A 1,000 MW WINDPLANT DELIVERING HYDROGEN FUEL FROM THE GREAT PLAINS TO A DISTANT URBAN MARKET

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ABSTRACT

We model a 1,000 MW (1 GW) (nameplate) windplant in the rich 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 300 km 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 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. We present a more complete analysis in a larger paper. [2]

1. INTRODUCTION

We imagine a transmission-constrained world, where large new windplants must pay all transmission costs for delivering their energy to distant markets.

Fig. 2. A 1,000 MW windplant produces about 200 MMscfd of GH2 at full output; 80 MMscfd at 40% average capacity factor (CF). It could deliver GH2 fuel 500 miles by pipeline for an unsubsidized price of $3.28/kg, assuming;

- Estimated year 2010 technology and costs, expressed in year 2005 $US;
- All wind energy is converted to GH2 and delivered via 20 inch diameter pipeline at 1,500 psi inlet and 500 psi delivery pressures, at distant urban market;
- No compressors, at pipeline inlet or midline;
- Capital Recovery Factor (CRF) of 15%;
- Average pipeline CF of about 15%;
- For a given diameter and pressure, GH2 pipelines can be built for same capital cost as for natural gas (NG), although serious line pipe materials challenges must be met: Section 7.

Given the low pipeline CF in this 1,000 MW scenario, the 20” pipeline would need to serve considerable additional windplant generating capacity to approach full CF.

Windplants are the lowest-cost new renewable energy sources. The largest and richest resources, with high average annual windspeed, are stranded in the North American 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 expect a large market for renewable-source hydrogen fuel in today’s nascent carbon-constrained world, for transportation and potentially for distributed generation of retail-value electricity on the customers’ side of the meter. GH2 pipeline transmission may offer important technical and economic advantages and synergies vis-à-vis electric transmission, at large scale: [3]

- Adding value to wind generation assets by “firming” their energy output with energy storage;
- Sharing power electronics between wind generation and electrolysis systems saves substantial capital, O&M, and energy conversion loss costs; however, wind generation COE will not improve much by removing requirements to deliver grid-quality electricity. [4]

- Underground location of the GH2 transmission pipeline may be more socially acceptable and more secure from natural and human threats vis-à-vis overhead electric transmission lines.
- The oxygen byproduct of electrolytic production of hydrogen from wind-source electricity may be sold to adjacent biomass and coal gasification plants;
- Pipeline CF may be improved by synergistic sharing with diverse renewable GH2 sources in the same 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, 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.

We modeled pipeline performance using hydraulic equations standard in pipeline design practice. Pipeline diameter would be chosen to:

- Eliminate intermediate compressor stations, while delivering hydrogen fuel to the city gate at adequate pressure;
- Optimize system economics (CRF; IRR and NPV).
- Optimize the energy storage value via compressed hydrogen "packed" in the pipeline;

We estimate 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.

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). [5] This paper's analysis is applicable to large, diverse, stranded, renewable 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.

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

Table 3 estimates year 2010 technology and costs, expressed in 2005 $US, from industry consensus and USDOE goals. [6]

We recognize several possibilities for upstream energy storage:

- Hydrogen storage in underground geologic structures;
- Hydro reservoirs, but only if electricity grid available.

2. COE: COST OF ENERGY, AT END-OF-PIPE

Table 3; Fig. 4. We used a simple Capital Recovery Factor (CRF) model [7] by which we estimate the cost of renewable-source hydrogen fuel delivered to the distant city gate, from calculated cost per unit energy-distance for the assumed GH2 pipeline transmission systems. We analyzed three "value-added" cases and the "unsubsidized" case, for both 1 GW and 2 GW windplants, because Table 2 shows that the 20" pipeline has capacity for 2 GW. The delivered cost of energy (COE) would be reduced to about $1.46 / kg by the sum of these value-adding steps:

- US fed production tax credit (PTC), now $.018 / kWh;
- Byproduct oxygen sales to adjacent gasification plants;
- Carbon-emissions-offset credits or payments;
- Increase windplant to 2,000 MW.

3. GAS TRANSMISSION PIPELINE SYSTEMS

Pipelining GH2 costs approximately 1.3 to 1.8 times the NG cost because (a) the volumetric energy density of hydrogen is one-third that of methane; (b) hydrogen embrittlement of pipeline steel must be prevented and controlled: section 7.

Design and construction of a large, long-distance, high pressure hydrogen pipeline and conventional NG transmission lines are similar. Three 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:

- Pipeline utilization: CF
- Hydrogen embrittlement of line pipe
- Compression

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 CFs (about 40%) and intermittent 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.

4. GH2 COMPRESSION

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 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.

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. Fig. 3 is energy conversion efficiency at HHV for KOH.

6. GH2 ENERGY STORAGE

As demand for hydrogen grows, demand for hydrogen storage capacity will grow, to:

- Allow producers to meet peak demand levels in excess of production capacity. Large amounts of natural gas are produced (mined) and stored during the summer months for use in the winter, when demand is higher. With the storage capacity, the gas mining industry does not have to maintain mining capacity equal to peak winter gas demand. This lowers costs significantly. Seasonal fluctuations in the price of gas provide producers with the incentive to develop storage capacity, because storage allows them to sell more of their gas during peak periods, when prices are higher.
- Increase the utilization rate of expensive delivery infrastructure. As with natural gas, 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, i.e. CF.

6.1 GH2 Storage in Pipeline

Table 5. 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. "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.

A long pipeline could provide a significant amount of storage capacity. Table 5 shows storage capacity in an 800-km line would range from 10 GWhs (a 20" pipeline operating between 300 and 600 psi) to 107 GWhs (a 36" pipeline operating between 500 and 1500 psi).

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 the IRHTDF. The pipeline would need to maximize its utilization rate by receiving hydrogen from other producers in order to be economically viable. 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.

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.

6.2 GH2 Storage in Wind Generator Towers

NREL has investigated this potential. [8] 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.

6.3 GH2 Storage in End-user Devices

This would reduce peak demand, but it would not help smooth the wind farm output.

6.4 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.

7. MATERIALS CHALLENGES: H2 EMBRITTLEMENT

Today's large diameter, cross country NG pipelines are constructed from very high strength steel for which crack-arresting properties are a major design and material selection criterion. Higher steel strength reduces resistance to propagation of small cracks into large, dangerous cracks.

The crack propagation properties of the pipe material must be balanced against the pressure retaining strength of the material, in GH2 as well as in NG pipeline design.

Pipeline material would be chosen to resist hydrogen embrittlement in the severe cyclic loading of "renewables-hydrogen service" (RHS), accommodating large pressure fluctuations as windplant and other renewable-source-energy output power varies: Composite Reinforced Line Pipe (CRLP)™ and X-65 "sour service" grade are candidates. TransCanada Pipelines has proposed CRLP™ for hydrogen transmission. [9]

Hydrogen gas can compromise the structural integrity of high-pressure containment or delivery systems.[10] In particular, the interaction between hydrogen gas and surface flaws can promote failure of pressurized steel structures. [11] Hydrogen interacts with material at the tip of a flaw and can cause embrittlement by one of several well-established mechanisms. [10, 12] 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.

Structures containing flaws can be safely designed through the application of fracture mechanics. Flaw propagation is sensitive to the material-dependent, critical value of the stress-intensity factor, K_C. Flaws in pipelines can result from handling, corrosion, metallurgical defects, or welding. [10, 13] These flaws can be located on the interior and exterior surfaces of the pipeline.

Fig. 1 shows results from a fracture mechanics analysis applied to the pipelines described in Table 2. The plots in Fig. 1 show maximum flaw depths *vs* critical values of the stress-intensity factor, K_C, similar to those in Reference 10. The pipeline materials, operating pressures, and pipeline dimensions assumed in the calculations are summarized in Table 1. 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. The relationships between K_C and flaw depth in Fig.1 were calculated from stress-intensity factor solutions for semi-elliptical flaws in hollow cylinders. [14]

The significance of the plots in Fig. 1 is as follows. A maximum allowable flaw depth is associated with each value of K_C; pipeline flaws that are smaller than the allowable flaw size will not propagate, while pipeline flaws that exceed the allowable flaw depth will ultimately propagate through the wall.

Fig. 1 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_C, 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_C.)
- 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_C.)

The most severe limitation on the fracture mechanics-based design illustrated in Fig.1 is the availability of K_C for pipeline steels exposed to hydrogen gas environments. Few studies have measured K_C values for ferritic steels in high-pressure hydrogen gas. [15, 16, 17] The material, environmental, and mechanical conditions used to measure K_C values must replicate the service conditions, since K_C is sensitive to many variables including: material yield strength [16], processing history (e.g., welding) [15], and alloy composition [18], hydrogen gas pressure [16, 17]; hydrogen gas purity [19]; and loading mode (e.g., static loading *vs* fatigue loading). [15, 17] We propose materials testing on CRLP™ and X-65 that explores a range of variables, particularly fatigue loading and welding.

Although data is limited, exposure of pipeline steels to hydrogen gas is expected to decrease K_C and thus reduce the maximum allowable flaw depth compared to exposure to methane gas. Several approaches can be followed to maximize the allowable flaw depth in hydrogen gas pipelines. One approach is to maximize K_C. This can be accomplished through materials selection (e.g., materials with lower yield strength [16]) or possibly by altering the gas composition (e.g., adding small amounts of oxygen [19]). Another approach is to increase wall thickness or lower wall stress. The latter could be accomplished through the use of innovative materials systems such as CRLP™.

TABLE 1. PIPELINE PARAMETERS USED IN FRACTURE MECHANICS CALCULATIONS

Material	Yield Strength, S_y (psi)	Pressure, p (psi)	Design Factor, F	OD (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.

8. CONCLUSION

With various "value-adders", wind-source GH2 may be delivered to distant markets at apparently-competitive cost. But pipeline energy storage is probably inadequate to "firm" windpower to command full wholesale price at the city gate. Line pipe materials must be tested for H2 embrittlement.

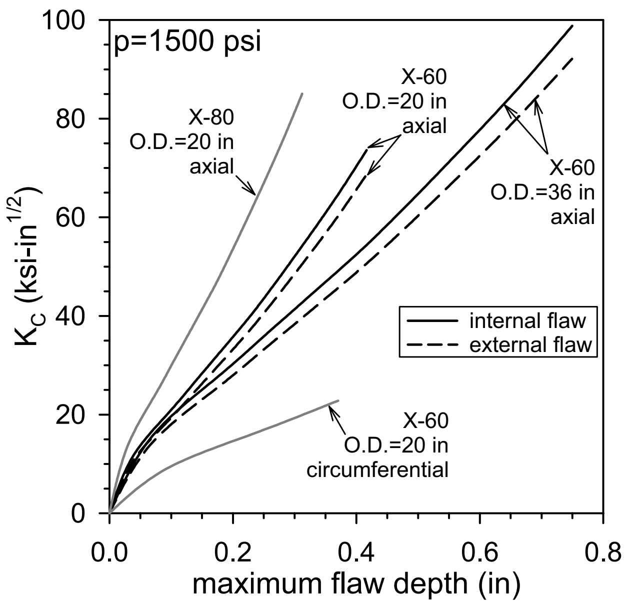

Fig 1. Plots of maximum allowable flaw depth *vs* critical stress-intensity factor, K_C, for different pipe dimensions, materials, flaw orientations, and flaw locations.

TABLE 2: GH2 PIPELINE CAPACITY, WITHOUT INLET OR MIDLINE COMPRESSION

Assume: Inlet pressure 1,500 psi; outlet pressure 500 psi
"Capacity": Fully turbulent flow achieved "Storage Capacity": Unpack from 1,500 to 500 psi

Distance, km	Distance, miles	Outside Diameter, inches	Capacity GW	Capacity MMscfd	Capacity Million Nm3 / day	Capacity Tons per day, metric	Storage Capacity, MMscf	Storage Capacity, Tons
480	300	20	2.3	573	14.8	1,526	211	562
480	300	36	10.2	2,580	66.7	6,869	675	1,798
800	500	20	1.8	444	11.5	1,182	352	936
800	500	36	7.9	1,998	51.7	5,319	1,126	2,997
1,600	1,000	20	1.2	313	8.1	833	703	1,872
1,600	1,000	36	5.6	1,413	36.5	3,762	2,251	5,994

TABLE 3: CAPITAL COSTS: 1,000 MW WINDPLANT, ELECTROLYZERS; 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**

TABLE 4: COST OF WIND-SOURCE GH2 FUEL DELIVERED AT END-OF-PIPE AT DISTANT CITY GATE

Assumes: Unsubsidized (no federal PTC, or other); No oxygen sales
Windplant @ $US 830 / kW Total Installed Capital Cost (TICC)
Electrolyzers @ $ 330 / kW Total Installed Capital Cost (TICC)
Pipeline 20" OD @ $US 29 / inch diam / m length

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

TABLE 5: 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	**Outside Diam, inches**	**Volume, Cubic Meters**	**Inlet Press, psi**	**Delivery Press, psi**	**Energy Storage, Nm3**	**Energy Storage, MMscf**	**Energy Storage, Tons**	**Energy Storage, GWh**	**Energy Storage, Days ***
800	20	146,338	1500	500	9,954,938	352	936	33	3.5
800	36	468,605	1500	500	31,877,861	1,126	2,997	107	11.2
800	20	146,338	600	300	2,986,481	105	281	10	1.0
800	36	468,605	600	300	9,563,358	338	899	32	3.3
1600	20	292,675	1500	500	19,909,875	703	1,872	67	7.0
1600	36	937,209	1500	500	63,755,722	2,251	5,994	214	22.3
1600	20	292,675	600	300	5,972,963	211	562	20	2.1
1600	36	937,209	600	300	19,126,717	675	1,798	64	6.7

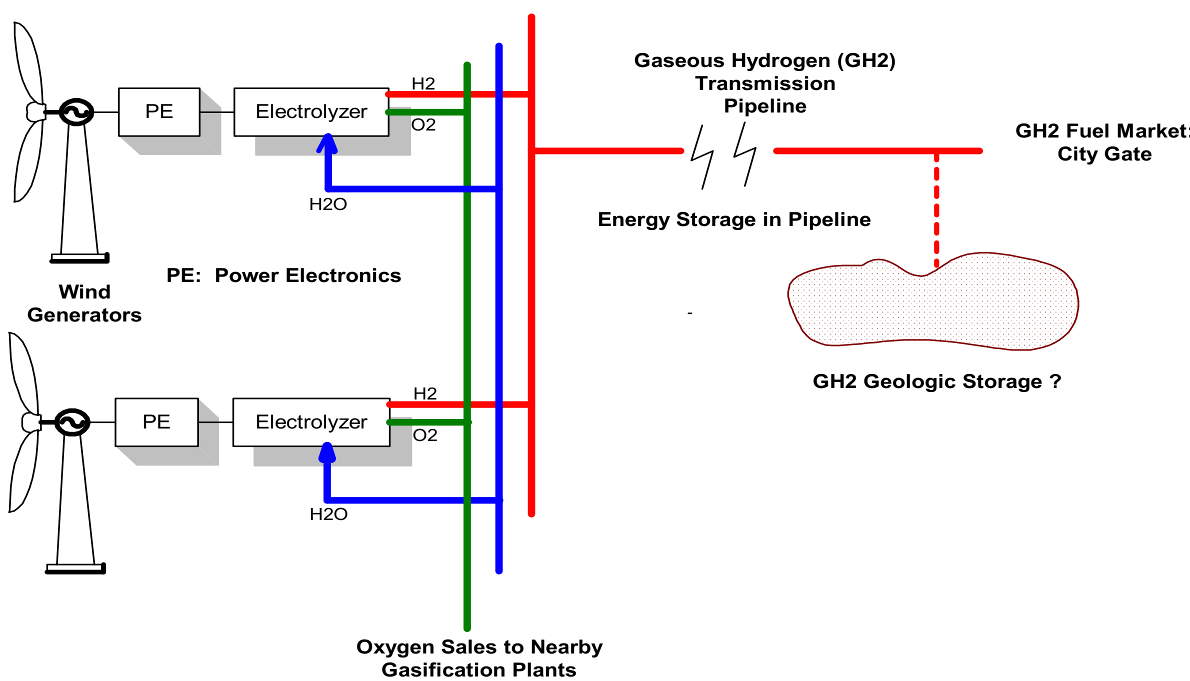

Fig. 2: System Diagram. All wind energy is converted to GH2 for transmission; none is delivered to electricity grid.

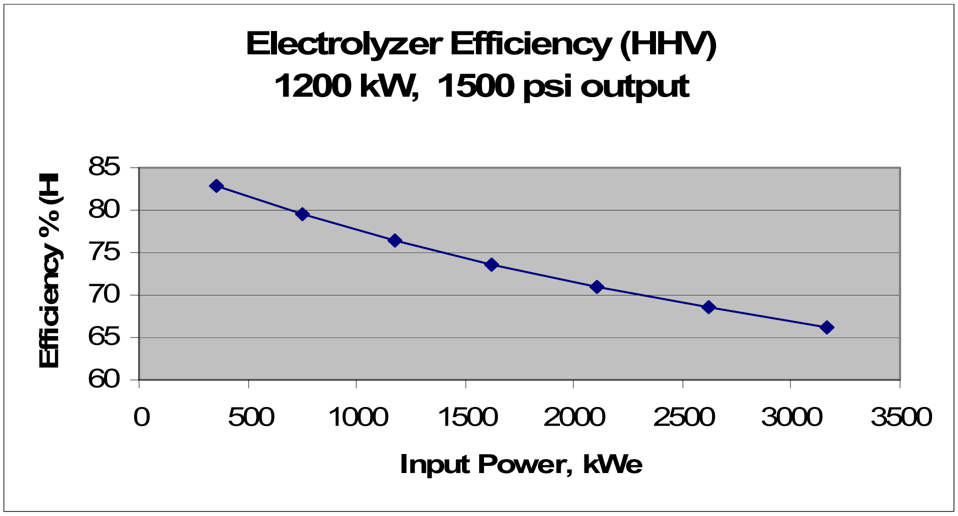

Fig. 3: Electrolyzer Energy Conversion Efficiency vs. Operating Capacity

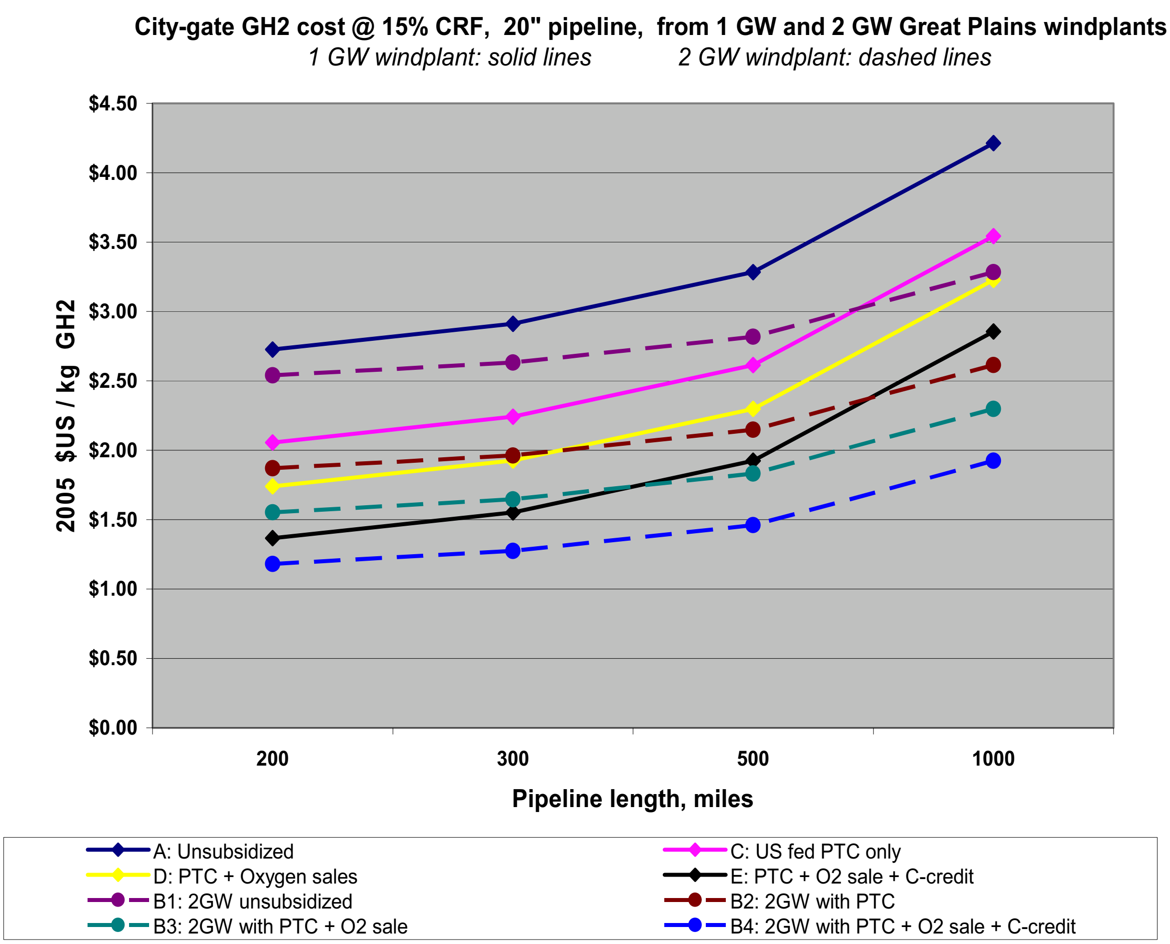

Fig. 4. At 1,500 psi inlet, 500 psi delivery pressure, pipeline capacity is 1.7 GW at 500 mile length; a 2 GW windplant improves pipeline CF, lowers delivered COE, vis-à-vis 1 GW. Four “value-add” cases shown for each windplant size.

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