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RUNNING THE WORLD ON RENEWABLES: HYDROGEN TRANSMISSION PIPELINES WITH FIRMING GEOLOGIC STORAGE

William C. Leighty
The Leighty Foundation, Box 20993, Juneau, AK 99802, USA

Abstract:

The world's richest renewable energy 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. 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. Electric energy storage cannot affordably firm large renewables at annual scale.

At gigawatt (GW = 1,000 MW) scale, renewable-source electricity from diverse sources, worldwide, can be converted to hydrogen and oxygen, via high-pressure-output electrolyzers, with the hydrogen pipelined to load centers (cities, refineries, chemical plants) for use as vehicle fuel, combined-heat-and-power generation on the retail side of the customers' meters, ammonia production, and petroleum refinery feedstock. The oxygen byproduct may be sold to adjacent dry biomass and / or coal gasification plants. Figures 1 - 3. New, large, solution-mined salt caverns in the southern Great Plains, and probably elsewhere in the world, may economically store enough energy as compressed gaseous hydrogen (GH2) to "firm" renewables at annual scale, adding great market and strategic value to diverse, stranded, rich, renewable resources. Figures 2 and 3. For example, Great Plains, USA, wind energy, if fully harvested and "firmed" and transmitted to markets, could supply the entire energy consumption of USA. If gathered, transmitted, and delivered as hydrogen, about 15,000 new solution-mined salt caverns, of ~8 million cubic feet (225,000 cubic meters) each, would be required, at an incremental capital cost to the generation-transmission system of ~5%.

We report the results of several studies of the technical and economic feasibility of large-scale renewables – hydrogen systems. Windplants are the lowest-cost new renewable energy sources; we focus on wind, although concentrating solar power (CSP) is probably synergistic and will become attractive in cost. The largest and richest renewable resources in North America, with high average annual windspeed and sunlight, are stranded in the Great Plains: extant electric transmission capacity is insignificant relative to the resource potential. Large, new, electric transmission systems will be costly, difficult to site and permit, and may be difficult to finance, because of public opposition, uncertainties about transmission cost recovery, and inherently low CF in renewables service.

The industrial gas companies' decades of success and safety in operating thousands of km of GH2 pipelines worldwide is encouraging, but these are relatively short, small-diameter pipelines, and operating at low and constant pressure: not subject to the technical demands of renewables-hydrogen service (RHS), nor to the economic challenge of delivering low-volumetric-energy-density GH2 over hundreds or thousands of km to compete with other hydrogen sources at the destination. The salt cavern storage industry is also mature; several GH2 storage caverns have been in service for over twenty years; construction and operating and maintenance (O&M) costs are well understood; O&M costs are low.

Key words: bedded salt deposits, domal salt, caverns for gas storage, renewable energy, Great Plains, stranded, hydrogen, gaseous hydrogen, GH2, NG, pipelines, firming, transmission, capacity factor

Introduction

On every continent, diverse renewable resources could supply all humanity's future energy needs. Earth's richest renewable energy resources – large in geographic extent, high intensity – are usually stranded: far from end-users without gathering and transmission systems. The output of most renewables varies greatly, at time scales of seconds to seasons: the energy capture assets thus operate at inherently low CF, and energy delivery is not "firm". New electric transmission systems dedicated to renewables will suffer the same low CF, cannot affordably firm most renewables, and represent substantial stranded capital assets.

At GW scale, renewable-source electricity can be converted to hydrogen and oxygen, via high-pressure-output electrolyzers, and pipelined to load centers for use as vehicle fuel, combined-heat-and-power generation on the retail side of the customers' meters, ammonia production, and petroleum refinery feedstock. New, large, man-made, solution-mined salt caverns in the Great Plains, Gulf of Mexico (GOM) coast, and probably elsewhere in the world, can economically store enough energy as compressed hydrogen gas to "firm" renewables at annual time scale. This adds great market and

Figure 1. System Diagram: topology option. All wind energy is converted to GH2 for transmission; no electricity is delivered to the grid. Windplant infrastructure is primarily piping, with a small supply of electricity distributed only for controls. Byproduct oxygen cannot be pipelined far, at competitive cost.

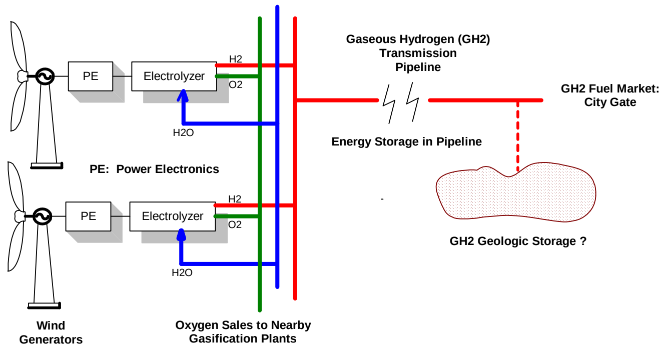


Figure 2. System diagram. 100 bar output electrolyzers directly feed the pipeline without compressors. Gaseous hydrogen (GH2) delivery to the city gate market is at ~30 bar, after pipeline friction losses: a good pressure for urban distribution; a tradeoff for eliminating compressors.

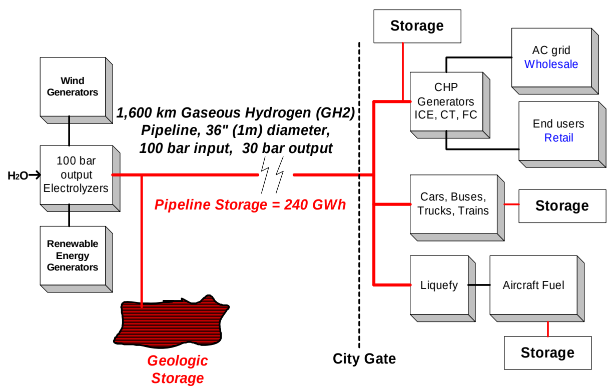


Figure 3. System diagram, with potential "value adding" features of byproduct oxygen sale to adjacent gasification plants, improved pipeline CF, and seasonal-scale geologic storage of GH2, and perhaps O2, at the source, which would allow transmission pipeline length up to 1,600 km.

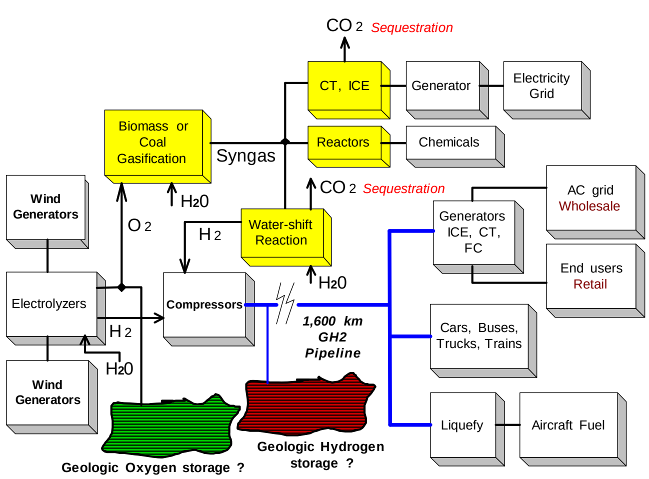


Figure 4. GH2 pipeline capacity, function of diameter and length: GW

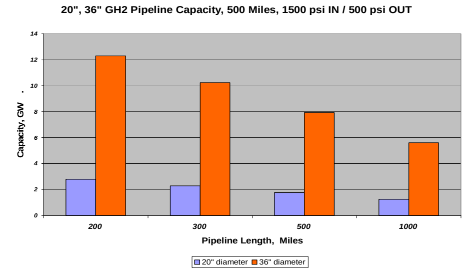
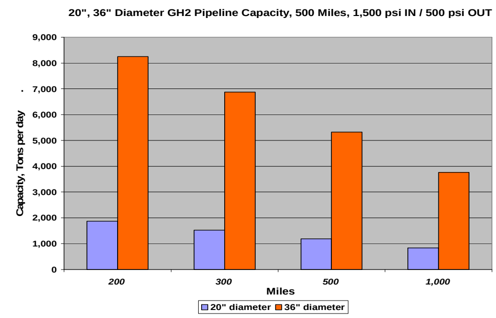


Figure 5. GH2 pipeline capacity, function of diameter and length: Metric tons (Mt) / day



strategic value to diverse, stranded, rich, renewable resources, rendering them dispatchable. Figures 10 - 14 show salt cavern storage concepts and options. Natural geologic formations, such as deep aquifers and depleted natural gas reservoirs, may also provide GH2-tight storage, but this has not been investigated. This is a worldwide opportunity for low-cost, annual-scale, firming storage.

Great Plains, USA wind energy alone, if fully harvested and pipelined to markets, could supply all USA energy, ~100 quads (quad = quadrillion Btu = 10^15 Btu = 10^12 MJ) per year. About 15,000 new, large, solution-mined salt caverns in the Great Plains and GOM coats could economically store enough energy as compressed hydrogen to "firm" this windpower at annual scale, at an incremental capital cost to a GH2 generation-transmission system of 5-10 %.

We report the results of several studies of the technical and economic feasibility of large-scale renewables-hydrogen systems. [1, 2, 3, 4, 5, 6] Windplants are now the lowest-cost renewable energy sources. The largest and richest wind resources in North America, with high average annual windspeed, are stranded in the twelve Great Plains, USA states: extant electric transmission capacity is insignificant relative to the resource potential.

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

We assume a transmission-constrained world, where large new wind and other renewable energy conversion plants must pay all transmission costs for delivering their energy products to distant markets. Increasing the capacity of extant electricity transmission corridors is an attractive immediate strategy. Large, new, electric transmission systems will be difficult to site and permit, may be difficult to finance, and provide no energy storage for the inherently time-varying, "intermittent", output of renewable sources. Building new underground oil and natural gas pipelines, for example, has historically been easier and faster than new electric transmission lines.

We assume a large nascent market for renewable-source hydrogen fuel in today's carbon-constrained world, for transportation fuel and potentially for distributed generation in combined heat and power (CHP). We assume distributors will buy all the GH2 fuel from the transmission pipeline at the city gate. GH2 pipeline transmission and geologic storage may offer important technical and economic advantages and synergies vis-à-vis electric transmission, at large scale: [6]

1. Value is added to renewables generation assets by "firming" their energy output with energy storage;
2. Sharing power electronics between renewables generation and electrolysis systems might save substantial capital, O&M, and energy conversion loss costs; removing requirements to deliver grid-quality electricity will improve wind generation cost of energy (COE) slightly; [7]
3. Locating GH2 transmission pipelines underground may be more socially acceptable and more secure from natural and human threats;
4. Selling the oxygen byproduct of electrolytic production of hydrogen from wind-source electricity to adjacent dry biomass and coal gasification plants could add significant revenue, lowering COE;
5. Pipeline CF would be improved by:
    - Geologic storage, if available at the renewable sources;
    - Synergistic sharing with diverse renewable GH2 sources in the same geographic area, complementing wind's time-variability, for example.

"Firm" refers to contract terms under which the seller guarantees delivery of the energy (and must procure energy in the market if seller cannot generate it). "Firm" usually means available at any hour of the year. Buyers pay more for firm energy than for non-firm energy. Storage capacity, especially at annual scale, could benefit the renewables plants by allowing them to sell more "firm" energy than if the energy were transmitted via electricity lines.

Consider GH2 pipeline versus electricity for wind energy transmission 320 km (200 miles) for a 4,000 MW (nameplate) windplant; at 40 % CF typical for the Great Plains, the windplant will produce ~14 Terawatt-hours (TWh = billion kWh) of electricity per year. The complete 20-inch (~0.5 m) diameter pipeline system will have an estimated capital cost of $US 210 million, at $US 35 per inch diameter per meter length. Pipeline annual O&M costs are low, unless frequent "pigging" inspection is required, if the pipeline is made of steel. A new 320 km electric transmission line, dedicated to the windplant, with 4,000 MW capacity, capable of capturing all wind-generated energy with zero or small curtailment, would probably be an HVDC system with estimated capital costs of:

• Converter stations @ $150 / kW per station pair	$ 645 M
• Overhead transmission line, 600 kv bipole @ $2 M / km, 300 km long	$ 640 M
Total capital cost	$ 1,285 M

However, 320 km is rather short for an HVDC system, where allocating converter stations cost per km is a large cost component. HVDC transmission losses are ~0.6 % per converter station plus ~0.4 % per 100 km of line = 2.4 % total; ~$ 33 M / year on 14 TWh @ $50 / MWh. The dedicated electric transmission line will operate at ~40 % CF, the same as the windplant, presenting a substantial stranded capital asset. Electricity transmission can provide no affordable seasonal-scale firming energy storage. A VRB-ESS (vanadium redox battery energy storage system) was recently sold by Canada's VRB Power Systems for $3.6M; rated 1.5 MW, 12 MWh. Annual-scale firming of the energy of a 4,000 MW windplant would require ~105,000 of these VRB-ESS plants, or their equivalent, at $378 billion total capital cost. However, in mass-production large VRB-ESS systems would surely cost much less.

The industrial gas companies' success and safety in operating thousands of km of GH2 pipelines worldwide is encouraging, but these are relatively short, small-diameter, and operating at low and constant pressure: not subject to the technical demands of RHS, nor to the economic challenge of delivering low-volumetric-energy-density GH2 over hundreds or thousands of km to compete with other hydrogen sources at the destination. The time-varying output of windplants will cause large, frequent pressure fluctuations in GH2 pipelines in RHS unless firming storage is installed at the sources. These pressure cycles induce and exacerbate hydrogen embrittlement (HE): Results, Materials challenge, below.

Design and construction of large, long-distance, high pressure GH2 pipelines and conventional natural gas (NG) transmission lines are similar. Four technological aspects differentiate a GH2 line from an NG line and will need to be addressed if this concept is to be attractive to industry; most analyses show that pipelining GH2 costs approximately 1.3 to 1.8 times more per unit energy-distance than pipelining NG because:

1. The volumetric energy density of hydrogen is one-third that of methane (CH_4, primary component of NG);
2. Pipeline utilization: CF would be reduced without geologic storage at the sources;
3. HE of pipeline steel must be prevented and controlled;
4. GH2 compression is very costly in capital, O&M, and energy.

The materials challenges of GH2 transmission pipelines may result in new materials or hybrids, with reduction in GH2-capable pipeline system costs to that of today's NG pipelines.

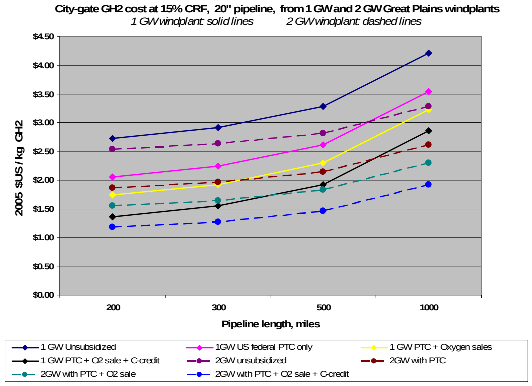
Other attractive transmission and firming storage schemes for large-scale renewable-source hydrogen include conversion to:
1. Anhydrous ammonia (NH_3), with transmission and storage as liquid in pipelines and refrigerated above-ground tanks of 30 – 60,000 metric tons (Mt) each;
2. Fischer-Tropsch liquids (FTL's), transmission and storage in pipelines and tanks;
3. Magnesium hydride, aluminum-gallium, and several other chemical forms.

As an alternative to the GH2 scheme for windplant-to-electricity transmission, Cavallo has proposed system optimization to enhance electricity transmission CF and increase firmness of supply by "oversizing" the windplant and by using compressed air energy storage (CAES). [8, 9] This scheme requires significant natural gas fuel for efficient recovery of the energy stored as compressed air. [10]

Method

We surveyed manufacturers of wind generators, electrolyzers, and compressors, to obtain expected performance and capital costs in year 2020, with costs expressed in year 2007 $US. Table 1 estimates year 2020 technology and capital component costs from industry consensus and USDOE goals. [11] However, in 2006 the installed cost of large wind generators in large windplants was typically $1,600 / kW; this high cost may be temporary, due to limited turbine supply, but a decline to $800 / kW may be unrealistic.

Figure 6. Unsubsidized and four "value-added" cases are shown for both 1 GW and 2 GW windplant size. Cost per kg GH2 would be about the same for a 4 GW windplant.



We surveyed engineers, geologists, and constructors in the USA solution mining salt cavern industry. [12]

We modeled the technical and economic performance of a large 4,000 MW (4 GW) nameplate capacity windplant delivering its entire output as GH2 fuel, by pipeline, to an urban "city gate" market 320 – 1,600 km away. Figures 1 - 3. [13] Such large generation and transmission systems would achieve full economy of scale.

We considered several modeling options; see Tables 3 - 4 and Figures 4 - 6. First, we modeled pipeline performance, using hydraulic models standard in the NG pipeline industry, and assuming no compressors in the system, either at source or at midline, to find:

1. Pipeline transmission capacity (power rating);
2. Pipeline energy storage capacity, assuming "packing" the pipeline to 100 bar, "unpacking" to 30 bar, for adequate distribution delivery pressure at the distant urban market;
3. Dynamic energy storage behavior, as windplant output varies with time.

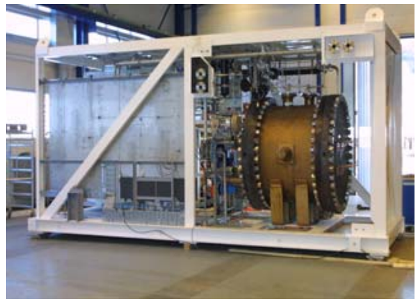
Second, for this large-scale windplant in the Great Plains, we used a simple capital recovery factor (CRF) model to calculate average annual wholesale, untaxed COE for GH2 fuel in $USD 2007, at the end-of-pipe at a distant urban market, considering a range of CRF: Table 2 and Figure 6. [14] For expected year 2020 technology and year 2007 $US costs, we assumed:

- No electric energy is delivered to the grid; all is converted to GH2 for the pipeline;
- Others will buy all the end-of-pipe wholesale GH2 fuel, for distribution to refineries, chemical plants, and cities;
- For a given diameter and pressure, GH2 pipelines can be built for the same capital cost as for NG, recognizing serious line pipe materials challenges, especially for RHS;
- Total installed capital costs in Table 1;
- Wind generator CF = 40 %;
- CRF = 12 – 21 %; a good compromise for this analysis is 15 %, as used in Figure 6;

Results: general

System and pipeline capacity: Table 2. A 4,000 MW windplant produces about 20 x 10^6 Nm3 / day of GH2 at full output, or 8 x 10^6 Nm3 / day, at 40% average CF. The continuous capacity of an 800 km long, 20" diameter, GH2 pipeline is ~11.5 x 10^6 Nm3 / day, without compressors. This may be an optimum capacity match, as shown in Figure 8, assuming:

Figure 7. Hydro Hydrogen Systems electrolyzer system, KOH type, without gas cleanup equipment. 560 kW input, 4.2 – 4.3 kWh per Nm3 output, at 30 bar, 130 Nm3 / hour.



- Potential added value from byproduct oxygen sale, USA federal production tax credit (PTC) for wind, and renewable energy certificates (REC's): Figure 6.

Third, we modeled system economics, to find the optimum nameplate capacity ratios among windplant, electrolyzers, and pipeline, as shown in Figure 8.

We described potential system capital cost savings from optimizing wind generator power electronics (PE) to supply low voltage DC to the electrolyzers, rather than high quality AC to the grid, thus eliminating the "transformer-rectifier" component of electrolysis systems and the inverter section of PE.

Based on these pipeline modeling results in Tables 3 - 4 and Figures 4, 5, and 8, we chose 20" diameter and 100 bar maximum allowable operating pressure (MAOP) as:

- Amenable to modern pipeline design practice and economy-of-scale;
- Adequate for a 4,000 MW windplant 320 km from the city gate market, without firming storage;
- Capable of 800 km transmission if firming storage is installed at the windplant (or other renewable sources).

We also modeled this system to include "value-adding" features which reduce the cost of GH2 fuel delivered at end-of-pipe at the distant urban market. Figure 6.

1. US federal PTC: $0.019 / kWh in year 2007;
2. Byproduct oxygen sale to adjacent gasification plants at $20 / Mt for dry biomass, and perhaps for coal (assuming carbon capture and sequestration): Figures 1 and 3;
3. Estimated future carbon-emission offset payment or REC of $0.01 / kWh.

Finally, we estimate the cost and potential contribution of GH2 pipeline transmission and geologic storage for "smoothing" and "firming" the time-varying output of windplants, increasing its value. We calculate the quantity of energy storage required for annual-scale firming of Great Plains wind. We also suggest several topics for further research and analysis.

- "Packing" and "unpacking" the GH2 pipeline;
- Slight curtailment in wind generation, thus slight loss of energy production.

The 4,000 MW windplant could deliver wind-source GH2 fuel 800 km by pipeline to the city-gate wholesale market for an unsubsidized price of ~$3.28 / kg, assuming:

1. Estimated year 2020 technology and costs, expressed in year 2007 $US;
2. All wind energy is converted to GH2 and delivered via 20" diameter pipeline at 100 bar inlet pressure and 30 bar delivery pressure at the distant urban market;
3. No compressors, at pipeline inlet or at midline;
4. CRF of 15%.

Results of modeling pipeline transmission and storage capacity, using hydraulic equations standard in pipeline design practice, are shown in Tables 3 - 4 and Figures 4 - 5. This assumes:

1. 100 % GH2;
2. 100 bar input, 30 bar output pressures;
3. Capacity: fully turbulent flow achieved;
4. Storage capacity: "pack" and "unpack" the pipeline from 100 bar to 30 bar;
5. Pipeline lengths of 320, 480, 800, and 1,600 km;
6. 20" and 36" (~0.5 and 1m) nominal industry-standard pipeline diameters.

In a mature renewables-GH2 system, many nodes of production, storage, and utilization may be distributed along the transmission pipeline. These nodes are much less complex and costly than the substations required for accessing electricity transmission lines. Synergistic and distributed harvest of diverse renewable energy resources will improve pipeline CF and reduce geologic storage required for firming.

Cost of energy (COE) at end-of-pipeline: Table 2 and Figure 6. Based on results in Table 3 and Figures 4 and 5, we analyzed three "value-added" cases as well as the "unsubsidized" case, for both 1 GW and 2 GW windplants. 4 GW costs per kg H2 would be approximately those for a 2 GW plant, assuming that both achieve full economy of scale in asset manufacturing and installation. Table 3 shows that the 20" pipeline has continuous transmission capacity of ~2.8 GW (~18 x 10^6 Nm3 / day) at 100 bar inlet, 30 bar delivery pressure, at 320 km length: adequate for a 4 GW windplant assuming "smoothing" storage in the pipeline and downstream firming storage, or with firming storage at the windplant. Figure 9.

GH2 compression: We have completely eliminated compressors from the system modeled in this paper, because:

1. Hydraulic modeling of the pipeline for the assumed 2 GW windplant shows that midline compressors are not needed if we accept pipeline friction losses from 100 to 30 bar over the total distance; pipeline friction losses are smaller for GH2 than for NG, because of these gases' different physical properties;
2. 100 bar output electrolyzers should be feasible, and perhaps available, by year 2020, especially if a market seems promising; the electrolyzers will directly feed the pipeline at 100 bar;
3. GW-scale compressors for GH2 will remain costly in capital, O&M, and operating energy: a large cost burden on the system, to be avoided.

The economic cost of GH2 "compression", in this compressorless system, is the incremental cost of building the electrolyzer system capable of 100 bar output, vis-à-vis lower pressure output. Pressurizing the H_2O feed water to 100 bar costs very little.

Hydrogen compression is a difficult problem at GW scale. Since GH2 has one-third the energy of NG, by volume, compressor power and energy are greater for pipelining GH2 than for NG. Positive-displacement compressors are necessary for high pressure (>10 bar). Large reciprocating compressors, up to 12,000 kW electric motor drive, are available from Dresser-Rand: model HHE-VL is used for GH2 and for NG. Figure 15. Technological breakthroughs and development are needed in this field, for transmission pipelining of GH2 from sources other than electricity because biomass, solar thermal, etc. are generally low-pressure sources. However, most compressor research today is focused on low-volume, high-pressure (300 – 700 bar) service for vehicle fueling.

Therefore, we have modeled our system entirely without compression, to take full advantage of high-pressure-output electrolyzers feeding the pipeline input at 100 bar, assuming that 30 bar is a good city-gate delivery pressure for urban distribution.

High-pressure-output electrolyzers: We assume high-pressure-output electrolyzers will be available at attractive capital and O+M cost; technologies may include proton exchange membrane (PEM), alkaline (KOH), high temperature ceramic, or a combination thereof. We assume they will directly feed the pipeline at 100 bar. PEM electrolyzers are now available at > 100 bar output, at ~10 kW scale; they may not economically scale to MW. KOH is the only technology presently available at MW scale, at 30 bar output: Figure 7. An R&D program will be required to reduce incremental capital cost, primarily for a stronger stack containment vessel and for more durable stack materials, to achieve 100 bar output. [15]

Shared power electronics (PE): Figure 1. Replacing the transformer-rectifier subsystem of the electrolyzer with PE shared with the wind generator will save ~5 % in electrolyzer system capital cost and ~1 - 2 % in energy conversion loss. Modern wind generators pass 100% of their output power through PE which provides variable-speed operation, low voltage ride through (LVRT) (electricity grid fault tolerance and recovery), and power conditioning to deliver grid-quality AC.

PE topology includes an internal DC bus which, with PE redesign, would feed the electrolyzer, or several electrolyzers in series or series-parallel arrays. This wind generator DC bus voltage is typically 800 - 1,000 VDC, while MW-scale electrolyzers typically operate at 200 VDC. This impedance-mismatch problem might be solved by connecting several electrolyzers in series or series-parallel, although this presents electrical isolation and safety problems.

PE is 10 - 15% of wind generator capital cost. Since the system in Figure 1 delivers no energy to the grid, the inverter section of the PE is eliminated. The distribution-voltage transformer and underground wiring are also eliminated, replaced with piping for H_2O feedstock, H_2 and O_2, and a small AC electricity supply for controls. This probably will achieve a significant saving in wind generator capital and O&M cost.

Materials challenge: hydrogen embrittlement: Hydrogen gas can compromise the structural integrity of high-pressure containment or delivery systems. [16] In particular, the interaction between hydrogen gas and surface flaws can promote failure of pressurized steel structures [17]. Hydrogen interacts with material at the tip of a flaw and can cause embrittlement by one of several well-established mechanisms. [18] The high stresses at the flaw tip coupled with the presence of embrittled material facilitate propagation of the flaw. The design of hydrogen gas containment or delivery systems must consider the presence of flaws in the structure.

Although HE can operate in steel exposed to high-pressure gas, flaw-tolerant structures can be designed through the application of fracture mechanics. Flaws in pipelines can result from handling, corrosion, metallurgical defects, or welding. [19] These flaws can be located on the interior and exterior surfaces of the pipeline. Hydrogen-assisted flaw propagation is sensitive to material- and environment-dependent fracture mechanics properties.

HE of high-pressure pipelines can be accommodated through the application of fracture mechanics. The critical design parameters are the maximum allowable flaw depth under static pressure loading and the number of cycles required to grow a small flaw under cyclic pressure loading to the maximum allowable flaw depth. Several approaches can be followed to maximize the allowable flaw depth. One approach is to maximize K_{IH}. This can be accomplished through materials selection (e.g., materials with lower yield strength) or possibly by altering the gas composition (e.g., adding small amounts of oxygen). Another approach is to increase wall thickness or lower wall stress. Similar considerations apply to fatigue loading; in this case, favorable properties are achieved by decreasing $(da/dN)_H$ as a function of ΔK.

Results: System optimization

Topology: At GW scale, if operating from a single AC or DC bus, KOH-type electrolyzers might most economically be arranged in series, series-parallel, or "star" modules, sharing electrolyte circulation and gas cleanup piping. However, a wind generator array may not provide a single electricity bus; shared PE and piping may require a MW-scale electrolyzer at every wind generator, as in Figure 1. This paper does not attempt this topology optimization.

Component capacity; system optimization simulation: Figures 8, 9. Using a confidential year-long data set of actual hourly output of a northern Great Plains windplant, we modeled the system of wind generators, electrolyzers, and pipeline to estimate:

- Optimum ratio of component capacity for minimum cost of delivered GH2: Figure 8;
- Smoothing of delivered GH2 provided by pipeline storage: Figure 9.

Optimum electrolyzer capacity is difficult to estimate, because of the stochastic nature of the wind energy resource. Electrolyzers may be operated above their rated capacity for a short time, at an energy conversion efficiency penalty, but at reduced duty cycle to avoid overheating the electrolyzer system.

However, if much of the operating time above nominal capacity is at high duty cycle, the electrolyzers may overheat, forcing more curtailment of wind generation than we have assumed. Empirical data from pilot plants like the proposed IRHTDF, below, will be necessary to guide more valid and accurate modeling of the wind generator-electrolyzer subsystem.

Figure 8. With the above electrolyzer rating assumptions, the electrolyzers become relatively more expensive than the wind generators, so the economic optimum undersizes them relative to the maximum wind capacity, to increase their CF. Windplant capacity slightly exceeds pipeline capacity at optimum. This "wastes" some wind energy, by curtailing wind generation to avoid overheating the electrolyzers and overpressurizing the pipeline, but increases the CF of electrolyzers and pipeline.

Energy storage as GH2: Hydrogen storage can be anywhere along the pipeline path, or anywhere in the entire system from production to end-use: Figures 1 - 3. As demand for hydrogen grows, demand for hydrogen storage capacity will grow, to:

1. Allow producers to meet peak demand levels in excess of production capacity. For example, large amounts of NG is produced (mined) and stored during the summer months for use in the winter, when demand is higher. With the storage capacity, the NG mining industry does not have to maintain mining capacity equal to peak winter NG demand. This lowers costs significantly. Seasonal fluctuations in the price of NG provide producers with the incentive to develop storage capacity, beause storage allows them to sell more of their NG during peak periods, when prices are higher. This may also apply to renewable-source GH2, to some extent.
2. Increase the utilization rate (i.e., CF) of expensive pipeline and other delivery infrastructure. As with NG, storage capacity at the upstream end of a pipeline will result in higher pipeline utilization than a scenario without storage. Financing capital-intensive infrastructure is far more likely when potential investors project a high utilization rate.

GH2 storage in pipelines: A long pipeline could provide a significant amount of storage capacity. Table 4 shows that storage capacity in an 800-km-long pipeline would range from 10 GWh (a 20" pipeline operating between 20 and 40 bar) to 107 GWh (a 36" (1m) pipeline operating between 30 and 100 bar). The throughput of the pipeline drops substantially when used as a storage vessel. For NG, pipeline storage is economical only when used to cover for short compression equipment outages.

GH2 storage in wind generator towers: National Renewable Energy Laboratory (NREL) has investigated this potential. [20] Because tower storage would be at much lower pressure (15 – 30 bar) than required for pipeline transmission, the cost of required pipeline input compression may defeat this storage value.

GH2 storage in end-user devices: Figure 2. Ground vehicle and aircraft fuel tanks, equipment for distributed generation (DG) of electricity, and peak-shaving reversible fuel cells may provide significant aggregate distributed GH2 storage. This would reduce peak demand, but it would not help firm the wind farm output, because pipeline and end-user storage is relatively small.

GH2 storage in geologic formations: Figures 10 - 14. Low-cost, seasonal-scale, storage is needed for renewable-source GH2, as it is for NG. Man-made solution-mined salt caverns are GH2-tight to ~140 bar and are the lowest-cost method of large-scale GH2 storage and perhaps also of large-scale electricity storage, invoking the "hydricity" energy economy concept. Storage caverns may be constructed in both "domal" and "bedded" salt. No GH2 storage caverns have been attempted in bedded salt, where leakage loss through non-salt strata may be excessive and unacceptable.

In Tees County, UK, >1,000 tons of GH2 is stored in several solution-mined salt caverns, for industrial use. [21] The "ChevronPhillips Clemens Terminal" cavern has been in service > 20 years, storing ~2,500 net tons of GH2 at up to 140 bar. [22]

The US stores helium beneath an aquifer in Texas. Similar aquifers may be abundant and GH2-tight. This resource needs exploration and assessment: Recommended further study, below.

For example, consider the quantity of GH2 storage required to "firm" the output of a very large 4,000 MW (nameplate) windplant which produces ~14 TWh in an average year. Using the numbers from "Seasonal Variability of Wind Electric Potential in the United States" [22], for "North Central", normalized, yields these "seasonality factors":

Winter 1.20 Spring 1.17 Summer 0.69 Autumn 0.93

We find that expected average seasonal energy production for the 4,000 MW windplant would be (14 TWh / 4) = (3.5 TWh) x seasonality factor, above:

Winter = 3.5 x 1.20 =	4.20 TWh
Spring = 3.5 x 1.17 =	4.10 TWh
Summer = 3.5 x .69 =	2.42 TWh
Autumn = 3.5 x .93 =	3.26 TWh

The biggest difference between seasons is between Winter and Summer: 4.20 - 2.42 = 1.78 TWh. If all windplant energy is converted to GH2 for export, at the 80% efficiency typical of large-scale electrolyzers, this is apparently 1.42 TWh of GH2 storage needed. However, the biggest difference between adjacent, sequential seasons is between Spring and Summer: 4.10 - 2.42 = 1.68 TWh. If all windplant energy is converted to GH2 for export, at 80% electrolyzer efficiency, apparently [1.68 x 0.8 = 1.34] TWh of GH2 storage is needed. The latter case is more relevant.

A 1,600 km 36" diameter GH2 pipeline, packed to 65 bar and unpacked to 30 bar, stores ~120,000 MWh = 0.12 TWh. A higher-pressure pipeline, packed to 130 bar, unpacked to 65 bar, would store twice as much = 0.24 TWh. GH2 transmission pipelines are likely to operate at 100 – 150 bar maximum input pressure, with city-gate delivery at ~30 bar. Assume, for this analysis, 0.12 TWh of pipeline storage.

Thus, geologic storage needed to seasonally "firm" 4,000 MW (nameplate) of Great Plains wind, over the maximum average seasonal variation, is: 1.34 - 0.12 = 1.22 TWh, which is equivalent to ~36,000 Mt of GH2.

Characteristics of the "ChevronPhillips Clemens Terminal" GH2 storage cavern (near Freeport, TX): [23]

- Age is 20 years;
- Physical volume is 6.4 million cubic feet (198,000 cubic meters);
- "Useable capacity" is 2,500 Mt of GH2; gross capacity is 5,300 Mt of GH2;
- Maximum pressure is 110 bar; maximum operating allowed pressure (MAOP);
- Estimated cavern capital cost, 2007 $US, is $5 million;
- Leakage rate unknown; acceptably small; probably very small;
- O+M cost is unquantified; probably small; some periodic and preventive maintenance (PM) required.

Praxair has constructed a similar GH2 storage cavern nearby, in the same salt dome. [24] It will begin service in 2007. Praxair reports that it cost more to construct than the ConocoPhillips estimate, above. [25] Several solution-mining industry contacts estimated construction of such caverns at $US 10 - 15 M. Therefore, we have conservatively estimated new cavern construction at $US 15 M, plus the cost of GH2 "cushion gas" at ~$5M.

Thus, 36,000 Mt / 2,500 Mt per cavern = 14 caverns are required @ $20 million capital cost each ($15 million construction + $5 million for "cushion gas") = $ 280 million, to "firm" 4,000 MW (nameplate) of Great Plains wind: a small fraction of total generation-transmission system cost. Cavern useable capacity might be slightly larger for renewable energy transmission service, if pipeline pressure is designed to vary from 100 – 150 bar input to 30 bar delivery at city-gate end of pipeline, and if the cavern can endure the lower pressure.

Adding $ 280 million in firming cavern storage to Table 1 presents a ~6 % incremental capital cost to the complete generation-transmission-storage system.

Totally harvesting the wind energy of the twelve Great Plains states, on about half the land area of these states, would require ~3 million MW (nameplate) of wind generation, and would produce ~10,000 TWh per year, about 100 quads, which is the present entire energy consumption of the USA, from all sources .[26] With ~14 caverns per 4,000 MW, or ~4 caverns per 1,000 MW, about 15,000 caverns like the "ChevronPhillips Clemens Terminal" cavern would be needed to firm all Great Plains wind at annual time scale. This storage requirement would probably be reduced by seasonally-synergistic harvest and transmission of GH2 from diverse Great Plains renewables, as proposed in the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) concept, below.

Markets and firming for wind-generated GH2 fuel; implications for other renewables

Because pipeline developers will seek to maximize throughput (minimizing needed storage) and other hydrogen producers using the line would make storage unreliable for wind generators, we believe there is likely to be little storage value in a hydrogen pipeline dedicated to windplants. More work could be done to test this hypothesis, enabled by empirical data from the IRHTDF pilot plant, below. The pipeline would need to maximize its utilization rate by receiving hydrogen from other producers in order to be economically attractive. The production from these other facilities would reduce the pipeline storage available to the wind generators. Further, the activities of the other hydrogen producers using the pipeline would make storage highly uncertain for wind generators, without inherent seasonal synergy among diverse renewables.

As shown in Figure 9, the energy storage in the pipeline would "smooth" the output of the windplant somewhat, but hydrogen delivered from the pipeline at the city gate would still be quite variable. Typically, a variable supply of any energy product is less valuable than a firm supply, as evidenced by lower priced "interruptible" NG and electricity tariffs. The owner of the windplant-pipeline project would have two options for firming the hydrogen: storage and firming purchases.

In a firming strategy based on spot purchases, the windplant-pipeline company would purchase from other suppliers the hydrogen necessary to provide firm service. If it took the hydrogen from another company's distribution system, it would pay something closer to a retail price. As long as the hydrogen could be purchased at a price equal to or below the retail price of hydrogen, the pipeline company would not lose money using this firming strategy. However, if the company could be caught short during a period of extremely high wholesale prices, using spot purchases as a firming strategy would be more risky.

The key question in evaluating purchases as a firming strategy is: what is the annual profile of wholesale hydrogen prices at the city gate? If the profile is relatively flat, purchases could be a less costly firming strategy than storage. If the price profile were highly variable, purchases would be more risky and storage may be the lower-cost option.

Consider the NG industry: because NG demand is heavily driven by space heating, spot market NG prices are higher during the winter than the summer, and they can be extremely high in the coldest periods of the winter. Market purchases are a particularly poor strategy for firming NG supply, because supply interruptions are most likely to occur precisely when spot prices are high. The windplant-pipeline company might not face a correlation between low production periods and high hydrogen prices. A much smaller portion of hydrogen would probably be used for space heating than is currently the case with NG, because transportation fuel is expected to be a major hydrogen demand driver. Strong hydrogen demand from the transportation sector might well prevent heating and cooling demand from causing seasonal swings in spot market prices. However, if NG becomes the main fuel input for hydrogen production, spot market hydrogen prices might follow the seasonal variations of NG prices.

Thus, without functioning hydrogen markets to observe, it is difficult to predict how risky a firming strategy based on spot purchases would be. However, with projections of annual hydrogen prices and the cost of storage, it would be simple to determine the lower-cost firming strategy.

For the use of the wind-generated and renewables-generated hydrogen supply in commodity energy markets, the most obvious source of supply firming is the use of NG / hydrogen blends.

Hydrogen can be mixed directly into the NG supply, either in the NG transmission system or into NG storage, resulting in a lower-btu, cleaner-burning fuel. Typically, NG consuming devices can accept up to 10% hydrogen by volume, often with efficiency or emissions improvements. Provided material compatibility of the transmission and distribution system is adequate, and that metering can be easily adjusted, the concentration of hydrogen can be increased over time as hydrogen supply increases. If the concentration of hydrogen does not increase more than 10 - 15% over the life of the burner tip appliances, new hardware can be introduced to accept higher concentrations of hydrogen, in parallel with the change in fuel concentration. Such a scenario could avoid the cost of maintaining a parallel fuel infrastructure for hydrogen or introducing large scale fuel switching over a short period of time.

The EC is now studying this blended fuel strategy via the "NaturalHY" project, conducted by Gasunie Research, The Netherlands. [27, 28]

Conclusions

Figure 6. With various "value-adders", wind-source and other renewable-source GH2 may be delivered to distant markets, 200 to 1,600 km distant, at an untaxed wholesale energy unit cost apparently competitive with:

- hydrogen fuel made from NG by steam methane reforming (SMR);
- gasoline and diesel, at 2007 prices.

"Firming" this GH2 energy at annual scale costs little, if suitable geology for storage in salt caverns or other geologic formations is available, in the Great Plains and GOM coastal regions. This opportunity probably exists, for diverse stranded renewables, worldwide. Thus, with enough GH2 transmission pipelines and storage caverns, the world can run entirely on renewables.

Figure 9. Pipeline energy storage smooths windplant output variations at time scales of minutes to days, but is inadequate to "firm" windpower to command full wholesale market price at the city gate. However, low-cost, annual-scale, geologic storage of GH2 could theoretically firm wind energy at annual time scale, adding significant value. Such renewable energy storage remains unexplored and unproven in the Great Plains.

Assuming that 100 bar output electrolyzers feed the GH2 pipeline directly, no compressors are needed in the system, for a large saving in capital, energy, and other O&M costs.

Line pipe materials must be tested and selected, and perhaps invented, and other measures taken, to control the critical phenomenon of HE of steel, especially in the RHS discussed herein.

Solution-mining of storage caverns in salt formations is a mature industry. Large-scale, low-cost, high-pressure GH2 storage has been proven in "domal" salt but not in "bedded" salt formations.

Figures 8 and 9. To better understand the economics of the windfarm-electrolyzer-pipeline system, we performed several simulation analyses using actual hourly production data from an operating, Great Plains windplant. Based on the relative costs of these three system components, the most economical design point appears to be to size the electrolyzer units to match the maximum pipeline capacity and then to slightly oversize the wind generation, which wastes some wind generation but increases the overall CF of the system and minimizes the cost of GH2 delivered to the city gate .

There is a quantifiable difference between the prices of firm and non-firm NG today, but the annual price profile of hydrogen may be quite different from today's NG price profile. A remaining challenge is determining whether storage or spot purchases is the lower-cost firming option for wind-source and renewable-source GH2 fuel, in a mature "hydrogen sector" of a continental energy economy.

This paper may support building a pilot-scale hydrogen pipeline system, optimized for bringing large-scale, diverse, stranded, renewable energy sources to distant markets as compressed hydrogen gas, as an International Partnership for the Hydrogen Economy (IPHE) project: the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF). [29] This paper's analysis is applicable to large, diverse, stranded, renewable energy resources worldwide.

Perhaps all new NG pipelines, worldwide, could be built capable of future RHS, at little incremental capital cost, if:

- Fracture mechanics tests in hydrogen prove suitable line pipe material(s) in RHS;
- The IRHTDF pilot plant results are promising.

Pipeline RHS-capability would be an important strategy for building the infrastructure for a "hydrogen sector" of a carbon-emissions-free, global energy economy.

Recommended further study

Linepipe material testing: Composite Reinforced Line Pipe (CRLP)™ and X-42 or X-65 "sour service" grade are candidates for RHS. Testing these materials for accelerated fatigue life, in pressure cycling over a 2:1 range, is needed to establish "fitness of purpose" for large-scale (high-pressure, large-diameter, long-distance) GH2 transmission pipelines for the severe cyclic loading of RHS, and consequently also "fitness of purpose" for less-demanding use in GH2 pipelines from new nuclear and coal gasification plants. TransCanada Pipelines proposed CRLP™ for hydrogen transmission at the ASME International Pipeline Conference (IPC04), Calgary, 4 - 8 Oct 04. [30]

System optimization: Hydraulic modeling and topology and engineering design and economic optimization of the hydrogen collection, compression, and pipeline system, to estimate components size and to optimize their placement. System optimization of capital cost components depends on dynamic fluid mechanics of the pipeline with time-varying input from the wind generator – electrolyzer subsystems. This is now poorly understood; modeling improvement may depend on empirical data from operation of a pilot plant like the proposed IRHTDF.

Firming value: Assess and estimate economic value of firming windplant output via the several strategies discussed above.

Geologic storage: Figures 10 - 14. Verify GH2 storage feasibility in bedded salt geology. Low-cost, large-scale, geologic storage of GH2 in formations other than solution-mined salt caverns, which are man-made, relatively rare, and limited in size, would be very valuable to the wind and other renewables energy industries. Smoothing windplant output at seasonal scale, to deliver a firm, dispatchable energy supply, would greatly increase the usefulness and value of renewables-generated energy. Specifically:

a. Geologists should prospect for subterranean formations, for salt caverns or other storage, capable of containing GH2 at > 100 bar, with an acceptable annual loss rate:
   1. Calculate what reservoir (formation) volume and projected surface land area is required, for 1 GW and for 10 GW scales;
   2. Estimate total USA storage potential;
   3. Extend this prospecting worldwide.
b. Construct a tall, small-diameter test cavern by solution-mining in deep and thick bedded salt; test for leakage when pressurized to ~100 bar with GH2. Consider brine underground injection control (UIC) options; [31]
c. Estimate solution-mining cavern design and construction methods for clustered cavern arrays storing only GH2 at the same pressure; estimate construction cost for the commissioned total GH2 storage cavern array; investigate leasing option.

Electrolyzer integration, duty cycle, and overload tolerance: Consider wind-source systems: we need to optimize the windplant-to-electrolyzer nameplate capacity ratio. Electrolyzer systems need to be optimized for handling heat rejection from short-duration overloads, driven by the stochastic nature of the wind resource. We need to know the incremental capital cost of increased heat rejection capability, as a function of duty cycle and ambient temperature. Families of curves might be useful. Both time and frequency domain data on wind generator output may be essential. Then, we can optimize for an amount of wind generation curtailment to best match the overload capability of electrolyzer systems: Figure 8. In real systems, the individual electrolyzers' control systems, and probably PE, would be integrated with the wind generators' control systems, so that at a high temperature limit, the electrolyzer forces a reduction (curtailment) of wind generation output.

Electrolysis feedwater required: Calculate the quantity of required electrolysis feed fresh water for large-scale export of stranded renewables from each candidate geographic region. Investigate supply options, including pipeline transmission of water from GH2 pipeline destination back to the source, in the same trench.

Compression options: Figure 15. Find compression options and costs for GH2: available equipment and suppliers; capital and energy and other O&M costs. Model diverse renewable energy sources, synergistic with wind, to reduce GH2 storage and perhaps compression requirements, and to better utilize the wind-electrolyzer plant area.

International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF): Begin feasibility, preliminary engineering, and cost estimation for this pilot-scale facility proposed as a project for the IPHE (International Partnership for the Hydrogen Economy). [32] It will yield empirical operational data enabling refinement of the analyses in this paper.

Table 1. Capital costs: 4,000 MW windplant, electrolyzers, and 36" (~1 m) pipeline 300 km long.

	Total Installed Capital Cost (TICC) $ / kW in Year 2020	Total (million 2007 $US)
Windplant	$ 800	$ 3,200
Windplant power electronics incremental cost	$ 30	$ 120
Electrolyzers: 100 bar output, KOH type	$ 330	$ 1,320
Pipeline: 20", 300 km long	$ 35 / inch diam / m length	$ 210
TOTAL		**$ 4,850**

Table 2. Unsubsidized cost of wind-source GH2 fuel delivered at end-of-pipe at distant city gate, as a function of CRF and pipeline length. Assumes: Unsubsidized (no US federal PTC, or other); no "value adders" in byproduct oxygen sales or carbon emissions offset credits or payments.

Pipeline Length	320 km	480 km	800 km	1600 km
	Cost / kg	Cost / kg	Cost / kg	Cost / kg
@ CRF = 12%	$2.19	$2.34	$2.64	$3.38
@ CRF = 15%	$2.72	$2.91	$3.28	$4.21
@ CRF = 18%	$3.26	$3.48	$3.93	$5.04
@ CRF = 21%	$3.75	$4.01	$4.53	$5.82

Table 3. GH2 pipeline transmission and storage capacity, without inlet or midline compression.

Length km	Length miles	Nominal Diameter inches	Capacity GW	Capacity MMscfd	Capacity Million Nm3/day	Capacity Tons per day	Storage Capacity MMscf	Storage Capacity Tons
320	200	20	2.8	702	18.1	1,869	141	374
320	200	36	12.3	3,100	80.1	8,253	450	1,199
480	300	20	2.3	573	14.8	1,526	211	562
480	300	36	10.2	2,580	66.7	6,869	675	1,798
800	500	20	1.8	444	11.5	1,182	352	936
800	500	36	7.9	1,998	51.7	5,319	1,126	2,997
1,600	1,000	20	1.2	313	8.1	833	703	1,872
1,600	1,000	36	5.6	1,413	36.5	3,762	2,251	5,994

Table 4: Energy storage as compressed GH2 in pipeline. *Energy Storage, Days: # of days of storage of 1,000 MW windplant output @ 40% CF (9.6 GWh / day)

Length km	Nominal Diam inches	Volume, Cubic Meters	Inlet Press bar	Delivery Press bar	Energy Storage Nm3 x 10^6	Energy Storage MMscf	Energy Storage Tons	Energy Storage GWh	Energy Storage Days *
800	20	146,338	100	30	10	352	936	33	3.5
800	36	468,605	100	30	32	1,126	2,997	107	11.2
800	20	146,338	40	20	3	105	281	10	1.0
800	36	468,605	40	20	10	338	899	32	3.3
1,600	20	292,675	100	30	20	703	1,872	67	7.0
1,600	36	937,209	100	30	64	2,251	5,994	214	22.3
1,600	20	292,675	40	20	6	211	562	20	2.1
1,600	36	937,209	40	20	19	675	1,798	64	6.7

Figure 8. Wind - Hydrogen Pipeline System Optimization Simulation: unsubsidized; 1,600 km long GH2 transmission pipeline. Wind generators, electrolyzers, and 1,600 km transmission pipeline system. Optimal (minimum GH2 delivered cost) point is where the maximum wind capacity slightly exceeds the maximum pipeline capacity. This "wastes" some wind energy but increases the utilization of the electrolyzers and pipeline.

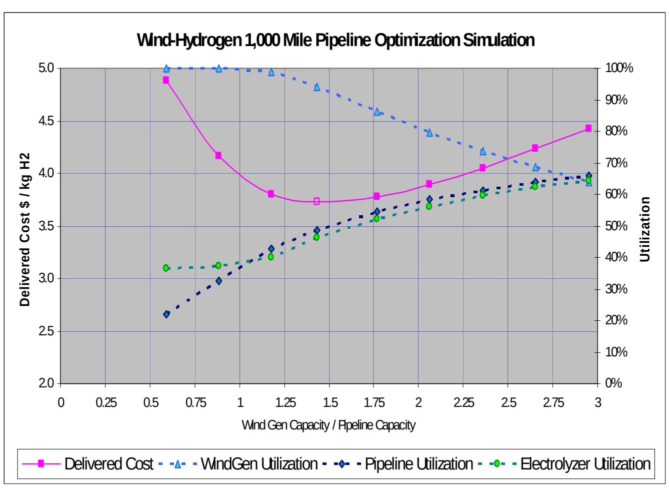


Figure 9. 800 km pipeline, actual output, northern Great Plains windplant, first week of September. The lag effect and pipeline transit time is about 22 hours. This smooths some of the hourly and shorter period wind generation variations. Input is limited at 1,700 MW by pipeline and electrolyzer capacity, resulting in some lost wind energy via curtailed generation, but greater long-term pipeline utilization factor (CF).

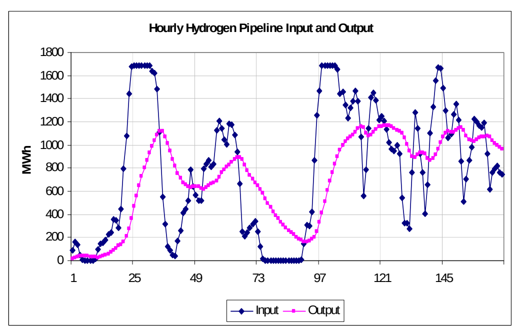


Figure 10. Large underground dry salt formations which may be suitable for solution mining, to create large GH2 storage caverns.

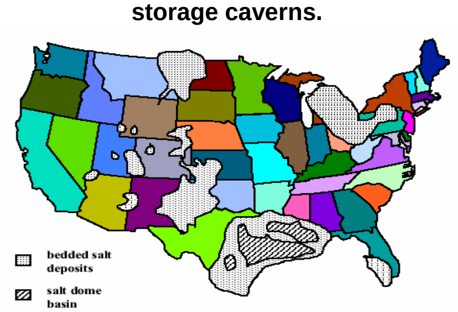


Figure 11. Extant storage caverns in “dome” and “bedded” salt in Texas. “Dome” salt deposits are thicker and more homogeneous than “bedded”.

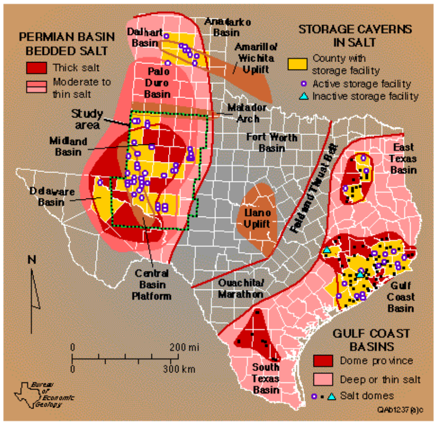


Figure 12. Solution-mined storage salt caverns in “domal” salt typical of the Gulf of Mexico coast, USA. Depth below ground level, meters. Oil and natural gas wells are in adjacent formations.

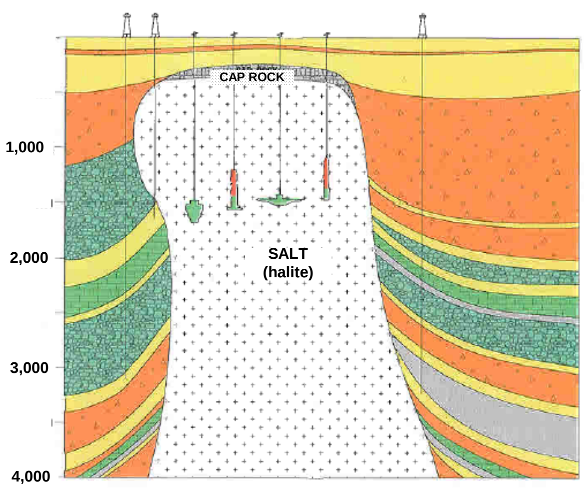


Figure 13. Solution-mining of storage salt caverns in “bedded” salt typical of the Great Plains, north of the Gulf of Mexico coast. Excavating caverns in “bedded” salt is riskier than in “domal” salt because of potential leakage through non-salt (non-halite) strata.

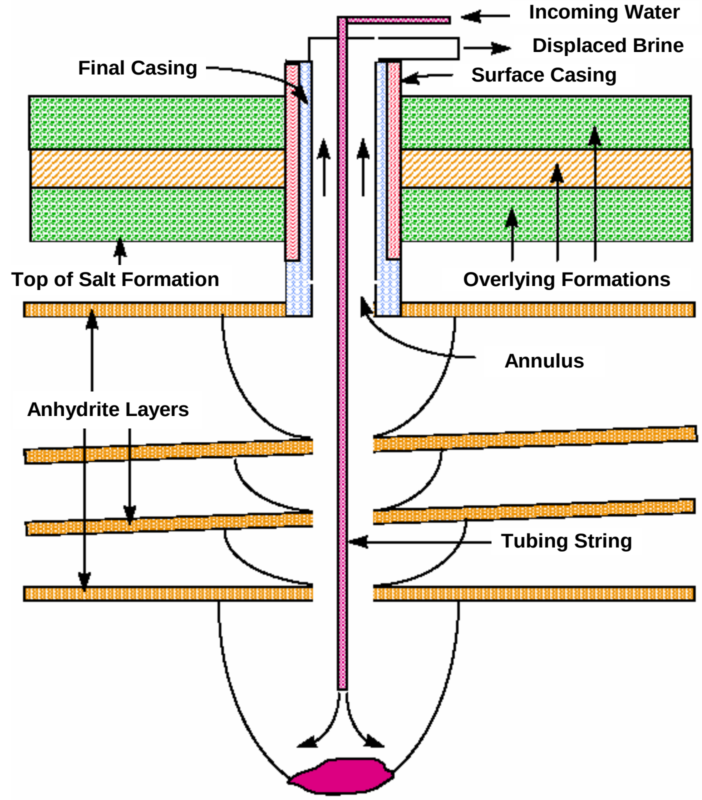


Figure 14. Theoretical maximum packing density of 200 ft diameter solution-mined salt caverns, with minimum 200 ft web horizontal separation: approximately 200 caverns per square mile of favorable geology. “Web” is undisturbed salt formation between caverns, for structural integrity of the array. 14 new caverns, in red, are required for this project, for total required gross cavern volume ~280 million cubic feet (Mft3): 14 caverns, each ~20 Mft3. Total net GH2 storage ~35,000 metric tons (Mt).

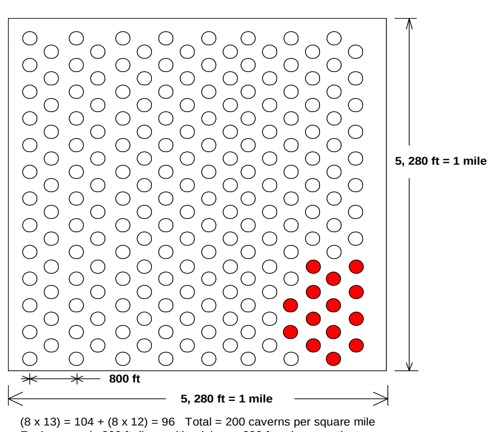


Figure 15. Large reciprocating compressors for natural gas and hydrogen service; 8,000 – 22,000 hp electric motor drive. Dresser-Rand model HHE-VL.

Three 8500 horsepower HHE-VL units compress natural gas to 2700 psi into underground storage caverns.

5500 horsepower HHE-VL hydrogen make-up compressor.

References

1 Leighty W, Hirata M, O'Hashi L, Benoit J. Large Stranded Renewables: The International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF). Proceedings of the 19th World Energy Conference, Sydney, AUS, Sept 04. www.leightyfoundation.org/earth.php

2 Leighty W, Holloway J, Merer R, Somerday B, San Marchi C, Keith G, White D. Compressorless Hydrogen Transmission Pipelines Deliver Large-scale Stranded Renewable Energy at Competitive Cost. Proceedings of the 16th World Hydrogen Energy Conference, Lyon, FR, June 06. www.leightyfoundation.org/earth.php

3 Leighty W, Hirata M, O'Hashi K, Benoit J, Keith G. Large Renewables-Hydrogen Energy Systems: Gathering and Transmission Pipelines for Windpower and other Diffuse, Dispersed Sources. Proceedings of the 22nd World Gas Conference, IGU, Tokyo, Jun 03. www.leightyfoundation.org/earth.php

4 Leighty W. Running the world on renewables: Hydrogen transmission pipelines and firming geologic storage, *Int. J. Energy Res.* 2008; 32:408-426, Wiley Interscience www.leightyfoundation.org/earth.php

5 Holbrook J, Leighty W. Transmission and Firming of GW-Scale Wind Energy via Hydrogen and Ammonia, *Wind Engineering*, Volume 32, NO. 1, 2008, Multi-Science Publishing Company, UK www.leightyfoundation.org/earth.php

6 O'Hashi K, Hirata M, Leighty W. From a Natural-gas-based to a Hydrogen-based Society: Proposal for a Northeast Asian Hydrogen Highway. Proceedings of the 23rd World Gas Conference, IGU, Amsterdam, NL, June 06. www.leightyfoundation.org/earth.php

7 Personal communication, L. Fingersh, NREL, 10 Feb 05.

8 Cavalho A. High Capacity Factor Wind Energy Systems. Journal of Solar Energy Engineering, May 1995, Vol. 117, pp 137-143, Transactions of the ASME. Center for Energy and Environmental Studies, Princeton University.

9 Cavalho A, Beck M. Cost Effective Seasonal Storage of Wind Energy. SED - Vol 16, Wind Energy, Book No. H00926 - 1995, Center for Energy and Environmental Studies, Princeton University.

10 http://www.wapa.gov/es/pubs/esb/2003/03Aug/esb084.htm

11 Fingersh LJ. Optimized Hydrogen and Electricity Generation from the Wind. NREL/TP-500-34364, Table 1, Jun 03.

12 www.solutionmining.org

13 Leighty W, Holloway J, Merer R, Keith G, White D, Somerday B, San Marchi C. Compressorless Hydrogen Transmission Pipelines Deliver Large-scale Stranded Renewable Energy at Competitive Cost. Proceedings of Power-Gen Renewables, Las Vegas, NV, Apr 06. www.leightyfoundation.org/earth.php

14 "Wind-H2-PipelineModel.xls" at: www.leightyfoundation.org/earth.php

15 Bourgeois R, Swalla D, Ramsden T. Low Cost Electrolyzer Technology for Industrial Hydrogen Markets, Proceedings of National Hydrogen Association annual meeting, 30 Mar – 3 Apr 08, Sacramento

16 Swisher JH, Keeton SC, West AJ, Jones AT. Survey of Hydrogen Compatibility Problems in Energy Storage and Energy Transmission Applications. SAND74-8219, Sandia National Laboratories, Livermore, CA, 1974.

17 Kesten M, Windgassen KF. Hydrogen-Assisted Fatigue of Periodically Pressurized Steel Cylinders. Hydrogen Effects in Metals. Bernstein IM and Thompson AW, eds. American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1981, pp. 1017-1025.

18 Birnbaum HK, Robertson IM, Sofronis P, Teter D. Mechanisms of Hydrogen Related Fracture - A Review. Corrosion-Deformation Interactions, CDI '96. Magnin T, ed. The Institute of Materials, London, 1997, pp. 172-195.

19 Swisher JH. Hydrogen Compatibility of Structural Materials for Energy-Related Applications. Effect of Hydrogen on Behavior of Materials. Thompson AW, Bernstein IM, eds. American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1976, pp. 558-577.

20 Kottenstette R, Cottrell J. Hydrogen Storage in Wind Generator Towers. NREL, September 2003 • NREL/TP-500-34656

21 http://www.teesvalley-jsu.gov.uk/

22 Schwattz M, Elliott D, Gower G, Seasonal Variability of Wind Electric Potential in the United States, PNL, 01 Jul 93, OSTI 10178386, DE93018182, PNL-SA-22090.

23 http://www.internationalpipelineconference.com/presentation_files/1030_PARKS-Clemens_Release-Final.ppt.zip

24 http://www.praxair.com/praxair.nsf/AllContent/3A0AB529A089B473852571F0006398A3?OpenDocument&URLMenuBranch=19B4D941A5B182EE852571FC005510B2

25 Personal communication, Gary Koeppel, Praxair, 25 Sept 06 and 4 Jan 07.

26 Elliott D, Wendell L, Gower G. 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.

27 www.naturalhy.net

28 Florisson O. Investigations of the conditions under which the existing natural gas system can be used for hydrogen-natural gas mixtures (NATURALHY-project) The EU "NaturalHy" project. Gasunie Research, N.V., The Netherlands. International Pipeline Conference 2004 (IPC04), ASME, Calgary, 4-8 Oct 04.

29 Leighty W, Hirata M, O’Hashi K, Benoit J. International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF). 19th World Energy Congress, Sydney, Sept 04. http://www.worldenergy.org/wec-geis/congress/bycountry.asp#United%20States. www.leightyfoundation.org/earth.php

30 Stephen G. Composite Reinforced Line Pipe-CRLP for Hydrogen Transportation. International Pipeline Conference 2004 (IPC04), ASME, Calgary, Canada, 5 Oct 04. TransCanada PipeLines Ltd. Calgary, Canada.

31 UIC 2007 meeting handbook: http://www.gwpc.org/GWPC_Meetings/Information/UIC-2007/UIC07%20Handbook.pdf

32 Implementation and Liaison Committee (ILC) meeting of the IPHE, 22-24 March, Rio de Janiero, Brazil.

