Grid Security: Low-cost, GWh-scale, High-purity, Gaseous Hydrogen (GH_2) Storage & Transmission System: "Packed" Pipeline Storage for VER Sources, On- or Off-Grid, via Novel Polymer-Nonferrous-Metal Hybrid Linepipe Immune to Hydrogen Embrittlement (HE)

CATEGORY 1, SUBCATEGORY E: Grid Storage

GH2 gaseous hydrogen (H2, H_2)	**DER** Distributed Energy Resources
HE Hydrogen Embrittlement	**VER** Variable Energy Resources (wind, solar, etc.)
HCC Hydrogen Corrosion Cracking	**CEF** CO2-emission-free
MAOP Maximum Allowed Operating Pressure	**MMt** Million metric tons
GOM Gulf Of Mexico; domal salt geology	**RD&D** Research, Development, Demonstration
NG Natural Gas	**LCC** Life Cycle Cost
TEA Technical and Economic Analysis	**CAPEX** Capital expenditure

Budget: ARPA-E $ 470,000 Match, in-kind: $ 118,000 Total: $ 588,000 Duration: 24 months

Applicant and Prime Recipient: Alaska Applied Sciences, Inc. (AASI)
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Team members:

- PNNL, Richland, WA. H_2 permeation testing for linepipe samples. System TEA; further tests design.
- SRNL, Aiken, SC. H_2 permeation testing for linepipe samples. System TEA; further tests design.
- University of California Irvine (UCI), Advanced Power and Energy Program (APEP). Pipeline system TEA.

Qualified vendors for samples of custom-design polymer-metal-hybrid pipe for H_2 permeation testing:

- Smart Pipe Company, Houston
- NOV Fiberspar, Houston

A. Concept, Innovation "Packing" secure, underground GH2 pipelines -- both new and repurposed, relined extant NG and oil -- to MAOP, "unpacking" to ~ 1/3 MAOP provides GWh-scale, near-zero-cost (CAPEX and OPEX) energy storage. A 36" GH2 pipeline 1,600 km long will store ~ 120,000 MWh. [1]

This project's empirical data and TEA will show the superior value -- vis-a-vis Grid expansion and storage -- of HE-immune hybrid polymer-nonferrous metal pipelines for, low-cost, secure, transmission and near-zero-cost, GWh-scale storage of high-purity GH2 from VER (wind, solar) energy, including that now curtailed in CA and TX, plus new large-scale VER from large areas without Grid transmission.

Sample linepipe lab tests, GH2 pipeline system construction cost estimates, and systems TEA will guide future R&D. Such VER transmission, gathering, and distribution pipelines, subject to frequent and large pressure excursions, will also enable access to distant, GWh-scale GOM salt cavern storage, and must:

1. Be immune to the Hydrogen Embrittlement (HE) and Hydrogen Corrosion Cracking (HCC) such pressure excursions will inflict upon steel linepipe, because the H_2 is often supplied from diverse VER: wind and solar. This project will consider Al, Cu, non-Fe polymer-metal hybrid linepipe.
2. Have low enough LCC per GW-km of energy transmission capacity to rival steel pipelines used in NG service, and to LCC-cost-compete with electricity transmission, storage, distribution systems;
3. Be manufactured on-site, in continuous unlimited length, for direct installation in excavated trenches for new GH2 pipelines, or pulled into an extant pipe to repurpose it for safe GH2 service. Figs 1, 2.

Therefore, novel polymer-metal hybrid linepipe will probably be required, for transmission and near-zero-cost energy storage of VER as GH2. Such linepipe has not been designed, tested, nor certified for VER-driven GH2 service; ORNL experimented in 2000's. We advance that proof-of-concept to TRL 4+.

B. Impact Figs. 1-4. Goal 1: Low-cost, multi-GWh-scale energy storage, regional-to-continental-scale GH2 pipeline, at near-zero cost. Develop safe, affordable, self-monitoring linepipe for systems by which

[1] Pipeline volume ~1.2 million m^3, "packed" to 100 bar, "unpacked" to 30 bar = 84 Mm^3 GH2 working gas storage

to build the GH2 infrastructure for HFTO's "H2@Scale", including inherent, near-zero-cost, GWh-scale GH2 "packing" storage. Goal 2: Access the domal salt geology of Gulf Of Mexico (GOM) coast, where hundreds of large, deep, salt caverns may be constructed at very low cost (< $ 1.00 / kWh CAPEX). Goal 3: Large new land areas without electricity transmission will be open to wind, solar, and other VER harvest as high-purity H_2, at low plant-gate cost, low-cost GH2 pipeline transmission, free storage. Goal 4: The nascent federal "infrastructure" bill will include pipelines for CEF GH2: R&D, construction

Overcome Grid, H_2 system Challenges VER-capable GH2 pipeline systems are necessary for both H_2 transmission and near-zero-cost, GWh-scale, "packing" storage. Linepipe sample H_2 impermeability verification enables comprehensive TEA to enable investments in complete H_2 transmission and storage systems potentially superior to electricity systems, less subject to acts of God and man, i.e. lower OPEX.

Current state-of-art GH2 pipeline networks for VER-source H_2 do not exist; extant GH2 pipelines for SMR-to-refinery service are short, costly, and must be operated at near-constant pressure to avoid HE and HCC. No linepipe is available for low-cost, high-capacity, GH2 pipelines in VER service. Present steel GH2 pipelines are restricted to low (< ~ 20 bar) constant pressure to prevent HE, HCC -- thus of inadequate energy storage capacity. The necessary low-alloy steels suffer high CAPEX per unit of transmission service (kg H_2 / inch diam / day); cannot be used for "packing" storage for Grid assist.

Performance targets Near-zero net cost of GH2 storage by packing within the GH2 pipeline systems between MAOP and 1/3 MAOP. All system components must maintain immunity to HE, HCC and near-zero permeability at MAOP after thousands of pressure cycles. We will test before and after > 100 air-water P-cycles, with GH2, extrapolating results for further testing and new linepipe samples design.

C. Work Figures 1, 2. Qualified vendors will design and build, using diverse manufacturing processes, multiple linepipe samples with a thin, continuous, sealed layer of nonferrous metal embedded in the multi-layer polymer pipe wall, as the H_2 permeation barrier. An FRP layer on pipe exterior provides MAOP rating and limits pipe expansion and contraction under pressure variations, limiting metal and polymer fatigue. Fig. 2: One project vendor built a proof-of-concept pipe sample ten years ago, without exterior FRP reinforcement, Al foil in pipe wall; was not designed for, nor tested for H_2 impermeability.

Deliverables (a) Several samples of 6" diameter hybrid polymer-nonferrous-metal hybrid linepipe, tested for pipe wall GH2 impermeability and evidence of any degradation of pipe properties, after several hundred pressure cycles from 1 bar to MAOP, with full documentation; (b) TEA of fitness for service of this linepipe design and construction for GH2 energy storage by frequent "packing" cycles in GH2 pipeline systems for gathering, transmission, packing, distribution of diverse VER, as wind & PV.

Risks No linepipe is proven for VER service; project samples ~ TRL 3. Success may require more R&D investment to improve upon the TEA's than we can do, based upon our experimental lab data. Testing the hybrid linepipe samples at PNNL and / or SRNL is for linepipe wall H_2 impermeability, at MAOP and after hundreds of pressure cycles, of the polymer-nonferrous-metal hybrid linepipe samples to be produced by project partner(s). Pressure cycling is with air-over-water; impermeability with GH2. Challenge: terminating pipe sample ends to eliminate fitting leakage obscuring pipe wall H_2 permeation. Pipe samples may burst, delaminate, degrade, indicating pathways to design improvements and test.

Analysis, results TEA requires lab-scale data produced from testing multiple samples of polymer-nonferrous-metal hybrid linepipe, with reinforcing Fiber Reinforced Plastic (FRP) overwrap, to discover the likely cost of building and operating new HE- and HCC-immune GH2 pipeline systems. TEA will focus on California (CA) in year 2050, embedded in WECC region, where CA may interchange large amounts of "green" H_2 via dedicated GH2 pipelines, as alternatives to over-dependence upon, and over-investment in, the electricity Grid. Our models, via extant NREL tools, apply anywhere, adjusted for local, regional markets for energy services, on proximity to CEF energy sources; guidance to DOE R&D

Impacts: Grid, H2@Scale, HFTO, total decarbonization Project TEA will guide the Hydrogen & Fuel Cell Tech Office (HFTO) strategy: accelerate H2@Scale achievement goals via RD&D and policy:

a. What are the costs of building and operating GH2 pipeline systems, at local-to-continental scales for VER service, of novel linepipe immune to HE, HCC, vis-a-vis similar capacity Grid system?
b. How much energy storage will packing GH2 pipeline systems provide; at what benefits, costs?
c. How do (a, b) inform the optimum strategic allocation of R&D cost and infrastructure CAPEX among Grid and H_2 systems for the nascent fed and state "clean energy revolution" programs, for the urgent total de-carbonization of the entire human enterprise? How may we prevent over-dependence upon, and over-investment in the Grid, for VER-source electricity+storage systems?

Figs 1-4. USA, and world, will require new, dedicated, underground, high-purity, GH2 pipeline systems for gathering, transmission, and distribution of H_2 fuel from diverse, CEF, "green" VER sources. These new VER-capable GH2 pipeline system must safely, synergistically, and long-term profitably:

1. Provide significant zero-cost energy storage, as the NG industry does, by "packing" GH2 pipelines to MAOP, when CEF H_2 production is strong, "unpacking" pipelines to a minimum pressure, to meet customer demand when CEF H_2 production is weak; night or winter for PV; low windspeed.
2. Be built of linepipe(s) of near-zero permeability to GH2 through the pipe wall and at terminations;
3. Be immune to HE, HCC in VER service: frequent, large, H_2 pressure fluctuations must be endured;
4. Include both extant pipelines, repurposed and re-lined, and new pipelines in new excavations;
5. Be technically and economically superior to other methods of transporting and storing H_2, at scale;
6. Enable distributed VER-source H_2 production on large land areas without electricity transmission;
7. Provide access to the large, low-cost, GH2 salt cavern storage available at Gulf Of Mexico (GOM);
8. Require on-site, in-field linepipe manufacture in mobile factories to (a) minimize pipeline joints, and (b) allow re-lining extant pipelines by pulling in new GH2-capable linepipe, several km at once;
9. Be a very large capital investment, staged over the 2025 - 2050 period, providing many good jobs.

This project's success, confirmed by lab test data of novel linepipe materials and GH2 storage fitness, will improve prospects for early progress in H2@Scale, by reducing the dispensed cost of VER-source H_2, by first decreasing CAPEX + OPEX for gathering, transmission, and packing energy storage. It opens a large new market for wind+PV energy, perhaps larger than the electricity Grid; opens large windy, sunny land areas, without electricity transmission, to energy harvest as H_2 & NH_3, C-free fuels.

ARPA-E funds value Linepipe technology R&D is now too risky for private sector investment; markets for dedicated, large-scale, high-purity VER-source GH2 transmission and packing storage are distant and uncertain. Without risk-tolerant ARPA-E funds, synergistic systems storage languishes. ARPA-E investment will produce valuable IP and USA market leadership, via tech R&D data, TEA.

D. Team qualifications

Alaska Applied Sciences, Inc. William C Leighty, BSEE, MBA, Stanford, Principal. Founded ' 90. Successful DOE-funded research project, 2005: https://www.osti.gov/biblio/859303-oXetpM/
PNNL Richland, WA. H_2 permeation testing for FRP linepipe. Kevin Simmons, Ph.D, Staff Scientist. Co-Lead, DOE H-Mat program for polymers. 30 years in polymer and composite material processing, characterization, test. Battelle Distinguished Inventor. On H_2 programs for > 10 years: storage pressure vessels, cryogenic materials testing, hoses, and materials compatibility in hydrogen environments.
SRNL Aiken, SC. H_2 permeation testing for FRP linepipe. Charles (Will) James, Sr. Fellow, Program Manager, (Office): 803-725-5427 (Cell): 803-646-0163 charles.james@srnl.doe.gov

UC Irvine, APEP (Advanced Power and Energy Program) Dr. Jeff Reed, Chief Scientist, Renewable Fuels and Energy Storage. Board chair, California Hydrogen Business Council. Former Sempra Utilities

Equipment and facilities Both PNNL and SRNL have excellent H_2 lab facilities, and staff experience with H_2 pipe & vessel testing, for both gaseous hydrogen (GH2) and air-over-water for fatigue test P-cycling. FRP linepipe samples manufacturers TBD; all have mature design and manufacturing facilities.

Teaming on prior work Applicant, NOV Fiberspar, SRNL, and PNNL collaborated on a DOE FOA # 2446 Concept paper funding proposal, for essentially this project, 15 Jan 21; "not encouraged".

Figure 1. This proprietary continuous process by Smart Pipe Company fabricates flexible multilayer FRP pipe on-site, of any length, without joints. Non-ferrous polymer-metal hybrids may be necessary to provide adequate H2 permeation barrier without HE, HCC. Allows energy storage by pipeline "packing" as the natural gas network does.

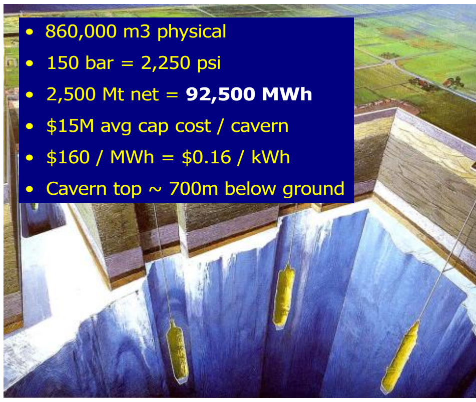

Figure 2. Very low cost, GWh-scale, domal salt cavern energy storage, via continental-scale GH2 pipelines

Figure 3. Sample of polymer-metal hybrid linepipe for gathering, transmission, near-zero-cost "packing" storage, and distribution of VER GH2. Non-ferrous; no Hydrogen Embrittlement (HE), Hydrogen Corrosion Cracking (HCC), other corrosion. Thin layer of Al or Cu within the pipe wall is the H_2 permeation barrier. Made on-site in unlimited length to 24"+ diam by Smart Pipe, Houston. We will test several hybrid designs for H2 permeation, and perhaps for P cycling, repeat. Then, correlate back to benchmark burst strength for TEA.

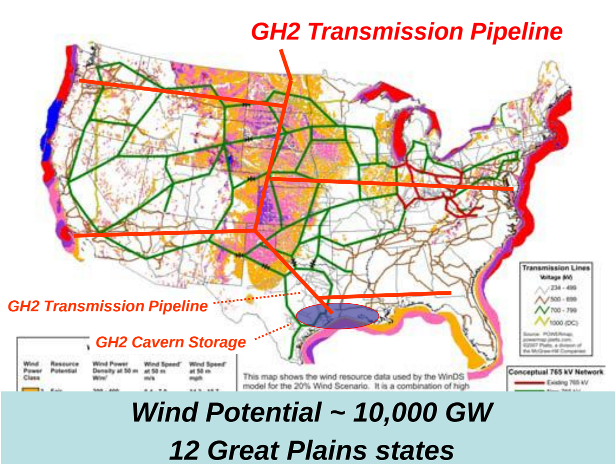

Figure 4. H2@Scale will allow and require importing RE-source H_2 fuel from dedicated Great Plains wind and solar plants without Grid connection. As other states and regions emulate California's RE regulatory and GH2 pipeline network construction experience, a nascent continental H_2 fuel market will require an extensive GH2 gathering, transmission, storage, and distribution pipeline network, allowing accessing and interconnecting Great Plains energy and low-cost, TWh-scale and annual-scale energy storage, in packed pipelines and salt caverns. A 1,600 km, 36" GH2 pipeline stores 120,000 MWh as H_2 chemical energy, "packed and unpacked" at 100 bar <--> 30 bar.