Compressorless Hydrogen Transmission Pipelines Deliver Large-scale Stranded Renewable Energy at Competitive Cost

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ABSTRACT

We modeled a 1,000 MW (1 GW) (nameplate) windplant in the large wind resource of the North America Great Plains, delivering exclusively hydrogen fuel, via a new gaseous hydrogen (GH2) pipeline, to an urban market at least 200 miles distant. All windplant electric energy output would be converted, at the windplant, to hydrogen, via 1,500 psi output electrolyzers, directly feeding the GH2 transmission pipeline without costly compressor stations at inlet or at midline. The new GH2 pipeline is an alternative to new electric transmission lines. We investigate whether the pipeline would provide valuable energy storage. Large-scale electricity and hydrogen pipeline systems are comparable in capital and O&M costs. [1] We present a simple model by which we estimate the cost of wind-source hydrogen fuel delivered to the distant city gate in year 2010, at GW scale. Cavern GH2 storage may allow "firming" the Great Plains wind resource at modest cost.

1. INTRODUCTION

We assume a transmission-constrained world, where large new windplants must pay all transmission costs for delivering their energy to distant markets. Large, new electric transmission lines are difficult to site and permit. Building new underground pipelines has historically been easier and faster. Increasing capacity of extant electricity transmission corridors is an attractive immediate strategy, although this provides no energy storage for the inherently time-varying output of renewable sources.

Windplants are the lowest-cost new renewable energy sources. The largest and richest resources in North America, with high average annual windspeed, are stranded in the Great Plains: extant electric transmission capacity is insignificant relative to the resource potential. Large, new, electric transmission systems will be difficult to site and permit, and may be difficult to finance, given current uncertainties about transmission cost recovery.

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 of retail-value electricity on the customer's side of the meter. GH2 pipeline transmission may offer important technical and economic advantages and synergies vis-à-vis electric transmission, at large scale: [2]

1. Adding value to wind generation assets by "firming" their energy output with energy storage;
2. Sharing power electronics between wind generation and electrolysis systems saves substantial capital, O&M, and energy conversion loss costs; removing requirements to deliver grid-quality electricity will improve wind generation COE slightly. [3]
3. Underground location of the GH2 transmission pipeline may be more socially acceptable and more secure from natural and human threats;
4. The oxygen byproduct of electrolytic production of hydrogen from wind-source electricity may be sold to adjacent biomass and coal gasification plants;
5. Pipeline CF may be improved by synergistic sharing with diverse renewable GH2 sources in the same geographic area, complementing wind's time-variability.

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 miles to compete with other hydrogen sources at the destination. The time-varying output of windplants will cause large, frequent pressure fluctuations in GH2 pipelines, which induces and exacerbates hydrogen embrittlement: Section 3.7.

Design and construction of large, long-distance, high pressure hydrogen 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:

1. The volumetric energy density of hydrogen is one-third that of methane;
2. Pipeline utilization: capacity factor (CF);
3. Hydrogen embrittlement of pipeline steel must be prevented and controlled: Section 3.7;
4. Compression is very costly in capital, O&M, and energy.

Most analyses show that pipelining GH2 costs approximately 1.3 to 1.8 times more than pipelining NG because of these four factors.

Pipelines are very expensive to design and construct and must have high utilization to justify the initial capital cost. They must have a large, relatively continuous, source of product. In the NG industry, underground storage at the upstream and / or downstream ends of pipeline systems provide high pipeline CF. A GH2 pipeline with wind generation as the sole source of energy would be severely handicapped by the wind turbines' low CF (about 40%) and time-varying production, on hourly to seasonal time scales. Thus, wind energy would have to be complemented with other electricity or hydrogen generation at the upstream end of the pipeline in order to provide consistent energy to the pipeline, high pipeline CF, to "firm" supply to markets: Section 3.10.

The materials challenges of GH2 transmission pipelines may result in new materials or hybrids, with reduction in GH2-capable pipeline system costs to below that of today's NG pipelines: Section 3.7.

Energy storage as compressed GH2 in large, underground, solution-mined salt caverns may allow "firming" the Great Plains wind resource, at modest incremental cost, especially in synergy with other Great Plains renewables.

2. METHOD

We modeled the technical and economic performance of a large 1,000 MW nameplate capacity windplant delivering its entire output as GH2 fuel, by pipeline, to a distant urban market: Figure 1. First, we modeled pipeline performance, using hydraulic models standard in the gas pipeline industry, and assuming no compressors in the system, either at source or at midline:

1. Pipeline transmission capacity;
2. Pipeline energy storage capacity, assuming "packing" the pipeline to 1,500 psi, "unpacking" to 500 psi, for adequate delivery pressure for distribution at the distant urban market;
3. Dynamic energy storage behavior, as windplant output varies with time.

Based on the pipeline modeling, we chose 20" diameter and 1,500 psi maximum allowable operating pressure (MAOP) as amenable to modern pipeline design practice and economy-of-scale.

We estimated system capital cost savings from optimizing wind generator power electronics 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.

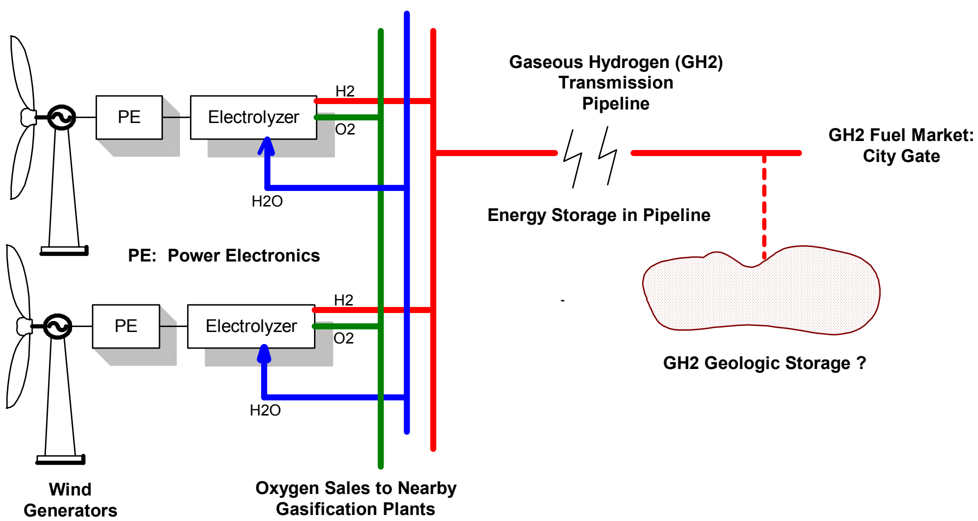


Figure 1. System Diagram. All wind energy is converted to GH2 for transmission; no electricity is delivered to the grid. Windplant infrastructure is primarily piping, with a small supply of electricity distributed only for controls.

We surveyed manufacturers of wind generators, electrolyzers, and compressors, to obtain expected performance and capital costs in year 2010, with costs expressed in year 2005 $US. Table 1 estimates year 2010 technology and capital component costs from industry consensus and USDOE goals: [4]

1. Wind generators in a large, dense windplant will offer significant economy-of-scale in manufacture and installation. Technology improvements, shared power electronics (PE), and freedom from electricity grid delivery will reduce total installed capital cost (TICC) to $800 / kW. We add $30 / kW for PE specialized for electrolyzer drive at low voltage direct current (DC).
2. Electrolyzers with 1,500 psi output capability, at MW scale, will be available. Less the transformer-rectifier subsystem, in a large-volume order, TICC will be $330 / kW.
3. The 500 mile long, 20" diameter, GH2 pipeline will be built of materials that control H2 embrittlement, at no cost premium over NG pipeline construction at the same diameter and pressure. TICC for the 36" diameter, 2,000 mile long Alliance Pipeline, North America's newest large NG pipeline system, was $25 per inch diameter per meter length. We assume $29 / inch diam / m length, to account for higher current steel prices and lower economy-of-scale for a shorter pipeline length than Alliance.

Table 1. Capital costs: 1,000 MW windplant , electrolyzers, and 20" pipeline 500 miles long.

	TICC $ / kW in Year 2010	**Total (million 2005 $US)**
Windplant	$800	$800
Power electronics incremental cost	$30	$30
Electrolyzers: 1,500 psi output	$330	$330
Pipeline: 20", 500 miles (800 km) long	$29 / inch diam / m length	$464
TICC (total installed capital cost)		**$1,624**

We calculated cost of energy (COE) at the end-of-pipe at a distant urban market, considering a range of capital recovery factors (CRF): Table 2 and Figure 6. We used a simple Capital Recovery Factor (CRF) model [5] by which we estimate the untaxed cost of renewable-source hydrogen fuel delivered at wholesale to the distant city gate, from calculated cost per unit energy-distance for the assumed 20" diameter GH2 pipeline transmission system. We chose 15% as a good compromise for this paper's analysis, for year 2010 technology and year 2005 $US costs.

We also modeled system economics, to find the optimum capacity ratio among windplant, electrolyzers, and pipeline: Figures 23-25.

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 2:.

1. Byproduct oxygen (O2) sale to adjacent gasification plants for dry biomass, and perhaps for coal (assuming carbon capture and sequestration); Figure 2;

2. US federal production tax credit, $0.019 / kWh in year 2005;
3. Estimated future carbon-emission offset payment or credit of $0.01 / kWh
4. Improved pipeline CF.

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 production tax credit (PTC), or other); no "value adders" in byproduct oxygen sales or carbon emissions offset credits or payments.

Pipeline Length	320 km / 200 miles	480 km / 300 miles	800 km / 500 miles	1600km / 1000 miles
	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

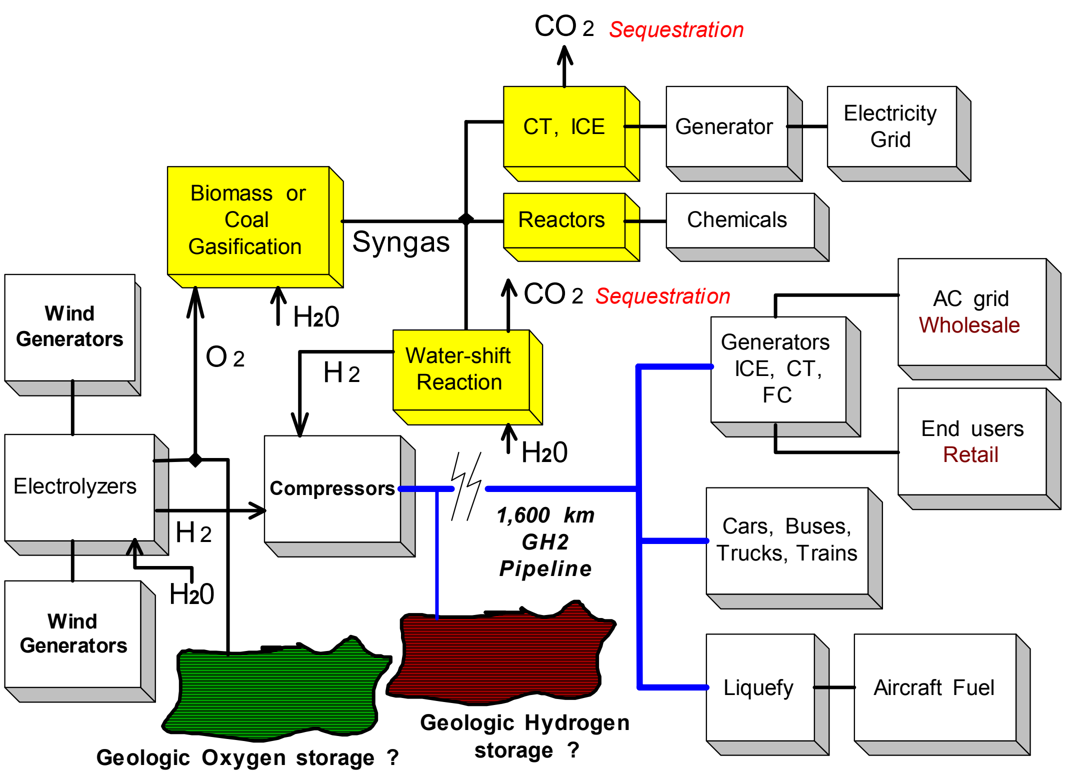


Figure 2. System diagram, with potential "value adding" features of byproduct oxygen sale to adjacent gasification plants, improved pipeline CF, and seasonal-scale geologic storage of GH2.

We recognized several possibilities for upstream energy storage, although we did not consider or model them:

- Hydrogen storage in underground geologic structures;
- Hydroelectric reservoirs, but only if large electricity grid capacity is available and connected.

We report expertise on the critical problem of hydrogen embrittlement of pipeline steel, which will be exacerbated in "renewables-hydrogen service" (RHS) where the time-varying output of renewable sources like windpower will cause frequent, large excursions in pipeline pressure: Section 3.10 and Figures 26-28.

Finally, we address the potential contribution of GH2 pipeline transmission and cavern storage to "firming" the time-varying output of windplants, increasing its value. We also suggest several topics for further research and analysis: Sections 3.10 and 5.

3. RESULTS

3.1 PIPELINE CAPACITY

Results of modeling pipeline transmission and storage capacity, using hydraulic equations standard in pipeline design practice, are shown in Table 3 and Figures 3-5

1. 100 % GH2
2. 1,500 psi input, 500 psi output pressures
3. Capacity: fully turbulent flow achieved
4. Storage capacity: "unpack" pipeline from 1,500 psi to 500 psi
5. Pipeline lengths of 200, 300, 500, and 1,000 miles
6. 20" and 36" nominal diameter (inside diameter)

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

3.2 SYSTEM CAPACITY

A 1,000 MW windplant produces about 200 MMscfd of GH2 at full output; 80 MMscfd at 40% average capacity factor (CF). The continuous capacity of a 500 mile long, 20" diameter, GH2 pipeline is ~ 400 MMscfd, without compressors. It could deliver wind-

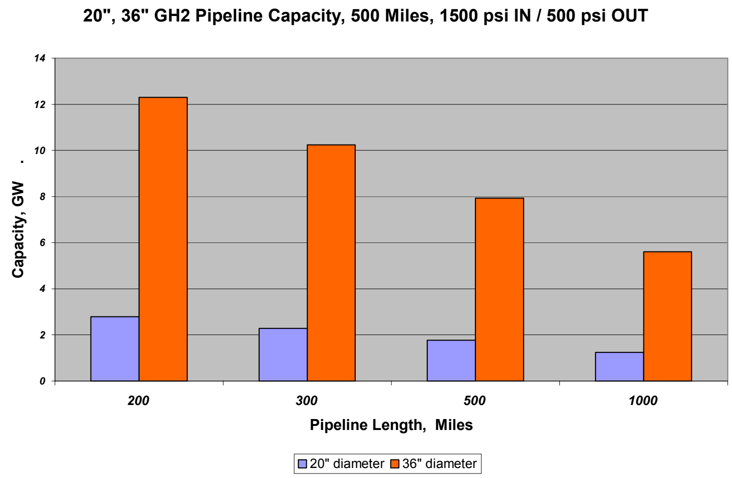


Figure 3. 500 mile long gaseous hydrogen (GH2) pipeline capacity as function of diameter and length: GW

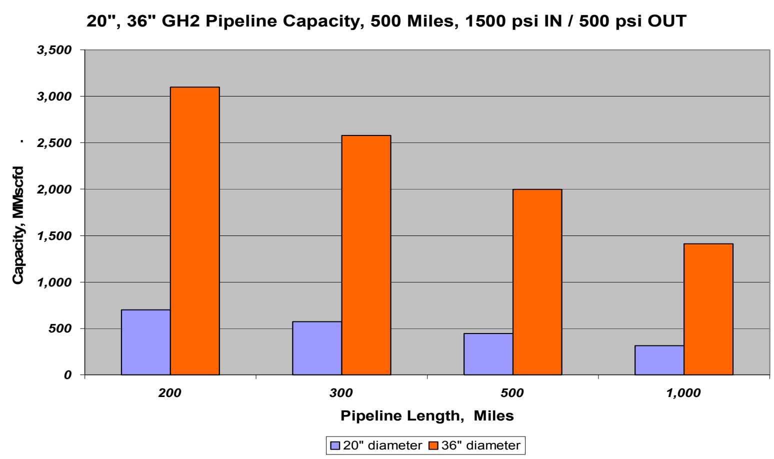


Figure 4. 500 mile long gaseous hydrogen (GH2) pipeline capacity as function of diameter and length: MMscfd

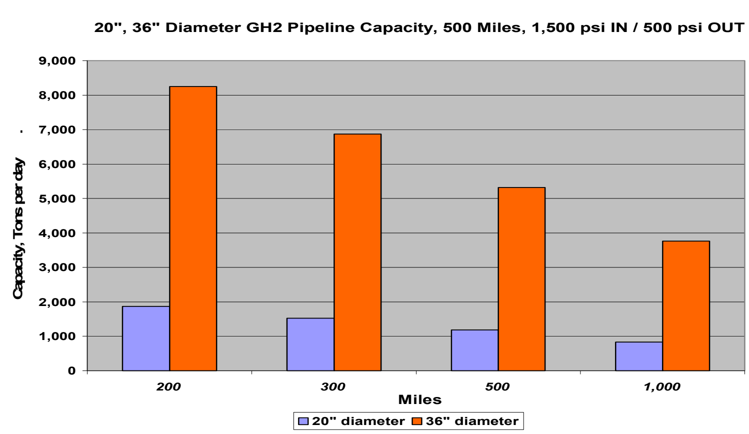


Figure 5. Gaseous hydrogen (GH2) pipeline capacity as function of diameter and length: Tons per day

source GH2 fuel 500 miles by pipeline for an unsubsidized price of
~$3.30 / kg, assuming;

1. Estimated year 2010 technology and costs, expressed in year 2005 $US;
2. All wind energy is converted to GH2 and delivered via 20” diameter pipeline at 1,500 psi inlet pressure and 500 psi delivery pressure, at the distant urban market;
3. No compressors, at pipeline inlet or at midline;
4. Capital Recovery Factor (CRF) of 15%;
5. Average pipeline CF of about 15%;
6. For a given diameter and pressure, GH2 pipelines can be built for the same capital cost as for natural gas (NG), although serious line pipe materials challenges must be met: Section 3.7.

Given the low pipeline CF in this 1,000 MW scenario, the 20” pipeline would need to serve considerable additional windplant generating capacity, > 2,000 MW, to approach full CF. In a mature wind-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: Section 3.8.

3.3 COST OF ENERGY (COE) AT END-OF-PIPE

We analyzed three “value-added” cases as well as the “unsubsidized” case, for both 1 GW and 2 GW windplants, because Table 3 shows that the 20” pipeline has continuous transmission capacity of ~1.7 GW at 1,500 psi inlet, 500 psi delivery pressure, at 500 mile length: Tables 1-2, and Figure 6. A 2 GW windplant improves pipeline CF, lowers delivered COE, vis-à-vis 1 GW. The delivered cost of energy (COE) through a 500 mile, 20” pipeline would be reduced to about $1.50 / kg by the sum of these value-adding steps:

1. US federal production tax credit (PTC), $.019 / kWh in year 2005;
2. Byproduct oxygen (O2) sales to adjacent dry biomass (and perhaps coal) gasification plants @ $20 / ton;
3. Future carbon-emissions-offset credits or payments, estimated at $0.01 / kWh;
4. Increase windplant to 2,000 MW.

Sensitivity of delivered GH2 fuel cost and capital component CF to pipeline length is shown in Figures 7-8.

3.4 GH2 COMPRESSION

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

1. Hydraulic modeling of the pipeline for the assumed 1 GW windplant shows that midline compressors are not needed;
2. 1,500 psi output electrolyzers should be feasible, and perhaps available, by year 2010, especially if a market seems promising; the electrolyzers will directly feed the pipeline at 1,500 psi;

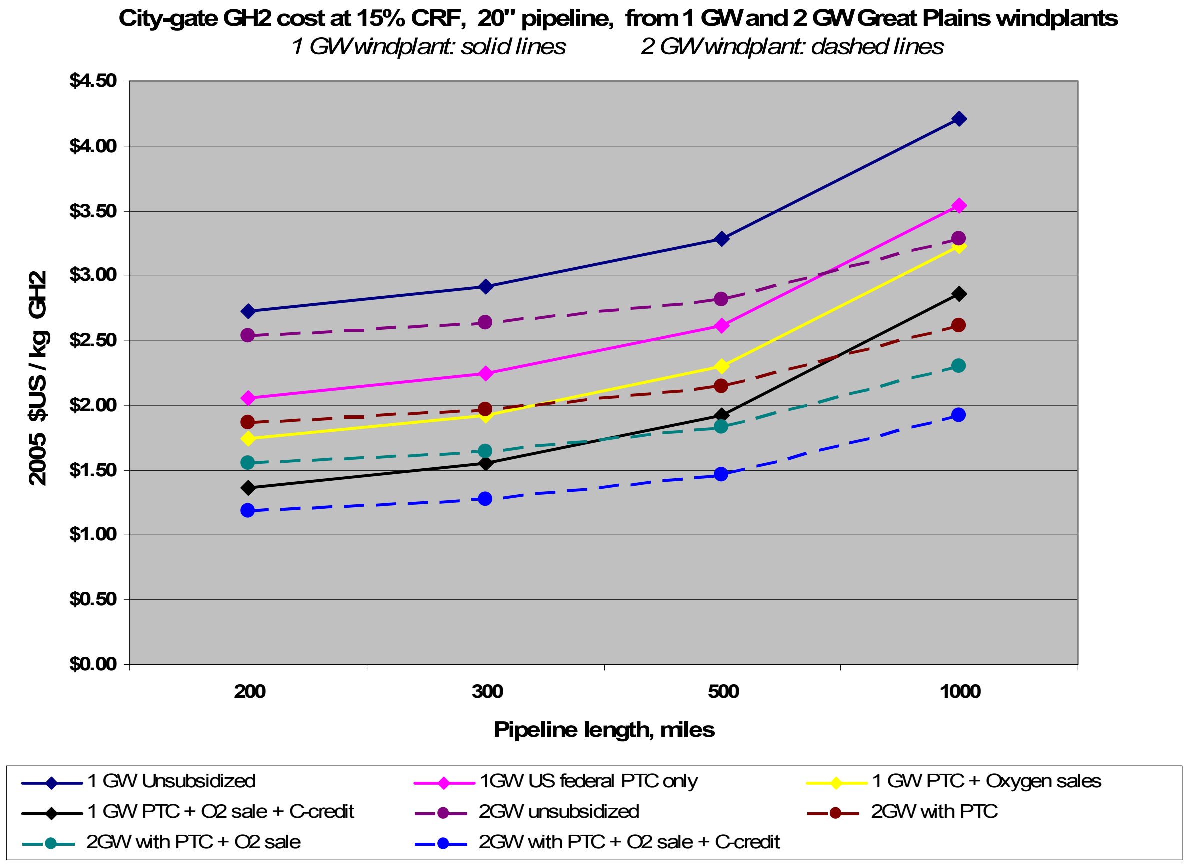


Figure 6. Unsubsidized and four "value-added" cases are shown for both 1 GW and 2 GW windplant size.

3. GW-scale compressors are not readily available for GH2; some technologies will be hard to scale to GW;
4. GW-scale compressors will be costly in capital, O&M, and operating energy—a large cost burden on the system.

The economic cost of GH2 compression, in this compressorless system, is the incremental cost of building the electrolyzer system capable of 1,500 psi output, vis-à-vis low pressure output. Pressurizing the H2O feed water to 1,500 psi costs very little.

Hydrogen compression is a difficult problem at GW scale. Since GH2 has one-third the energy of NG, by volume (324 btu vs. 1060 btu per scf), compressor power and energy are greater for pipelining GH2 than for NG: Table 4 and Figures 9-10. Several compressor technologies are candidates for GH2 at GW scale, but no mechanical compressors of such size are available now, for GH2; therefore, we cannot estimate costs for them. Technological breakthroughs and development are needed in this field, for transmission pipelining of GH2 from sources other than electricity: biomass, solar thermal, etc. are inherently low-pressure sources. Most compressor research today is focused on low-volume, high-pressure (5-10,000 psi) service for vehicle fueling.

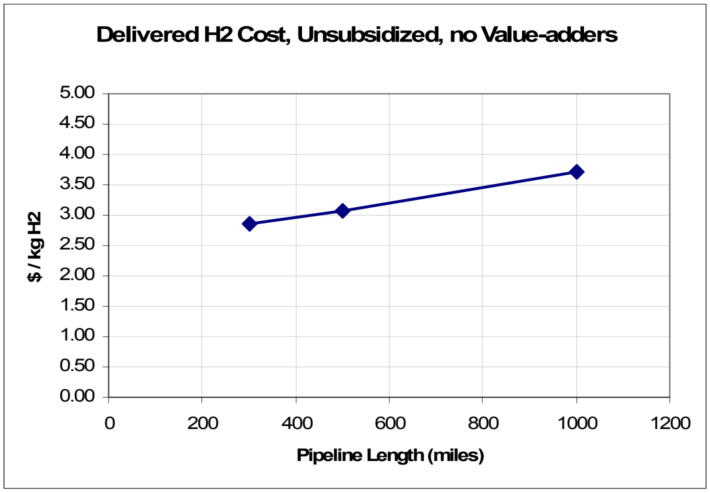


Figure 7. Sensitivity of delivered GH2 fuel cost to pipeline length. Unsubsidized: no US fed PTC, no byproduct oxygen sales, no carbon-emission-offset credit.

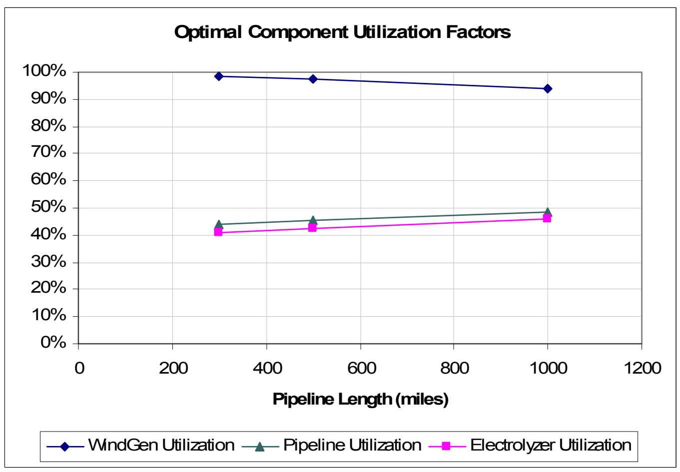


Figure 8. Sensitivity of capital component utilization to pipeline length. System component utilization, as percentage of rated, maximum continuous capacity.

Large diameter cross country NG pipelines use centrifugal compressors driven by either large electric motors or by gas turbines. The stations are in the 20-40,000 hp range and often consist of a single compression package. Hydrogen is much more difficult to compress than NG due to its low specific gravity. In our model, compressing hydrogen from 500 psig to 1,500 psig would require up to 60 stages of centrifugal compression, while the same NG compression would need 4 or 5 stages. This large number of required GH2 centrifugal compression stages eliminates usual NG compression technology. Various reciprocating compressors may be used for GH2, but the large volumes and pressures we assume in this paper require equipment of such complexity and size that it becomes difficult to consider.

Therefore, we have modeled our system entirely without compression, to take full advantage of high-pressure-output electrolyzers feeding the pipeline input.

Table 4. Compressor technology candidates for GW-scale GH2 pipeline transmission. All are costly in capital, energy, and O&M costs. In this paper's system, we employ the 1,500 psi electrolyzer output to directly feed the transmission pipeline, eliminating all compressors from the system.

Type	**Description**	**Benefits / Problems**
Reciprocating	A well proven technology for many different types of gases. Hydrogen, with its low molecular weight, becomes very difficult to contain in compression cylinders and therefore requires very specialized designs.	Positive displacement, capable of high pressure output. Oiled and oil-less lubrication types available. Oil lubrication may be necessary to contain GH2, but will contaminate the GH2. Usually electric motor driven. Well-proven in 1,000 kW size range for NG service. Few other advantages for GW-scale GH2 transmission pipeline service, where both the physical size and number of machines required make this type of compression a very remote possibility.
Centrifugal	A well proven technology for many different types of gases, in sizes up to over 20,000 hp. Hydrogen, with its low molecular weight, is very difficult to compress. Approximately 60 compression stages would be required for boost from 500 to 1500 psi, which would be a very costly machine.	The mechanical tolerances between a large number of stages become very difficult to maintain, which compromises interstage sealing, with very detrimental effects on compression efficiency and equipment capital cost.
Diaphragm	Compatible with all types of gases. Triple diaphragm construction isolates GH2 from hydraulic oil, preventing any contamination of the process gas or leakage into the atmosphere. High output pressure (> 10,000 psi) available.	High compression ratio per stage, compared to reciprocating compressors, may reduce capital costs. Not available in large sizes for GH2 pipeline transmission; may be difficult and costly to scale up. Largest currently available: 2,000 Nm3 / hr.
Electro-Chemical	Multi-stage Electro-Chemical compression uses a series of membrane electrode assemblies (MEAs), similar to those used in proton exchange membrane (PEM) fuel cells. An electrical potential across the MEA causes the transfer of hydrogen with increasing output pressure from stage-to-stage.	This non-mechanical compressor addresses a number of shortfalls inherent in traditional compressors. It has no moving parts, so reduces the wear-and-tear, noise, and energy intensity problems of mechanical compressors. It is also significantly more compact, thus adaptable to a range of applications. The challenges of building units large enough for GH2 transmission pipeline service and preventing GH2 contamination have yet to be addressed.
Hydride	Compressors using reversible metal hydride alloys offer an economical alternative to traditional mechanical compressors for GH2. The simplicity and passive operation of the hydride compression process offers many advantages over mechanical compressors.	Hydride compressors are compact, silent, do not have dynamic seals, require very little maintenance, and can operate unattended for long periods. However, they are a very new technology and may be difficult to be built at the scale required for GH2 transmission pipeline service.

Figure 9. A large diaphragm compressor by PDC Machines.

Figure 10. A large reciprocating compressor, NG service; 3,000 hp electric motor drive.

3.5 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 1,500 psi: Figures 11-13. Figure 13 shows energy conversion efficiency at HHV for a MW-scale KOH electrolyzer, the only technology presently available at MW scale. PEM electrolyzers are now available at > 1,500 psi output, at ~10 kW scale; they may not economically scale to MW. KOH electrolyzers are now available at 450 psi output; 1,500 psi output will require an R&D program and incremental capital cost, primarily for a stronger stack containment vessel.

3.6 SHARED POWER ELECTRONICS

Replacing the transformer-rectifier subsystem of the electrolyzer with power electronics (PE) shared with the wind generator will save ~ 10% in electrolyzer system capital cost and ~ 3% in energy conversion loss (the difference between the two curves in Figure 13). Figure 1. 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.

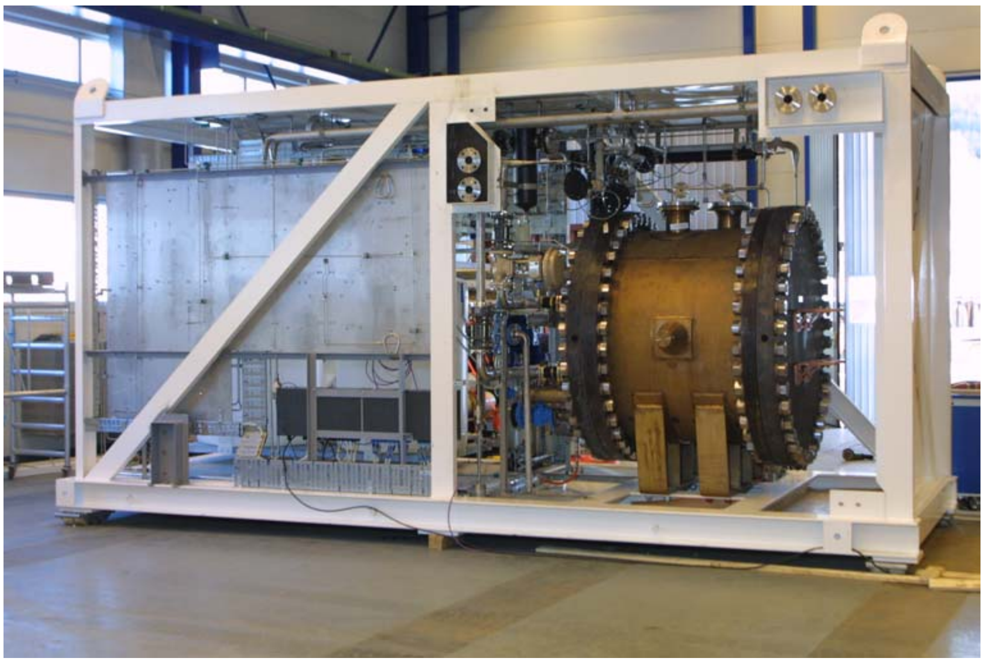


Figure 11. Norsk Hydro electrolyzer system, KOH type, without gas cleanup equipment. 560 kW input, 4.2 – 4.3 kWh per Nm3 output, at 450 psi (30 bar), 130 Nm3 / hour.

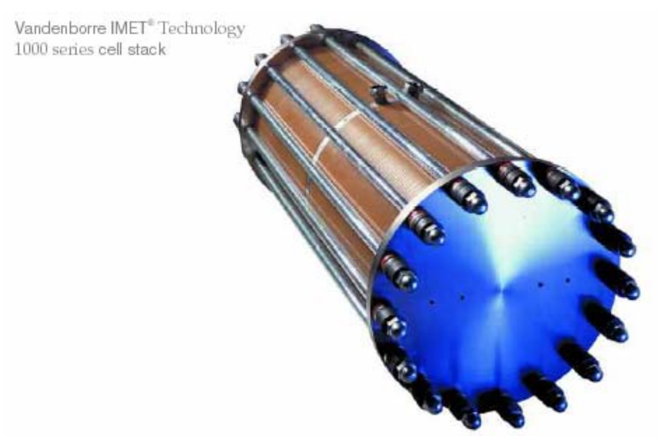


Figure 12. Hydrogenics electrolyzer stack, 450 psi (30 bar)

This 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, 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, for a small saving in wind generator capital and O&M cost. 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.

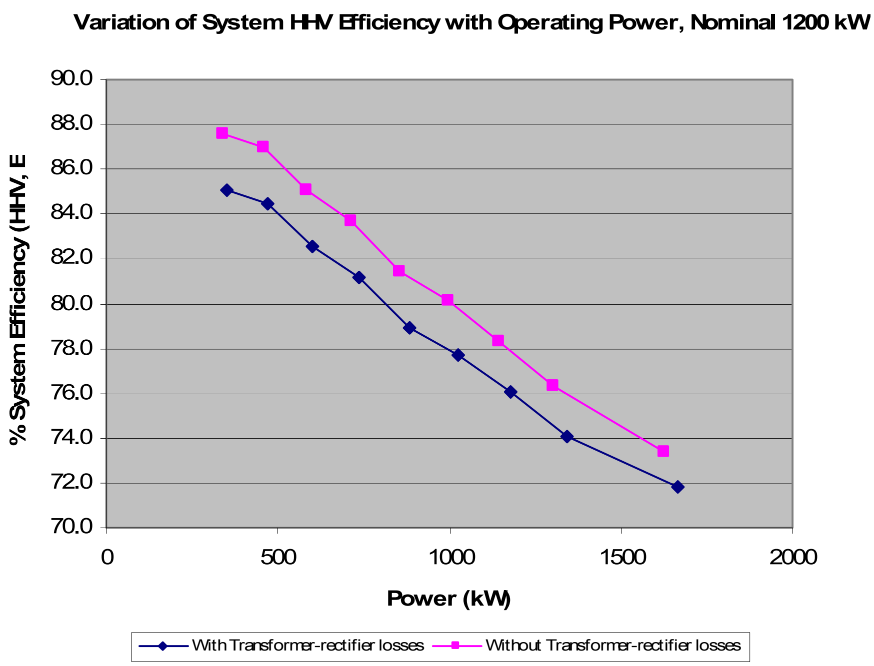


Figure 13. Electrolyzer energy conversion efficiency vs. operating capacity, year 2010 technology. Power electronics (PE) sharing between wind generator and electrolyzer could eliminate a large part of the transformer-rectifier subsystem capital cost and ~ 3% energy loss (difference between the two curves, above).

3.7 MATERIALS CHALLENGE: HYDROGEN EMBRITTLEMENT

Hydrogen gas can compromise the structural integrity of high-pressure containment or delivery systems [6]. In particular, the interaction between hydrogen gas and surface flaws can promote failure of pressurized steel structures [7]. Hydrogen interacts with material at the tip of a flaw and can cause embrittlement by one of several well-established mechanisms [6, 8] : Figure 15. 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 hydrogen embrittlement 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 [6, 9] . 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.

Fracture Mechanics Methodologies

Pipeline wall stresses generated from either static pressure or pressure cycling can cause hydrogen-assisted flaw propagation. The fracture mechanics property relevant to static pressure loading is K_{IH}, which is a material- and environment-dependent value of the stress-intensity factor. The fracture mechanics property used for pressure cycling, or fatigue loading, is the crack growth increment per cycle *vs* stress-intensity factor range, $(da/dN)_H$ *vs* ΔK. This relationship also depends on material and environmental variables.

Damage-tolerant design using fracture mechanics is illustrated for the case of static pressure loading. Figure 14 shows results from a fracture mechanics analysis applied to pipelines relevant to this study. The plots in Figure 14 show maximum flaw depths *vs* values of the fracture mechanics property, K_{IH}, similar to those in Reference 6. The pipeline materials, operating pressures, and pipeline dimensions assumed in the calculations are summarized in Table 5. The surface flaws were assumed to be planar, semi-elliptical in shape, and have two possible orientations: flaw plane parallel to the pipe axis and flaw plane parallel to the pipe circumference. (Such flaws could result from incomplete fusion during seam welding and girth welding, respectively.) The semi-ellipse is oriented with the minor radius as the flaw depth and the major diameter in the surface of the pipe; the ratio of minor radius-to-major diameter is 1:10. Flaws located on both the interior and exterior surfaces were considered. Figure 15 is a schematic showing the depth dimension of an axial flaw on the inner surface of a pipeline. The relationships between K_{IH} and flaw depth in Figure 14 were calculated from stress-intensity factor solutions for semi-elliptical flaws in hollow cylinders [10] .

The significance of the plots in Figure 14 is as follows. A maximum allowable flaw depth is associated with each value of K_{IH}; pipeline flaws that are smaller than the allowable flaw size will not propagate under static pressure loading, while pipeline flaws that exceed the allowable flaw depth can ultimately propagate through the wall.

Figure 14 reveals that the maximum allowable flaw depth is a function of flaw orientation, flaw location, pipe dimensions, and wall stress. By comparing maximum allowable flaw sizes at fixed K_{IH}, the following conclusions are established:

- Pipelines can tolerate larger circumferential flaws compared to axial flaws.
- Flaws on the interior and exterior of the pipeline have approximately equal impact. (An important assumption for this conclusion is that material at the interior and exterior has the same K_{IH}.)
- Larger flaws can be tolerated in the 36 in diameter pipe compared to the 20 in diameter pipe. This results from the greater wall thickness of the 36 in diameter pipe.

- Larger flaws can be tolerated in X-60 pipe compared to X-80 pipe. This results from the lower wall stress and greater wall thickness of the X-60 pipe. (An important assumption for this conclusion is that the two materials have the same K_{IH}.)

Fracture mechanics analyses such as that illustrated in Figure 14 depend on the availability of K_{IH} values. However, fracture mechanics data for steels in high-pressure hydrogen gas is extremely limited [11, 12, 13]. In addition, data must be used selectively since K_{IH} can depend sensitively on material, environmental, and mechanical variables. Conditions used to measure K_{IH} values must replicate the service conditions. The effects of numerous variables that must be considered in establishing K_{IH} are described in the next section.

Fracture mechanics analyses can be conducted for fatigue loading as well. Fatigue loading must be considered when the pipeline is subjected to pressure cycling, particularly since flaws can propagate under lower applied K levels compared to static loading. Fatigue analysis predicts the growth of a small postulated flaw, e.g., existing flaw depth equal to 5% of the wall thickness, as a function of the number of loading cycles. This calculation is conducted using the $(da/dN)_H$ *vs* ΔK relationship for the relevant material and environment. The critical design parameter is the number of cycles required for the small postulated flaw to grow to the maximum allowable flaw depth calculated from K_{IH}, e.g., Figure 14. Similar to fracture mechanics calculations using K_{IH}, analyses of fatigue crack growth depend on the availability of $(da/dN)_H$ *vs* ΔK data. Detailed guidance on fracture mechanics analyses for both fatigue loading and static loading are contained in the ASME Boiler and Pressure Vessel Code Section VIII, Division 3.

Effect of Variables on K_{IH} and $(da/dN)_H$ vs ΔK

Values of K_{IH} and $(da/dN)_H$ vs ΔK relationships are not fixed for a given material; these fracture properties can be a sensitive function of environmental, material, and mechanical variables. Data demonstrating the effects of numerous variables on K_{IH} and $(da/dN)_H$ *vs* ΔK for steel are presented below. Only limited data exists for pipeline steels in hydrogen gas, so many of the effects are illustrated using hydrogen-assisted fracture data for similar steels. The effects of variables are primarily demonstrated for K_{IH}, although many of the variables impact $(da/dN)_H$ *vs* ΔK in a similar fashion.

Several environmental variables affect hydrogen-assisted crack extension in steels, including hydrogen gas pressure, temperature, and gas impurities. Figure 16 shows the typical effect of hydrogen gas pressure on K_{IH}; i.e., K_{IH} decreases as hydrogen gas pressure increases. Although the data in Figure 16 are for low-alloy pressure vessel steels [12], a similar trend was measured for pipeline steels [11]. Additionally, data for the low-alloy steel 4340 in Figure 17 shows that K_{IH} is nearly constant between –40 ^{o}C and room temperature [14] . In contrast, K_{IH} increases three-fold between room temperature and 100 ^{o}C. The dependence of K_{IH} on temperature is expected to follow similar trends for pipeline steels. Finally, certain gas impurities can inhibit hydrogen-assisted fracture in steels. Figure 18 demonstrates the dramatic effect of oxygen on hydrogen-assisted fracture in H-11 steel [15] . The plot in Figure 18 shows that crack extension in hydrogen gas is halted by the introduction of oxygen into the environment. Replacing the gas with pure hydrogen allows the crack to continue propagating. Similar effects were reported for hydrogen-assisted fracture in pipeline steels [11]. Other impurities, such as CO and CO_2, have inhibiting effects similar to oxygen [16]. The inhibiting effect may be governed by the absolute partial pressure of impurities in the hydrogen gas; small concentrations of impurities may affect crack extension at high hydrogen gas pressures but not at low pressures [16]. Gas impurities likely hinder the adsorption of hydrogen on steel surfaces, which precludes uptake into the metal [15,16].

The material variables that significantly impact hydrogen-assisted fracture in steels include yield strength, composition, and processing history. Figure 19 illustrates the well-known effect of material yield strength on K_{IH} [12]; as strength increases, K_{IH} decreases. The data in Figure 19 are for low-alloy pressure vessel steels, but a similar trend is expected for pipeline steels. The effect of alloy composition, specifically, concentrations of Mn, Si, P, and S, on K_{IH} in the low-alloy steel 4340 is demonstrated in Figure 20 [17]. The compositions of the steels identified in Figure 20, e.g., B1, 841, etc., are summarized in Table 6. The results in Figure 20 and Table 6 show that K_{IH} is governed by concentrations of Mn and Si in the steels; K_{IH} decreases as concentrations of Mn and Si increase. Although pipeline steels contain significant concentrations of Mn and Si, it is not conclusive that K_{IH} will be affected by these elements similar to the trend in Figure 20. Finally, one of the most important variables to consider is material processing history, in particular changes in material microstructure due to welding. Results for pipeline steels show that K_{IH} in the weld heat-affected zone can be lower than K_{IH} in the base metal [11].

Structural loading variables can affect hydrogen-assisted fracture in steels. One of the important variables affecting $(da/dN)_H$ *vs* ΔK relationships is the frequency of loading. Figure 21 shows the effect of loading frequency on $(da/dN)_H$ *vs* ΔK for the pipeline steel SA-105; as the loading frequency decreases, the crack growth rate increases.

The K_{IH} and $(da/dN)_H$ *vs* ΔK properties can be measured for pipeline steels under the relevant environmental, material, and mechanical conditions using existing testing standards. Such standards include ASTM E1681 for measuring K_{IH} and ASTM E647 for measuring $(da/dN)_H$ *vs* ΔK.

Materials Challenge Summary

Hydrogen embrittlement 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. The analysis presented in Figure 14 shows that 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.

Table 5. Pipeline parameters used in fracture mechanics calculations

Material	Yield Strength, S_y (psi)	Pressure, p (psi)	Design Factor, F	O.D. (in)	*Wall Thickness, t (in)
X-60	60,000	1500	0.72	20	0.46
X-60	60,000	1500	0.72	36	0.83
X-80	80,000	1500	0.72	20	0.35

*Wall thickness (t) was determined from the operating pressure (p), pipe diameter (d), yield strength (S_y), and class location design factor (F), i.e., $t = pd/2S_yF$. Calculations employed the maximum design factor of 0.72, which yielded the lowest value of wall thickness.

Table 6. Compositions of steels in Figure 20

Steel	Mn (wt%)	Si (wt%)	P (wt%)	S (wt%)
B7	0.007	0.002	0.003	0.003
840	0.020	0.010	0.014	0.003
843	0.090	0.010	0.012	0.005
842	0.020	0.270	0.0036	0.005
846	0.230	0.010	0.009	0.005
841	0.720	0.010	0.008	0.005
B2	0.680	0.080	0.009	0.016
B6	0.720	0.320	0.003	0.005
B1	0.750	0.200	0.006	0.004

3.8 SYSTEM OPTIMIZATION

3.8.1 TOPOLOGY At GW scale, if operating from a single AC or DC bus, KOH-type electrolyzers can most economically be arranged in "star" modules, sharing electrolyte circulation and gas cleanup piping: Figure 22. 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.

3.8.2 COMPONENT CAPACITY: SYSTEM OPTIMIZATION SIMULATION Figures 23-25. Using a 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:

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

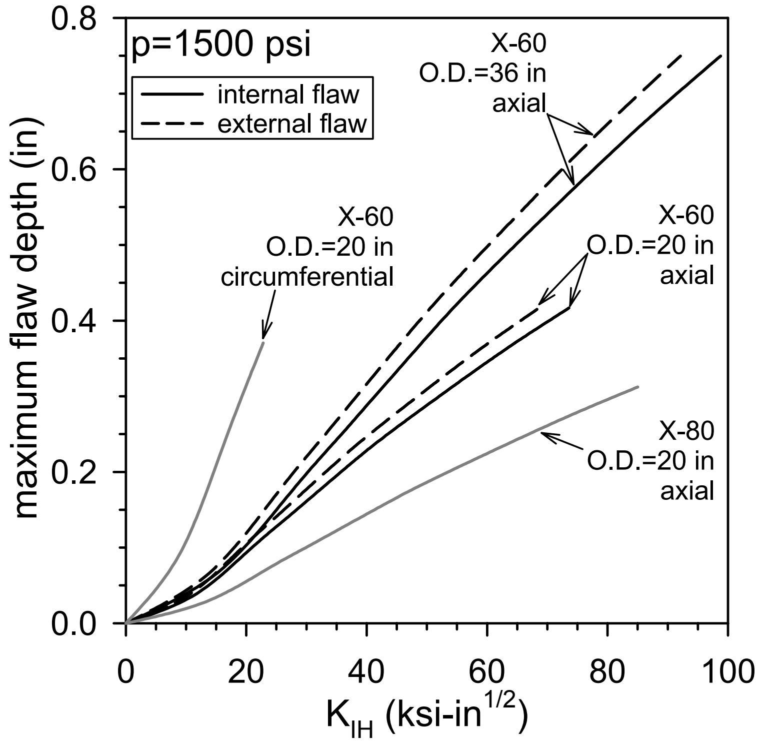


Figure 14. Plots of maximum allowable flaw depth *vs* critical stress-intensity factor, K_{IH}, for different pipe dimensions, materials, flaw orientations, and flaw locations.

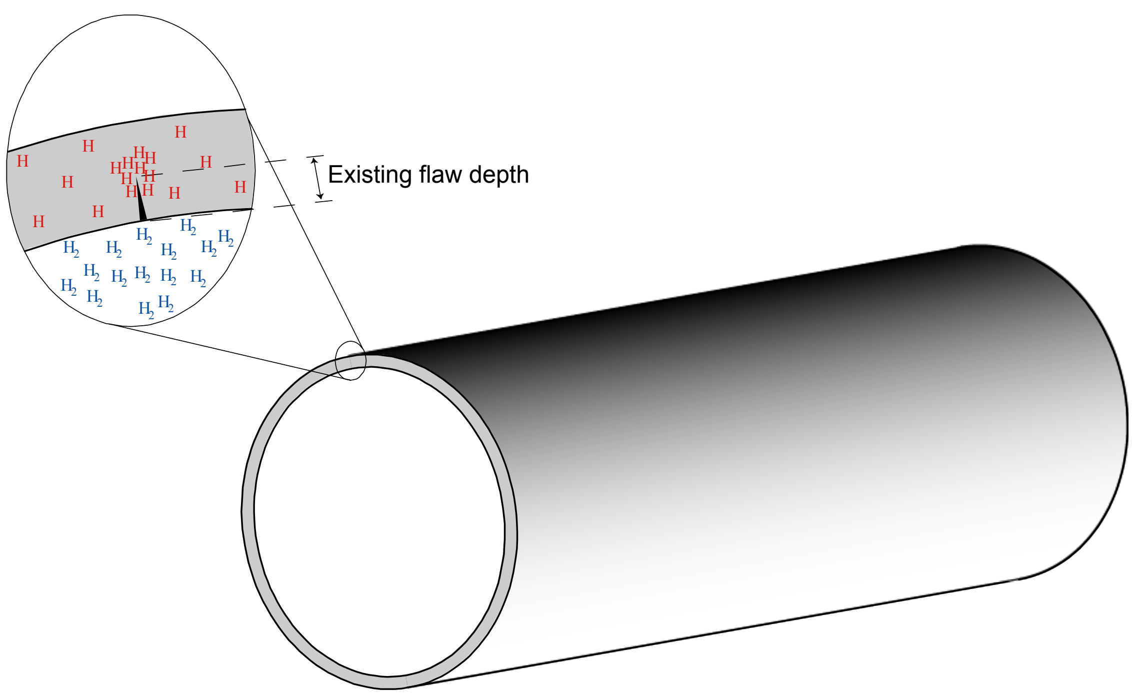


Figure 15. Schematic showing the depth of a flaw oriented along the axis of a pipeline transporting high-pressure hydrogen gas.

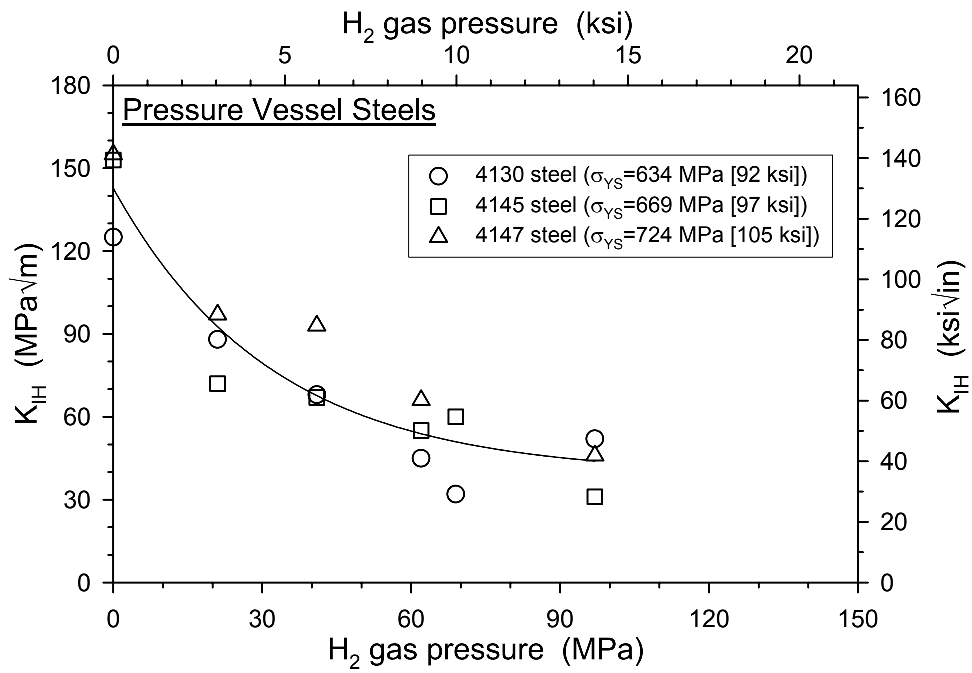


Figure 16. Effect of hydrogen gas pressure on K_{IH} in low-alloy pressure vessel steels. (after Ref. 12)

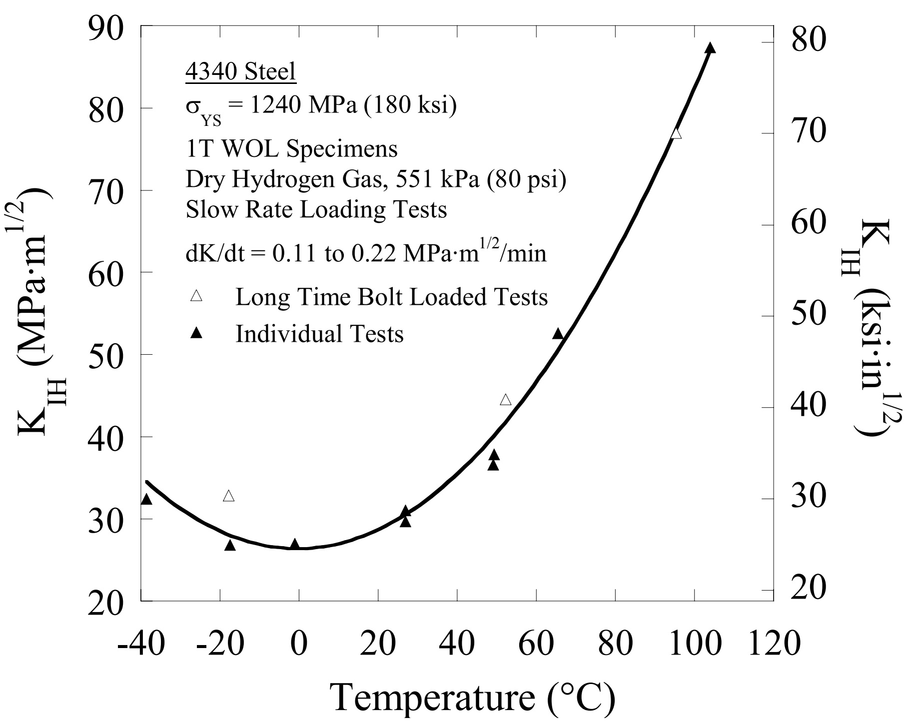


Figure 17. Effect of temperature on K_{IH} in the low-alloy steel 4340. (after Ref. 14)

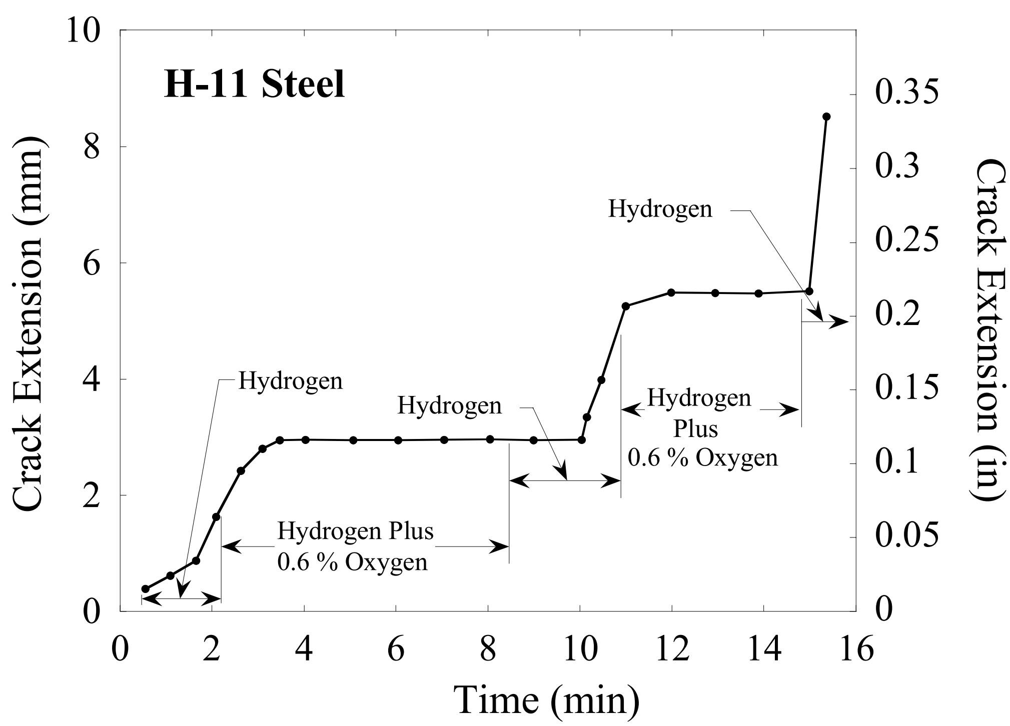


Figure 18. Effect of oxygen on hydrogen-assisted crack extension in H-11 steel. (after Ref. 15)

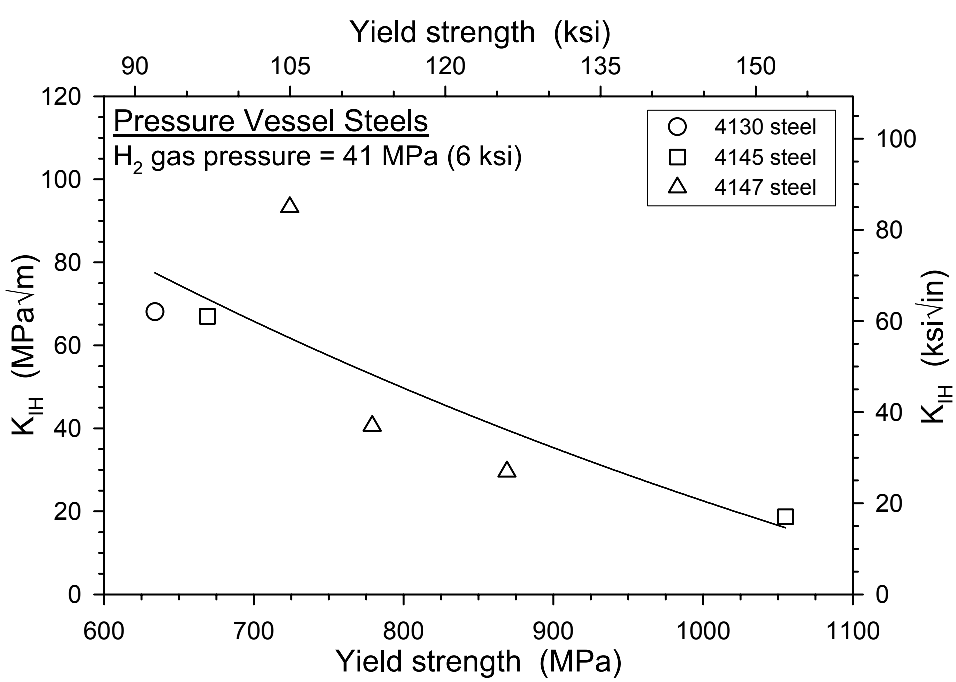


Figure 19. Effect of yield strength on K_{IH} in low-alloy pressure vessel steels. (after Ref. 12)

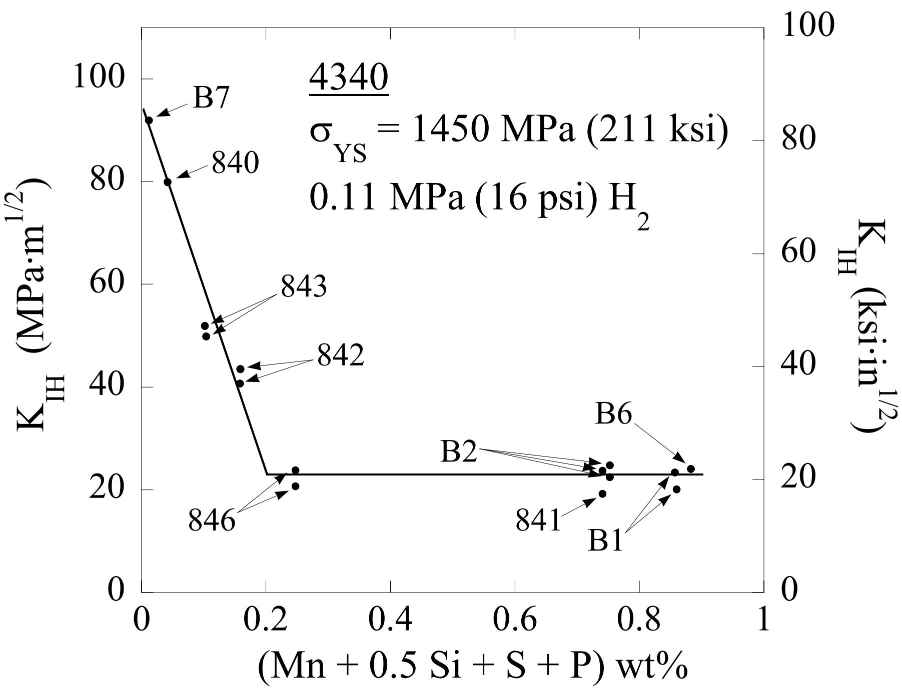


Figure 20. Effect of Mn, Si, S, and P content on K_{IH} in the low-alloy steel 4340. (after Ref. 17)

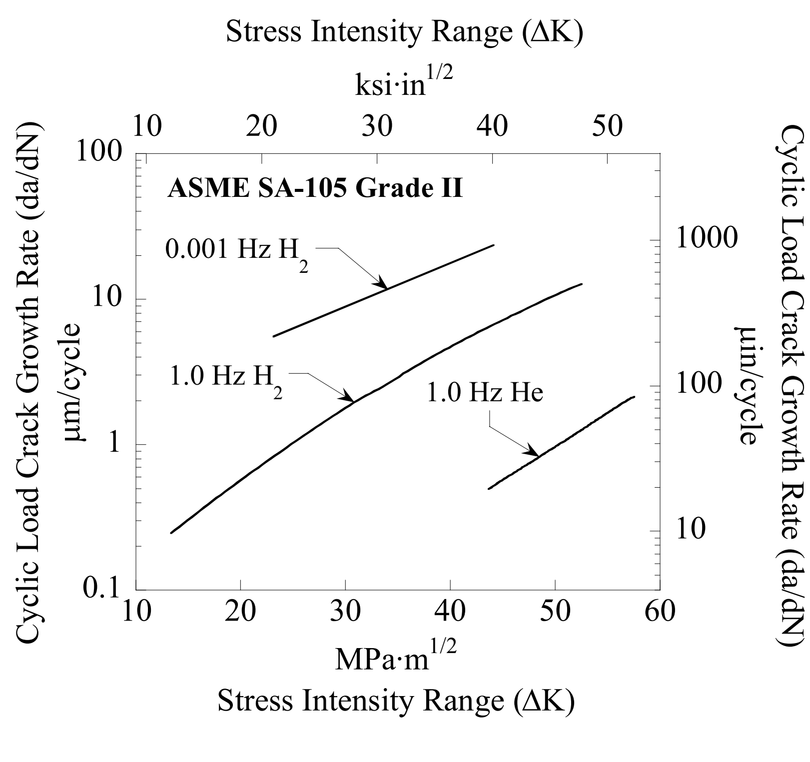


Figure 21. Effect of loading frequency on the $(da/dN)_H$ *vs* ΔK relationship for the pipeline steel SA-105. (after Ref. 13)

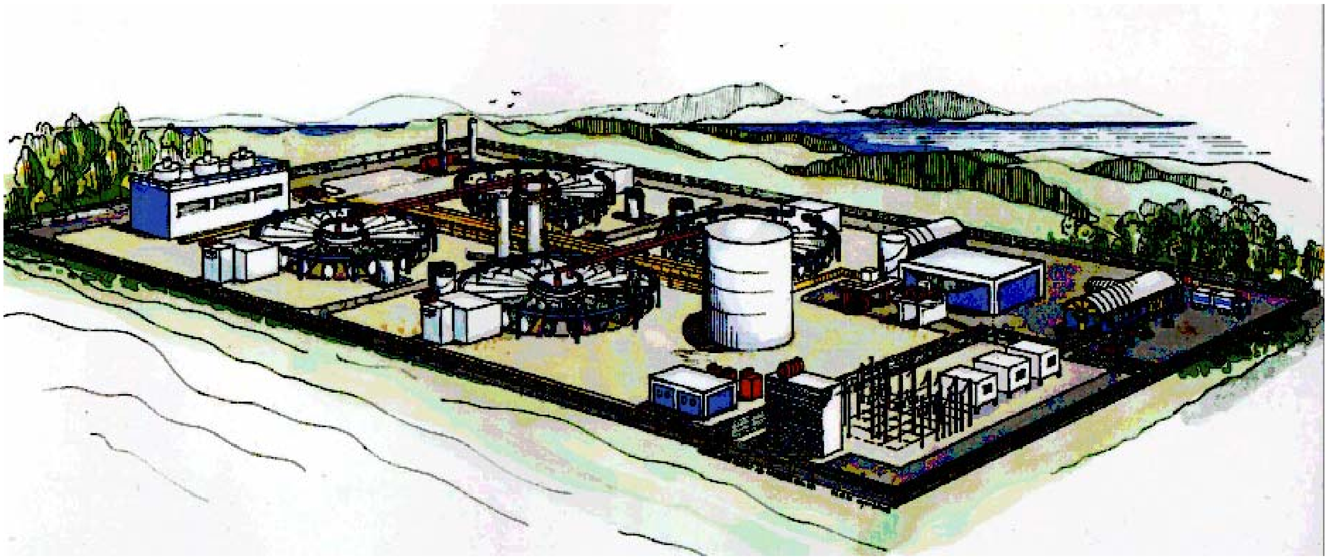


Figure 22. 265 MW electrolyzer plant, a proposed candidate configuration of four "star" modules of individual electrolyzers. Plant contains 96 electrolyzers, each with 230 cells @ 2.0 vdc in series; current is 6,000 A, 2.76 MWe input per electrolyzer.

Optimum electrolyzer capacity is difficult to estimate, because of the stochastic nature of the wind energy resource. Figure 13 shows that electrolyzers may be operated above their rated capacity at an energy conversion efficiency penalty, but at reduced duty cycle to avoid overheating the electrolyzer system. We have applied this operating range limit to our model, which requires the electrolyzers to operate above nominal rating ~ 10% of the time:

- Minimum 360 kW 82.9 % efficiency
- Nominal 1,200 kW 75.8 % efficiency
- Maximum 1,620 kW 73.3 % efficiency

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 IRHTDF (Sections 4.8 and 5.6) will be necessary to guide more valid and accurate modeling of the wind generator-electrolyzer subsystem.

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 utilization factor (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 utilization (CF) of electrolyzers and pipeline. For windplant-to-electricity transmission, Cavallo has proposed system optimization to enhance transmission CF and increase firmness of supply by "oversizing" the windplant and by using compressed air energy storage (CAES) [18, 19].

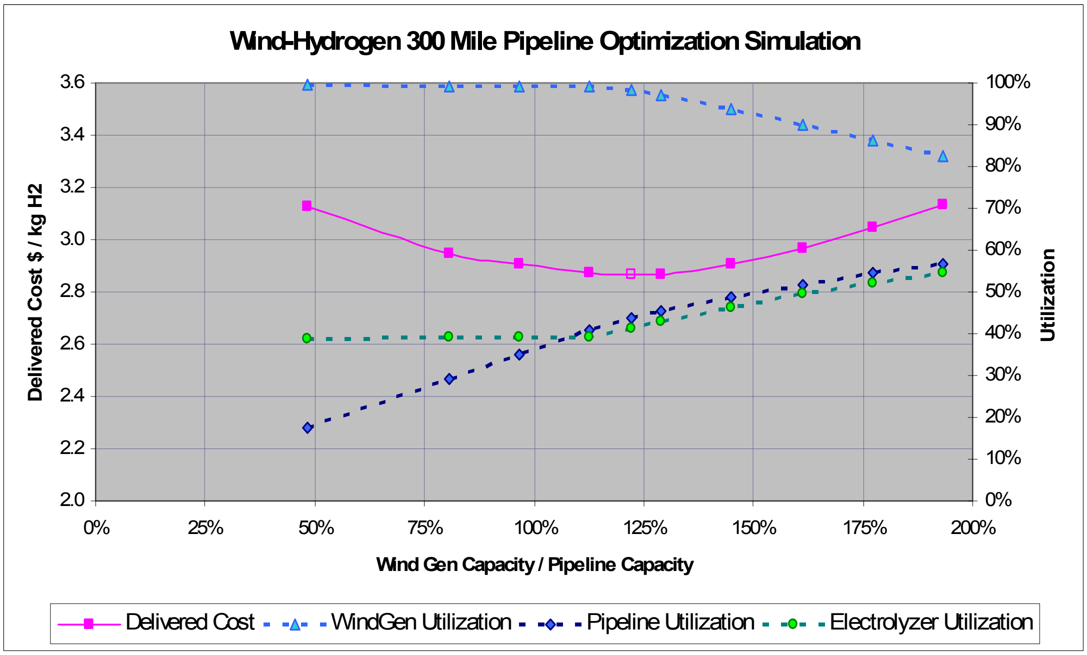


Figure 23. Wind - hydrogen pipeline system optimization simulation: unsubsidized; 300 mile long GH2 transmission pipeline. Wind generators, electrolyzers, and 300 mile transmission pipeline system. Optimal point is where the maximum wind capacity slightly exceeds the maximum pipeline capacity. This "wastes" some wind energy but increases the utilization of the electrolyzers and pipeline.

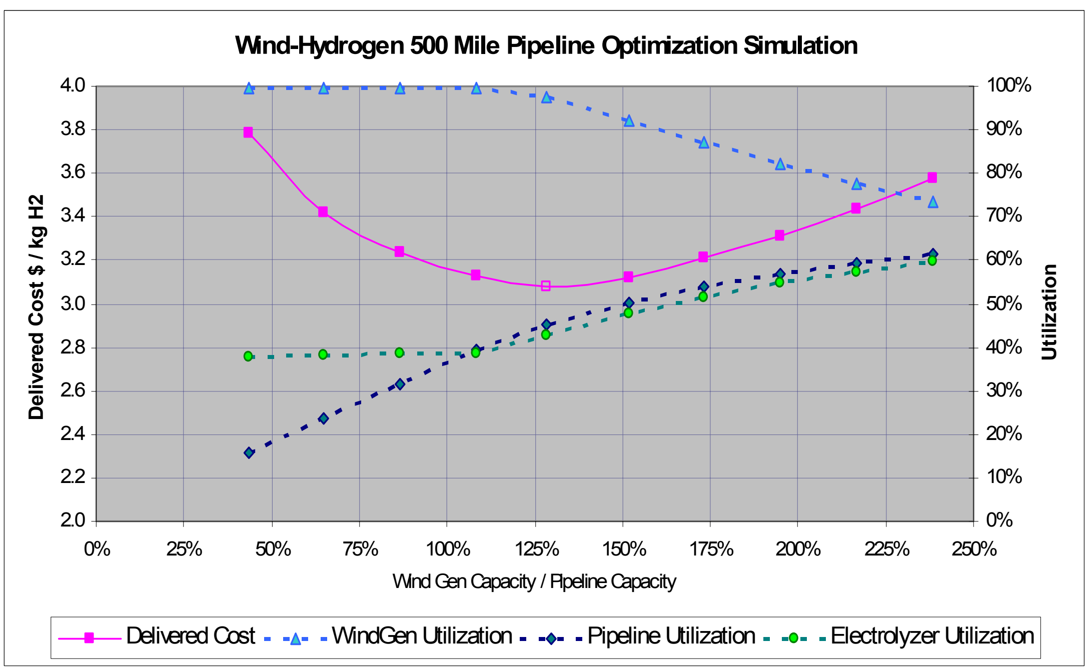


Figure 24. Wind - Hydrogen Pipeline System Optimization Simulation: unsubsidized; 500 mile long GH2 transmission pipeline. Wind generators, electrolyzers, and 500 mile transmission pipeline system.

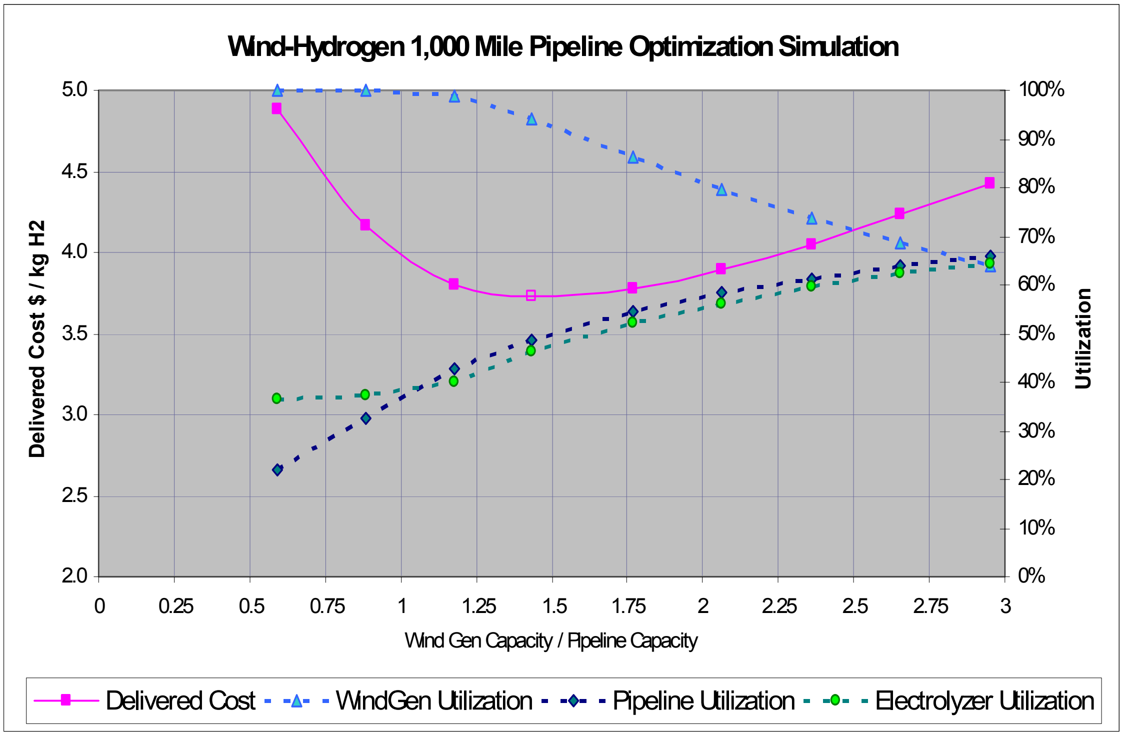


Figure 25. Wind - Hydrogen Pipeline System Optimization Simulation: unsubsidized; 1,000 mile long GH2 transmission pipeline. Wind generators, electrolyzers, and 1,000 mile transmission pipeline system.

3.9 ENERGY STORAGE AS GH2

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. 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, because storage allows them to sell more of their NG during peak periods, when prices are higher.
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.

3.9.1 GH2 STORAGE IN PIPELINE

A long pipeline could provide a significant amount of storage capacity. Table 7 shows storage capacity in a 500-mile-long pipeline would range from 10 GWh (a 20" pipeline operating between 300 and 600 psi) to 107 GWh (a 36" pipeline operating between 500 and 1500 psi).

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.

Table 7: Energy storage as compressed GH2 in pipeline.
*Energy Storage, Days: Number 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 psi	Delivery Press psi	Energy Storage Nm3 x 10^6	Energy Storage MMscf	Energy Storage Tons	Energy Storage GWh	Energy Storage Days *
800	20	146,338	1,500	500	10	352	936	33	3.5
800	36	468,605	1,500	500	32	1,126	2,997	107	11.2
800	20	146,338	600	300	3	105	281	10	1.0
800	36	468,605	600	300	10	338	899	32	3.3
1,600	20	292,675	1,500	500	20	703	1,872	67	7.0
1,600	36	937,209	1,500	500	64	2,251	5,994	214	22.3
1,600	20	292,675	600	300	6	211	562	20	2.1
1,600	36	937,209	600	300	19	675	1,798	64	6.7

3.9.2 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 (200-500 psi) than required for pipeline transmission, the cost of required pipeline input compression may defeat this value.

3.9.3 GH2 STORAGE IN END-USER DEVICES

Ground vehicle and aircraft fuel tanks, and 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 smooth the wind farm output, because pipeline storage is relatively small.

3.9.4 GH2 STORAGE IN GEOLOGIC FORMATIONS

Low-cost, seasonal-scale, storage is needed for renewable-source GH2, as it is for NG. Solution-mined salt caverns are GH2-tight to > 1,000 psi, but these formations are rare; most are man-made. The US stores helium beneath an aquifer in Texas. Similar aquifers may be abundant and GH2-tight. This resource needs exploration and assessment, given the potential to firm, and render dispatchable, large, indigenous, clean energy sources of inherently time-varying output. In Tees County, UK, >1,000 tons of GH2 is stored in several solution-mined salt caverns, for industrial use. [21] The ChevronPhillips cavern has been in service over 20 years, storing ~ 2,500 tons of GH2 at up to 2,000 psi.

Using the numbers from "Seasonal Variability of Wind Electric Potential in the United States" [22], 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 would be 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 (~600 kWe input) 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, that is apparently 1.34 TWh of GH2 storage needed. The latter case is more relevant.

A 1,000 mile 36" diameter GH2 pipeline, packed to 1,000 psi and unpacked to 500 psi, stores ~120,000 MWh = 120 GWh = 0.12 TWh. Packed to 2,000 psi, unpacked to 1,000 psi, it would store twice as much = 0.24 TWh. GH2 transmission pipelines are likely to operate at 1,500 - 2,000 psi, with city-gate delivery at ~500 psi. 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: 1.42 - 0.12 = 1.3 TWh.

- 1 MWh = 10,500 scf; 1 TWh = (10,500 scf) x 10^6 = 10.5 x 10^9 scf;
  1.3 TWh = 13.6 x 10^9 scf of GH2
- 1 kg H2 = 375.6 scf
- (13.6 x 10^9 scf) / 375.6 scf / kg = 3.6 x 10^7 kg = 36 million kg = 36,000 metric tons (MT) of GH2

ChevronPhilips Clemens Terminal GH2 storage cavern (near Freeport, TX) characteristics: [23]

- Age is 20 years.
- Volume is 6.4 million cubic feet (580,000 m^3).
- "Useable capacity" is 2,500 MT; gross capacity is 5,300 MT.
- Maximum pressure is 2,200 psi; maximum operating
- Estimated capital cost, 2005 $US, is $5 million.
- Leakage rate unknown; probably very small.
- O+M cost is unquantified; probably small; some periodic and preventive maintenance (PM) required.

Thus, 36,000 MT/ 2,500 MT = 14 caverns are required @ $10 million capital cost each ($5 million construction + $5 million for “cushion gas”) = $140 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 1,500 - 2,000 psi input to 500 psi delivery at city-gate end of pipeline, and if the cavern can endure the lower pressure.

Total capital cost of a 4,000 MW windplant with a 500 mile GH2 transmission pipeline would be:

Wind generators @ $1,000 / kW, installed	$4,000 million
Electrolyzers @ $500 / kW, installed	$2,000 million
1,000 mile 36" Pipeline	$2,700 million
14 GH2 storage caverns	$ 70 million
“Cushion gas” in 14 variable-pressure caverns	$ 70 million (“Cavern manage”)
TOTAL	$8,840 million

Cavern storage fraction of total = $140 / $8,840 = 1.6 %

4,000 MW would be a very large windplant, fully realizing economies of scale. Total installed wind generation nameplate capacity, by end of 2005, will be:

USA ~ 5,000 MW;
World ~ 50,000 MW.

Cost of energy storage in the assumed 6.4 million cubic ft GH2 cavern: (MT = metric ton = 1,000 kg):

Capital:	$10 million / [“useable capacity” = 2,500 MT]	= $4,000 / ton GH2
	(1 MT = 35.8 MWh):	= $112 / MWh

Energy: Depends on cycling dynamics of GH2 into and out of the cavern; Assumes no compressors in the system; 100 bar output electrolyzers feed pipelines and storage caverns directly.

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.[24] With 14 caverns per 4,000 MW, or ~4 caverns per 1,000 MW, about 12,000 caverns like the ChevronPhilips Clemens Terminal cavern would be needed. This storage requirement would probably be reduced by synergistic harvest and transmission of GH2 from diverse Great Plains renewables, as proposed in the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) concept. Figure 29 shows the distribution of salt deposits in USA; not all will be suitable for GH2 storage caverns. Figure 30 shows extant caverns in Texas, primarily for NG.

3.10 MARKETS AND FIRMING FOR WIND-GENERATED GH2 FUEL

The most attractive markets for wind-generated hydrogen in the near term are the traditional industrial and commercial markets, given the higher value of hydrogen in these markets than in commodity energy markets. Typically, hydrogen is produced by large steam methane reformers (SMR), which can generate hydrogen at no less than 50-60% higher than the cost of the natural gas feedstock.

This storage capacity could benefit the wind plant by allowing it to sell more energy on a "firm" basis than if the energy were transmitted via power lines: Table 7 and Figures 26-27. "Firm" refers to contract terms under which the seller guarantees delivery of the energy (and must procure energy in the market if he cannot generate it). Buyers pay more for firm energy than for non-firm energy.

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; Sections 4.8 and 5.6. 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. Wind generators would not be able to count on the storage capacity, making firm contracts for hydrogen sales risky.

As shown in Figures 26-28, 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" gas and electricity tariffs. The owner of the windplant-pipeline project would have two options for firming the hydrogen: storage and firming purchases.

Hydrogen storage could occur anywhere along the pipeline path. Storage options include:

1. Underground storage – using suitable underground reservoirs, hydrogen can be stored in volumes up to 10^{10} standard cubic feet (scf).
2. Liquid storage – typically used for the storage and distribution of large volumes of hydrogen today, where pipelines are not available. Liquid production systems are typically sized for 10^6 to 10^7 scf per day, with a liquid trailer delivering approximately 1-2 x 10^6 scf.
3. Hydrogen tube trailer storage – typically used for delivery of lower volumes of hydrogen to industrial and commercial customers. Typically, tube trailers operate at up to 2,300 psia with volumes of 1-2 x 10^5 scf.

In addition to large-scale storage as part of the pipeline project, the pipeline company could target customers with storage capacity. Large tanks at transportation fueling facilities (like the underground tanks used at gas stations today) represent one option for customer-site storage.

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 the company had hydrogen tank trucks and could take the gas directly from production plants, it might pay a wholesale price. If it took the gas 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.

Thus, 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. Because NG demand is heavily driven by space heating, spot market gas prices are higher during the winter than the summer, and they can be extremely high in the coldest periods of the winter.[25] A much smaller portion of hydrogen would probably be used for space heating than is currently the case with NG, because transportation is expected to be a major hydrogen demand driver. In other words, 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 a simple matter to determine the lower-cost firming strategy.

Additional large-scale sources of hydrogen generation might include:

1. Coal gasification, with carbon capture and sequestration (CCS);
2. Electrolysis, ideally from hydroelectric, photovoltaic and concentrated solar power (CSP), or nuclear-source electricity, for near-zero C-emissions;
3. Thermal, from solar radiation or nuclear.

For the use of the wind-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, 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 can avoid the onerous task 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, Netherlands. [26] [27]

4. CONCLUSIONS

Figure 6. With various "value-adders", wind-source GH2 may be delivered to distant markets, 200 to 1,000 miles distant, at an untaxed wholesale energy unit cost apparently competitive with:

- hydrogen fuel made from NG by SMR;
- gasoline, 2005 price.

Figures 26-28. Pipeline energy storage smooths windplant output variations at time scales of minutes to days, but is probably inadequate to "firm" windpower to command full wholesale market price at the city gate. However, low-cost, seasonal-scale, geologic storage of GH2 could theoretically firm wind energy, adding significant value. Such storage remains technically unexplored and unproven in the Great Plains.

Line pipe materials must be tested and selected, and other measures taken, to control the critical phenomenon of H2 embrittlement of steel.

Assuming that 1,500 psi 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.

For the 20" diameter, 1,500 psi, GH2 pipeline assumed here, optimum windplant capacity, for minimum cost of GH2 fuel delivered to the city gate, is 1.5 GW (for 1,000 mile pipeline) to 3.5 GW (for 200 mile pipeline).

To better understand the economics of the windfarm-electrolyzer-pipeline system, we performed several simulation analyses using hourly wind data. A sample of these results is shown in Figures 23-25. 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 utilization factor of the system.

Our research for this paper will not adequately inform the energy industry about future hydrogen markets (particularly the annual price profile) to be able to say anything quantitative about firming the supply. 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. The remaining challenge is determining whether storage or spot purchases is the lower-cost firming option for wind-source GH2 fuel.

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 hydrogen gas, as an International Partnership for the Hydrogen Economy (IPHE) project: the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF). [28] 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 or no incremental capital cost, if:

- Fracture mechanics tests in hydrogen prove suitable line pipe material(s);
- The IRHTDF 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.

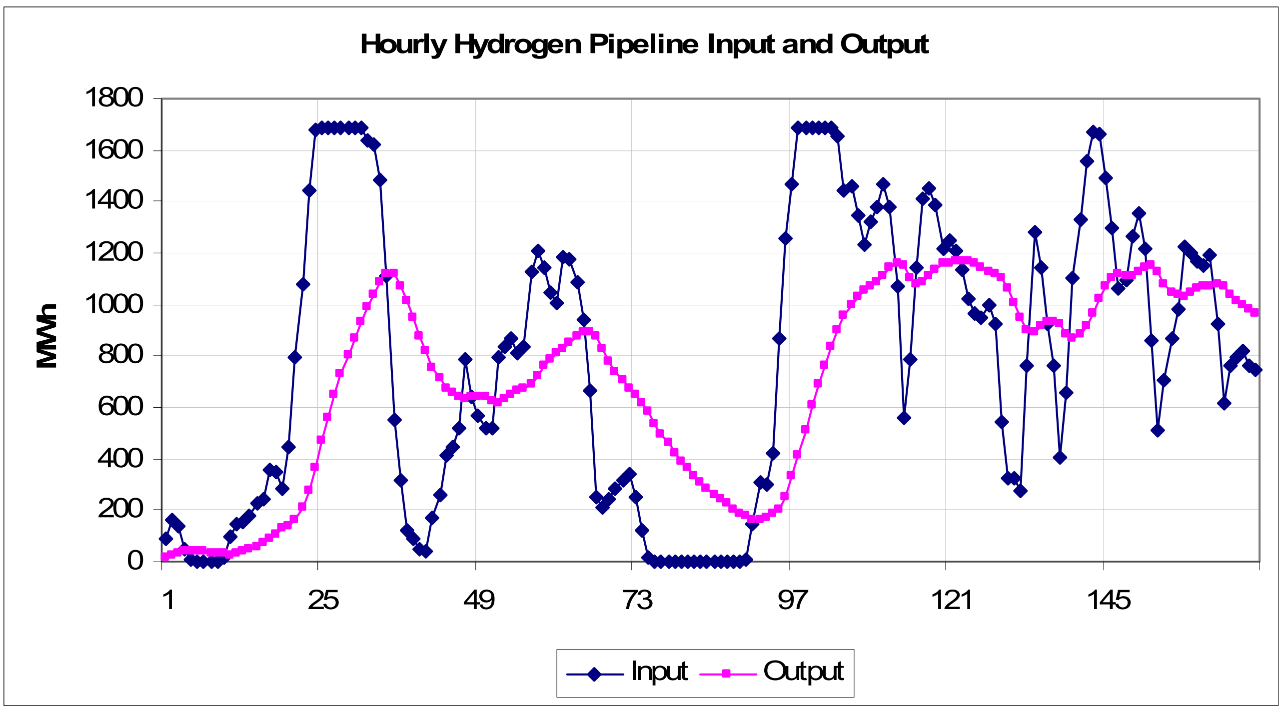
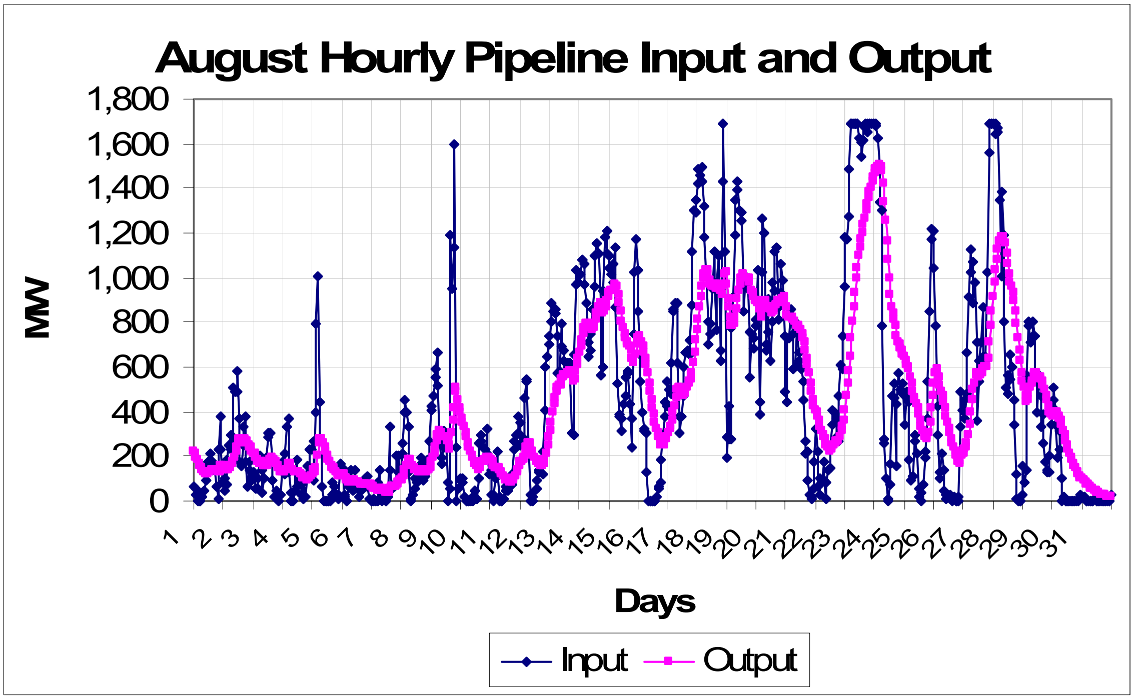


Figure 26. 500 mile pipeline, first week of September. The lag effect and pipeline transit time is about 22 hours. This smooths some of the hourly and shorter period wind generation variations. Input is limited at 1,700 MW by pipeline and electrolyzer capacity, which results in some lost wind energy via curtailed generation, but which results in greater long-term pipeline utilization factor (CF).



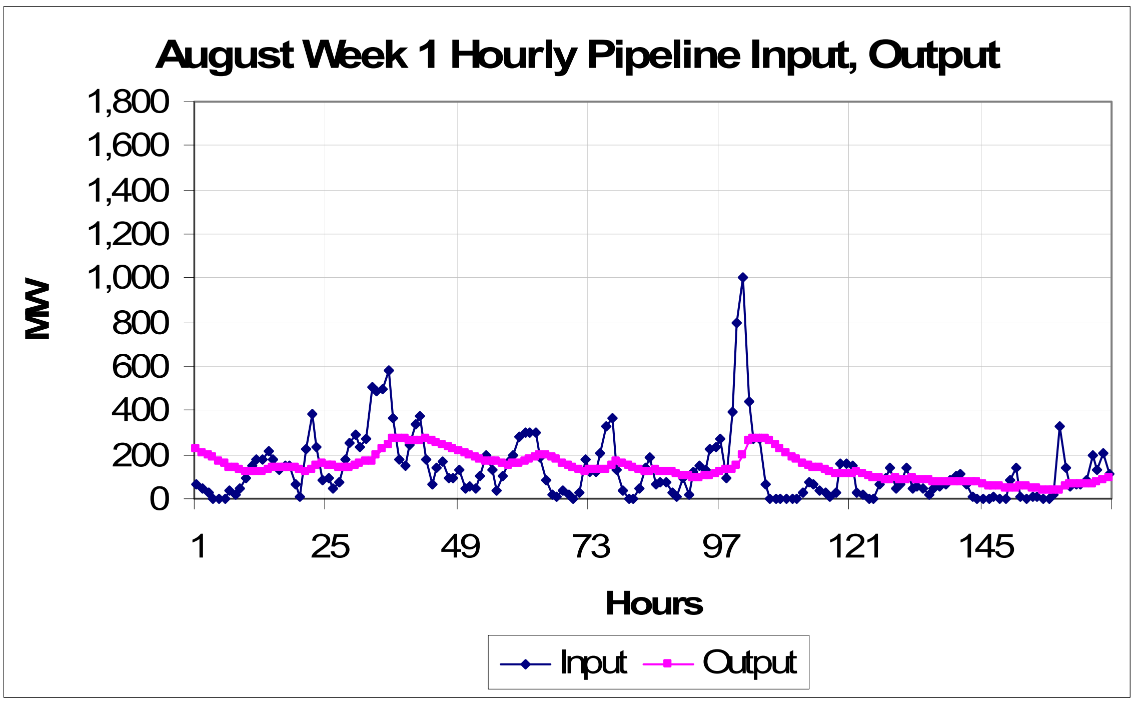


Figure 27. 500 mile pipeline: August month, and first week. The lag effect and pipeline transit time is about 22 hours. This smooths some of the hourly, and shorter period, wind generation variations. Note apparent minimal input limitation at 1,700 MW by electrolyzer capacity, 24-25 Aug, which results in a very small amount of lost wind energy via curtailed generation.

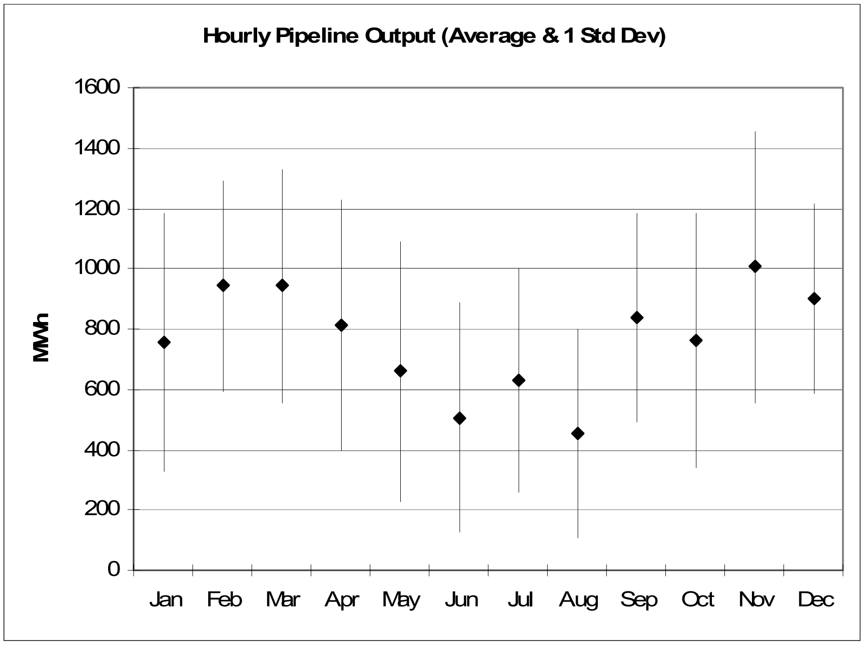


Figure 28. High variability in hour-to-hour delivery of H2 at the end of pipeline, with short-term smoothing provided by energy storage in pipeline. From year-long actual hourly output data from a northern Great Plains windplant.

5. RECOMMENDED FURTHER STUDY

5.1 LINEPIPE MATERIALS TESTING Composite Reinforced Line Pipe (CRLP)™ and X-65 "sour service" grade and are candidates for RHS. We propose testing both materials for accelerated fatigue life, in pressure cycling over a 2:1 range, to establish its "fitness of purpose" for large-scale (high-pressure, large-diameter) 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 ASME International Pipeline Conference (IPC04), Calgary, 4-8 Oct 04.[29]

5.2 SYSTEM OPTIMIZATION Further optimization simulation. 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 IRHTDF. We also need to more accurately estimate the economic value of pipeline energy storage, and that of potential large-scale geologic storage.

5.3 "FIRMING VALUE" Assess and estimate economic value of firming windplant output via strategies discussed in 3.10 and 5.2, above.

5.4 GEOLOGIC STORAGE 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 energy industry. If we could smooth windplant output at seasonal scale, to deliver a firm, dispatchable energy supply, we would greatly increase the usefulness and value of wind-generated energy. Specifically:

a. Geologists should prospect for subterranean formations capable of containing GH2 at 1,500 psi, for a year, with an acceptable loss rate;
b. Calculate the quantity of GH2 needed to completely "firm" 1 GW of Great Plains wind generation; what reservoir (formation) volume and projected surface land area is required, for 1 GW and for 10 GW.

5.5. ELECTROLYZER DUTY CYCLE AND OVERLOAD TOLERANCE 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. In real systems, the individual electrolyzers' control systems 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.

5.6 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). [30]

Figure 29. Large underground dry salt formations which may be suitable for solution mining, to create large GH2 storage caverns.

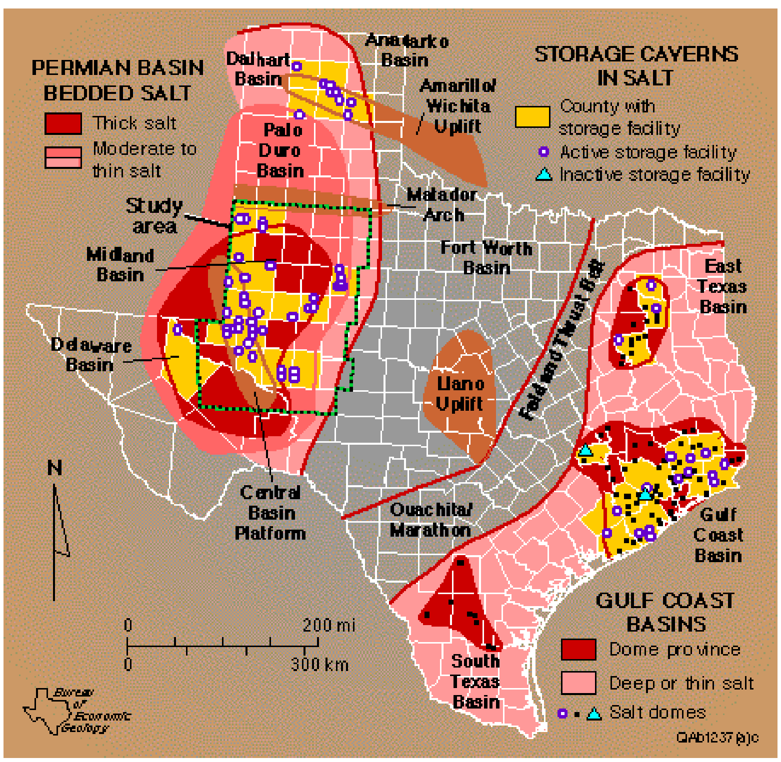


Figure 30. Extant storage caverns in “dome” and “bedded” salt in Texas. “Dome” salt deposits are thicker and more homogeneous than “bedded”.

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