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Please begin with essence, page 6. Then, please see Figures and REFERENCES, beginning Page 7: the pathway for integrated "H2 Production + Electrolysis" and "H2Hubs" to reveal urgent R&D&D needs and to inform policies for allocating markets and CAPEX among Grid, H2, NH3, and perhaps other systems and strategies. Our emphasis is on whole systems, especially the dedicated, high-purity, underground, safe, economical, gaseous hydrogen (GH2) pipeline networks -- both repurposed and new-builds -- which will enable them. Humanity's demand for "clean" H2 and NH3 will soon be so large that we must think, plan, and commit "beyond electricity" with continuous vigilance: CAPEX allocations among Grid, H2, NH3 and nascent competition, Figs 27-33. Fig 34: complete systems.

Part I: Clean Hydrogen Equipment Manufacturing, Recycling (Please see "Other ...", Page 6)

Clean Hydrogen Equipment Manufacturing

A) 1-4: Simplify electrolysis plant design by assuming off-Grid Variable Energy Resource (VER) (wind, solar, etc.) harvest, with direct delivery to new infrastructure: high-purity gaseous hydrogen (GH2) pipeline transmission -- both repurposed and new-builds -- and "packing" storage. Apply to existing infrastructure: add PV to windplants, SEIG mode to turbines, abandon Grid tie. Figs 1, 3, 4. REF 7, 29

A) 5-6, 8: Design novel linepipe designs and their on-site, in-field, continuous manufacturing processes to achieve immunity to hydrogen embrittlement (HE, HCC), for both repurposing extant pipelines and new-builds. Design new FOAs to motivate a design and advanced manufacturing consortium, through field test to certification, for complete H2 production systems, including both (a) linepipe and (b) SEIG-mode wind turbines and novel integrating power electronics & controls. Figs 14-19. REF 6, 13, 14.

A) 11: Prioritize "whole system" design, in both "H2Hubs" and "H2 Production + Electrolysis", from photons and moving air and water molecules to delivered Energy + Industrial Feedstocks [E+IF], including most of synergistic and optimized features, below: (Figs 1, 3, 4. REF 5, 26, 30-31)

a. Off-Grid; co-located, co-generated, synergistic wind + PV and other VER's; wind turbines operating in Self Excited Induction Generator (SEIG) mode using low-cost squirrel cage induction motors; PV in DC strings; via novel power electronics + integrated single-SCADA control. Figs 3, 4, 12, 27. REF 7, 11.

b. Diverse, off- or on-Grid, VER's integrated on "wild DC" bus, close-coupled and Z-matched to electrolysis stacks arrays. Simplify; delete AC-DC power supplies; dedicated H2 production delivered to new GH2 pipeline networks. Reduce electrolyzer CAPEX, OPEX, and plant-gate H2 LCCOE.

c. Enable simpler, lower-cost, electrolysis plants with higher capacity factor (CF), especially in curtailed energy harvest service, with dedicated delivery to new GH2 pipeline networks. Figs 1-4. REF 3, 5, 21.

d. "Whole system" program success, via several R&D&D FOA-enabled projects, will enable:

(1) Preventing over-dependence upon, and over-investment in, the Grid, vis-a-vis H2, NH3 systems;
(2) New, multi-decade policy research optimizing markets and CAPEX allocations among Grid, H2, NH3

B) 1, 2, 5: Design and production of novel linepipe immune to hydrogen embrittlement (HE), compatible with both relining extant pipelines and new-builds; amenable to on-site, in-field manufacturing to minimize joints. Polymers, including novel polymers, and novel hybrid polymer-nonferrous-metal linepipe designs and on-site manufacturing methods must be developed and tested for lifetime H2 impermeability and tolerance for frequent and large P fluctuations in VER GH2 service. Some candidate materials are mature; novel hybrids would not be. Figs 14-20. REF 12-14; 2, 3, 6

B) 5: Novel linepipe designs immune to HE, HCC need samples testing first at PNNL, SRNL. Then, ASME (American Society of Mechanical Engineers), PRCI (Pipeline Research Council International), ASTM testing and certification for GH2 VER, pipeline "packing", and other service. Figs 14-20. REF 6, 12-14.

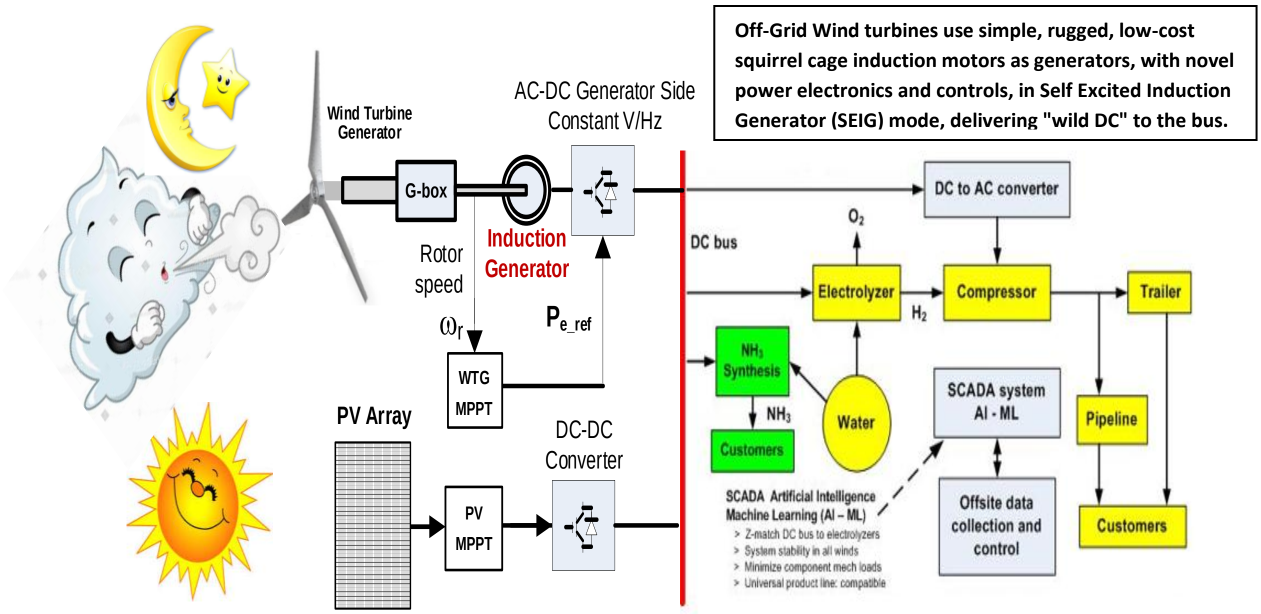
Increase Reuse and Recycling of Clean Hydrogen Technologies

F) 4: This "Clean H2 Center ..." would be especially useful for design and test of novel designs, materials, and manufacturing methods for linepipe immune to hydrogen embrittlement (HE, HCC), compatible with both relining extant pipelines and new-builds; amenable to on-site, in-field manufacturing to minimize joints. But such Centers can be cumbersome, delaying results; better to accomplish via short-timeline FOA's. We could incorporate within scope of an International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF). Figs 6, 12. REF 6, 8, 9, 12-14, 20, 26

Part II: Clean Hydrogen Electrolysis Program (Please see "Other ...", Page 6)

1) a: Prioritize "whole system" design, from photons and moving air and water molecules to delivered Energy + Industrial Feedstocks [E+IF], including most of these synergistic, optimized features: REF 26

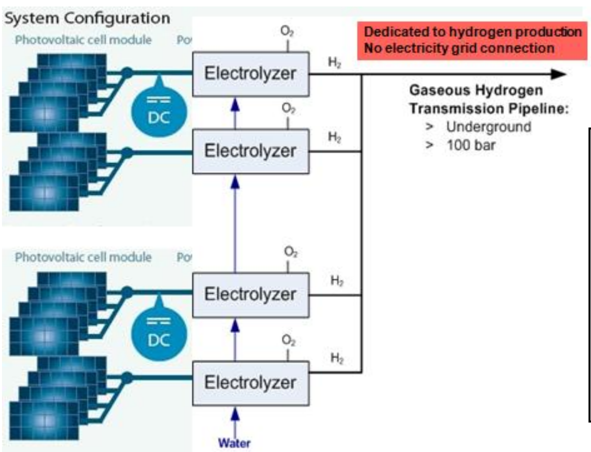
Simplify electrolysis plant design, thus electrolyzer design, by assuming off-Grid VER harvest, with direct delivery to high-purity gaseous hydrogen (GH2) pipeline transmission capable of "packing" storage -- from MAOP to ~ 1/3 MAOP. Apply to existing infrastructure: add PV to windplants, SEIG mode to turbines, abandon Grid tie at PTC or PPA expiration. Figs 1, 3, 4. REF 5-7, 28



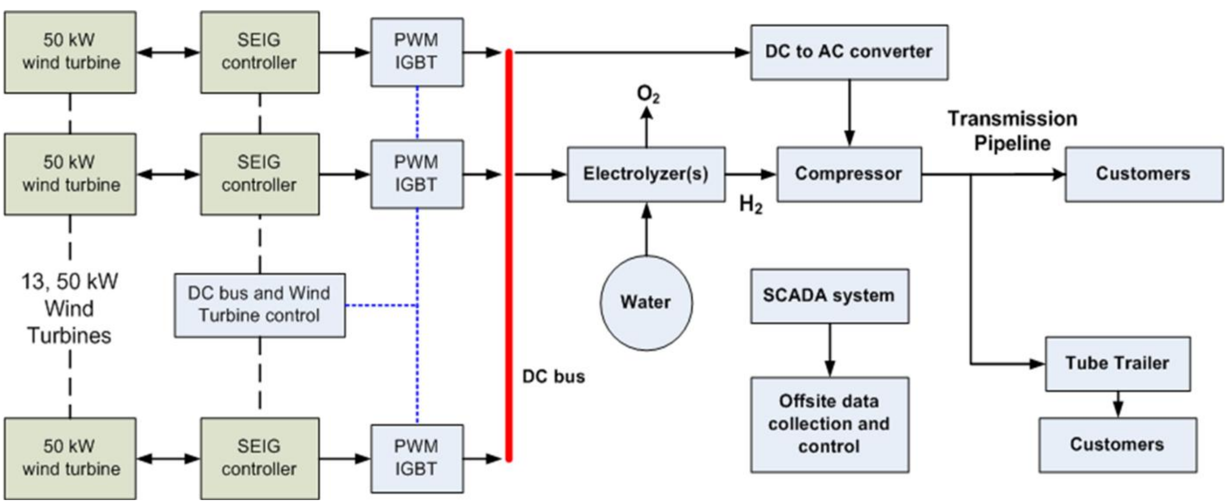
(1). Off-Grid; co-located, co-generated, synergistic wind + PV and other VER's; wind turbines operating in Self Excited Induction Generator (SEIG) mode using low-cost squirrel cage induction motors; PV in DC strings; all via novel power electronics, integrated single-SCADA controls. Figs 3, 4, 12, 27. REF 7, 11.
(2). Diverse VER's integrated on "wild DC" bus, close-coupled and Z-matched to electrolysis stacks array. Simplify; delete AC-DC power supplies; direct H2 production delivery to GH2 pipeline network:
(a). Enable simpler, lower-cost, electrolysis plants with higher capacity factor (CF) for curtailed energy.
(b). "Whole system" program success, via several FOA-enabled R&D&D projects, will result in:
(i) Preventing over-dependence upon, and over-investment in, the Grid, vis-a-vis whole energy systems based on GH2 and liquid NH3 pipeline networks;
(ii) New, multi-decade policy research: optimize markets + CAPEX allocations among Grid, H2.
(3). "Designs" should include complete, integrated, renewables-source-driven electrolysis systems, from photons and moving air and water molecules to delivered Energy + Industrial Feedstocks [E+IF], with electrolysis stacks in a series-parallel configuration for Z-matching and close-coupling to the "wild DC" bus gathering the output of diverse VER resources. "Whole system" design also must include drying, compression, and all BOS, for CF improvement, to reduce plant gate LCCOE for H2 delivered to

new, dedicated, high-purity, high-pressure GH2 pipeline gathering and transmission systems.
Figs 1-4, 12-21, 22-26, 27. REF 5, 7-9, 12-14, 21, 24

1) d: Wind turbines operating off-Grid in Self Excited Induction Generator (SEIG) mode, equipped with squirrel cage induction motors as generators, with novel SEIG power electronics and controls, integrated via a single whole-system SCADA system, with PV in DC strings, with custom power electronics for optimized integration of "wild DC" from the SEIG-mode wind turbines, probably on a common DC bus. "Wild DC" bus(es) are close-coupled to electrolysis stacks array, probably a series-parallel topology for impedance (Z) matching. Demonstrate efficient integration of wind + PV by single SCADA, and system stability. Demonstrate improved CF profitably harvesting curtailed VER's. Figs 1-4.



Off-grid wind, solar, and co-located, co-generating, synergistic, wind + solar plants can deliver all their captured energy as GH2 to dedicated, high-purity, GH2 pipeline networks. This simplifies the electrolyzer plant, eliminating AC-DC power supplies, direct-coupling "wild DC" from SEIG-mode turbines and PV DC strings to the electrolyzer stacks array on a common DC bus.



1) e: Methods: Emphasize demonstration field trials, above, in 1)d: Install prototype system described. Analyze SCADA data to model performance and plant-gate LCCOE; determine metrics from that; improve prototype off-Grid wind + PV + single SCADA system; repeat. Figs 1-4. REF 7-11.

1) f: The human and environmental impacts of delaying rapid de-carbonization and de-GHG-emission are profound and could be very damaging. Therefore, we should now "think beyond electricity", to accelerate arrest of global climate change (GCC) by: (a) enabling harvest of wind, solar, and perhaps other renewables on large land areas without electricity transmission; (b) motivating building a new, dedicated, high-purity, underground, GH2 pipeline system -- of repurposed extant pipelines plus new-builds -- for gathering, transmission, no-cost "packing" storage, and distribution of GHG-emission-free H2; (c) scaling up to multi-TW, continental-scale H2 and NH3 systems. DAC's will benefit most, by greatly improved Quality Of Life, by prioritizing clean "new energies" delivery to them.

2) e: "Balance Of System (BOS) includes the entire off-Grid H2 production system, from GHG-emission-free electric energy sources to GH2 delivery via dedicated, high-purity, GH2 pipelines immune to HE, HCC. This "whole system" must be optimized, at regional-to-continental scales: (a) far more emissions-free H2 will be needed than the Grid can profitably deliver to electrolysis plants; (b) deleting system components required in on-Grid renewables plants to deliver Grid-quality AC will reduce CAPEX, OPEX, and delivered H2 cost; (c) the electrolysis plant design can be optimized to accept "wild DC" inputs from the diverse renewable sources, integrated on a common DC bus close-coupled to a single array of electrolysis stacks in impedance-matched series-parallel; (d) wind turbines in SEIG mode, solar PV in DC strings, and other renewables, can simply and economically deliver "wild DC" to the common stacks-array-driving DC bus. This "electrolyzer" strategy opens large land areas, without electricity transmission, to renewables-source H2 production. IP-protected novel power electronics and controls, including for SEIG-mode wind turbines, integrated in a single SCADA, are needed. A program of FOA-funded, proof-of-concept RD&D projects, achieving ~ TRL 4-6, would cost ~ $ 5 million, assuming total 250 kW "wild DC" input to a custom-design, state-of-art, electrolysis plant as destination for all electric energy produced by the synergistic wind + PV system. See 1.d, above. Figs 1, 3, 4, 22-26. REF 5, 7, 21.

3) a: See "Other ...", Page 6. See 1) d and 2) e, above. We ignore "benefits and value ... to the bulk power system": the Grid will serve the H2 and NH3 systems, not vice versa. Most interesting "module size": Because the technically- and economically-optimum electrolysis stack will probably be 250-1,000 kWe input @ 150-200 VDC, the optimum electrolysis plant for off-Grid H2 production from VER wind + PV will probably contain 8 to 20 stacks, in a floating series-parallel array, for a plant nameplate capacity of 2-20 MWe input on the "wild DC" (unregulated) bus driving the stacks array. This concept assumes:
(1) Off-Grid electrolysis, and perhaps NH3, plants for Distributed Energy (DE) input, dedicated to H2 and / or NH3 production from all captured wind, solar, and other VER energy; Figs 1-4, 27-31.
(2) Avoid unnecessary Grid interface CAPEX and OPEX burden on the plant-gate H2 LCCOE; Figs 22-26.
(3) As electrolyzer kWe rating and production volume increase, power electronics and controls fraction of CAPEX increases: incentive is simpler off-Grid stacks drive from "wild DC" bus; single SCADA;
(4) Optimization for off-Grid opens large land areas without electricity transmission to energy production, assuming a new high-purity GH2 pipeline network for gathering, transmission, distribution;
(5) The "bulk power system" is based on a regional-to-continental-scale GH2 pipeline network which provides gathering, transmission, storage, distribution, rather than the Grid. Electrolyzers enable us to think "bulk energy" rather than "bulk power"; to think beyond electricity. At the large scale of "clean" H2 we will need for both Energy and Industrial Feedstocks [E+IF] sector, GH2 pipeline systems, and the simpler integrated sources-to-electrolyzer systems they enable, are probably technically and economically superior to Grid-based systems. Figs 22-26. REF 10, 11

3) b: The off-Grid wind + PV to H2 "proof-of-concept" system, as proposed for the ARPA-E 2021 "OPEN" FOA for execution in Palm Springs, CA, would validate the improved electrolysis plant: Figs 1-4 and REF 6, 7. GH2 pipeline R&D&D should be integrated into both the "Clean H2 Mfg + Electrolysis" and "H2Hubs" programs, in multiple Hubs in each of the 4 categories. Figs 14-20. REF 12-14. See: https://vimeo.com/209160500 "Begin Now: Design and Build a Renewables-Source Hydrogen Transmission Pipeline Pilot Plant". The R&D&D for design and test of enabling linepipe, immune to HE, HCC, should begin at PNNL and SRNL, and at industry, as proposed in Fig 12 and REF 6. Figs 3, 4.

4) a, b: We want to avoid all GH2 storage associated with electrolyzers and the integrated renewables-to-H2 systems in which they are embedded, by assuming that all electrolytic hydrogen is delivered at plant-gate to dedicated, high-purity, GH2 pipelines and / or to trucks, in 3) a, above. Therefore, all H2 storage will be accomplished by "packing" GH2 pipeline networks, and in large salt or rock storage caverns to which the pipelines are connected. No on-plant storage is needed. Figs 5-13.

4) c, d: See 3.a, b and 4.a, b above. Storage cost: GH2 pipeline network packing is large-capacity, and "free". Large salt, and perhaps rock, cavern storage, with GH2 transmission pipeline access, is < $ 1.00 / kWh CAPEX, where geology is available. Storage capacity: both "packing" and caverns are in 10 - 200 GWh range; multi-salt-cavern arrays to TWh, achieving annual-scale firming. Storage safety: underground GH2 pipelines and caverns are relatively safe from acts of God and man; pipelines must be made of linepipe immune to HE, HCC or operated within strict Maximum Allowed Operating Pressure (MAOP) and P variation limits. Figs 9, 10, 13, 14, 28. REF 5, 21. Storage codes and standards will be needed for GH2 linepipe of novel materials and on-site, continuous-process, manufacturing methods, especially for pipeline networks to be used for "packing" storage in VER service. Figs 14-21.

Efficiency, both technical and economic: depends on complete renewables-source system design, as in 1) a and 1) d, above; depends on electrolysis plant design for "wild DC" stacks array drive, single SCADA, GH2 pipeline delivery integration into whole system; depends on whether byproduct heat has value, at either, or both, electrolyzer and fuel cell. In CHP it generally has; in transportation it may have; transmission via GH2 pipeline costs less than via Grid transmission. Figs 3, 4, 11. REF 5-9, 26.

5) a: Palm Springs, CA, 2015: Alaska Applied Sciences, Inc. (AASI) demonstrated proof-of-concept of Self Excited Induction Generator (SEIG) mode on one operating, off-Grid wind turbine, delivering "wild DC" to a resistive load simulating an off-Grid electrolyzer system stacks array probably of series-parallel topology, for dedicated, off-Grid, H2 production in a multi-MW wind + PV co-located, co-generating plant. REF 28-31 Now, the pilot-scale demonstration needs to add: (a) the OEM-custom-design, off-grid electrolysis plant; (b) the novel design power electronics and controls for SEIG mode wind turbine operation; (c) a co-located, co-generation PV plant, of series-DC-strings of appropriate kWe size to match the 4 wind turbines at the Palm Springs site, for the valuable culmination of this demonstration, as proposed in a Concept Paper, REF 7: https://alaskaappliedsciences.com/wp-content/uploads/FOA-2459-1-E-3339-5Apr21.pdf "Not encouraged"; no Full App submitted. The demonstration pilot plant area is within an operating windplant, far from population. REF 28-31.

5) b: The off-Grid complete renewables-source H2 production system described in 3) a and 5) a, above, and in Figs 1, 3, 4, 27 and REF 7, 28-31, includes novel electrolysis plant concept close-coupling "wild DC" sources from SEIG-mode wind turbines and DC-string PV modules. This system design CAPEX and OPEX benefit from (a) the simpler design and economies-of-scale in Figs 22-26; (b) by omitting all costly Grid-tie infrastructure, and (c) by assuming delivery of all captured renewable energy as high-pressure GH2 to new, dedicated, high-purity gathering and transmission underground pipeline systems. Field testing success at the proposed Palm Springs wind + PV site, or any similar site, will "... accelerate commercialization of electrolyzer produced hydrogen", especially if such a complete H2 production and GH2 pipeline system is included in every renewables-driven "H2Hub".
(i), (ii) "Audience" is all [E+IF] sector, ideally in setting of the several renewables-source "H2Hubs" plus the policymakers+ investors who enable them, intent on de-GHG-emission of entire human enterprise.
(iii) These off-Grid demonstrations support "existing mfg processes and infrastructure" because simpler electrolysis plants and single SCADA systems, for lower system CAPEX and OPEX, have much in common with Grid-tied components. Scaling, in nameplate kWe and volume, is rewarding: Figs 22-26. Program cost to advance complete, integrated, off-Grid-optimized electrolysis plants to TRL 8-9, including codes, standards, and certifications will be $ 100-300 million, 3 years, joint public-private.

6) Rank High (5) to low (1): 5, 1, 2, 4, 3

10) Structure New FOA's to embrace 5, above: Off-Grid R&D&D. Include a complete [H2 electrolysis + pipeline production + "packing" storage + delivery] system in each Renewables-driven "H2Hub". New consortium focused on preventing over-dependence on, and over-investment in, Grid vis-a-vis H2, NH3.

"Other Relevant Topics ... not specifically requested" Our response, below, is for both:
Part I: Clean Hydrogen Manufacturing and Recycling
Part II: Clean Hydrogen Electrolysis Program

As we better understand, and appreciate, the expanding potential roles and value of complete, integrated, totally-decarbonized, GHG-emission-free, "clean" Energy + Industrial Feedstocks [E&IF] systems based on hydrogen (H2), we are realizing that: (See all Figs: comprehensive case for H2, NH3)

1. We will need so much clean H2 that the electricity Grid -- as large and "smart" as we may build it -- will be technologically and economically inferior to dedicated, high-purity, high-pressure, underground gaseous hydrogen (GH2) pipeline systems for gathering, transmission, free "packing" storage, and distribution of the large amount of [E+IF] H2 for meeting humanity's urgent goals:
    a. Total de-carbonization and de-GHG-emission of the entire human enterprise, beyond Grid;
    b. Transform the world's largest industry from 85% fossil to ~ 100% GHG-emission-free [E+IF].
2. We should emulate the natural gas (NG) industry's nearly-ubiquitous underground pipeline system and succeed it, by repurposing extant pipelines and building new ones, for safe, economical, and profitable gathering, transmission, "packing" storage, and distribution of "clean" GH2 for [E+IF] at local, regional, to continental and global scales. But NG pipelines are not ready for high-purity GH2.
3. Regional-to-continental-scale GH2 pipeline networks will enable: (Figs 2, 5, 8, 11-12, 21, 29-31)
    a. Supplying total [E+IF] demand at all scales -- regional, national, and global;
    b. Accessing domal salt geology wherein many large, solution-mined salt caverns may be constructed and arrayed to achieve low-cost, annual-scale, firming storage + supply dispatch;
    c. Gathering Variable Energy Resource (VER)(wind, solar) production which will inflict large and frequent pressure fluctuations upon the pipelines, which must therefore be built of linepipe and fittings immune to hydrogen embrittlement (HE), hydrogen corrosion cracking (HCC).
4. Therefore, we should now design, mass-produce, and deploy VER-source [E+IF] systems optimized for off-Grid energy harvest, based on secure underground GH2 pipeline systems accessing low-cost salt cavern storage -- assuming that Grid will support the pipeline system, not vice versa. Figs 5-10.
5. Therefore, electrolysis and other H2 production systems should be optimized for off-Grid deployment, including synergistic [wind + PV] co-location and co-H2-generation, with plant gate delivery of all captured energy as compressed GH2 directly to pipeline networks for gathering, transmission, storage, and delivery -- and / or to trucks in unusually-favorable situations. Figs 1-4.
6. Consequently, we must design simplified H2 production systems, including electrolyzer stacks and electrolysis plants, optimized for off-Grid operation, accepting "wild DC" from SEIG-mode wind turbines and DC-string PV arrays, via novel power electronics and controls: (Figs 3, 4, 22-26).
    a. Lower system CAPEX and OPEX delivers significantly lower plant gate H2 LCCOE;
    b. Controls are integrated, simplified; Fig 3, 4, 24-27
    c. Reliability and OPEX are Improved: no Grid interface, AC-DC power supplies;
    d. We may access large land areas with rich VER assets, without Grid access;
    e. We improve electrolyzer capacity factor (CF) and efficiency; reduce parasitic loads;
    f. Clean H2 is competitive with [E+IF] services + products via Grid; pays for electrolyzer low CF.
7. Therefore, our response to this RFI focuses on all of the above, suggesting that new FOA's:
    a. Activate specific R&D&D projects: Figs 3, 4, 23-27. REF 7, 11, 18, 21.
    b. "Think beyond electricity": to Grid supporting H2, not vice versa; optimum intersector cplg.
    c. Optimize year 2050 policy allocations of markets and CAPEX among Grid, H2, NH3 systems.
    d. Embrace DER, regional, continental, global scope: Figs 5-8, 12, 21, 27-31. REF 5, 6, 8, 23, 24
    e. Anticipate benign competition from NH3, and DHDRG DER (less transmission). Figs 28-33
8. Therefore, "H2 production" and "Electrolyzer design" R&D&D must be in context of complete, continental-scale H2 system optimization, to serve entire [E+IF] sector, integrated with "H2Hubs".

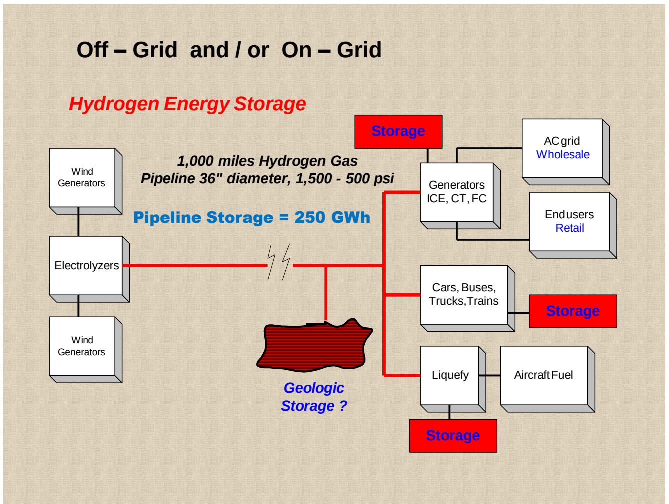


Figure 1. REF 5-8, 17. By 2035 - 2050, total continental hydrogen demand will require off-Grid, dedicated, high-purity, high-pressure, GH2 pipeline networks, of linepipe and accessories immune to hydrogen embrittlement (HE, HCC), for safe, economical gathering, transmission, "free" pipeline "packing" 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 ΔP = 67 bar, no marginal CAPEX, OPEX.

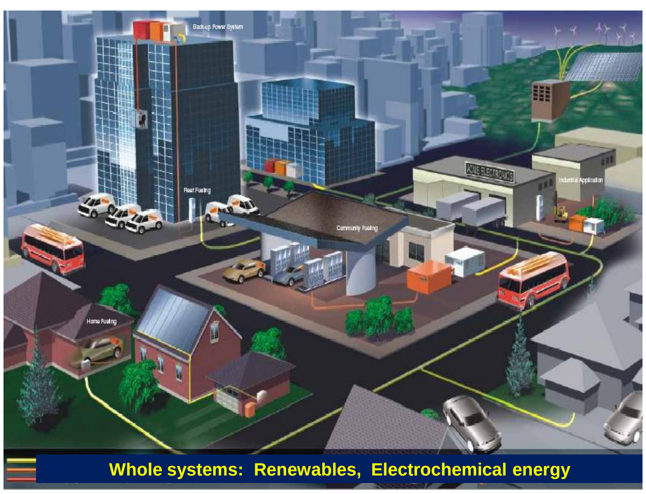


Figure 2. REF 5, 7, 17 Complete, integrated, synergistic, optimized, systems for [Energy + Industrial Feedstocks], [E+IF]. Distant, diverse, renewable, GHG-emission-free sources of H2 are delivered to load centers via dedicated, high-purity underground pipeline networks for gathering, transmission, "free" pipeline "packing" storage, and distribution.

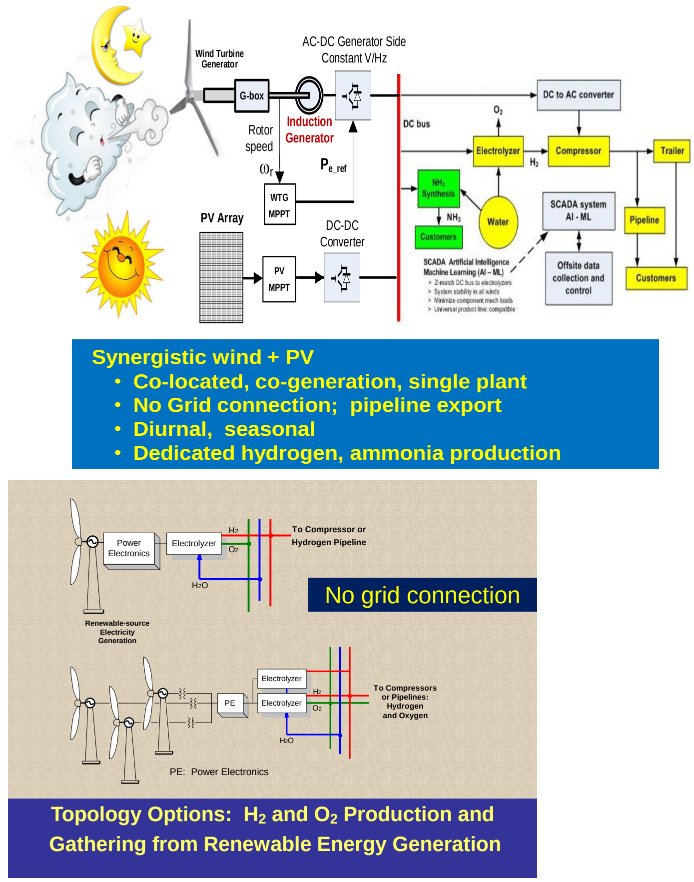


Figure 3. REF 6, 7, 18 Renewables-source Hydrogen Hub(s) should include off-Grid, co-located, co-generation, wind + PV plant(s) dedicated to H2 or NH3 production, with electrolysis plants customized for "wild DC" close-coupling to series-parallel stacks arrays, omitting AC-DC power supplies, with single system SCADA for simplified integrated controls.

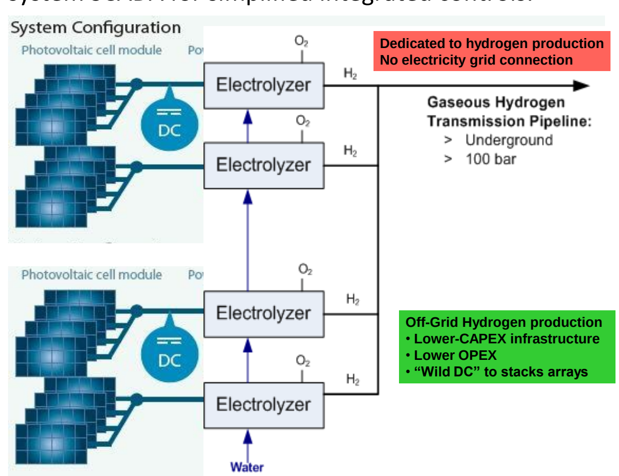


Figure 4. REF 3, 5, 17. PV example. Whole energy systems optimized for dedicated, off-Grid, high-purity, GHG-emission-free , Hydrogen production. Large CAPEX and OPEX savings by eliminating need to deliver Grid-quality AC. Electrolyzers optimized to receive "wild DC", for lower plant-gate Hydrogen cost.

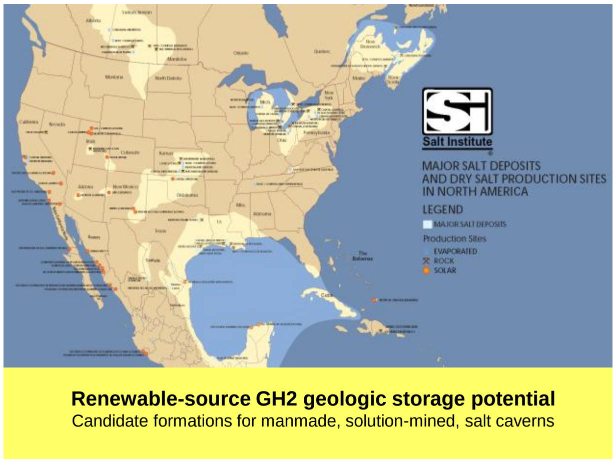


Figure 5. Low-cost geologic storage. The domal salt of the Gulf Of Mexico (GOM) region is ideal for hundreds or thousands of large GH2 storage caverns needed for annual-scale firming of the Great Plains synergistic variable energy resources (VER) like wind + solar. CAPEX, cavern + surface facility, 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

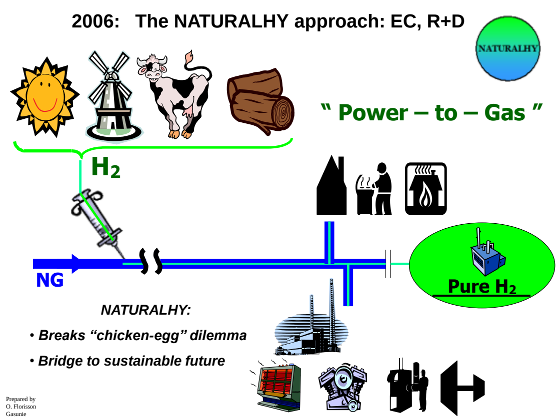


Figure 6. European Commission (EC) "NaturalHY" R&D, 2006. How much H2 may be blended in NatGas pipelines without encountering metallurgy or downstream customer apparatus problems ? Approaching 20% by volume, < 10% by energy. Blending in USA is a short-term option (1) to build market for "green" H2, (2) to marginally decarbonize pipeline network NatGas blend. The Ukraine tragedy will motivate Europe to pursue this.

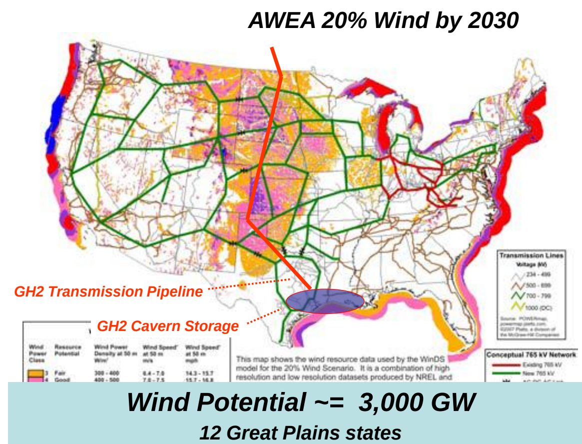


Figure 7. Multi-GW, Multi-GH2-pipeline corridor gathering and transmission system delivers high-purity, VER-source hydrogen to large-scale Gulf Of Mexico (GOM) salt multi-cavern firming storage, with potential to supply 100 % of total USA energy + industrial feedstocks [E + IF] demand, dispatchable 100+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

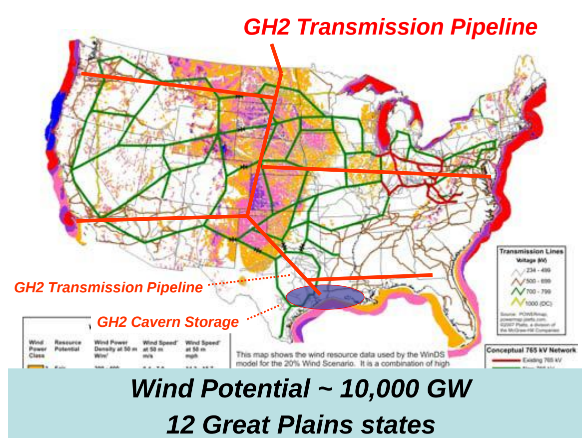


Figure 8. The high-purity GH2 transmission pipeline backbone supplies a continental-scale GH2 pipeline network, to supply all 100+ Quads of USA energy + energy-derived industrial feedstocks demand, [E + IF], as annually-firm, dispatchable, and decarbonized.

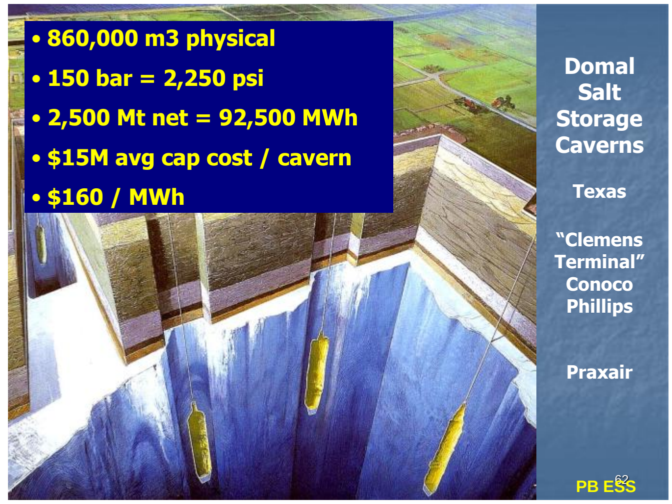


Figure 9. A single salt cavern stores ~ 100 GWh, as the chemical energy in ~ 2,500 Mt of H2 working gas, on ~ 1,000 Mt of cushion gas, at ΔP ~ 150 <--> 50 bar. Mt = metric ton CAPEX, cavern + surface facility, < $ 1.00 / kWh
The Solution Mining Research Institute (SMRI) represents the technical experts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

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

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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. "Bedded" salt geology may be less H2-tight, thus less useful. Two H2 storage salt caverns in Texas have been used for decade, without incident.

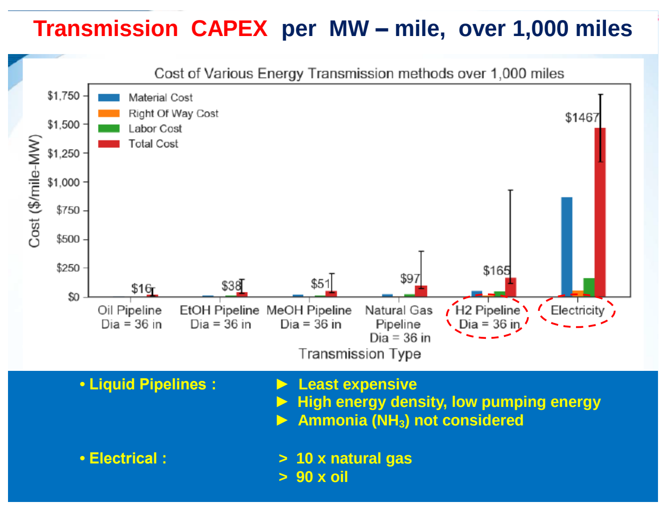


Figure 11. REF 8. Energy transmission CAPEX, per MW-mile, is lower for GH2 pipelines than for electricity systems, i.e. "Grid". GH2 pipelines provide substantial "free" energy storage by "packing" to max allowed operating pressure (MAOP) when variable energy resources (VER) (wind, solar example) are strong, "unpacking" to ~ 1/3 MAOP.

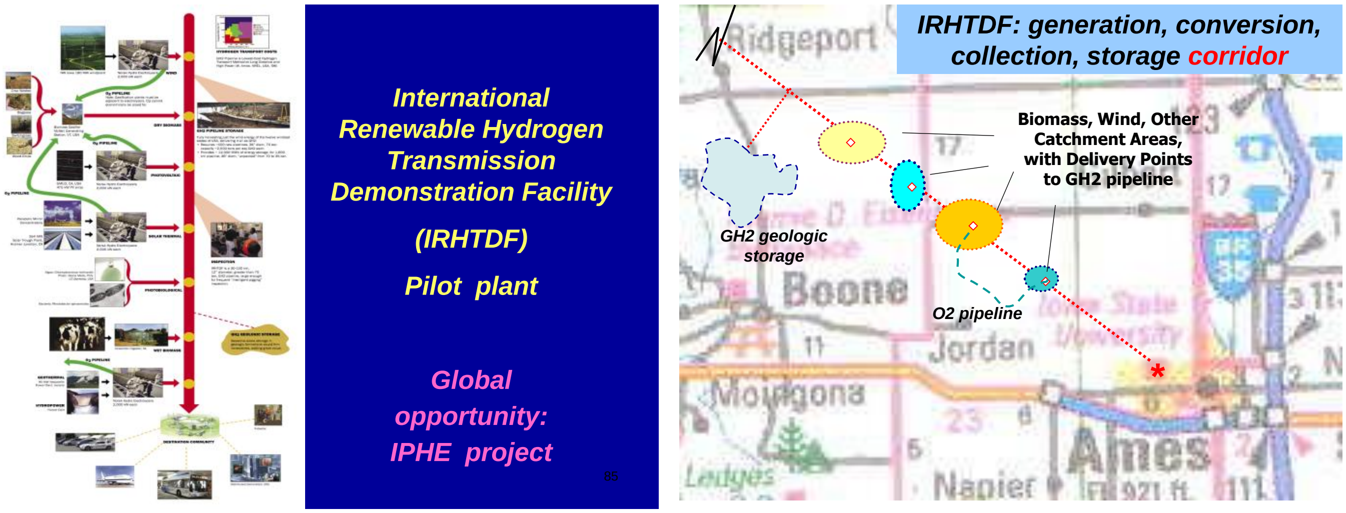


Figure 12. REF 25, 26 Safe, economical, large-scale pipelining of high-purity GH2 from variable energy resources (VER) is a global opportunity and challenge. Novel linepipe, valves, meters, couplings, entry and takeoff fittings need field testing, demonstration, specification, and certification, in optimized 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

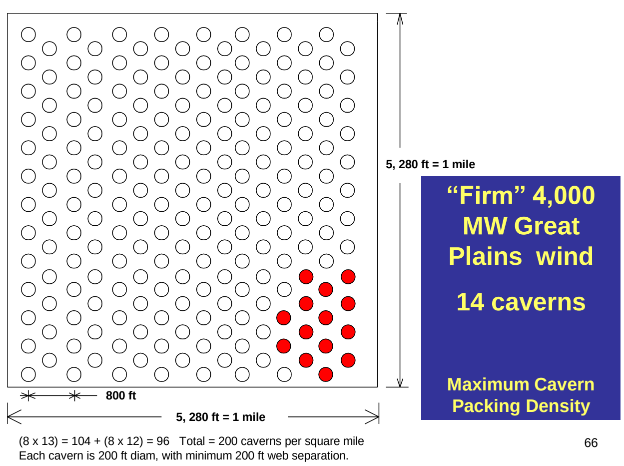


Figure 13. Multiple large salt caverns may be clustered at unusually high density, if manifolded together at the same pressure, reducing construction cost. They may share the same surface facility (compressor, dryer, meters, pipeline) for CAPEX and OPEX savings: more important if the deep salt caverns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

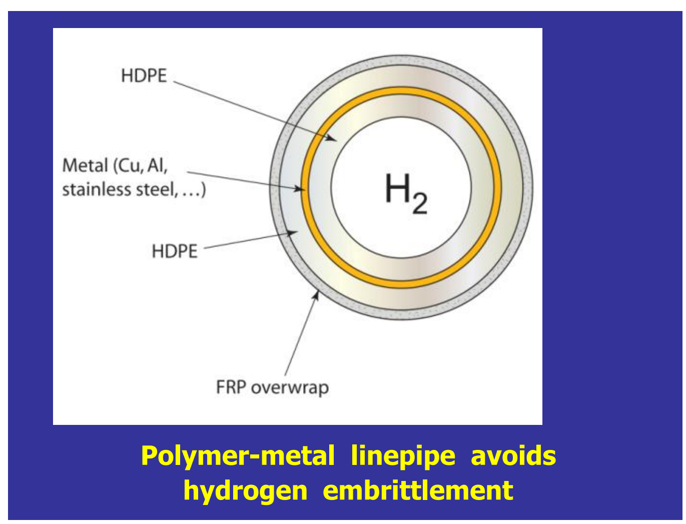


Figure 14. REF 6, 14-16. We need certified, novel, hybrid, polymer + non-ferrous metal, high-pressure linepipe, immune to HE and HCC, for high-purity GH2 gathering, transmission, "free" storage by "packing", and distribution, especially for VER GH2 sources which will inflict large, frequent pressure fluctuations upon the pipeline 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

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.

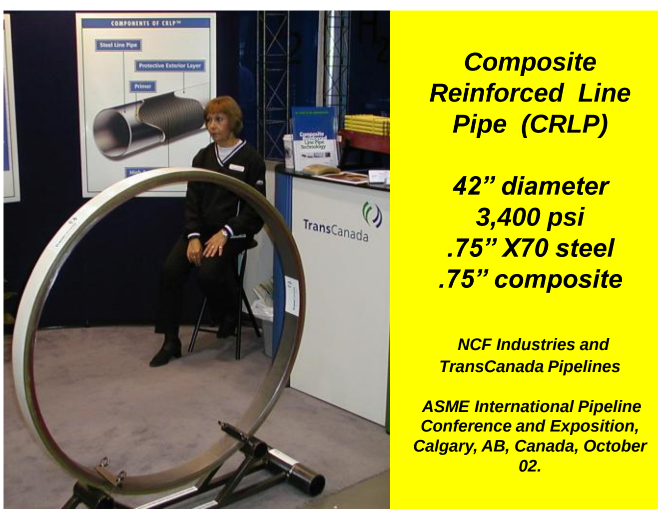


Figure 17. Composite Reinforced Linepipe (CRLP), ASME International Pipeline Conference, Calgary, 2002.

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.

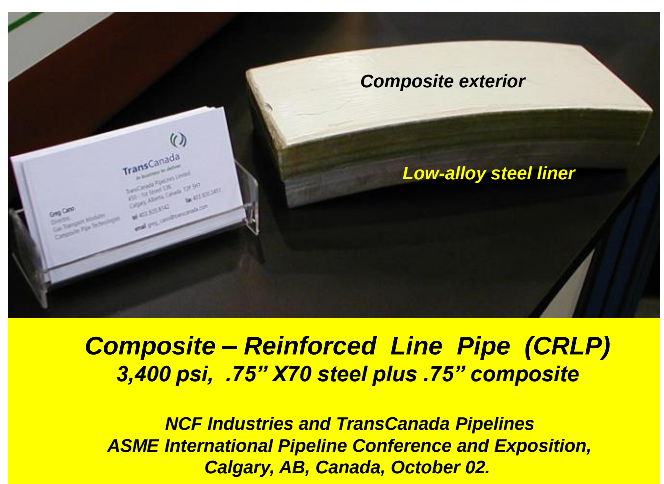


Figure 18. CRLP, TransCanada booth, ASME Pipeline Conference, Calgary, 2002.

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.

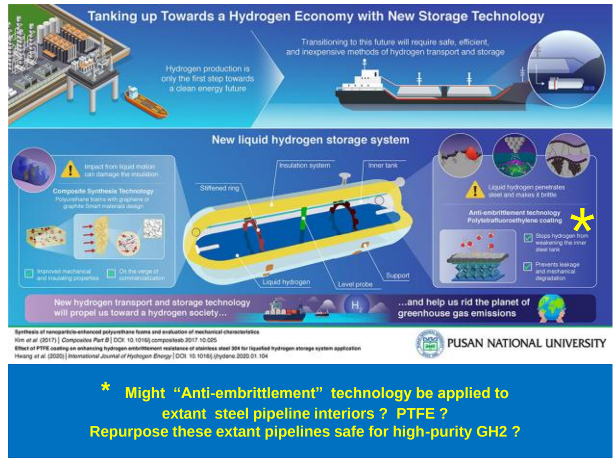


Figure 20. Might we be able to perfectly and permanently coat the interior of extant steel pipelines, via pigging, rendering them completely immune to hydrogen embrittlement (HE, HCC), to repurpose them for high-purity, high-pressure, VER-source, GH2 service ? With zero "holidays" in the coating and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

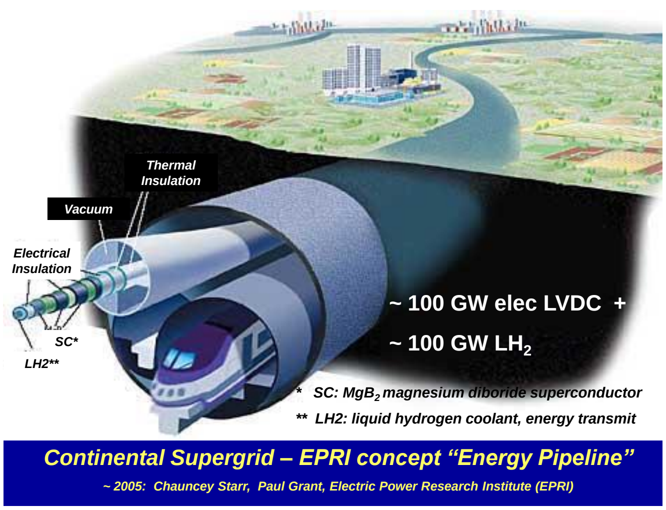


Figure 21. EPRI "Energy Pipeline" concept. Dual LH2-cooled superconducting LVDC electricity plus LH2 energy transmission: about 100 GW each. Transcontinental scale. Needs to be installed in a stable, serviceable, tunnel bored in rock. EPRI concept by Chauncey Starr and Paul Grant, ~ 2005.

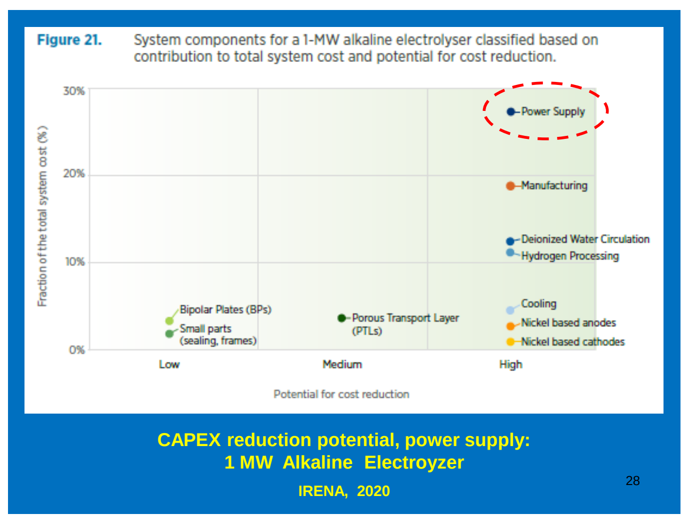
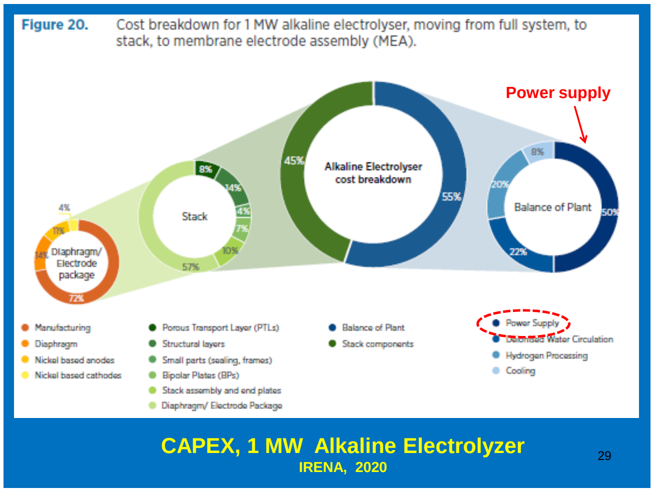


Figure 22. IRENA, 2020. Power supply, to feed DC to electrolysis stacks, is a large fraction of electrolyzer plant CAPEX. Less potential for manufacturing scaleup cost reduction than for stacks.
IRENA: International Renewable Energy Agency, Abu Dhabi, UAE. https://www.irena.org/
Founded: January 26, 2009 Membership: 165 states and the European Union (2021)



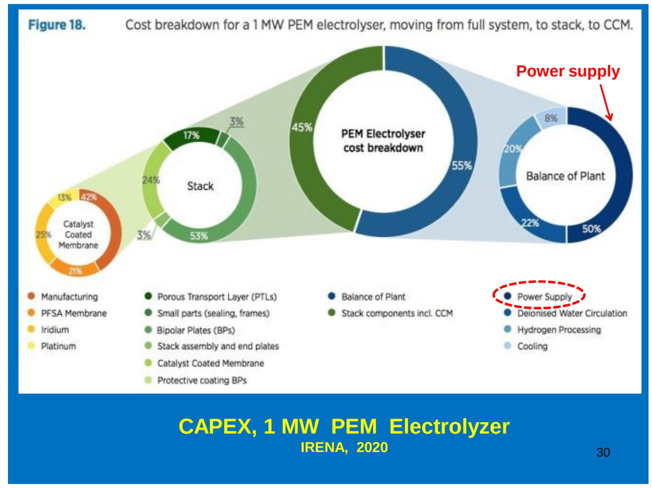


Figure 23. REF 11 Power supply is ~ 27 % of PEM or Alkaline CAPEX. For off-Grid VER plants, this may argue for a series-parallel stacks array topology, composed of optimum-size stacks, allowing higher DC input voltage to the stacks array. This provides impedance matching of off-Grid, "wild DC" sources, close-coupled to the stacks array, replacing "power supply" in the electrolysis plants. R&D&D needed. See 3) a, above.

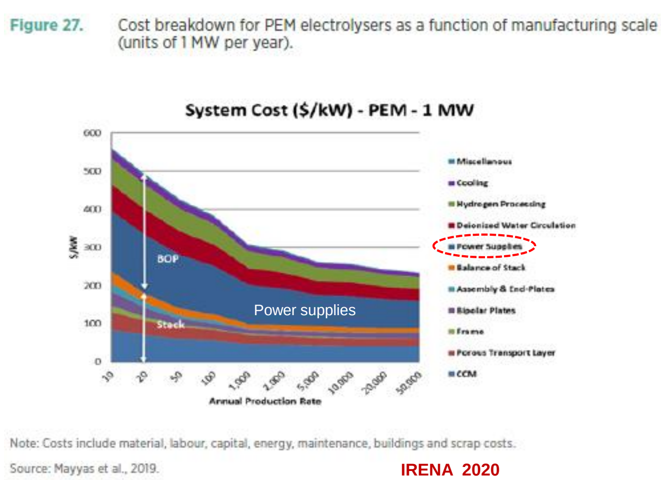


Figure 24. REF 11 IRENA, 2020. Electrolyzer power supply remains a large fraction of CAPEX at high build rate, thus encouraging simplifying electrolysis plants by (a) operating them in off-Grid VER (wind, solar) plants; (b) eliminating AC-DC power supplies; (c) driving floating series-parallel electrolysis stacks arrays via a "wild DC" bus whereby SEIG-mode and PV DC strings are synergistically combined.

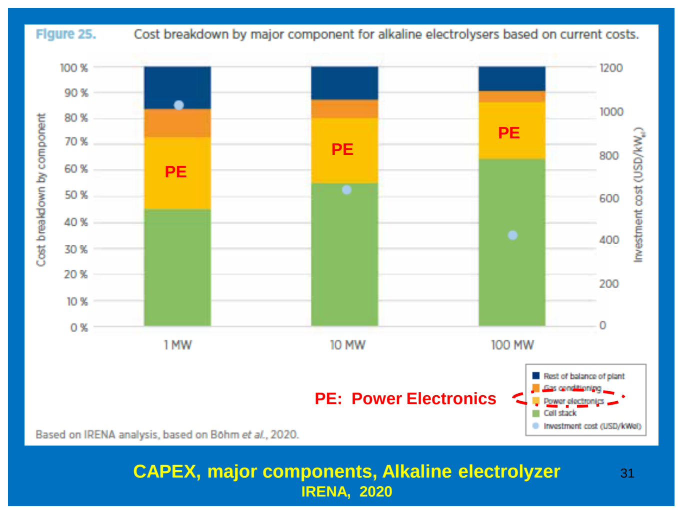


Figure 25. Power supply electronics CAPEX fraction decreases with module build size: relative diseconomies of scale for large size stacks. This may argue for series-parallel array topology, composed of optimum-size stacks, allowing higher stacks array DC input voltage, for impedance matching to close-coupled,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

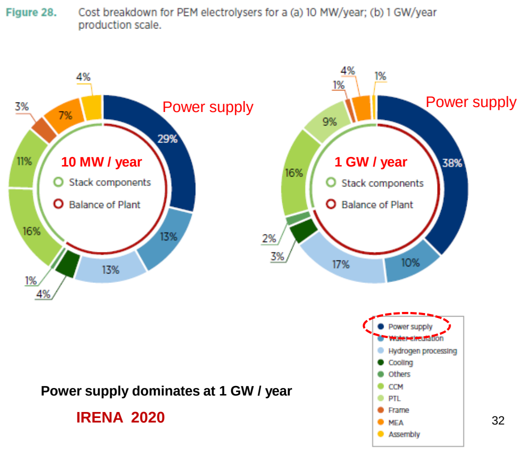


Figure 26. REF 11 Electrolyzer power supply CAPEX fraction increases with build rate. See Fig 22-25

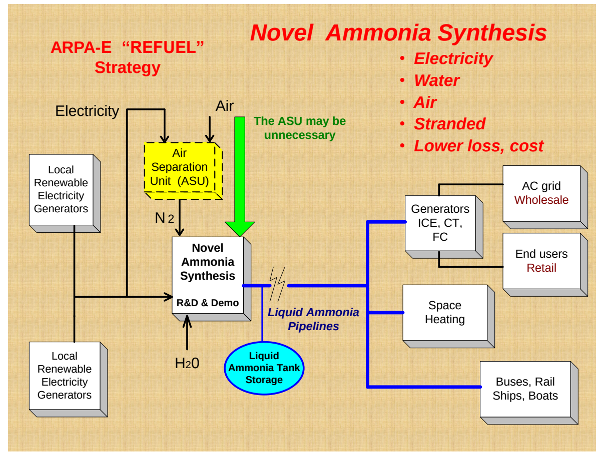


Figure 27. The ARPA-E "REFUEL" strategy attempts to commercialize "direct ammonia" (NH3) synthesis, directly from off-Grid or on-Grid, GHG-emission-free renewables-source electricity, water, and air, via novel technologies -- rather than by electrolysis + Haber-Bosch (EHB) process.

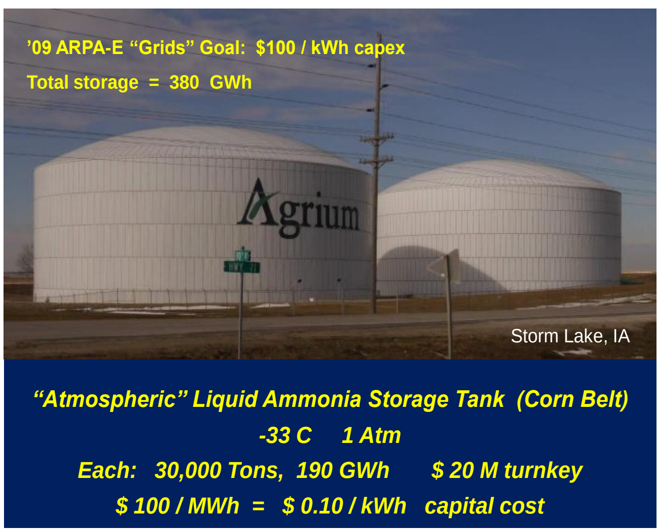


Figure 28. Liquid anhydrous ammonia storage is ubiquitous in the Corn Belt; very-low-cost energy storage. Liquid ammonia, NH_3, contains 70% more Hydrogen atoms, per liter, than liquid Hydrogen, LH2.

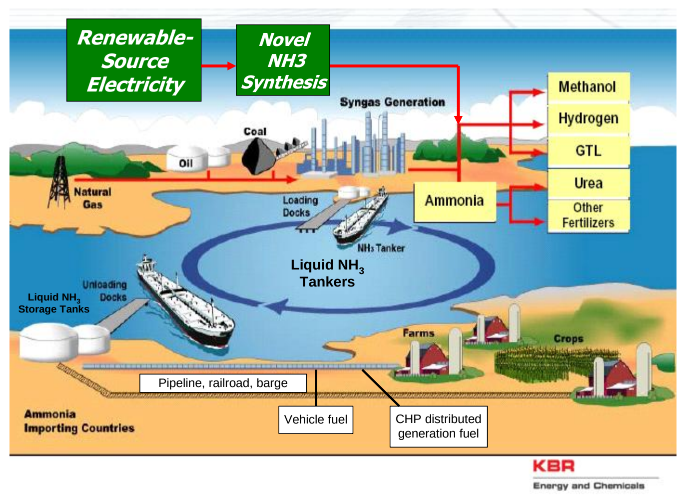


Figure 29. Global anhydrous ammonia trade is ~ 100 million Mt / year, mostly for N-fertilizer and industrial feedstocks. A new global market for "green" or "blue" NH_3 could greatly increase this. NH_3 may be co-fired with coal or oil in electricity generation plants.

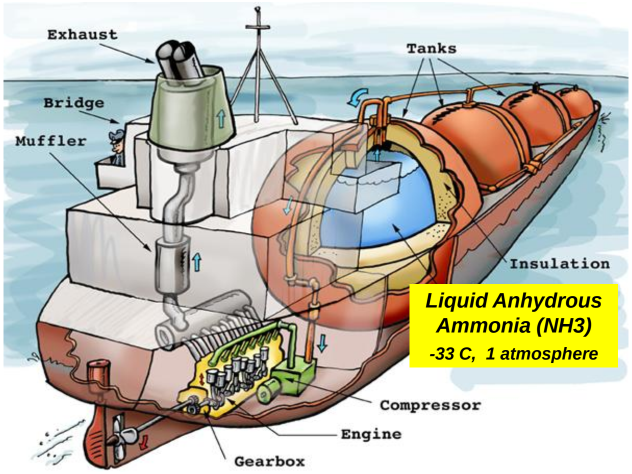


Figure 30. Liquid NH_3 -- "the other hydrogen" -- is a better Hydrogen carrier than liquid Hydrogen (LH2). Liquid ammonia, NH_3, contains 70% more Hydrogen atoms, per liter, than LH2. About 100 MMt (million metric tons) per year is tankered to distant markets.

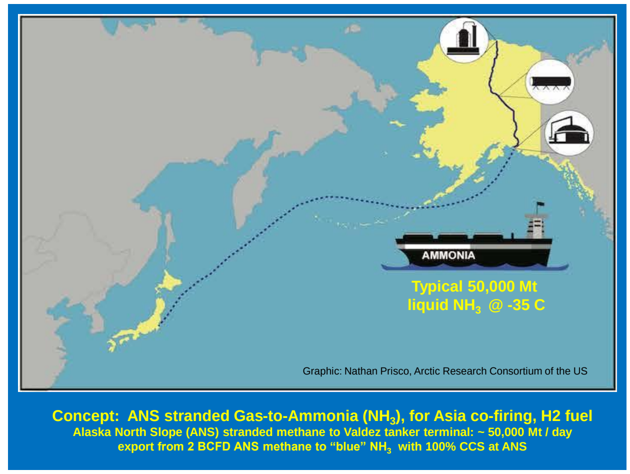


Figure 31. Stranded Alaska North Slope (ANS) NatGas could be converted, at ANS, to liquid NH_3 for shipment to tidewater at Valdez, either (1) via new pipeline parallel to Trans Alaska Pipeline System (TAPS), or (2) mixed with crude in TAPS (a Shell patent from 60's). At Valdez NH3 is flashed from the TAPS mix, re-liquefied, loaded on cryogen liquid tankers for export. Scale: 2 BCFD at TAPS yields ~ 50,000 MtD liquid NH_3 (one tanker load per day), exported for co-firing with fossil fuels and / or cracked to yield high-purity H2 fuel

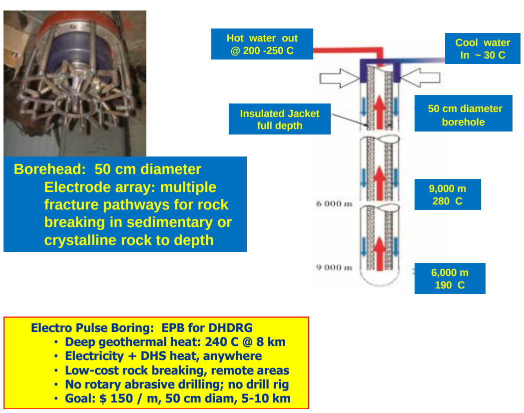


Figure 32. Deep Hot Dry Rock Geothermal (DHDRG) energy, 6 - 10 km deep, is nearly ubiquitous on Earth, but we can't yet bore "deep enough, cheap enough" to profitably reach it. Several novel technologies, like Electro Pulse Boring (EPB), are nearing field trials; a tough engineering challenge. R&D&D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

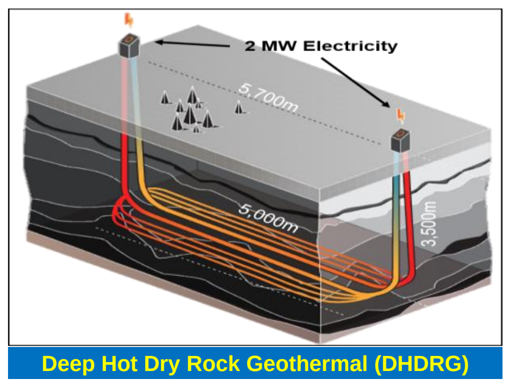


Figure 33. When we can bore "deep enough, cheap enough" (6 - 10 km) to reach DHDRG energy, via the large contact area required, we may proliferate "Eavor Loops" -- www.eavor.com -- to profitably extract nearly-ubiquitous medium-T thermal energy for electricity generation and district heating and cooling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

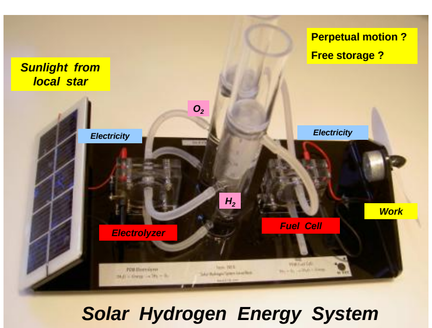


Figure 34. REF 15 Solar-H2 demonstrator: complete, integrated system including "free" pipeline "packing" storage. Shows importance of "whole systems" approach to providing all Energy & Industrial Feedstocks [E+IF] for the entire human enterprise from renewable sources, as H2 via underground pipelines.
Product code # 1071007 "Junior Pro" from: https://www.fuelcellstore.com/j102-junior-pro?search=junior%20%20pro

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