RUNNING THE WORLD ON RENEWABLES VIA HYDROGEN TRANSMISSION PIPELINES AND FIRMING GEOLOGIC STORAGE

William C. Leighty
The Leighty Foundation
Box 20993
Juneau, AK 99802 USA
wleighty@earthlink.net

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 energy to distant loads. 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. At GW 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 at ~$1.50-3.50 / kg.

New, large, solution-mined salt caverns in the southern Great Plains, and probably elsewhere in the world, can 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, worldwide. Great Plains, USA, wind energy alone, if fully harvested and "firmed" and transmitted to markets, could supply the entire energy consumption of USA: ~100 quads / year. If gathered, transmitted, and delivered as hydrogen, about 15,000 new solution-mined salt caverns, of ~8 million gross cubic feet each, would be required, at an incremental capital cost to the generation-transmission system of ~5%. See our complete analysis: SMRI paper at www.leightyfoundation.org/earth.php.

1. 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 to deliver the energy to distant markets. 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". Large, new electric transmission systems dedicated to renewables will suffer the same low CF, will be costly and difficult to site and permit and finance, cannot affordably firm most renewables, and represent substantial stranded capital assets, which increases the cost of delivered renewable-source energy.

"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. GH2 storage capacity could benefit the renewables plants by allowing them to sell more "firm" energy than if the energy were transmitted via electricity lines.

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 natural gas (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. The EC is now studying this blended fuel strategy via the "NaturalHY" project, conducted by Gasunie Research, The Netherlands.

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. Building new underground pipelines has historically been easier and faster than new electric transmission lines; less NIMBY.

At gigawatt (GW = 1,000 MW) scale, renewable-source electricity from diverse sources, 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 (NH_3) production, and petroleum refinery feedstock. Figs 1-2. The oxygen byproduct may be sold to adjacent dry biomass and / or coal gasification plants. New, large, solution-mined salt caverns in the southern Great Plains, Gulf of Mexico coast, and probably elsewhere in the world, can 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, rendering them "dispatchable".

Figs 5 - 6 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. The salt cavern storage industry is mature; several high-pressure (>2,000 psi) GH2 storage caverns have been in service for over twenty years; construction and operating and maintenance (O&M) costs are well understood.

Although windplants are the lowest-cost new renewable energy sources, concentrating solar power (CSP) is probably seasonally and technically 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.

For example, Great Plains, USA, wind energy alone, if fully harvested and "firmed" and transmitted to markets, could supply the entire energy consumption of USA: ~100 quads per year. If gathered, transmitted, and delivered as hydrogen, about 15,000 new solution-mined salt caverns, of ~8 million gross cubic feet each, would be required, at an incremental capital cost to the generation-transmission system of ~5%.

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 electricity transmission, at large scale; Fig 3: [1]

1. Adding value to renewables generation assets by "firming" their energy output with energy storage, delivering GH2 fuel to end-of-pipeline, wholesale, city-gate markets at ~\$2-3.50 / kg;
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); [2, 3]
3. Locating GH2 transmission pipelines underground may be more socially acceptable and more secure from natural and human threats; pipelines have large capacity: Fig 2.
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. Improving pipeline CF 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.

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 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 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).

Design and construction of large, long-distance, high pressure GH2 pipelines and conventional natural gas (NG) transmission lines are similar. Pipelines have high capacity: Figs 2-3. 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;
2. Pipeline utilization: CF would be reduced without geologic storage at the sources;
3. HE of pipeline steel must be prevented and controlled; new line pipe materials developed;
4. GH2 compression is very costly in capital, energy, and O&M.

2. SYSTEM MODELING

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. [3] However, in 2006 the installed cost of large wind generators in large windplants was typically $1,600 / kW; this high cost may be temporary, but a decline to $800 / kW may be unrealistic. We surveyed engineers, geologists, and constructors in the USA solution mining salt cavern industry. [4]

First, 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. Figs 1 - 3. [5] Such large generation and transmission systems would achieve full economy of scale, in manufacture and construction.

Second, for this large-scale windplant in the USA Great Plains, we used a simple capital recovery factor (CRF) model to calculate average annual wholesale, untaxed COE for GH2 fuel in $US 2007, at the end-of-pipeline at a distant urban market, considering a range of CRF, shown in Table 2.

Third, we modeled system economics, to find the optimum nameplate capacity ratios among windplant, electrolyzers, and pipeline, as shown in Fig 4.

Fourth, we modeled this system to include "value-adding" features which reduce the cost of GH2 fuel delivered at the end-of-pipe at the distant urban market. Figs 1 and 3:

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);
3. Estimated future carbon-emission offset payment or renewable energy certificate (REC) of $0.01 / kWh.

Fifth, we modeled our system entirely without compression, assuming that 100 bar output electrolyzers feed the GH2 pipeline directly, for a large saving in capital, energy, and other O&M costs. This also assumes that 30 bar is a good city-gate delivery pressure for urban distribution. Midline compressors are not needed if we accept friction losses of 100 to 30 bar.

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 GH2 energy storage required for annual-scale firming of total Great Plains wind, ~100 quads / year. Tables 2-3, Figs 2-4.

3. RESULTS

Table 3. 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 4, assuming:

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

Table 2, Fig 3. 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 ~$1.50 - 3.50 / 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 12 - 18%.

4. SYSTEM OPTIMIZATION

Figs 5-6. Low-cost, annual-scale, storage is needed for renewable-source GH2, as it is for natural gas (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. The "ChevronPhillips Clemens Terminal" cavern in bedded salt has been in service ~20 years, storing ~2,500 net tons of GH2 at up to 140 bar.

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 (billion kWh) in an average year. Using the numbers from "Seasonal Variability of Wind Electric Potential in the United States" [6], Table 3, 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, the more conservative 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. This would require ~14 large GH2 salt storage caverns.

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 .[7] 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. [1, 5]

5. CONCLUSIONS

Fig 3. With various "value-adders", wind-source and other renewable-source GH2 fuel may be delivered via new pipelines 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), and with gasoline and diesel, at 2007 prices. 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. Renewable-source energy can be "firmed" as GH2 stored in salt caverns at low cost, adding value.

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

We should begin feasibility, preliminary engineering, and cost estimation studies for the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF). This pilot-scale facility has been proposed as a project for the IPHE (International Partnership for the Hydrogen Economy). [8] It will yield empirical operational data enabling refinement of the analyses in this paper, guiding future investments.

Other attractive transmission and firming storage schemes for large-scale, stranded, renewable-source hydrogen include conversion to:

1. Anhydrous ammonia (NH_3), 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), with transmission and storage in pipelines and tanks;
3. Magnesium hydride, aluminum-gallium, and several other chemical forms.

Recommended future study:

1. Verify GH2 storage feasibility in bedded salt; construct a tall, small-diameter test cavern by solution mining in deep and thick bedded salt; test for leakage when pressurized to ~100 bar.
2. Hydraulic modeling, topology and engineering and economic optimization, of a continental system for renewable-source hydrogen collection, transmission, firming storage, and delivery as pressurized GH2.

TABLE 1: CAPITAL COSTS, 4,000 MW WINDPLANT, ELECTROLYZERS, AND 36" PIPELINE 300 km

	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
* TICC (total installed capital cost)		**$ 4,850**

TABLE 2: UNSUBSIDIZED COST OF WIND-SOURCE GH2 FUEL DELIVERED AT END-OF-PIPE

Delivered at end-of-pipe at distant city gate, as a function of CRF and pipeline length; 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, NO 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

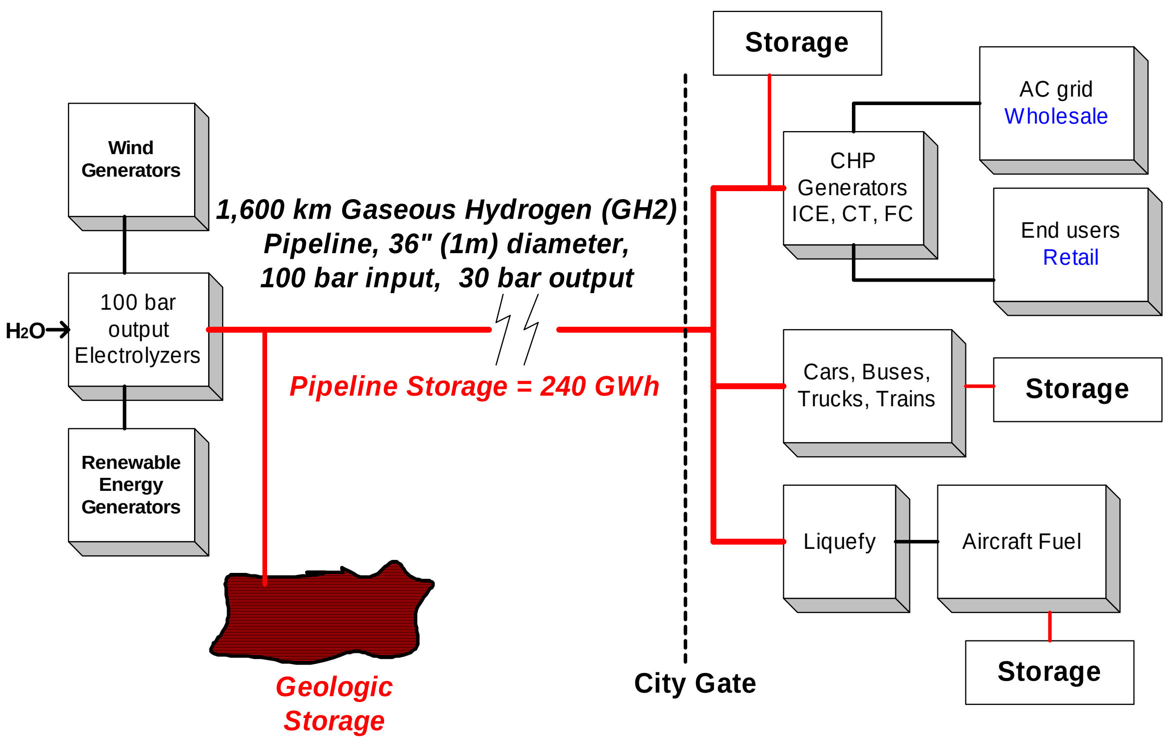

Fig 1. System diagram. 100 bar output electrolyzers directly feed the pipeline without compressors. Gaseous hydrogen (GH2) delivery to the city gate market is at ~30 bar, after pipeline friction losses: a good pressure for urban distribution. Pipeline and end-user storage provides renewables smoothing, but not annual-scale firming.

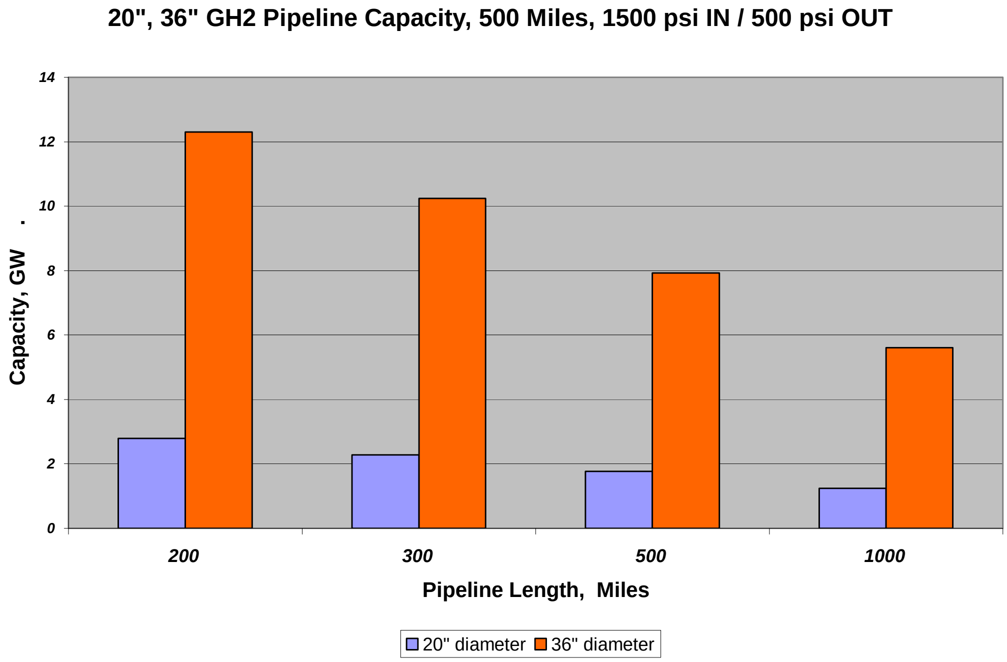

Fig 2. 800 km long GH2 pipeline capacity, function of diameter and length: GW

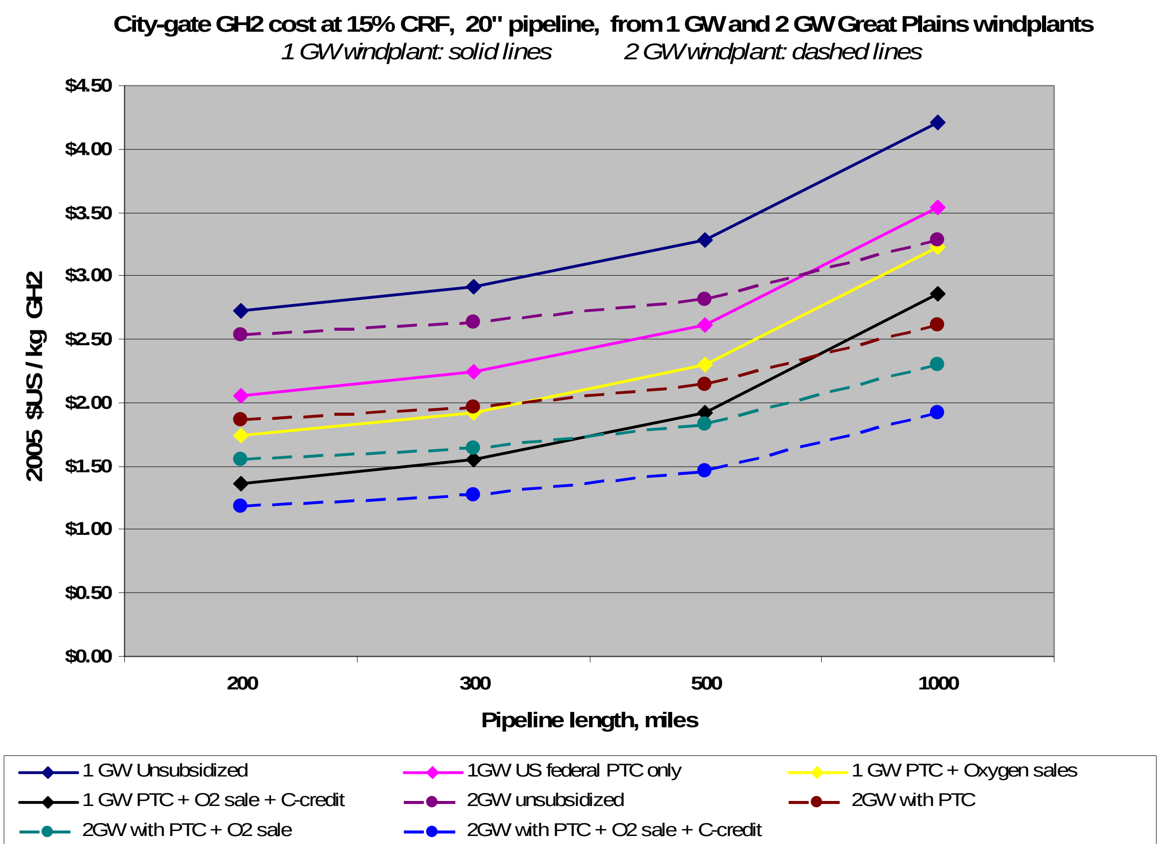

Fig 3. Unsubsidized and four “value-added” cases for wholesale price of GH2 fuel at city gate, for both 1 GW and 2 GW windplant size. Cost per kg GH2 would be about the same for 2 GW and 4 GW windplants.

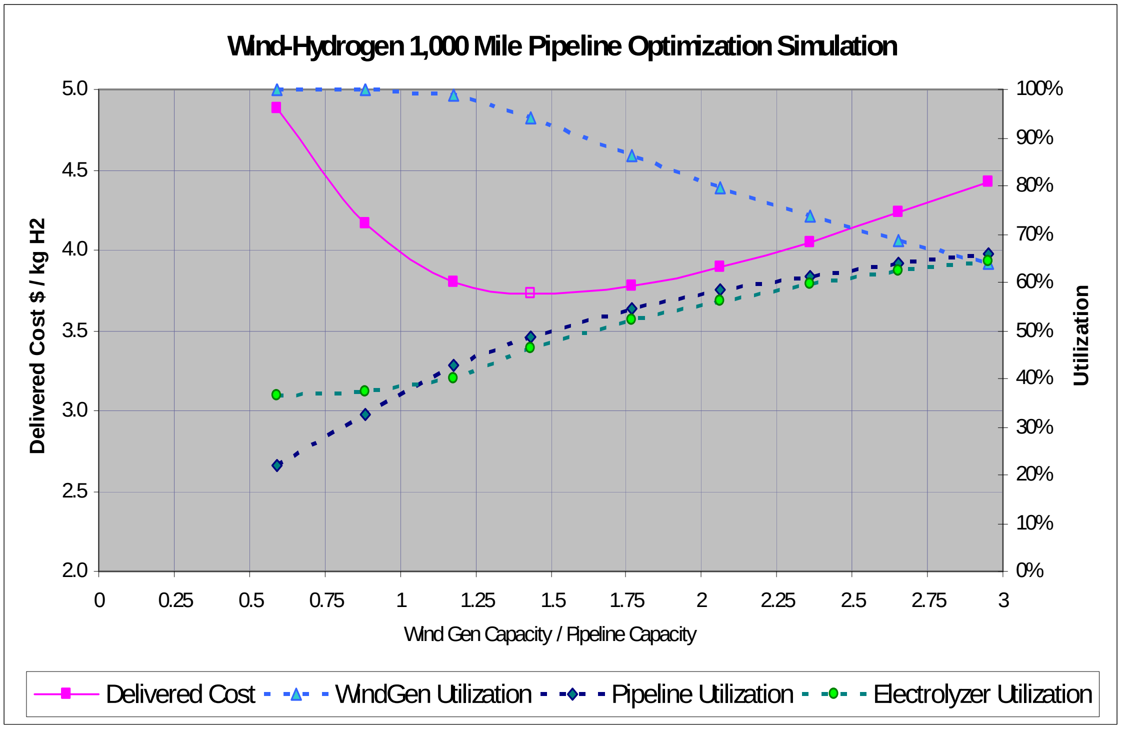

Fig 4. Wind - Hydrogen Pipeline System Optimization Simulation: unsubsidized; 1,600 km long GH2 transmission pipeline. Wind generators, electrolyzers, and 1,600 km transmission pipeline system. Optimal, minimum-cost point is where the maximum wind capacity exceeds the maximum pipeline capacity by about 40%. This "wastes" some wind energy but increases the utilization (CF) of the electrolyzers and pipeline.

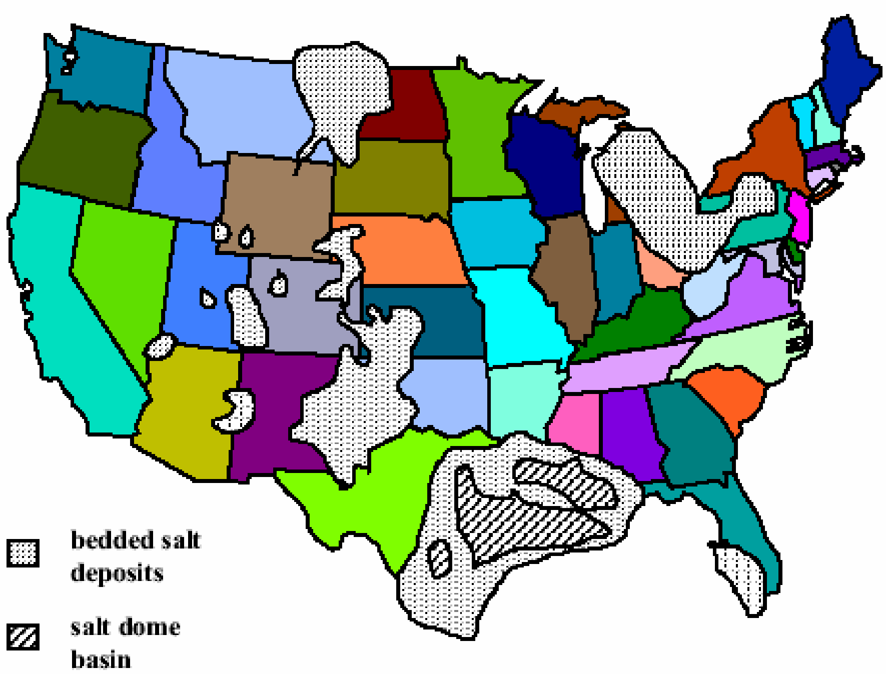

Fig 5. Large underground dry salt formations which may be suitable for solution mining, to create large GH2 storage caverns.

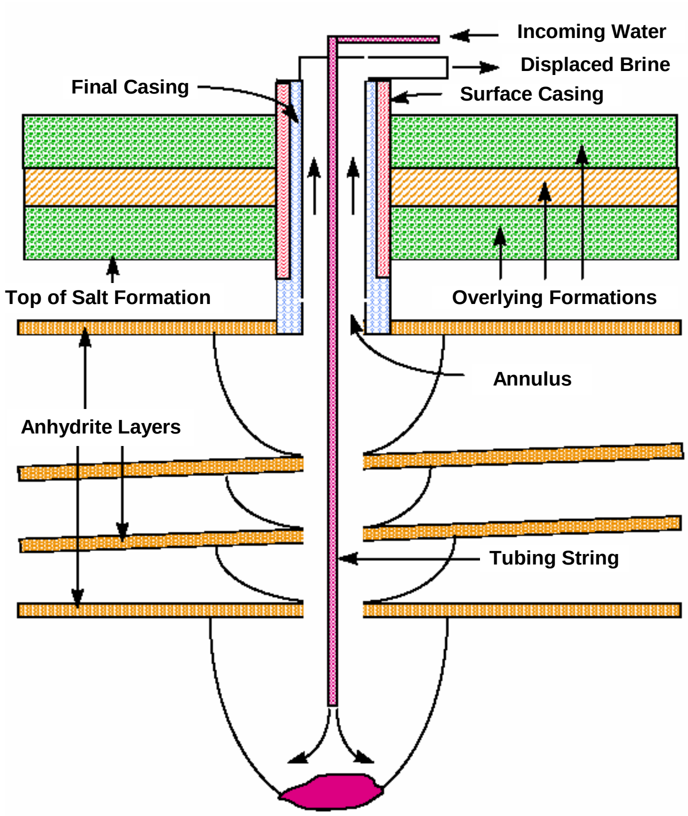

Fig 6. Solution-mining of storage salt caverns in “bedded” salt typical of the Great Plains and the Gulf of Mexico coast. Excavating caverns in “bedded” salt is riskier than in “domal” salt because of potential leakage through non-salt (halite) strata. Gross cavern size of >8 million cubic feet can easily be solution-mined in domal salt.

6. REFERENCES

[1] 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.

[2] Personal communication, L. Fingersh, NREL, 10 Feb 05.

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

[4] www.solutionmining.org

[5] 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.

[6] Schwartz MN, Elliott DL, Gower GL., Seasonal Variability of Wind Electric Potential in the United States, PNL, 01 Jul 93, OSTI 10178386, DE93018182, PNL-SA-22090.

[7] 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.

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