Large Renewables - Hydrogen Energy Systems: Gathering and Transmission Pipelines for Windpower and other Diffuse, Dispersed Sources

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1. INTRODUCTION

We need many large new transmission systems for gathering and delivering Earth's vast, diverse, dispersed, renewable energy resources. Both high voltage direct current electricity (HVDC) and gaseous hydrogen (GH2) pipeline are attractive, complementary, and competitive.

New natural gas (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. Sour-service X65 or composite reinforced line pipe (CRLP™) [1] may be well-suited. 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. These pipeline systems may be retrofitted with compressors, meters, valves and other fittings necessary for future RHS, for the nascent "renewables-hydrogen economy".

Pipelining GH2 costs ~1.3 - 1.8 times the 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.

Although the industry has been safely pipelining GH2 for decades, these systems are not designed for frequently-varying pressure and for large-scale, long-distance, cross-country collection, from many dispersed nodes from diverse sources, as required by RHS. No pipelines for such service exist. 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 Test Facility (IHTTF), is needed.

We investigated whether GH2 pipeline or HVDC might provide a higher benefit / cost merit for transmission of large-scale North Dakota wind energy 1,600 km to Chicago, where the GH2 would then be converted back to electricity in large or small distributed generation (DG) plants and / or be used to fuel buses, cars, and aircraft. Although GH2 can in some cases be transported more efficiently than electricity over long distances [2], system benefit / cost depends on the choice of AC or DC electric transmission, and whether GH2 or electricity is to be sold, presumably at wholesale, at the destination market [3].

We recommend further technical and economic investigations.

2. LARGE STRANDED RENEWABLE RESOURCES

"All renewables suffer from low areal power densities… intermittent dispersed sources unsuited to baseload without transmission, storage, and power conditioning [4]."

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) generating capacity of 2,800 GW [5]. Existing electricity or gas pipeline transmission could collect and export to major load centers only a very small fraction of that energy.

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) [6, 9] or by other processes [7, 8]. In Denmark, biomass energy delivered for human food consumption is < 10 % of total biomass energy capture [9].

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 100% GH2 transmission so that:

- NG is transmitted, initially;
- Methane could be converted to GH2 and CO_2 at the NG fields, via steam methane reformation (SMR);
- The GH2 produced by SMR is pipelined to distant nascent markets for hydrogen fuel;
- The CO_2 is injected into the NG reservoirs *in situ* to maintain reservoir pressure and to sequester the CO_2;
- As the NG is depleted, these transmission pipelines gather GH2 from inexhaustible, clean, renewable resources all along the right-of-way (ROW), reaching 100% GH2 pipeline gas;
- GH2 could be mixed with NG to form hythane®, a cleaner-burning gas, but with lower volumetric energy than NG;
- If coal deposits occur along the pipeline ROW, future "near-zero emissions" coal plants, with *in situ* sequestration of byproduct C and / or CO_2, could also supply GH2 to the pipelines [7].

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 pipelines to fully harvest and export the wind resources alone, as GH2, would require [3, 5]:

- About 60 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.

Harvesting wave, tidal, geothermal, and direct solar radiation may also be economical, and perhaps synergistic with wind and biomass in sharing large-scale transmission.

3. PROPOSED NEW ASIAN PIPELINE SYSTEMS

Figure 1. 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 natural gas from Asia to Japan [10]. Hirata, Verikhov, and O'Hashi have proposed GH2-capable pipelines from North Asia via Sakhalin, and via Kamchatka and the Kuril Islands to Hokkaido, for natural gas and future renewable-source GH2 transmission [11, 13]. O'Hashi has proposed pipelines from Alaska's Aleutians via Kamchatka and Kuril Islands, bringing wind-generated GH2 via Hokkaido to Japan [12]. Hirata and O'Hashi have proposed that these new NG pipelines evolve into a widely distributed hydrogen community whereby GH2 is distributed via NG pipelines installed throughout Northeast Asian countries, including Japan [13].

The Eastern Siberia to Far East (ESFE) pipeline project being contemplated by Russia, China, South Korea, and Japan, provides a unique opportunity to research some of the issues associated with alternative energy developments. It may bring hydropower from China as hythane® [14]. However, HVDC or six-phase electricity transmission is formidable economic competition for gas pipelines for baseload hydropower.

3.1 Future conversion to hydrogen capability

GH2 enrichment of gas in these new Northeast Asia NG pipelines will become economically and environmentally attractive well within the lifetime of the pipeline. Once laid, the NG pipelines will have a semi-permanent life [11]. Thus, these new pipelines should be built of line pipe capable of RHS, if:

1. The pipeline ROW traverses areas rich in renewable energy resources, and perhaps in coal for "near-zero-emissions" coal gasification plants, including total C-sequestration [7, 33];
2. Line pipe for this service can be specified, manufactured, and installed with complete confidence in its future utility for RHS;
3. The present value of the future benefits of RHS exceed the incremental capital cost of the installed "hydrogen capable" pipeline over the cost of a standard NG pipeline.

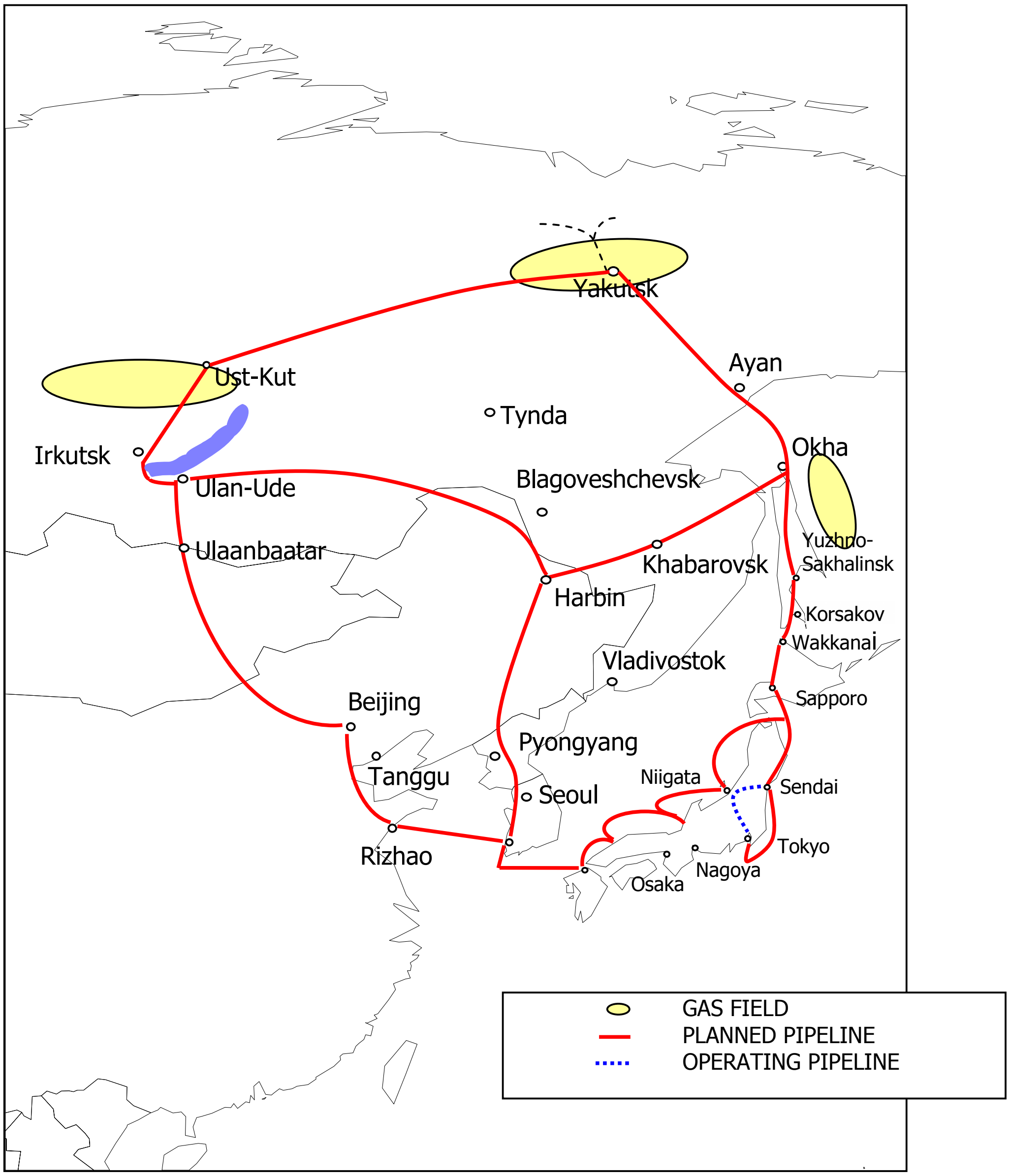

Figure 1. Proposed Northeast Asia Pipeline Network Loop [12]

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 [15]. For economical GH2 transmission they must be capable of continuous service at >14 MPa, although NG pipelines at this pressure are now very rare. The Alliance Pipeline, North America's newest large dense-phase NG pipeline, operates at 12 MPa. Upgrading compressors and other components to GH2-rich service will require large capital investment.

3.2 The International Hydrogen Pipeline Forum (IHPF)

These proposed Asian pipelines have catalyzed a new initiative, the IHPF, whereby world leaders in hydrogen transportation technologies can meet, discuss issues and direct the focus of future hydrogen research. It is intended to promote research into the design, construction and operation of long distance hydrogen pipelines. The scope of the research is to include pipelines and all ancillary facilities associated with the transportation of hydrogen gas, hythane® and hydrothane via pipeline systems [13].

4. HYDROGEN PIPELINE SYSTEM DESIGN

Design of cross-country GH2 pipelines is still uncommon. No industry-accepted codes and standards have been developed to guide the engineering and design of such facilities [16]. Figures 2 and 4 show conceptual wind-GH2 pipeline systems.

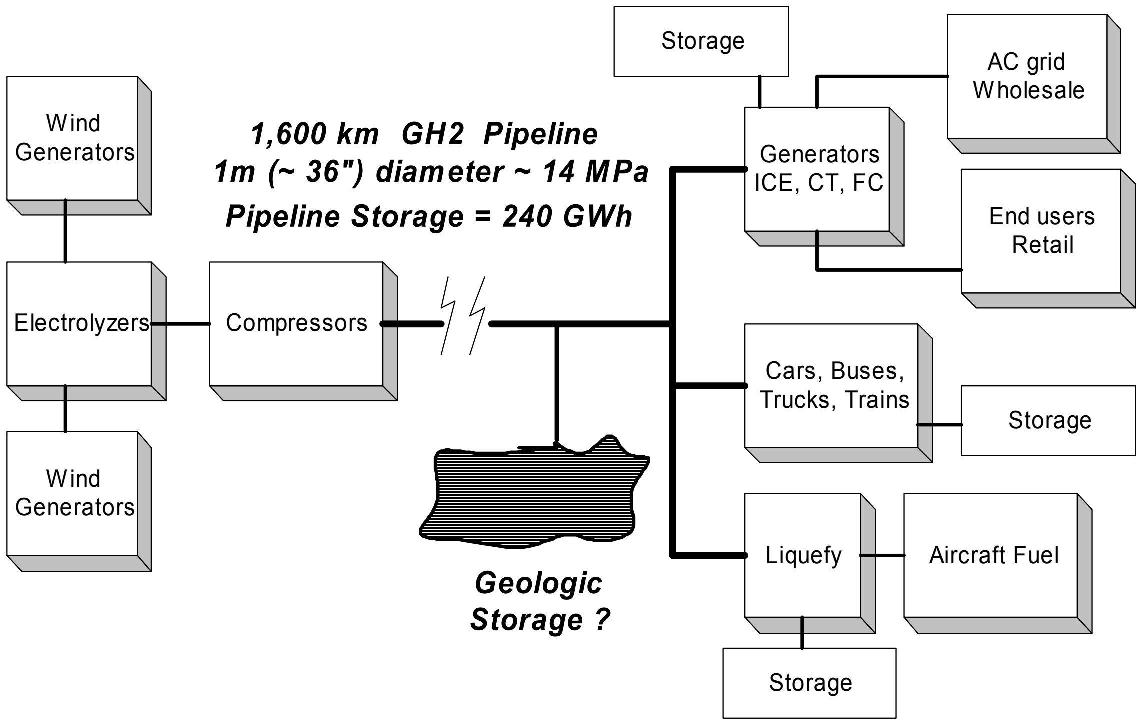

Figure 2. “Renewables Hydrogen Service” (RHS) pipeline Transmission, delivering GH2 from distant wind resources to various users, with potential storage schemes in addition to pipeline storage.

“A greatly expanded distributed infrastructure will be needed to support the expected development of hydrogen production, storage, conversion, and applications… [we should] focus on the development of… pipeline materials, compressors… [17].“ Existing NG pipelines can be used for <15-20% GH2, by volume, without danger of hydrogen attack on the line pipe steel [18]. 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, since the energy content of GH2 is only 10,000 kJ / Nm3, while NG is 33,000 kJ / Nm3 [15]. More compressor power and energy are needed for GH2 service. Integrating generation-conversion-transmission system design for RHS will be important for cost minimization.

4.1 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® 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.

4.2 New specification for RHS needed

The power output of renewable energy sources-- especially wind-- is time-varying at hourly-to-seasonal scale, often unpredictably and randomly. This may be mitigated at regional and continental scale by large-scale transmission integration and geographic-diversity smoothing [19], but this may not benefit individual pipelines. 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.

4.3 Optimizing generation / transmission ratio

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 an 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 an optimum generation / transmission rated capacity ratio.

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.

4.4 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 [15, 16, 20]

In the absence of a GH2-specific specification, Canadian regulatory boards required a GH2 pipeline built in the 1980's to meet [16]:

- Maximum material grade 290; design factor < 0.6;
- Toughness > 30% higher than for comparable NG service;
- Operating temperature < 40 deg C;
- Limit pressure reversals > 3 MPa to fewer than 100 cycles per year.

Furthermore, if steel line pipe is to be used for 100% GH2, it should generally meet [21, 22, 23]:

- Lower-strength, probably X65 maximum grade;
- Sour service standards, which will specify alloys and processing; homogeneous microstructure, less center segregation;
- Very high quality: very few, very small inclusions;
- Low Mn, very low S (< 10 ppm), relatively-low C; low hardenability;
- Thicker wall than for NG, to allow mild HE to the inside surface region, while retaining overall pipe strength and toughness.

Other options for steel pipe for 100% GH2 service [24]:

- Al - Fe (aluminum-iron) alloy, whereby the aluminum provides the inner H_2 barrier, keeping H_2 from permeating the bulk of the steel;
- Variable-hardness pipe, with the harder material in the interior, softer toward the exterior, so that any H2 which diffuses into the interior steel diffuses rapidly outward and escapes.

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.

4.5 CRLP™ line pipe

Figure 3. Composite Reinforced Line Pipe, CRLP™, being developed by TransCanada Pipelines under license from NCF Industries, may be especially attractive for RHS. A high 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. The composite is wound over the external surface of the pipe; its primary function is to increase the pressure carrying capacity of the pipeline by reinforcing the

steel pipe in the hoop direction, and serves as a durable, external anti-corrosion coating [1]. 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 [25].

The stress-strain curves are quite different for the steel liner and 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 [26].

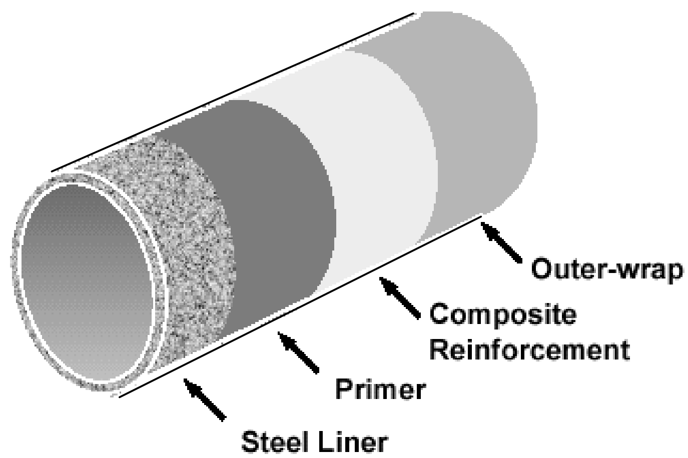

Figure 3. Composite Reinforced Line Pipe (CRLP™).
TransCanada Pipelines, manufactured under license from NCF Industries, Inc. [1].

4.6 Electrolyzers

Electrolyzers crack H_2O into H_2 and O_2 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;
- 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 [3]. 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, and no capital cost estimates are available. GH2 output of the prototype Mitsubishi High-compressed Hydrogen Energy Generator (HHEG) is at up to 34 MPa, so no compressor is needed to feed the pipeline: a major saving in capital and compression energy cost [27]. Proton Energy achieves 14 MPa with their "Unigen® RFC" regenerative fuel cell with no compressor, and might achieve MW-scale [28]. PEM-type electrolyzers now require Pt or other costly catalysts, a barrier to low capital cost.

4.7 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 [29]. However, another study shows compressor power as 145% that required for NG service [35]. Fresh design models for RHS are needed to resolve this important system capital cost. Low density and low molecular weight of H_2 make centrifugal compressors, widely used for NG, useless for GH2 at 14 MPa due to stall and axial rotor displacement. 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. Gas combustion turbines powering mid-line compressor stations would also be custom-designed to operate on pipeline GH2 fuel.

A budgetary capital cost estimate for a 3 MW packaged electric motor drive reciprocating compressor, driven by wind-generated electricity at an input station, is $US 500/ kW [30]. For a 6 GW GH2 pipeline, compression from atmospheric pressure electrolyzer output to 7 MPa requires ~ 200 MW. Gas turbine driven compressors for intermediate stations are available at 20 MW.

4.8 Synergy with wind generators

Modern wind turbines use power electronics to allow variable speed constant frequency operation, for improved annual energy production, to limit drivetrain torque, and to supply quality power to the electric utility grid. If the wind turbine is supplying only an electrolyzer load, deleting the grid-quality requirement may allow significantly lowering the capital and O&M costs of the turbine's electrical generating system, and lowering the transformer - rectifier energy losses now part of the electrolysis process. This is being investigated by USDOE National Renewable Energy Laboratory (NREL) [31].

Norsk Hydro has installed a wind-to-hydrogen energy system, with storage, on the Norwegian island of Utsira, population 250, to investigate this synergy [32].

5. BYPRODUCT OXYGEN SYNERGY

Figure 4 shows a conceptual large-scale, long-distance wind-hydrogen transmission system, suggesting the topology opportunities for gathering, storing, and transmitting GH2, and for using the oxygen byproduct from electrolysis for oxygen-blown gasification of biomass and / or coal. Approximately 18% of world hydrogen production is now from coal gasification [16]. If large-scale carbon sequestration is proven feasible, much more hydrogen could be made from coal in "near-zero emissions" gasification plants [7, 33]. Near-total CO_2 capture and sequestration may be technically practical, at a cost of < $US 0.01 / kWh [33].

The O_2 byproduct of electrolytic production of H_2 from H_2O, is worth ~ $US 12 - 20 / ton at the coal or biomass gasification plant gate. This improves the economics of renewable-source electricity-to-hydrogen production, if the gasification plant is nearby [3]. However, oxygen cannot economically be pipelined far; the electrolyzers must be adjacent to the gasification plant.

6. LARGE-SCALE HYDROGEN ENERGY STORAGE

Figure 4. A 1 m (~36") pipeline, 1600 km long, will store 240 GWh of GH2 if packed to 14 MPa, then unpacked to 7 MPa [3]. Large-scale geologic storage feasibility and cost for hydrogen and oxygen is unknown. Hydrogen, H_2, energy density by volume is one-third that of methane, CH_4. 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, distributed generation (DG) of electricity at the pipeline destination may be always on-peak, drawing GH2 fuel from the pipeline and / or geologic reservoir(s).

Large-scale geological oxygen storage would allow the biomass or coal gasification plants to continue operating when windpower output is low. Oxygen 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.

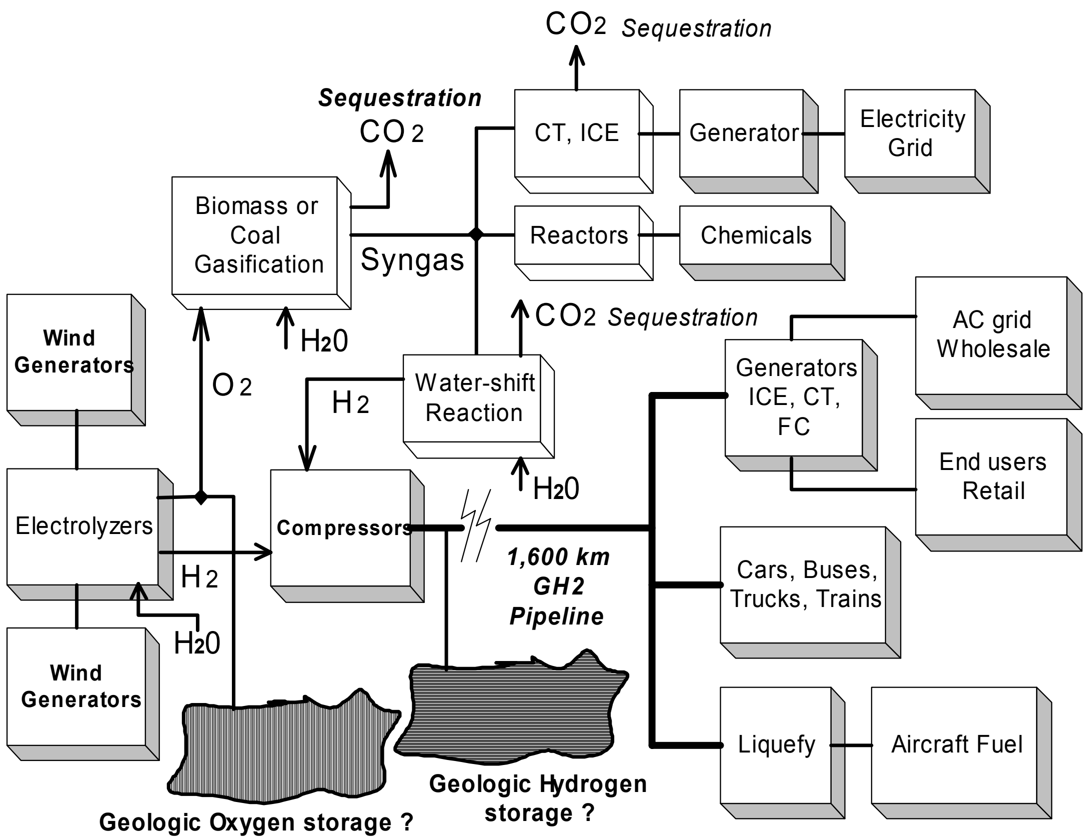

Figure 4. Synergy with biomass gasification or "zero emissions" coal gasification plants adjacent to wind energy sources, using byproduct oxygen from electrolyzers for oxygen-blown gasification. Large-scale geologic storage feasibility of hydrogen and oxygen is unknown.

We now store helium in Texas in rock strata beneath an aquifer, whereby water seals the rock fissures above the helium reservoir, sealing in the He atoms. The H2 molecule may behave enough like the He atom for GH2 storage to work in this way.

The city of Kiel, Germany has been storing town gas (60% - 65% hydrogen) in a gas cavern since 1971; Gaz de France… has stored hydrogen-rich refinery product gases in an aquifer structure near Beynes, France; and Imperial Chemical Industries stores hydrogen in salt mine caverns near Teeside, UK [34]. However, these are smaller scale storage than would be required for large-scale RHS transmission.

Capital costs for underground storage have been estimated at $US 16 - 80/GJ [34] depending on the type of storage used, with solution-mined salt caverns or mechanically excavated caverns at the high end of the range. Amos [36] estimated the capital costs at $US 73/GJ. Taylor et al. [35] projected the lowest capital investments for salt caverns ($US 6.6/GJ) and the highest for depleted gas wells ($US 18/GJ). Operating costs for underground storage are primarily for compression power [37]. However, if high-pressure-output electrolyzers feed the pipeline, the compression equipment and energy costs may be greatly reduced or eliminated.

7. HYDROGEN VS. ELECTRICITY TRANSMISSION FOR WINDPOWER

All sustainable energy sources require conversion from their original form. Conversion to electricity and/or hydrogen will constitute two prominent, complimentary options in the future [36].

A recent study compared the costs of transmitting 4,000 MW (nameplate, peak) of new windpower 1,600 km from North Dakota to Chicago via new HVDC electric lines or via a new GH2 pipeline [3]. Figures 5 and 6 summarize the results of the seven cases analyzed:

- H2-A: 1 m diam pipeline; low-pressure-output electrolyzer requires compressor capital investment and operating energy; electrolyzer efficiency 70% (HHV).
- H2-B: same as H2-A except high-pressure-output electrolyzer eliminates compressor, energy.
- H2-C: 0.5 m diam pipeline; high-pressure-output electrolyzer at 90% efficiency (HHV).
- ELEC-D: two, 2 GW bipoles on two sets of towers.
- ELEC-E: two, 2 GW bipoles on one set of towers, as in Figure 7 (which shows three bipoles).
- ELEC-F: same as ELEC-D, except last 160 km at destination is underground.
- ELEC-G: same as ELEC-E, except last 160 km at destination is underground.

In only the optimistic case, H2-C, does conversion to, and transmission as, hydrogen compare favorably to electricity transmission; conversion and compression losses are big penalties for GH2.

In Figure 6 these lumped conversion and transmission losses are added to the unsubsidized cost of North Dakota wind generation (the same in all cases), resulting in the wholesale selling price of energy delivered to Chicago. Electricity is delivered to utility substation(s). GH2 would be distributed and delivered, at additional cost, as fuel for vehicles and / or for DG of electricity.

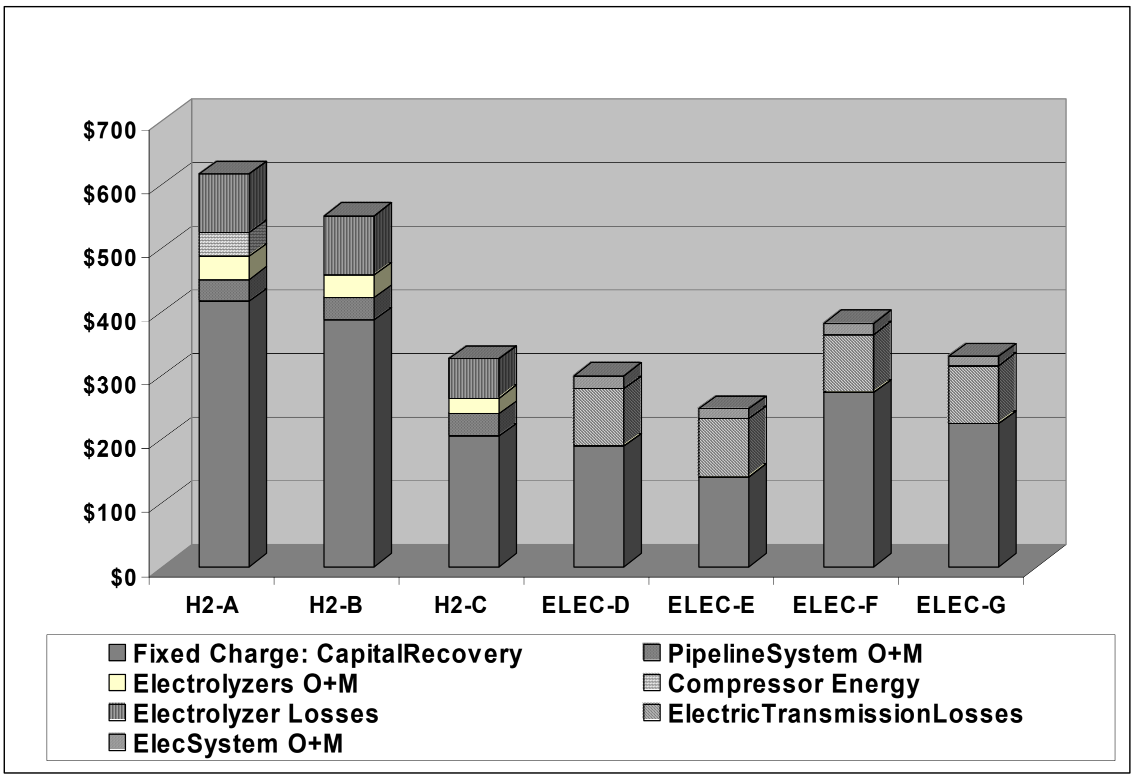

Figure 5. Annual Transmission Costs and Energy Losses, $US 2001 millions.
4 GW (nameplate) windplant, 1600 km transmission from North Dakota to Chicago.
"H2- " are hydrogen pipeline cases; "ELEC- " are HVDC electric transmission cases [3].

Figure 7 shows the relative size of large-scale transmission system components, with multiple maximum-capacity 3 GW HVDC bipole circuits on a single row of towers. DC transmission does not induce currents in the pipeline, so both could share the ROW. The economic choice between these two transmission methods is primarily determined by:

1. Transmission distance. Over ~ 800 km, HVDC is more economical than high voltage alternating current (HVAC); HVDC becomes more economical than GH2 pipeline as distance increases, although we have no empirical evidence of this.

2. Capacity scale. Lowest transmission cost per energy unit for HVDC is achieved at ~ 3 GW per bipole; for GH2 it is probably > 6 GW, but has not been adequately studied. The Great Plains USA wind resource is ~ 2,800 GW [5], so full economy-of-scale should be easily achievable.
3. Whether electricity or GH2 is to be delivered in Chicago, presumably at wholesale. If electricity: the double-conversion from electricity at the wind generator, to GH2 for pipeline transmission, back to electricity in Chicago burdens the pipeline scenario with severe capital costs and energy conversion losses. If GH2: the transmission costs are comparable to HVDC, but the GH2 delivered by the pipeline in Chicago must compete in price with GH2 made in Chicago from NG by SMR. The breakeven price for NG in Chicago, without C-taxes and subsidies, is \$US ~15 - 20 / J x 10^9 (\$US ~15 - 20 / MMBtu).
4. Capacity factor (CF) of the transmission system. If the HVDC system capacity equals the nameplate generating capacity it serves, it will operate at the CF of the generation: about 40%, in the case of the energetic wind resource in North Dakota, USA. The GH2 pipeline system may be somewhat undersized in rated capacity, thus enjoying higher CF than HVDC, because of storage inherent in the pipeline. But CF will be lower than for NG pipelines, unless large-scale geologic storage of GH2 is feasible. Occasional intentional curtailment of generation may be necessary to achieve economic optimality over the complete generation-conversion-transmission system. See discussion in 4.3.
5. Capital costs and energy conversion losses of the components of each transmission system. HVDC is the more mature technology; its costs and losses are better known. Since large pipelines for RHS have not been built, component capital and O&M costs are not known.

Other probable advantages of GH2 pipeline vis-à-vis HVDC transmission would be the relatively:
1. Greater security of underground pipelines vs. overhead electric lines;
2. Greater public acceptance and lower cost permitting for underground pipelines;
3. Lower cost ROW purchase or lease, if less ROW width is required for pipeline.

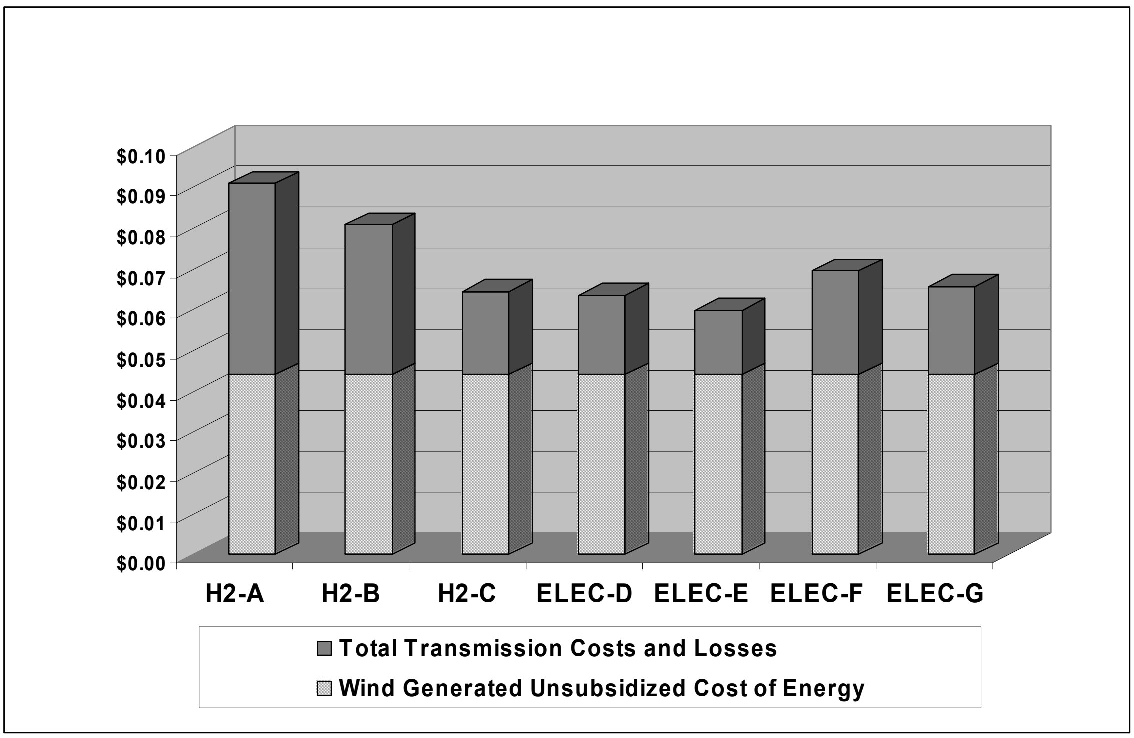

Figure 6. Wholesale price of North Dakota wind energy delivered to Chicago via HVDC and GH2. "H2- " are hydrogen pipeline cases; "ELEC- " are HVDC electric transmission cases, from Figure 5 [3].

7.1 Cost of hydrogen pipeline transmission

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) [37]. 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 [15].

A large-scale GH2 pipeline for RHS, as contemplated herein, has not been built. The costs of extant GH2 pipelines operated by industrial gas and oil & gas companies have not been disclosed, and may be of limited relevance to large-scale RHS. Thus, the capital and O&M costs of large, new GH2 pipelines must be estimated. As in NG pipeline design, interactive optimization of diameter, compressor power, and flow rate is very important to transmission cost minimization. GH2 pipeline energy transmission costs are based on hydraulic engineering principles and the physical properties of the hydrogen gas. A literature survey follows:

- Beghi [37]: Transmission cost is \$US (1973) 0.40 = \$US (2002) 1.63 per GJ of GH2 in this assumed pipeline:
  - a. distance 2,000 km
  - b. flowrate 1,540 Nm3 / sec
  - c. 1.6 m diameter
  - d. compressor power 107 MW
- Pottier [20]: At economic optimum size GH2 transmission system, the cost of GH2 transmission, per unit energy per unit distance, is ~ 1.8 times the cost for NG.
- Ogden [29]: GH2 pipeline capital costs are generally ~ 50 % higher than for NG; the overall cost of GH2 transmission is 1.5 - 3 times that for NG, over a range of pipeline sizes; transmission cost per unit energy generally decreases with distance.
- Reynolds, Slager [38]: In a properly designed system, the cost of GH2 pipeline transmission is 30 - 50 % more than for NG, per unit energy. Compressor power is estimated at 45 % more than for NG.
- Amos [39]: For a 2,600 km GH2 pipeline, flowrate 20,600 Kg / hr, 0.25 m diam, with no input compressor, transmission cost is \$US (1998) 0.46 / Kg.
- Padro, Putsche [40]: Surveys published studies and reports a wide range of GH2 transmission cost resulting from a wide range of size, operating conditions, and assumptions.
- Mann, Spath, Amos [41]: For 10^{12} g GH2 / day transmission for 1,600 km distance, liquid hydrogen (LH2) via rail cars costs less than GH2 transmission via pipeline.
- Mohitpour [15]: It has been estimated that for the same energy flow, GH2 will cost 30 - 50 % more to transport than NG [42].

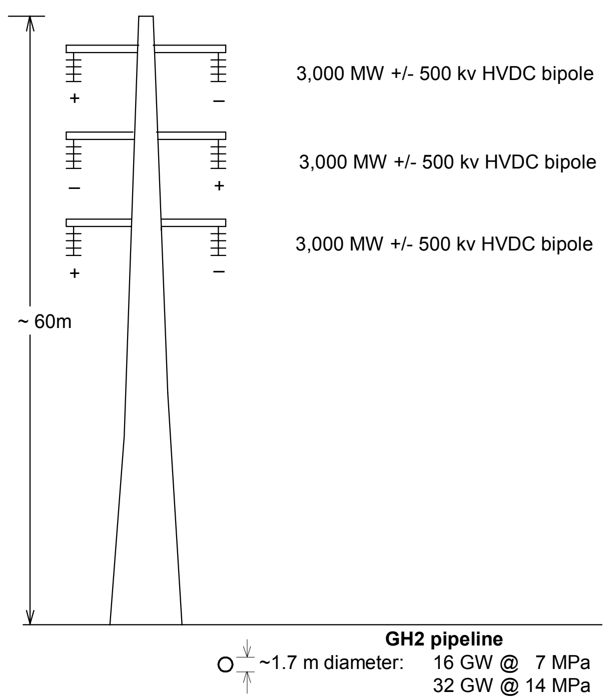

Figure 7. Comparison of high-capacity, long-distance HVDC electric and GH2 pipeline transmission. Total capacity shown: ~9 GW HVDC and GH2 pipeline at ~16 and ~32 GW.

7.2 Advanced transmission concepts: superconducting "Energy Pipeline"

Figure 8. Perhaps neither large-scale GH2 pipeline nor HVDC or six-phase electric transmission is adequate to the task of bringing the renewable energy resources of the Great Plains, Russian Far East, and the Aleutians to market. The Electric Power Research Institute (EPRI) has proposed a superconducting (SC), low voltage direct current (LVDC), liquid hydrogen (LH2) cooled, "Energy Pipeline", with an estimated power capacity of ~100 GW electrical plus ~100 GW LH2 if the coolant is transported and delivered as hydrogen fuel [43, 44, 45, 46, 47]. Installed in a rock tunnel ~ 100 m underground, it would be the backbone of a "Continental Supergrid" [43, 44]. But the Great Plains peak wind energy potential would require the capacity of 10 - 15 of these SC systems [5]. SC-LVDC transmission has been compared to other large-scale schemes: HVDC and gas pipeline [47].

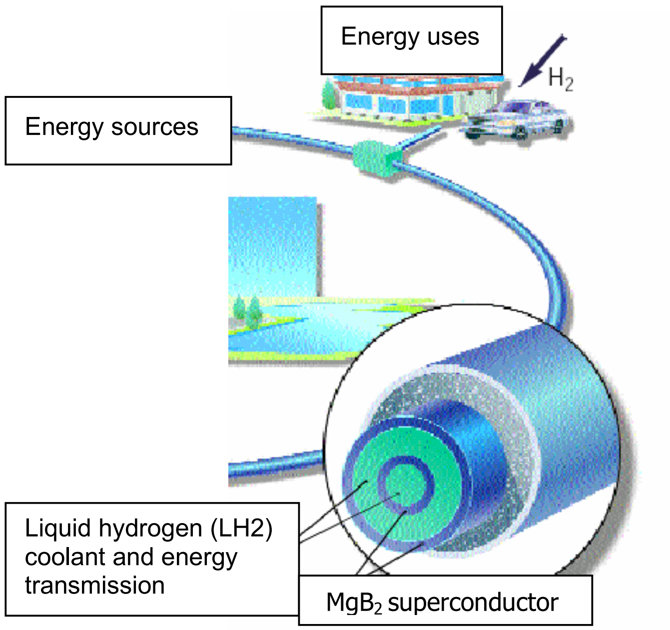

Figure 8. Superconducting low voltage direct current (LVDC-SC) "Energy Pipeline" proposed by Electric Power Research Institute (EPRI) [45]. Estimated 100 GW electrical plus 100 GW liquid hydrogen power transmission capacity. Magnesium diboride (MgB_2) superconductor.

8. IHTTF: INTERNATIONAL HYDROGEN TRANSMISSION TEST FACILITY

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 prospects for RHS pipeline transmission. Fully testing materials and systems for a new technology, gaining regulatory and industry acceptance, often takes decades. CRLP is still in development and testing after six years [1].

Figure 9. The IHTTF 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.

"Research, development, and demonstrations are needed to improve and expand methods of economically producing hydrogen... Demonstrations that integrate production technology with other elements of the hydrogen infrastructure, including a market use, will be more cost effective. These demonstrations should highlight safety and other benefits to stimulate market interest… Demonstrations of developing technologies are rare, leading to a lack of early adopters willing to invest in new technologies and commercialization. Without demonstrations, technologies remain unproven, consumer demand for new products remains weak, and financing and investment communities are slow to feed the capital pipeline. [17] "

8.1 IHTTF Purpose

The proposed IHTTF 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.
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.
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;
    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.

8.2 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. Ames, Iowa, USA, would be a suitable destination: Midwest; population 51,000; home of Iowa State University, USDOE Ames Laboratory.

8.3 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 [48]. 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 IHTTF 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 IHTTF might be a $US 50 - 80 million project.

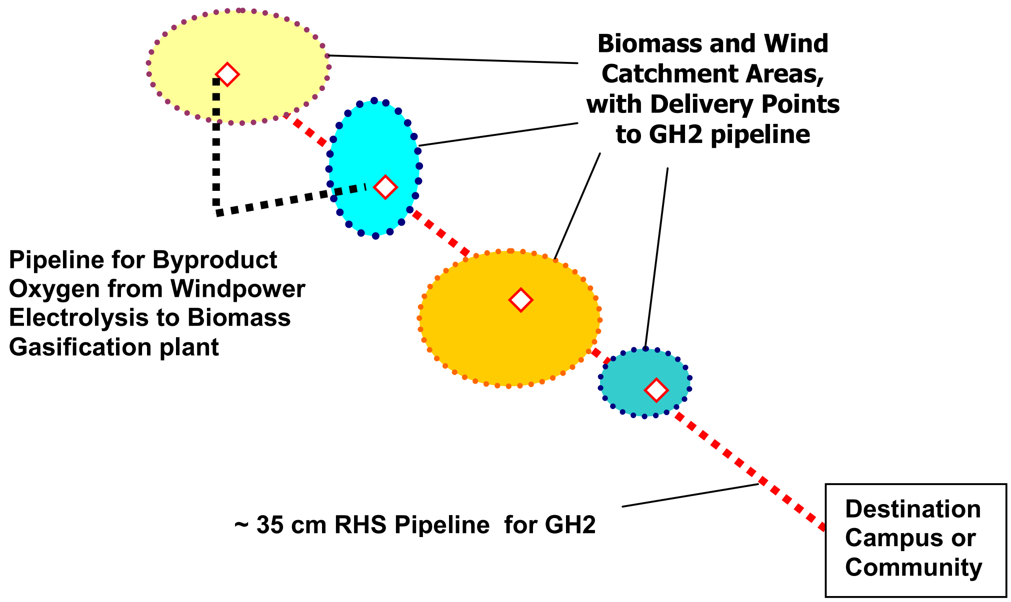

Figure 9. International Hydrogen Transmission Test Facility (IHTTF) concept: a corridor of distributed collection from distributed generation. RHS pipeline ~ 50-100 km long, ~ 10-100 MW , ~ 35 cm diam.

9. RECOMMENDED RESEARCH

9.1 Current best practices

Learn how extant GH2 pipeline systems are designed and operated; what these systems cost to build and operate, per delivered energy-distance unit, long-term. Survey what materials and devices are used. Discern how this experience is applicable to design and costs of large-scale RHS pipelining.

9.2 RHS specification; codes and standards

Engineering, permitting, insuring, and financing RHS pipelines will require confidence in understanding and accommodating their service conditions. RHS must be defined for pipelines capable of and optimized for:

1. Mixtures of NG and GH2 up to 100% GH2; long-term service at 100% GH2;
2. High-pressure (>14 MPa), high-capacity (>5 GW), long-distance (>500 km), cross-country;
3. Buried terrestrial or subsea for their entire length;
4. >100 pressure cycles per year of >7 MPa.

Ensuing from this service definition, appropriate codes, specifications, and engineering standards must be developed for:

1. Line pipe, compressors, meters, and other pipeline system components;
2. Pipeline system design, inspection, and operation.

9.3 Materials and components

Gathering and transmission line pipe must be technically and economically optimized for RHS, as defined, including steel and other metals, composites, and metal-composite hybrids like CRLP™. The line pipe specs must include material composition (alloy; allowed impurities), processing method, microstructure, and allowed inclusions (type, number, size, location, orientation, i.e."quality"); such extreme care is justified as GH2 pipelines emerge from industrial reservations and regions into more public exposure in the nascent "hydrogen economy", in novel RHS.

Nippon Steel has done extensive laboratory testing of line pipe materials exposed to hydrogen, concluding that "sour service X65" of high quality should be suitable for GH2 service [21, 22]. However, they have not operated a long-term test loop at RHS conditions to subject the pipe to cyclic loading, fatigue, and delayed failure. Designers and investors could not now confidently specify line pipe to build an RHS-capable pipeline.

Materials and designs for large-scale compressors, valves, leak detection, and other components must be proven and optimized.

9.4 System design

We need to simulate GH2 pipeline system behavior with time-varying renewable energy inputs, at 100% renewable-source energy, to determine delivery point pressure variability and expected number and magnitude of annual pressure variation cycles, over a range of assumed:

1. Mix of renewable sources, up to 100% wind;
2. Smoothing of renewable-source variability, from geographic diversity [31];
3. Ratio of peak generation to maximum power transmission rating of pipeline; optimum CF;
4. Adjunct GH2 storage, geologic or other, directly available to the pipeline.

This simulation is necessary to define RHS and to optimize pipeline system design and economics: pipeline size and material, pressure range, compression power and station spacing, block valve spacing, and control strategy.

9.5 Large-scale geologic storage

If large quantities of GH2 can be inexpensively stored in geologic formations along RHS pipeline routes, the value of renewable-source energy-- especially windpower-- will be enhanced; this storage has not been tried, and should be investigated.

9.6 Economics

No recent studies of GH2 pipeline economics for RHS have been done, resulting in a circular-reference consensus in the literature that large-scale GH2 pipeline transmission will cost ~ 1.3 to 1.8 times the cost of NG transmission, per unit energy-distance. For designers and investors to have adequate confidence to consider new RHS-capable pipelines, we need to:

1. Build a public-domain Excel model for GH2 pipeline design and economic analysis, proceeding from hydraulic equations and gas properties, with open access to all parameters to encourage interactivity and improvement of the model by its users;
2. Calculate the capital cost differential to build a typical high-capacity, long-distance NG pipeline as RHS-capable;
3. Analyze NPV and IRR of multiple scenarios for converting new RHS-capable NG pipelines to RHS, to determine if new pipelines should be built of RHS-capable line pipe.

10. CONCLUSION

"Even as evidence for global warming accumulates, the dependence of civilization on the oxidation of coal, oil, and gas makes an appropriate response difficult [4]." "By many measures, the world's energy system is not keeping pace with the goals of sustainable development [49]."

"The role of hydrogen to become the ultimate fuel has long been overemphasized. It will eventually not be alternative fuels but the general acceptance of renewable energies that will be required to reduce human health threats… mitigate the greenhouse effect… improve the quality of life… avoid growing political instabilities… [50]."

Bringing 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 both attractive and comparable in unit-energy-distance cost. GH2 pipeline transmission provides energy storage; electricity does not.

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 IHTTF 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 IHTTF 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.

"The Eastern Siberia Far East (ESFE) Pipeline Project provides a unique opportunity to research some of the issues associated with alternative energy developments… The ESFE project should be used as a platform to determine effective means of transporting non-renewable and renewable energies to Asian markets. [14] "

REFERENCES

1. Zimmerman, T., Stephen, G., Glover, A. (2002). Composite Reinforced Line Pipe (CRLP™) for Onshore Gas Pipelines. IPC2002-27125. *Proceedings of IPC02, 4th International Pipeline Conference*, Oct 2002, Calgary. CRLP™ is a trademark of NCF Industries, Inc. CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and foreign patents have been issued and are pending.

2. Harris, R., Saint-Just, J., Asaoka, Y., Thatcher, D. (2001). The Potential for Natural Gas to Contribute to a Hydrogen Energy Future. *Proceedings of the 18th World Energy Congress*, 21-25 Oct 01, Buenos Aires.

3. Leighty, W., Keith, G. (2001). Transmitting 4,000 MW of New Windpower from North Dakota to Chicago: New HVDC Electric Lines or Hydrogen Pipeline. *Proceedings of the International Conference on Hydrogen Age of Asia*, 27-28 Nov 01, Tokyo, Japan.

4. Hoffert, et al (2002). Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. *Science*, 298 - 5598, pp 981-7, 1 November

5. Elliott, D., Wendell, L., Gower, G. Pacific Northwest Laboratory (1991). An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States. Pacific Northwest Laboratory, PNL-7789 / NTIS no. DE91018887, September.

6. Sorensen, B. (2002). Biomass for Energy: How Much is Sustainable? Roskilde Univ., Institute 2, Energy & Environment Group, Denmark mmf.ruc.dk/energy

7. Zero Emissions Coal Alliance www.lanl.gov/energy/est/zeca/ZECA_Factsheet.pdf .

8. www.virent.com Virent Energy Systems, Madison, WI. Aqueous-phase carbohydrate reforming (ACR)

9. Sorensen, B. (2002). Biomass for Energy: How Much is There? Roskilde Univ., Institute 2, Energy & Environment Group, Denmark. mmf.ruc.dk/energy

10. O'Hashi, K. (2001). Northeast Asian Natural Gas Pipeline Network Concepts Proposed by Countries Concerned. October.

11. Hirata, M., Verikhov, E., O'Hashi, K. (2000). Proposals of Japanese and Russian Scientific Engineers Just Before the Okinawa Summit. Zaikai Nippon, pp 60-70. June.

12. O'Hashi, K., Hirata, M., Ono, K. (2001). Wind Power - Hydrogen Hybrid systems and Natural Gas Pipeline Systems in Northeast Asia. *Proccedings of The 14th KKNN Symposium on Civil Engineering*, Kyoto. November 5-7.

13. O'Hashi, K., Hirata, M., Velikhov, E., Knyasev, V., Kuznetsov, V., Benoit, J., Rambach, G. Wind Power – Hydrogen Hybrid Systems and Natural Gas Pipeline System in Northeast Asia.

14. AGRA Earth & Environmental Japan (2000). Hydrogen Technologies and Alternative Energy Sources in the 21st Century. Submitted to Nippon Steel Corp., Tokyo, Japan. February.

15. Mohitpour, M., Golshan, H., Murray, A. (2000) Pipeline Design and Construction: A Practical Approach. ASME Press, NY.

16. Mohitpour, M., Pierce, C., Hooper, R. (1988). The Design and Engineering of Cross-Country Hydrogen Pipelines. *ASME Journal of Energy Resources Technology*, Vol. 110, pp 203-207, December.

17. National Hydrogen Energy Roadmap (2002). USDOE, Nov. www.eren.doe.gov/hydrogen/pdfs/national_h2_roadmap.pdf

18. Ogden, J., Strohbehn, J. (1995). Draft 1/18/95. Assessment of the Feasibility of using Hydrogen Blends and Pure Hydrogen in the Existing Natural Gas System. January.

19. Czisch, G., Ernst, B. (2001). High Wind Power Penetration by the Systematic Use of Smoothing Effects Within Huge Catchment Areas Shown in a European Example. *Proceedings of Windpower 2001*, American Wind Energy Association (AWEA). ISET, Universitat Gesamthochschule Kassel, Germany.

20. Pottier, J. (1995). Hydrogen Transmission for Future Energy Systems. Hydrogen Energy Systems, 1995, pp 181-193.

21. Asahi, H., Ishitsuka, T. Applicability of Line Pipe to Transportation of Hydrogen-Containing Gas. Steel Research Laboratories, Nippon Steel Corporation.

22. Asahi, H., Hirata, M., O'Hashi, K. Hydrogen-Related Damage in Line Pipes. Nippon Steel Corporation.

23. Personal communication, H. Asahi, Nippon Steel, 15 Jan 03

24. Personal communication, W. Chen, University of Alberta, 2 Oct 02

25. Personal communication, Greg Cano, TransCanada Pipelines, Calgary, Jan 03. www.transcanada.com

26. Chen, W., Wang, S., (2002). Room Temperature Creep Behaviour of Pipeline steels and its Influence on Stress Corrosion Cracking. *Proceedings of IPC02, 4th International Pipeline Conference.* IPC2002-27273, Calgary, October.

27. Personal communication, H. Harada, Mitsubishi Corp, Jan 03

28. Personal communication, W. Smith, Proton Energy, Nov 01

29. Ogden, J. (1999). Prospects for Building a Hydrogen Energy Infrastructure. *Annual Review of Energy and Environment*, 24:227-79.

30. Personal communication, Inayat Virani, ENERFLEX Systems Inc., Houston, Oct 02. www.enerflex.com

31. Personal communication, L. Fingersh, NREL, Nov 02

32. www.hydro.com/en/press_room/news/archive/2002_04/utsira_en.html, www.hydro.com/en/products/showroom/winds_change.html

33 . Williams, R. (2001). Toward zero emissions from coal in China. *Energy for Sustainable Development*, Vol V, No. 4, 39 - 65. December.

34. Carpetis, C. (1994). Technology and Costs of Hydrogen Storage. *TIDE (TERI Information Digest on Energy)*, Vol.: 4:1, March, pp. 1-13.

35. Taylor, J., Alderson, J., Kalyanam, K., Lyle, A., Phillips, L. 1986. Technical and Economic Assessment of Methods for the Storage of Large Quantities of Hydrogen. *International Journal of Hydrogen Energy*, Vol. 11, No. 1.

36. C. Elam, C. Padro, et al (2002). Realizing the Hydrogen Future: the International Energy Agency's Efforts to Advance Hydrogen Energy Technologies. *Proceedings of the 14th World Hydrogen Energy Conference*, Montreal, 9-13 June 02.

37. Beghi G., Dejace, J. (1975). Economics of Pipeline Transport for Hydrogen and Oxygen. Hydrogen Energy, *Proceedings of the Hydrogen Economy Miami Energy (THEME) Conference*, March 18-20, 1974, pp 545-560. T. N. Veziroglu, editor.

38. Reynolds, R., Slager, W. (1974). Pipeline Transportation of Hydrogen. *Hydrogen Energy, Part A and Part B, Proceedings of the Hydrogen Economy Miami Energy (THEME) Conference*, March 18-20, 1974, pp 545-560. Plenum Press, NY and London, 1975. T. N. Veziroglu, editor

39. Amos, W. (1998). Costs of Transporting and Storing Hydrogen. NREL/TP-570-25106. November.

40. Padro, C., Putsche, V. (1999). Survey of the Economics of Hydrogen Technologies. NREL (U.S. DOE), NREL / TP-570-27079, September.

41. Mann, M., Spath, P., Amos, W. (1999). Studies on the Production and Delivery of Hydrogen from Renewable Resources. Presented at the U.S. DOE Hydrogen Program Review. NREL / CP-570-26938, pp 754-772. http://www.nrel.gov/docs/fy00osti/26938.pdf

42. McAuliffe, C. (1980). Hydrogen and Energy. The MacMillan Press Ltd., London

43. Electric Power Research Institute (EPRI), (1999). Electricity Technology Roadmap. p. 4, 30 www.epri.com

44. Starr, C. (2001). Electric Power Research Institute (EPRI). National Energy Planning for the Century. American Nuclear Society, Annual Meeting, Reno, NV. 13 Nov.

45. Grant, P., (2001). Electric Power Research Institute (EPRI). Will MgB_2 Work?, *The Industrial Physicist*, Nov-Dec 2001, pp 22-23.

46. Garwin, R., Matisoo, J. (1967). Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances, *Proceedings of the IEEE*, Vol. 55, No. 4, April.

47. Schoenung, S., Hassenzahl, W. (1997). System Study of Long Distance Low Voltage Transmission Using High Temperature Superconducting Cable, WO8065-12 Final Report, Longitude 122 West, Inc. March.

48. Personal communication, K. O'Hashi, Nippon Steel Corp., March 01.

49. The Program on Energy and Sustainable Development at Stanford, Research Plan. April 2002

50. U. Buenger, (2001). LBST, Ottobrunn, Germany. Current Status and Perspectives of Hydrogen Energy related Activities in Germany. The Japan Hydrogen Forum. *Proceedings of The International Conference on Hydrogen Age of Asia*, Tokyo, 27-28 Nov 01.