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Pipelining Hydrogen; World Gas Conference paper

Please see our "Pipelining Hydrogen ..." paper presented at the World Gas Conference, Daegu, Korea, 23-27 May 22: (a) It warns that we do not know how to safely and profitably pipeline GH2, blended or high-purity, in extant NatGas or other steel pipelines, because of HE, HCC danger and of great difficulty in assessing FFS of extant pipelines; (b) It recommends commencing immediate RD&D program to develop and certify novel linepipe designs and in-firld, on-site manufacturing methods to enable re-lining extant steel pipelines with new linepipe with very low GH2 permeation and very high resistance to HE, HCC; (c) It recommends immediate launch of plan, design, build, operate tasks for a complete renewables-source, underground pipeline system of H2 generation, gathering, transmission, "packing" storage, and distribution of "clean" GH2 -- which might be included in "Angeles Link" scope, or in a separate pipeline system; (d) It warns to beware of imminent tech and econ progress toward profitable energy delivery from deep hot dry rock geothermal (DHDRG) energy, which is generally ubiquitous on Earth, and could thus obviate the need for new transmission and energy storage infrastructure CAPEX of either Grid or GH2 systems, and perhaps obsolete large, distant, wind and PV VER plants. Perhaps this will help guide the Clean Hydrogen Program through the pipeline challenge and opportunity we now face. Thank you.

Additional submitted attachment is included below.

William Leighty
Director, The Leighty foundation
Aron Ekelund
Director of Operations, Smartpipe® Technologies
Robin McIntosh
Director of Business Development, Smartpipe® Technologies

Industry Insights: **II12**
Cleaner Energy: Which Role will New Gases like Hydrogen, Biogas or Syngas Play in the Future?

Pipelining Hydrogen: Why ? Gas or Liquid ? Blend with NatGas or high-purity ? Continental Scale ? Repurpose Old Pipes or New-Build ? Free "Packing" Storage ? Salt Cavern storage access ? REV D

A. INTRODUCTION

We assume that humanity's, and the gas industry's, urgent goals are:

1. Near-total de-carbonization and de-GHG-emission of the entire human enterprise, as quickly as we prudently and profitably can: Prudently -- this will be disruptive, but we must not cripple the global economy. Profitably -- the large amount of capital needed will flow only to investments with attractive reward-to-risk ratios, favoring large economic and geographic scales. [1-10, 13-17, 38-42]
2. Transforming the world's largest industry from ~ 85 % fossil to ~ 100 % renewable, GHG-emission-free, "clean", energy resources, like "green" hydrogen (H2). Our present Climate Emergency requires rapid transformation: we need all the clean energy we can get, via all the safe and profitable pathways we can deploy, including gaseous hydrogen (GH2) and liquid anhydrous ammonia (NH3), "the other hydrogen"; pipeline systems for gathering, transmission, free "packing" storage for GH2; and distribution from diverse, dispersed, off-Grid clean sources.
3. Repurposing extant oil and gas (O&G) pipeline assets for safe and profitable long-term supply of energy services and industrial feedstocks [E+IF], via molecules derived from GH2 and NH3 as energy carriers, storage media, and fuels, at diverse, distributed points-of-use.

The nascent renewables-source H2 and NH3 industries, and the total [E+IF] economic sector in which they are embedded, are now at a transforming, promising, but dangerous point:

1. Without totally eliminating anthropogenic GreenHouse Gas (GHG) emissions, primarily carbon dioxide (CO2) and methane (CH4), by about 2050, humanity risks catastrophic global climate change (GCC). Fig. 39. [8, 9, 19-23]
2. We need to think, plan, and invest in synergistic "whole systems" strategies for the total [E+IF] demand of the entire human enterprise; our horizon is beyond year 2050. Figures 2 - 8. [1-11, 13-20, 55-60, 67, 68]
3. Attempting this total GHG abatement via the electricity system, i.e. Grid, alone, will probably be technically and economically suboptimum, and take too long, vis-a-vis systems and strategies based on H2 and NH3 carbon-free energy carriers, energy storage media, and fuels. Fig 11. [4-10, 11, 12].
4. Very large amounts of GHG-emission-free H2 and NH3 will be required for this [E+IF] transformation; most of it will be produced in off-Grid solar, wind, and other renewables plants, reducing CAPEX, OPEX, and plant-gate H2 cost vis-a-vis plants designed only for Grid delivery, thus opening large new land areas without electricity transmission to renewables energy harvest. Figs. 3.5. [18-26]

   Moving "clean" energy made from photons, moving air and water molecules, and / or from other renewable or even benign nuclear sources, to delivered energy services and industrial feedstocks

[E+IF], will require pipelining H2 and NH3. Trucks cannot practically nor profitably move the H2 and NH3; new, large, dedicated, high-purity, high-pressure, variable-pressure, GH2 and perhaps also liquid H2 (LH2) pipeline networks will be necessary, for gathering, transmission, "packing" storage, and distribution. Conversion to liquid NH3, "the other hydrogen", is easier. [3, 6-8, 11, 21-23]

5. We don't know how to design and build such GH2 pipeline networks that will be safe -- especially from H2 embrittlement (HE) and H2 corrosion cracking (HCC) of steel -- and to be profitable and publicly acceptable. Current enthusiasm for H2's role in arresting rapid GCC lacks appreciation for the difficulties and dangers of handling H2, as a molecule and a commodity, at large volumes and geographically pervasive scales; [23, 25, 26]
6. Heed E, below. We don't know how to expeditiously convert extant pipeline networks to safe and profitable GH2 service," blended" or high-purity, primarily because of the difficulty of assessing these pipelines' Fitness For Service (FFS), thus free of HE, HCC danger of each and every candidate GH2 pipeline, including every square cm of linepipe and weld joint -- all vulnerable to HE, HCC.
7. Public-private collaborative investment in many R&D&D projects for pipelining H2 should begin now; let us catalog the projects, estimating their costs in dollars and time, and earnestly sell them to patrons and investors. [16-18, 28, 29, 31-33]
8. We now also need to create a continuous and persistent analytic mechanism -- to at least year 2050 -- for adjusting optimum allocation of policy, markets, and CAPEX among Grid, H2, and NH3 as the "whole [E+IF] system" for our urgent goals, above. We depend upon profit-motivated markets to efficiently pursue these allocations, once established in policy.

B. OBJECTIVES

We wish to warn the Oil & Gas (O&G) and H2 industries not to assume that extant pipeline assets are "Hydrogen ready", nor that they may be safely, technically, and economically refurbished for GH2 service fed by Variable Energy Resource (VER) (wind, solar, and other time-varying output, GHG-emission-free, renewable) sources. Don't assume "H2 certified" linepipe safe for VER GH2 use. [74,75]

Furthermore:

1. The energy industry is slowly realizing that we cannot adequately, and quickly enough, decrease anthropogenic GHG emissions via only the Grid; Fig. 11, 38. [18-26]
2. H2- and NH3-based energy systems will only be strategically useful and profitable at very large geographic and economic scales, requiring pervasive new pipeline-based infrastructures;
3. Recent rapidly-growing interest in H2, as a carbon-free energy carrier, storage medium, and fuel, has attracted many to "the next big thing", perhaps a much-anticipated but elusive Climate Change panacea, who don't realize "how difficult hydrogen is" -- as a molecule, substance, strategy, integrated and optimized system, and business case.
4. We do not now know how to safely and profitably pipeline GH2 at the scale we will probably need to quickly and economically achieve humanity's goals, above. The nascent H2 industry cannot tolerate any significant pipeline failures. We will learn from a spectrum of great R&D&D investments; we catalog the urgent ones, below. Meantime, heed E, below.
5. We assume, and focus upon, local-to-global energy systems that are at once: benign, complete and integrated, baseload, firm and dispatchable, synergistic, and inexhaustible -- from photons and moving air and water molecules, to delivered energy services and energy-derived industrial feedstocks [E+IF]. Figs. 2 - 11. [1-11, 13-20, 55-60, 67-68]

Therefore, this paper will explore several diverse aspects of pipelining H2, to improve prospects for technical and business and society success, and for safety. Our wise investments and preparations for beyond year 2050 should profit from these opportunities:

1. By 2050, total daily and annual demand for H2, in USA and globally, for total [E&IF], will be larger than total electricity demand, in markets like California and USA. By 2050, California will probably need ~ 7 million tons (MMT) per year of high-purity hydrogen fuel for all sizes of highway transport vehicles; rail, marine, and aviation demand is harder to predict, but will increase that to well beyond 7 MMT / year. Grid transmission cannot supply it; attempting Grid supremacy will delay total global de-carbonization and inflate its cost. We shall avoid this suboptimal strategy. Figs. 10-11. [43-54]

2. Trucking large volumes of high-purity GH2 or LH2 is logistically impractical, and will be unprofitable; GH2 pipeline networks, for gathering, transmission, "packing" storage, accessing low-cost annual-scale firming storage, and distribution will be required. These will be a combination of repurposed and refurbished -- perhaps re-lined -- extant steel pipelines and new-builds, the latter perhaps of novel linepipe designs, materials, and manufacturing methods. Figs. 7-12.

3. New, dedicated, high-pressure, variable-pressure, high-purity GH2 pipeline networks sourced by GHG-emission-free VER's (wind, solar, etc.) must be built of linepipe highly resistant to HE and HCC, to endure the large and frequent pressure fluctuations that VER's will inflict upon pipeline networks, especially at gathering lines. Today's SMR-to-refinery protocols for low and constant pressure are too constraining for profitable VER-source service. Figs. 13-15, 31-35. [77]

4. Realize low-cost, annual-scale, TWh-scale, energy storage, by which to render diverse renewables profitably firm, and dispatchable at continental and total [E+IF] scales. "Packing" GH2 pipelines will provide large "free" energy storage, if they are built of linepipe highly resistant to HE, HCC, as in 3, above. A continental-scale GH2 pipeline network could access domal salt and / or hard rock geology suitable for cavern storage of compressed GH2, for affordable annual-scale firming storage at < $1.00 / kWh CAPEX, plus modest OPEX, mostly for compression. North America Gulf Of Mexico (GOM) domal salt could host thousands of solution-mined salt caverns at ~ 100 GWh each, as chemical energy in GH2 molecules, enabling "running the USA on renewables" via C-free gas. Figs. 7-10.

5. Compare Grid, H2, and NH3 whole-system strategies. Attempting to expand and "smarten" electricity systems, i.e. the Grid, to achieve total de-carbonization and de-GHG-emission of the entire human enterprise, as quickly as we prudently and profitably can, may be technically, economically, and aesthetically inferior to building hydrogen systems as discussed in this paper. [18-22]

6. Consider how to prevent over-dependence upon, and over-investment in, electricity systems, i.e. the Grid. This attempt to optimally allocate policy, markets, and CAPEX among total [E&IF] systems based on electricity, hydrogen, anhydrous ammonia (NH3), and perhaps other energy carriers and storage media, will be essential and should begin soon, by creating a new, continuous, interdisciplinary, analysis and optimization process to beyond year 2050.

7. Explore novel linepipe materials, designs, and manufacturing methods for profitably repurposing extant pipeline systems, and for new-builds, highly resistant to, or immune to, HE and HCC, for GH2 service. Figs. 13-19, 31-33. [77]

C. METHODS Figs. 2-11, 40 [1-11, 13-20, 55-60, 67-68]

The "total systems" optimization approach guides this paper, to propose complete, integrated, GHG-emission-free [E&IF] systems designed to accelerate achieving humanity's goals in A, above.

We intend this paper, and The Leighty Foundation responses to the 2021 DOE RFI FOA's # 2466 and 2498, to help guide the necessary hypothesis testing program work, below: [38-42]

1. "Think beyond electricity", to total [E&IF] systems design, at regional, continental, and global scales, and to certifying new GH2 linepipe designs and manufacturing processes highly resistant to HE, HCC. The goal is safe, whole-system profitability -- from energy capture and conversion to H2, to

gathering and transmission of H2, to "free" energy storage by pipeline "packing", to distribution for end use energy services and energy-derived industrial feedstocks [E+IF].

2. Assume that most of our new clean [E+IF] will come from off-Grid, rich (high intensity, geographically extensive), diverse, stranded, remote, VER renewable resources -- such as wind and solar -- via new GH2 and NH3 pipeline systems. We thus greatly expand our renewables energy harvest to large land areas now without electricity transmission. Build GH2 transmission, instead.
3. Imagine that off-Grid, GHG-emission-free H2 production will prevail over the Grid for total [E+IF], thus requiring a new GH2 pipeline infrastructure, a combination of repurposed legacy pipelines and new-builds. GH2 and NH3, as optimized systems, comprise "complementary vectors" to the Grid, which may evolve to be the technically and economically superior "primary" vectors.
[10-12, 18-26, 44]
4. Anticipate near-total de-carbonization and de-GHG-emission of the entire human enterprise, whereby the gas pipelines evolve to become the strategic optimization of Grid vis-a-vis complete H2 and NH3 systems. We prevent over-dependence upon, and over-investment in, electricity (Grid) systems. Describe and justify the need to develop -- and maintain for decades --a new analytical framework for continuous analysis and optimized allocation of policy, markets, and CAPEX among Grid, H2, NH3, and perhaps other GHG-emission-free systems, to supply total [E+IF] for the entire human enterprise, in an expeditious and profitable total system transformation.
5. Regard every H2 and NH3 pipeline as also a water pipeline, often as vectors of inter-basin transfers from energy source feedstock H2O for H2 and NH3 production, to recovery of the valuable, high-purity H2O exhaust byproduct at points-of-use. This must be part of total [E+IF] system Technical + Economic Analysis (TEA). That pure exhaust H2O must be recovered and well used.
6. Explain the limitations to steel linepipe and pipeline systems, especially from dangerous HE, HCC, in E, below:
    a. All steel components; H2 degradation of other metals, and in polymers;
    b. Linepipe, weld joints, couplings, valves and meters, input and output fittings are affected; legacy pipeline damage and external stresses may dominate;
    c. Establishing high-confidence "Fitness For Service" (FFS) of legacy pipelines for safe VER-source GH2 service may be very difficult, expensive, or impractical;
    d. Caution gas utilities about considering repurposing legacy steel pipelines for GH2 service, whether for blending GH2 with NatGas or for high-purity GH2;
    e. Encourage considering extant pipeline systems as durable, fully amortized conduits:
        i. Hosting new pulled-in linepipe highly resistant to HE, HCC, at higher MAOP;
        ii. Capturing fugitive H2 leaking from linepipe and splices for safe scavenging;
        iii. See J.5.c, below .
7. Question claims by NatGas utilities and linepipe suppliers that their pipelines and linepipe products are declared "qualified for H2" or "ready for H2": [74,75]
    a. Under what circumstances could they safely be usable, as FFS, with great certainty ?
    b. How could we practically and affordably inspect, assess, and certify such legacy pipeline FFS, especially for VER-source GH2 service ? (6.c, above)
8. Describe the R&D&D needed for design and high volume manufacturing methods; for codes and standards for, and certification of, novel linepipe materials and BOS components highly resistant to HE, HCC for GH2 in VER (wind, solar, etc.) service at high volume. This service embraces: regional- to continental-scales; transmission service; gathering, "packing" storage, and distribution GH2 pipeline service, both onshore and from offshore renewables sources, with acceptable H2 system leakage. Figs. 13-15, 16-18, 20, 31-38. [55-58]
9. Describe how we will discover, through comprehensive R&D&D, how to design, repurpose, or new-build GH2 pipeline systems for safe and profitable "clean" VER-source service, including linepipe,

couplings, valves, meters, and input / output nodes. Safety includes minimizing fugitive H2 infrastructure emissions, which have some global warming potential (GWP). [33-36]

10. Consider how to build both supply and demand volume and revenue for clean GH2 for total [E&IF]:
    a. Reduce delivered long-term H2 cost / kg, both at plant gate and at point-of-use (POU) via volume production of both capital equipment and of H2;
    b. Incrementally, then grossly, decarbonize total [E&IF] for the entire human enterprise;
    c. Achieve profitability at all H2 and NH3 industry components and enterprises. [1-10]
11. Adopt regulatory and industrial policies to optimize allocation of markets and CAPEX among Grid, H2, NH3, and other [E&IF] technologies and strategies; avoid over-dependence upon, and over-investment in, the Grid; create a novel mechanism for continuous analysis and for updating corrections to this optimization. [1-10, 55-58]
12. Invest wisely the new 5-year USDOE funding for both "Hydrogen Hubs" and "Hydrogen Production and Electrolysis" programs, to launch this new "whole-systems" approach to pursuing our urgent goals, above. This should include an "International Renewable Hydrogen Transmission Demonstration Facility" (IRHTDF), as some sort of an over-arching R&D&D project to discover and demonstrate the above needs and steps. Every "H2Hub" should include an R&D&D GH2 pipeline system of adequate size and complexity to produce useful technical and economic R&D&D results in the context of an IRHTDF or similar facility. Fig 12. [46-54]
13. Consider how the nascent H2 and NH3 industries may help, and benefit from, establishing linepipe designs, and pipeline operations and management protocols and standards, as will be required for the nascent projects in G, below, as they require moving large quantities of GH2 via pipelines.
14. Consider the potential for pipelining liquid hydrogen (LH2) short distances, especially for bunkering cruise ships, where NH3 fuel is probably too dangerous. The Port of Vancouver, BC, could soon become a part of the world’s first cruise-led “green corridor” – a maritime route championing zero greenhouse emission practices – stretching from Seattle to Alaska. The Vancouver Fraser Port Authority joined a number of other ports and cruise lines in May '22 to announce the “First Mover Commitment,” to explore the feasibility of a green maritime corridor in the Pacific Northwest. [79]

D. WHY PIPELINE HYDROGEN ?

1. For decades the O&G industry has pipelined GH2 short distances (~ 1 - 100 km) from large NatGas-fueled Steam Methane Reformer (SMR) plants to, within, and among oil refineries for "hydrotreating". Most of today's global H2 production moves this way; this will continue. Fig. 1.
2. Humanity's present "Climate Emergency" presents a large, urgent demand for GHG-emission-free "clean" energy from all sources, via all benign and profitable energy systems, including those based on H2 and NH3. We will need all profitable energy moving and storage systems to satisfy growing global demand for high-purity H2 for [E+IF] at low "carbon intensity" (CI): "green", "blue", etc. [27, 28, 44]
3. We must encourage and allow profitable access to diverse, stranded, synergistic, large, GHG-emission-free renewable energy resources, including on large land areas without electricity transmission. Pipelining GH2 and liquid NH3 are lower- cost, better alternatives to electricity "transmission" and the Grid as a system: think pipes, not wires; new GH2 pipeline systems, both as repurposed extant pipelines and as new-builds. Figs. 2-11. [18-28]
4. Trucking is logistically impossible and too costly at the high GH2 "transmission" volume and long distances required to move total [E+IF] H2 and / or NH3 for the entire human enterprise.
5. Underground GH2 pipeline systems require lower CAPEX and OPEX than electricity transmission, per MW-km of transmission capacity, at large scale and long distance, and are more resilient than electricity systems and protected from acts of God and man: Figs 2-12, 25-29 [55-58, 61, 62, 66-72]
    a. Multi-GW capacity: ~ 10 GW, as GH2 equivalent kg / second, for a 36" GH2 pipeline;

   b. Aesthetically preferable to overhead electricity lines; faster permitting for new-builds;
   c. No perceived EMF danger to humans;
   d. Less susceptible to CME and EMP and cyberattack;
   e. Less liability threat: fires, electrocution;
   f. Lower threat to wildlife;
   g. Lower OPEX, including O&M.
6. GH2 pipeline systems provide "free" energy storage by "packing", from MAOP to ~ 1/2 to 1/3 MAOP, if the linepipe is adequately resistant to HE, HCC. Figs. 3, 7, 8, 38. [17-25, 73]
7. Low-cost access to domal salt geology where large, man-made, solution-mined salt caverns may be constructed for profitable annual-scale firming storage of GH2.
8. New linepipe designs and construction methods will probably be needed, and will be designed and commercialized for profitable regional-to-continental-scale service, to enable:
   a. Long-term high resistance to HE, HCC;
   b. Relining and repurposing extant steel pipelines; redesign, certify at higher MAOP than 100 bar. See F, below. Figs. 13-15, 29-38. [29-32, 59-62, 77]
9. Economical renovation and repurposing potential for extant legacy O&G pipelines:
   a. Phasing out hydrocarbons creates stranded assets: 290,000 km of NatGas transmission pipelines, 30 - 36 inch diameter; ~ 5 million km total of legacy pipelines in North America.
   b. Extensive extant infrastructure, but difficult to assess for GH2 service: blend or high-purity ?
   c. Options to safely refurbish, renovate, reline, or internally coat for HE, HCC immunity are now unknown and unproven: a major R&D&D opportunity. [13-19]
10. Liquid H2 (LH2): Mature technology; limited demand, unless widely adopted by aviation and marine. Applications are apparently only for short distances (~ 1 km) except (e), below.
    a. Rocket fuel: legacy, at launch ports. Supply via LH2 truck from SMR plants.
    b. Truck fleet fuel: high utilization; boiloff loss less important
    c. Aviation: aircraft, probably 737 and larger, a la Airbus "Cryoliner", circa 2005. Fig. 24
    d. Cruise ship bunkering, especially for Alaska tours from Vancouver, BC, and Seattle, WA. [79]
    e. Continental "SuperGrid" -- EPRI concept, 2005. Fig 20. [59, 79]
11. Blending a small (~ < 20%) amount of GH2 in NatGas pipeline networks may be useful in short term: [45-47, 69]
    a. Transmission marginal cost is very low, or negligible; utilities tariffs will probably not be;
    b. Energy storage marginal cost, by "packing", is very low, or negligible;
    c. Gas utilities' service charge for a, b are unknown;
    d. A blending standard, analogous to the RPS for electricity, would provide a very large market for GHG-emission-free H2, scaling-up "green" H2 production, thereby lowering CAPEX for both renewable energy capture and H2 conversion equipment and reducing plant-gate H2 cost; OPEX is also lowered by scaling;
    e. Incrementally decarbonizing the fuel supply to all downstream NatGas utility customers.
12. Gathering and transmission of offshore wind to onshore markets, assuming off-Grid electrolysis and / or NH3 synthesis, at each wind turbine or at offshore gathering and conversion module:
    a. Electrolysis in seafloor modules, enjoying "free" GH2 compression by the water depth. [60]
    b. Optimum topology needed for gathering and transmission to shore by GH2 seafloor pipeline.
13. Today's large market for ammonia (NH3) production requires very large quantities of GH2, usually pipelined short distances from an integrated or adjacent SMR plant, now without CCS for the SMR byproduct CO2. However, future replacement of fossil-source H2 with "clean" H2 may require long-distance GH2 pipeline transmission to NH3 plants, with inherent pipeline "packing" storage if the H2 is from VER sources. Figs. 4, 21-23. [11,12]

14. Ammonia, NH3, is a higher-H-density hydrogen carrier than LH2: a liter of liquid NH3 contains ~ 70% more H atoms than a liter of LH2. Thus, for several technical and economic reasons, we may prefer pipelining H as NH3 rather than as GH2. NH3 is a liquid at ~ 10 bar at 25 C; it does not attack steel. Legacy O&G pipelines could easily be converted to ~ 10 bar liquid NH3 service at high power (energy / time) (MT / hour). NH3 energy density per barrel is about half that for crude oil; NH3 viscosity and pumping cost per barrel-km is lower. Figs. 21-23. [11, 12, 18-21]

E. STEEL PIPELINES FOR GH2 SERVICE

HyBlend report by C. San Marchi, J.A. Ronevich, Sandia National Laboratories, Livermore CA. [64-73]

Gaseous hydrogen has a considerable effect on fatigue and fracture resistance of steels, including line pipe steels. These effects are important because fatigue crack growth and fracture resistance are properties used directly in fitness-for-service (FFS) assessments of pressure pipe as described in API 579/ASME FFS-1 and ASME B31.12. If the appropriate properties are measured in the relevant service environment, the FFS process is largely unchanged for a hydrogen-containing system; only the materials property inputs are different.

More work is necessary to establish the bounds on the consistency of fatigue and fracture properties, for steels and for all materials, in gaseous hydrogen environments. However, general trends from the literature suggest that line pipe steels show consistent fatigue crack growth in gaseous hydrogen across API grades and fracture resistance greater than the threshold value in ASME B31.12. If these general trends can be firmly established, then the baseline performance of the materials is largely known; statements by pipe manufacturers that their steels are compatible with hydrogen are likely an acknowledgement of these trends. However, structural integrity assessment is dependent on two additional considerations: (1) characteristics of the structure, including defects, damage, state of the welds, etc., and (2) externally applied stresses and strains. In other words, identifying a material as appropriate for hydrogen service is not equivalent to identifying a pipeline as safe for hydrogen service. It is a common misconception that the materials determine the suitability of a system for hydrogen service. However, if materials properties are known and do not vary substantially, FFS will be determined principally by the structural defects (e.g. welds), operating conditions, and external influences.

Since the structural aspects of a pipeline are specific to the installation, it is difficult to generalize the *structural performance* of pipelines. However, the *materials performance* can be generalized to some degree. FFS is determined by two basic phenomena: fatigue and fracture. The fatigue and fracture properties of line pipe steels are unequivocally affected by concurrent exposure to gaseous hydrogen in laboratory tests. Fatigue crack growth rates, for example, are known to be substantially increased in the presence of hydrogen. The fatigue crack growth in gaseous hydrogen is not dependent on the steel grade, as shown in Figure A. All grades seem to show similar fatigue crack growth rates for the same hydrogen gas pressure. The observation that different grades of pipeline steel show similar fatigue crack growth in hydrogen should not be surprising, since different grades show similar fatigue crack growth in air; API 579/ASME FFS-1 provides Paris Law relationships for fatigue crack growth rate in air or in non-aggressive environments that are generic to the class of steel (not the grade), such as ferritic steels or ferritic-pearlitic steels.

Detailed characterization of fatigue crack growth of line pipe steels reveals two principal regimes of fatigue crack growth: (1) a high stress-intensity regime that is independent of hydrogen partial pressure, where fatigue crack growth rate in hydrogen exceeds the rate in air by a factor of more than 10; and (2) a low stress-intensity regime that depends on the partial pressure of hydrogen. This trend has been shown to extend to hydrogen partial pressures of as low as 1 bar (ASME PVP2021-62045). Additionally, since the fatigue behavior in gaseous hydrogen is consistent for these grades of steel, general fatigue crack growth relationships can represent an upper bound behavior. The dashed line in Figure A represents a two-part power law of the form:

For high stress intensity (ΔK): $\frac{da}{dN}\,[\mathrm{m/cycle}] = 1.5 \times 10^{-11}\left(\frac{1+2R}{1-R}\right)\Delta K^{3.66}$

For low stress intensity (ΔK): $\frac{da}{dN}\,[\mathrm{m/cycle}] = 7.6 \times 10^{-16}\left(\frac{1+0.4286R}{1-R}\right)\Delta K^{6.5} f^{1/2}$

where crack growth rate (*da/dN*) is the lower of the two values for a given stress intensity factor range (ΔK in units of MPa $m^{1/2}$); the load ratio (*R*) is defined in the usual way and *f* is the fugacity (in units of bar) of the gaseous hydrogen (see ASME PVP2021-62045 for relationship between pressure and fugacity). In the high stress-intensity regime, hydrogen partial pressure of 1 bar has the same effect as for partial pressure of 100 or 200 bar [ASME, PVP2021-62045]. In contrast, when the "cyclic stresses" are sufficiently low, the fatigue crack growth rates converge with behavior in air. These basic trends are demonstrated in Figure B, showing both the pressure dependent regime and convergence with air at low stress intensity, as well as the pressure independent regime at high stress intensity.

The fracture resistance (or fracture toughness) of steel in gaseous hydrogen shows more variability associated with the steel pedigree than fatigue crack growth. High-quality steels are generally associated with greater fracture toughness. The available fracture data are generally limited; however, these data show a general (decreasing) trend with (increasing) tensile strength. The effect of pressure on fracture resistance has been assumed to follow a square root dependence on fugacity, resulting in a steep decrease of fracture resistance with pressure for low partial pressure and a comparatively shallow decrease at higher partial pressure. In other words, low partial pressure (~ 1bar) has a substantial effect on fracture resistance, whereas the pressure dependence on fracture nominally saturates at higher partial pressure (>10 to 100 bar).

The fatigue and fracture properties of welds are generally consistent with the base metals. When residual stress in the test articles is appropriately considered, fatigue crack growth rates of welds are essentially identical to the base metals. This result should not be surprising since the fatigue response is not substantially affected by the details of the steel (Figure A). The fracture resistance of welds should consider the local strength of the weld. The response of a weld in a structure, however, will depend on the details of the structure, such as residual stress in the structure, over-matching or under-matching of the strength relative to the base metal, and potential welding defects. The bulk of the tested steels and welds are modern (e.g. post-1990s), although a few vintage steels have been tested in hydrogen and follow the same trends. As over half of the natural gas pipelines in operation in the United States were installed pre-1970s, there is need to evaluate the fatigue and fracture behavior of the vintage pipes and welds to elucidate their behavior.

Over 1,600 miles of dedicated, high-purity, gaseous hydrogen pipeline exist in the United States. Thus, it should be clear that safe conveyance of hydrogen by pipeline is possible. As the description above asserts, the fatigue and fracture properties of pipeline steels and their welds may not vary substantially based on the *pedigree of the material*. However, the *pedigree of the pipeline* is another matter. Defects in the structure and operational conditions vary substantially from one pipeline to another and these characteristics will determine the appropriateness of the structure for conveyance of gaseous hydrogen. Moreover, the partial pressure of hydrogen has a relatively modest effect on fatigue properties, especially in the high stress-intensity regime. Thus, it seems unlikely that the percentage of hydrogen in the system will be a determining factor in the lifetime of a pipeline.

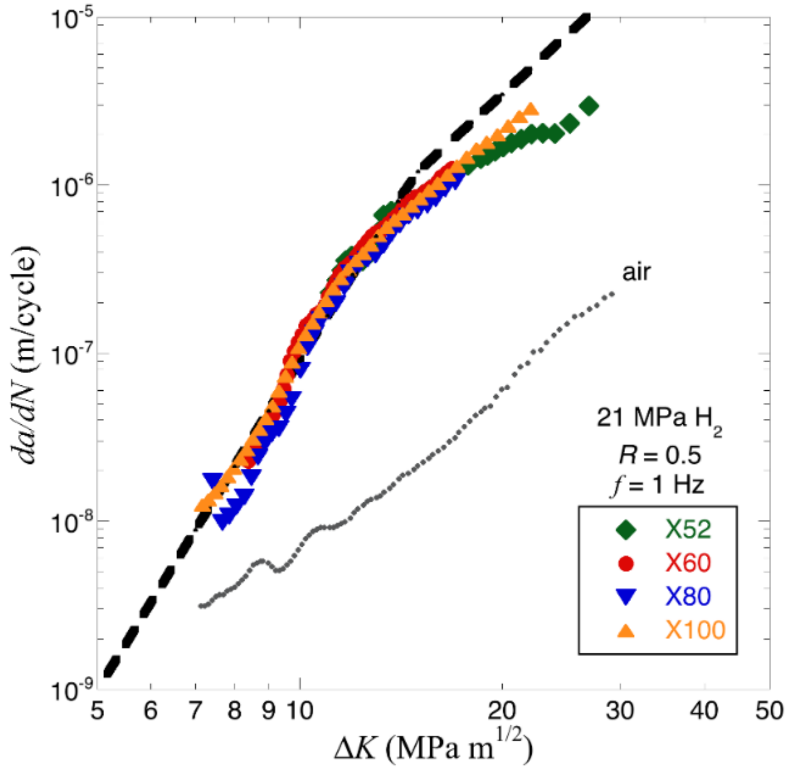


Figure A. Fatigue crack growth of a diverse range of pipeline steels in gaseous hydrogen

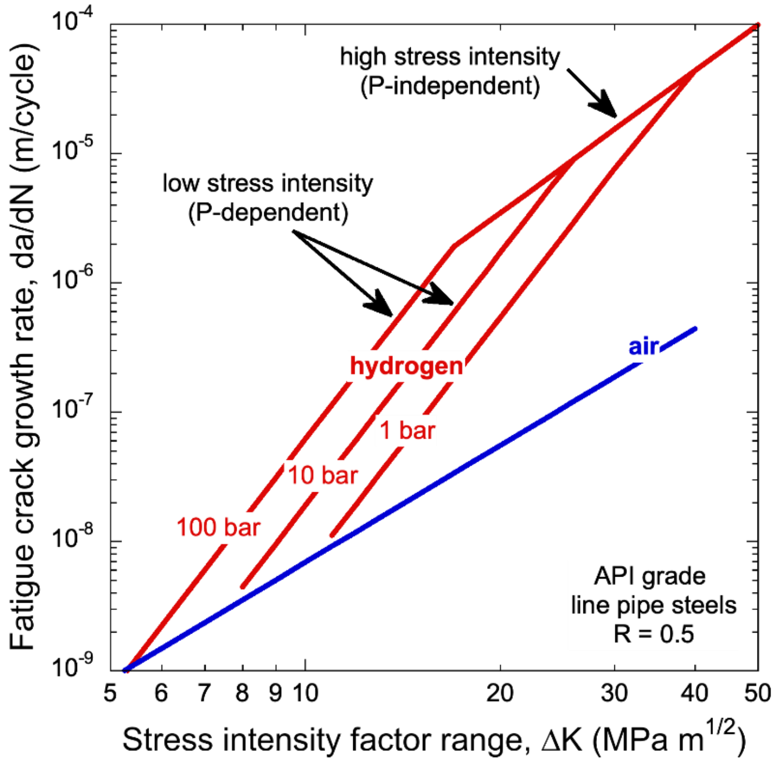


Figure B. Idealized fatigue crack growth rate curves for hydrogen at several pressures (from the two-part power relationship described in the text) and for air (from from API 579).

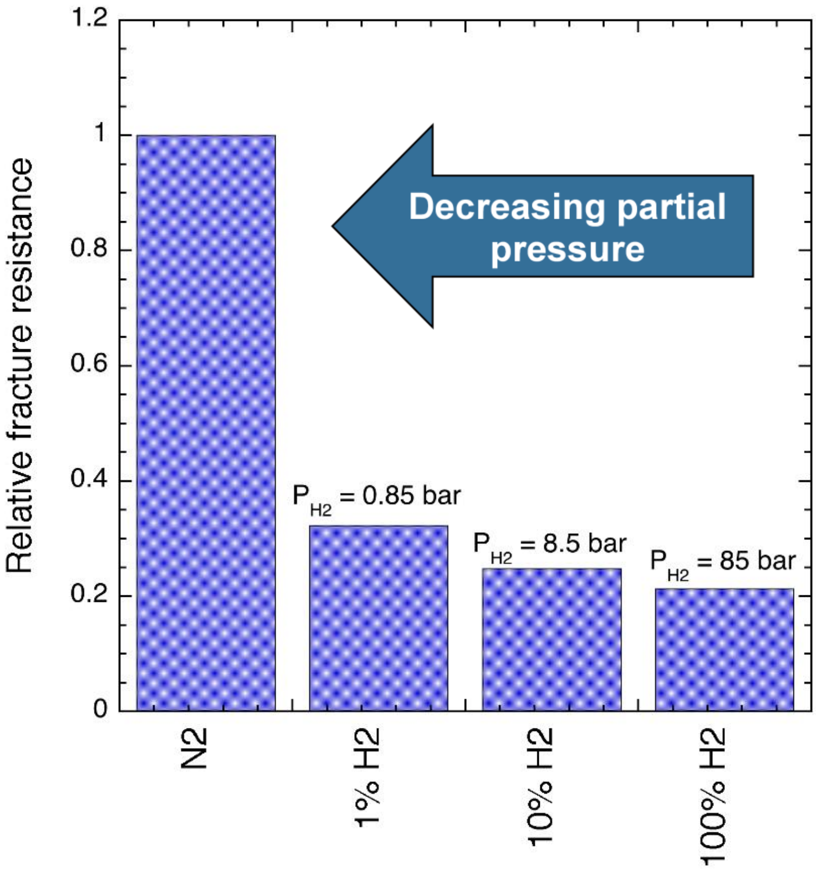


Figure C. Fracture resistance does not scale linearly with pressure/fugacity. <1 bar of H2 reduces fracture resistance. 1% H2 is only modestly different than 100% H2. Blending a small amount of H2 in NatGas pipelines may be unsafe; may cause hydrogen-assisted fracture via HE and HCC even at low H2 partial pressure. Ref: Briottet et al, PVP2018-84658

Below is from 29 March 22, DOE HFTO, H2IQ webinar: Chris San Marchi, Sandia National Lab [64-66]

Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends

" Can GH2 be safely injected into natural gas transmission pipe? It depends… " ["Blending" service]

1. Structural integrity depends sensitively on the pipe dimensions, the pipe condition (i.e. flaws and damage), and operating conditions.
2. External loading and the condition of the pipeline (e.g. defects) will likely dominate overall risk exposure. However, finding and repairing all defects, required for safe operation in high stress GH2 service, will often be technically difficult, expensive, and perhaps impossible.
3. For given pipe dimensions and operating conditions, the base material is a secondary consideration.
4. Pressure cycling will likely need to be managed; how the pipeline is operated, i.e. P-cycling, will be more important than Pmax.
5. Hard spots, like vintage welds, could be problems.
6. Blending ratio will not be the principal concern in most cases.
7. Under modest stress: Pmax = 10 MPa; hoop stress = 34 % SMYS
   - The blending ratio has a non-proportional effect on crack evolution
   - The pressure cycle has a much larger effect on crack evolution than the blending ratio

8. Under high stress: Pmax = 20 MPa; hoop stress = 68 % SMYS
   - The blending ratio has no effect on fatigue response
   - The pressure cycle dominates
9. Materials behavior of pipeline steels in GH2 service:
   - Fatigue crack growth is accelerated by >10x, at high ΔK
   - Fracture resistance is reduced by >50%
   - Does the magnitude of pressure affect fatigue and fracture; can hydrogen effects be ignored below a threshold ?
     - Fatigue and fracture are affected by the magnitude of pressure
     - Even small amounts of hydrogen, small fractions of "blended" GH2 in NatGas pipelines, have large effects
   - What materials variables influence the fatigue and fracture in GH2 ?
     - Materials pedigree has surprisingly little effect on fatigue crack growth
     - Hydrogen-assisted fracture is influenced by strength

F. NOVEL LINEPIPE AND MANFACTURING PROCESSES FOR GH2 IN "VER" SERVICE

Substitutes for steel to safely and profitably move and store, by pipeline system "packing", the very large volumes of renewables-source, GHG-emission-free, H2 will probably be needed to achieve the urgent goals, in A, above. Such linepipe substitutes may be used for repurposing, by re-lining, and for new-builds.

However, H2 also attacks polymers and nonferrous metals, so the path to novel linepipe design and manufacturing methods will require significant R&D&D, which should begin now: design, manufacture, test, certification of novel linepipe for GH2 service, perhaps via new ASME and/or other standards. [25]

The H2 leak rate through a 36-in diameter, 0.5-in thick steel pipeline at 25 °C and 5,000 psi is ~4×10-7 mol/s per meter (about 20 times lower leak rate than for HDPE) [32]

Examples of candidate "novel" linepipe:

1. Tenaris: "Tenaris line pipe qualified for hydrogen transportation. Tenaris's pipeline technology team has carried out an experimental activity to qualify medium and large diameter pipes of up to X70 grade for high-pressure gaseous hydrogen transportation with a hydrogen content of up to 100 percent at 200 bars." --- Tenaris Pipeline Technology Senior Director and Chairman of the DNV H2PIPE joint industry project on hydrogen pipelines, Philippe Darcis. https://www.tenaris.com
   Other vendors: Mannesman: "H2 Ready"; Corinth: "Hydrogen Certified Linepipe" [74, 75]

   We need to know the definition of "qualified" as used by Tenaris and other steel linepipe vendors; qualified by whom; to what specifications and test protocols; to what pressure fluctuations, i.e. magnitude and frequency. What FFS may be derived, for linepipe and commissioned pipelines ?

2. TC Energy: Trans Canada Pipeline presented its R&D program results with Composite Reinforced Line Pipe (CRLP) at ASME's International Pipeline Conference, Calgary, 2002. We need an update on CRLP; in what conditions it might be useful for GH2, VER, service. www.tcenergy.com [62]

3. Smartpipe Technologies: Figs. 13-15, 31-38. [29-32] Smartpipe® is the only large diameter (≤16", soon ≤24"), high pressure, reinforced thermoplastic pipe that is assembled in the field. With the benefit of C-forming and reforming, continuous lengths of several miles may be pulled-in to renovate, upgrade, and repurpose extant pipelines without any couplings. The Smartpipe® system includes embedded fiber optic monitoring for leak detection and third-party intrusion monitoring. Smartpipe® is designed as a stand-alone pipeline system but will, in the near future, be focused on

repurposing the vast existing pipeline infrastructure for GH2, becoming by far the safest pipeline system available.

Smartpipe® fills the technology gap between current small diameter FRP's and the ability to efficiently transport and simultaneously store large volumes of GH2 through either existing pipeline infrastructure or through new pipeline systems, with minimal impact to public safety or environmental security. Large diameter GH2-capable linepipe, up to 5 mile continuous length and 100 bar service P, is manufactured, with in-pipe-wall GH2 permeation barrier, on-site, to pull-in repurpose extant pipelines. Figs. 13-15, 31-38.

Fig. 36 compares the estimated CO2 emissions per km of fabrication and installation, for 20" and for 24" pipe, for conventional steel and Smartpipe®, which produces ~ 80% less CO2, ~ 1,200 MT for this example.

Smartpipe® can be manufactured and installed at ~ 1.6 Km per 24-hour day, while a comparable steel pipeline may take weeks or months, with most of the equipment and crews on site for the duration.

The non-metallic Smartpipe® system ID and OD will not corrode. The Fiber Optic monitoring and comm system notifies the pipeline operator of a potential accidental excavator threat.

4. Extruded polymer (plastic) pipe, or co-extruded multi-layer polymer pipe, may be adequate for:
   a. Low-pressure distribution of NatGas, now common practice;
   b. Perhaps also for high-purity, low-pressure GH2 distribution.

   This polymer pipe may be adequate to allow convenient conversion of legacy low-pressure distribution networks -- now usually of yellow polyethylene pipe -- to high-purity GH2 service with acceptable leakage. But that is not clear, despite several planned major projects, which apparently assume so, without a better understanding of "acceptable" linepipe GH2 leakage and degradation over time in exposure to high-purity GH2. [33-36]

5. Spoolable Fiber Reinforced Plastic (FRP) pipe is a generic term generally applied to both commodity and bespoke engineered products:
   a. Small diameter spoolable (3 to 8 inch OD) pipe of continuous length, limited by spool capacity. Often used for O&G gathering. It may:
      i. Be useful for blended or high-purity GH2 distribution, at low pressure;
      ii. Suffer an unacceptable through-wall H2 permeation rate, thus leakage and high Greenhouse Warming Potential (GWP);
      iii. Be amenable to manufacturing processes that include durable, long-life, GH2 permeation barriers built into the pipe wall.
   b. Rigid "fiberglass" pipe in standard lengths with diverse matching fittings

G. NASCENT GH2 PIPELINING PROJECTS

1. European Hydrogen Backbone [55]
2. H21 North Of England [57]
3. Netherlands: RWE + Neptune Energy [58]
4. SoCalGas "Angeles Link" [50, 43-54]
5. USDOE "H2Hubs" R&D&D initiative [38-42]
6. "HyDeal LA" https://www.ghcoalition.org/hydeal-la [51]

These are nascent and evolving; follow their websites, from References.

H. WHY PIPELINE ANHYDROUS AMMONIA (NH3), "THE OTHER HYDROGEN", INSTEAD OF GH2 ?

1. NH3 is a carbon-free energy carrier, storage medium, and fuel; it may be "cracked" to recover H2;
2. Volumetric Hydrogen density of NH3 is 70% greater than LH2: it is liquid at ~ 10 bar, 25 C;
3. Economical and safe to move via underground liquid pipeline or barge; railcar is becoming obsolete;
4. Very-low-cost energy storage in large, double-wall, carbon steel, "atmospheric" tanks refrigerated to -35 C: < $ 1.00 / kWh CAPEX; Figs. 21, 22, 40.
5. Can be stored in common, steel "propane" tanks with SS fittings, in a variety of sizes and locations, at ~ 10 bar at 25 C;
6. NH3 pipelines are low-cost carbon steel at ~ 10 bar, requiring pumping energy to overcome friction losses. USA has > 4,800 km of liquid NH3 pipelines, delivering from NOLA import terminal and NH3 plants in TX and OK to markets throughout the Midwest Corn Belt Figs. 21-23, 40. [11, 18-22, 63]

I. PIPELINING H2 AND NH3 VIS-A-VIS ELECTRICITY TRANSMISSION AND SYSTEMS

Figure 11 [27, 28] shows that, at the large scale discussed in this paper, energy transmission CAPEX, per MW-km of transmission capacity, is lower for GH2 pipelines than for electricity systems, i.e. "Grid". OPEX is lower per MWh-km of transmission service, because friction loss is less than wire I^2R loss; underground pipelines are better protected from acts of God and man, including Coronal Mass Ejection (CME) and Electromagnetic Pulse (EMP).

GH2 pipelines also provide substantial "free" energy storage by "packing" to max allowed operating pressure (MAOP) when variable energy resources (VER) (wind, solar, for example) are strong, then "unpacking" to ~ 1/3 to 1/2 of MAOP when VER input is weak while GH2 demand remains strong.

Assuming that the world gas industry, the world energy and renewable energy industries, and the governments and peoples of the world wish to promptly achieve the goals in A, above, at minimum economic and environmental and social disruption, we need to avoid over-dependence upon and over-investment in, the Grid. To do so, we need to develop a new, perennial, persistent surveillance and analysis and policy tool to continuously guide optimum allocation of policy, markets, technology, and CAPEX among Grid, H2, and NH3 -- through at least year 2050. The Grid may be technically and economically suboptimal as humanity's primary near-total de-GHG-emission system and strategy: it operates at light speed; must instantly be "balanced"; energy infrastructure and storage are costly; it is vulnerable to acts of God and man. Grid O&M is thus costly. This optimization tool building and maintenance should begin, now, as a global interdisciplinary strategic collaboration. [55-58, 67-73]

J. RESULTS AND RECOMMENDATIONS

1. DECADES OF GH2 PIPELINING SUCCESS The Oil & Gas (O&G) industry has pipelined GH2 safely and profitably for decades, via low-alloy and carbon steel pipelines, at low and constant pressure, from SMR plant sources to oil refineries via established industrial pipeline corridors. VER service, gathering and transmission over long distances at high and varying pressure, including "packing" storage, will be different. We need to learn how to safely advance to high-capacity VER service.

2. VARIABLE ENERGY RESOURCE (VER) SERVICE Today's default "renewables" -- wind, solar, wave, tidal, etc. -- are all time-varying-output resources; time constants vary from seconds to years. Delivering their energy harvest, from on-Grid or off-Grid plants, as GH2 to pipelines, will inflict large and frequent pressure fluctuations upon the pipelines, especially at upstream gathering. How to define "VER service" and specify and build GH2 pipelines to accommodate it ? Figs. 2-12.

3. LEGACY HYDROCARBON PIPELINES (See "Limitations ..." below). Legacy pipelines and networks, i.e. Oil & NatGas, and perhaps others, are valuable assets of very large replacement value. The gas industry

needs to invest significantly, now, to learn how to repurpose them for safe and profitable GH2 and / or liquid NH3 service, considering: [55-58, 64-66]

a. "Blending" with NatGas vs. high purity GH2 service;
b. FFS assessment; new inspection tools, protocols; must achieve very high confidence level;
c. Repurposing, inspection, and rehabilitation vs. replacement;
d. Interior coating and / or "lining" potential; Fig. 19.
e. Codes, standards, certifications, permitting;
f. Operating protocols: MAOP; power capacity (MW, kg H2 / hour); storage capacity. Pressure variation regulation;
g. Legacy pipeines as host conduits for "lining" with novel linepipe highly immune to HE, HCC.

4. HEED LIMITATIONS OF STEEL LINEPIPE AND PIPELINES FOR GH2 SERVICE, BLEND OR HIGH-PURITY

a. Hydrogen Materials Compatibility of Line Pipe Steels : Hydrogen Embrittlement (HE) and hydrogen corrosion cracking (HCC) are well recognized. E. METALLURGY, above.
b. Legacy pipelines and networks: Oil & NatGas. Valuable assets: Figs. 28, 29, 40.

   How to repurpose them for safe and profitable GH2 and / or liquid NH3 service. Operational pressure regulation; repurposing; rehabilitation; coating and / or relining or replacing. GH2 service: MAOP; power capacity (MW, kg H2 / hour); energy storage capacity.

c. Consider legacy steel pipelines of all kinds as potential convenient, low-cost, protective conduits for GH2 and NH3 pipelines for gathering, transmission, and distribution:
   1. If the risks of assessing, renovating, and repurposing legacy pipelines -- especially out-of-service and abandoned pipelines -- is too high, consider the host conduit option;
   2. Host new pulled-in linepipe highly resistant to HE, HCC, for rehab for VER GH2 service;
   3. These conduits should be sound enough to contain small and large leaks of GH2 and NH3 product, so that the leaked product may be scavenged before the host pipeline is stressed; Example: Smartpipe, in F.3, above.
   4. Hosted GH2 pipelines may be designed for, and operate at, MAOP and service pressure well above 100 bar:
      i. To increase pipeline flow rating and capacity;
      ii. To contain most burst events within the host pipeline.
   5. Danger: Trying to contain H2 in a host conduit -- extant steel pipeline, for example -- creates a detonation hazard if one cannot guarantee separation from air. Trying to contain leaking H2 may be more trouble than it is worth. Over time, small H2 leakage into the host conduit should expel the air, via positive increasing partial-P of GH2.
   6. Resolving this danger will require an exhaustive R&D&D project; start planning now.

d. Expect new codes, standards, and specifications for Variable Energy Resource (VER) (wind, solar, etc.) GH2 service where frequent and large P fluctuations will be inflicted upon the pipeline systems may be needed; ASME and USDOT PHMSA may be the lead.

Consider diverse DOE National Laboratory capability and work: Figs. 31-35. [64, 73]

5. ENERGY STORAGE: "PACKING", CAVERN ACCESS In VER service, "packing" GH2 pipelines to Maximum Allowed Operating Pressure (MAOP) when wind and solar output is high, allowing customers to "unpack" the pipeline network to ~ 1/3 MAOP when wind weakens and sun goes down, adds significant "free" energy storage value to the dedicated, high-purity, high-pressure, GH2 pipeline system. However, this intentional pressure cycling may be unacceptably dangerous, or otherwise costly, in the case of attempts to use legacy steel pipelines for VER-service GH2 pipeline systems. The urgent R&D&D projects suggested in this paper should enable techno-economic optimization analyses (TEA) to resolve this.

A continental-scale GH2 pipeline system will allow affordable bi-directional access to very-low-cost energy storage in large, deep, man-made, solution-mined caverns in domal salt geology, at Gulf Of Mexico (GOM), or Magnum Dome in Utah, for examples. Figs. 7-12. GOM is a far larger salt resource.

6. LIQUID HYDROGEN (LH2) PIPELINES NASA legacy for connecting large stationary storage facilities, typically cryogenic spheres, via short (<10 km) LH2 pipelines, for rocket launches . Legacy truck delivery of "Gray" LH2 to the launch site storage. Figs. 24, 40, 41.

EPRI "Energy Pipeline" or "SuperGrid". Trans-continental LH2 + superconducting LVDC energy transmission installed in a deep bedrock tunnel for maintenance access. Economic optimum bored tunnel diameter is ~ 5m; a single or double pax + freight rail line may be accommodated in the tunnel, adding critical synergistic value. Status of this concept is unknown. Fig 20. [59]

Potential mid-term applications via short (~ 1-10 km) LH2 pipelines, might be:

1. Bunkering cruise ships; liquid NH3 is probably unacceptably toxic; Fig. 41.
2. Other marine, of various sizes;
3. Aviation, especially medium-to-large airliners; smaller aircraft may be GH2-fueled; Fig. 24.
4. On-airport GH2 and LH2 production, with short LH2 pipelines, may be possible; nuclear fission or fusion small modular reactors (SMR's) may become available;
5. Long-haul truck fleets;
6. Rail, of all sizes.

We need to learn where, why, and how LH2 pipelines are being considered elsewhere in the world, to calibrate our LH2 strategy.

7. COMPRESSION AND COMPRESSORS Fig 27. [1-10, 15, 63] GH2 compression CAPEX and OPEX costs, for several technologies, are high, per kgH2-bar, in any GH2 system, under any circumstances. Compressors will probably continue to operate on electricity, but might operate on a GH2-pipeline-fueled prime mover. DOE HFTO "Earthshot" goals wisely include making compressors lower CAPEX, and more durable and reliable, for lower OPEX. As with all things hydrogen, scaling-up and high-volume production of compressors of all sizes and types will advance these cost reduction and reliability goals.

Hydraulic modeling of GH2 transmission pipeline networks shows that GH2's high molecular mobility and low viscosity probably allows building and profitably operating GH2 pipelines, hundreds of km long, without midline compression; bearing the pipe friction losses is more profitable than owning and operating midline compressor(s). This needs to be validated in an IRHTDF. Fig. 12 [26] However, compression CAPEX and OPEX for high-pressure (~ 100 bar), high-purity, GH2 pipeline and cavern storage systems will remain a major cost impediment to regional-to-continental-scale GH2 pipeline systems.

"Compressorless" medium-distance (~ < 800 km) high-purity GH2 pipelines can theoretically be built for profitable large-volume transmission, without mid-line compression, enjoying the lower viscosity and higher mobility of H2 vis-a-vis CH4 molecules and bulk gas. Such a compressorless 800 km, 1 m diam, 100 bar input, GH2 pipeline capacity is ~ 8,000 MW, from hydraulic modeling. Compressor(s) on multiple gathering lines would feed the transmission line at ~ 100 bar. [15]

D. Clark, et al report a new method for extracting H from NH3, and from CH4 and perhaps other hydrocarbons, with inherent potential for economical compression of GH2 to ~ 140 bar. [63]

8. CONTINUOUS OPTIMIZATION OF COMPLETE SYSTEMS Humanity must avoid over-dependence upon, and over-investment in, the electricity system, i.e. Grid, because the Grid may be technically and economically suboptimal vis-a-vis [E+IF] systems based on GH2 and NH3 via pipeline transmission, at the scales we need, enabling very-low-cost energy storage.

9. CALIFORNIA (CA) LEADS IN POLICY, INFRASTRUCTURE, FUELING FOR H2 [43, 54]

a. Many laws and executive actions encouraging H2 infrastructure and markets. [43]
b. Proposed "Angeles Link" renewables-source GH2 pipeline to Los Angeles Basin. [50]
c. By 2050, total demand for "clean" total transportation energy > total electricity. [44]
d. Therefore, other states should simply emulate CA; WA has done so; do not reinvent. [43-48]

10. USA's BIPARTISAN INFRASTRUCTURE BILL (INFRASTRUCTURE INVESTMENT AND JOBS ACT, IIJA) The gas industry should plan to influence application of results of the first H2-related RFI FOA's to the consequent FOA's for R&D&D projects including this paper's suggestions for a "Sustainable Future Powered by Gas". [38-42]

11. PROPOSED NASCENT GH2 TRANSMISSION PIPELINE INFRASTRUCTURE Collaborate and interact with all, ideally in the IRHTDF context: (C.12 and G, above)

a. UK's BEIS Cluster Sequencing Phase 1 - East Coast Cluster in the Humber Fig 25. [57]
b. Netherlands offshore wind-to-H2 Fig. 26 [58]
c. "Angeles Link" by Southern California Gas [50]
d. "HyDeal LA" https://www.ghcoalition.org/hydeal-la [51]

12. POTENTIAL DISRUPTION: Fig. 30 Profitable access to Deep Hot Dry Rock Geothermal (DHDRG) energy. When the energy industry is able to bore "deep enough, cheap enough" to profitably access DHDRG energy, which is benign, inexhaustible, baseload, firm and dispatchable, provides free storage -- by leaving heat in deep rock until needed -- and is generally ubiquitous on Earth, we will not need long-distance, high-capacity, GH2 and NH3 pipelines, nor high-capacity, annual-scale energy storage, via GH2 pipeline "packing" and in large salt caverns, nor via "atmospheric" liquid NH3 storage. This paper becomes irrelevant. Several companies are in R&D for diverse DHDRG boring technologies. [76]

Also potentially disruptive: If small modular reactors for nuclear fission or fusion become available, as Distributed Energy Resources (DER), the GH2 and NH3 infrastructure needs, above, will also wane.

SUMMARY, CONCLUSIONS

1. THE GAS INDUSTRY GOAL MUST BE RAPID, TOTAL DE-CARBONIZATION AND DE-GHG-EMISSION. All of humanity must collaborate to prevent the bleak and dangerous fossil-dominated future in Fig. 39. All industry assets must be repurposed or replaced to provide GHG-emission-free Energy + Industrial Feedstocks [E+IF] for the entire human enterprise, as quickly as we prudently and profitably can:

- Prudently: this will be disruptive, but we must not cripple the global economy;
- Profitably: the large amount of capital needed will flow only to investments with attractive reward-to-risk ratios. [17-20, 25-26]

This global transition is both threat and opportunity for the gas industry; we focus on the latter.

2. THE ONLY CARBON-FREE FUELS, HYDROGEN AND ANHYDROUS AMMONIA (NH3), WILL BE MAJOR WHOLE SYSTEMS, VECTORS, AND STRATEGIES. Today's gas industry will embrace and optimize them to prevent over-dependence upon, and over-investment in, the electricity system, i.e. Grid, which may be technically and economically suboptimal for rapidly achieving the goal in 1, above.

3. WE NEED A VERY LARGE AMOUNT OF "CLEAN"AND FIRM H2 AND NH3; GRID CANNOT MOVE OR STORE IT. Trucks cannot practically nor economically move it. New, underground, high-capacity, high-pressure, variable-pressure, low-leakage, GH2 pipeline systems and networks will soon be needed, if GHG-emission-free "clean" H2, NH3, and perhaps other energy carriers and systems are to reach their technical and economic potential for urgent GCC emission reduction, to elimination. [1-11, 17, 18]

4. WE DO NOT KNOW HOW TO REPURPOSE EXTANT NOR NEW-BUILD GH2 PIPELINES FOR LONG, SAFE, PROFITABLE SERVICE LIVES. Be careful repurposing legacy pipelines for GH2 service, especially from VER sources. Whether for blending a small (< 20%) (mass, volume, or energy ?) quantity of GHG-emission-free "clean" GH2 into extant NatGas "pipeline" gas, or for high-purity, high-pressure GH2 service, in extant steel pipeline networks, metallurgical and operational limits must be heeded, reliable FFS procedures invented, and regulations, codes, and standards adopted, to achieve safe and profitable long-term success in pipelining GH2 in legacy steel pipelines. Liquid NH3 pipelining is relatively safe; a mature industry. LH2 pipelines will probably remain short; a mature industry.

" Blending small amounts of hydrogen into natural gas pipelines, where possible based on case-by-case assessments, can also jumpstart local usage ... " [22]

5. WE HAVE LISTED AND DISCUSSED MANY REASONS FOR PIPELINING GH2 AND LIQUID NH3, ABOVE.

6. HERE IS A CATALOG OF URGENTLY NEEDED R&D&D INVESTMENTS.

a. Discover and demonstrate how legacy and new-build pipelines may safely and profitably use steel linepipe in "blend" and/or in high-purity "VER" GH2 service. Establish codes, standards, inspection, and operating procedures and protocols for extant legacy steel pipelines proposed for repurposing; assume MAOP and P cycling range and frequency is specified for all options.
b. Invent reliable inspection and assessment methods, including novel field inspection tools and AI software, by which to qualify and certify extant pipelines for GH2 service, blended and / or high-purity, including:
    i. VER-source service, inflicting large and frequent P fluctuations on the pipelines;
    ii. "Packing" storage, whereby large and frequent P fluctuations are intentionally applied;
    iii. Develop rehabilitation specs + procedures by which to certify legacy steel pipelines FFS
c. Develop novel linepipe designs and manufacturing methods to achieve great resistance to, HE and HCC in VER GH2 service. Include hybrid polymer-nonferrous-metal options; include novel linepipe designs and in-field, on-site manufacturing methods, by which to deliver pipelines that are:
    i. Highly resistant to HE, HCC;
    ii. Suitable for both pull-in rehabilitation and renovation of extant pipelines and for new-builds;
    iii. Manufactured on-site, in long continuous sections, to minimize linepipe joints;
    iv. Capable of high-capacity, large-diameter, high-pressure, for transmission, and capable of lower-capacity, smaller-diameter, perhaps lower pressure, for gathering.
d. Develop novel BOS fixtures (couplings, valves, meters, input / output nodes) for these novel GH2 linepipe(s) and integrated systems.
e. Investigate internally-applied coatings for extant legacy pipelines to render them highly-immune to HE, HCC; expect an extensive variety of internal processes and materials. Perhaps consider exterior structural cladding, as supplemental, or alternative: unlikely. Fig. 19.
f. Evaluate the "conduit" strategy of safely containing GH2 leakage from the legacy pipeline after it has been "lined" with a novel linepipe highly immune to HE, HCC:
    i. Scavenge low-pressure GH2, slightly > ambient 1 bar, within the host steel pipeline, for compressor return to the "lining" GH2 pipeline;
    ii. Exclude air and O2 from the volume between host pipeline and "lining";
    iii. Safely contain any explosion or combustion in the inter-pipe volume.

We invite others to help enlarge, and to circulate, this catalog of urgently needed R&D&D.
Please respond to Bill Leighty, who will update the catalog: wleighty@earthlink.net

7. PREVENT OVER-DEPENDENCE UPON AND OVER-INVESTMENT IN THE "GRID".

We now need to develop a new, perennial, persistent surveillance and analysis and policy tool to continuously guide optimum allocation of policy, markets, technology, and CAPEX among Grid, H2, and NH3 -- through at least year 2050. The Grid may be technically and economically suboptimal as humanity's primary de-GHG-emission system and strategy: operates at light speed; energy infrastructure and storage are costly; vulnerable to acts of God and man. O&M is thus costly.

8. WELCOME BENIGN TECHNICAL AND ECONOMIC DISRUPTIONS IN THE TOTAL [E+IF] LANDSCAPE.

- The climate change imperative is the main driver of the nascent global policy focus on hydrogen.
- Hydrogen is likely to further disrupt energy value chains in coming years, more competitive and less lucrative than oil and gas, because it is based on conversion, not an extraction, and can be produced competitively in many places, limiting capturing economic rents.
- Countries with an abundance of low-cost renewable electricity could produce "green" H2, with global economic and political effects. While renewable energy costs fall, transporting H2 will remain expensive, causing more regionalization.
- H2 development and deployment is part of a much bigger energy transition scenario. Priorities and policies will determine H2 scale-up speed and role in that total de-GHG-emission transition.
- All CAPEX and OPEX are likely to fall sharply with learning and scaling-up of needed infrastructure, including pipelines for GH2 and liquid NH3.
- Equipment manufacturing offers an opportunity to profit in the coming years and decades.
- Hydrogen trade and investment flows will spawn new patterns of interdependence and bring shifts in bilateral international relations.
- Countries with an abundance of low-cost renewable electricity could become producers of green hydrogen, with consequent geoeconomic and geopolitical consequences.
- Hydrogen could be an attractive avenue for fossil fuel exporters to help diversify their economies and develop new export industries.
- Supporting the advancement of renewable energy and green hydrogen in developing countries is critical for decarbonising the energy system, contributing to global equity, stability, and prosperity.
- International co-operation will be necessary to devise a transparent hydrogen market with coherent standards and norms that powerfully contribute to climate change efforts.

Fig. 30. For example, When we have invented and commercialized novel technologies by which to bore "deep enough, cheap enough" (6 - 10 km) to profitably harvest deep hot dry rock geothermal (DHDRG) energy, via the large heat exchanger contact area required at depth, we may globally proliferate "Eavor Loops" to profitably extract medium-T (200-300 C) thermal energy for organic Rankine cycle (ORC) genset electricity production and district heating and cooling systems (DHCS), nearly anywhere on Earth. This is "Advanced Geothermal Systems" (AGS), which bores multiple parallel conduits at-depth instead of "Enhanced Geothermal Systems" (EGS) which requires seismic-risking "fracking" at-depth to create the heat exchanger contact area. See: Eavor, Tetra Corporation [21, 76, 80]

This would be the ultimate in distributed energy resources (DER): DHDRG energy is benign, inexhaustible, baseload, firm and dispatchable, generally ubiquitous on Earth, equitable and monopoly-resistant, with free energy storage -- leave heat in the ground until needed. Hydrogen transmission pipelines and storage caverns would not be needed: all humanity's electricity and low-grade heat could be produced, distributed, and consumed within a proliferation of autonomous micro- and mini-grids -- perhaps loosely-interconnected for redundancy and resilience. Hydrogen is produced, distributed, and consumed within these local geothermal-source systems, via underground GH2 and / or LH2 pipeline networks.

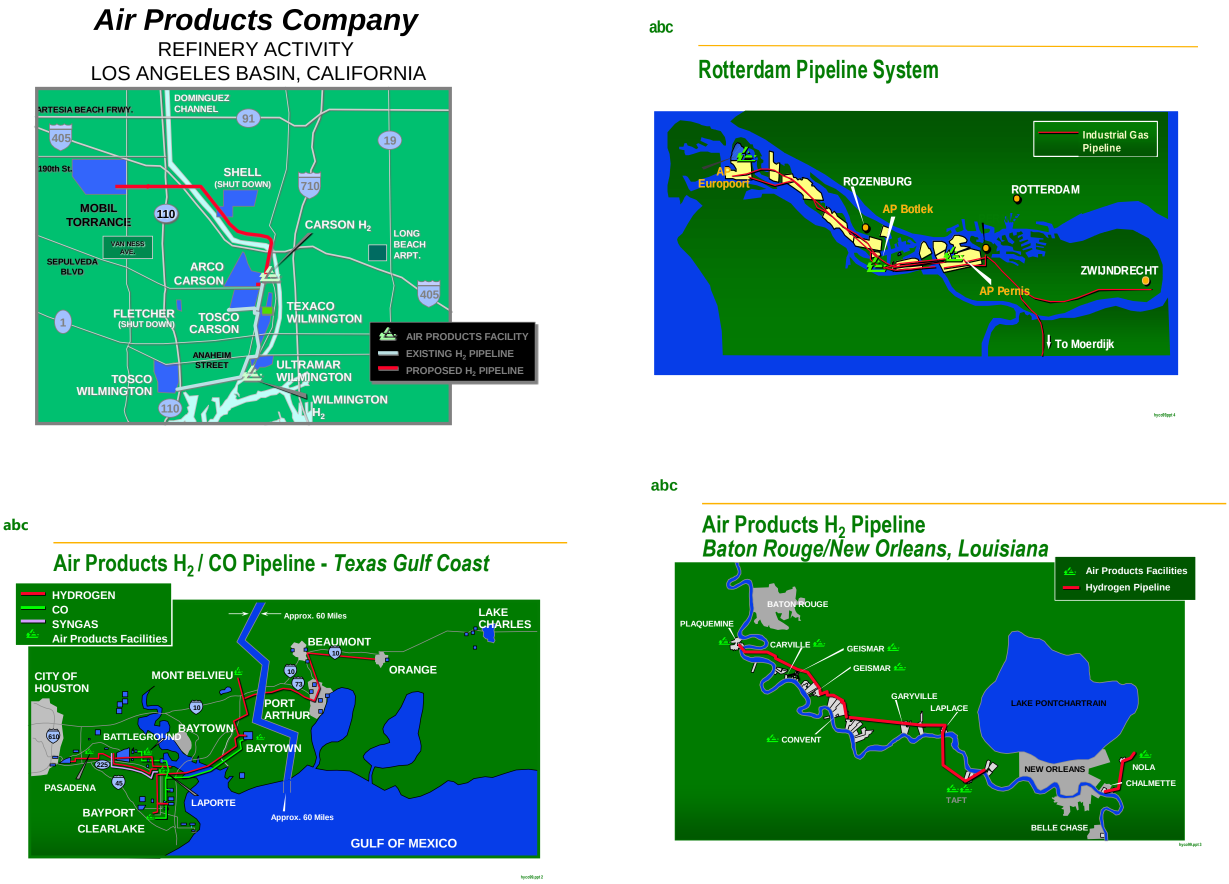


Figure 1. Extant GH2 pipelines from large NatGas-fueled Steam Methane Reforming (SMR) plants to oil refineries for "hydrotreating"; generally on long-term contracts, owned by industrial gas companies. Built of low-alloy or carbon steel linepipe, operated at low and constant pressure (~ 10-20 bar) to avoid HE, HCC. Relatively short length; generally confined to established industrial corridors. They have a good safety record. Such pipelines are probably not profitable in long-distance, VER, GH2 service. SMR CO2 waste is now dumped into Earth's atmosphere. Future SMR plants may capture total SMR CO2 waste production for Carbon Capture and Sequestration (CCS), thus yielding "blue", CO2-emission-free H2.

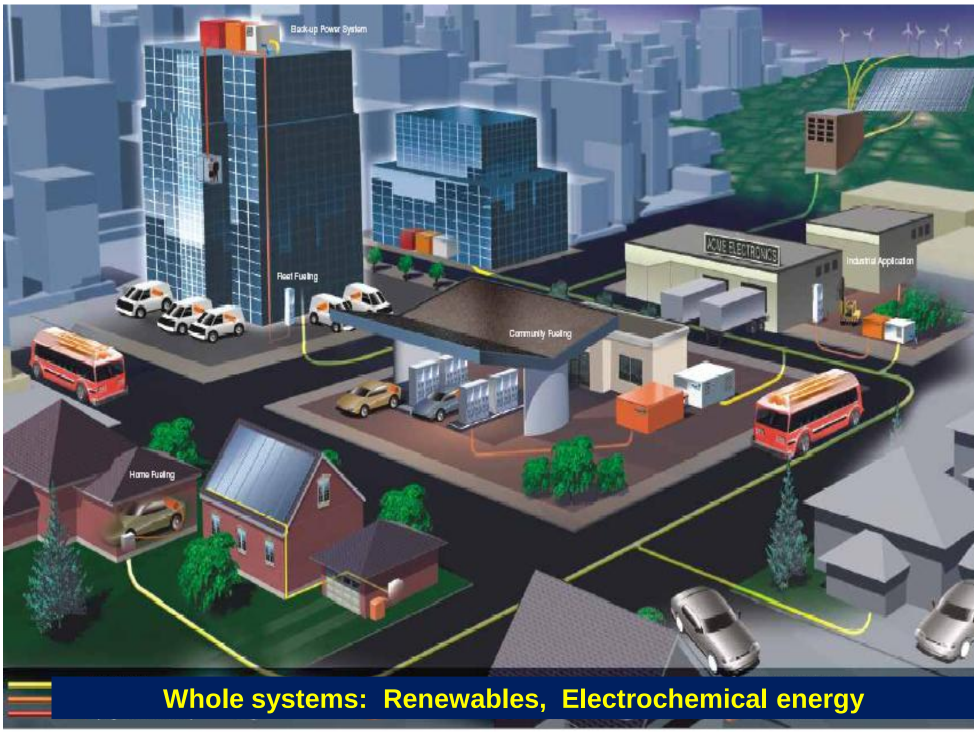


Figure 2. Complete, integrated, synergistic, optimized, systems for [Energy + Industrial Feedstocks], [E+IF]. Distant, diverse, renewable, GHG-emission-free sources of H2 are delivered to load centers via dedicated, high-purity underground pipeline networks for gathering, transmission, "free" pipeline "packing" storage, and distribution. [18, 22]

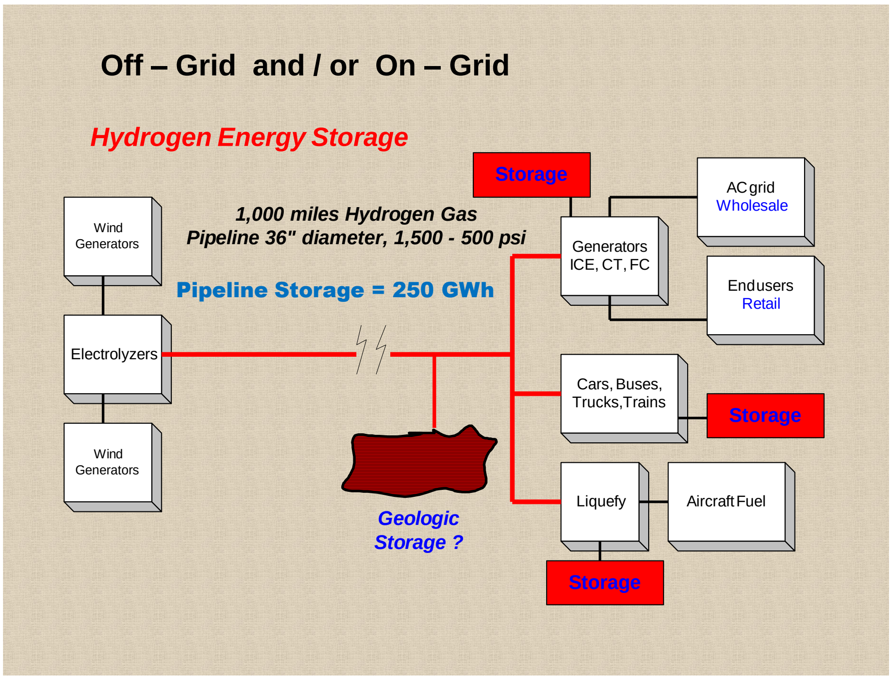


Figure 3. By 2035 - 2050, total continental hydrogen demand will require off-Grid, dedicated, high-purity, high-pressure, GH2 pipeline networks, of linepipe and accessories highly resistant to hydrogen embrittlement (HE, HCC), for safe, economical gathering, transmission, "free" pipeline "packing" and salt cavern geologic storage, and distribution of VER-source hydrogen fuel for transportation, combined heat and power (CHP), and energy-derived industrial feedstocks [E+IF]. "Packing" a single large transmission pipeline stores
~ 250 GWh at ΔP = 67 bar, with no marginal CAPEX or OPEX, thus "free". [1-10, 18, 39, 41]

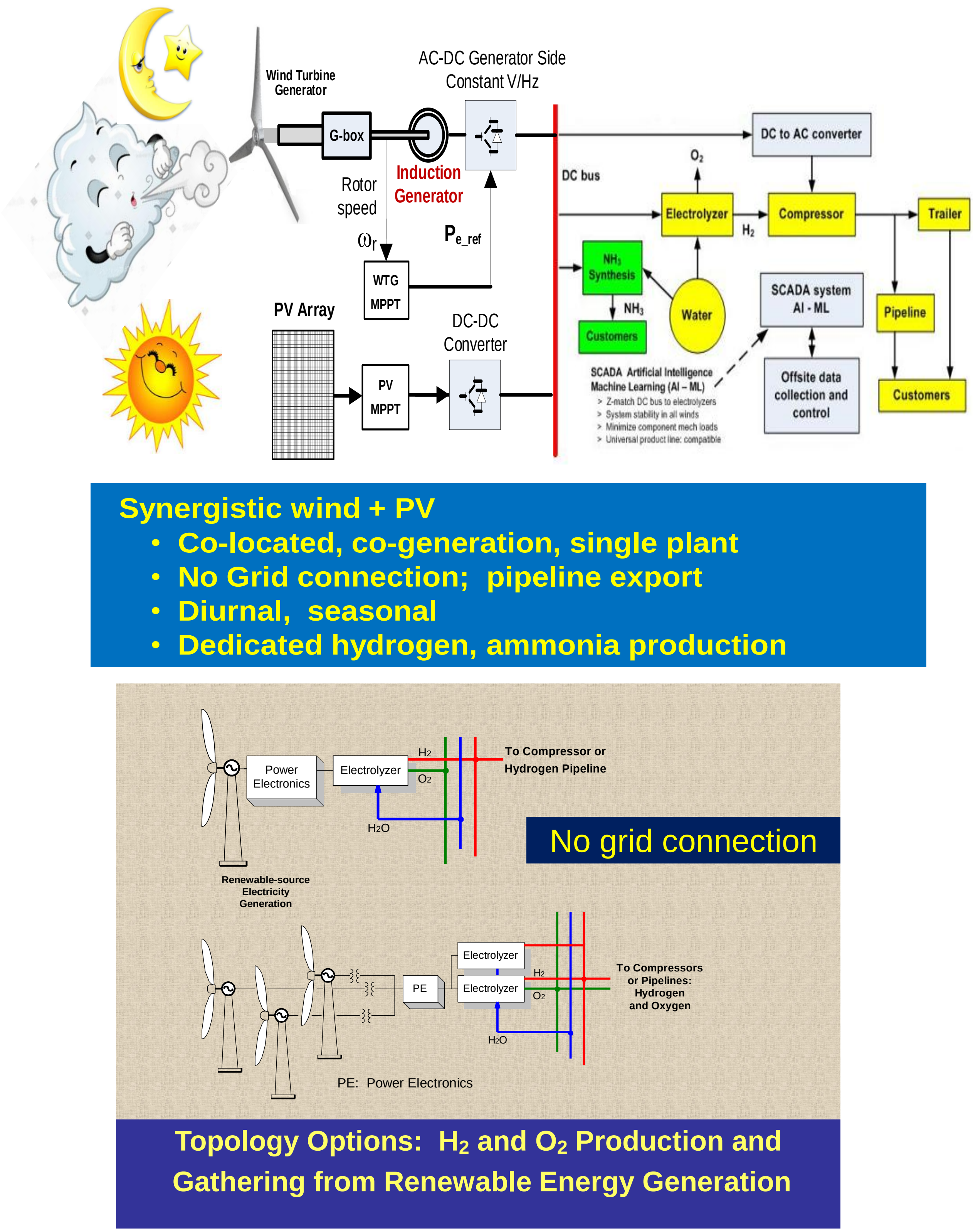


Figure 4. Renewables-source Hydrogen Hub(s) should include off-Grid, co-located, co-generation, synergistic wind + PV plant(s) dedicated to H2 or NH3 production, with electrolysis plants customized for "wild DC" inputs close-coupled for Z-matching to series-parallel stacks arrays, omitting AC-DC power supplies, with single system SCADA for simplified integrated controls. This reduces CAPEX, OPEX, and plant-gate cost of H2 delivered to GH2 pipelines, and / or to trucks. [25, 26, 39, 41]

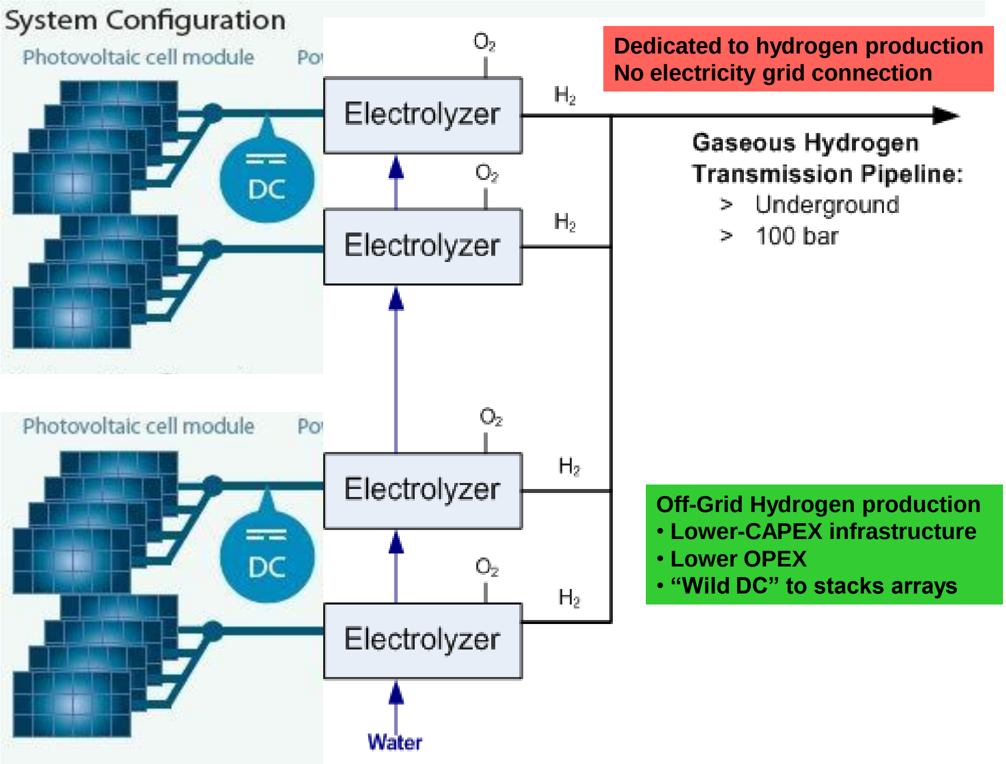


Figure 5. PV example. Whole energy systems will be optimized for dedicated, off-Grid, high-purity, GHG-emission-free , Hydrogen production. Large CAPEX and OPEX savings are realized by eliminating the need to deliver Grid-quality AC. Electrolyzers are optimized to receive "wild DC", for lower plant-gate H2 cost, for delivery to GH2 pipelines and / or to trucks. [25, 26, 39, 41]

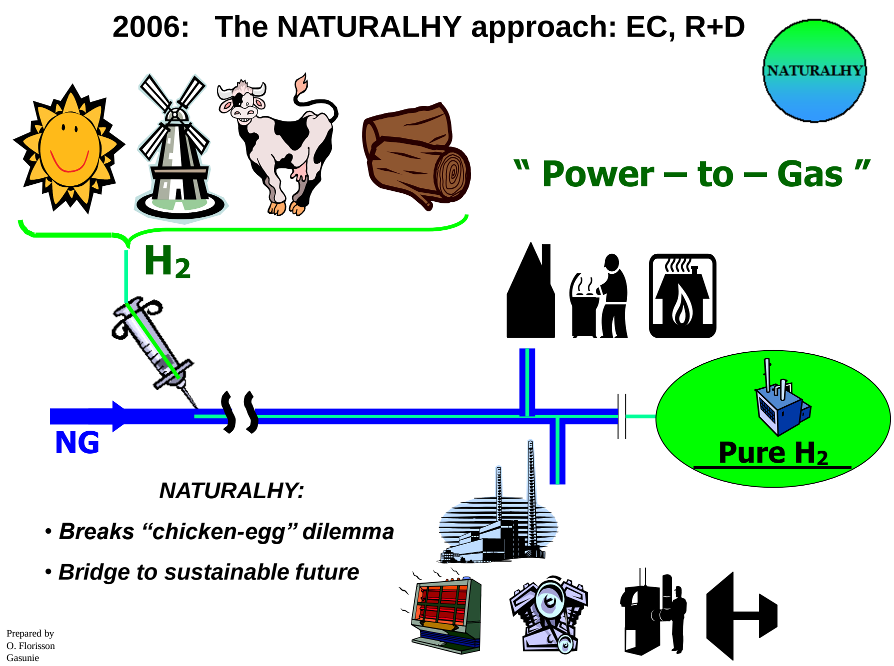


Figure 6. European Commission (EC) "NaturalHY" R&D, 2006. They asked, "How much H2 may be blended in NatGas pipelines without encountering metallurgy or downstream customer apparatus problems ?" Approaching 20% by volume, ~ 10% by energy. Blending in USA is a short-term option (1) to build market for "green" H2, to marginally decarbonize pipeline network NatGas blend. The Ukraine tragedy will motivate Europe to accelerate this strategy and the up-front R&D&D it requires.

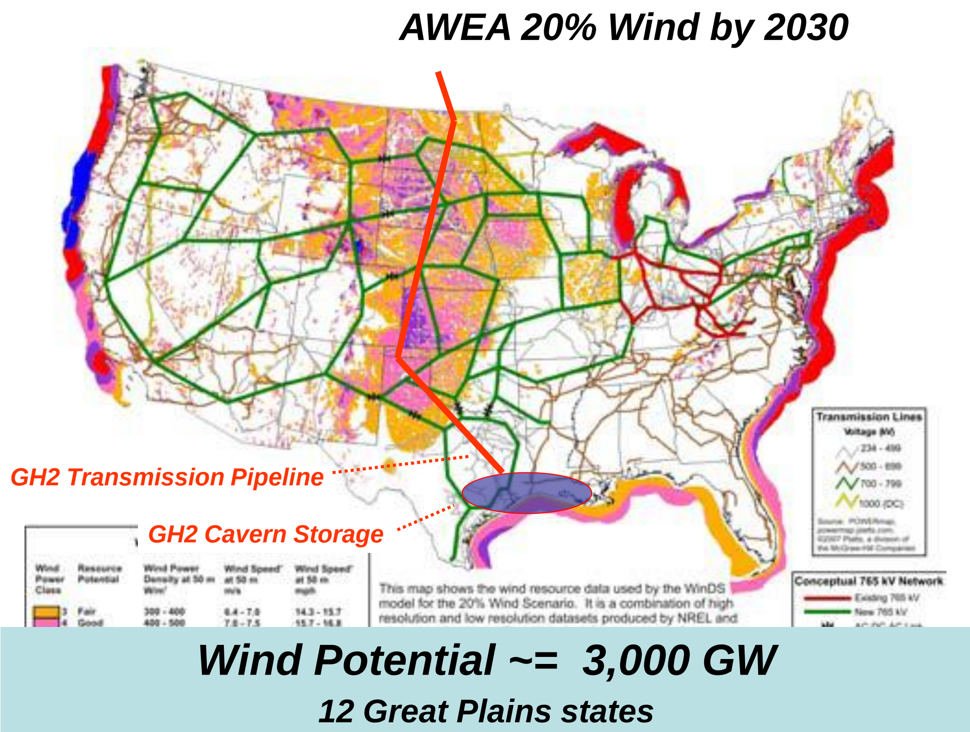


Figure 7. At Great Plains scale, a multi-GW, multi-GH2-pipeline corridor gathering and transmission system delivers high-purity, VER-source hydrogen to large-scale Gulf Of Mexico (GOM) multi-salt-cavern firming storage, with potential to supply 100 % of total USA energy + industrial feedstocks [E + IF] demand of ~ 100 Quads per year as annually-firm and dispatchable. GOM salt could host thousands of large GH2 storage caverns, especially as compact multi-cavern arrays manifolded at the same GH2 pressure, for zero inter-cavern ΔP.

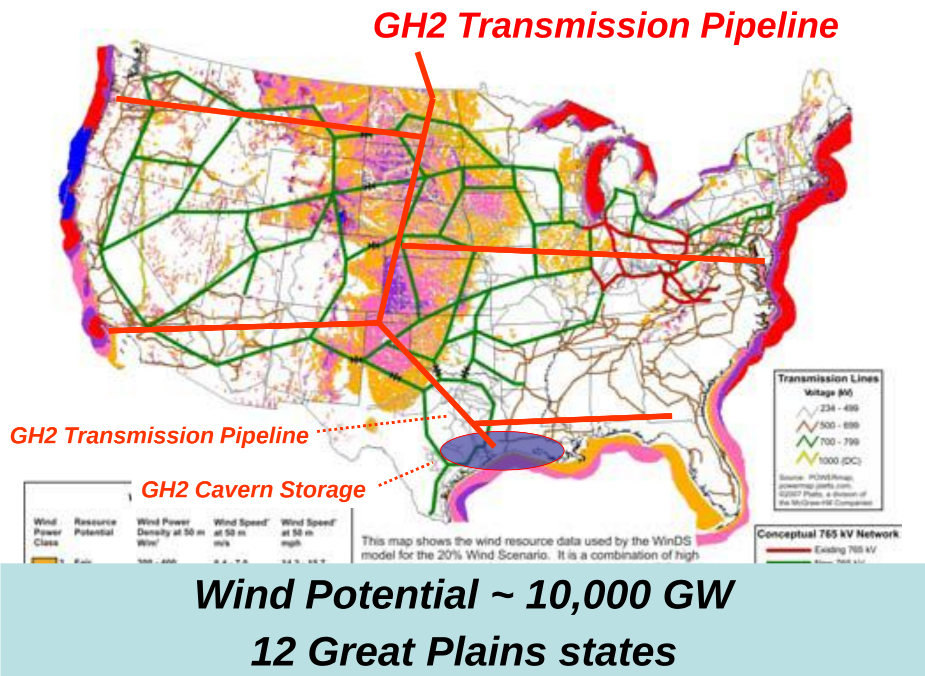


Figure 8. At continental scale, the high-purity GH2 transmission pipeline backbone supplies a continental-scale GH2 pipeline network, to supply all 100+ Quads of USA energy + energy-derived industrial feedstocks demand, [E + IF], as annually-firm, dispatchable, and decarbonized GH2 fuel and feedstocks.

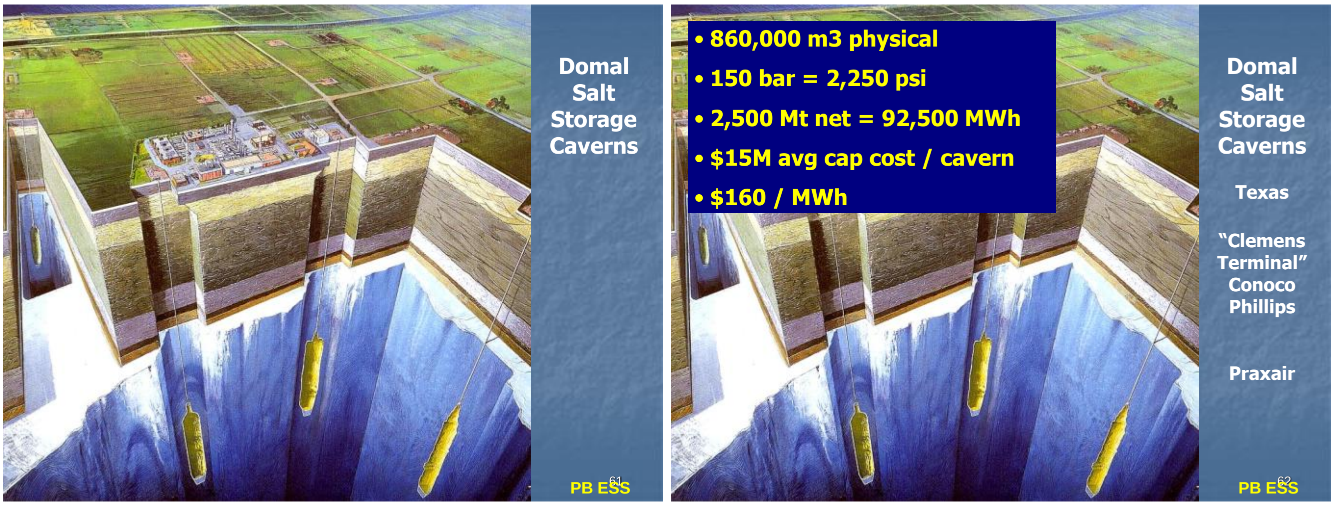


Figure 9. A single salt cavern stores ~ 100 GWh, as the chemical energy in ~ 2,500 MT of H2 working gas, on ~ 1,000 MT of cushion gas, at ΔP ~ 150 <--> 50 bar. Mt = MT = metric ton Total CAPEX, for caverns + surface facility, < $ 1.00 / kWh The Solution Mining Research Institute (SMRI) represents the technical experts in constructing, i.e. "washing", operating, and maintaining these large man-made underground structures. www.solutionmining.org Annual conferences, USA,EU

Off-Grid dedicated wind-to-H2 plant
Estimated Total Installed CAPEX
1,000 mile Pipeline, from 1,000 MW windplant
"Annual-scale Firming" GH2 cavern storage

Windplant size **1,000 MW nameplate**

	[million]
Wind turbines, installed	$ 2,000
Electrolyzers	500
Pipeline, 20"	1,100
Salt storage caverns (4)	
Caverns @ $10M ea	40
Cushion gas @ $5M ea	20
TOTAL	$ 3,660

Cavern storage: ~ 2 % of total CAPEX

26

Figure 10. Domal salt cavern storage, at Gulf Of Mexico (GOM) and in Utah, capable of annual-scale firming storage, at costs about 2 % of total system CAPEX, i.e. < $ 1.00 / kWh CAPEX for the salt cavern energy storage subsystem. "Bedded" salt geology may be less H2-tight, thus less useful, or useless. Two H2 storage salt caverns near Moss Bluff, Texas have been used for decades, without incident.

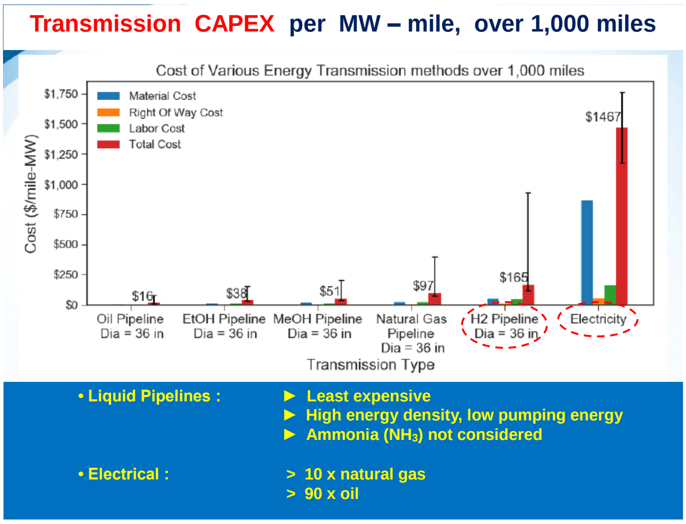
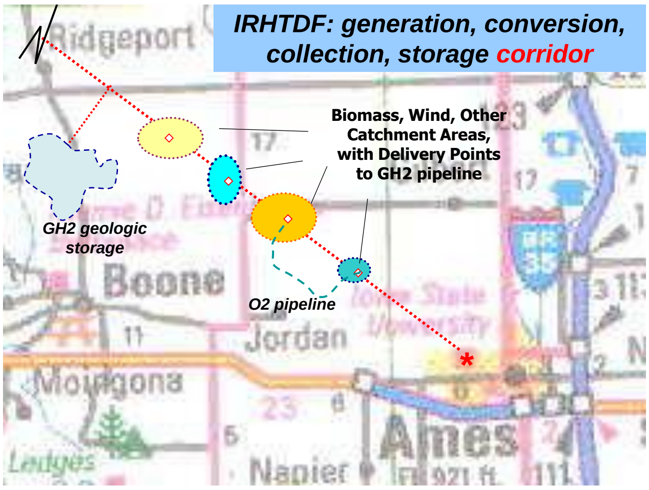


Figure 11. Energy transmission CAPEX, per MW-km, is lower for GH2 pipelines than for electricity systems, i.e. "Grid". OPEX is lower; buried pipelines are less vulnerable to acts of God and man. GH2 pipelines provide substantial "free" energy storage by "packing" to max allowed operating pressure (MAOP) when variable energy resources (VER) (wind, solar, for example) are strong, "unpacking" to ~ 1/3 MAOP, when VER input is low. [27,28]



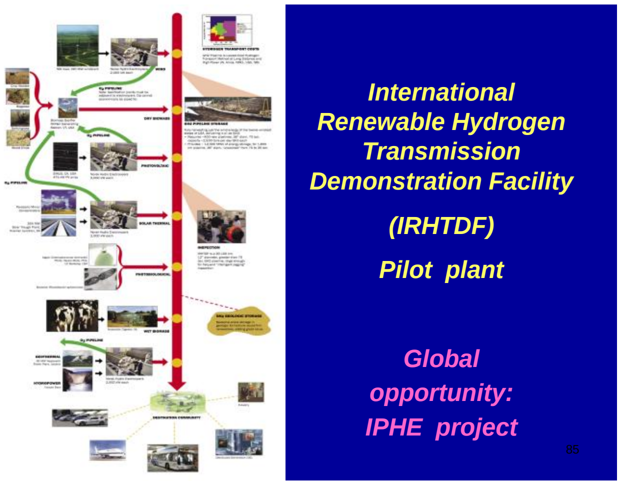


Figure 12. The IRHTDF concept should be part of the USDOE "H2Hubs" program. Safe, economical, large-scale pipelining of high-purity GH2 from variable energy resources (VER) is a global opportunity and challenge. Novel linepipe, valves, meters, couplings, entry and takeoff fittings need lab and field testing, demonstration, specification, and certification, in optimized integrated systems. This should begin at one or more International Renewable Hydrogen Transmission Demonstration Facilities (IRHTDF) to verify endurance in VER service, with large, frequent pressure fluctuations inflicted by wind, solar, other sources.

Such pilot plants should be included in the USDOE 5-year "H2Hubs" program.

Consider central Iowa, destination Ames, Iowa State University, Ames Laboratory, and retail H2 fueling stations.
Source: http://www.leightyfoundation.org/wp-content/uploads/Bill.Leighty.4Aug-H2NH3-13Jul21.pdf
[17, 39, 41]

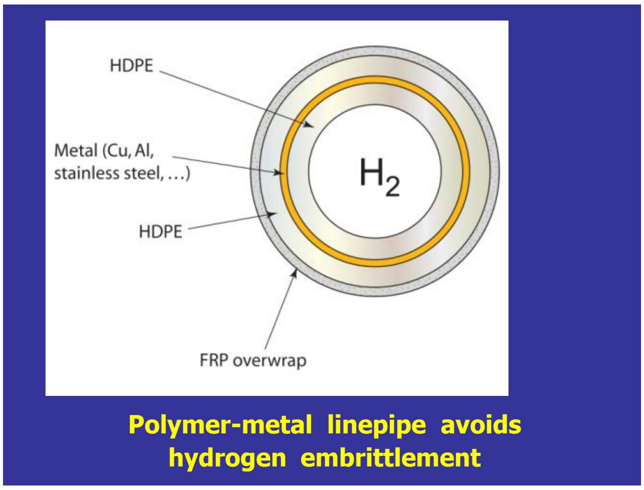


Figure 13. We probably need novel, certified, hybrid, polymer + non-ferrous metal, high-pressure linepipe, highly resistant to HE and HCC, for high-purity GH2 gathering, transmission, "free" storage by "packing", and distribution, especially for VER GH2 sources which will inflict large, frequent pressure fluctuations upon the pipeline network. A thin non-ferrous metal layer in pipe wall is the H2 permeation barrier, less susceptible to HE, HCC than ferrous metal. Polymers are also vulnerable to H2 attack. Multiple polymer layers (HDPE or others) in pipe wall may mitigate this attack plus improve pipe wall impermeability to H2. R&D&D programs are needed to design such novel linepipe(s) and manufacturing processes for them. **[25]**

FRP: Fiber Reinforced Plastic (fiberglass) overwrap for hoop strength

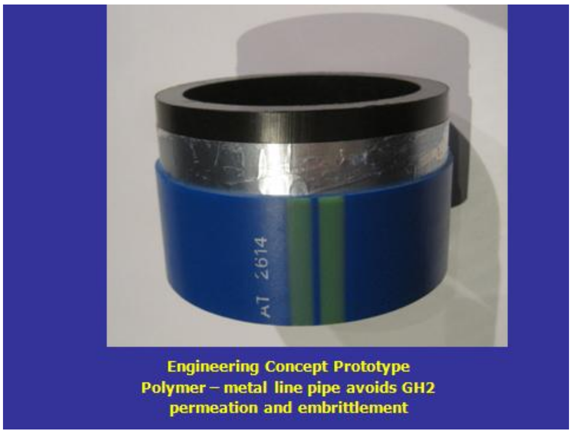


Figure 14. A proof-of-concept sample of linepipe, without outer FRP layer, with a mid-wall Aluminum foil layer for a GH2 permeation barrier highly resistant to HE, HCC. Yhis concept now needs an R&D&D program for production samples with high-pressure overwrap FRP, testing and qualification -- perhaps to a new ASME standard -- for a novel, continuous on-site, in-field manufacturing process.

Figure 15. See Figs. 13, 14, 31-37. Onsite continuous-process factory produces custom composite pipeline in unlimited length, for pull-through rehabilitation or re-purposing of extant pipelines for high-purity, high-pressure, variable-pressure, GH2 service including VER-source, or for new-builds. A non-ferrous metal foil, Cu or Al, may be built into pipe wall as the GH2 permeation barrier; foil seams perhaps laser-welded. FRP reinforced overwrap: MAOP hoop strength.

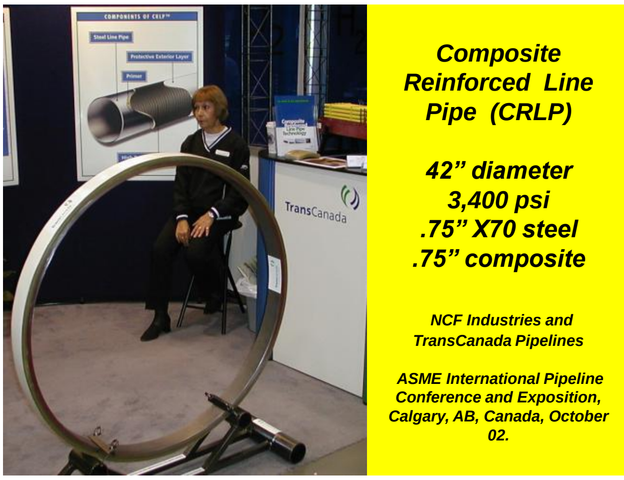


Figure 16. Composite Reinforced Linepipe (CRLP), ASME International Pipeline Conference, Calgary, 2002. [62]

X70 steel core. The exterior fiber reinforced plastic (FRP, fiberglass) provides hoop strength. In hydrotesting the completed pipeline, applied overpressure (> MAOP) permanently expands and deforms the steel, confined by the FRP. At normal pressure, the steel linepipe remains in compression, less likely to allow H2 atoms to invade the crystal structure. Large, frequent pressure excursions in VER high-purity H2 service may inflict less, or negligible, HE and HCC on the core steel. Untested in high-pressure GH2 service.

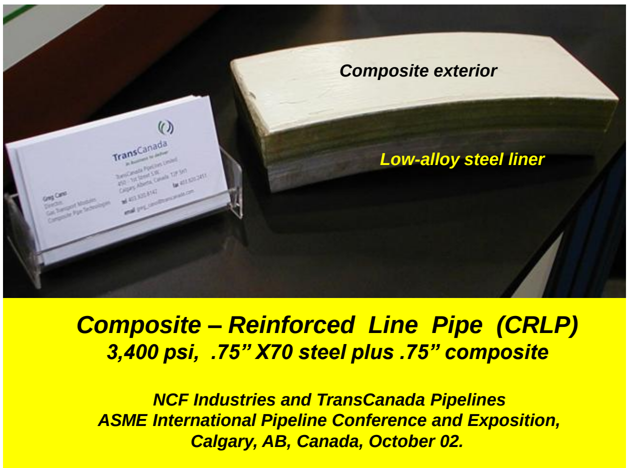


Figure 17. CRLP, TransCanada booth, ASME Pipeline Conference, Calgary, 2002. [62]

Figure 18. [62] CRLP test section, TransCanada, Alberta, ~ 2002. Weld joints on X70 are field overwrapped with FRP and cured before overpressure hydrotesting, which deforms steel core pipe. Thus, at MAOP steel is still in compression, and may be less susceptible to HE, HCC. Not tested for GH2 in VER service.

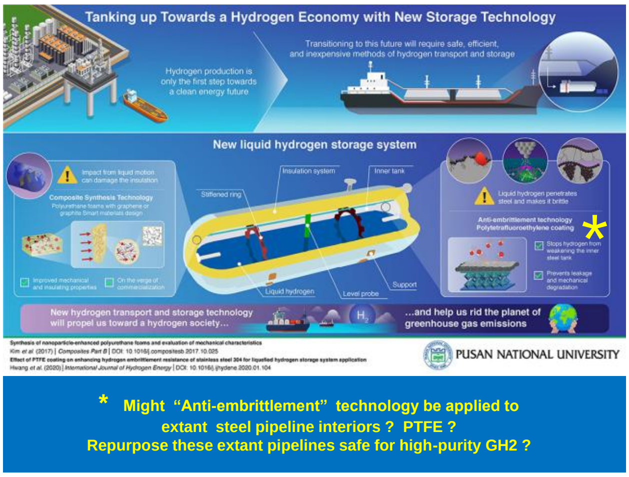


Figure 19. We may be able to perfectly and permanently coat the interior of extant steel pipelines, via pigging or other, rendering them highly immune to hydrogen embrittlement (HE, HCC), to repurpose them for high-purity, high-pressure, VER-source, GH2 service. But, can we reliably achieve zero "holidays" in the coating necessary to achieve low OPEX and excellent safety ?

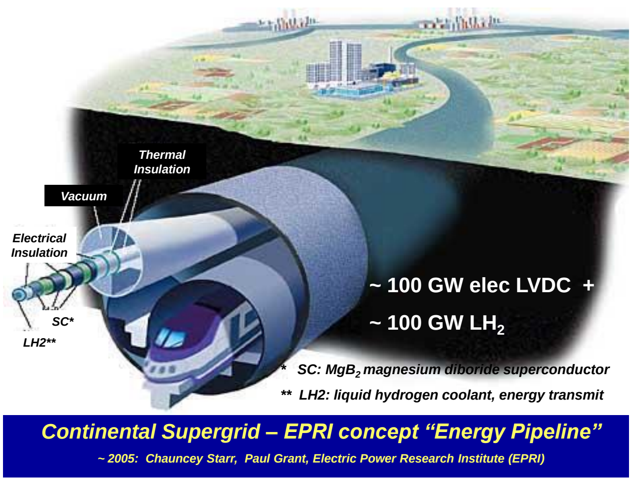


Figure 20. Electric Power Research Institute (EPRI) "Energy Pipeline" concept. Dual LH2-cooled superconducting LVDC conductors for electricity plus LH2 energy transmission: about 100 GW each. Transcontinental scale. Needs to be installed in a stable, serviceable, tunnel bored in rock. EPRI concept by Chauncey Starr and Paul Grant, ~ 2005. [59]

Figure 21. The ARPA-E "REFUEL" strategy attempts to commercialize "direct ammonia" (NH3) synthesis, directly from off-Grid or on-Grid, GHG-emission-free renewables-source electricity, water, and air, via novel technologies -- rather than by electrolysis + Haber-Bosch (EHB) process. NH3 is a better H carrier than LH2: 70 % more H atoms in a liter of NH3 than in a liter of LH2 [11, 18]

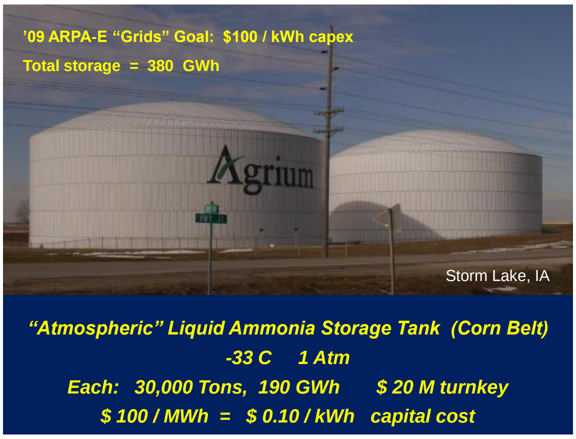
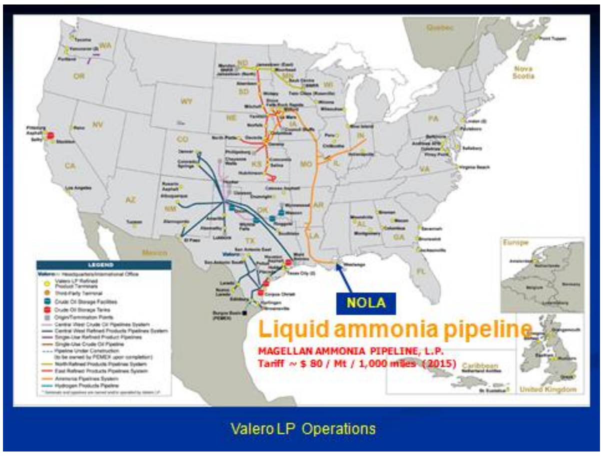


Figure 22. Anhydrous ammonia (NH3) is a better hydrogen carrier and storage medium than H2. NH3 is a liquid at ~ 10 bar @ 25 C, and at 1 bar at -35 C. We now store bulk energy in such "atmospheric" tanks at < $ 1.00 / kWh CAPEX, in the Corn Belt for N-fertilizer. [11, 18]



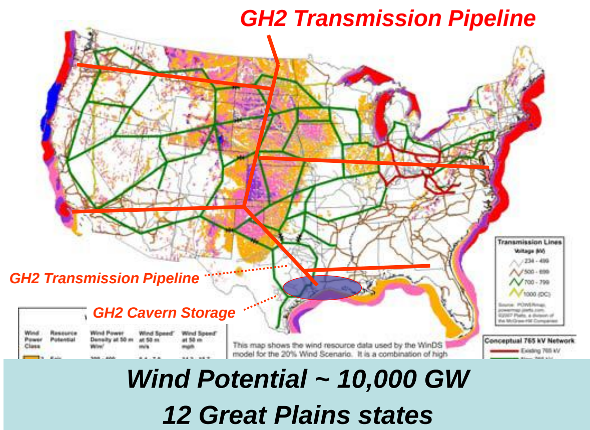


Figure 23. USA pipeline networks: extant liquid NH3; future continental GH2 accesses salt dome storage. NH3 is pipelined in low-cost underground carbon steel pipelines; in USA, over 3,000 miles serving the Midwest Corn Belt. [11, 18]

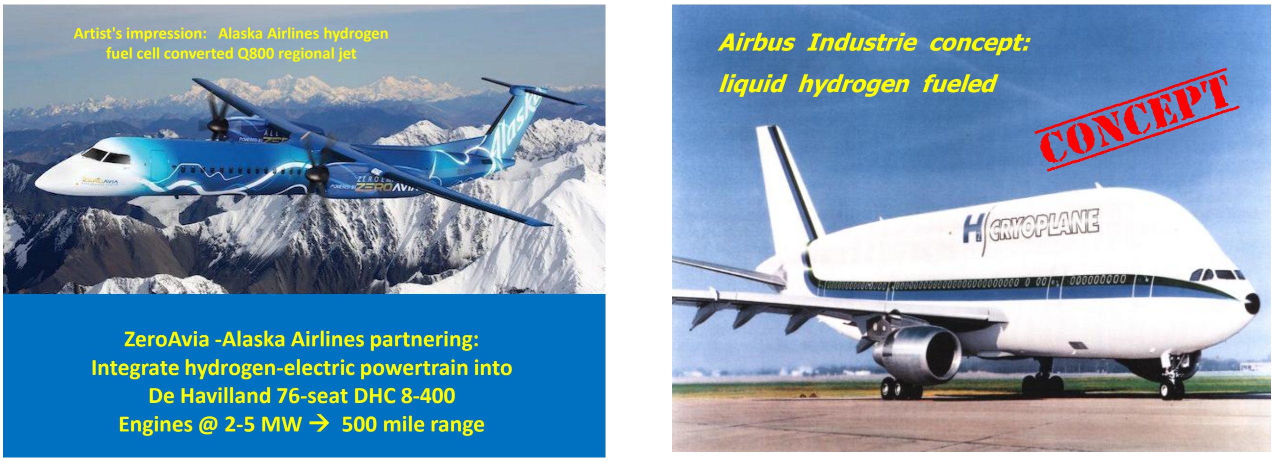


Figure 24. Aviation may require LH2 fueling, probably via short pipelines from local bulk storage. GH2-fueled smaller aircraft, up to ~ 70 pax class prop-driven, will pioneer. Hundreds of airports must provide, or *ad hoc* access, H2 fuel for accidental and emergency diversions from destination airports. A continental GH2 pipeline network will be required for aviation maturity on H2 fuels: GH2 and LH2. [44, 46, 48, 50]

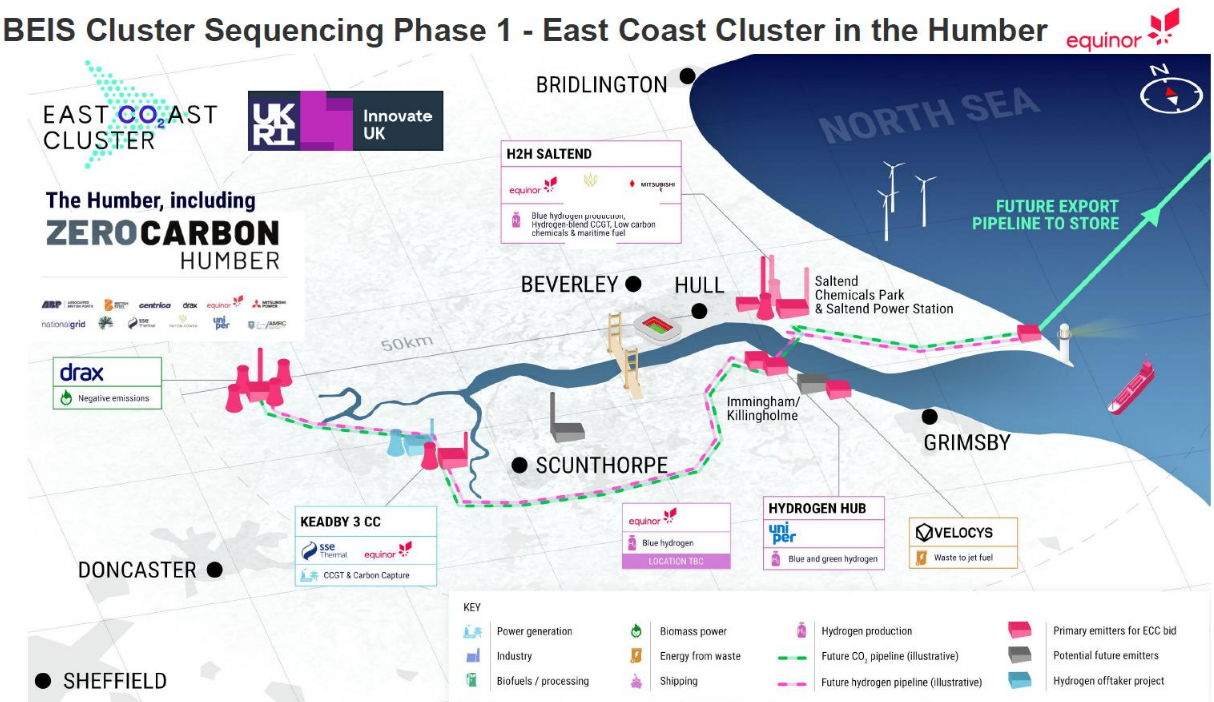


Figure 25. [57]. "Zero Carbon Humber", Dan Sadler: VP, UK Low Carbon Solutions, Equinor. Future H2 pipelines.

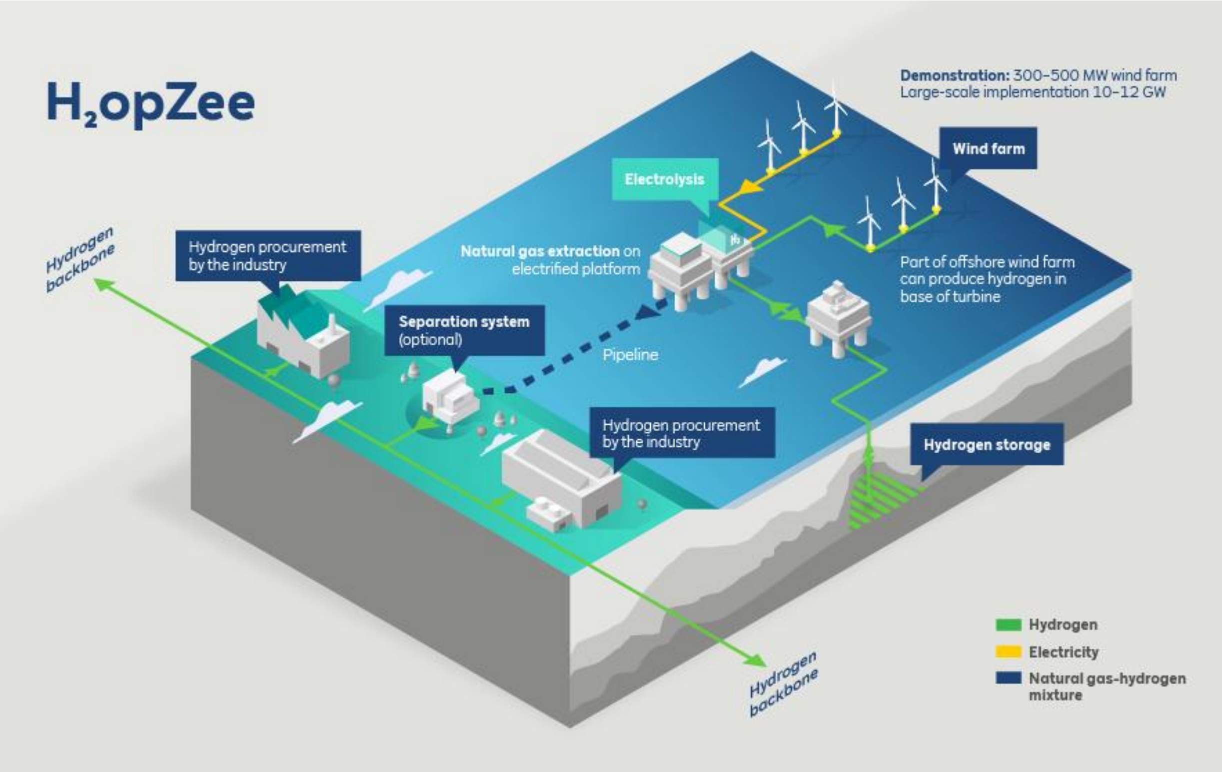


Figure 26. [58] RWE and Neptune Energy, by 2030. H2opZee, R&D&D project, intends 300 to 500 MW electrolyzer capacity far out in the Dutch North Sea, to produce green H2 from offshore wind. GH2 will be transported to land through an existing pipeline, of capacity 10 - 12 gigawatts (GW), for further North Sea wind-to-GH2-to-pipeline energy delivery.

Figure 27. Typical reciprocating, positive-displacement, un-lubricated, GH2 compressor; electric motor drive.

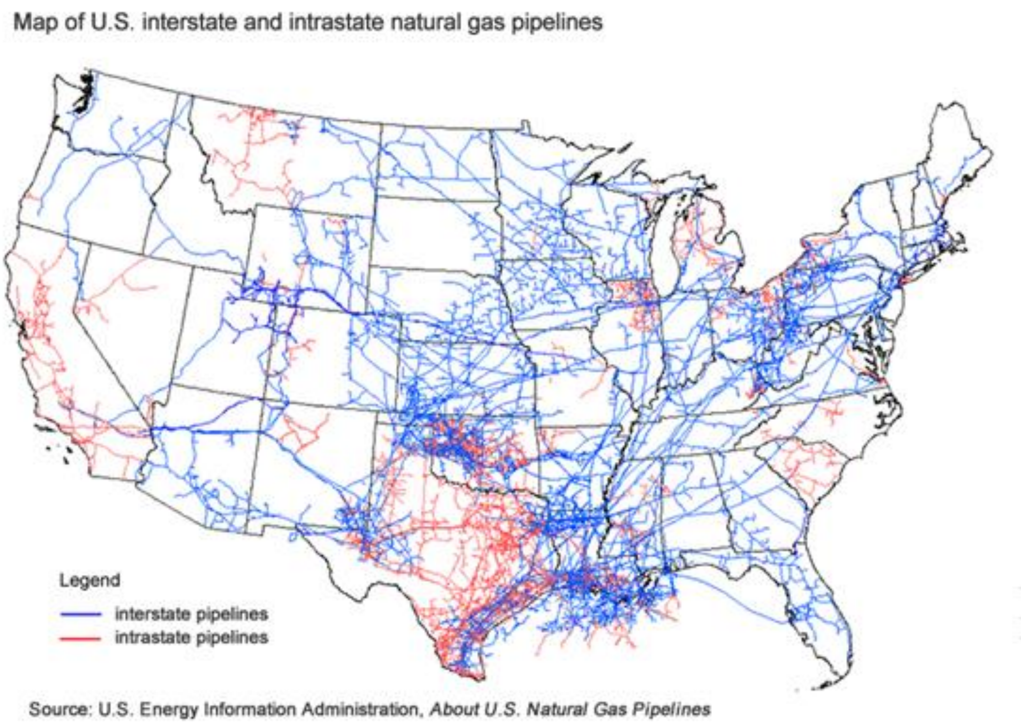


Figure 28. Natural gas pipelines: Interstate and Intrastate in United States.

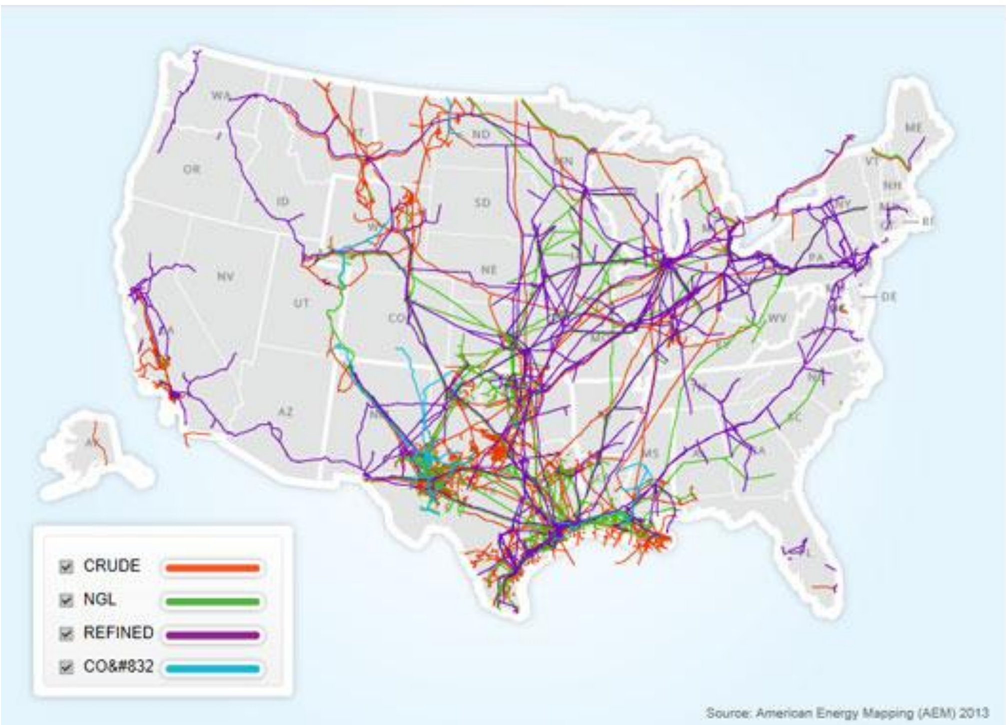


Figure 29. Liquid hydrocarbon pipelines in United States

Repurposing parts of these vast resources for profitable VER-source GH2 service is an urgent opportunity, presently fraught with uncertainties and dangers, requiring immediate R&D&D investments to resolve and mitigate these risks. Repurposing for liquid NH3 service will be technically and economically easier.

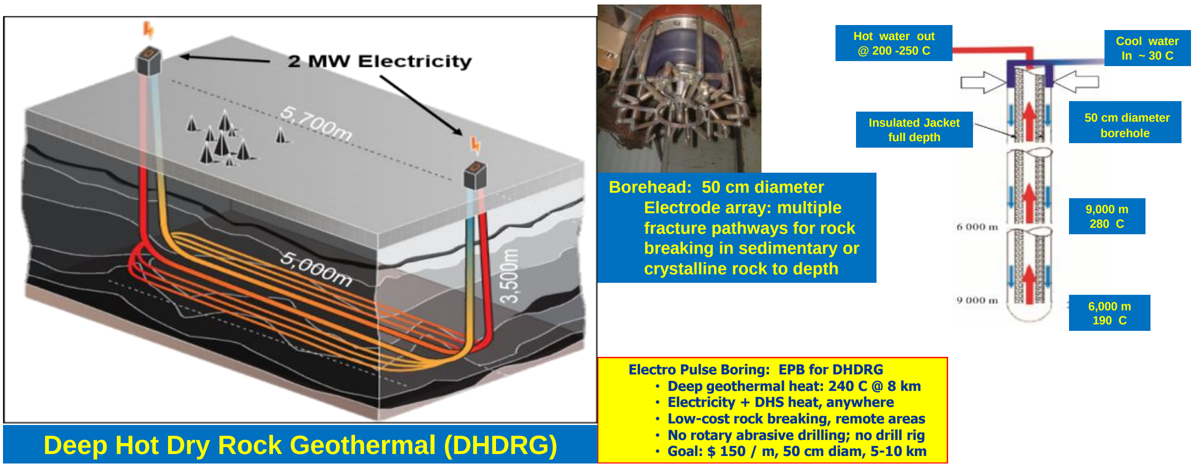


Figure 30. When we can bore "deep enough, cheap enough" (6 - 10 km) to reach DHDRG energy, via the large heat exchanger contact area required at depth, we may proliferate "Eavor Loops" to profitably extract medium-T (200-300 C) thermal energy for ORC genset electricity production and district heating and cooling systems (DHCS), nearly anywhere on Earth. This would be the ultimate in DER: DHDRG energy is generally ubiquitous on Earth, benign, inexhaustible, baseload, firm and dispatchable, with free energy storage -- leave heat in the ground until needed. Hydrogen transmission pipelines and storage caverns would not be needed. www.eavor.com [21, 76]

Figure 31. Smartpipe proprietary C-forming technology for relining legacy in-place pipelines, including those damaged, failed, out-of-service, or abandoned..
Mylar overwrap maintains "C" shape during pull-in to host pipe in up to ~ 8 km continuous lengths. Pressure testing after the Smartpipe is terminated at each end ruptures the Mylar, returning the Smartpipe to its normal "O" shape, for maximum host pipe cross-section fill and flow capacity. [77]

Figure 32. The Smartpipe continuous manufacturing plant shown in Figure 31. [77]

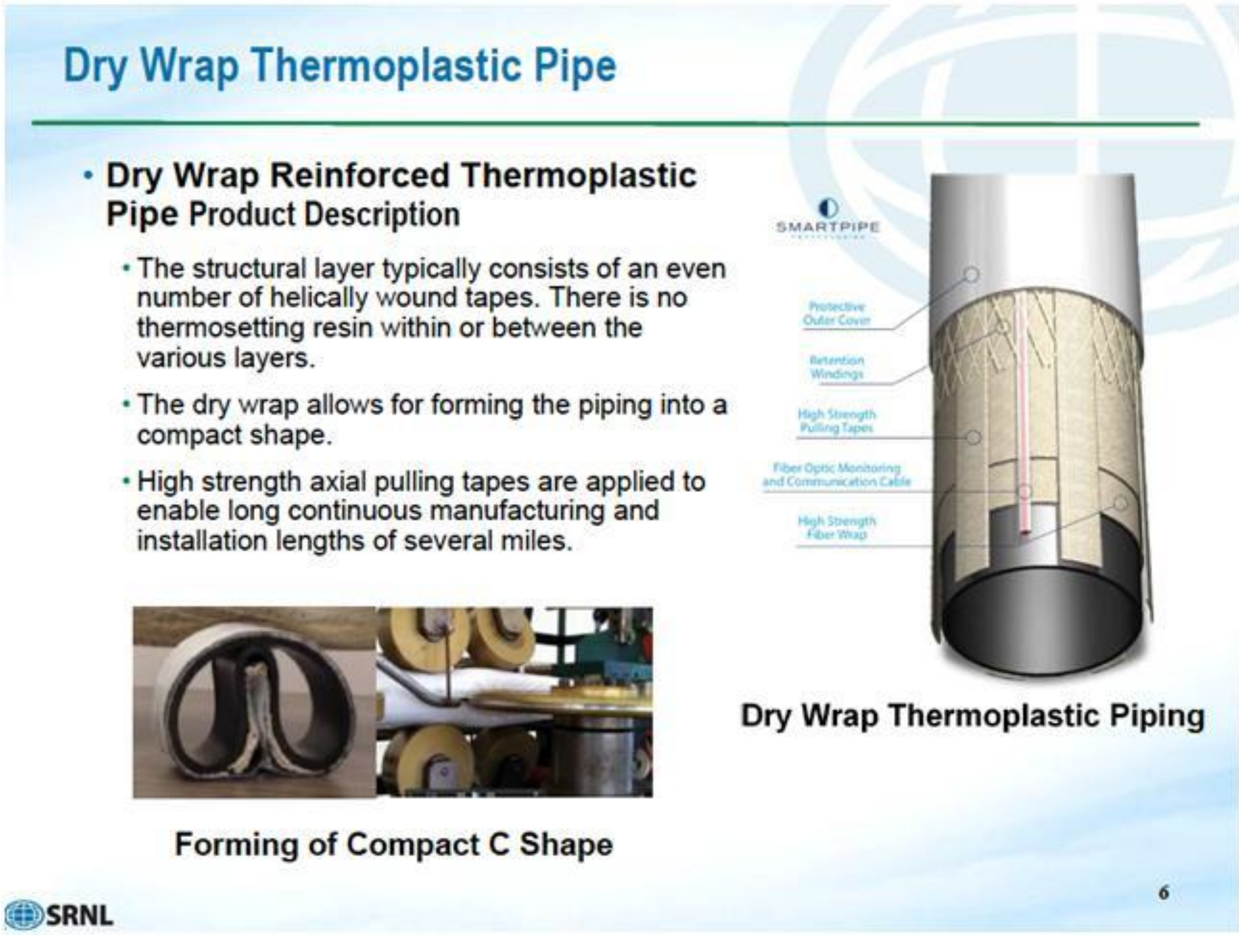


Figure 33. Smartpipe Technologies testing by DOE. Proprietary C-forming of Smartpipe to enable long length pulls to rehab extant pipelines. From Savannah River National Laboratory (SRNL, USDOE) [77]

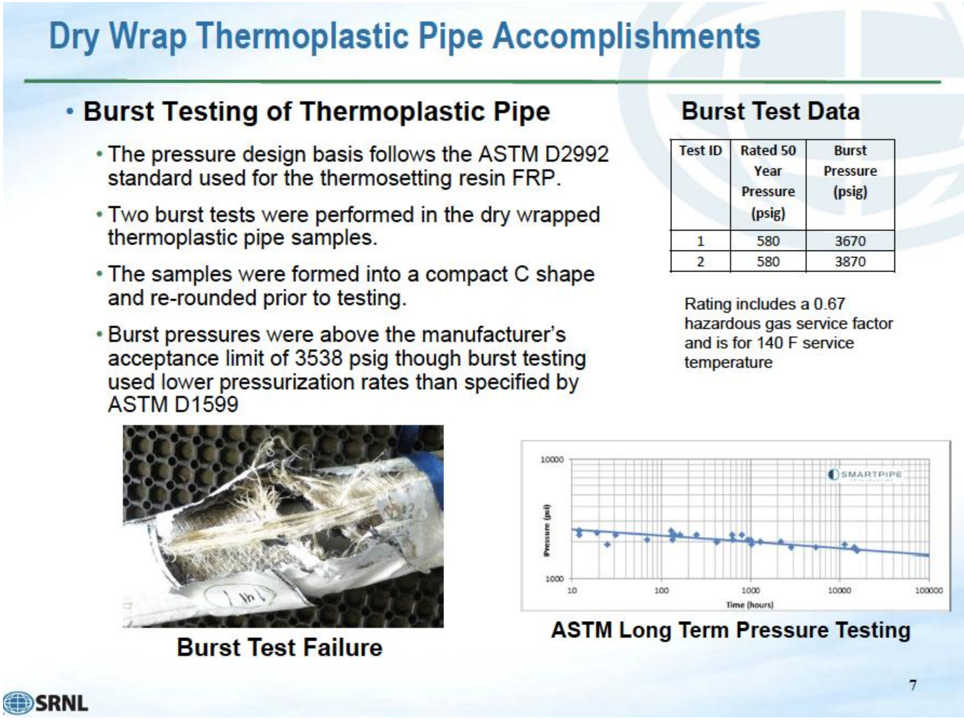


Figure 34. Smartpipe Technologies testing by DOE. Burst test of Smartpipe at Savannah River National Laboratory (SRNL, USDOE)

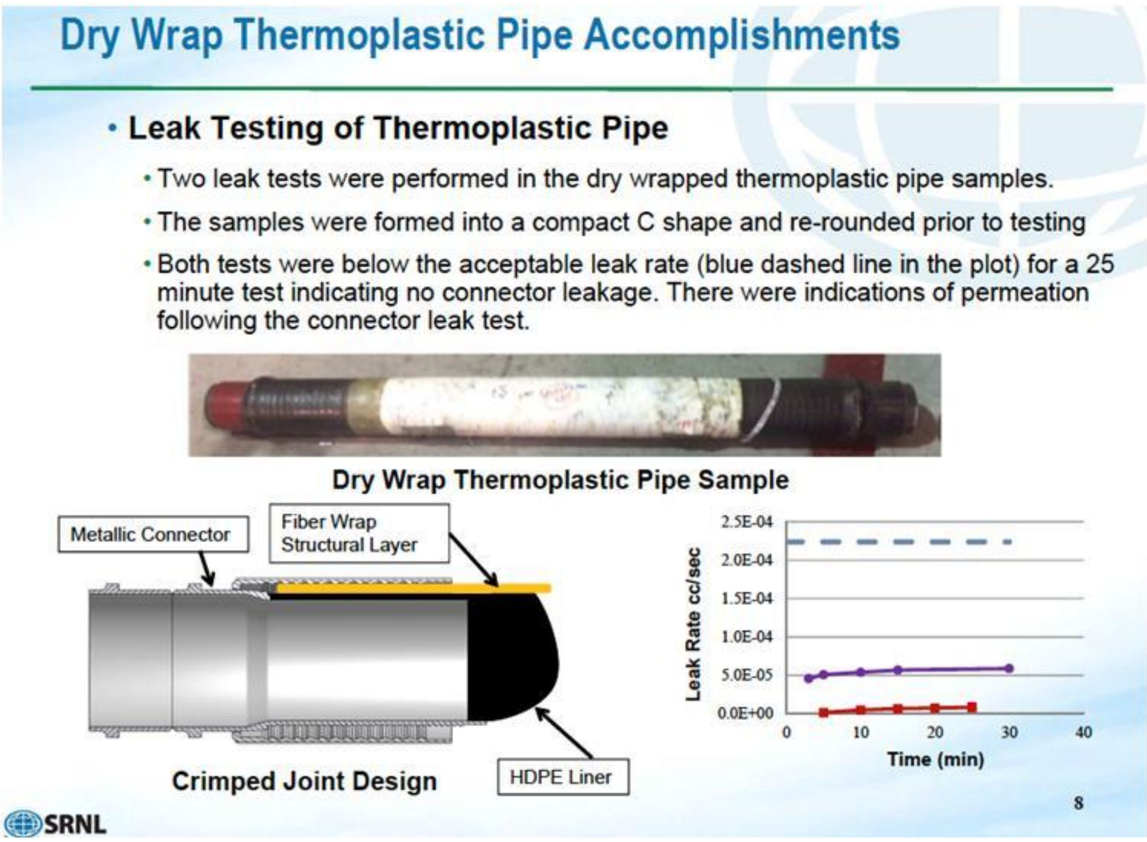


Figure 35. Smartpipe Technologies testing by DOE. Through-wall leak test of Smartpipe at Savannah River National Laboratory (SRNL, USDOE)

	CO2 Emissions (Tons per Kilometer of Pipe)											
	Materials		Transportation		Fuels		Coating & Welding		Overhead		TOTAL	
	20"	24"	20"	24"	20"	24"	20"	24"	20"	24"	20"	24"
Smartpipe®	48	75	11	13	2.07	2.07	0	0	0.68	0.68	61.75	90.75
Steel Pipeline	206	259	16	22.3	53.4	84	8.6	10.4	40.7	40.7	325.06	415.98

Figure 36. Comparing total CO2 emissions from manufacture and installation of steel vis-a-vis Smartpipe pipelines.

Calculation of pipeline quantity and size
(via manipulation of Panhandle B equation)

City Size	Peak H_2 Demand (kg/d)	Daily H_2 Demand (kg/d)	4.5-inch ID Pipelines Required	ID Required for Single Pipeline (inches)
200,000	58,600	41,000	4	7.25
1,000,000	293,000	205,000	17	13.75

Figure 37. Calculation for small-diameter GH2 pipelines with arbitrary "City" demand assumption. A single, larger-diameter pipeline replaces many smaller lines: the Smartpipe advantage in nonferrous linepipe manufacturing.

A relatively common spoolable FRP pipe in USA is 6.5" OD. For the equivalent service, a 14" OD Smartpipe has a 4x flow cross-section. Larger diameter FRP-reinforced polymer linepipe is necessary for the GH2 scale-up discussed in this paper. The delivery capacity differences between smaller and larger diameter pipe is apparent; H2 permeation leakage loss is a function of pipe wall area.

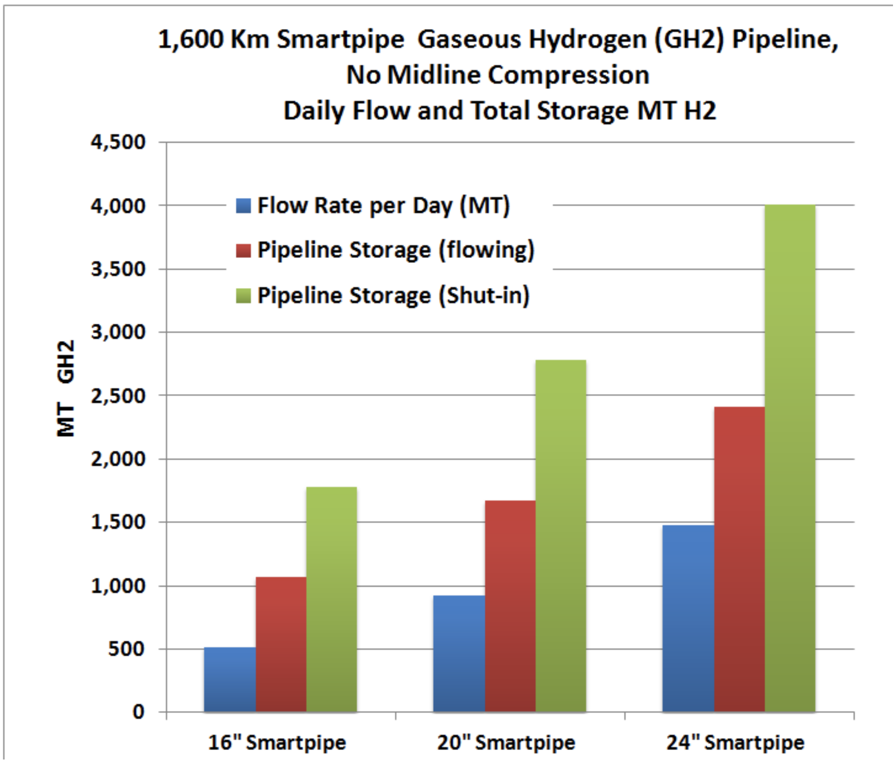


Figure 38. Flow capacity and "packing" energy storage capacity of Smartpipe FRP-reinforced high-pressure hybrid polymer linepipe, Metric tons gaseous hydrogen per day (MT GH2 / day), without midline compression, for a 1,600 km (1,000 mile) GH2 transmission pipeline. From hydraulic modeling at Smartpipe Technologies, Houston.

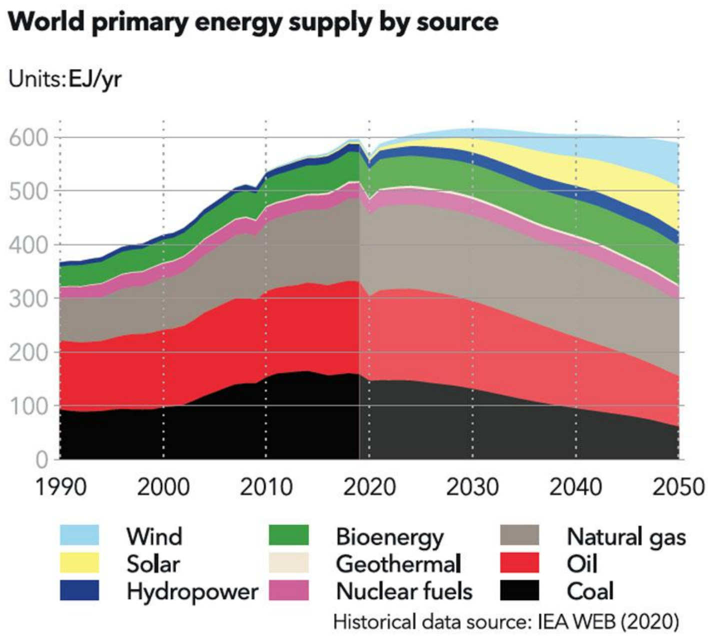


Figure 39. From DNV Energy Transition Outlook 2021. Fossil fuels supply ~ 50% of humanity's primary energy in 2050. Energy-derived Industrial Feedstocks, not included, emit significant GHG to total [E+IF] for the entire human enterprise. This paper urges expeditious profitable technical and economic innovations, by all, by which to escape this bleak and dangerous future. [9]

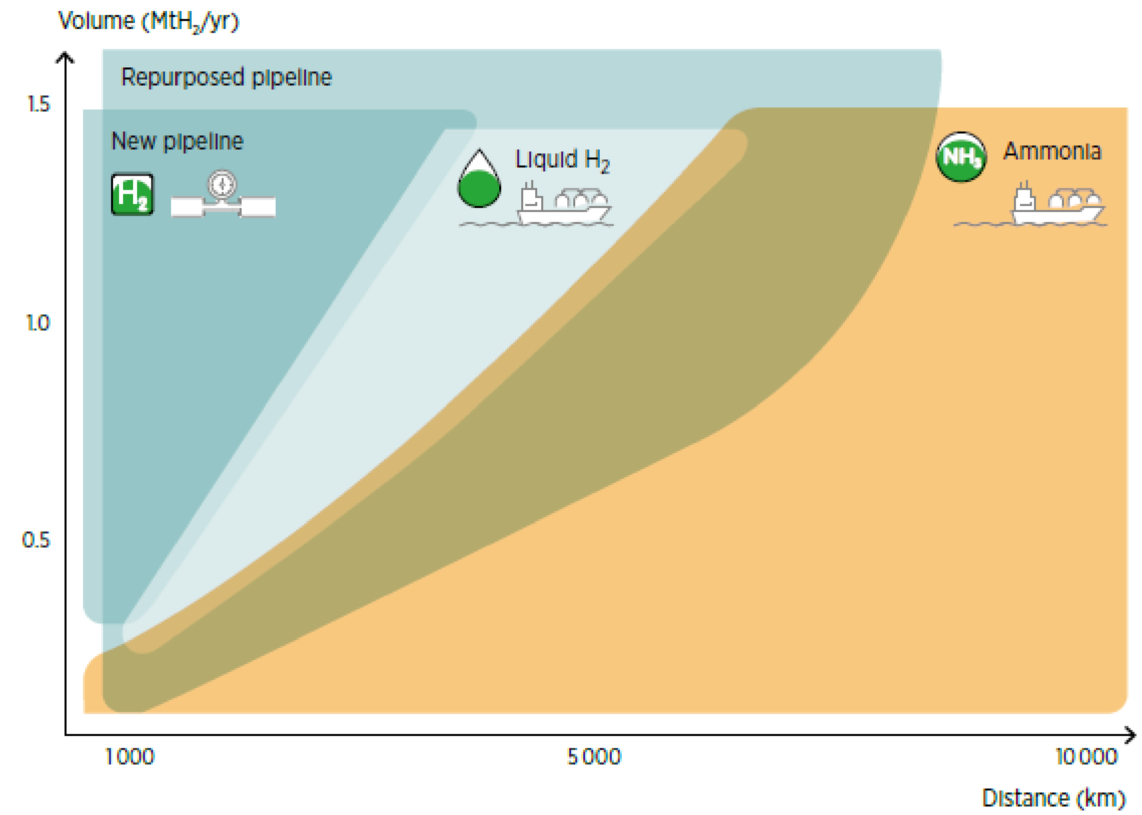


Figure 40. Long-distance, high-volume H2 transmission modes. Liquid NH3 transmission and low-cost storage, at continental and global scales, is a mature technology and industry. From IRENA [3, 4].

Figure 41. Bunkering liquid hydrogen (LH2) fuel to cruise ships and other large marine vessels will require short-distance LH2 pipelines from the liquefier plants to the bunkering tanker docks. Bottom photo is the world's only oceangoing LH2 tanker, by Kawasaki Heavy Industry. [79]

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ABBREVIATIONS AND DEFINITIONS

BOS	Balance Of System
CI	Carbon Intensity: The amount of carbon by weight emitted per unit of energy consumed.
"Clean"	Any H2, NH3, or other energy carrier produced without GHG emissions, from any energy source or feedstock
DER	Distributed Energy Resource, generally on the customer's side of the energy meter (electricity, or other), or connected to the distribution-level energy network
[E+IF]	Energy + Industrial Feedstocks
FFS	Fitness For Service
GCC	Global Climate Change
Grid	The electricity system: generation, transmission, energy storage, distribution
"Green"	H2 produced via electrolysis of water using GHG-emission-free electricity source(s)
GWP	Global Warming Potential
LH2	Liquid Hydrogen
MAOP	Maximum Allowed Operating Pressure
NatGas	Natural gas, as now specified for pipelining in USA and EU
O&G	Oil and Gas industry
SMR	Steam Methane Reformer: a plant in which methane (CH4) is cracked to yield H2 and CO2 gases; the latter is usually released to the atmosphere, while H2 is pipelined to the NH3 synthesis reactor. SMR is usually integrated in the NH3 plant; short pipeline
SMYS	Specified Minimum Yield Strength
ΔK	Stress intensity factor range ($MPa \cdot m^{1/2}$)