North America Smart Energy Week 2019, 23 - 26 September, Salt Lake City

Solar Power International Hydrogen and Fuel Cells Energy Storage International

Deep Decarbonization of Total Global Energy: Hydrogen and Ammonia Fuels as Integrated CO_2 - Emission - Free (CEF) Energy Systems

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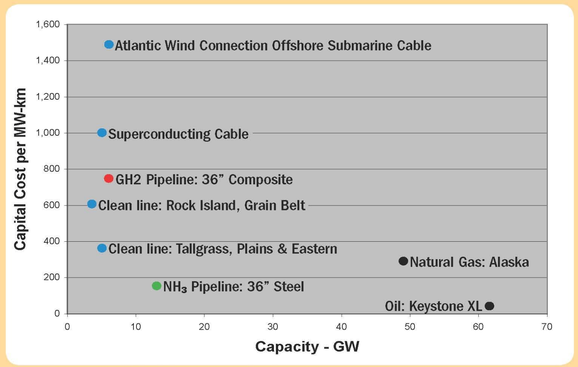
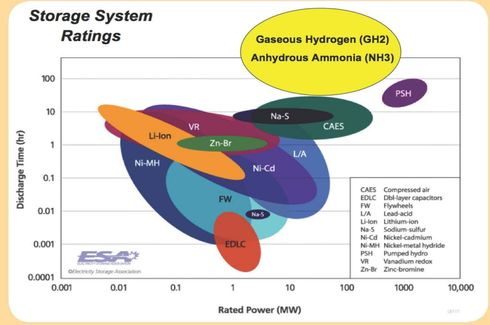
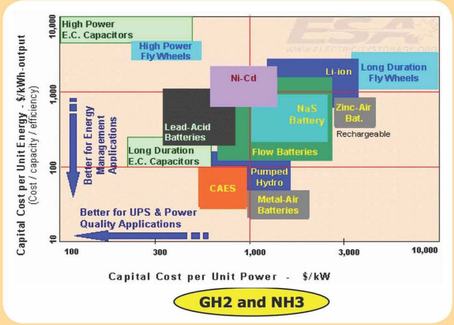
- **Use pipeline networks, rather than the electricity grid, solving the three salient technical problems of renewable energy (RE) at lower cost:**
  1. Transmission: from diverse, stranded, remote, rich RE resources
  2. Storage: intermittent RE becomes annually firm and dispatchable
  3. Integration: with conventional, extant energy, for firm quality supply
- **Design and optimize complete RE systems, at local and continental scales, from sunlight, wind, and water resources to dispatchable, delivered energy services:**
  - Generation - Gathering - Firming storage - End use
  - Conversion - Transmission - Combined-heat-and-power (CHP)
- **Annually-firm RE supplied via very low capital cost storage, less than $US 1.00 / kWh:**
  - ➥ Gaseous Hydrogen (GH2) in large salt caverns, where geology is available
  - ➥ Liquid Ammonia (NH_3) in carbon steel surface tanks
  - ➥ Interconnected via continental underground pipelines, adding storage
  - ➥ Lower cost than any contemplated “electricity” storage components
- **We now need pilot plants for both GH2 and NH_3 RE systems, by which to:**
  - ➥ Discover and demonstrate scaleable technical proof-of-concept and economics
  - ➥ Explore optimum system topology for sources, components, and end-uses
  - ➥ Motivate private-public collaboratives to conceive RPF’s and RFQ’s for the plants
- **Humanity’s goal is to eventually “Run the World on Renewables” – plus some nuclear?**
  - ➥ Earth’s richest RE is stranded, far from markets with no transmission
  - ➥ We cannot do this entirely via electricity, and should not try to do so; “Smart Grid” is demand side management (DSM); no inherent new capacity
  - ➥ Therefore, we design alternatives and adjuncts to the electricity grid:
    - Convert all RE at sources to Gaseous Hydrogen (GH2) or Ammonia (NH_3) fuels
    - Deliver these C-free fuels via underground pipelines for transport and CHP



PIPELINE TRANSMISSION CAPITAL COST COMPARABLE TO or lower than electricity transmission, per MW-km of transmission service.



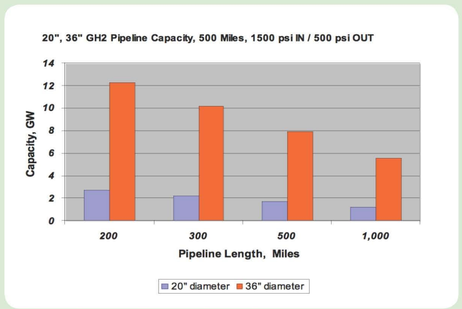
HYDROGEN AND AMMONIA STORAGE
Capacity is Far Larger than any Electricity Storage



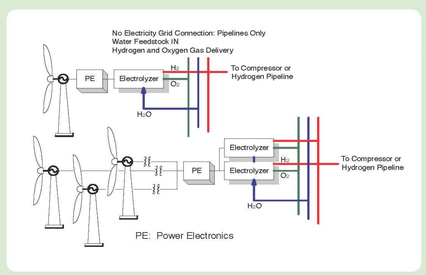
HYDROGEN AND AMMONIA STORAGE
Capital Cost is Far Smaller than any Electricity Storage

GASEOUS HYDROGEN (GH2)

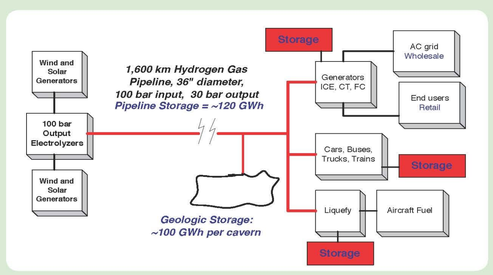
- **RE-source electricity splits water to Hydrogen (H2) and Oxygen (O2) in electrolyzers**
  - ➥ H2 is buoyant, low-viscosity, low volumetric energy density, C-free fuel
  - ➥ ICE, CT, and Fuel Cell run well on H2 , with only H2O exhaust
  - ➥ Byproduct O2 may be sold to adjacent biomass and coal gasification
- **High-capacity underground pipelines gather and deliver GH2 fuel:**
  - ➥ Via local and continental networks, including storage caverns
  - ➥ From diverse sources: pipeline pilot plant concept
  - ➥ For transportation fuel via Fuel Cells to electric drive
  - ➥ For combined-heat-and-power (CHP) stationary plants
- **High-pressure-output electrolyzers allow:**
  - ➥ Feeding the transmission pipeline directly, or with minimum compression, at ~ 100 bar
  - ➥ Long-distance transmission with no mid-line compression; low-viscosity H2 saves capital and energy costs
- **Low-cost, large-scale storage provides firm, dispatchable, RE supply:**
  - ➥ By pipeline packing
  - ➥ In salt cavern arrays at < $US1.00 / kWh capital cost
  - ➥ At end-users in mobile and stationary GH2 fuel tanks



GH2 PIPELINES HAVE GREAT CAPACITY
No compressors; high-pressure electrolyzers directly feed pipeline
100 bar input; 30 bar delivery at market



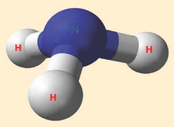
TOPOLOGY OPTIONS:
H2 and O2 Production and Gathering from Renewable-source Electricity Generation



COMPRESSORLESS PIPELINE SYSTEM STORAGE:
Pack Pipeline, Salt Caverns, Distributed at End-users

ANHYDROUS AMMONIA (NH_3)

- **Both Fuel and Fertilizer: C-free, “the other hydrogen”**
  - ➥ ICE, CT, and Fuel Cell run well on NH_3 with only H2O and N2 exhaust
  - ➥ High-energy-density Hydrogen carrier and energy storage medium
  - ➥ Half the volumetric energy density of diesel
  - ➥ Inhalation hazard; toxic at high concentration, detectable at very low
  - ➥ Buoyant, dissipates, great affinity for water
- **Easily pipelined and stored at low cost, as liquid**
  - ➥ Liquid at 10 bar or -33 C at 1 atm
  - ➥ Carbon steel pipelines and tanks common in Corn Belt, USA
  - ➥ Decades of good safety record: >140M tons / year worldwide N-fertilizer
- **Infrastructure in place for “green” NH_3 transmission and storage in USA:**
  - ➥ 4,000 km underground pipelines, New Orleans through Corn Belt
  - ➥ Many surface tanks of 10,000 to 60,000 tons each
  - ➥ Rollout strategy: “wheel” RE-source “green” NH_3 to fuel customers, via extant infrastructure, as utilities now wheel green electricity
- **Eight annual Ammonia Fuel Association conferences hosted by Iowa State University:** http://www.energy.iastate.edu/renewable/ammonia/ammonia.htm



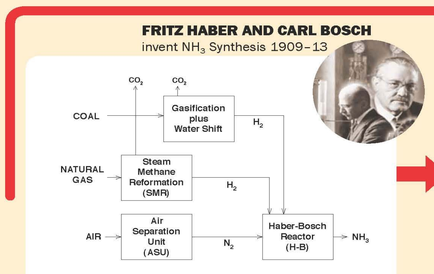
“THE OTHER HYDROGEN” — 18% H BY WEIGHT
Anhydrous Ammonia NH_3
N Nitrogen
H Hydrogen
Molecular weight = ~ 17
$NH_3 + O_2 = N_2 + H_2O$

NORTHWEST IOWA, USA
2.5 MW wind turbines, connected at great expense to the electricity grid, could be producing “green” NH_3 fuel and fertilizer for the farms, with no grid connection.

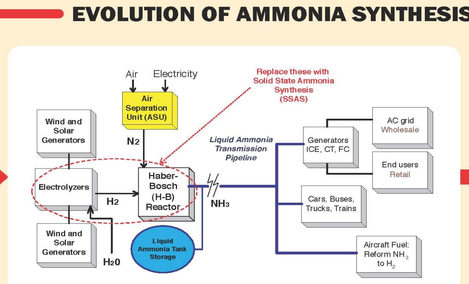
“ATMOSPHERIC” LIQUID AMMONIA STORAGE TANK -33 C, 1 atm
30,000 Tons NH3 = 190,000 MWh energy storage
$US 15M turnkey capital cost:
$ 80 / MWh
$ 0.08 / kWh

EVOLUTION OF AMMONIA SYNTHESIS

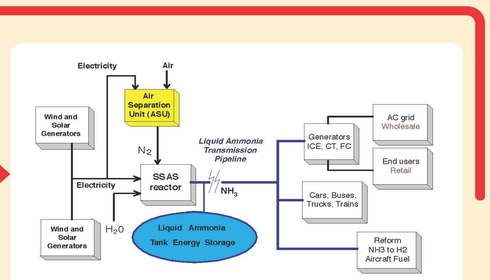
FRITZ HABER AND CARL BOSCH
invent NH_3 Synthesis 1909–13



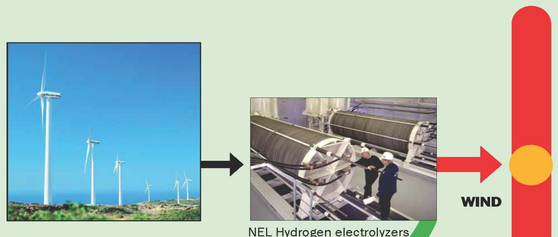
MOST AMMONIA TODAY IS MADE FROM NATURAL GAS OR COAL via Haber-Bosch (H-B) synthesis. The air separation unit (ASU) supplies atmospheric nitrogen.

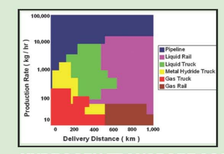


ELECTROLYSIS PLUS H-B IS TOO COSTLY for “green” ammonia synthesis from renewables-source electricity



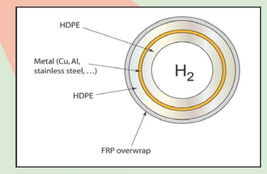
SOLID STATE AMMONIA SYNTHESIS (SSAS) replaces the electrolyzer and H-B reactor for lower-cost RE-source ammonia fuel and fertilizer



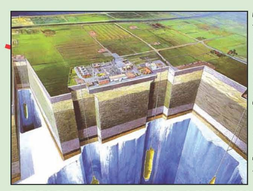


HYDROGEN TRANSPORT COSTS
GH2 Pipeline is Lowest-Cost Hydrogen Transport Method at Long Distance and High Power (W. Amos, NREL, USA, '98)

GH2 PIPELINE STORAGE
Fully harvesting just the wind energy of the twelve windiest states of USA, delivering it all as GH2:
- Requires ~400 new pipelines, 36” diam, 70 bar, capacity ~2,500 tons per day GH2 each
- Provides ~ 120,000 MWh of energy storage, for 1,600 km pipeline, 36” diam, “unpacked” from 70 to 35 bar.

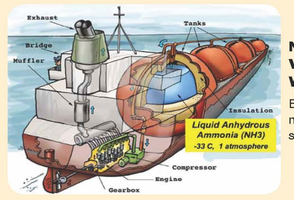


POLYMER-METAL COMPOSITE LINEPIPE
Up to 1m Diameter
Avoids Hydrogen Embrittlement
Continuous field fabrication process for unlimited length



TYPICAL GH2 STORAGE CAVERNS IN DOMAL SALT: Multiple Caverns Share Surface Facility
800,000 cubic meters physical volume
Pressure: 150 bar max, 50 bar min
2,500,000 kg GH2 net “working” storage
90,000 MWh net energy storage
$US 15M / cavern capital cost
$US 160 / MWh = $0.16 / kWh

4,000 KM OF NH3 PIPELINE AND STORAGE TANKS
are in place in Corn Belt, USA, for “green” ammonia fuel market rollout.
NuStar Energy LP ammonia system (orange)



NH3 IS THE SECOND-HIGHEST-VOLUME CHEMICAL IN WORLD TRADE.
Bulk “green” RE-source NH3 may thus be exported from large, stranded, RE resources.

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