

The Leighty Foundation

William C Leighty, Director Box 20993, Juneau, AK 99802 907-586-1426 wleighty@earthlink.net

Please see Figures and REFERENCES, beginning Page 6: a comprehensive case for H2Hubs.

**Category 1: Regional Clean Hydrogen Hub Provisions, Requirements** See Category 5, Figures, below.

1.a Close proximity: See 5.B, 5.C and Figures 1-8. See 5.A.6, 9 REF 3, 4 Figure 12 shows that one renewables-source Hub should feature an "IRHTDF" as an R&D&D lighthouse for complete "clean" GH2 energy systems, at regional-to-continental scales, to achieve the "H2 Earthshot" in USA and globally. The Texas hub could include access to salt cavern storage and major refinery and ammonia plants.

1.b, c Existing and new infrastructure, pipelines: 6 to 10 Hubs total; 3 to 4 "renewables" Hubs. See 5.A.3, 6, and 9 See 5.B See Figures 7, 8, 10-12, 19-21. Collaborative and technical success will enable H2Hubs as the defining catalyst for large, complete, integrated, global energy systems, which will only be important at very large power and energy capacity, at regional and continental scales. Large, dedicated, high-purity, underground GH2 pipelines will be essential. We do not now know how to design and build such pipelines for technical and economic optimality and safety: linepipe, valves, meters, junctions. Thus, all Hubs should include at least one multi-km-scale R&D&D pipeline. REF 1-5

2.c, d Network, policies, infrastructure: See 5.A.1, 4, 7, 8, 11, 12. See all Figures: a complete system view. Policies: national 2% "clean" H2 blend standard for NatGas transmission pipeline, an "H2 RPS". "Successful and sustainable" will depend on disruptive progress discussed in 5.D; prepare Hubs for it.

2.e Measure progress: > 20% projected reduction in off-Grid plant gate H2 cost for delivery to new GH2 pipeline network, of repurposed extant and new-build lines. See 5.A.6, 7, 9. Figures 1, 2, 7, 8, 12

3.a No, do not incentivize larger Hubs via FOA's. We want diversity, whole systems design, not mass. See all Figures: an integrated, renewables whole system. See 5.A.4, 5, 11, 12. Figures 1, 23, 3, 12, 27.

3.b CF, intermittency, storage accomplished by GH2 pipelines. See 5.A.6, 8, 9. Figures 7, 8, 11-18 REF 6

3.c GH2 purity at offtaker control panel: to trucks and / or to NatGas blend or high-purity pipeline.

3.e,f Policies: national 2% "clean" H2 blend for NatGas transmission pipeline, an "H2 RPS". Off-Grid clean electricity dedicated to lower-cost GH2 production: intersects with RFI # DE-FOA-0002698. Example: <https://alaskaappliedsciences.com/wp-content/uploads/FOA-2459-1-F-3379-5Apr21.pdf>

4.a END-USE DIVERSITY: Off-taker agreements must be part of Hub proposals, but remain non-exclusive and flexible, allow markets evolution during 5 year program. See 5.A.4, 5, 7. Figs 2, 3, 12, 27

4.c By multiple, geographically-diverse, "renewables" Hubs. Consider NH3. See 5.B Figures 27-30

5.a GEOGRAPHIC DIVERSITY: See 5.A.9, 5.B, 5.C Figures 7, 8, 11, 12, 21. "Region" defined by pipelines, by markets, by applicants, in order to achieve 5.A.6, 7.

5.b All 12 factors in 5.A are important. Design FOA to achieve them. All Figures are factors in the case for Hubs. Figures 14-21 and 22-26 and 27-30 intersect with RFI # DE-FOA-0002698, as they should.

7.a EMPLOYMENT: All 12 factors in 5.A are important in this achievement. FOA should not emphasize this criterion. Hub emphasis must be on innovation and whole-systems thinking, for rapid scale-up.

## Category 2: Solicitation Process, FOA Structure, and H2Hubs Implementation Strategy

**8. Funding.** Several H2Hubs FOA's may be required to achieve all 12 criteria in 5.A; perhaps different mechanisms for each. Assuming integration of results from RFI # DE-FOA-0002698 in Hubs, several FOA methods are needed to insure inclusion of diversity of enterprises, technologies, and business plans.

**9. Review criteria.** Design to optimize all program objectives in 5.A, and all other factors in 5, below. Expect a TRL range, complicating Phase 1-2 transitions. FOA's must be flexible, alert. Figures 27, 32, 33

**10. Multiple launches.** Good strategy, for same reasons as in 9. Attempt many Hubs, multiple regions.

**11. Specific activities.** Keep FOA design and process simple, to encourage innovation, partnering, and flexibility over the 5 years. Emphasize whole-system design. Consider all Figures and Category 5, below

**12, 13, 14. Phase 1 time; funding; adding new.** Same as 11, above.

**17. Reviews and permitting challenges.** Because these will vary with geographic location and political jurisdiction, Hub siting is important, especially to accommodate considerations if 5.A.6 - 11

**19, 20. External partners.** The FOA design and selection process should include, early, ASME and other codes, standards, and certification groups. Be sure to poll respondents to the two RFI's for candidates, explain how they may, and should, use the H2MatchMaker tool.

**24. Cross-cutting support.** All National Labs, and universities with extant expertise should help, within their budgets. All non-profit organizations (NPO's) with relevant expertise, should be invited: RHA, GHC, RMI, CHBC, Colorado Hydrogen Network, ASME, IEEE, et al. Private enterprises may be important advisors, whether or not included in a Hub FOA application or funded project. Figure 11, 12. REF 1-4. Department of State could facilitate an "IRHTDF" via the IPHE and via IRENA. REF 11-14

**25. Impact data, "clearinghouse".** See 5.A.8 objective. All Hub technical components have, or are embraced by, a SCADA system for auto data collection of many kinds. PBS and other media experts for Hub site tours, briefings, video series for NOVA and other outlets. Frequent demonstrations: how soon the innovations & total systems will be available, GCC mitigation potential.

**26. Leverage other RFI, funding.** See 8, above. Include results of RFI # DE-FOA-0002698 in FOA design.

## Category 4: Market Adoption and Sustainability of Hubs

**32. Market-based supply-demand mechanisms.** FOA design to encourage applicants to propose any of these. Insure Hubs max non-proprietary openness to private enterprise, large & small. See 2.c, d above. FOA design for max flexibility, evolution, over 5 year program. Focus on 5.A.3

**33, 35, 36, 38, 39. Support reliable supply and demand.** See 5.A.4, 9, 10. Launch and maintain a multi-disciplinary, long-term, modeling study -- including multi-DOE-Lab plus diverse other participants, to prevent over-dependence upon, and over-investment in, the electricity Grid, as Hubs program reveals advantages to multiple-scale and continental-scale H2 and NH3 whole-energy-systems. Figures 32, 33; Figures 27-30, Figure 21: include potential for disruptive technologies to change H2 role and utility.

Figures 11, 12. Include in a "renewables" Hub an R&D&D for systematic inclusion of diverse supply and demand. A Texas hub includes access to salt cavern storage and major refinery and ammonia plants.

**Category 5: Other      Question 40: Regional Clean H2 Hub RFI; specific criteria**

**A.** Specific criteria: The following 12 "H2Hubs" program objectives should guide the FOA(s) design, for long-term benefit of the entire USA and global energy communities:

1. Hubs' conception, design, construction, and operation should lead to a comprehensive appreciation of complete, integrated, synergistic, optimized, Energy + Industrial Feedstocks [E + IF] systems based on GHG-emission-free hydrogen and anhydrous ammonia (NH<sub>3</sub>) as carbon-free energy carriers, storage media, and fuels. This will integrate with RFI # 2698, which will affect USA's total strategy for de-carbonization and de-GHG-emission of the entire [E + IF] enterprise. This will require large off-Grid H<sub>2</sub> production from wind + PV, with delivery to a new gaseous H<sub>2</sub> (GH<sub>2</sub>) pipeline system for gathering, transmission, and distribution; CAPEX + OPEX savings will reduce plant-gate H<sub>2</sub> cost. REF 7

2. Answer many of the questions posed in the RFI; do not attempt to answer them, now, for FOA design. This is a high-risk, frontier, multi-stage program, necessarily iterative, with unpredictable outcomes. Hubs diversity and inter-stage flexibility are required; explicitly declare so in the FOA's. Thus, multiple Hubs of each of four types will probably be needed.

3. The US and global energy communities -- industry, DOE and other labs, universities, investors -- are enabled and motivated to test these five hypotheses and act upon the results:

- a. In humanity's totally-decarbonized, zero-GHG-emission, future, electricity is generally confined to the first-and-last km, or several, of the Energy + energy-derived Industrial Feedstocks [E + IF] economic sectors and systems, while all intervening infrastructure is based on the C-free fuels, H<sub>2</sub> and NH<sub>3</sub>, via underground pipeline networks, with very-low-cost energy storage in "packed" pipelines, salt caverns, and -- in NH<sub>3</sub> case -- in liquid surface tanks in a wide range of sizes.
- b. The electricity Grid supports the H<sub>2</sub> and NH<sub>3</sub> infrastructure, not vice-versa.
- c. At large scale, GH<sub>2</sub> and NH<sub>3</sub> transmission and energy storage systems cost less, in LCC CAPEX and OPEX, *ceteris paribus*, than electricity systems.
- d. USA's recent energy policy and research emphasis has been over-dependent upon, and over-invested in, the electricity system, i.e. Grid, with insufficient emphasis on H<sub>2</sub> and NH<sub>3</sub> as complete [E + IF] systems, at the expense of advancement and appreciation of the latter; this policy misalignment should be immediately corrected.
- e. Humanity will choose to supply all its [E + IF] in Distributed Energy Resource (DER) systems, from local-to-regional sources, so that inter-regional and continental-scale transmission and energy storage, via gaseous hydrogen (GH<sub>2</sub>) and liquid NH<sub>3</sub> pipelines, caverns, and tanks are no longer needed -- If, and when, these three -- and / or perhaps other -- novel technologies become competitive, safe, large-scale sources of GHG-emission-free energy:
  - i. Deep Hot Dry Rock Geothermal (DHDRG) energy; see D, below
  - ii. Nuclear fission via SMR and other nascent technologies and deployment concepts
  - iii. Nuclear fusion

Thus, energy policy and investment, at all levels, must be resilient to the potential obsolescence of:

- i. Wind, solar, and other Variable Energy Resources (VER);
  - ii. H<sub>2</sub> and NH<sub>3</sub> as large-scale transmission and storage assets and strategies.
4. To achieve 3, above, during the 5 years of the Hubs program, continuously evaluate ongoing attempts to overcome Grid inherent limitations, to advance Grid potential, vis-a-vis nascent demonstrations of H<sub>2</sub> and NH<sub>3</sub> systems' capabilities and benefit:cost, to compare the systems. This is major outcome of H2Hubs: prevent over-dependence upon, and over-investment in, the Grid, suffering higher costs and delays in achieving total de-GHG-emission of entire human enterprise.

5. The [E + IF] community develops a roadmap for, and catalog of, necessary investments in R&D&D and infrastructure, and of policies and funding at all levels, for urgent progress toward "H2@Scale".

6. Every Hub includes a dedicated, high-purity pipeline system immune to hydrogen embrittlement (HE) and hydrogen corrosion cracking (HCC), capable of GH2 VER service whereby large and frequent P fluctuations are inflicted upon pipeline systems. One or more renewables-source Hub(s) features a complete pipeline system for gathering, transmission, packing storage, and distribution. This enables linepipe and pipeline codes, standards, and certification for continental-scale proliferation. We do not know how to build a safe, economical, dedicated, high-purity, high-pressure, pipeline -- of any capacity -- immune to HE, HCC in VER service. We urgently need a FOA, followup to RFI # 2698, for linepipe design, mfg, installation processes. Relevant example Concept Paper our company submitted: <https://alaskaappliedsciences.com/wp-content/uploads/FOA-2459-1-E-3339-5Apr21.pdf>

7. No hub energy will be supplied by the electricity Grid, to avoid the perception by anyone that H2 systems are, and should remain, an adjunct to the Grid; hub energy shall be produced as H2 from diverse sources within the hub, or imported from outside the hub via dedicated, high-purity, GH2 pipeline or extracted -- at potentially-profitable cost -- from blended pipeline [NatGas + GH2] gas mix as fuel-cell-grade H2.

8. Excellent technical, economic, operational, and safety data collection and analysis to yield:

- a. Diverse technical economic analyses (TEA) and scale-up projections;
- b. Next-generation, advanced-TL, design improvements for hubs and all H2 infrastructure;
- c. Codes, standards, and certification procedures for dedicated, high-purity, high-pressure, GH2 linepipe; for GH2 pipeline systems including accessories like valves, meters, couplings, input and output fittings; for siting and permitting such pipelines;
- d. Optimizing design of off-Grid wind + PV co-located, co-generation, dedicated H2 systems.

9. The US and global energy communities understand that (a) large-scale GH2 pipeline systems will be necessary to supply likely total US demand by 2030; (b) we do not now know how to build such large pipeline systems that are safe and economical; (c) therefore, R&D&D effort should begin soon for design and test of linepipe and pipeline system components, for TRL advance and certification. REF 6

10. The US and global energy communities understand that such large amounts of H2 will be required that -- if from wind, solar, and other VER's from rich resources like the great Plains, far from markets -- off- Grid production plants need prompt R&D&D, including SEIG-mode wind turbines, DC PV strings, and electrolysis plants optimized for multiple-source "wild DC" inputs. REF 7

11. Include anhydrous ammonia (NH3) as an option, at least theoretically, and for energy transmission and storage when NH3 synthesis technologies emerge at high TRL from the ARPA-E "REFUEL" program.

12. Measure and calibrate H2 leakage from particular and diverse Hub sources; GCC effects. REF 23

**B.** At least three renewables-source Hubs; will be geographically and technically diverse; all should include a dedicated, high-purity, high-pressure, GH2 pipeline system immune to HE, HCC in VER service. Gather H2 from diverse sources, deliver for diverse uses. Figures 1-4, 12. Candidate sites:

1. Central Iowa: west of Fort Dodge to Ames. Gathering from wind, solar, biomass sources. Byproduct O2 for biomass gasification to H2. Delivery to Iowa State Univ, DOE and NVSL Ames Laboratories, retail fueling stations, for transport and CHP fuel. Pipeline easier to permit, site across farmland.
2. Southeast Colorado: from NE of Pueblo to Colorado State Univ Pueblo, Pueblo Chemical Depot, as in Ames, IA. Gathering from wind, solar, biomass sources. O2 for biomass gasification to H2.

3. Southern CA: join SoCalGas "Angeles Link" GH<sub>2</sub> pipeline project, from diverse "clean" sources to LA Basin with pipeline inputs and delivery nodes along alignment ROW.
4. Pacific Northwest: surplus Columbia-Snake River hydro and eastern WA wind to Tri-Cities. Deliver to PNNL and / or Hanford Site. Or to Portland or Seattle for large & small marine vessel bunkering.
5. Texas: gather off-Grid wind + solar energy, pipelined to multiple input / output nodes to connect:
  - a. oil refineries;
  - b. multi-salt-cavern GH<sub>2</sub> storage in GOM domal salt;
  - c. other customers: diverse transport, CHP, industrial feedstocks, N-fertilizer plants

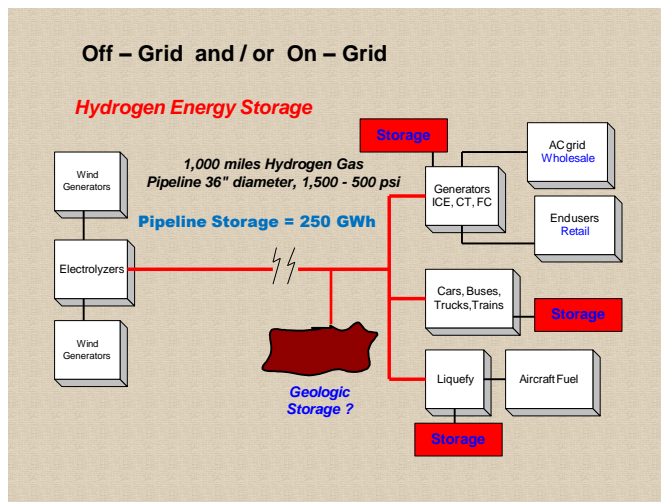
**C.** "Region" and "close proximity" definitions should be determined by the geography and topology of "clean" H<sub>2</sub> sources, customers for it, and the GH<sub>2</sub> pipeline infrastructure to achieve A.3, 4, above. Hubs FOA scale should anticipate Hubs program advancement to continental and global scales, in 5.E, below.

**D.** Disruptive potential of Deep Hot Dry Rock Geothermal (DHDRG) energy. Figures 32, 33. REF 20  
When we have invented, proven, and commercialized novel drilling methods by which to bore "deep enough, cheap enough" (6 - 10 km) to profitably harvest DHDRG energy, humanity will enjoy the ultimate in distributed energy resources (DER): inexhaustible, benign, closed-loop, baseload, firm and dispatchable, equitable, nearly ubiquitous on Earth, with inherent "free" energy storage -- leave heat in the ground until needed.

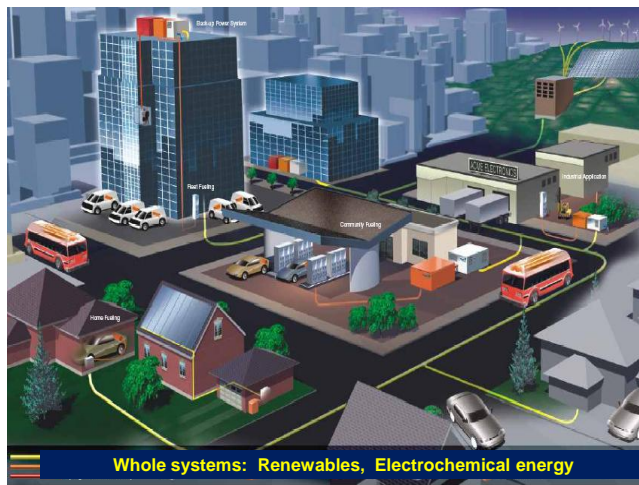
We could then supply all of humanity's electric energy, plus copious low-grade heat as hot water for processes and district heating and cooling systems (DHCS), via an autonomous or loosely-interconnected network of micro- and mini-grids. Wherever energy is needed, bore a deep heat exchanger into basement rock, from one or two small surface footprints; repeat to satisfy total demand. From abundant electricity we can produce hydrogen and energy-derived industrial feedstocks, including Fischer-Tropsch drop-in fuels.

Neither hydrogen transmission pipeline networks nor salt cavern storage will be needed. Hydrogen and perhaps ammonia fuels will be distributed within the micro- or mini-grid via underground distribution GH<sub>2</sub> and / or NH<sub>3</sub> pipeline networks. H<sub>2</sub>'s role will become transportable fuels and industrial feedstocks, sourced from the indigenous DHDR micro-mini-grids.

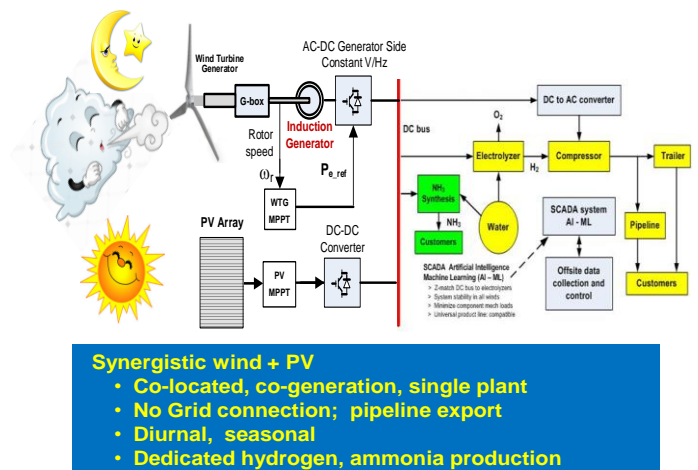
**E.** Figures 11, 12. REF 1-4, 9, 11, 23. The Hubs program should culminate in a follow-on "IRHTDF" which would apply Hubs outcomes to conceive whole-systems designs at "H<sub>2</sub> Earthshot" scale, enabling USA and global optimization of market and CAPEX allocations to Grid vis-a-vis H<sub>2</sub> and NH<sub>3</sub> systems, for accelerating de-GHG-emission at total human enterprise scale. See 5.A.3, above. Hydrogen will only be important in large, complete, integrated, global energy systems, at very large power and energy capacity, at regional and continental scales. Large, dedicated, high-purity, underground GH<sub>2</sub> pipeline systems will be essential. We do not now know how to design and build such pipelines for technical and economic optimality and safety: linepipe, valves, meters, junctions. Thus, all Hubs should include at least one multi-km-scale R&D&D pipeline, to urgently commence this process. REF 1-5 See: "Begin Now: Design and Build a Renewables-Source Hydrogen Transmission Pipeline Pilot Plant" <https://vimeo.com/209160500>



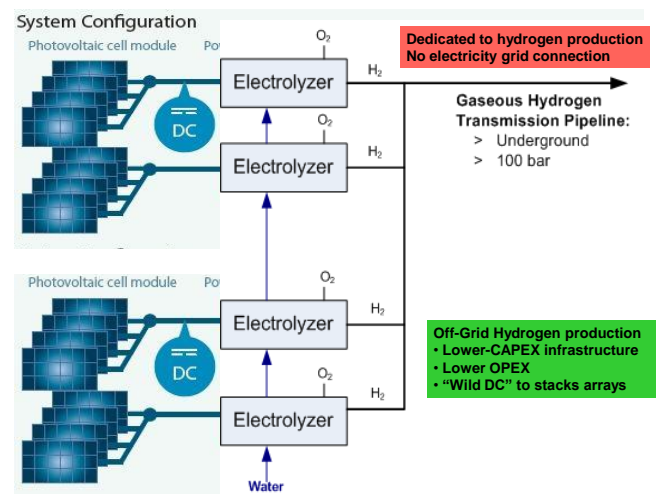
**Figure 1.** REF 5, 17 By 2035 - 2050, total continental hydrogen demand will require off-Grid, dedicated, high-purity, high-pressure, GH<sub>2</sub> pipeline networks, of linepipe and accessories immune to hydrogen embrittlement (HE, HCC), for safe, economical gathering, transmission, "free" pipeline "packing" and salt cavern storage, and distribution of VER-source hydrogen fuel for transportation, combined heat and power (CHP), and energy-derived industrial feedstocks. Single large transmission pipeline stores ~ 250 GWh at  $\Delta P = 67$  bar, no marginal CAPEX, OPEX.



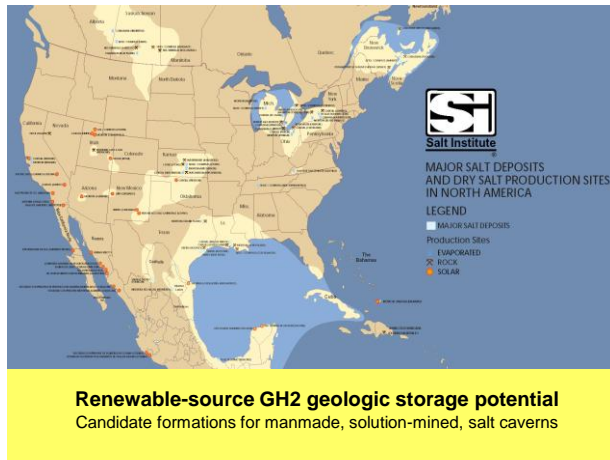
**Figure 2.** REF 5, 7, 17 Complete, integrated, synergistic, optimized, systems for [ Energy + Industrial Feedstocks ], [E+IF]. Distant, diverse, renewable, GHG-emission-free sources of H<sub>2</sub> are delivered to load centers via dedicated, high-purity underground pipeline networks for gathering, transmission, "free" pipeline "packing" storage, and distribution.



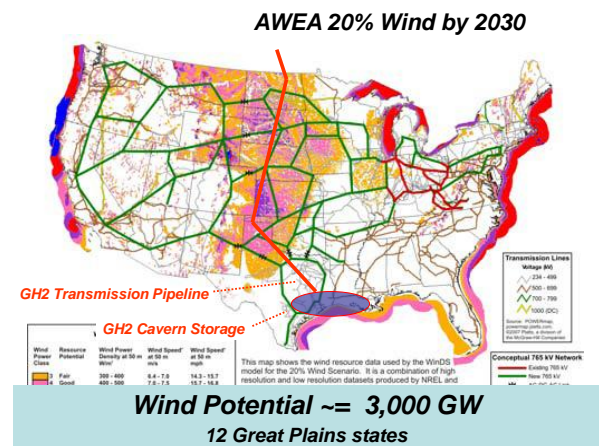
**Figure 3.** REF 6, 7, 18 Renewables-source Hydrogen Hub(s) should include off-Grid, co-located, co-generation, wind + PV plant(s) dedicated to H<sub>2</sub> or NH<sub>3</sub> production, with electrolysis plants customized for "wild DC" close-coupling to series-parallel stacks arrays, omitting AC-DC power supplies, with single system SCADA for simplified integrated controls.



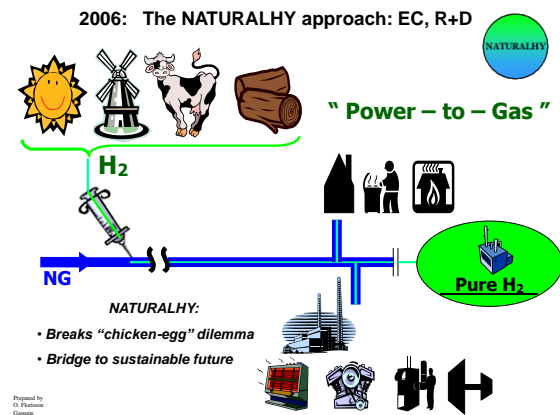
**Figure 4.** REF 3, 5, 17. PV example. Whole energy systems optimized for dedicated, off-Grid, high-purity, GHG-emission-free, Hydrogen production. Large CAPEX and OPEX savings by eliminating need to deliver Grid-quality AC. Electrolyzers optimized to accommodate unregulated "wild DC", for lower plant-gate Hydrogen cost.



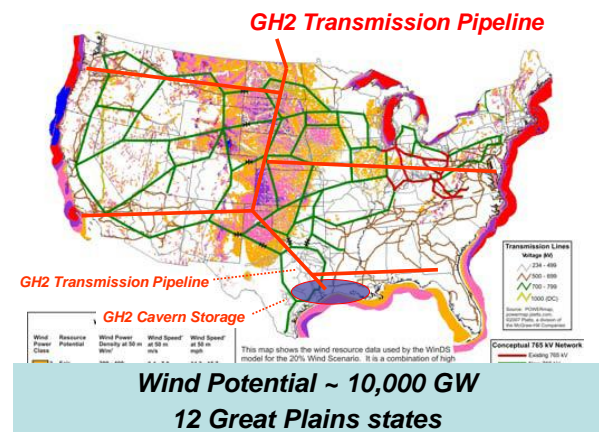
**Figure 5.** Low-cost geologic storage. The domal salt of the Gulf Of Mexico (GOM) region is ideal for hundreds or thousands of large GH2 storage caverns needed for annual-scale firming of the Great Plains synergistic variable energy resources (VER) like wind + solar. CAPEX, cavern + surface facility, < \$ 1.00 / kWh



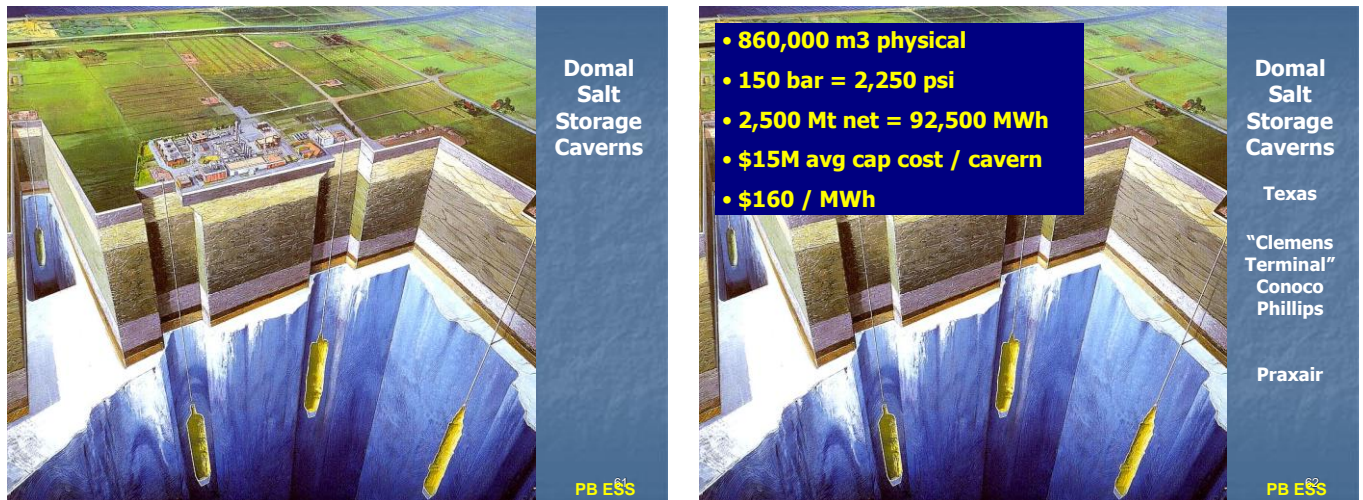
**Figure 7.** Multi-GW, Multi-GH2-pipeline corridor gathering and transmission system delivers high-purity, VER-source hydrogen to large-scale Gulf Of Mexico (GOM) salt multi-cavern firming storage, with potential to supply 100 % of total USA energy + industrial feedstocks [E + IF] demand, dispatchable 100+ Quads per year. GOM salt could host thousands of large GH2 storage caverns.



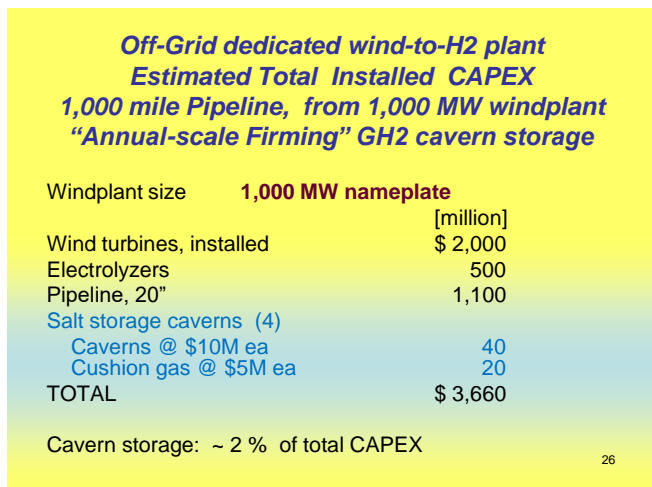
**Figure 6.** European Commission (EC) "NaturalHY" R&D, 2006. How much H2 may be blended in NatGas pipelines without encountering metallurgy or downstream customer apparatus problems ? Blending in USA is a short-term option (1) to build market for "green" H2, (2) to marginally decarbonize pipeline network NatGas blend.



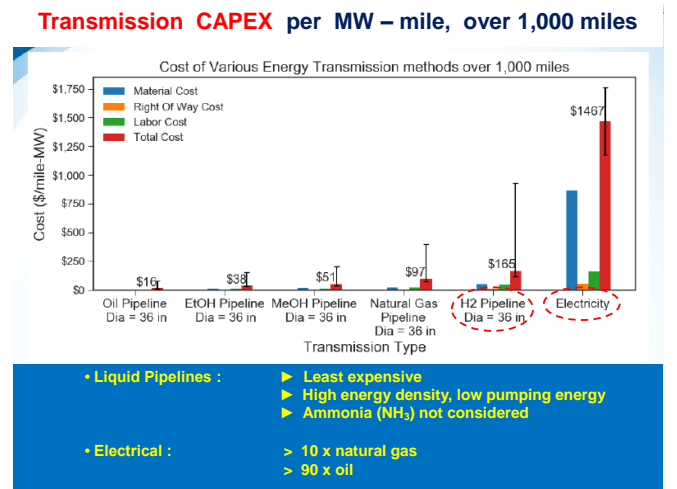
**Figure 8.** The high-purity GH2 transmission pipeline backbone supplies a continental-scale GH2 pipeline network, to supply all 100+ Quads of USA energy + energy-derived industrial feedstocks demand, [E + IF], as annually-firm, dispatchable, and decarbonized.



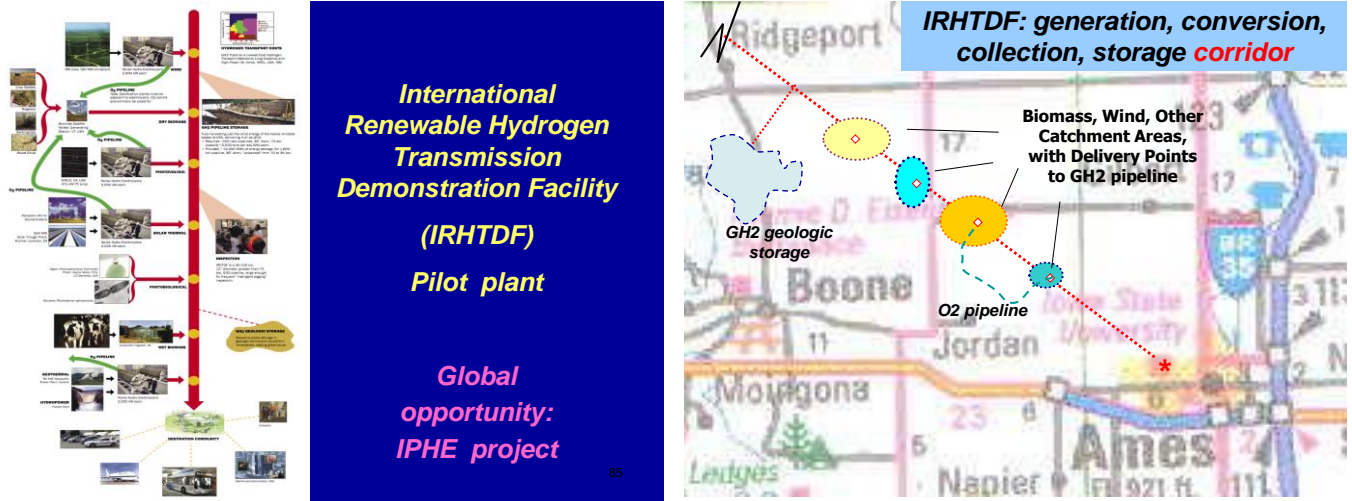
**Figure 9.** A single salt cavern stores ~ 100 GWh, as the chemical energy in ~ 2,500 Mt of H<sub>2</sub> working gas, on ~ 1,000 Mt of cushion gas, at  $\Delta P \sim 150 \leftrightarrow 50$  bar. Mt = metric ton CAPEX, cavern + surface facility, < \$ 1.00 / kWh



**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 cavern energy storage subsystem.

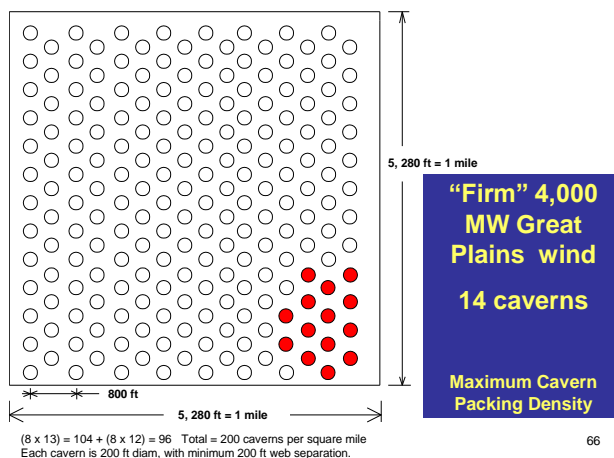


**Figure 11.** REF 8. Energy transmission CAPEX, per MW-mile, is lower for GH<sub>2</sub> pipelines than for electricity systems, i.e. "Grid". GH<sub>2</sub> pipelines provide substantial "free" energy storage by "packing" to max allowed operating pressure (MAOP) when variable energy resources (VER) (wind, solar example) are strong, "unpacking" to ~ 1/3 MAOP.

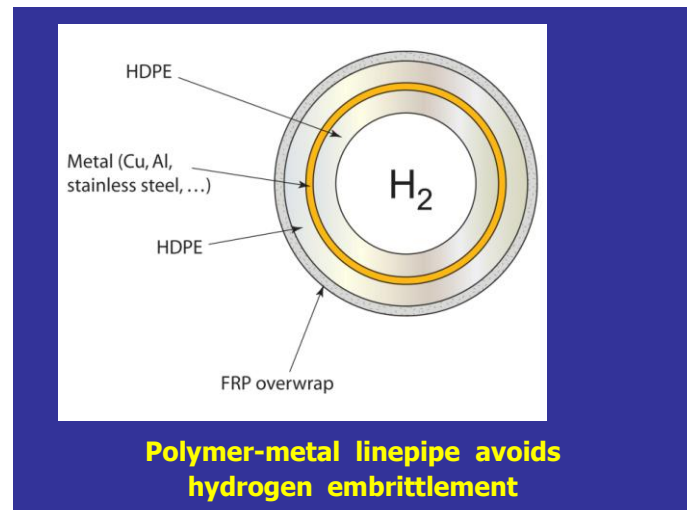


**Figure 12.** REF 25, 26 Safe, economical, large-scale pipelining of high-purity GH<sub>2</sub> from variable energy resources (VER) is a global opportunity and challenge. Novel linepipe, valves, meters, couplings, entry and takeoff fittings need field testing, demonstration, specification, and certification, in optimized integrated systems. This should begin at several International Renewable Hydrogen Transmission Demonstration Facilities (IRHTDF) to verify endurance in VER service, with large, frequent pressure fluctuations inflicted by wind, solar, other sources. Try central Iowa, destination Ames, Iowa State University, Ames Laboratory, retail fueling stations.

Source: <http://www.leightyfoundation.org/wp-content/uploads/Bill.Leighty.4Aug-H2NH3-13Jul21.pdf>



**Figure 13.** Multiple large salt caverns may be clustered at unusually high density, if manifolded together at the same pressure, reducing construction cost. They may share the same surface facility (compressor, dryer, meters, pipeline) for CAPEX and OPEX savings: more important if the deep salt caverns are offshore.

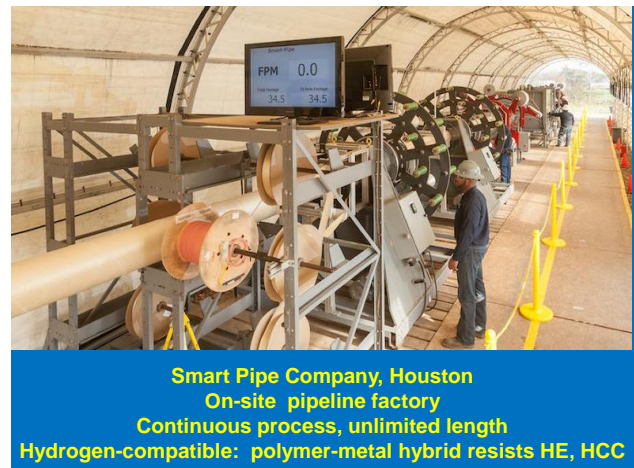


**Figure 14.** We need certified, novel, hybrid, polymer + non-ferrous metal, high-pressure linepipe, immune to HE and HCC, for high-purity GH<sub>2</sub> gathering, transmission, "free" storage by "packing", and distribution, especially for VER GH<sub>2</sub> sources which will inflict large, frequent pressure fluctuations upon the pipeline net.

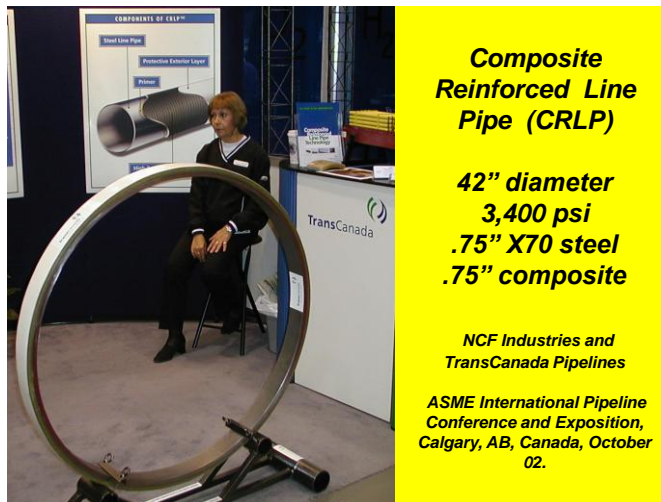
**FRP:** Fiber Reinforced Plastic (fiberglass) overwrap for hoop strength



**Figure 15.** A proof-of-concept sample of linepipe, without outer FRP layer, with a mid-wall Aluminum foil layer, for a GH2 permeation barrier immune to HE, HCC. Needs R&D&D, certification, continuous on-site, in-field manufacturing process. By Smart Pipe, Houston. [www.smart-pipe.com](http://www.smart-pipe.com)



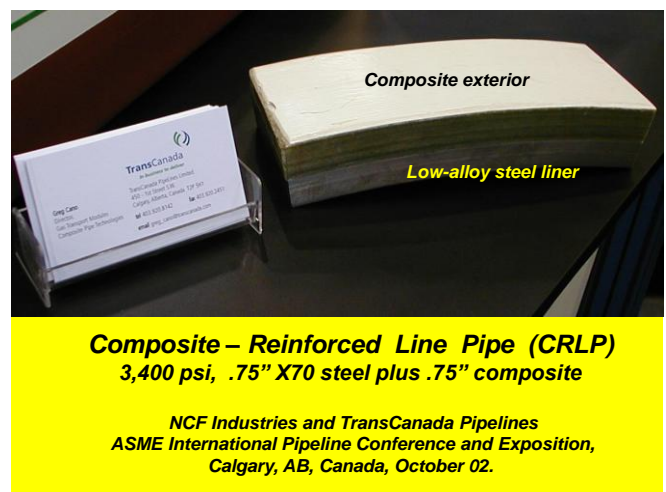
**Figure 16.** Onsite continuous-process factory produces custom FRP linepipe in unlimited length, for pull-through rehabilitation or re-purposing of extant pipelines for high-purity, high-pressure, variable-pressure, GH2 service including VER-source, or for new-builds. A non-ferrous metal foil, Cu or Al, may be built into pipe wall as the GH2 permeation barrier; foil seams perhaps laser-welded. FRP overwrap for MAOP hoop strength. See Fig 15.



**Figure 17.** Composite Reinforced Linepipe (CRLP), ASME International Pipeline Conference, Calgary, 2002.

Low-alloy steel is less susceptible to hydrogen embrittlement and hydrogen corrosion cracking (HE, HCC) than high-alloy steel. The exterior fiber reinforced plastic (FRP, fiberglass) provides hoop strength. In hydrotesting the completed pipeline, applied overpressure (> MAOP) permanently expands

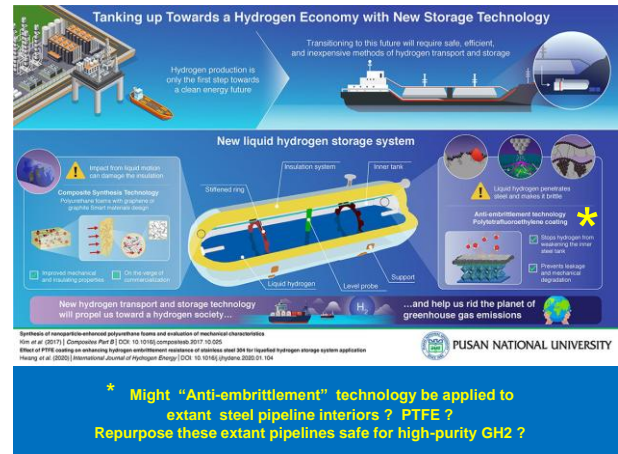
and deforms the steel, confined by the FRP. At normal pressure, the steel linepipe remains in compression, less likely to allow H2 atoms or nuclei (one proton) to invade the crystal structure. Large, frequent pressure excursions in VER high-purity H2 service may inflict less, or negligible, HE and HCC on the core steel.



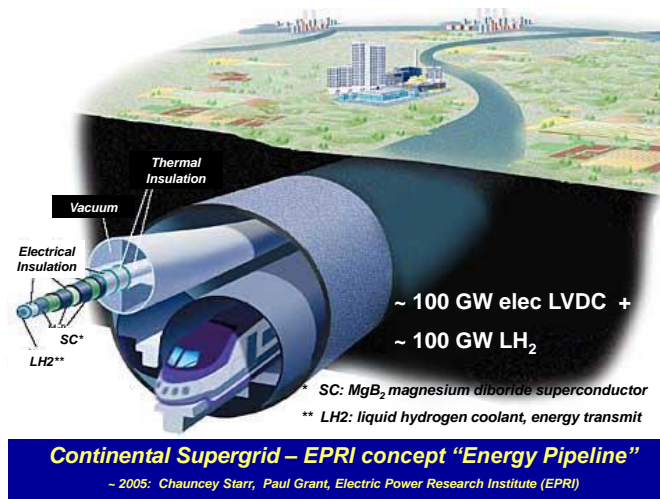
**Figure 18.** CRLP, TransCanada booth, ASME Pipeline Conference, Calgary, 2002.



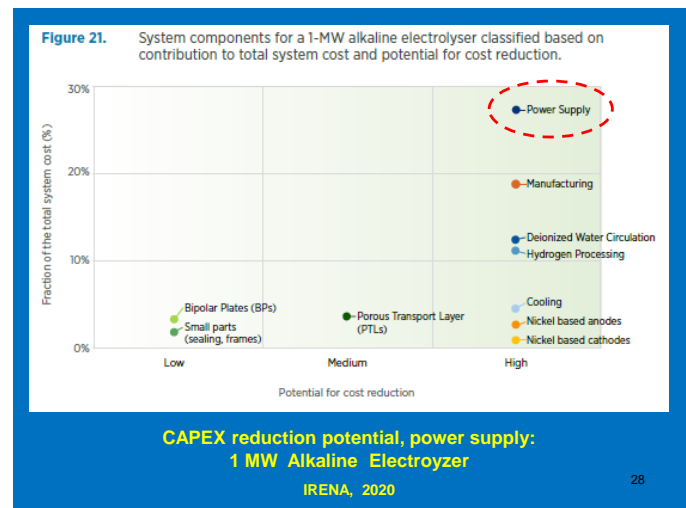
**Figure 19.** CRLP test section, TransCanada, Alberta, ~2002. Weld joints on X70 are field overwrapped with FRP and cured before overpressure hydrotesting, which deforms steel. Thus, at MAOP steel is still in compression, may be less susceptible to HE, HCC. Not tested for GH2 in VER service.



**Figure 20.** Might we be able to perfectly and permanently coat the interior of extant steel pipelines, via pigging, rendering them completely immune to hydrogen embrittlement (HE, HCC), to repurpose them for high-purity, high-pressure, VER-source, GH2 service? With zero "holidays" in the coating and low OPEX and excellent safety?

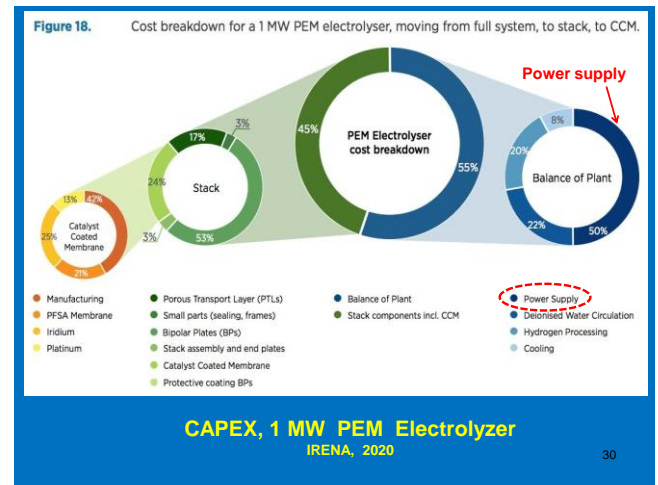
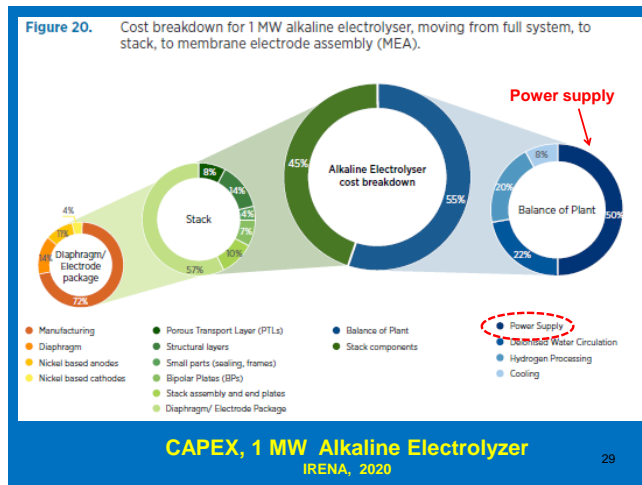


**Figure 21.** EPRI "Energy Pipeline" concept. Dual LH2-cooled superconducting LVDC electricity plus LH2 energy transmission: about 100 GW each. Transcontinental scale. Needs to be installed in a stable, serviceable, tunnel bored in rock. EPRI concept by Chauncey Starr and Paul Grant, ~2005.



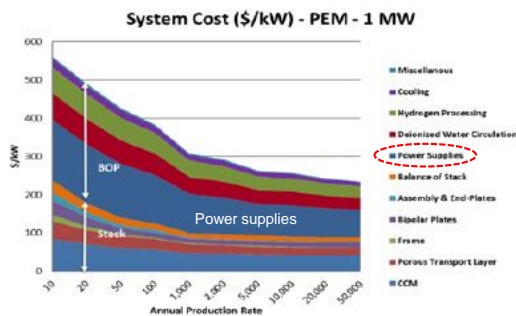
**Figure 22.** IRENA, 2020. Power supply, to feed DC to electrolysis stacks, is a large fraction of electrolyzer plant CAPEX. Less potential for manufacturing scaleup cost reduction than for stacks.

IRENA: International Renewable Energy Agency, Abu Dhabi, UAE. <https://www.irena.org/>  
Founded: January 26, 2009 Membership: 165 states and the European Union (2021)



**Figure 23.** REF 11 Power supply is ~ 27 % of PEM or Alkaline CAPEX. For off-Grid VER plants, this may argue for a series-parallel stacks array topology, composed of optimum-size stacks, allowing higher DC input voltage to the stacks array. This provides impedance matching of off-Grid, "wild DC" sources, close-coupled to the stacks array, replacing "power supply" in the electrolysis plants. R&D&D needed. See (D), above.

**Figure 27.** Cost breakdown for PEM electrolyzers as a function of manufacturing scale (units of 1 MW per year).



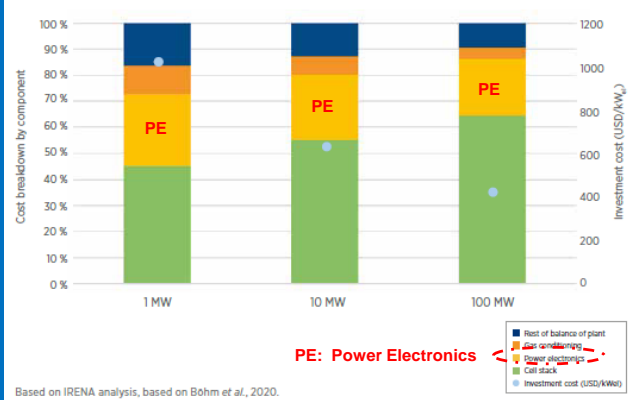
Note: Costs include material, labour, capital, energy, maintenance, buildings and scrap costs.

Source: Mayyas et al., 2019.

**IRENA 2020**

**Figure 24.** REF 11 IRENA, 2020. Electrolyzer power supply remains a large fraction of CAPEX at high build rate.

**Figure 25.** Cost breakdown by major component for alkaline electrolyzers based on current costs.



**Figure 25.** Power supply electronics CAPEX fraction decreases with module build size: relative diseconomies of scale for large size stacks. This may argue for series-parallel array topology, composed of optimum-size stacks, allowing higher stacks array DC input voltage, for impedance matching to close-coupled, off-Grid, "wild DC" sources like wind and solar, replacing "power supply" in the electrolysis plants. R&D&D needed.

Figure 28. Cost breakdown for PEM electrolyzers for a (a) 10 MW/year; (b) 1 GW/year production scale.

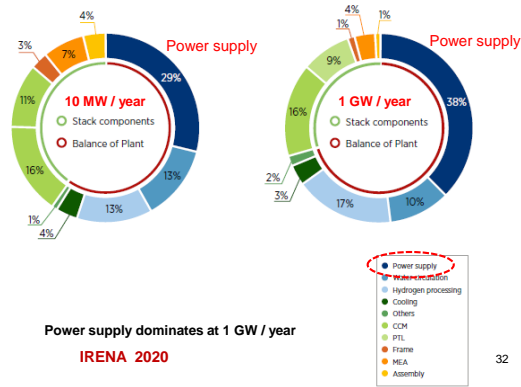


Figure 26. REF 11 Electrolyzer power supply CAPEX fraction increases with build rate.

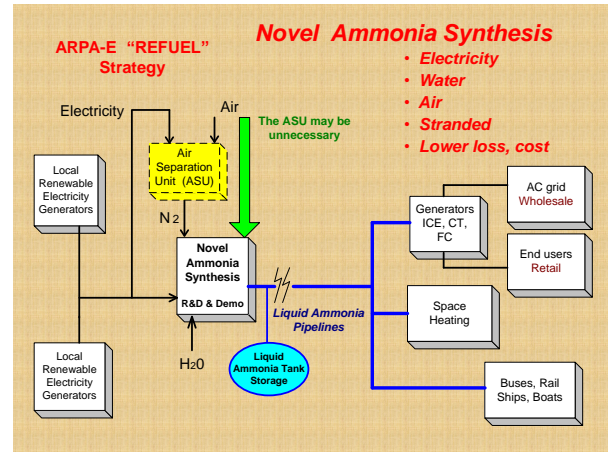


Figure 27. The ARPA-E "REFUEL" strategy attempts to commercialize "direct ammonia" (NH<sub>3</sub>) synthesis, directly from off-Grid or on-Grid, GHG-emission-free renewables-source electricity, water, and air, via novel technologies -- rather than by electrolysis + Haber-Bosch (EHB) process.

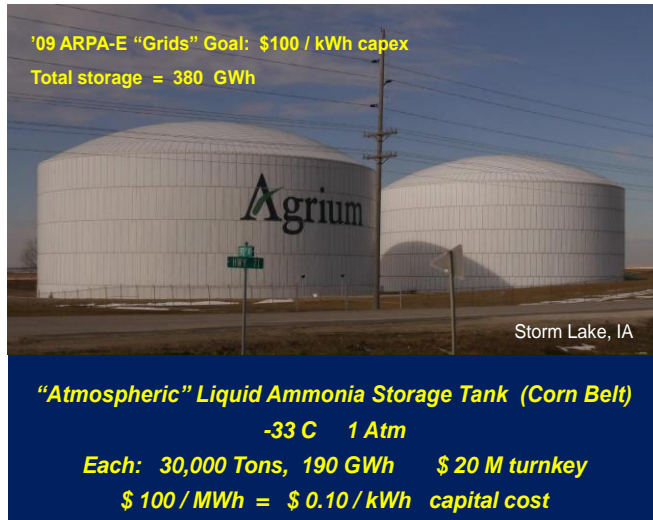


Figure 28. Liquid anhydrous ammonia storage is ubiquitous in the Corn Belt; very-low-cost energy storage. Liquid ammonia, NH<sub>3</sub>, contains 70% more Hydrogen atoms, per liter, than liquid Hydrogen, LH<sub>2</sub>.

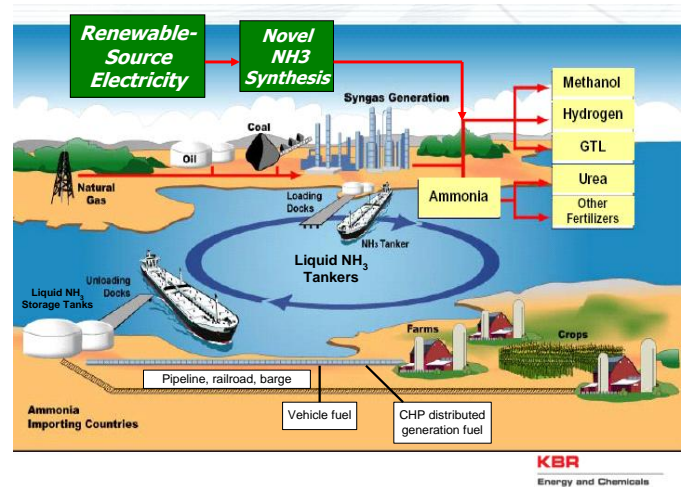
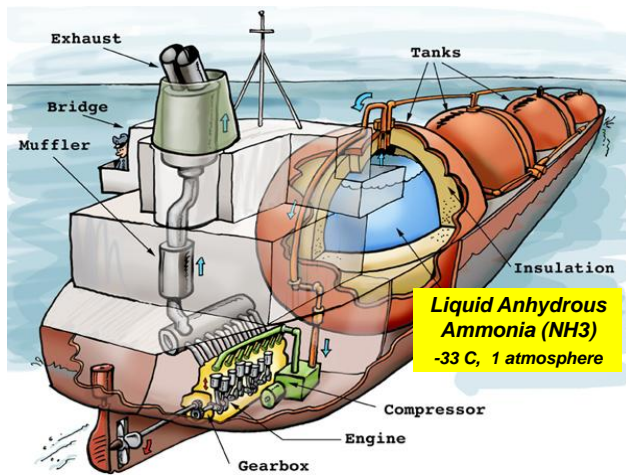
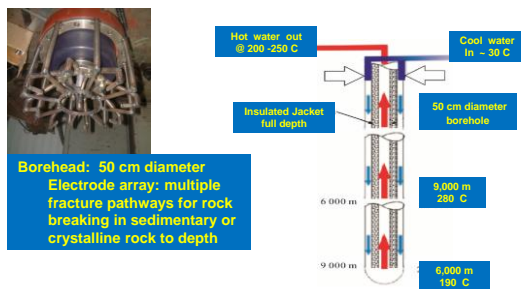


Figure 29. Global anhydrous ammonia trade is ~ 100 million Mt / year, mostly for N-fertilizer and industrial feedstocks. A new global market for "green" or "blue" NH<sub>3</sub> could greatly increase this. NH<sub>3</sub> may be co-fired with coal or oil in electricity generation plants.



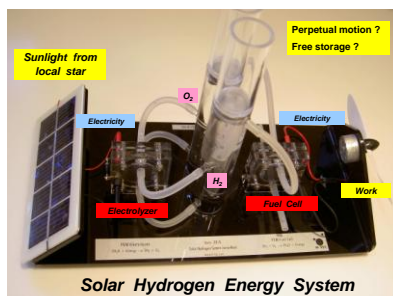
**Figure 30.** Liquid  $\text{NH}_3$  -- "the other hydrogen" -- is a better Hydrogen carrier than liquid Hydrogen ( $\text{LH}_2$ ). Liquid ammonia,  $\text{NH}_3$ , contains 70% more Hydrogen atoms, per liter, than  $\text{LH}_2$ . About 100 MMt (million metric tons) per year is tankered to distant markets.



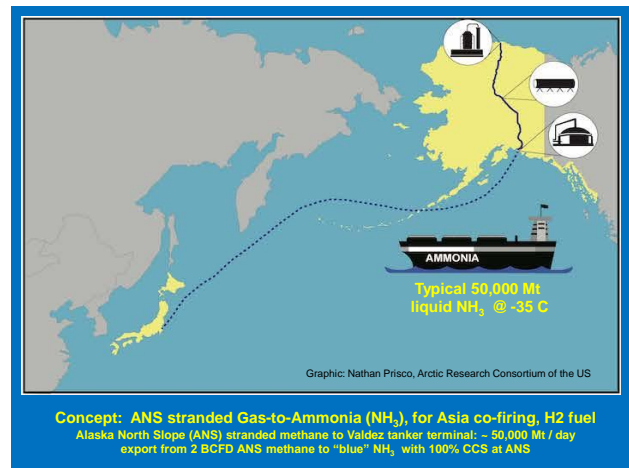
**Electro Pulse Boring: EPB for DHDRG**

- Deep geothermal heat: 240 C @ 8 km
- Electricity + DHS heat, anywhere
- Low-cost rock breaking, remote areas
- No rotary abrasive drilling; no drill rig
- Goal: \$ 150 / m, 50 cm diam, 5-10 km

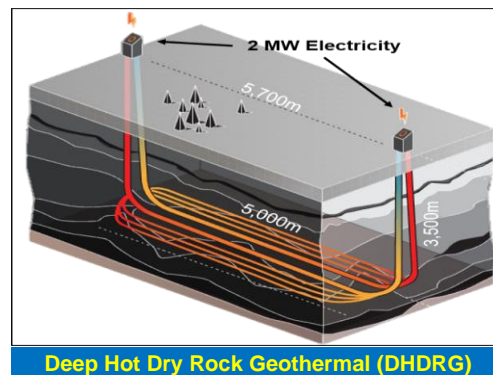
**Figure 32.** Deep Hot Dry Rock Geothermal (DHDRG) energy, 6 - 10 km deep, is nearly ubiquitous on Earth, but we can't yet bore "deep enough, cheap enough" to profitably reach it. Several novel technologies, like Electro Pulse Boring (EPB), are nearing field trials; a tough engineering challenge. R&D&D is needed.



**Figure 34.** REF 15 Solar- $\text{H}_2$  demonstrator: complete, integrated system including "free" pipeline "packing" storage.



**Figure 31.** Stranded Alaska North Slope (ANS) NatGas could be converted, at ANS, to liquid  $\text{NH}_3$  for shipment to tidewater at Valdez, either (1) via new pipeline parallel to Trans Alaska Pipeline System (TAPS), or (2) mixed with crude in TAPS (a Shell patent from 60's). At Valdez  $\text{NH}_3$  is flashed from the TAPS mix, re-liquefied, loaded on cryogen liquid tankers for export. Scale: 2 BCFD at TAPS yields ~ 50,000 MtD liquid  $\text{NH}_3$  (one tanker load per day), exported for co-firing with fossil fuels and / or cracked to yield high-purity  $\text{H}_2$  fuel



**Figure 33.** When we can bore "deep enough, cheap enough" (6 - 10 km) to reach DHDRG energy, via the large contact area required, we may proliferate "Eavor Loops" -- [www.eavor.com](http://www.eavor.com) -- to profitably extract nearly-ubiquitous medium-T thermal energy for electricity generation and district heating and cooling systems (DHCS). This would be the ultimate in DER; hydrogen pipelines and storage would be obviated.

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