THE CONVERSION PROJECT AND THE INTERNATIONAL HYDROGEN TRANSMISSION DEMONSTRATION FACILITY (IHTDF): ACCELERATING THE SWITCH FROM GASOLINE TO WIND-SOURCE HYDROGEN FOR VEHICLE FUEL

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ABSTRACT

The first large market for large-scale Great Plains wind energy may be hydrogen vehicle fuel, rather than electricity to the grid. Gasoline has become too costly, when myriad external costs are included, to continue to be used for vehicle fuel. Congress needs to request its GAO to reveal the full cost of gasoline, and to build the initial electric and gaseous hydrogen (GH2) transmission systems, so that the USA, and world, may accelerate our conversion from oil-source fuel to renewable-source hydrogen fuel for transportation. Renewable-source hydrogen may be competitive; wind is the lowest-cost renewable. New GH2 pipelines may be preferable to new electric lines for transmission of large-scale stranded Great Plains wind and biomass energy. If we wish to seriously consider pipelining renewable-source GH2 fuel to markets, we will need a pilot-scale transmission system to demonstrate synergy, safety, and economy; this is a global opportunity and technology and economic challenge; this pipeline would be an international hydrogen transmission demonstration facility (IHTDF).

INTRODUCTION

We need many new, large, long-distance transmission systems for gathering and delivering Earth's vast, diverse, dispersed, renewable energy resources. Wind-generated electricity may be transmitted to distant markets as either electricity via wires or as hydrogen gas (GH2) via pipeline; the electrolytic conversion of electric to hydrogen energy may be done at either source or end of transmission. This hydrogen fuel can be produced on-site from electricity or distributed and retailed from the GH2 transmission pipelines.

Year 2002 USA total gasoline consumption of ~ 130 billion gallons could be replaced by "clean" hydrogen (H2) fuel made from about one-fourth of the total harvestable Great Plains wind energy -- a secure and inexhaustible source. If our society can agree that the aggregate external costs of gasoline exceed ~ $ 1.00 / gallon, and can impose taxes or subsidies upon ourselves to monetize this external cost, wind-source H2 fuel can probably compete in the retail vehicle fuel market.

Both high voltage direct current electricity (HVDC) and gaseous hydrogen (GH2) pipeline systems are attractive, complementary, and competitive, as compared in a recent study.[1]

Figure 1. At the scale of GW capacity and 1,000 km distance, the costs of electric and hydrogen pipeline transmission are comparable. Pipelines provide valuable energy storage: a 1,600 km GH2 pipeline, 1 m (~36") diameter, stores 120 GWh if "packed" (compressed) to 7 MPa (1,000 psi) and "unpacked" to 3.5 MPa (500 psi).

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[1] G. Keith and W. Leighty, "Transmitting 4,000 MW of New Windpower from North Dakota to Chicago: New HVDC Electric Lines or Hydrogen Pipeline", draft report, 28 Sept 02

Pipelining GH2 costs ~1.3 - 1.8 times the natural gas (NG) cost because (a) the volumetric energy density of hydrogen is one-third that of methane, and (b) hydrogen attack on pipeline steel must be prevented and / or controlled. The initial incremental investment in line pipe oversized in diameter and pressure capability for NG service may be difficult to justify; it represents excess, unused capacity during the period of NG service.

New NG transmission pipeline systems may be built with line pipe capable of 100% GH2, for future conversion to "renewables-hydrogen service" (RHS) at up to 100% GH2, to bring energy from windpower, biomass and other renewable sources to market as, and after, the NG is depleted. Since well-constructed and well-maintained pipelines have very long service lives, the increased investment required for construction with RHS-capable line pipe may be justified.

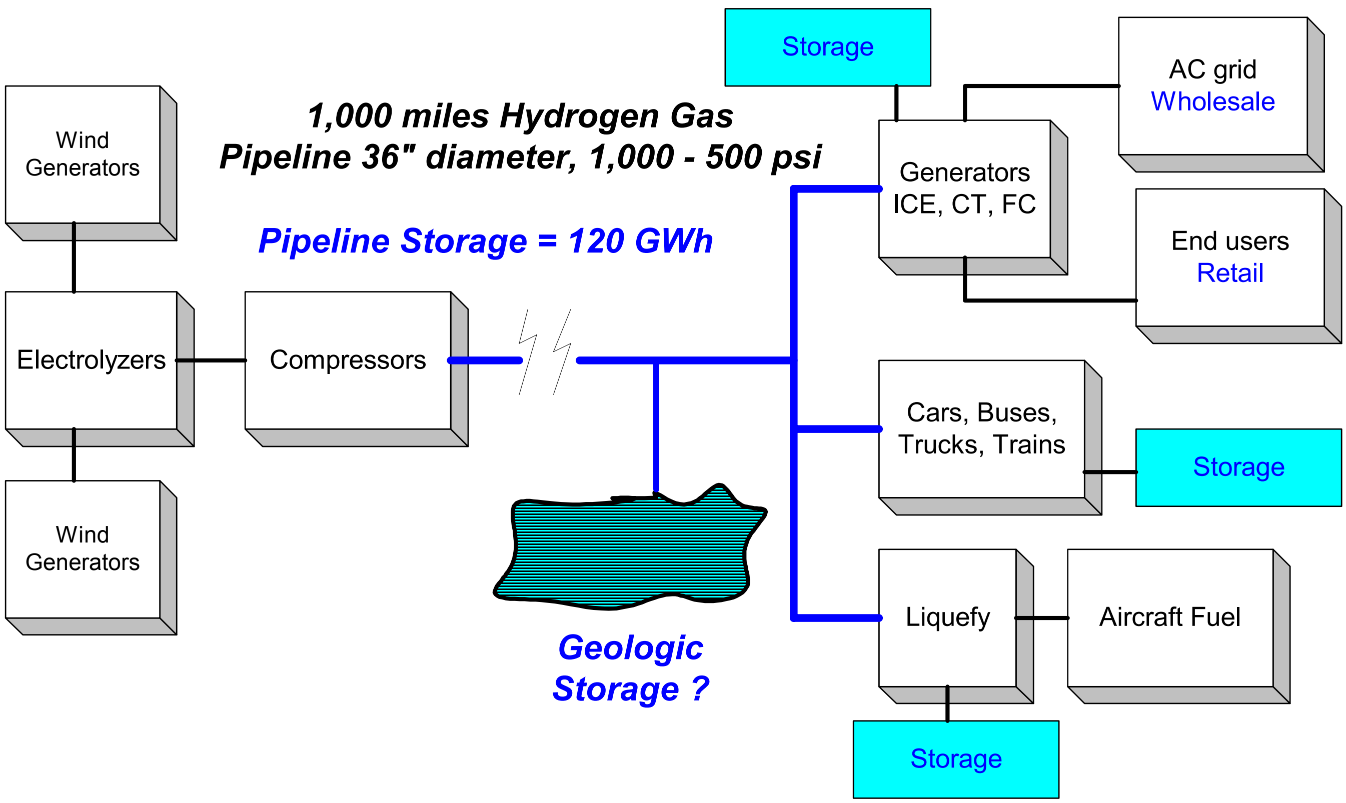

FIGURE 1. Hydrogen transmission with pipeline storage and diverse users of hydrogen fuel. Pipeline, alone, stores 120 GWh. Prospects for large-scale geologic storage in Great Plains are unknown, but could make wind energy "dispatchable".

1. <u>LARGE STRANDED RENEWABLE RESOURCES</u>

Table 1. Fully harvesting just the wind energy of the 12 windiest states in the USA, from about half the land area of each of these states, could supply the entire year 2000 energy needs of the USA, about 10,000 TWh, from an installed nameplate (peak)

TABLE 1. Average windpower annual energy production (AEP) potential, by state, of the 12 windiest states, with number of new 36" hydrogen gas (GH2) pipelines or HVDC electric lines necessary to export it, with costs for 500 mile average distance. Wind energy source: PNL-7789, 1991. (Note 7)

State	Annual Energy Production (AEP), TWh (Note 1)	Wind Gen MW (nameplate) (40% CF) (Note 2)	6 GW 36" GH2 export pipelines (Notes 3,4)	$ Billion Total Capital Cost (Note 5)	3 GW export HVDC lines	$ Billion Total Capital Cost (Note 6)
North Dakota	1,210	345,320	50	50	100	60
Texas	1,190	339,612	48	48	100	60
Kansas	1,070	305,365	43	43	100	60
South Dakota	1,030	293,950	41	41	100	60
Montana	1,020	291,096	41	41	90	54
Nebraska	868	247,717	35	35	80	48
Wyoming	747	213,185	30	30	70	42
Oklahoma	725	206,906	29	29	60	36
Minnesota	657	187,500	26	26	60	36
Iowa	551	157,249	22	22	50	30
Colorado	481	137,272	19	19	40	24
New Mexico	435	124,144	17	17	40	24
TOTALS	9,984	2,849,316	401	$ 401	890	$ 534

Note 1: TWh = Terawatt-hour = billion kWh. TOTAL annual AEP of nearly 10,000 TWh is approximately the total energy consumption, of all forms of energy, in the USA in year 2000 (99 quads, per EIA).

Note 2: Assume wind generators operate at average 40% capacity factor: Installed wind generation capacity = AEP / (8,760 hours per year) / (0.4 capacity factor) = MW nameplate (peak generating capacity) requiredto fully harvest the resource.

Note 3: Assume continuous energy throughput of a 36" diameter GH2 pipeline at 1,000 psi (~70 bar; 7 MPa) = 6,000 MW = 1.5 million scf GH2 per day = 4 tons GH2 per day. If the GH2 pipelines are larger diameter and / or operating at higher pressure, fewer pipelines would be needed; the transmission cost per delivered unit of energy would decline slightly.

Note 4: If these 401 pipelines average 500 miles each, total is ~200,000 miles of new, 36" pipelines.

Note 5: Assume GH2 pipeline system (including compressors, meters, valves, terminals) capital cost is 1.4 times that of natural gas pipeline systems, which cost ~ $25 / inch diameter / meter length. Thus, GH2 pipeline, 36" diameter =~ $2 million / mile =~ $1 billion per 500 mile pipeline system

Note 6: Assume largest practical HVDC lines, at lowest unit cost, per 500 mile system: $400K / mile for lines; $68K / mile for ROW; $130 / kW for converter stations pair =~ $ 600 million

Note 7: An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States, Pacific Northwest Laboratory, Aug 91, PNL-7789, DE91018887, D. Elliott, L. Wendell, G. Gower generating capacity of 2,800 GW. Existing electricity or gas pipeline transmission could collect and export to major load centers only a very small fraction of that energy. Roughly $400 billion capital investment in new electric lines or GH2 pipelines would be needed to export all this wind energy from the 12 states.

World biomass (crop residues, waste wood, intentional energy crops) resources available for energy are also large, and can be converted to GH2 by pyrolysis, partial oxidation (POX), anaerobic digestion (AD) or by other processes. In Denmark, biomass energy delivered for human food consumption is < 10 % of total biomass energy capture.

Almost all of this wind and biomass energy is stranded, with neither electricity nor pipeline transmission available. New NG transmission systems from, or passing through, regions with rich renewable energy resources of hydro, wind, biomass and geothermal, and / or coal resources, could be built of line pipe capable of future 100% GH2 transmission.

Harvesting just the vast stranded wind energy resources of North Asia and the Great Plains of North America will require many large, new transmission systems: HVDC or six-phase electric lines or GH2 pipelines. Using 1 m (~36") diameter, 7 MPa (1,000 psi) pipelines to fully harvest and export the wind resources alone, as GH2, would require:

- About 50 pipelines for North Dakota, the USA state with the greatest wind energy potential;
- About 250 pipelines for the 12 windiest USA Great Plains states;
- A large, unknown number for Northeast Asia, where the wind and biomass resources are very large but have not been assessed. Figure 7; IHTDF interest by Japan, others.

2. THE CONVERSION PROJECT

A nascent group effort believes the USA should accelerate our conversion from oil-source gasoline, diesel, and jet transportation fuels to wind-source hydrogen. This may be a bigger market for wind energy than grid electricity, given the dearth of electric transmission from the Great Plains. Key assumptions:

a. Gasoline has become too costly, when the myriad external costs are included, to continue to be used as vehicle fuel. Energy supply security, climate change, and air pollution are principal external costs.
b. Vehicles fueled by hydrogen, for their on-board fuel cell or internal combustion engine (ICE) powerplants, will soon be available; modified ICE's run well on hydrogen.
c. Wind is the lowest-cost renewable, carbon-free energy source. At very large scale, wind-source hydrogen fuel will be less expensive than the real cost of gasoline.

d. Many large, new transmission systems, perhaps both electric lines and GH2 pipelines, will be needed to bring stranded wind and other clean energy resources to major markets. Clean hydrogen fuel can be made from clean-source electricity, at or near end-users, via electrolyzers. Clean-source hydrogen fuel, pipelined to markets, can be distributed to end-users.

e. Hydrogen fuel made by gasification of coal or from other fossil fuels presents the carbon dioxide (CO2) disposal problem; large-scale CO2 sequestration is unknown in technical feasibility and cost.

Key strategic steps in The Conversion Project:

a. Launch a major advertising and public education program leading to political action on a national level to change the direction of U.S. energy policy, to accelerate conversion from oil to hydrogen as our source of vehicle fuel. The hydrogen fuel will be produced from benign, indigenous energy sources.

b. Congress requests a General Accounting Office (GAO) study to estimate what gasoline really costs, to help Congress and the public understand the importance and urgency of the conversion. A 2002 Princeton draft study presents a methodology which GAO might emulate.[2]

c. Congress enacts the novel “Renewable Energy Hydrogen Production Act” (The Act), to:

    1. Subsidize hydrogen production from various renewable sources;

    2. Upgrade the national transmission infrastructure, both electric and hydrogen pipeline, to export the large stranded Great Plains renewables: a very large capital project.

We can probably reach a broad societal consensus in the USA that the external costs of gasoline are at least $1.00 per gallon, consistent with the Ogden, et al, Princeton study. Therefore, The Act would pay producers of renewable-source hydrogen $1.00 per gallon-gasoline-energy-equivalent (125,000 BTU) for ten years, sunsetting after:

1. market forces have reduced the cost of renewable-source hydrogen fuel;

2. the external costs of hydrocarbon fuels have been internalized into their market prices, by other mechanisms;

3. the several subsidies to the fossil fuel industries have been repealed, driving up their market prices.

New transmission capacity to fully harvest and export Great Plains wind would cost about the same, whether as electric lines or as hydrogen pipelines: from Table 1, about $400 billion. Although this may seem an unrealistically-large number, consider:

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[2] J. Ogden, R.H. Williams and E.D. Larson, "Societal Lifecycle Cost Comparison of Cars with Alternative Fuels/Engines", Energy Policy, in press, 2003.

1. a decade or more will be required for this amount of transmission design, permitting, and construction, averaging $20 - 50 billion / year;
2. the current USA annual defense spending is $400 billion;
3. In the 30's, President Roosevelt proposed a network of superhighways, which would become the National Highway System, employing thousands over several decades, improving our homeland defense.

The ensuing "National System of Interstate and Defense Highways" cost about $28 billion in 1956: $175 billion in 2002 dollars. The Conversion Project is about 2-3 times as big. A gasoline tax of $ .20 per gallon would initially raise $26 billion per year, declining as hydrogen fuel replaces gasoline, directly funding about half the total capital cost of new transmission infrastructure.
We can now imagine that harvesting our indigenous Great Plains wind for hydrogen vehicle fuel would similarly employ many thousands, many of them permanently, improving the security of our nation's energy supply and protecting all Earth from dangerous climate change.

Total USA year 2002 gasoline consumption was ~ 130 billion gallons (EIA, DOE). Since a proton exchange membrane fuel cell electric vehicle (PEMFCEV) would be about twice as efficient, at converting fuel energy to miles traveled, as a gasoline internal combustion engine (ICE), if all year 2002 driving was in PEMFCEV's, ~ 65 billion gallons-gasoline-energy-equivalent (GGEE) would have been consumed as H2 fuel. This is ~ 8 x 10^15 Btu = 2,400 TWh (TWh = billion kWh), about one-fourth the potential annual energy production (AEP) of the 12 windiest states (Table 1). An ICE operating on H2 fuel is ~ 20-30% more efficient at fuel energy conversion than on gasoline fuel. Thus, enough Great Plains windpower is available (though stranded) to power all USA's year 2002 gasoline-fueled vehicles on wind-source hydrogen fuel.

The Conversion Project approach is simple: subsidize production of renewable-source hydrogen fuel and build the first, or several, large-scale transmission systems to bring it to markets, thus encouraging private enterprise to optimize and invest in the generation and transmission systems, and the hydrogen-fueled vehicles, to initiate our conversion from oil-source fuels. No R+D, nor particular technology, is directly advocated or supported.

The Conversion Project expects to initiate the novel "Renewable Energy Hydrogen Production Act" as federal legislation in year 2003.[3]

3. THE PHOENIX PROJECT [4]

Another nascent group advocates "Shifting from oil to hydrogen with wartime speed", to supply all of USA's energy from windpower, delivered as hydrogen fuel, within ten years:

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[3] Contact Alvin Duskin, alvinduskin@att.net, 415-386-9251
[4] www.phoenixproject.net; www.h2pac.org; phone 602-977-0888; contact Mr. Harry Braun

- Because of the exponential nature of the global energy and environmental problems, we cannot wait for fuel cells and fusion; we need not wait for fuel cell vehicular power plants to be perfected and in low-cost mass production, because internal combustion engines (ICEs) operate well on hydrogen fuel;
- In the 1930's, thousands of existing vehicles (including submarines and torpedoes) were modified to use hydrogen fuel in Germany and the UK; autos used the Erren dual-fuel system; USA's extant fleet of gasoline-fueled, ICE-powered vehicles can be so modified.
- Make America energy independent of all fossil and nuclear fuels by mass-producing 12 million one-MW wind systems and modifying every existing vehicle (including aircraft) to use hydrogen fuel;
- Wind systems are similar to automobiles from a manufacturing perspective; mass-production will drive down capital cost / MW for wind generators;
- Hydrogen is the only "universal fuel" that can power any existing vehicle or appliance, including SUVs, Hybrids, Model T Fords or a Coleman stove on a mountain top;
- A new federal "Fair Accounting Act" would eliminate subsidies to fossil and nuclear fuels, and factor in "external costs" as a temporary carbon tax on gasoline that will fund tax credits to modify existing vehicles to use hydrogen

4. THE BALD EAGLE POWER COMPANY, INC. (BEPC) [5]

This nascent private enterprise has applied for US Army Corps of Engineers (USACOE) permits to use 402 square miles of Outer Continental Shelf, south of Long Island from Block Island Sound to Belmar, NJ, for a hydrogen-producing wind farm project as large as 1,925 wind turbines of 3.6 MW each, producing over 1 billion kg of hydrogen fuel per year-- more than enough to fuel all the cars in the Los Angeles basin, for example.[6] All wind-generated electric energy would be converted to hydrogen fuel offshore, transported to onshore markets via method(s) not yet determined.

BEPC expects the USACOE to Public Notice in midyear 03. If permits, funding, and markets are secured, Phase I will be a ~ 20 MW demonstration.

5. COMPETITION FOR RENEWABLE-SOURCE HYDROGEN

If large-scale carbon dioxide (CO2) capture and sequestration can be proven technically feasible, reliable (near-zero leakage), and economical, hydrogen fuel production from coal gasification and steam methane reformation (SMR) of NG, by which most of global hydrogen is now produced, will be formidable competition for renewable-source

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[5] Personal communication, 16May 03. BEPC describes itself as "an environmentally oriented company that is focused on promoting major offshore wind energy for the purposes of advancing the hydrogen economy and creating clean air, land and water." In 1993 BEPC was certified by FERC as a Qualified Independent Power Production Facility.

[6] J. Ogden, "Prospects for Building a Hydrogen Energy Infrastructure", Annu Rev Energy Environ, 1999. 24: 227-79. One small FCEV car driven 11,000 miles / year requires ~ 109 scf H2 / day. 100% of cars in LA basin would require 900 x 10^6 scf H2 / day = 854,000 tons H2 / year.

hydrogen, including stranded Great Plains wind that must be transmitted long distances to most major markets.

A recent paper advocating integrated gasification combined cycle (IGCC) coal plants for China[7] estimates that near-total CO2 capture and sequestration can be achieved, at large scale, for ~ $ 0.01 / kWh. Such IGCC plants would produce both electricity and hydrogen fuel; abundant coal reserves in China and in USA make this an attractive "clean" energy strategy.

However, proving that CO2 leakage to Earth's atmosphere from large-scale CO2 sequestration will be an insignificant long-term climate change threat may be very difficult. Coal mining is disruptive; energy from coal can perhaps never be called "clean".

We should expect that producing large quantities of hydrogen fuel from North American NG resources will drive up NG price; we have seen volatility in recent years. However, USA NG price will probably be capped at ~ $ 6.00 / MMBTU by LNG imports, if enough new LNG terminals and ships can be timely built; much stranded NG is available globally. [8] However,

Here is a simple model for what wind-source H2 fuel will cost the retail motorist, assuming that the fuel cell electric vehicle (FCEV) is twice as efficient as the internal combustion engine hybrid electric vehicle (ICEV) in converting fuel energy to vehicle-miles-traveled, which is the desired transportation service ("drive train efficiency ratio"):

Retail hydrogen fuel cost in Chicago, from North Dakota wind, without PTC:

Wind-generated electricity in ND	$ 0.045 / kWh
Hydrogen conversion and 1,000 miles transmission	0.052 / kWh
Wholesale price of GH2 fuel in Chicago, end-of-pipe	$ 0.097 / kWh
Equivalent per-gallon-gasoline-energy price *	$ 3.49 / gal
Distribution and fuel station cost	$ 0.79 – 1.45 / gal
Retail price of GH2 fuel in Chicago	$ 4.28 – 4.94 / gal
Drive train efficiency ratio: FCEV / ICEV = 2	
Equivalent retail price GH2 fuel per vehicle-mile	**$ 2.14 – 2.47 / gal**

* 1 GJ = 278 kWh; 1 gallon gasoline = 0.13 GJ (HHV) = 36 kWh @ $ 0.08 / kWh = $ 2.89 / gallon

Notes: HHV means higher heating value of hydrogen.
GH2 means compressed gaseous hydrogen

[7] R. H. Williams, "Toward Zero Emissions from Coal in China", Energy for Sustainable Development, Volume V No. 4, December 2001, 65

[8] Personal communication, Dr. David G. Victor, Director, Program on Energy and Sustainable Development Stanford University, Dec 02

6. ELECTRIC VS. HYDROGEN PIPELINE TRANSMISSION FOR LARGE-SCALE GREAT PLAINS WIND; OPTIMIZING GENERATION / TRANSMISSION RATIO

Now, assume we are beyond the "cherry picking" era, by which all large wind projects now harvest the best wind resources, adjacent to electric transmission access, generally paying nothing for transmission. When grid capacity is no longer available, new windplants must pay the total cost of new energy gathering and transmission systems, from source to end-user, significantly increasing the delivered cost of windpower. A successful windplant will operate at about 40% capacity factor (CF); if its electric transmission system is rated at windplant nameplate (maximum), it will also operate at 40% CF, a great cost burden.

A GH2 transmission pipeline provides energy storage for time-varying renewable sources that electric transmission does not. Therefore, the peak (nameplate) generating capacity connected to a renewable-source hydrogen (RHS) pipeline may exceed the pipeline's rated continuous capacity, as the pipeline and any interconnected geologic storage, should such storage prove feasible, may be packed to maximum pipeline rated pressure. Beyond this pressure, GH2 input to the pipeline must be curtailed; some wind generators and other sources would be shut down. Economic optimization of this renewable energy generation-conversion-transmission-storage system will include some generation curtailment, yielding optimum generation / transmission rated capacity ratios.

Although electricity transmission provides no storage, it does allow a generation / transmission ratio slightly > 1 via controlled thermal overloading of system components. Economic optimization will presumably return a smaller generation / transmission ratio than for GH2 pipeline transmission.

Other comparative criteria for large-scale electric and hydrogen pipeline transmission:

a. Figure 2. Capital costs and energy transmission losses are comparable; delivered cost of energy (COE) depends on transmission scenario assumptions.
b. Pipelines will be installed underground, which should make them more secure from attack by natural forces and by humans; easier to route and permit; less obtrusive. Electric lines may be installed underground at 5-10 times the cost of overhead lines; AC underground lines are limited to ~ 20-50 km length by reactive power loading; DC lines may be any length.

7. SYNERGY WITH BIOMASS AND COAL

Figure 3. Biomass energy is abundant in many of the Great Plains states; coal is abundant in ND, MT, and WY. Gasification by partial oxidation (POX) of both biomass and coal can produce hydrogen (H_2) for pipeline transmission, and requires process oxygen (O_2). Approximately 18% of world hydrogen production is now from coal gasification.

The O2 byproduct of H2 production by electrolysis is valuable to adjacent biomass or coal gasification plants. A 4,000 MW (nameplate) wind-to-H2 plant will produce ~ 3 million tons of O2 per year, worth ~ $12 -19 / ton at the biomass or coal gasification plant gate. This improves the economics of renewable-source electricity-to-H2 production, if the gasification plant is nearby.[9] However, oxygen cannot economically be pipelined far; the electrolyzers must be adjacent to the gasification plant.

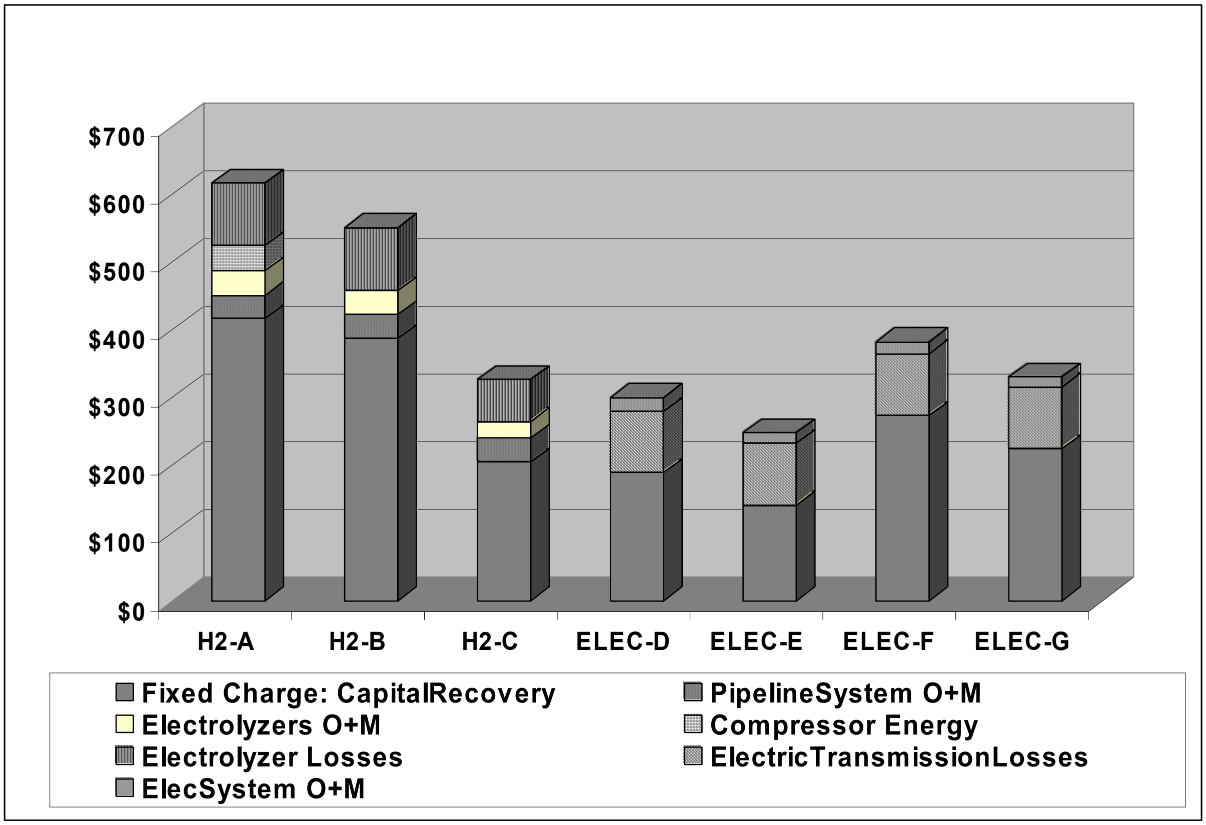

Figure 2. Annual Transmission Costs and Energy Losses, $US 2001 millions, for a 4 GW (nameplate) windplant, 1600 km transmission from North Dakota to Chicago. “H2- “ are hydrogen pipeline cases; “ELEC- “ are HVDC electric transmission cases

8. LARGE-SCALE HYDROGEN ENERGY STORAGE

Low-cost geologic storage of large-volume GH2, if technically feasible in the Great Plains, would add value to windpower, making it more “dispatchable”. This should be a priority research area; large-scale geologic storage feasibility and cost for hydrogen and oxygen is unknown, except for hydraulically-mined salt caverns:

[9] W. Leighty, G. Keith, “Transmitting 4,000 MW of New Windpower from North Dakota to Chicago: New HVDC Electric Lines or Hydrogen Pipeline”, draft Sept 02.

a. 1,000 tons of GH2 is stored in two salt caverns in Tees Valley, UK; [10]
b. A similar storage is in France;
c. Prof. Bent Sorensen, Roskilde Univ, Denmark, calculates that DK can supply *all* of its energy needs from windpower, by converting a fraction of wind-generated electricity to GH2, storing it in two extant salt caverns in DK now used for storing NG. [11]
d. Helium is stored in Texas beneath an aquifer, where water seals the rock fissures. The H2 molecule should be comparable to the He atom for confinement. The extent and availability of such geologic structures needs assessment.

Figure 1. A 1 m (~36" diameter) pipeline, 1600 km long, will store 120 GWh if "packed" (pressurized) to 7 MPa (1,000 psi), unpacked to 3.5 MPa (500 psi); it will store 240 GWh of GH2 if packed to 14 MPa (2,000 psi), then unpacked to 7 MPa (1,000 psi). Hydrogen, H2, energy density by volume is one-third that of methane, CH4. Thus, GH2 energy storage is more costly than NG storage. If GH2 can be economically stored at large scale in geologic formations along the pipeline ROW, the time-varying output of renewable energy sources may be smoothed, at even seasonal scale, adding value to the renewable-source energy. Consequently, GH2 fuel may be drawn from the pipeline and / or geologic reservoirs so that:

a. vehicle fuel is readily available;
b. distributed generation (DG) of electricity at the pipeline destination may be always on-peak, for maximum value.

Large-scale geological oxygen (O2) storage would allow the biomass or coal gasification plants to continue operating when windpower output is low. But O2 is so reactive that it might quickly clog the storage stratum. Commingling of hydrogen and oxygen, from juxtaposed subterranean reservoirs, and oxygen encountering coal deposits, must be prevented. Potential utility of geologic O2 storage is apparently unexplored and unknown.

9. SYNERGY WITH WIND GENERATOR SYSTEM DESIGN

Figure 4. Modern wind turbines use power electronics to allow variable speed constant frequency (VSCF) operation, for improved annual energy production, to limit drivetrain torque, and to supply quality power to the electric utility grid. However, if wind generators are supplying only direct current (DC) to electrolyzers, for exclusive conversion of wind energy to H2, rather than supplying quality alternating current (AC) to the electric grid, wind generator system design might be simplified, lowering capital and O&M costs, in both power electronics and in the rotating generator machine. Reducing the transformer - rectifier energy losses now part of the electrolysis process is

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[10] Tees Valley Hydrogen Project, www.epicc.com, contact John Auterson, j.auterson@tees.ac.uk
[11] Bent Sørensen, Chairman of Danish Hydrogen Committee, "Handling fluctuating renewable energy production by hydrogen scenarios", Roskilde University, Institute 2, POBox 260, 4000 Roskilde, Denmark, bes@ruc.dk. Presented at World Hydrogen Energy Conference, Montreal, Jun 02.

a major goal being investigated by NREL. Norsk Hydro has installed a wind-to-hydrogen energy system, with storage, on the Norwegian island of Utsira, population 250, to investigate this synergy.

10. INTERNATIONAL HYDROGEN TRANSMISSION DEMONSTRATION FACILITY (IHTDF)

Figures 5, 6. If we are to seriously consider large-scale RHS pipelines, we need a pilot-scale R&D and demonstration RHS pipeline

- ~ 40 - 100 km long;
- ~ 10 - 100 MW;
- Gathering GH2 from diverse, dispersed renewable energy sources;
- Delivering it to a campus or community to fuel pioneering vehicles and stationary devices.

This should be funded and operated by public and private sectors in an international consortium, dedicated to evaluating the worldwide prospects for RHS pipeline transmission. Fully testing materials and systems for a new technology, gaining regulatory and industry acceptance, often takes decades. As a “demonstration” facility, it must provide a dependable supply of GH2 fuel for end-users at the destination community. Commitment to build the IHTDF will motivate and focus the required precursor R&D and testing.

Although the industrial gas and oil & gas industries have been safely pipelining GH2 for decades, these systems are not designed for frequently-varying pressure and for large-scale, long-distance, cross-country collection and transmission, from many dispersed nodes from diverse sources, as required by renewables-hydrogen service (RHS). No pipelines for such service exist. No industry-accepted codes and standards have been developed to guide the engineering and design of such facilities. The public is unfamiliar with hydrogen and anxious about its safety. Thus, a new pilot-scale R&D and demonstration pipeline system, an International Hydrogen Transmission Demonstration Facility (IHTDF), is needed.

Several authors have examined hydrogen transport by pipeline, with diverse results. However, in most cases, the costs provided were based on extant natural gas pipelines or were very rough estimates (e.g. $US 1 million / mile with no specification on diameter). No study contemplates the very large scale gathering and transmission systems needed to harvest the USA Great Plains wind resource of ~2,800 GW (peak) generating capacity, or Northeast Asia’s unassessed resources. This pipeline design is a priority research topic.

The IHTDF demonstrates “distributed collection” from numerous “distributed generation” sources all along the pipeline route and ROW. It becomes a gathering, transmission, and storage corridor serving diverse, dispersed, generation-conversion plants.

10.1 IHTDF Purpose

The proposed IHTDF would:

1. Help us decide under what circumstances large-scale, cross-country collection and transmission of renewable-source energy in GH2 pipelines will be technically and economically attractive; it will demonstrate the probable long-term costs of such GH2 pipeline systems for large "stranded" renewable resources.
2. Demonstrate economic and technical synergy among renewable GH2 sources-- wind, biomass, and perhaps others-- embracing:
    a. Availability and output variations at hourly to seasonal time scales;
    b. Stockpiling and dispatch, especially of biomass;
    c. Possibly "near-zero-emissions" coal gasification plants.

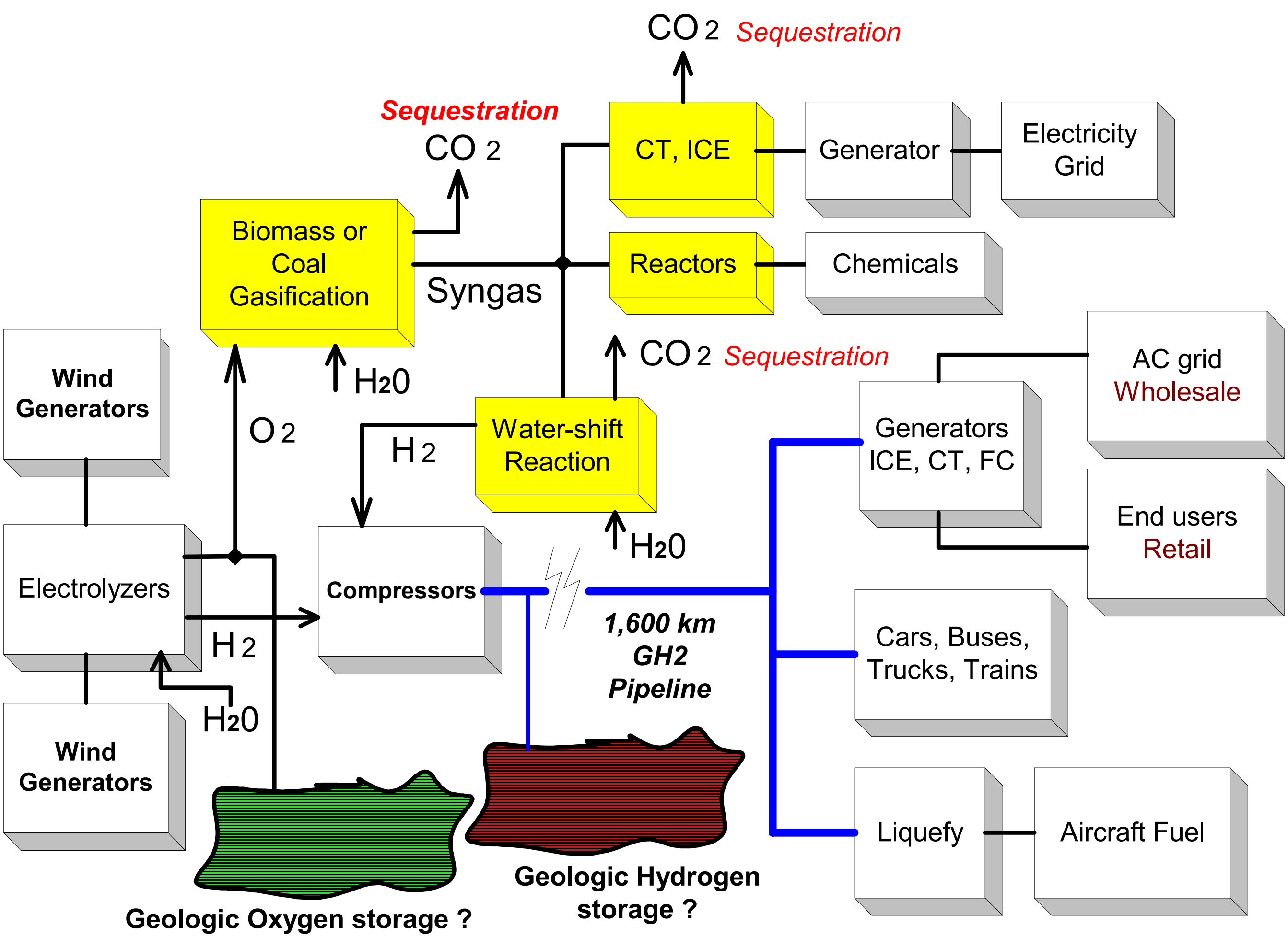

Figure 3. "Renewables Hydrogen Service" (RHS) pipeline transmission, delivering GH2 from distant wind resources to various users, with potential storage schemes in addition to pipeline storage. Synergy with biomass gasification or "zero emissions" coal gasification plants adjacent to wind energy sources, using byproduct oxygen from electrolyzers for oxygen-blown gasification. Large-scale geologic storage feasibility of hydrogen and oxygen is unknown.

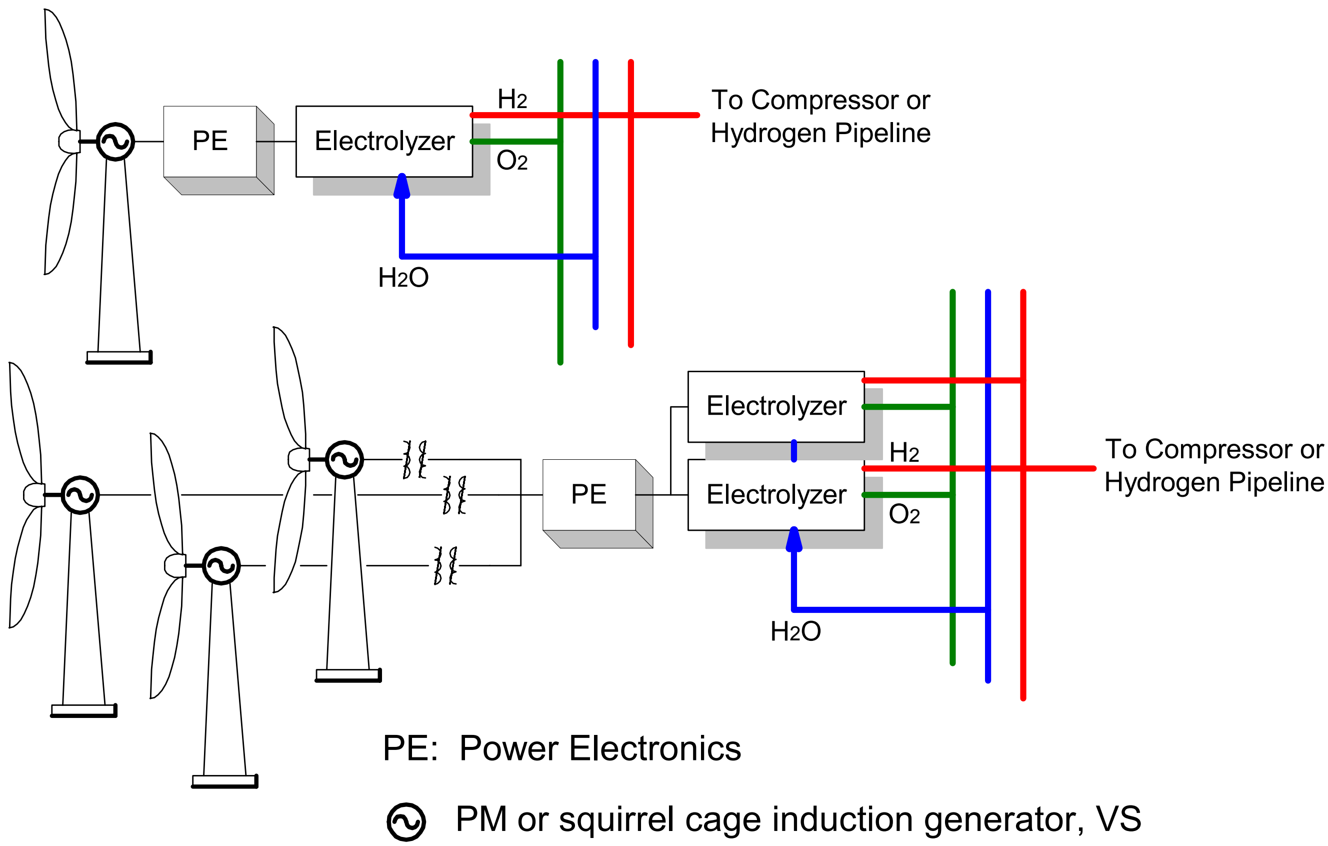

Figure 4. Wind generators driving only direct current (DC) electrolyzers, may simplify and lower the cost of power electronics. Variable speed (VS) permanent magnet (PM) or low-cost induction generators may be used, to further lower system capital and O&M costs.

3. Demonstrate “distributed collection” of diverse, dispersed, diffuse renewable resources, large and small, continuously along the GH2 pipeline ROW via frequently-spaced GH2 gathering input points; design and test the system topology and components to accomplish this.
4. Demonstrate the pipeline as an energy storage medium; discover pressure range limits and dynamics, management techniques; develop economic valuation models for this storage.
5. Investigate and prove feasibility and cost of large-scale geologic storage of GH2, along pipeline ROW, in:
    a. Extant NG storage structures, as available;
    b. Other geological formations.
6. Bring GH2 production, transmission, and use out of the laboratory and out of established industrial reservations, and into farmers’ fields, across private and public lands, to utilization at a major research university campus or community; improve public familiarity with hydrogen.

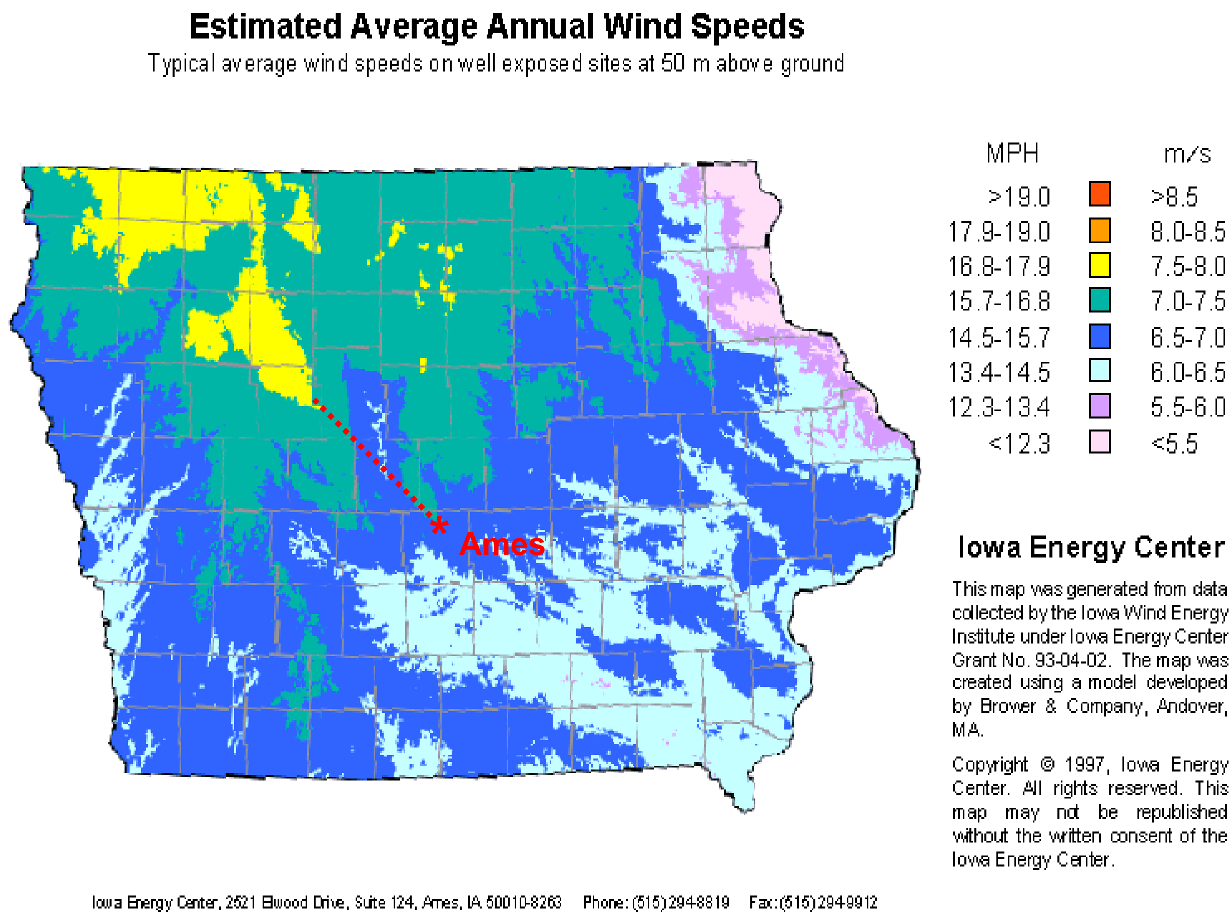

Figure 5. Candidate location for the IHTDF. Approximately 60 miles (100 km) GH2 pipeline from the windy region west of Ft. Dodge, Iowa, to Iowa State University and USDOE Ames Laboratory at Ames, Iowa.

7. Encounter and solve public and professional misunderstanding, apprehension, impediments in:
    a. Land use and zoning;
    b. Perception of hydrogen and hydrogen systems: design, function, and safety;
    c. Codes and standards;
    d. The insurance and banking industries.
8. Encounter and solve novel ROW acquisition and permitting problems.
9. Induce codes, standards, and insurance problem resolution via operating experience on a “real project”.
10. Estimate feasibility and costs of scale-up to multi-GW, long-distance, cross-country GH2 gathering and transmission pipeline systems; project what the cost of diverse large-scale Great Plains and Northeast Asia renewable energy resources, delivered at long distances as GH2, could be.
11. Verify long-term system:
    a. O+M costs;
    b. Component degradation;

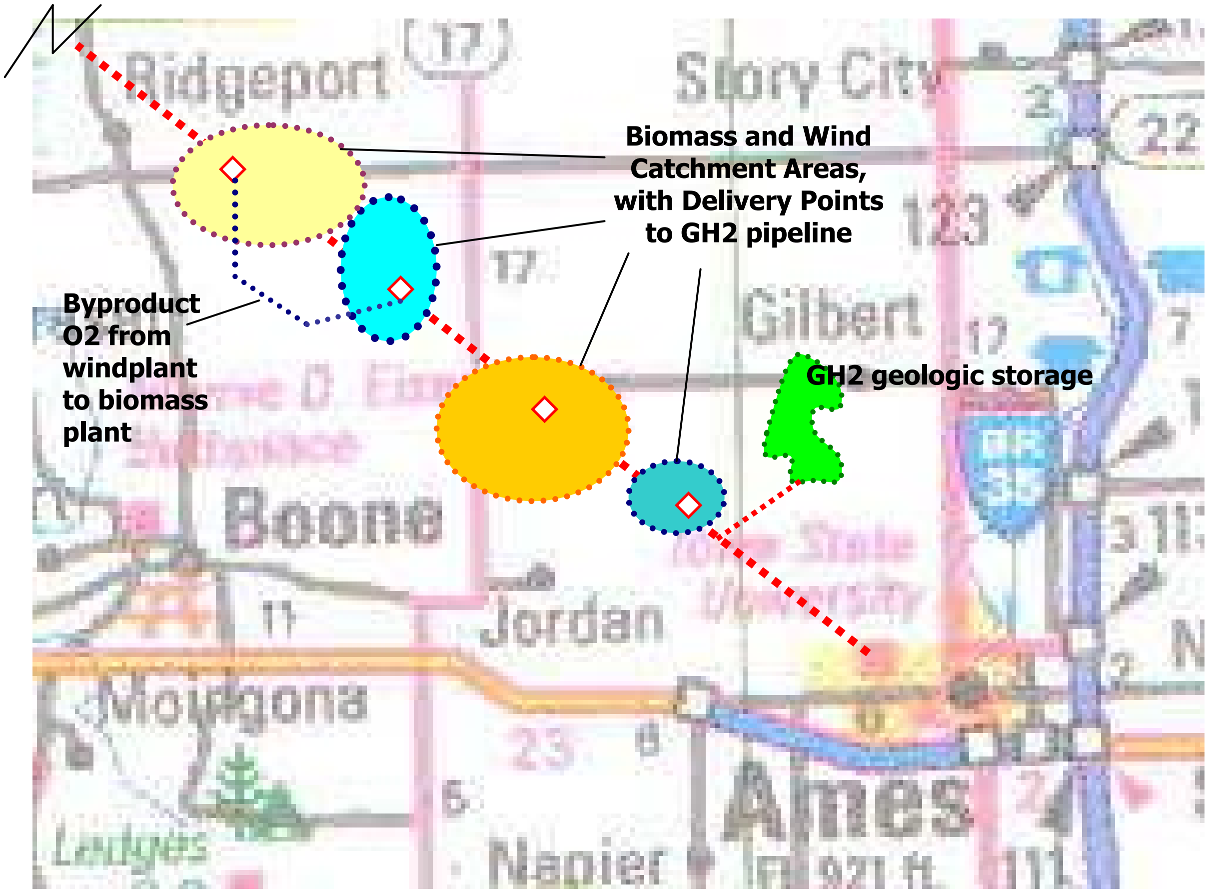

Figure 6. Detail of "Distributed Collection" (DC): GH2 gathering topology as a continuous collection and transmission corridor, rather than a transmission line. The economic gathering radius varies with each resource. Byproduct O2 from wind-to-hydrogen electrolysis is supplied to adjacent biomass gasification plants producing GH2 for the pipeline.

   c. Integrity inspection methods, especially for hydrogen corrosion and embrittlement of steel.

12. Be a dynamic test bed for evolving technology in GH2 collection and transmission:
    a. Electrolyzers;
    b. Compressors;
    c. Meters, valves, and other basic components;
    d. Gas quality monitoring, control, leak detection, and shutdown systems;
    e. Software for modeling, management, and control;
    f. Line pipe and pipeline inspection and integrity.
13. Be a dynamic test bed for evolving technology in energy conversion:
    a. Wind energy conversion equipment optimized to feed electrolyzers;
    b. Biomass energy conversion to GH2;
    c. "Near-zero-emission" coal gasification plants.
14. Encourage industry to market GH2-fueled vehicles: buses, cars, and eventually boats and aircraft.

15. Encourage industry to invest in GH2 production, collection and transmission, and distribution, from renewable energy sources and possibly from “zero emissions” coal.
16. Reveal energy policy implications for a carbon-free energy economy.

10.2 Location

The Northern Great Plains, USA, offers convenient opportunities for synergistically gathering GH2 from wind and biomass sources within a compact area for delivery to a campus or community using the GH2 fuel, minimizing GH2 pipeline length and cost. Candidate sites:

1. Ames, Iowa: population 50,000; home of Iowa State University, USDOE Ames Laboratory, Iowa DOT. Good wind and biomass resources nearby.
2. Southwest Minnesota: good wind resource; active hydrogen interest group embracing state government and industry.
3. Grand Forks, ND: Home of University of North Dakota and the North Dakota Energy and Efficiency Research Center.
4. Fort Collins, CO: Home of Colorado State University.

10.3 IHTDF Capital Cost

Large, new, terrestrial, cross-country, NG transmission pipeline systems typically cost $US 1 per mm diameter per meter length, complete with compressors, meters, controls, etc. About 300 mm diameter is necessary for inspection by “smart pigging.” Thus, total installed capital cost of a 300 mm diam NG pipeline 50 km long would be ~ $US 15 million. The novel GH2 pipeline for the IHTDF might cost 2 - 3 times as much, ~ $US 40 million. The lab-scale R&D work to precede it might also cost as much. Thus, the IHTDF might be a $US 50 - 80 million project.

11. GASEOUS HYDROGEN (GH2) PIPELINE SYSTEM DESIGN

More compressor power and energy are needed for GH2 service than for NG service. Integrating generation-conversion-transmission system design for RHS will be important for cost minimization.

11.1 Incremental Investment for RHS Capability

Any large new NG pipeline is a large capital investment; if it can be built as RHS-capable, for modest incremental capital cost, it may represent superior present value (NPV) vis-à-vis a standard NG pipeline if it soon begins transporting hythane® (methane - hydrogen mix) and transitions to 100% GH2. However, the initial incremental investment in line pipe oversized in diameter and pressure capability for NG service may be difficult to justify; it represents excess, unused capacity during the period of NG service.

11.2 New Specification for RHS Needed

The power output of renewable energy sources-- especially wind-- is time-varying at hourly-to-seasonal scales, often unpredictably and randomly. This may be mitigated at regional and continental scale by large-scale transmission integration and geographic-diversity smoothing, but this may not benefit individual pipelines. [12] This power variation can cause frequent and severe pipeline pressure cycling as the pipeline is packed and unpacked, attempting to (a) accept the total energy output of the diverse, dispersed sources, and (b) maintain delivery pressure and flow at the destination.

Although NG transmission pipelines routinely suffer cyclic pressure loading, accommodating this cyclic loading in RHS requires more costly line pipe, more frequent pipeline inspections, and perhaps intentional curtailment of generation to moderate this cycling. Thus, a new specification for RHS is needed to define stresses on pipeline system components and limitations on pipeline operations, in order to optimize GH2 pipelining economics and to guide engineering of line pipe and other system components. This specification will also facilitate insuring and financing RHS pipelines.

11.3 Steel Line Pipe Materials and Metallurgy

The oil and gas industry has always been troubled by internal and external hydrogen attack on steel pipelines, described variously as hydrogen-induced cracking (or corrosion) (HIC), hydrogen corrosion cracking (HCC), stress corrosion cracking (SCC), hydrogen embrittlement (HE), and delayed failure. These will likely be exacerbated in RHS. Surveys of extant GH2 pipelines show that a variety of steels, but primarily mild steel, is in use.

Existing NG pipelines can be used for <15-20% GH2, by volume, without danger of hydrogen attack on the line pipe steel. But any GH2 enrichment of NG, toward hythane®, or further to 100% GH2, will risk hydrogen embrittlement and reduce the power capacity of the pipeline.

These conditions will probably result in thicker-wall line pipe than for NG service, thus requiring more tons / km of line pipe and higher welding cost resulting in higher pipeline installed cost.

11.4 Composite and Hybrid Line Pipe

Composite Reinforced Line Pipe, CRLP™, being developed by TransCanada Pipelines under license from NCF Industries, may be especially attractive for RHS. [13, 14] A high

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[12] G. Czisch and B. Ernst, ISET, Universitat Gesamthochschule Kassel, Germany, *High Wind Power Penetration by the Systematic Use of Smoothing Effects Within Huge Catchment Areas Shown in a European Example*, in (50).

[13] www.transcanada.com/Transmission/Update/october_2002/oct_technologies.pdf

performance composite material reinforces a thin-wall, high strength low alloy (HSLA) (X42 to X80) steel pipe. The steel and composite work together, creating a hybrid that provides an economical alternative to higher strength all-steel pipe. For large pipelines, for RHS at > 14 MPa, the required line pipe strength is achieved with these benefits:

- Low alloy steel liner, which is more weldable and inherently less susceptible to HIC, HE, and SCC; girth welds designed for fatigue resistance;
- Technology applied from large scale composite reinforced pressure vessels (TransCanada's Gas Transport Modules), which are designed for cyclic service, can be applied to make girth and pipe seam welds highly fatigue resistant;
- Thin wall steel liner, reducing weight per unit length and welding time;
- Wide choice of liner pipe material, as hoop strength is provided primarily by the composite;
- Effective elimination of axial crack propagation by rapid arrest of axial crack growth;
- Higher burst to operating pressure ratio;
- Lower total installed capital cost than all-steel pipe, at large size and high pressure.

TransCanada estimates that the total installed cost of the pipeline needed for large scale GH2 transmission, >1.5 m diameter, > 14 MPa, would be 3 - 8 % lower than for a solid steel pipeline. The stress-strain curves are quite different for the steel liner and for the composite wrap. In hydrostatic testing of the completed pipeline, the correct overpressure is applied to expand and deform the steel liner against the composite, leaving the steel in static compression, the composite in static tension, over the complete pipeline operating pressure range. This maintains hoop strain compatibility, and will help prevent SCC and room temperature creep that may result from long-term cyclic loading.

Ameron International has developed "Bondstrand SSL", a combination of glass reinforced epoxy and steel strip laminate, capable of over 40 MPa (5,500 psi), that may be a foundation technology for large GH2 pipelines. [15]

11.5 Electrolyzers

Electrolyzers crack H2O into H2 and O2 gases, using electric energy in a fundamentally low-voltage, direct current process. The electricity may come from wind generators or other renewable sources. For large-scale RHS, the electrolyzers must have:

- MW - scale availability;
- High DC input voltage, > 200, or be series-connectable, to match high voltage output of large-scale wind turbine electrical generation system; integration into generation system design;

[14] T. Zimmerman, G. Stephen, A. Glover, COMPOSITE REINFORCED LINE PIPE (CRLP) FOR ONSHORE GAS PIPELINES, IPC02-27215. Proceedings of IPC2002: International Pipeline Conference, September 29 - October 3, 2002 Calgary, Alberta, Canada

[15] www.ameronfpd.com,

- High energy conversion efficiency: [kWh as GH2 (HHV) output] / [kWhe electric energy input];
- Low long-term O+M cost;
- Installed capital cost < $US 250 / kWe input.

MW-scale modules now available are KOH (potassium hydroxide; wet) process, are ~80 % efficient, but transformer-rectifier and balance-of-system losses reduce the complete electrolysis process efficiency to 60-70 %. Output pressure is near atmospheric, so costly compressors and energy are needed to feed the pipeline. Electrolyzer system capital cost for a large plant is now ~ $US 650 / kWe electric input, including transformer-rectifier, without compressor. High-volume production could realize ~ $US 250 - 300 / kWe, without transformer-rectifier. Volume production will be very important in reducing KOH process electrolyzer unit capacity cost.

Proton exchange membrane (PEM, PEFC type) electrolyzers, based on PEM fuel cell technology, are now under development, but MW-scale hardware is not expected soon; no capital cost estimates are available. PEM-type electrolyzers now require Pt or other costly catalysts, at high capital cost.

11.6 Compressors

Pipelining 100% GH2 requires about three times the compressor power; specific capital costs for large GH2 compressors are expected to be 20 - 30% higher, than for NG. Positive displacement, reciprocating compressors may be the best choice for large-scale GH2; they must be custom-designed for GH2-rich gas service. Lubrication may be a problem if hydrocarbons contaminate the pipeline GH2, degrading it from “fuel cell” quality.

12. PROPOSED NEW ASIAN PIPELINE SYSTEMS

For several years, the Northeast Asia Gas & Pipeline Forum (NAGPF) and the Asian Pipeline Research Society of Japan (APRSJ) have studied routes for a large new pipeline network to bring NG from Asia to Japan. The Eastern Siberia to Far East (ESFE) pipeline project is being contemplated by Russia, China, South Korea, and Japan. GH2 enrichment of gas in these new Northeast Asia NG pipelines may become economically and environmentally attractive well within the lifetime of the pipeline. Once laid, the NG pipelines will have a semi-permanent life.

However, these new pipeline systems, if and when used for 100% GH2, would have only about 30% of their NG power transmission capacity because of the difference in physical properties between NG and GH2. For economical GH2 transmission they must be capable of continuous service at >14 MPa, although NG pipelines at this pressure are now very rare.

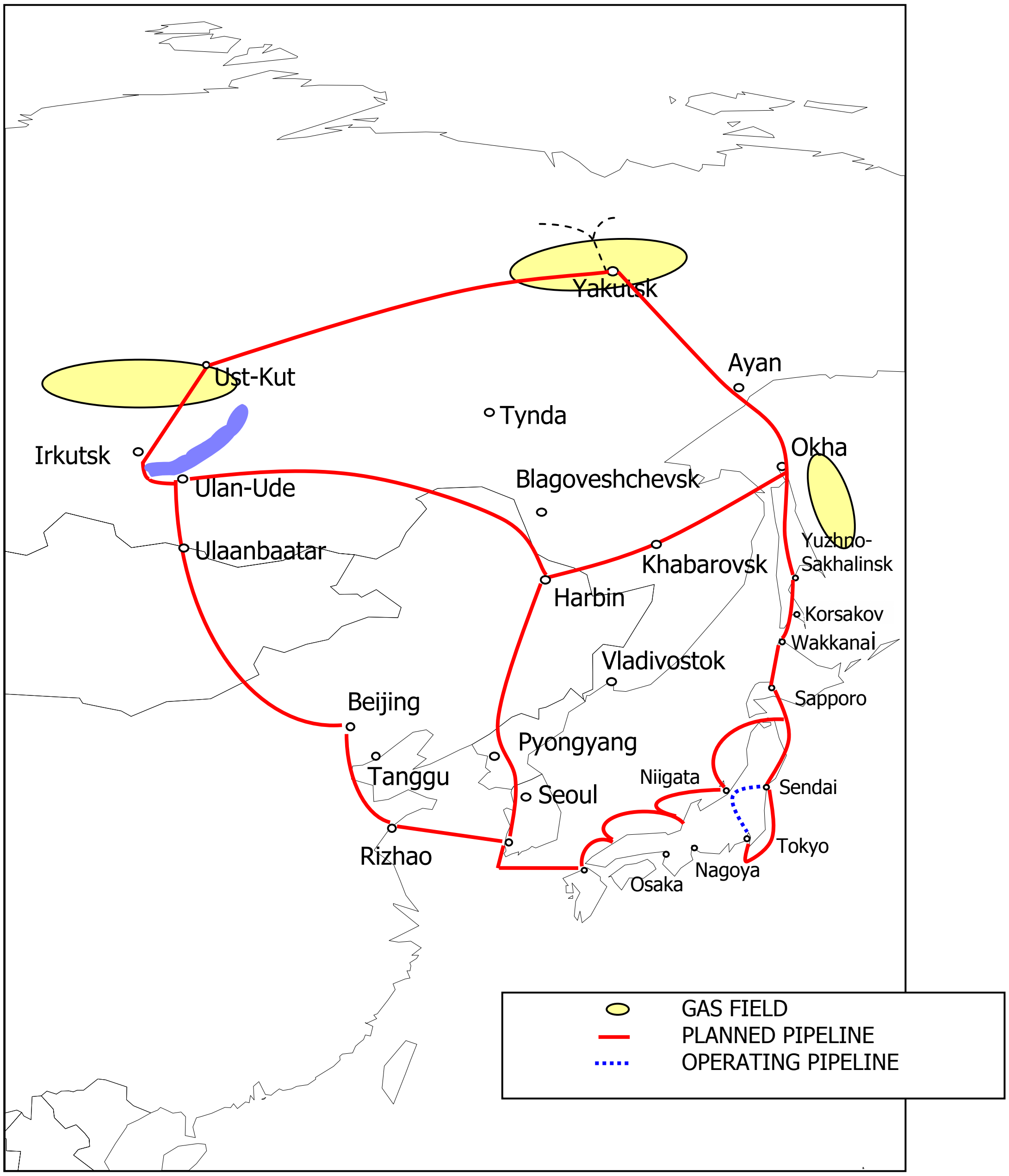

Figure 3. Proposed Northeast Asia Pipeline Network Loop

These proposed Asian pipelines have catalyzed a new initiative, The International Hydrogen Pipeline Forum (IHPF), whereby world leaders in hydrogen transportation technologies can meet, discuss issues and direct the focus of future hydrogen research. A principal concern and urgent research topic: Should these pipelines be built of hydrogen-capable line pipe, so that when the NG resources are depleted, these pipelines can transport GH2 from windpower, biomass, geothermal, hydro, and perhaps coal resources along, and nearby, the pipeline routes? Consequently, several Japanese wish to participate in the IHTDF.

13. CONCLUSION

Bringing Great Plains windpower and other stranded carbon-free renewable-source energy to market will require large investments in gathering and transmission systems, proven engineering principles by which to design and optimize them for long-term service, and leadership in conceiving and capitalizing these very large generation-conversion-transmission-storage systems. GH2 and HVDC or six-phase electric transmission are attractive and comparable in unit-energy-distance cost. GH2 pipeline transmission provides energy storage; electricity does not.

The largest market for Great Plains wind may be hydrogen transportation fuel, rather than electricity for the grid. If our society can agree that the aggregate external costs of gasoline exceed ~ $ 1.00 / gallon, and can impose taxes or subsidies upon ourselves to monetize this external cost, wind-source H2 fuel can probably compete in the retail vehicle fuel market. H2 fuel from NG by SMR and from coal by IGCC gasification plants, with total CO2 sequestration, will be formidable competition.

The energy industry needs to know whether, when, and under what circumstances, pipelines for renewables-hydrogen service (RHS) may be technically and economically attractive. For new NG pipelines, the initial incremental investment in line pipe oversized in diameter and pressure capability for NG service may be difficult to justify; it represents excess, unused capacity during the period of NG service.

No large RHS transmission system exists. R&D in materials and system design is necessary. An IHTDF is necessary to develop and prove pipelines and other components for RHS, to prove synergy among benign GH2 sources, and to allay public anxiety about hydrogen safety. If large RHS pipelines are proven technically or economically unfeasible, this option should be set aside, for well-documented reasons, so we may concentrate on electric transmission for renewable-source energy.

If the IHTDF and other relevant demonstrations are favorable, the energy industry should seriously consider building new NG pipelines as RHS-capable, whenever they traverse renewables-rich regions, at a predictable incremental capital cost, for superior long-term NPV, to hasten our conversion to carbon-free energy sources, and to geographically diversify our energy supply.

Appendix A: Energy Conversion Factors for Hydrogen

Volume				
1 Nm3 =	35.315 cubic ft (scf)			
Pressure				
1 Mpa =	145 psi =	9.9 atm		
1 atm =	14.696 psi =	1.01325 bar		
1000 psi =	68.9 bar =	68.05 atm		
Power				
1 kW =	10.5 scf per hr			
1 MW =	10,500 scf per hr =	297.5 Nm3 per hr =	3.6 GJ per hr	
1 GW =	10.5 Mscf per hr =	297,500 Nm3 per hr =	3,600 GJ per hr	
1 TW =	10.5 Bscf per hr =	297.5 MNm3 per hr =		
1 Mscf per hr =	327 mmBtu per hr			
Energy				
1 GJ =	277.8 kWh =	2,915 scf =	75.36 Nm3 =	10^9 J
1 kWh =	10.5 scf =	0.298 Nm3 =	0.95 mmBtu	
1 MWh =	10,500 scf =	297.5 Nm3 =	3.6 GJ	
1 GWh =	10.5 Mscf =	297,500 Nm3 =	3,600 GJ =	3,430 mmBtu
1 TWh =	10.5 Bscf =	297.5 MNm3 =	3.6 PJ	
1 kg H2 =	11.08 NM3 =	128.8 MJ (HHV) =	135,100 Btu =	375.6 scf
10^6 scf =	343 GJ =	26,850 Nm3		
1 lb H2 =	5.04 Nm3 =	0.0585 GJ (HHV) =	16.26 kWh =	187.8 scf
1 Nm3 H2 =	0.09 kg =	3.361 kWh		
1 scf H2 =	343 kJ =	325 Btu (HHV)		
1 kWh =	3,410 Btu			
1 scf natural gas = 1,010 Btu				

Kilo = 10^3, Mega = 10^6, Giga = 10^9, Tera = 10^12, Peta = 10^15, Quad = 10^15, Exa = 10^18