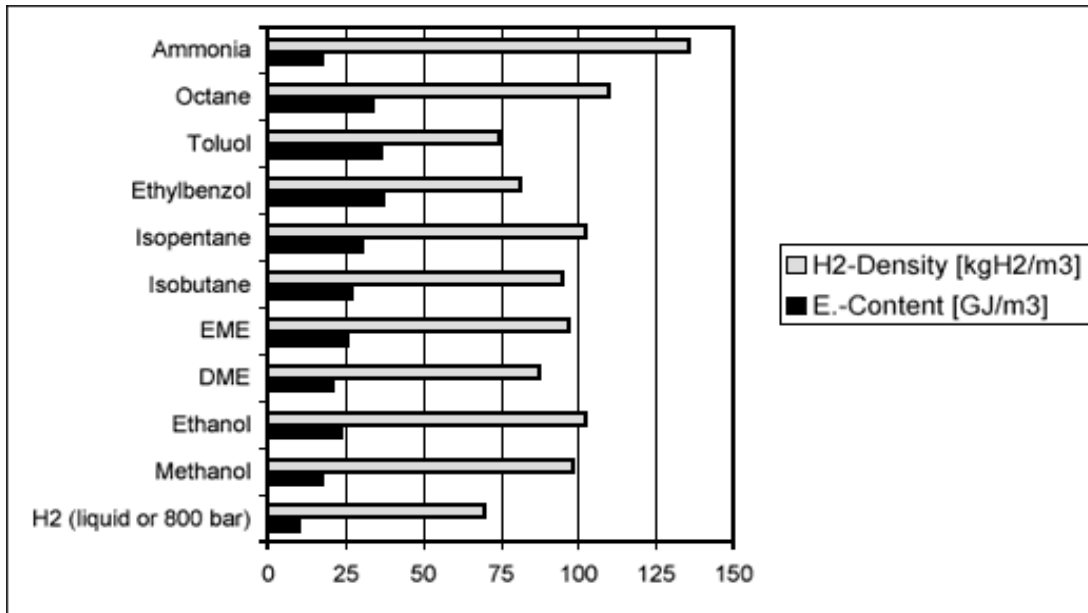
1. Conversion of electric energy to gaseous hydrogen (GH<sub>2</sub>), by electrolysis of water at high pressure (500 – 2,000 psi), GH<sub>2</sub> transmission and delivery by underground pipeline, with annual-scale firming storage of high-pressure GH<sub>2</sub> in deep, solution-mined salt caverns;
2. Conversion of electric energy to NH<sub>3</sub>, for transmission as liquid by underground pipeline, delivery via pipeline and truck, with annual-scale firming storage as liquid NH<sub>3</sub> in large (10,000 – 60,000 ton) refrigerated, above-ground tanks.

Anhydrous ammonia (chemical formula NH<sub>3</sub>) is an essential fertilizer, which has led to vastly improved agricultural output over the last century. Fritz Haber, the German inventor of the first industrial process to “fix” nitrogen from the air in the ammonia molecule, won the Nobel Prize in 1918. In the U.S. alone, farmers apply 15-20 million tons of anhydrous ammonia and other ammonia-based fertilizers every year. Worldwide production and consumption of ammonia is approximately 130 million tons annually.

However, ammonia is also an energy-dense, ultra-clean-burning, fuel, “sustainable” if made from renewable energy sources. Ammonia has just over half the energy density of gasoline by volume. All of ammonia’s energy is derived from its hydrogen content. Ammonia contains no carbon, so it emits zero greenhouse gases when it is burned. Only hydrogen (H<sub>2</sub>) fuel can also make this claim.

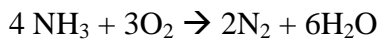
### **Ammonia as a Fuel**

Ammonia fuel is the same chemical as the liquid fertilizer, anhydrous NH<sub>3</sub>. Ammonia is nearly 18% hydrogen by weight and is slightly over half the energy density of gasoline on a volume basis. Ammonia is a liquid under moderate pressures (>125 psi) at ambient temperatures, which enables it to be easily stored and transported. Ammonia has the highest hydrogen content by volume of any liquid fuel, including gasoline, liquefied natural gas, liquefied propane gas, ethanol (by far), and even liquid hydrogen itself. (See Figure 1.) Indeed, liquid anhydrous ammonia, NH<sub>3</sub>, has more atoms of hydrogen per liter than liquid hydrogen itself. This ability of NH<sub>3</sub> to store hydrogen very compactly at ambient temperature is a key advantage.



**Figure 1.** Hydrogen density and HHV energy content of ammonia and selected synthetic liquid hydrocarbon fuels. Source—Bossel et al., *The Future of the Hydrogen Economy: Bright or Bleak?*, Oct 28, 2004 [http://www.oilcrash.com/articles/h2\\_eco.htm](http://www.oilcrash.com/articles/h2_eco.htm)

Like hydrogen, ammonia can burn directly in spark-ignited internal combustion engines and be converted directly in medium-temperature fuel cells. Ammonia combusts according to



with only nitrogen and water vapor as combustion products. Combustion of ammonia produces no CO<sub>2</sub> or other greenhouse gases, and produces no CO, SO<sub>x</sub>, or NO<sub>x</sub>. Like hydrogen, ammonia is lighter than air and is not itself a greenhouse gas. Also, like hydrogen, ammonia can be synthesized from water and nitrogen using renewable energy, such as wind, hydroelectric, oceanographic thermal energy conversion (OTEC), solar, and other renewables, and even from nuclear generated electricity. The nitrogen for this synthesis is simply taken from the air by a common industrial air separation plant (ASP), and is returned to the air when ammonia is consumed in an engine or fuel cell.

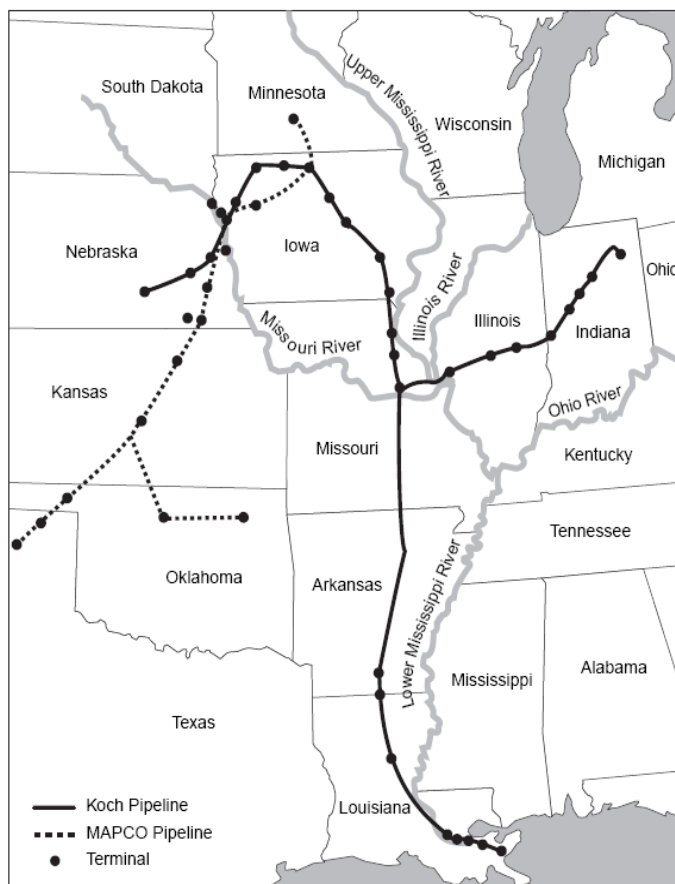
It is important to point out that a significant, proven ammonia delivery infrastructure already exists in the U.S., and which is safe and reliable. There are approximately 3,000 miles of carbon-steel ammonia pipeline already built and being used in America's agricultural heartland. There are also almost one hundred large terminals for ammonia storage along the pipeline. Barges, trains, and trucks round out the delivery system, which gets the ammonia to the farmer when he needs it for the growing season.. In the state of Iowa alone, there are over 800 retail outlets for farmers to buy ammonia.

It is also important to acknowledge ammonia's safety problems. These primarily stem from ammonia's reactivity with water which makes it an inhalation hazard. It is toxic at

>1% concentration in air. On the other hand, ammonia is not explosive, overly flammable, and does not need to be stored at high pressures. Like every chemical, ammonia requires handling equipment, training and experience, and respect. But, given the millions of tons of ammonia that are routinely delivered and handled in the U.S. every year, ammonia has an excellent safety record, as good as, or better than, any widely used hydrocarbon fuel.

### **Ammonia Storage and Distribution**

Because of its widespread use in the U.S. as a nitrogen fertilizer, ammonia has an extensive storage and delivery infrastructure. Figure 2 shows approximately 3,000 miles of mild carbon steel pipeline in place in the U.S. agricultural heartland. These pipelines carry liquid ammonia at pressures of 250 psi and above, and since ammonia is not corrosive to steel, these pipelines have very few maintenance problems or costs. Because the ammonia is piped as a liquid, these pipelines are in the 8-10 inch diameter size range, which is much smaller than natural gas pipelines, or those proposed to transport hydrogen gas. In addition to the pipelines, the distribution network includes a large number of tanker trucks, rail tanker cars, and river barges. The system also includes approximately 4.5 million tons of large-tank storage terminals, primarily situated along the pipeline, as shown in Figure 2.



**Figure 2.** U.S. ammonia pipelines and storage terminals.

## Energy Transmission Cost Analysis

NH<sub>3</sub> made from wind-generated electric energy, water, and atmospheric nitrogen is a potential major market and delivery pathway for wind energy, worldwide. The U.S. annually consumes 15-20 million tons of nitrogen fertilizers, as anhydrous NH<sub>3</sub> or as products made from NH<sub>3</sub>. A reasonable “market share” of 6 million tons per year (tpy) NH<sub>3</sub> would require the full output of about 17,000 MW of nameplate wind generation, at 40% CF. Total installed U.S. wind capacity in April 2007 is about 12,000 MW.

“Firm” energy is worth far more, in strategic and economic value, than raw renewable-source energy which – except for geothermal – is inherently time-varying in output. Here “firm” means able to deliver a contracted amount of energy every hour of every year, because the renewable-source(s) system includes adequate energy storage. As in current industrial and agricultural practice, NH<sub>3</sub> can be economically stored, at large scale, as liquid, in refrigerated above-ground tanks, to achieve annual-scale firming.

Cost comparison: We compared costs of GW-scale transmission and annual-scale “firming” energy storage for four cases, in a first-approximation analysis. <sup>2</sup>

1. HVDC electricity: 50% of 3,000 MW line
  - a. Without firming storage
  - b. (no affordable annual-scale firming storage anticipated)
2. Electricity → GH<sub>2</sub> → Gas Pipeline → City gate wholesale
  - a. Without firming storage
  - b. With firming storage at 100 – 150 bar in solution-mined salt caverns
3. Electricity → GH<sub>2</sub> → NH<sub>3</sub> → Liquid Pipeline → City gate wholesale
  - a. Without firming storage
  - b. With firming storage as liquid in above-ground refrigerated tanks

We do not consider the potentially important path Electricity → GH<sub>2</sub> → NH<sub>3</sub> → Liquid Pipeline → Reform to H<sub>2</sub>, in case hydrogen, rather than NH<sub>3</sub>, is the delivered product.

For this comparative analysis we assumed:

1. 2,000 MW nameplate windplant = 2,000 MWh / hr at full output, would power a 2,500 ton per day (tpd) NH<sub>3</sub> plant. This is probably near optimum economic size. Assuming Haber-Bosch NH<sub>3</sub> synthesis from GH<sub>2</sub> and atmospheric N<sub>2</sub>, in the system in Figure 3.
2. Annual energy production, Great Plains wind @ 40% CF, @100% energy conversion efficiency equivalent, is approximately:
  - 7,000,000 MWh / year, or
  - 196,000 tons H<sub>2</sub> / year, or
  - 1,100,000 tons NH<sub>3</sub> / year.
3. 1,000 mile transmission to city gate market requires either:
  - 2,000 MW HVDC electric transmission line, or

<sup>2</sup> <http://www.leightyfoundation.org/files/AmmoniaDenver/Leighty-NH3-Oct06-Denver-FromPPT.pdf>

- 20" GH<sub>2</sub> pipeline, or
  - 10" NH<sub>3</sub> pipeline.
4. Installed capital costs in year 2020 @ year '05 \$US:
    - Wind generators: \$1,000 / kW
    - Electrolyzers: \$350 / kW<sub>e</sub> input
  5. Installed capital costs in year 2020 @ year '05 \$US for a 2,500 ton per day (tpd) NH<sub>3</sub> plant:
    - ASP (Air Separations Plant) = \$75M
    - Synloop (Haber-Bosch Synthesis Loop) = \$225M
  6. NH<sub>3</sub> is delivered to city-gate wholesale market as liquid; optional reforming to H<sub>2</sub>
  7. Liquid NH<sub>3</sub> tank storage at sources, to maximize pipeline CF
  8. Multi-GW scale for all components, to achieve economy-of-scale:
    - GW sources, conversions, transmission (gases, synthesis, reforming NH<sub>3</sub>)
    - >10,000 ton liquid NH<sub>3</sub> storage
  9. 150 ton per hour (tph) pipeline, 10" diam, .25" wall thick, 1,300 psi nominal, 1,500 MAOP (maximum allowed operating pressure)
  10. 150 tph NH<sub>3</sub> pipeline flow = 300,000 lbs / hr = 52,817 gal / hr
  11. X42 or Grade B carbon steel line pipe, welded, 35 – 42,000 psi rating
  12. Simple capital recovery factor (CRF) annual capital cost model @ 15 – 18 % CRF
  13. Benchmark: actual Xcel Energy purchase price for wind-generated electric energy, at wind plant gate, from 3-year-old windplant:
    - \$ 0.057 / kWh unsubsidized
    - \$ 0.038 / kWh with extant federal PTC = \$ 0.019 / kWh
  14. Electrolyzers are 80% efficient (HHV) and provide high-pressure output (30 – 100 bar) to directly feed the transmission pipeline or NH<sub>3</sub> synloop.
  15. GH<sub>2</sub> compressors are eliminated from the GH<sub>2</sub> pipeline system; GH<sub>2</sub> transmission pipeline size requires no midline compressors.
  16. ASP is an industry-standard cryogenic plant, electrically powered.

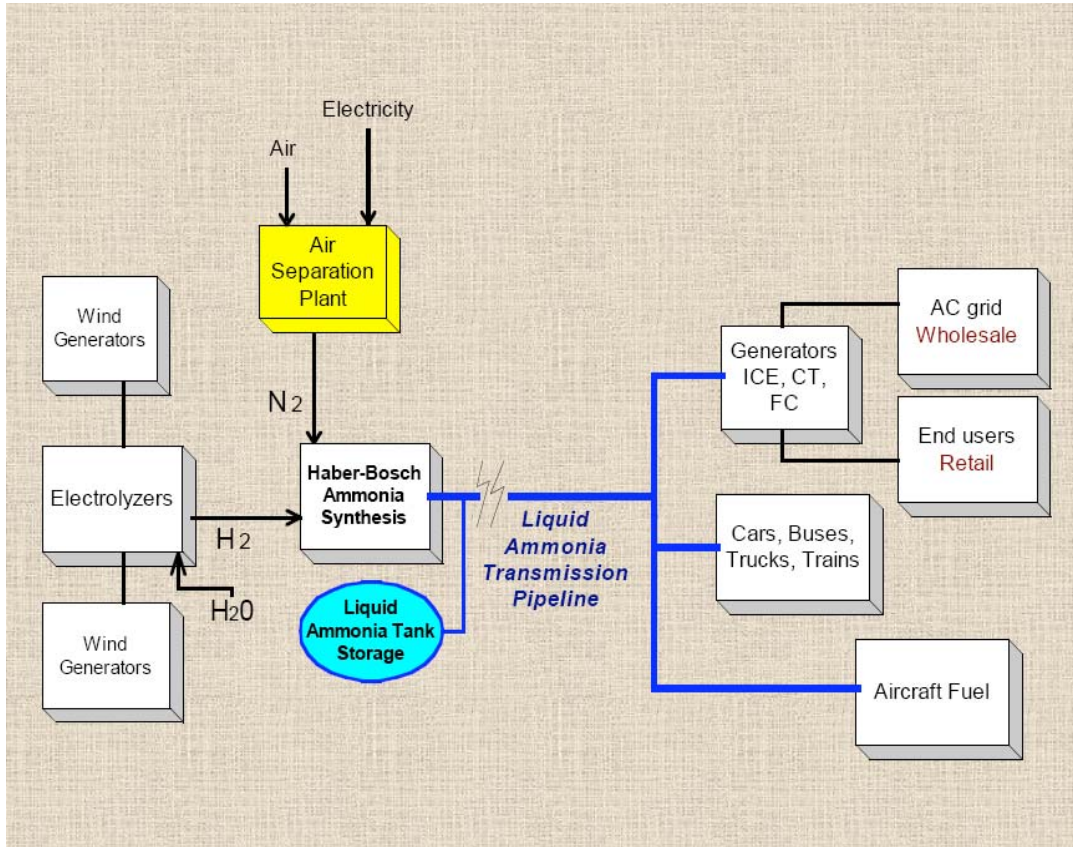
Industry-standard natural gas source NH<sub>3</sub> plants use air as their N<sub>2</sub> source; no air separation plant (ASP) is required. The wind-source NH<sub>3</sub> synthesis described here requires an ASP to provide atmospheric nitrogen, N<sub>2</sub>, to the ammonia synthesis loop ("synloop").

CF and "turndown" problems for NH<sub>3</sub>: Figures 3 and 4. We accept that wind generators will typically operate at 40% CF; this inflicts a similar low CF on the electrolyzers, ASP, and synloop, resulting in large stranded capital asset costs for these downstream components, because we have no H<sub>2</sub> storage in the system. Furthermore, the ASP and synloop have limited static and dynamic capacity range, thus limited ability to operate effectively or efficiently at low wind generator power output, and to respond to rapid variations in power output. NH<sub>3</sub> cost minimization will probably require windplant nameplate capacity > electrolyzer, ASP, and synloop nameplate capacities, with some consequent curtailment of high-output wind generation. These CF and turndown problems might be greatly reduced in Texas and other places where salt geology is available for constructing solution-mined storage caverns to firm the GH<sub>2</sub> supply to the NH<sub>3</sub> synloop.

GH2 transmission requires line pipe material and system components able to resist and control, or be immune to, hydrogen embrittlement.  $\text{NH}_3$  pipelines are moderate-strength, low-alloy, carbon steel;  $\text{NH}_3$  does not attack steel.

Markets and transmission infrastructure exist for  $\text{NH}_3$ , assuming that wind-source  $\text{NH}_3$  displaces fossil-source  $\text{NH}_3$ , whether from domestic sources or imported. Markets and infrastructure must be developed, designed, and built for GH2 transmission.

**Figure 3.**  $\text{NH}_3$  production, transmission, and firming storage system



New underground pipelines are generally less controversial, thus faster and easier to site and permit, than new overhead electric transmission lines. Pipelines are generally better protected from acts of God and man.

Electrolysis feed water: about 600 acre-feet of water per year is required for converting the entire electric energy output of a 2,000 MW, 40% CF windplant to hydrogen.

Based on the capital costs in Table 1, CRF of 18%, and wind-source electric energy at \$38.00 / MWh, the plant-gate price of  $\text{NH}_3$  would be about \$450 / ton, if the  $\text{NH}_3$  plant is operated at 95% CF; about \$650 / ton if the  $\text{NH}_3$  plant is operated at 40% CF. These results further assume:

- Capital cost of 30-bar-output electrolyzers = \$ 350 / kWe input;
- Electrolyzer efficiency = 80% HHV
- No NH<sub>3</sub> pipelines or storage tanks; no GH<sub>2</sub> storage
- NH<sub>3</sub> synloop energy conversion efficiency = 95%
- ASP O&M cost per ton N<sub>2</sub> (100% electric energy) = \$20
- H<sub>2</sub> compressor O&M cost per ton NH<sub>3</sub> (100% electric energy) = \$15

These costs are nearly competitive with year 2007 retail Corn Belt NH<sub>3</sub> price for fossil-fuel-source NH<sub>3</sub>, without carbon tax.

**Table 1.** Approximate capital costs of 2,500 tpd NH<sub>3</sub> plant driven by renewable-source electricity

Electrolyers @ \$350/MWe	\$ 180 M
Haber-Bosch reactor (synloop)	\$ 220 M
Air Separation Plant, for N <sub>2</sub>	\$ 75 M
Balance Of Plant + Contingency	\$ 75 M
Optional H <sub>2</sub> compressor (30 → 100 bar)	\$ 5 M
<b>TOTAL</b>	<b>\$ 555 M</b>

Lower costs for delivered energy, in all forms considered here, will require improvements in capital cost, O&M cost, and energy conversion efficiency for all system components. Large-scale production of optimal-economic-size electrolyzers and NH<sub>3</sub> synloops will be especially important. We assume optimized component and system design for maximum synergy among components, among diverse renewable electricity sources, and maximum CF.

### **Firming Storage**

Annual-scale firming of the output of a 2,000 MW (nameplate) windplant in the northern Great Plains requires energy storage of approximately:

- 900,000 MWh as electric energy, for which no affordable mechanism exists, or
- 31,000 tons of H<sub>2</sub>, requiring about 13 large, solution-mined salt caverns, or
- 220,000 tons of NH<sub>3</sub>, requiring about 4 large, refrigerated above-ground tanks.

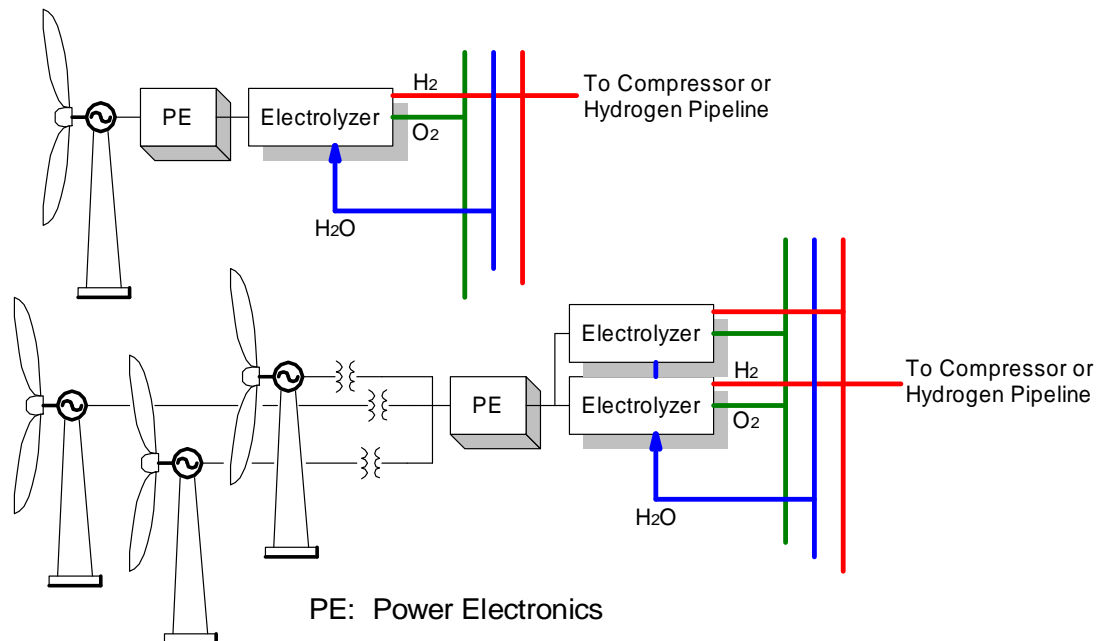
Total capital cost for the 13, H<sub>2</sub> caverns would be about \$190M; for the 4, NH<sub>3</sub> tanks would be about \$90M. This does not include conversion from H<sub>2</sub> or NH<sub>3</sub> back to electricity; the wind energy is now sold as GH<sub>2</sub> or NH<sub>3</sub>. These storage costs are included in Tables 3 and 4.

**Table 3.** Conversion + transmission costs per kg H<sub>2</sub> energy equivalent, at Multi-GW scale; Case 1 has only transmission costs with no conversion costs

Case	No firming	Firmed	Firming cost Increment
1. HVDC electricity	\$ 0.54	----	----
2. GH <sub>2</sub> pipeline	\$ 1.94	\$ 2.01	3.6 %
3. NH <sub>3</sub> pipeline, delivering NH <sub>3</sub>	\$ 2.57	\$ 2.65	3.1 %

- Table 3 Notes: 1. Delivery is wholesale electricity to city-gate market  
 2. No affordable annual-scale storage is available for electricity; “firmed” not shown  
 3. Firming cost increment is the annualized cost, at CRF, of storage capital cost

**Figure 4.** Topology options for wind-to-hydrogen energy conversion and gathering. The hydrogen may be delivered to transmission pipelines or to nearby anhydrous ammonia (NH<sub>3</sub>) synthesis plants. The oxygen byproduct of electrolysis may be sold to adjacent dry biomass or coal gasification plants. Alternatively, the hydrogen can be converted to NH<sub>3</sub> for firming.



### Potential new Technologies for “Green” Ammonia

From the results in Tables 3 and 4, the primary reason ammonia loses out to HVDC transmission and to transfer by gaseous H<sub>2</sub> is primarily associated with the additional capital costs for ammonia synthesis at the wind plant site. We have made very conservative estimates for capital equipment in this analysis to arrive at these preliminary results. Clearly, lowering ammonia synthesis capital costs could change the outcome, particularly in the case of firm energy transport. The authors are aware of a new “green” ammonia synthesis technology, for which a patent application has been filed, but is still too novel in performance and cost to include in the present analysis. At this point, all we know is that improved efficiencies are being claimed over the process analyzed herein which was based on electrolyzers followed by traditional Haber-Bosch synthesis. Additional claims for the new ammonia synthesis approach include significantly reduced capital equipment costs for a given ammonia production rate.

**Table 4.** Conversion + transmission costs per kg H<sub>2</sub> energy equivalent, at Multi-GW scale; HVDC has only transmission costs with no conversion costs

Energy Carrier	Capital Cost Synthesis (\$M)	Capital Cost Transmission (\$M)	Capital Cost Firming (\$M)	Cost per kg H <sub>2</sub> equivalent (\$)
HVDC Electric	0	500	-0-	0.54
GH <sub>2</sub> not firming	3000	930	-0-	1.96
GH <sub>2</sub> firming	3000	930	160	2.01
NH <sub>3</sub> not firming	3760	800	-0-	2.57
NH <sub>3</sub> firming	3760	800	100	2.65

Table 4 Note: It is important to recognize that in the comparisons shown in Table 4, the “end-states” are not the same. In fact, in the three cases summarized, the end-state energy carriers are 1) DC electric energy, 2) gaseous hydrogen, and 3) liquid anhydrous ammonia. In Table 4, for the far-right column for energy transmission cost, the case of HVDC electricity does not include cost for synthesis of H<sub>2</sub>, but includes only the cost for electricity delivered to the city gate. If the cost of converting to H<sub>2</sub> were included, that would add \$1.33 per kg of H<sub>2</sub> to that HVDC option, which would result in an aggregate H<sub>2</sub> transmission cost by HVDC of \$1.87 per kg of H<sub>2</sub>.

### Conclusions

- Electricity transmission costs are less, but no affordable firming storage is available or anticipated.
- “Firming” storage is a small incremental capital cost for GH<sub>2</sub> and NH<sub>3</sub> transmission.
- NH<sub>3</sub> firming storage tanks capital cost is less than for GH<sub>2</sub> salt caverns, per unit energy: both are good investments.
- A pilot plant will be needed to:
  - explore and quantify costs of NH<sub>3</sub> synthesis CF and turndown problems;
  - explore optimum nameplate capacity ratios for principal capital equipment components;
  - optimize system topology, size and location of major capital equipment (Figures 3 and 4)
- Plant-gate cost of wind-source NH<sub>3</sub> is produced, approximately:
  - \$ 450 / ton, if NH<sub>3</sub> plant is operated at 95% CF;
  - \$ 650 / ton, if NH<sub>3</sub> plant is operated at 40% CF.

## **Future Work**

This preliminary analysis indicates that ammonia could be an attractive candidate energy transmission and storage medium transmission for large-scale, stranded renewable electric energy, such as the Great Plains wind resource. The cost estimates for transmission by HVDC, gaseous H<sub>2</sub>, or liquid ammonia are relatively close. The analysis also indicates that annual-scale firming of Great Plains wind energy as ammonia in large above-ground tanks is only a small fraction of the total generation-transmission system estimated cost. Ammonia firming storage costs are about half that for cavern storage of GH<sub>2</sub>.

This preliminary analysis identifies primary areas for further examination and for improved accuracy in cost validation and reduction:

- Energy conversion system capital costs and efficiencies;
- Capital and O&M costs for large-scale GH<sub>2</sub> and NH<sub>3</sub> storage.