

Transmission and Firming of GW-Scale Wind Energy via Hydrogen and Ammonia

by

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ABSTRACT

This is a conceptual study, for MW to GW scale, comparing production, transmission, and storage costs for gaseous hydrogen (GH₂) and anhydrous ammonia (NH₃) fuels made from wind-generated electricity, with and without the low-cost, annual-scale, firming storage which would add great market and strategic value. Both fuels are suitable for vehicles and for distributed generation (DG) in stationary combined-heat-and-power (CHP), via fuel cells or internal combustion engines (ICE's). NH₃ is also a valuable fertilizer, and this study briefly examines the economics of renewable-source versus fossil-source production of NH₃ fertilizer. No pilot plant exists for confirming the system capital costs and conversion efficiencies we estimate in this study, although both GH₂ and NH₃ have been proposed for wind energy transmission and storage [1-6]. Hydrogen is promising as a clean-burning energy carrier, and modern electrolyzers can produce large volumes of high-pressure hydrogen, ready for direct pipeline transmission and/or for ammonia synthesis, from renewable energy sources. Renewable-source hydrogen can alternatively be stored and transported as NH₃, which can be readily synthesized, following electrolysis, using atmospheric nitrogen, and be used at the delivery end-point as a fertilizer or a fuel. Both GH₂ and NH₃ transmission and firming storage will accelerate our conversion from fossil to diverse renewable resources, via major new markets including, and beyond, the electricity sector.

1. INTRODUCTION

We compare energy transmission and delivery by electricity, GH₂, and NH₃. We examine producing GH₂ by water electrolysis using wind energy, optionally storing it in large solution-mined salt caverns, and delivering GH₂ by pipeline to a city gate market. Gaseous hydrogen suffers from low volumetric energy density, still falls short of on-board-vehicle storage targets, and, except for large-scale geologic storage, requires expensive storage devices.

We suggest building pilot plants. Although hydrogen and ammonia have been proposed as transmission and firming storage media for GW-scale wind energy, no pilot plant exists for confirming the system costs and efficiencies we estimate here. Hydrogen is promising as a clean-burning energy carrier. Modern electrolyzers can produce large volumes of high-pressure hydrogen from water, ready for pipeline transmission and/or ammonia synthesis, from renewable energy sources. Hydrogen's extremely low volumetric energy density requires its

compression or liquefaction to increase energy density, which consumes a significant fraction of the energy contained in the hydrogen. Gaseous hydrogen (GH₂) transmission and firming storage has been explored elsewhere, so we focus on anhydrous ammonia (NH₃) here [6], and its comparison with energy transmission by electricity and hydrogen.

Renewable-source hydrogen can be stored and transported as NH₃, which can be readily produced in an exothermic synthesis step following electrolysis using nitrogen (N₂) from the air. NH₃ synthesis consumes energy comparable to compression of gaseous hydrogen, and less energy than liquefaction of hydrogen; it requires additional capital equipment and O&M costs for N₂ supply and NH₃ synthesis.

Ammonia contains no carbon; has physical properties similar to propane; liquefies at ambient temperatures at about 10 bar or at -28 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.

We analyze producing NH₃ from wind using hydrogen from water electrolysis and nitrogen from the atmosphere, storing it in large-scale tanks, and delivering it either as nitrogen fertilizer or as fuel for vehicles and fuel cells, via pipeline, truck, rail, and barge, consistent with well-established global industry practice. Economical, large-scale storage of GH₂ in deep, solution-mined salt caverns, and of NH₃ in liquid tank storage could firm Great Plains wind at annual scale, adding great strategic and market value.

The United States of America (US) uses 15-20 million tons of NH₃ and NH₃-based fertilizer per year. Over half is imported from countries where fossil fuels (largely stranded natural gas (NG)) are used in the NH₃ production process, releasing enormous amounts of CO₂ into the atmosphere. The US Senate 07 Farm Bill included research initiatives for “renewable nitrogen fertilizer” [7] and for “...storage and conversion technologies for wind- and solar-generated power...” [8], which could include both GH₂ and NH₃ for both fertilizer and fuel.

2. WIND ENERGY POTENTIAL: TRANSMISSION OPTIONS

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 US: about 10,000 terawatt-hours (TWh = billion kWh), or about 100 quads (quadrillion btu) [12]. 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 and permit, because of public objection, as in NIMBY;
- Suffer the same low capacity factor (CF) (typically 40%) as the windplants they serve, unless wind generation is curtailed;
- Provide no affordable “firming” energy storage, thus taxing the “system balancing” ability of the electricity grid;
- Be vulnerable to damage by acts of God and man.

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 GH₂, by electrolysis of water, at high pressure (30 - 150 bar), GH₂ transmission and delivery by underground pipeline, with annual-scale firming storage of high-pressure GH₂ in deep, solution-mined salt caverns;

2. Conversion of electric energy to NH_3 , for transmission as liquid by underground pipeline, delivery via pipeline, rail, and truck, with annual-scale firming storage as liquid NH_3 in large (10,000 – 60,000 ton) refrigerated, above-ground tanks.

Without any expansion of electricity transmission capacity, or technology breakthroughs, wind energy may be totally converted to GH_2 or NH_3 transmitted over long distances using new or repurposed underground pipelines, firmed at annual scale in large GH_2 storage caverns and above-ground NH_3 tanks, and marketed as fuel for vehicles and for combined-heat-and-power (CHP) distributed generation in:

- Internal combustion engine (ICE) and combustion turbine (CT) gensets adapted for NH_3 fuel;
- PEM hydrogen fuel cells, for GH_2 and hydrogen “cracked” from NH_3 ;
- Direct-ammonia fuel cells.

The ICE operates efficiently on either GH_2 or NH_3 fuel, and is a mature technology for both.

GW-km is a measure of the total transmission service provided by the system, useful for comparing transmission means and strategies. Large electric transmission lines cost about \$1 million per GW-km: Frontier Line components [13], Section 8.

Total installed capital cost of large, underground NG pipelines is now \$US 50–60 per inch diameter per meter length, without compression, which adds ~15% to pipeline capital cost [14, 15]. Pipeline costs vary considerably, among projects, and with material prices and contractor availability. We assume that NH_3 pipelines, and GH_2 pipelines fit for renewables-hydrogen service, can be built for the same cost as NG pipelines of the same diameter and rated pressure, assuming no incremental capital costs for GH_2 -capable line pipe, valves, and meters.

As shown later in Figure 5, the capacity of a 36” GH_2 pipeline 800 km long is < 8 GW; thus total system capacity is 6,400 GW-km. From the estimate above, pipeline capital cost is ~\$US 1.6 billion, assuming no GH_2 compression. Then, cost per GW-km for the 36” GH_2 pipeline is ~\$250,000. Of course, this type of rating depends on pipeline diameter since the energy delivered depends approximately on the square of the pipe diameter, but the capital cost is linearly proportional to the pipe diameter. Accordingly, for a 800 km, of a smaller 20” GH_2 pipeline using the data in Figure 5, the GW-km rating is ~\$320,000

A 10” mild steel pipeline, 1,000 km long, for liquid NH_3 at <20 bar, has a continuous capacity of ~1 GW [16] of energy delivery, with adequate pumping at midline stations 100 miles apart, which would be adequate for a 2.5 GW nameplate windplant with internal NH_3 output smoothing or firming storage. Pipeline total installed capital cost is ~\$325,000 per km, including pumping stations. A 1,000 km pipeline would cost ~\$US 325 million; total system capacity is 1,000 GW-km; cost per GW-km is \$325,000.

Thus, the relative capital cost of transmission systems may be approximately compared:

- Electricity, 500 kV, AC or DC \$ 1 million per GW-km
- GH_2 pipeline (36” diameter NG pipeline), no compression \$250K per GW-km
- GH_2 pipeline (20” diameter NG pipeline), no compression \$320K per GW-km
- Liquid NH_3 pipeline, with pumping \$ 325K per GW-km

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.



Figure 1. Clipper Windpower 2.5 MW turbines in background with liquid anhydrous ammonia (NH_3) nitrogen fertilizer “nurse tanks”, $\sim 5 \text{ m}^3$ each. Wind-generated electricity can be locally converted to NH_3 for fertilizer and fuel, without expansion of the electricity transmission grid [9]. September '07, NE Iowa

3. HYDROGEN AND AMMONIA PRODUCTION FROM WIND AND OTHER RENEWABLE-SOURCE ELECTRICITY

Figures 1-4. The entire energy output of the stranded windplant is converted to GH_2 via electrolysis of water in electrolyzers. High-pressure-output electrolyzers directly feed the transmission pipeline at ~ 100 bar, for delivery to distant city gate wholesale merchant markets. Byproduct oxygen may be sold to adjacent coal and dry biomass gasification plants. No pilot plant has been built. Part or all of the hydrogen could also be delivered to NH_3 synthesis plants.

In the Twentieth Century Norway, Iceland, Peru, and Zimbabwe produced hydrogen for NH_3 synthesis from surplus hydropower via electrolysis, entirely for agricultural nitrogen fertilizer. But, lower-cost hydrogen from steam methane reforming (SMR) of NG displaced this electrolytic hydrogen by the 1980's. Electrolyzer manufacturers are now improving energy conversion efficiency and reducing capital costs, anticipating new interest in GH_2 and NH_3 fuels, driven by higher NG prices and the transmission and firming storage needs of diverse, large-scale, carbon-emission-free renewables.

3.1. The Ammonia Economy: Fertilizer

Figures 1-3. Anhydrous ammonia (NH_3) is an essential fertilizer, which has led to vastly increased agricultural consumption 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. The US annually consumes 15-20 million tons of nitrogen fertilizers, as NH_3 or as products made from NH_3 . Worldwide annual consumption is approximately 130 million tons [17].

NH_3 made from wind-generated electric energy, water, and atmospheric nitrogen is a potential major market and delivery pathway for wind energy, worldwide. A reasonable “market share” of 6 million tons per year (tpy) of NH_3 would require the full output of about 20,000 MW of nameplate wind generation, at 40% CF (Total installed US wind capacity in April 2007 was about 12,000 MW).

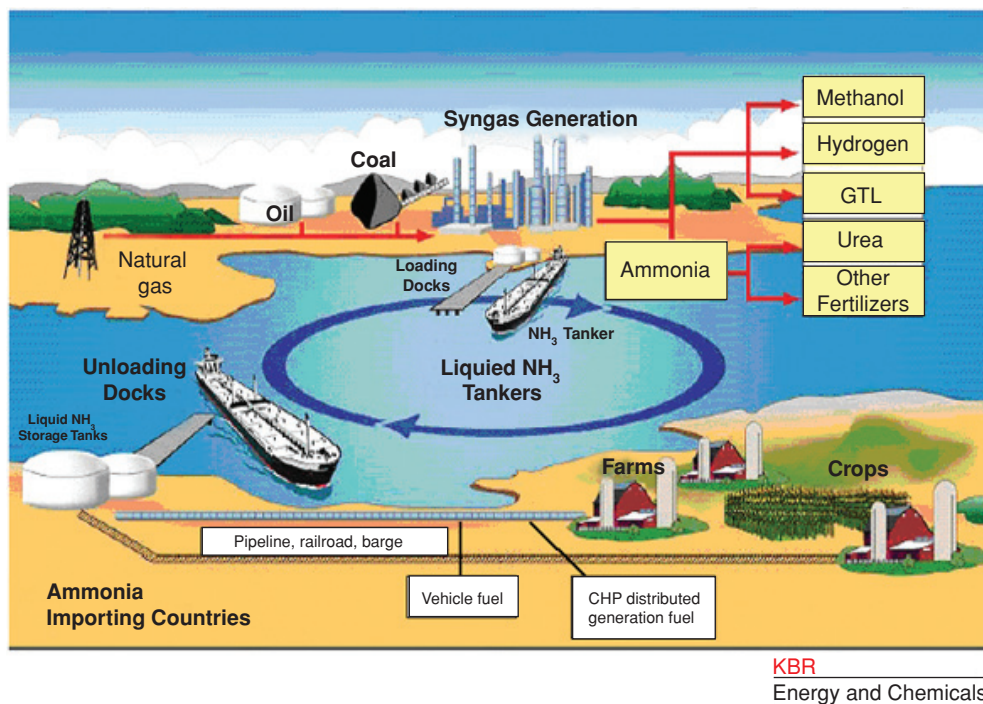


Figure 2. The global ammonia economy [10]. Liquid NH₃ is exported from plants fed by low-cost, stranded fossil fuels. Indigenous wind-source NH₃ may displace fossil-source imports. The future NH₃ fuel market may be larger than the fertilizer market

Figure 1 illustrates the opportunity for indigenous conversion of wind energy, where it is generated, to N-fertilizer, where it is consumed, without expansion of the electricity transmission grid. Figure 2 illustrates the global ammonia fertilizer economy, now operating primarily on natural gas and coal. A few decades ago the US produced all its ammonia from abundant, low-cost, North American NG, releasing the byproduct CO₂ to Earth's atmosphere. That NG is now too costly, so the US imports over half its NH₃ [18]. Future CO₂ emissions will probably be limited and costly. Several proposed new domestic coal-source NH₃ plants will suffer a worse CO₂ management problem than NG-source plants. Four annual conferences have tracked this evolution in the ammonia industry and the new opportunities in both supply and demand, including renewable-energy-source ammonia (RE-NH₃) [19].

Extensive markets and transmission and storage infrastructure currently exist for NH₃. Figure 3. If wind-source NH₃ is competitive in price and simply displaces fossil-source NH₃, whether from domestic fossil sources or imported, the existing delivery infrastructure would be adequate for delivering the wind-generated ammonia, since the demand is the same, with these exceptions:

1. A new gathering NH₃ pipeline system will be needed;
2. NH₃ use as vehicle and distributed generation (DG) - CHP fuel would increase total NH₃ demand.

3.2. The Ammonia Economy: Fuel

As well as an essential nitrogen fertilizer, ammonia is an energy-dense, ultra-clean-burning fuel. It is environmentally benign and "sustainable" if made from renewable energy sources. Since the 1930s, NH₃ has repeatedly been demonstrated as a clean and convenient fuel for ICE's, CT's, and fuel cells, encouraging recent interest in NH₃ fuel, domestically produced from renewables, to displace imported oil.

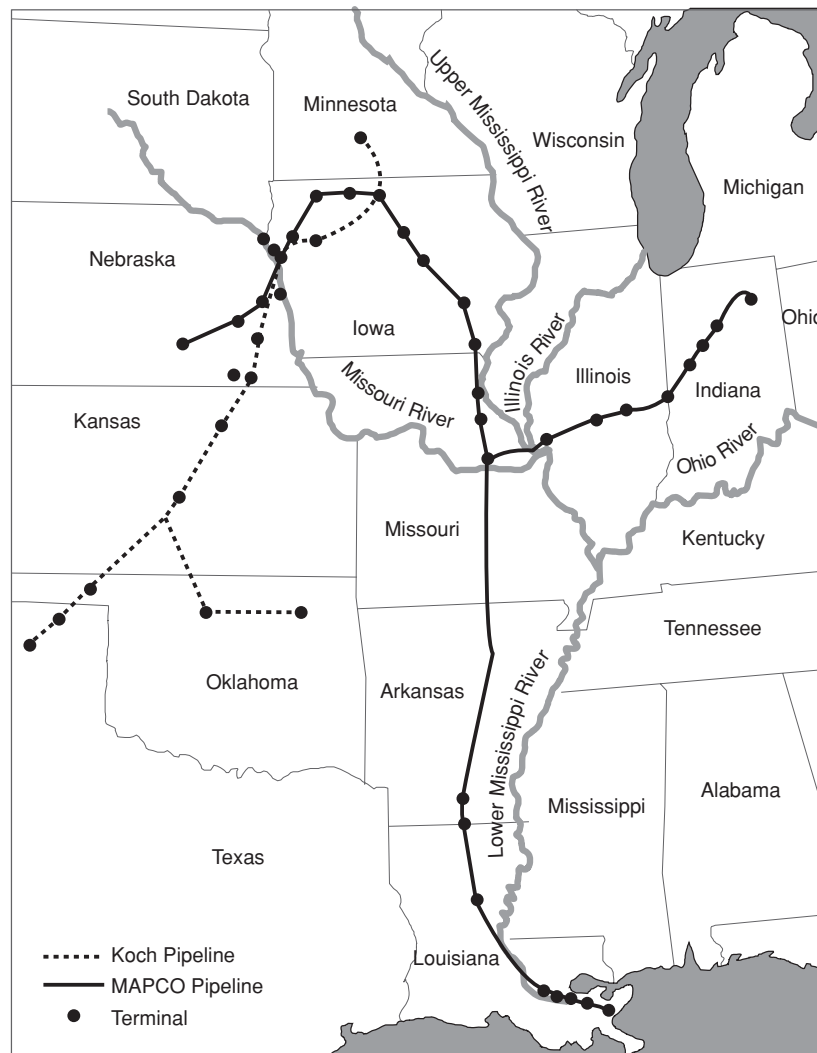


Figure 3. Existing ammonia (NH_3) pipelines and storage terminals [11]. Strong is in refrigerated, liquid, above - ground steel tanks of 10 - 60,000 tons each

Ammonia 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. Ammonia 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. Figure 6. Liquid anhydrous ammonia, NH_3 , has more atoms of hydrogen per liter than liquid hydrogen. This ability of NH_3 to store hydrogen very compactly at ambient temperature and moderate pressure is a key advantage for NH_3 over GH_2 .

Ammonia fuel is the same chemical as the liquid fertilizer, anhydrous NH_3 . Ammonia is a liquid under moderate pressures (>125 psi) at ambient temperatures, which enables it to be easily stored and transported in inexpensive, standardized tanks.

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. Ammonia combusts according to:

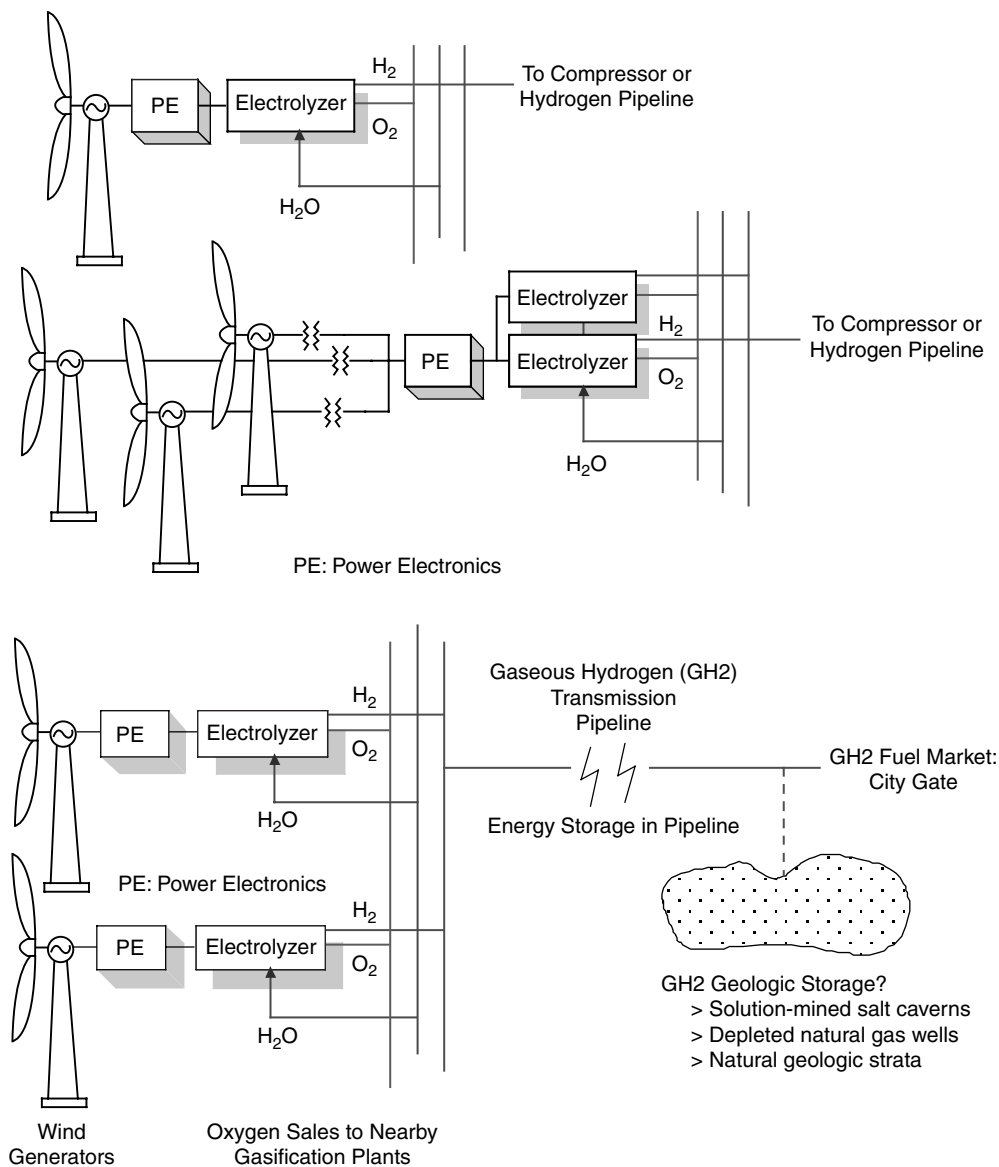
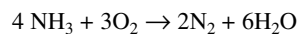


Figure 4. System topology options for wind-to-hydrogen energy conversion, gathering, and transmission. The hydrogen may be delivered to transmission pipelines or to nearby NH_3 synthesis plants. Both GH_2 and NH_3 may be stored for affordably firming wind



with only nitrogen and water vapor as combustion products. Like hydrogen, ammonia is lighter than air and is not a greenhouse gas.

3.3. The Ammonia Economy: Potential and Caveats

Figure 3 shows that a safe, reliable, proven ammonia delivery and storage infrastructure already exists in the US. 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, NH_3 .

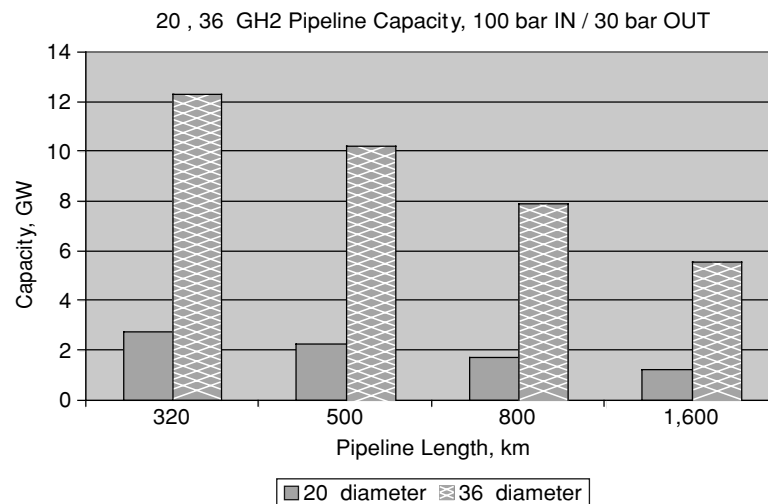


Figure 5. GW capacity of GH2 transmission pipelines with no input or midline compression. Assumes that 100-bar-output electrolyzers feed the pipeline directly. Total transmission service capacity of an 800 km, 36" pipeline is ~6,400 GW-km

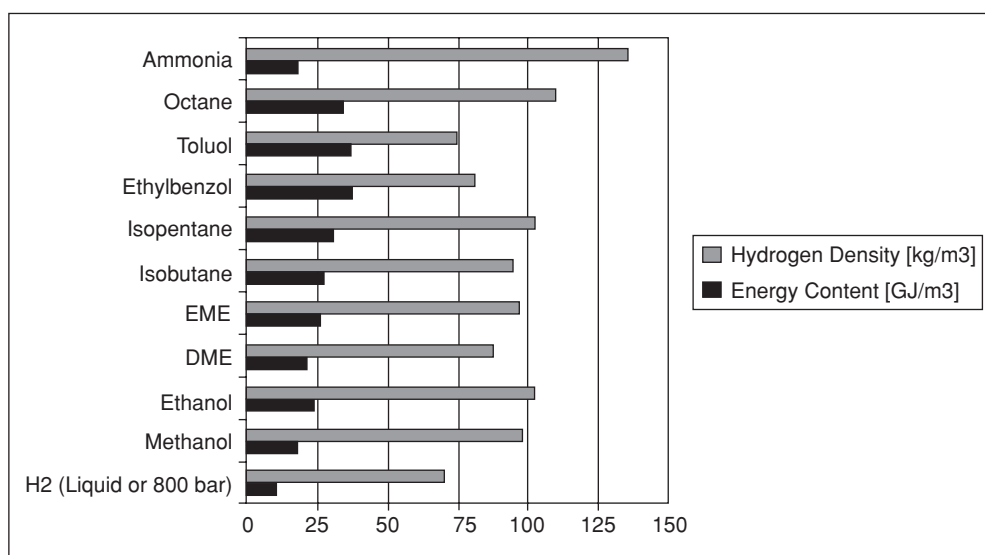


Figure 6. Hydrogen density and higher heating value (HHV) energy content of ammonia and selected liquid hydrocarbon fuels [20]

About 20,000 MW of nameplate Great Plains wind generation would be needed to produce 6 million tons of NH_3 per year, about one-third of the present US demand for ammonia based fertilizer [21]. This estimate is based on an overall 50% efficiency of converting wind power into energy stored as NH_3 . Several times as much wind, or other renewables generation, would be needed to produce all of the US NH_3 demand, especially if NH_3 also becomes widely adopted as a fuel.

Markets and infrastructure must be developed, designed, and built to expand the NH_3 gathering, transmission, and storage network if a large fraction of domestic NH_3 fertilizer demand, and the potential large, nascent market for NH_3 fuel, is to be met by wind and other diverse, dispersed renewables.

It is important to mention ammonia safety. Ammonia's safety challenges are primarily caused by its extreme reactivity with water, which creates an inhalation and tissue contact hazard. It is classified as "Hazard Zone D inhalation hazard (49 CFR 173.116 (a))". Hazard Zone

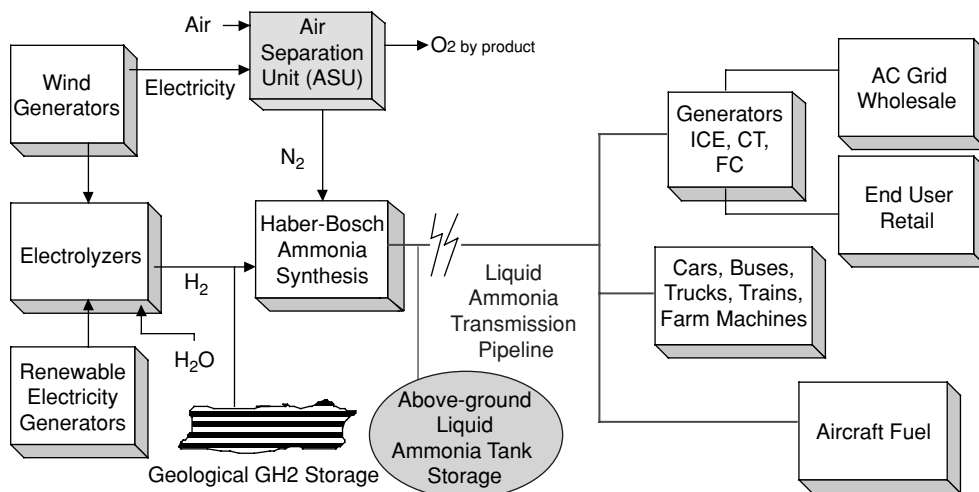


Figure 7. NH_3 production, transmission, and firming storage system. Low-cost, large-scale, high-pressure GH₂ storage probably requires deep domal or bedded salt formations for solution mining of large caverns. GH₂ storage allows the ASU and synloop to operate at high CF without the difficult dynamic range required to follow renewable energy generation output variations. Without large scale GH₂ storage, high efficiency conversion of the wind energy to NH_3 may require novel technical solutions

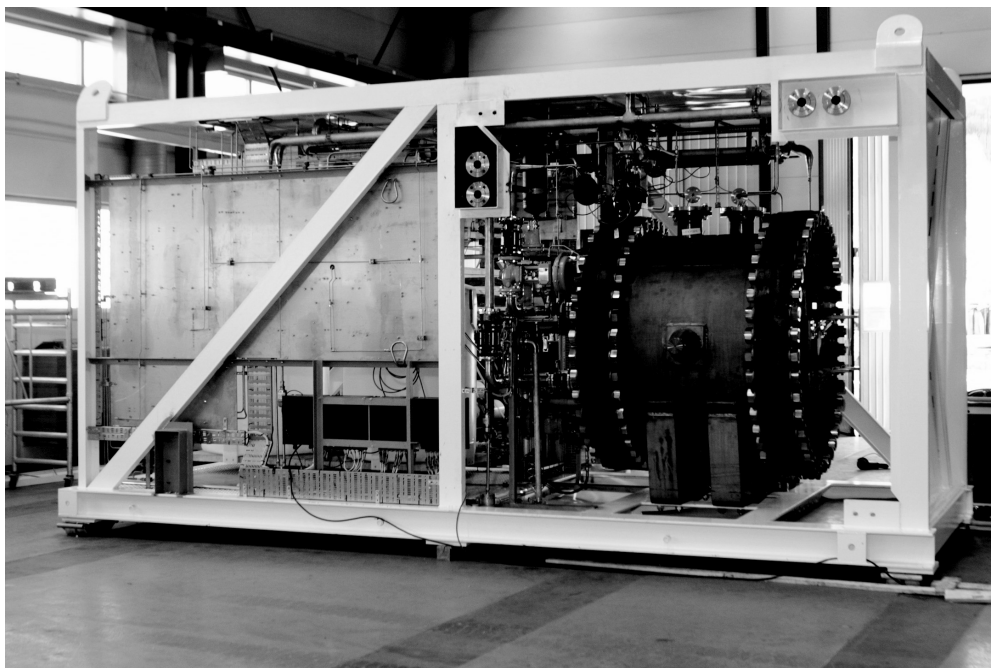


Figure 8. High-pressure-output electrolyzers are essential for either GH₂ or NH_3 transmission. Norsk Hydro electrolyzer, KOH type, 560 kWe input, 130 Nm³/hour output at 30 bar (450 psi)

D materials have a lethal concentration (LC 50) greater than 3,000 parts per million and less than or equal to 5,000 parts per million [22]. On the other hand, ammonia is not explosive nor highly-flammable, and does not need to be stored at high pressures. It is easily detected by its odor, thus providing its own alarm. Like every chemical, ammonia requires proper handling equipment, training and experience, and respect. But, given the millions of tons of ammonia 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 [23].

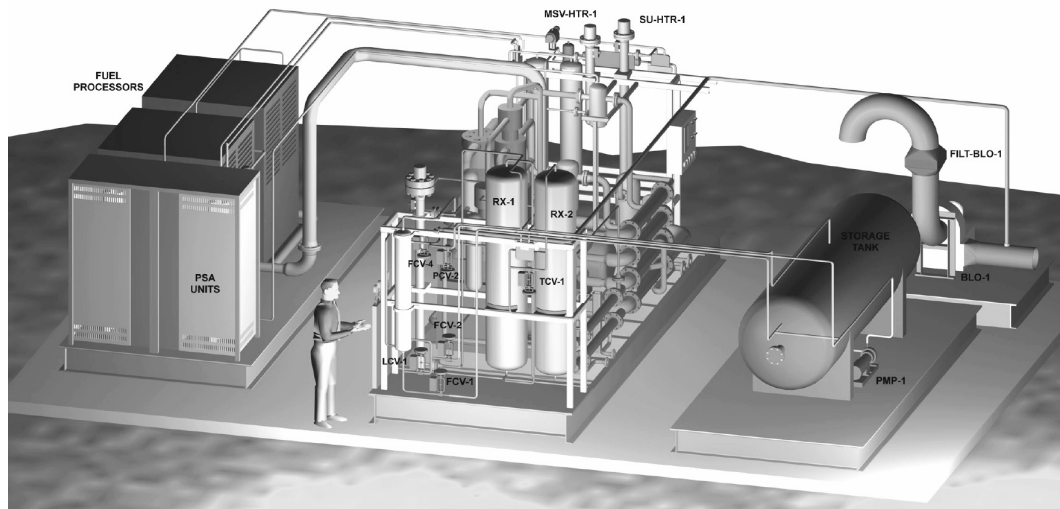


Figure 9A. A small, 3 ton per day (tpd), NG-source ammonia plant which would accommodate the peak (nameplate) output of a 1.5 MW wind generator or the average annual output of a 3.5 MW windplant operating at 40% CF, assuming GH₂ storage is available for windplant output leveling and firming. Suitable for distributed production of NH₃, but not achieving the economy-of-scale of industry-standard, NG-source, 1-3,000 tpd plants [36]. Synloop is center; ASU and SMR at left.



Figure 9B. NG-source ammonia plant, Indonesia, 2002, by Mitsubishi

3.4. Ammonia Synthesis Process and Production Plants

Ammonia is synthesized from hydrogen and nitrogen. Renewable-source electricity can be used to split the water molecule, via electrolysis, to make hydrogen. Diverse renewable energy sources and nuclear-generated electricity and heat can be used to produce the hydrogen.

Industry-standard NG-source NH₃ plants use air as their nitrogen (N₂) source using a process called air separation. The N₂ needed for this RE-NH₃ synthesis loop (“synloop”) is taken from air by a common industrial air separation unit (ASU), which may be cryogenic, PSA, or membrane technology. The nitrogen is returned to the atmosphere when NH₃ is consumed in an engine or fuel cell. In effect, the nitrogen acts as a hydrogen “carrier”.

Figures 7-9. Sixty per cent of the capital cost of a large, 1,000 - 3,000 ton per day (tpd), NG-source ammonia plant is required for hydrogen production from CH_4 (methane, the principal component of NG) by SMR [24]. This SMR system is eliminated in $\text{RE}\cdot\text{NH}_3$ synthesis plants fed directly by hydrogen from electrolysis, for a large saving in capital and operating cost, partially offsetting electrolyzer capital cost and conversion losses.

Figure 9A shows a small, 3 tpd, NG-source, NH_3 synloop plant, which perhaps represents a good size for distributed NH_3 production in the absence of, or as an alternative to, electricity transmission [25]. In Figure 9A, the synloop is at center; the ASU and SMR at left. If entirely wind powered, GH_2 from electrolyzers and N_2 from the ASU, both at 100 bar, would feed the synloop. The SMR would be eliminated. Assuming optimistic 80% electrolyzer efficiency and 80% NH_3 synloop efficiency, this mini-plant would accommodate the peak (nameplate) output of a 1.5 MW wind generator or the average annual output of a 3.5 MW windplant operating at 40% CF.

For wind-source NH_3 production, energy storage upstream of the synloop, possibly as GH_2 in geologic formations, would be essential to:

1. Harvest the full annual energy production (AEP) of the windplant, without curtailment;
2. Prevent overloading the synloop;
3. Prevent turndown (operation below rated capacity) of synloop and ASU;
4. Achieve high CF on synloop, ASU, and any associated compressors;
5. Maintain high system efficiency and produce NH_3 at cost reasonably competitive with fossil fuel-source NH_3 .

The produced NH_3 could be immediately used locally, stored on site in standard commercial storage tanks of various sizes, and/or shipped via truck, barge, or pipeline.

In October '07 a new, offshore, 2,500 tpd, NG-source, NH_3 plant, as shown in Figure 9B, will cost ~ \$US 970M to design and build. NH_3 production (variable) costs for a stranded NG-source plant is ~ \$US 125 - 150 per ton [25]. A coal-source NH_3 plant of the same size, with CO_2 capture for pipelining to nearby enhanced-oil-recovery (EOR) disposal, will cost ~70% more [26]. Several coal-source NH_3 plants are proposed for the US.

NH_3 prices in mid-October 07 were [27]:

Tampa	\$US 277 per ton
New Orleans (NOLA)	282 per ton
Corn Belt terminal	498 per ton
Corn Belt farmer (terminal + 25%)	620 per ton

Co-locating renewable-source generation, electrolysis, and NH_3 synthesis plants, with each other and perhaps with other facilities such as coal and dry biomass gasification plants, could allow synergistic sale of byproducts (electrolytic oxygen to adjacent gasification plants) and economies-of-scale.

3.5. CF and "Turndown" Problems for NH_3 Plants

Figures 4 and 7. We accept that wind generators will typically operate at 40% CF. This inflicts a similar low CF on the electrolyzers, ASU, and synloop, resulting in large stranded capital asset costs for these downstream components, unless we have large-scale GH_2 energy storage between electrolyzers and synloop. Furthermore, the ASU and synloop have limited static and dynamic capacity range and ramp rates, i.e. "turndown", thus limited ability to operate effectively or efficiently at low wind generator power output, and to respond to rapid variations in wind power output. NH_3 cost minimization will probably require windplant nameplate capacity to be greater than electrolyzer, ASU, and synloop nameplate capacities, with some consequent curtailment of high-output wind generation.

These CF and turndown problems could compromise overall system efficiency. One solution would be new NH_3 synthesis technologies that could “track” the time-variable wind power and maintain efficient production. See “Potential new technologies ...”, below. This problem might be greatly reduced in Texas and other places where salt geology is available for constructing high-pressure, solution-mined storage caverns to firm the GH_2 supply to the NH_3 synloop. Figures 10 and 11.

Figures 4 and 7. In the absence of such large-scale GH_2 storage, these problems may require the NH_3 plant to remain “always on”, which could result in low average efficiency, or require that a new ammonia synthesis technology — more tolerant of turndown — be developed. For the ASU, ionic membrane separation has inherently better turndown capability than cryogenic separation, for N_2 production.

4. Electricity Transmission

Our electricity transmission cost benchmark is the Frontier Line Feasibility Study, which considered many multi-GW electricity transmission expansions, all at 500 kV, both AC and DC, from Wyoming south and west, with these typical results [28, 29]:

- AC line construction cost \$ 29.90/MWh
- DC line construction cost \$ 19.10/MWh
- California system integration 3.00/MWh
- Line losses \$ 1.80/MWh

Analysis of individual Frontier Line transmission links gives these mean capital costs for mixed AC and DC lines:

- Per GW \$ 619 million
- Per mile \$ 4.9 million
- Per GW-mile \$ 1.4 million
- Per GW-km \$ 0.9 million

Analysis of complete Frontier Line transmission system alternatives gives these mean capital costs:

- Per GW \$ 1,375 million
- Per mile \$ 3.2 million
- Per GW-mile \$ 0.8 million
- Per GW-km \$ 0.5 million

GW-mile is a measure of the total transmission service provided by the system. Whether these Frontier Line estimates include ROW lease or purchase is unknown. Generally, large electric transmission lines cost \$500K – \$900K per GW-km.

5. STORAGE FOR ANNUAL-SCALE WIND FIRING

Consider the quantity of GH_2 storage required to “firm” the output of a 2,000 MW (nameplate) Great Plains windplant which produces ~ 7 TWh in an average year, at 40% CF. Using the numbers from “Seasonal Variability of Wind Electric Potential in the United States” [30], Table 3, for “North Central”, normalized, yields these “seasonality factors”:

Winter 1.20 Spring 1.17 Summer 0.69 Autumn 0.93



Figure 10. Salt deposits that may be useful for firming the time-varying output of wind and other renewables, as compressed GH₂ in solution-mined salt caverns, to provide a steady supply of GH₂ to ammonia synthesis plants. The GH₂ would be made from renewable-source electricity by electrolysis of water

We find that expected average seasonal energy production for the 2,000 MW windplant would be $(7 \text{ TWh}/4 \text{ seasons}) = (1.75 \text{ TWh}) \times (\text{seasonality factor})$, above:

Winter =	1.75×1.20	=	2.10 TWh
Spring =	1.75×1.17	=	2.05 TWh
Summer =	1.75×0.69	=	1.21 TWh
Autumn =	1.75×0.93	=	1.63 TWh

The biggest difference between seasons is between Winter and Summer: $2.10 - 1.21 = 0.89$ TWh. If all windplant energy is converted to GH₂ for export, at the 75% efficiency typical of large-scale electrolyzers, this is apparently 0.71 TWh of GH₂ storage needed. However, the biggest difference between adjacent, sequential seasons is between Spring and Summer: $2.05 - 1.21 = 0.84$ TWh. If all windplant energy is converted to GH₂ for export, at 75% electrolyzer efficiency, apparently $[0.84 \times 0.75 = 0.63]$ TWh of GH₂ storage is needed. The latter case is more relevant.

GH₂ transmission pipelines are likely to operate at 100–150 bar maximum input pressure, with city-gate delivery at ~30 bar. An 800 km, 20" diameter GH₂ pipeline, packed to 130 bar and unpacked to 65 bar, stores 936 tons of GH₂ = 33,500 MWh. = 0.03 TWh, which we assume for this analysis.

Thus, geologic storage needed to seasonally “firm” 2,000 MW (nameplate) of Great Plains wind, over the maximum average seasonal variation, is: $0.63 - 0.03 = 0.6$ TWh, which is equivalent to ~18,000 metric tons (Mt) of GH₂.

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

- 630,000 MWh as electric energy, for which no affordable mechanism exists, or
- 18,000 tons of GH₂, requiring about 6 large, solution-mined salt caverns [31], or
- 110,000 tons of NH₃ requiring about 4 typical, large, refrigerated, above-ground tanks.



Figure 11. Multiple large, solution-mined salt caverns in “domal” salt, suitable for high-pressure storage of GH₂. A typical cavern will store 2,500 net tons of GH₂ at 70-150 bar in 800,000 cubic meters of physical volume

No affordable electric energy storage technique or system capable of 630,000 MWh, for annual-scale firming of this quantity of Great Plains wind, is available or anticipated. The vanadium-redox battery energy storage system (VRB-ESS) presently provides the lowest-cost bulk electricity storage. VRB Power Systems, Canada, will sell a VRB-ESS flow battery to Tapbury Management, County Donegal, Ireland, for \$US 6.3 million: 1.5 MW (charge and discharge rate), 12 MWh (total energy storage capacity) [32]. Storing 630,000 MWh would require ~50,000 of this VRB-ESS, at total capital cost of > \$US 100 billion, if mass production halved VRB-ESS cost and if the optimum power: energy ratio for VRB-ESS components were determined.

Figure 10 shows salt deposit realms, some of which contain formations deep and tight enough to store GH₂ in man-made caverns at 150 bar with negligible leakage. Figure 11 shows GH₂ storage caverns. Total capital cost for the 6 required GH₂ caverns would be about \$95M; for the 4 required NH₃ tanks such as those shown in Figure 12 would be about \$90M. Tables 2 and 3 include these storage costs but do not include conversion from H₂ or NH₃ back to electricity at the market end of pipeline transmission. The wind energy is now sold as GH₂ or NH₃ fuels for vehicles and DG of electricity in stationary CHP.

6. GH₂ STORAGE AND DISTRIBUTION

GH₂ transmission requires line pipe material and system components able to resist and control, or be immune to, hydrogen embrittlement. In contrast, NH₃ pipelines are moderate-strength, low-alloy, carbon steel. NH₃ does not attack steel.



Figure 12. Typical large, refrigerated, liquid anhydrous ammonia (NH_3) storage tank at CF Industries terminal at Huntington, IN

Figure 11. GH_2 is stored at 100–150 bar in solution-mined salt caverns, typically 800,000 cubic meters physical volume, capable of storing $\sim 2,500$ net tons of GH_2 in addition to $\sim 2,000$ tons of “cushion” GH_2 . The cavern top is typically ~ 800 m below ground level. The surface facility provides compression (if needed), GH_2 gas drying upon withdrawal, and manifold of multiple caverns in a storage array. Typically, capital cost of a completed facility is half cavern excavation, half surface facility. In Texas onshore domal salt, in a multi-cavern facility achieving maximum economy of scale, each cavern will probably cost $\sim \$15$ – 20 million and will store $\sim 2,500$ net tons GH_2 . Leakage and O&M cost, except for compression energy (if required), are very low.

About 15,000 such salt caverns could firm, at annual scale, the entire Great Plains, US, wind resource, as GH_2 fuel: $\sim 10,000$ TWh (~ 100 quads) per year. Synergy with solar and other renewables would reduce required cavern storage, perhaps dramatically. However, customers must now purchase energy only as GH_2 fuel.

7. NH_3 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 3 shows approximately 5,000 km of mild carbon steel pipeline in place in the US agricultural heartland. These pipelines carry liquid ammonia at pressures of 15 bar and above, and since ammonia is not corrosive to steel, have very few maintenance problems or costs [33]. Because the ammonia is piped as a liquid, these pipelines only need to be 8–10 inch diameter, which is considerably smaller than NG pipelines, or those proposed to transport hydrogen gas, for equal energy-distance (GW-km) capacity. In addition to pipelines, the NH_3 distribution network includes a large number of tanker trucks, rail tank cars, and river barges, and approximately 4.5 million tons of terminal storage in large, above-ground, refrigerated liquid tanks, primarily situated along the pipeline, as shown in Figures 3 and 12. Tanks are typically 10–60,000 tons each, with contents at 1 atm and -28°C .

Figure 12. About 6,000 such NH_3 storage tanks, of 60,000 tons each, could firm, at annual scale, the entire Great Plains US wind resource as NH_3 fuel: $\sim 10,000$ TWh (~ 100 quads) per year. Synergy with solar and other renewables would reduce required cavern storage, perhaps dramatically. However, customers must now purchase energy only as NH_3 fuel.

8. ENERGY TRANSMISSION COST ANALYSIS

“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, annual-scale energy storage in some form.

This paper’s primary purpose is comparing costs of GW-scale transmission and annual-scale “firming” energy storage for the five cases below, in a first-approximation analysis [34]. Tables 1, 2, and 3.

1. Electricity: 500 kV AC or DC electricity: 50% of 3,000 MW line
 - a. Without firming storage. With firming storage case is not applicable, since no affordable annual-scale firming storage is available or anticipated
2. Hydrogen: Electricity → GH₂ → Gas Pipeline → City gate wholesale
 - a. Without firming storage
 - b. With firming storage at 100–150 bar in solution-mined salt caverns
3. Ammonia: Electricity → GH₂ → NH₃ → Liquid Pipeline → City gate wholesale
 - a. Without firming storage
 - b. With firming storage as liquid in above-ground refrigerated tanks.

We do not consider:

1. The path: Electricity → GH₂ → NH₃ → Liquid Pipeline → Reform to GH₂. This would be important if hydrogen, as GH₂ fuel, rather than NH₃, is the delivered product.
2. Large-scale storage of GH₂ between electrolyzer and synloop, to improve synloop CF and turndown behavior, although this might be important in TX, KS, and elsewhere in the Great Plains where good wind, salt geology, and synergistic other renewables coincide, where GH₂ could be economically stored to improve NH₃ synthesis CF.

For this analysis comparing electricity, GH₂, and NH₃ transmission we assumed:

1. 2,000 MW nameplate windplant = 2,000 MWh/hr at full output, would power a 2,400 ton per day (tpd) NH₃ plant at 40% average windplant CF and 80% average total energy conversion efficiency [35]. This is probably near optimum economic size, assuming Haber-Bosch NH₃ synthesis from GH₂ and atmospheric N₂, in the system in Figure 7.
2. Annual energy production of this 2,000 MW nameplate windplant, in Great Plains wind @ 40% CF, @100% energy conversion efficiency equivalent, is approximately:
 - 7,000,000 MWh/year, or
 - 196,000 tons H₂/year, or
 - 1,100,000 tons NH₃/year.
3. 1,000 mile transmission to city gate market requires either:
 - 2,000 MW, 500 kV, AC or DC electric transmission line (or two-thirds ownership of a 3,000 MW line), or
 - 20” GH₂ pipeline, or
 - 10” NH₃ pipeline.
4. Installed capital costs in year 2020 @ year ’05 \$US:
 - Wind generators: \$1,000/kW
 - Electrolyzers, without transformer-rectifier: \$350/kWe input. This is the USDOE goal, although current electrolyzer costs are over twice this. We assume that

Table 1. Approximate capital costs of 2,400 ton per day (tpd) NH₃ plant driven by a 2,000 MW windplant at 40% CF or other renewable-source electricity.	
Electrolyzers @ \$350/kWe, 30–100 bar output	\$ 700 M
Haber-Bosch reactor (synloop)	\$ 220 M
Air Separation Unit (ASU), for N ₂	\$ 75 M
Balance Of Plant + Contingency	\$ 75 M
Optional H ₂ compressor (30 → 100 bar)	\$ 10 M
Total	\$ 1,080 M

Table 2. Incremental cost of annual-scale firming storage, based on conversion + transmission + firming storage costs per MWh energy delivered at Multi-GW scale; Case I has only transmission costs, with no conversion or firming storage costs, because no affordable GWh-scale storage is available or anticipated.			
Case	No Firming	Firmed	Firming Cost Increment
1. Electricity	\$ 34.3	---	---
2. GH ₂ pipeline	\$ 56.1	\$ 58.2	3.7 %
3. NH ₃ pipeline, delivering NH ₃	\$ 34.3	\$ 36.2	5.5 %

Table 3. Incremental conversion, transmission, and firming storage costs at Multi-GW scale; 500 kv electricity has only transmission costs with no conversion or affordable firming storage costs. Assumed 2000 MW nameplate wind generation, annual-scale firming, and 1600 km (1000 mile) energy transmission distance. Capital costs for wind generators would be the same for all cases, and is not included.					
Energy Carrier	Capital Cost (\$M)				Incremental Cost per MWh Energy Delivered (\$)
	Conversion	Transmission	Firming	Total	
500 kV Electricity	Not Needed	1600	Not Economical	1600	34.3
GH ₂ Not Firmed	700	1920	-0-	2620	56.1
GH ₂ Firmed	700	1920	95	2715	58.2
NH ₃ Not Firmed	1080	520	-0-	1600	34.3
NH ₃ Firmed	1080	520	90	1690	36.2

Notes for Tables 2 and 3:

1. Capital cost of wind generation is not included in Total, above
2. Energy delivery is wholesale to city-gate markets.
3. No affordable annual-scale storage is available for electricity at this scale.
4. Firming cost increment is the annualized cost, at assumed CRF, of storage for the AEP of the 2,000 MW (nameplate) Great Plains windplant.
5. Electricity transmission is 500 kv, AC or DC, > 1 GW
6. CRF = 15% assumed
7. \$500K per GW-km for electricity transmission assumed.

In Table 3 we must recognize that we are not comparing the same “end states”. In the three cases summarized, the end-state energy carriers are:

1. AC or DC electric energy,
2. Gaseous hydrogen, GH₂, and
3. Liquid anhydrous ammonia.

design and materials improvements, shared power electronics with generating sources, and large-scale production will approach this goal.

5. Installed capital costs in year 2020 @ year '05 \$US for a 2,400 ton per day (tpd) NH_3 plant:
 - ASU (Air Separation Unit) = \$75M
 - Synloop (Haber-Bosch Synthesis Loop) = \$220M
6. NH_3 is delivered to city-gate wholesale market as liquid; optional reforming to GH2
7. Liquid NH_3 tank storage at sources, to maximize pipeline CF; tank capacity is 10-20% of source annual energy production; requires separate optimization study.
8. Multi-GW scale for all components, to achieve economy-of-scale:
 - GW sources, conversions, transmission (gases, synthesis, reforming NH_3)
 - >10,000 ton liquid NH_3 storage tanks; refrigerated, atmospheric pressure
9. NH_3 pipeline: 10" diam, 0.25" wall thick, X42 or Grade B carbon steel line pipe, welded, 35-42,000 psi rating, minimum specified yield strength (MSYS). NH_3 pipelines require regularly spaced in-line pumps, and these have been included in the total cost.
10. NH_3 pipeline flow = 150 tph = 300,000 lbs/hr = 52,817 gal/hr
11. GH2 pipeline: 20" diameter, 150 bar maximum allowable operating pressure (MAOP). GH2 compressors are eliminated from the pipeline system; transmission pipeline size and accepted friction losses requires no midline compressors.³
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 75% efficient (HHV) and provide high-pressure output (100 bar) to directly feed the transmission pipeline or NH_3 synloop.
15. ASU is an industry-standard cryogenic plant, electrically powered.
16. About 600 acre-feet of electrolysis feed water per year is required for converting the entire electric energy output of a 2,000 MW, 40% CF windplant to hydrogen. Producing the same amount of GH2 from NG via SMR would require 300 acre-feet of water.

9. NH_3 PRODUCTION AND DELIVERY COSTS

Based on the capital costs in Table 1, CRF of 18%, and wind-source electric energy at \$38.00/MWh (Xcel Energy; PTC-subsidized), the plant-gate price of NH_3 would be about \$450/ton, if the NH_3 plant is operated at 95% CF; about \$650/ton if the NH_3 plant is operated at 40% CF. These results further assume:

- Capital cost of 30-bar-output electrolyzers = \$350/kWe input;
- Electrolyzer efficiency = 75% HHV
- No NH_3 pipelines or storage tanks; no GH2 storage
- NH_3 synloop energy conversion efficiency = 95%
- ASU O&M cost per ton N_2 (100% electric energy) = \$20
- H_2 compressor O&M cost per ton NH_3 (100% electric energy) = \$15

These costs are nearly competitive with year 2007 retail Corn Belt NH_3 price for fossil-fuel-source NH_3 , without carbon tax.

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_3 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.

10. POTENTIAL NEW SYNTHESIS TECHNOLOGIES FOR “GREEN” AMMONIA

From the results in Tables 2 and 3, ammonia's primary disadvantage vis-à-vis electricity and hydrogen transmission is the additional capital costs for ammonia synthesis at the windplant 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, we only know 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.

11. CONCLUSIONS

1. This conceptual analysis indicates that both hydrogen and ammonia could be an attractive candidate energy transmission and storage medium for diverse, large-scale, stranded renewable energy, such as electricity generated from the Great Plains wind resource. The cost estimates for transmission by electricity, gaseous hydrogen, or liquid ammonia are relatively close.
2. Annual-scale firming of Great Plains wind energy as gaseous hydrogen, GH_2 , in large salt caverns or as anhydrous ammonia, NH_3 , in large above-ground tanks is only a small fraction of the total generation-transmission system estimated cost.
3. Ammonia firming storage costs are about half that for cavern storage of GH_2 , but producing NH_3 from GH_2 adds significant cost, in capital equipment amortization and energy conversion losses.
4. NH_3 firming storage tank capital cost is less than GH_2 salt cavern cost, per unit energy; both are good investments.
5. Great Plains wind can be economically firmed, adding great strategic and market value, if customers will accept their energy as GH_2 and/or NH_3 fuels.
6. Electricity transmission costs less than conversion to, and transmission by, GH_2 or NH_3 , but no affordable annual-scale firming storage for bulk electricity is available or anticipated.
7. The plant-gate cost of wind-source NH_3 is approximately:
 - a. \$ 450/ton, if the NH_3 plant is operated at 95% CF;
 - b. \$ 650/ton, if the NH_3 plant is operated at 40% CF.
8. A wind-to- NH_3 pilot plant will be needed to explore and quantify:
 - a. System design optimization; topology, size and location of major capital equipment (Figures 4 and 7);
 - b. Costs and efficiencies of GH_2 and NH_3 capital equipment;
 - c. Synloop and ASU dynamic behavior, and turndown problems; CF effect on costs;
 - d. Optimum nameplate capacity ratios for principal capital equipment components.

12. FUTURE WORK

1. Costs and prices for this analysis were developed in 2004-5. Recent material and energy prices and decline in value of the \$US have increased costs ~ 25-50%, requiring occasional updating of the costs and prices presented here:
 - Energy conversion system capital costs and efficiencies;
 - Capital and O&M costs for large-scale GH₂ and NH₃ storage.
 - Future high-volume production and technology improvements of wind generation, electrolysis, and NH₃ synthesis equipment which may improve these costs.
2. Begin immediately to design and build pilot plants for renewables-source GH₂ and NH₃ transmission and firming storage:
 - Perform technical and economic feasibility studies;
 - Propose preliminary design specifications;
 - Release a credible RFP or RFQ to determine costs to design, build, and operate the pilot plants;
 - Assemble a collaborative to fund the projects, to supply renewable-source GH₂ and NH₃ fuels to the pilot plants, and to use the delivered fuels.
3. Develop new technologies and components for higher energy conversion and synthesis efficiency at lower capital and O&M costs. Continuous improvement via R&D and demonstrations.

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