Pipelining Hydrogen:

- **Gas and Hydrogen: Promising + Perilous**
- **Total transformation by 2050:**
  - **Decarbonization, de-GHG-emission**
  - **Quickly, prudently, profitably**
    - **Prudently: disruptive; don't cripple economy**
    - **Profitably: large capital flows only to high reward-to-risk**

"Hydrogen is hard" -- difficult

- Molecule
- Substance
- Moving
- Storing
- System: leaks, hydrogen embrittlement
- Business case

Bill Leighty, Director
The Leighty Foundation

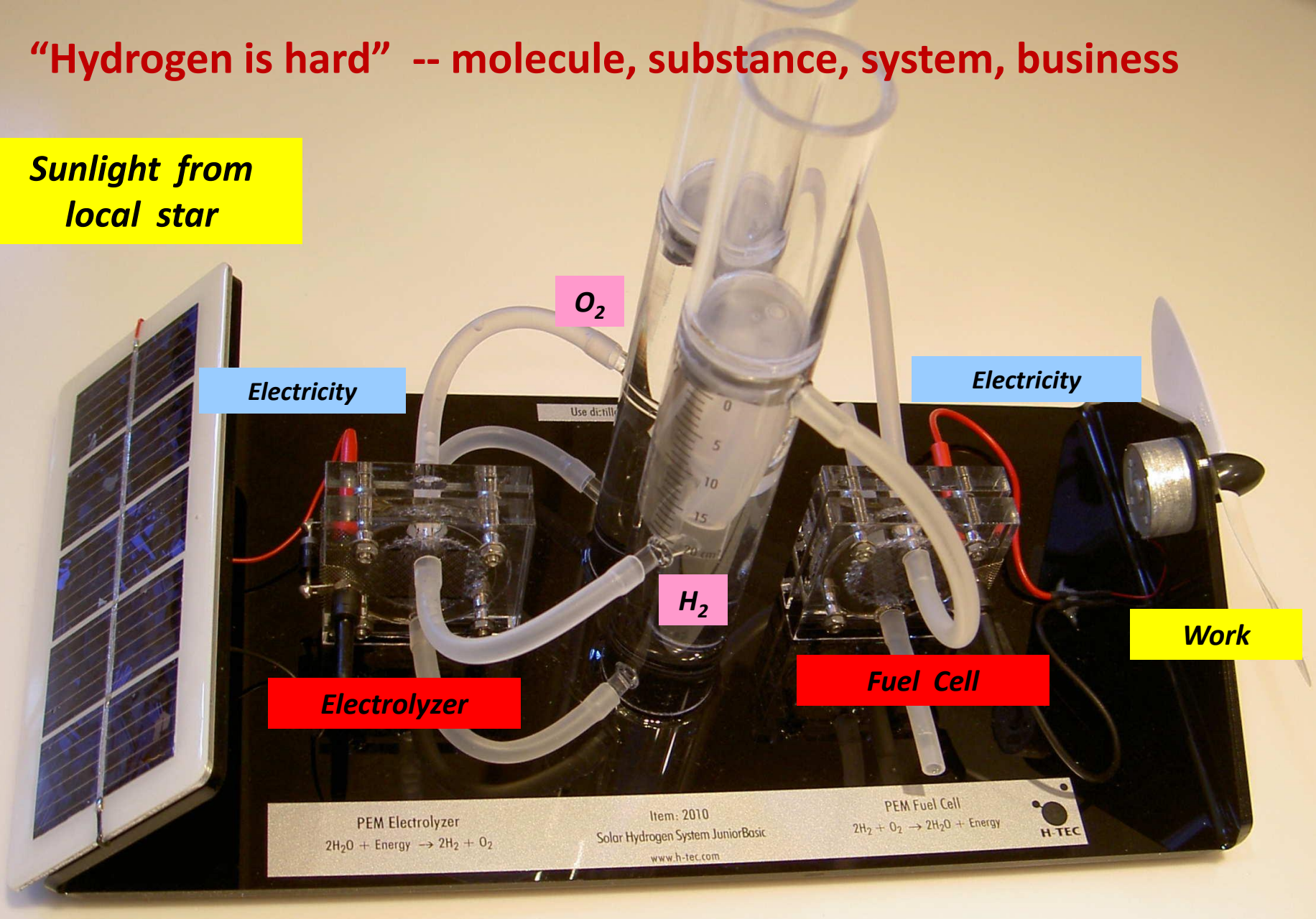
Pipelining Hydrogen:

Why ?
Gas or liquid ?
Blend with NatGas or high-purity ?
Repurpose old pipes or new-build ?
Free “packing" storage ?
Salt cavern storage access ?
Scale:

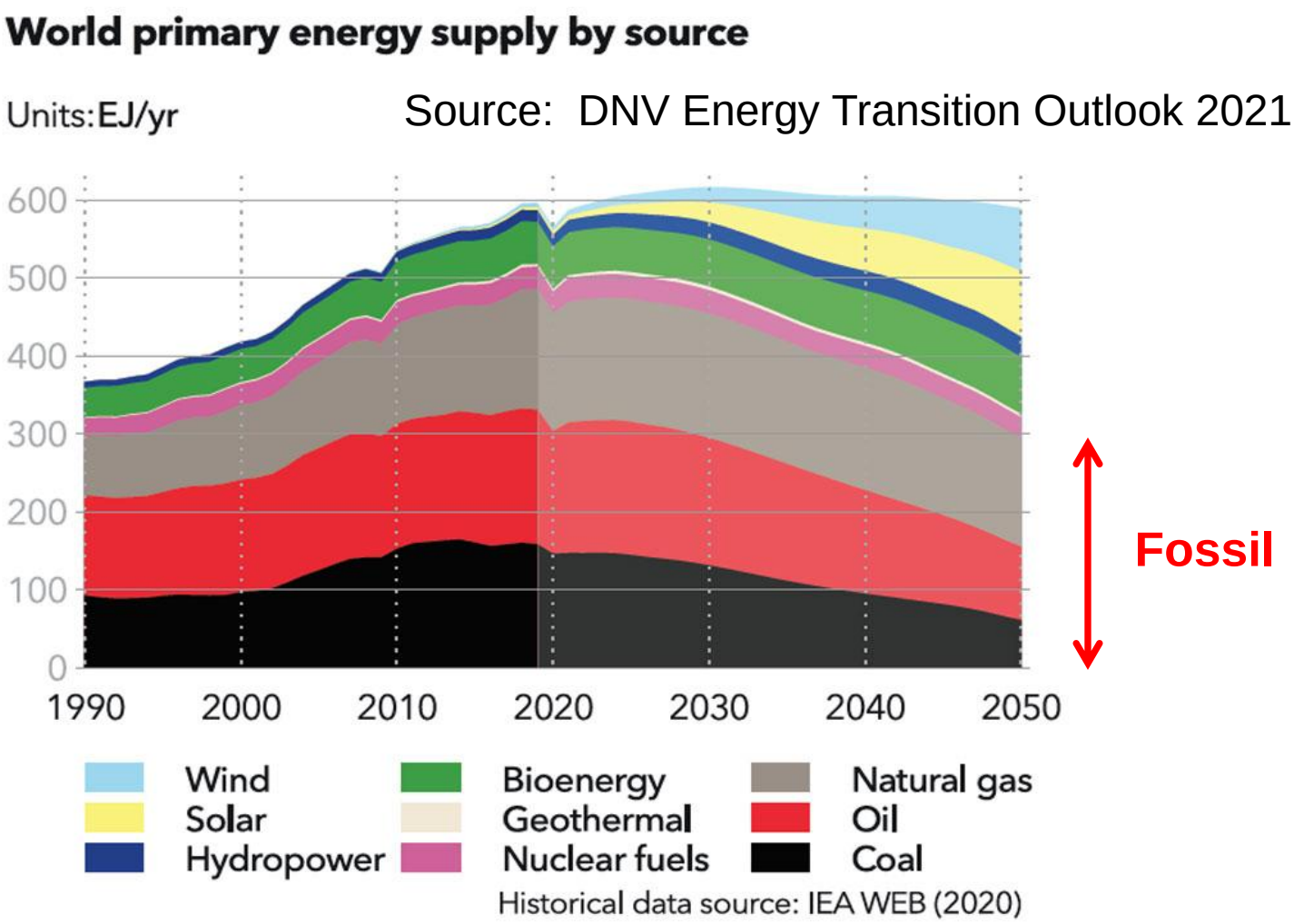
- **Continental, global**
- **Total Energy + Industrial Feedstocks**
- **Total human enterprise**

Bill Leighty, Director
The Leighty Foundation
Juneau, Alaska USA

"Hydrogen is hard" -- molecule, substance, system, business



Solar Hydrogen Energy System



2050 : **Total De-carb, de-GHG-emission: anthropogenic**
Entire human enterprise: Energy + Industrial Feedstocks
Fossil 50 % → Zero
Geothermal insignificant
Roles: Legacy Gas, Nascent Hydrogen ?
Arrest: Climate catastrophe

Pipelining Hydrogen:

- "Total Systems" approach: humanity's goals
  - Total Energy + Industrial Feedstocks [E+IF]
  - Benign, firm, ubiquitous, competitive
- Nascent Hydrogen vis-à-vis Grid ?
  - Grid can't: suboptimal
  - Trying delays total de-carb, de-GHG
  - Stop over-depending, over-investing
- Need gas industry: H2 ? Ammonia (NH3) ?
- Legacy gas assets: pipelines → NOW

Why pipeline H2 ?

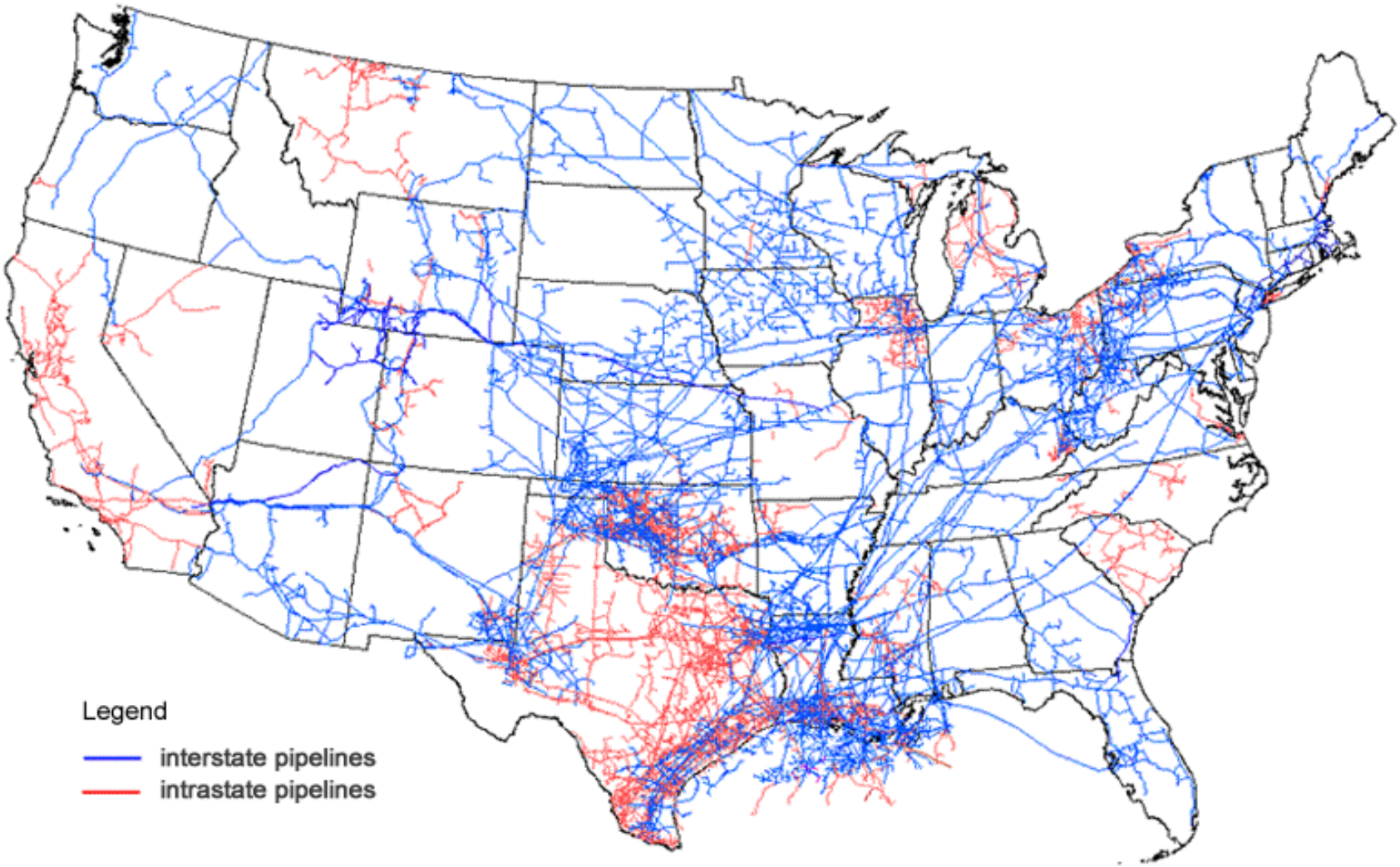
- Prevent catastrophic Climate Change
- Total de-carb, de-GHG-emission, entire human enterprise
- Carbon-free energy carrier, storage medium, fuel
- Transform world's largest industry
- Now: SMR to refineries
- Now: Blending in NatGas pipelines
- Access GHG-emission-free sources: "clean", "green"
- Lower cost than electricity:
  - Transmission
  - Storage
  - Off-Grid H2 production
- "Whole system": gather, transmission, storage, distribution
  - Resilient, Slow
  - Underground: safer, low O&M
  - "Free" storage by "packing"

Why pipeline H2 ?

- Lower-cost:
  - Transmission
  - Storage
  - Off-Grid H2 production
- “Whole system”: gather, transmission, storage, distribution
    - Diverse, dispersed “renewables”
    - “Free” storage
    - Underground: safer, low O&M
- **Large legacy pipeline assets: “Ready “ ?**
  - **Repurpose for GH2, liquid NH3 ?**
  - **Modify, renovate ? How ?**
  - **Replace; use ROW ? With what ?**
  - **Safety first**

NatGas pipelines

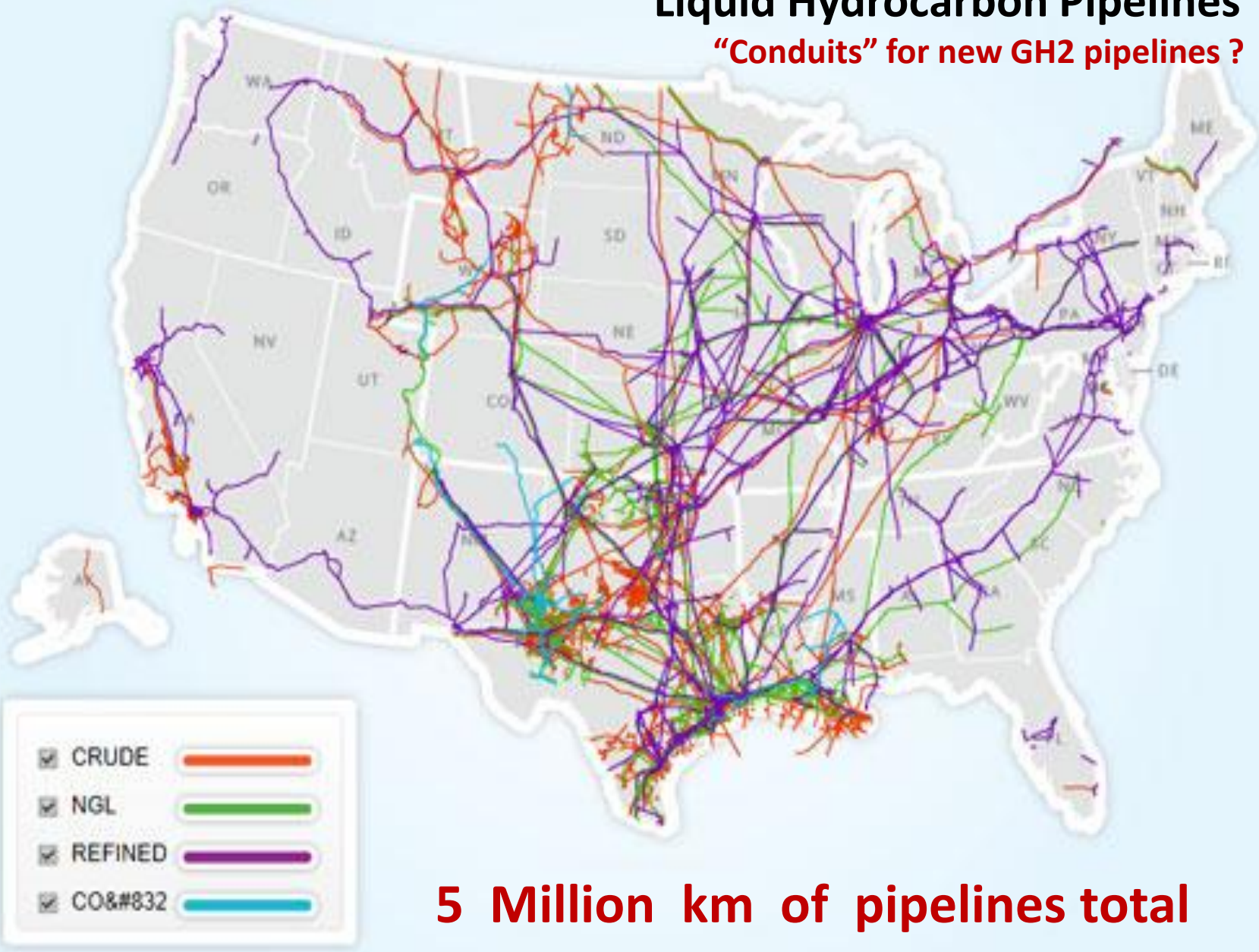
Map of U.S. interstate and intrastate natural gas pipelines



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

Liquid Hydrocarbon Pipelines

"Conduits" for new GH2 pipelines ?



5 Million km of pipelines total

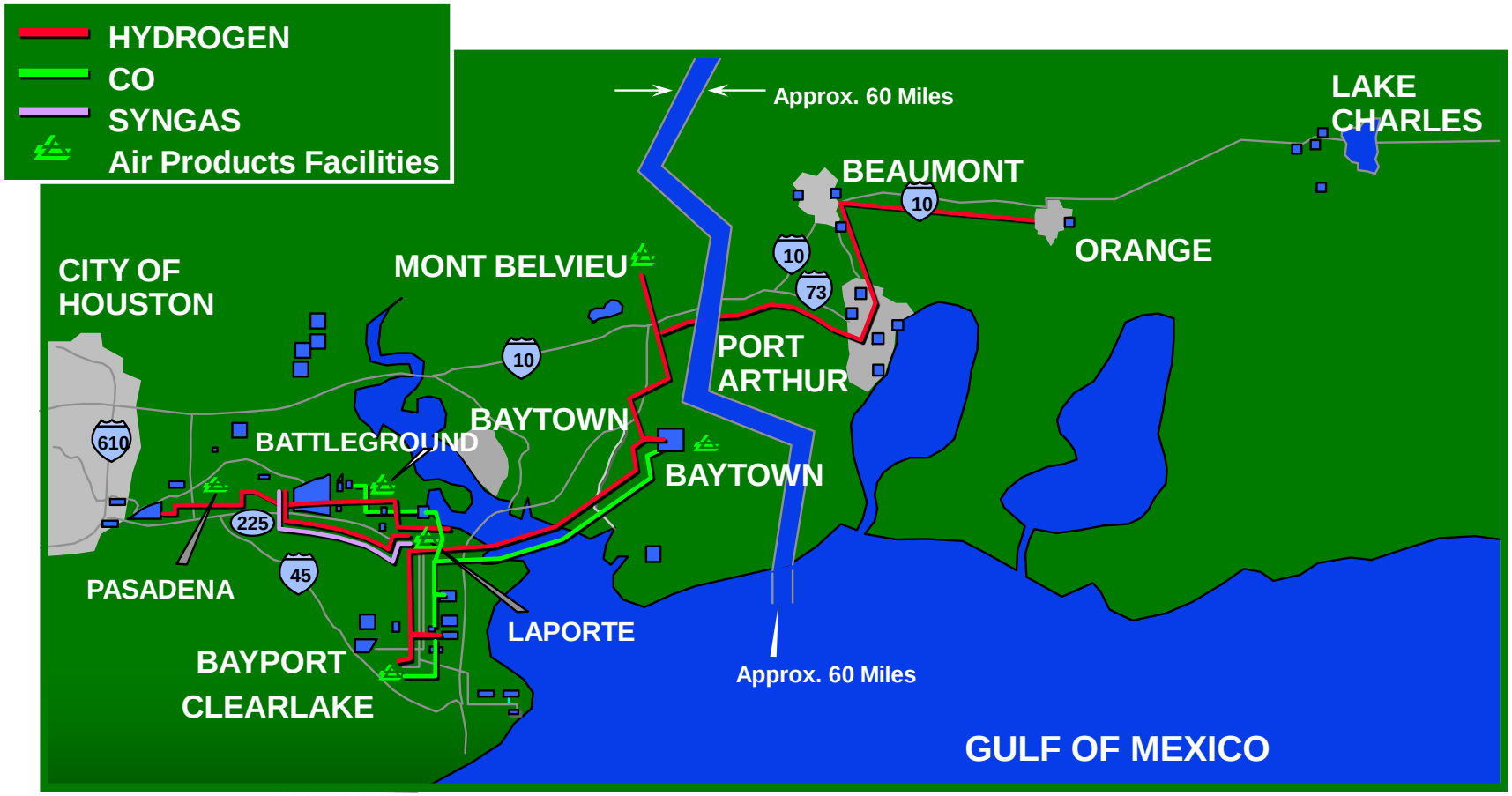
Source: American Energy Mapping (AEM) 2013

Already Pipelining Hydrogen

- ~ 100 MMT (million tons) per year, global
- ~ 5,000 km gaseous hydrogen (GH2) pipelines
- SMR * → Oil refineries
- Methane CH_4 → H_2 + CO_2
- GH2 pipelines:
  - Low pressure (~ 20 – 30 bar)
  - Constant pressure
  - Low-alloy or carbon steel
  - Thick wall
  - Industrial corridors
  - Good monitoring and repair

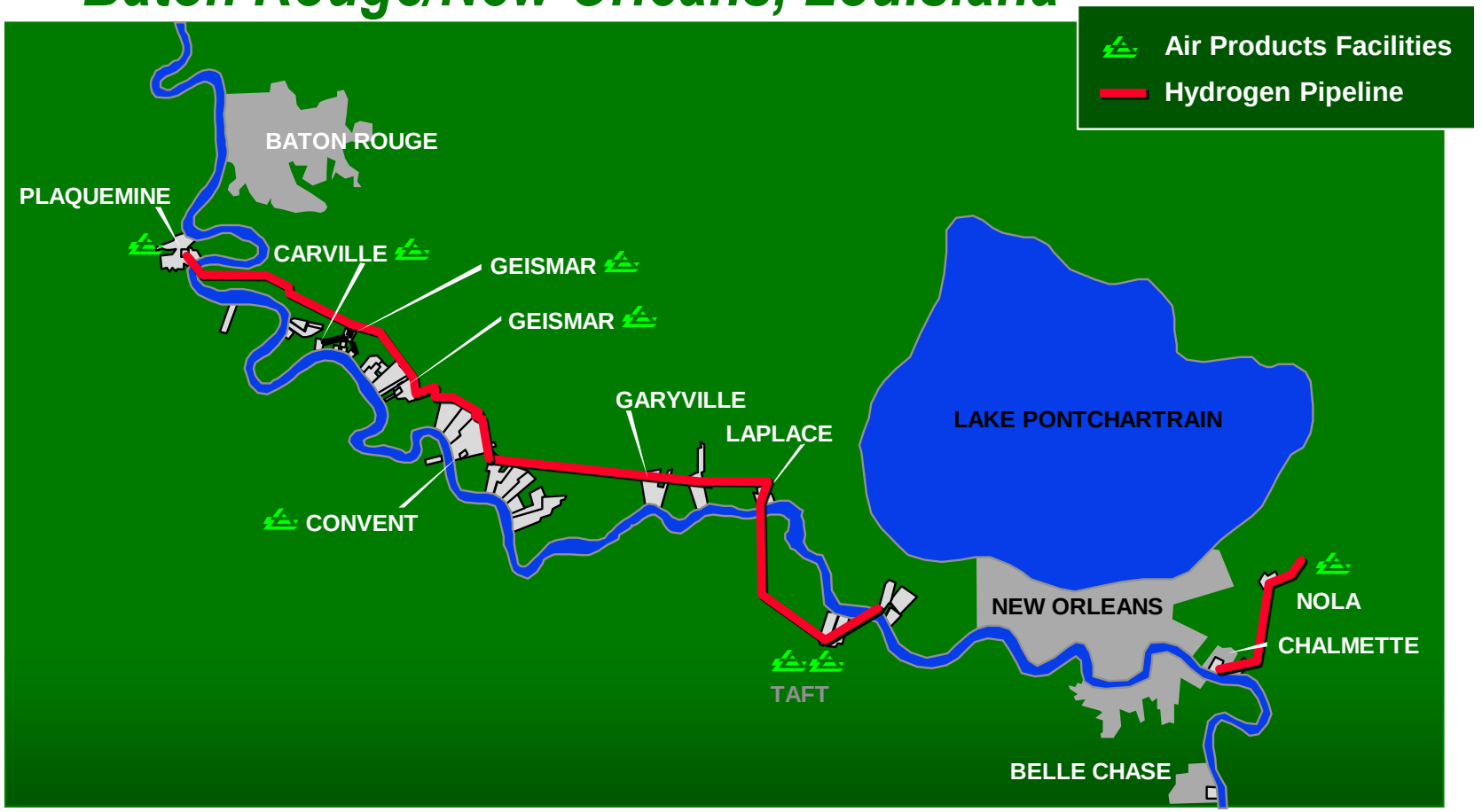
* SMR = Steam Methane Reformer

Air Products H_2 / CO Pipeline - *Texas Gulf Coast*



Refinery Hydrogen Pipeline
From SMR

Air Products H_2 Pipeline
Baton Rouge/New Orleans, Louisiana

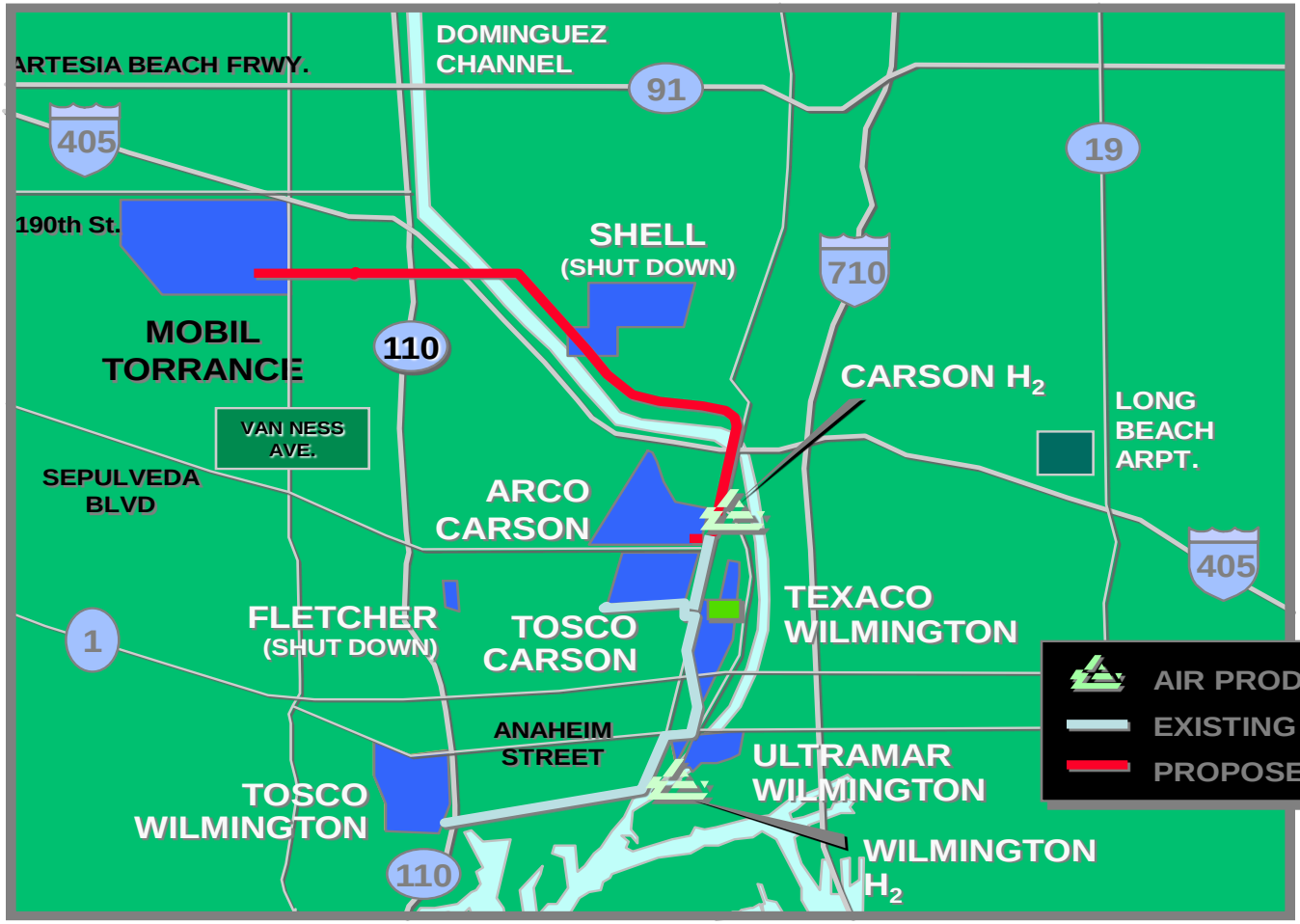


hyco99.ppt 3

Refinery Hydrogen Pipeline
From SMR

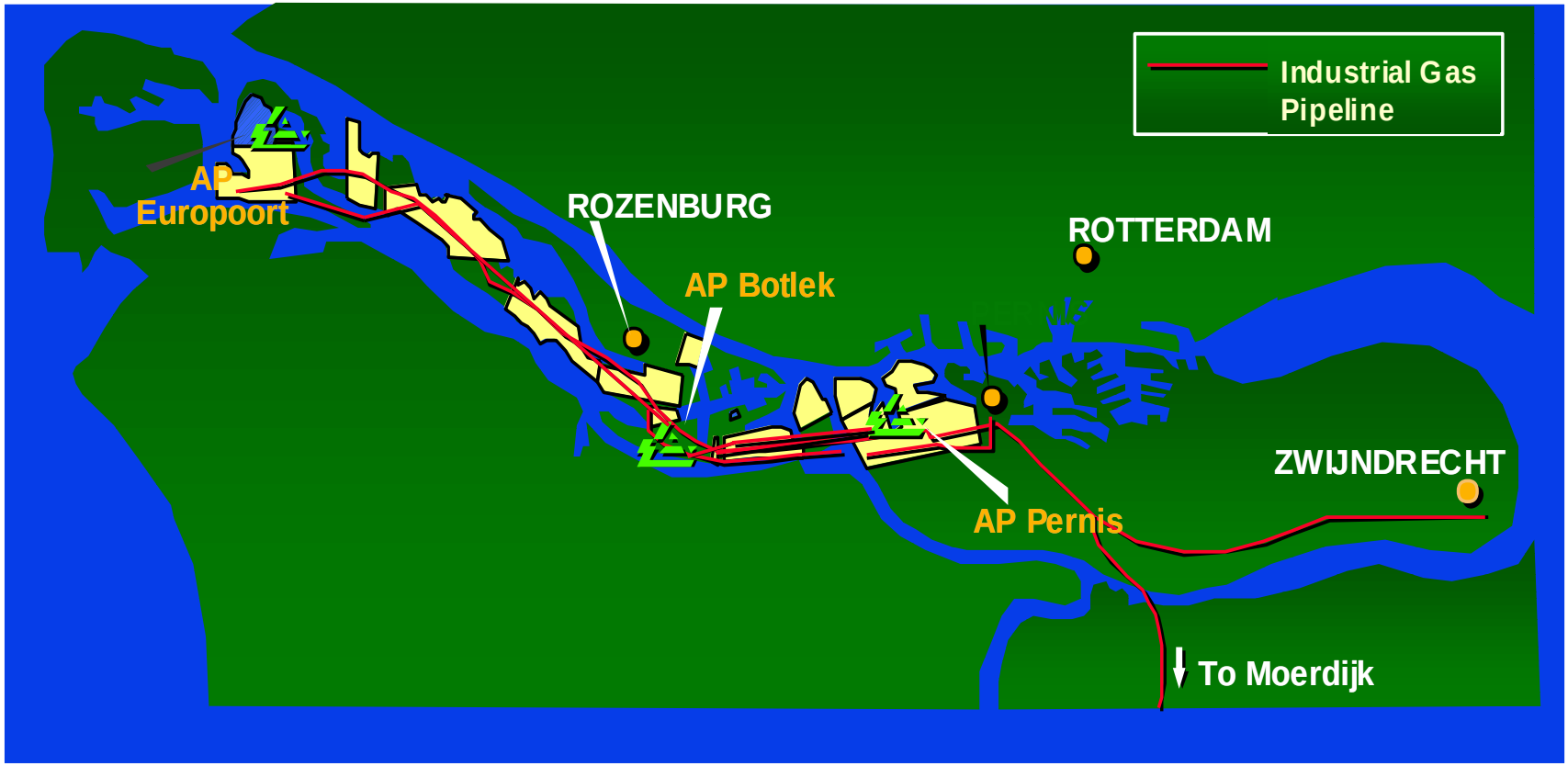
Air Products Company

REFINERY ACTIVITY
LOS ANGELES BASIN, CALIFORNIA



Refinery Hydrogen Pipeline
From SMR

Rotterdam Pipeline System



Refinery Hydrogen Pipeline From SMR

Dangers

"Hydrogen is hard" -- difficult

- Molecule
- Substance
- System
- Business
- Time, money

Hydrogen Embrittlement (HE)

Hydrogen Corrosion Cracking (HCC)

Legacy "Refinery" pipelines:

- Low-alloy steel
- High-quality steel: few flaws
- Low pressure
- Constant pressure
- Industrial corridors

Bill Leighty, Director
The Leighty Foundation
Juneau, Alaska USA

Hydrogen Embrittlement (HE)

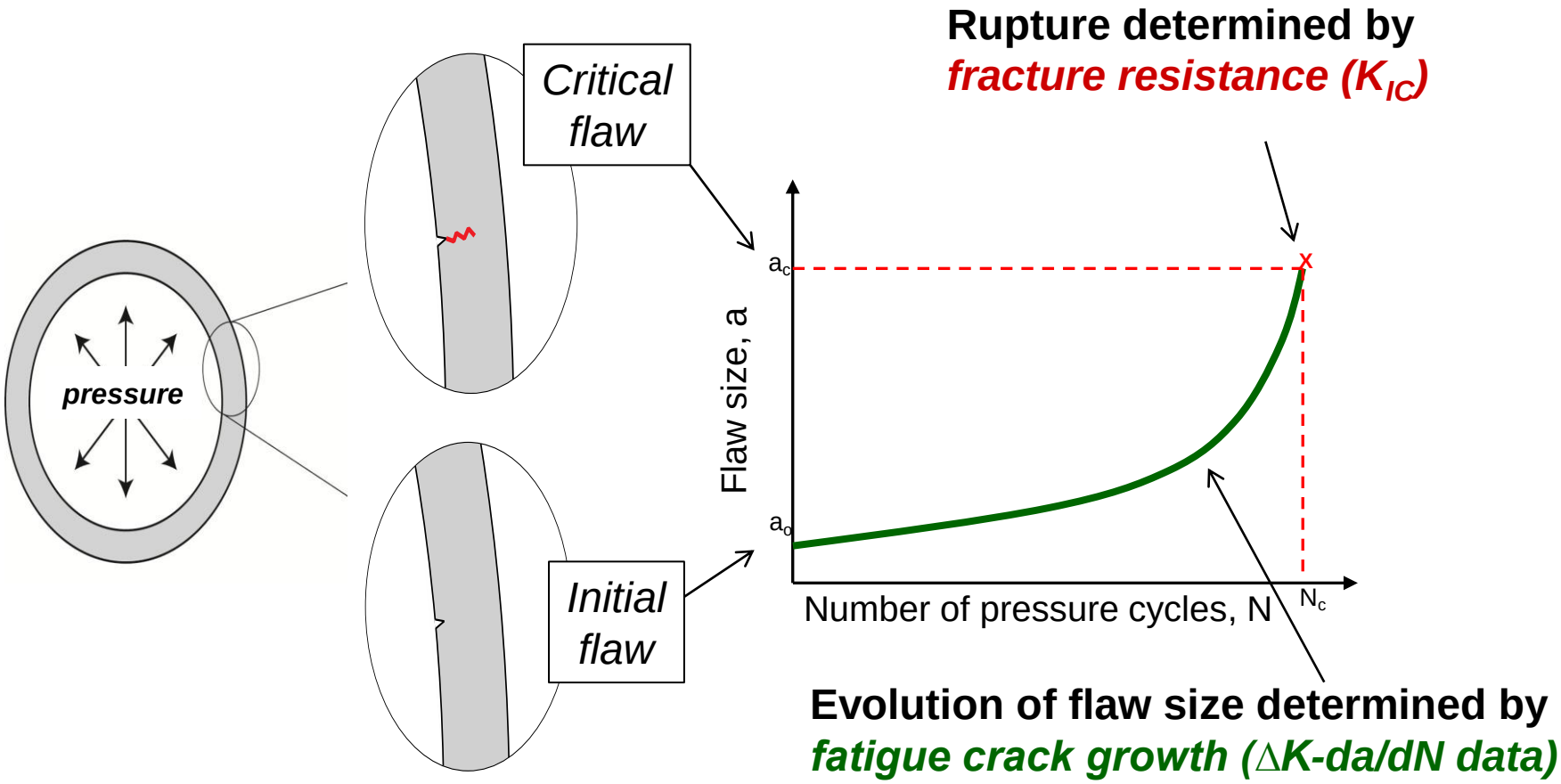
Hydrogen Corrosion Cracking (HCC)

- Independent of steel type
- Quality, welds important
- Little variance with GH2 % in blend
- Asset condition rules – flaws, damage, external stress
- Control pressure cycling

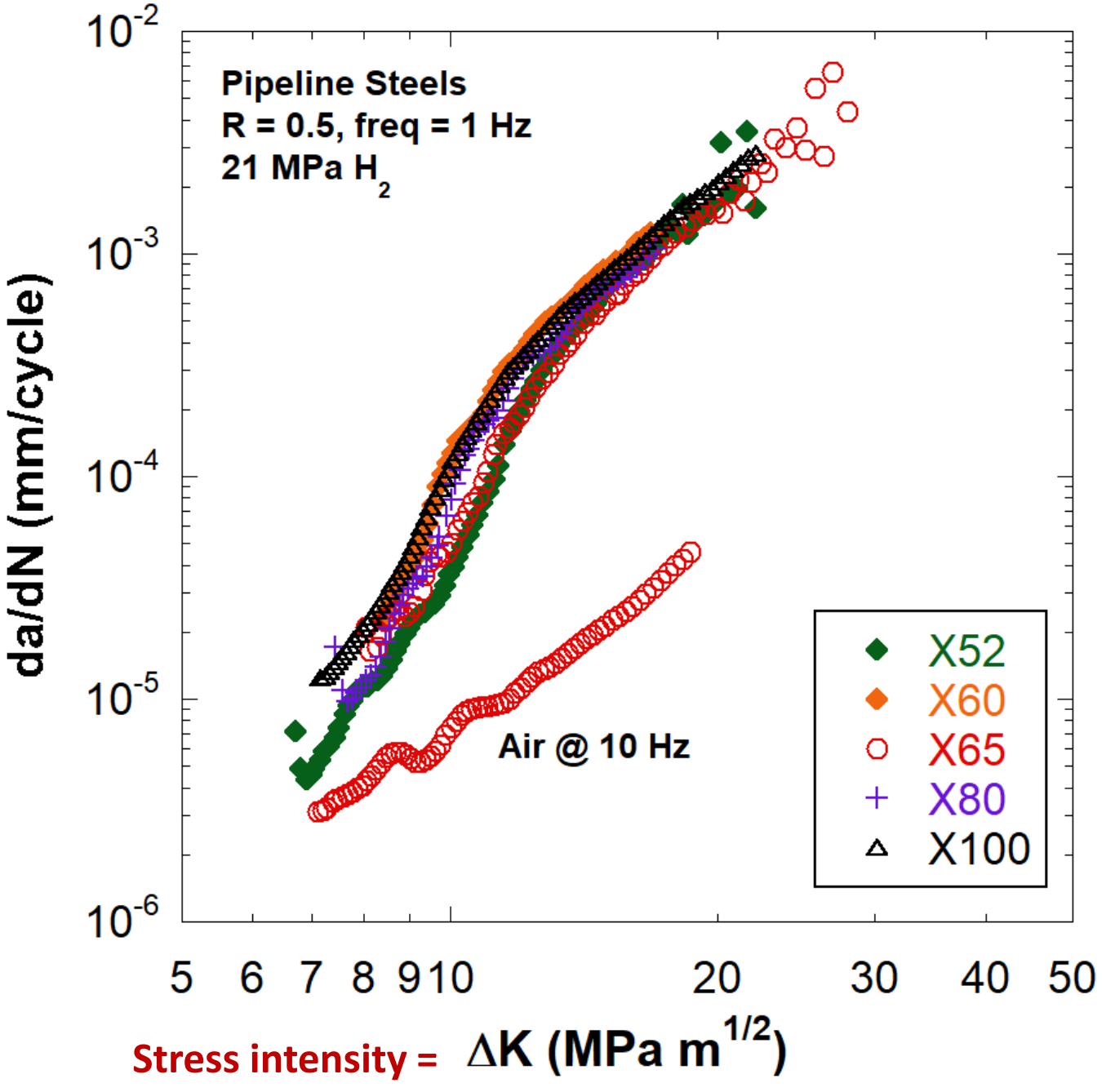
- How to inspect legacy pipelines to assess FFS ?
- How to control P cycling in VER * service ? Packing ?
  Magnitude, frequency
- Legacy pipelines only as “conduits” for relining ?

* VER = Variable Energy Resource (wind, solar, etc.)

Testing motivation:
Structural integrity assessment, fracture mechanics



ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

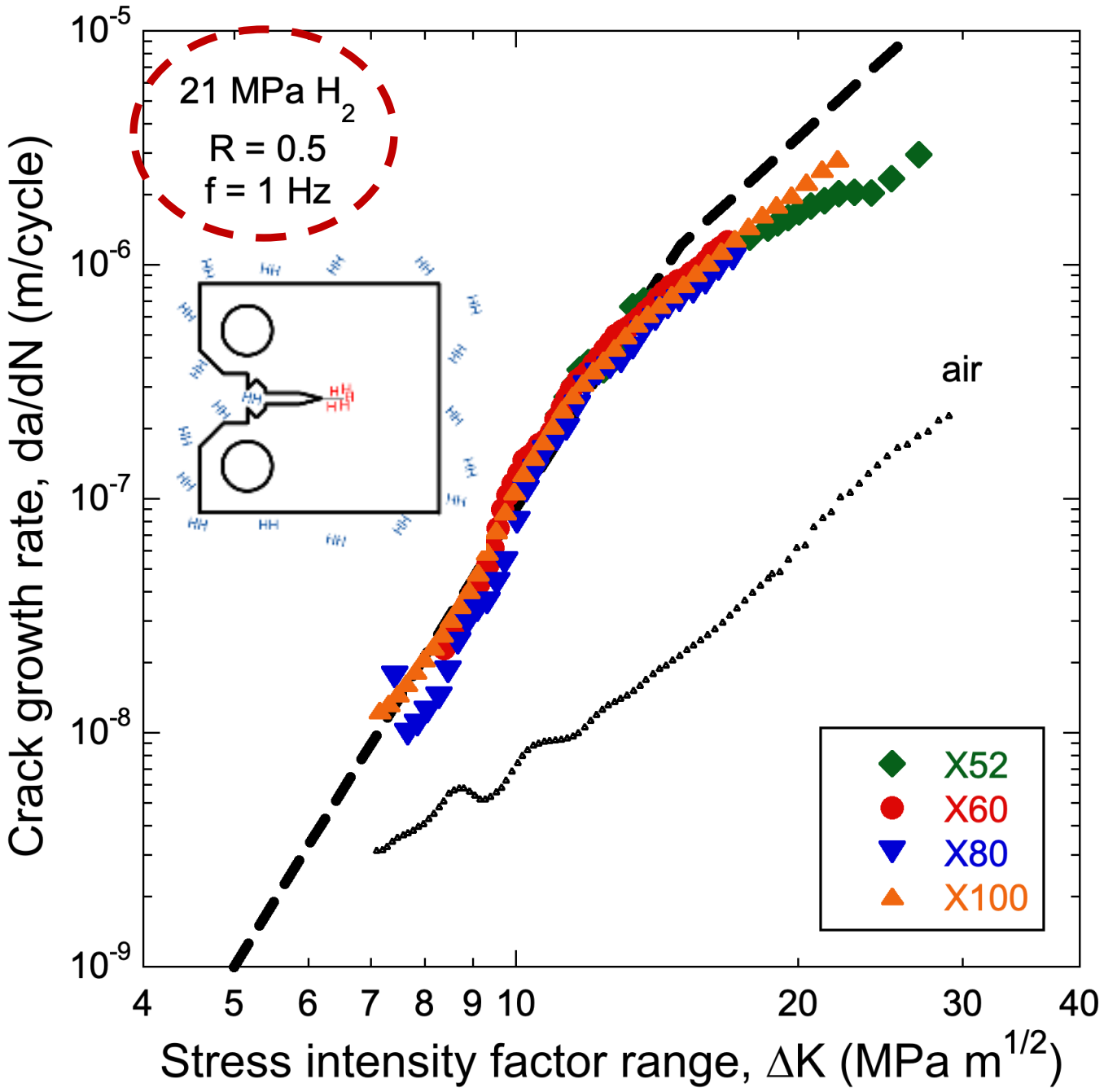


Variety of pipe steels

Same fatigue response

crack growth vs stress intensity

High – P GH2



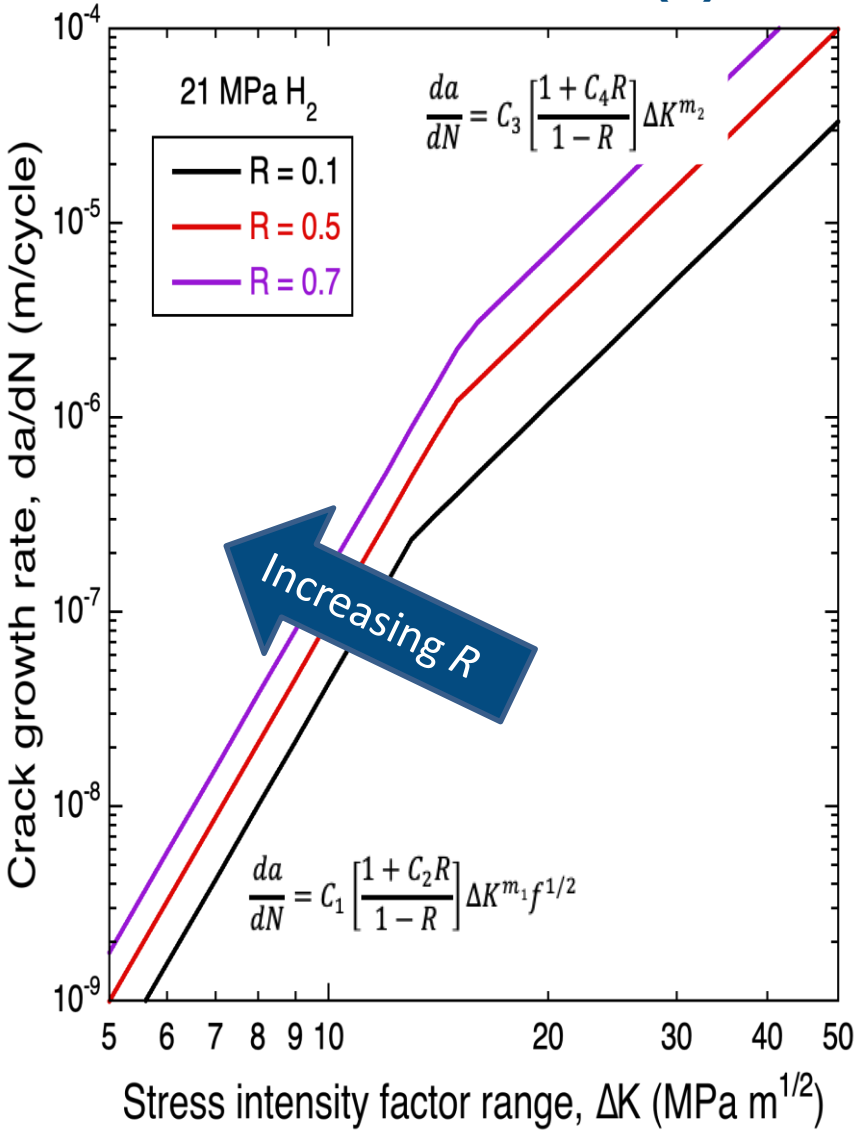
Pressure vessel design

ASME CC2938

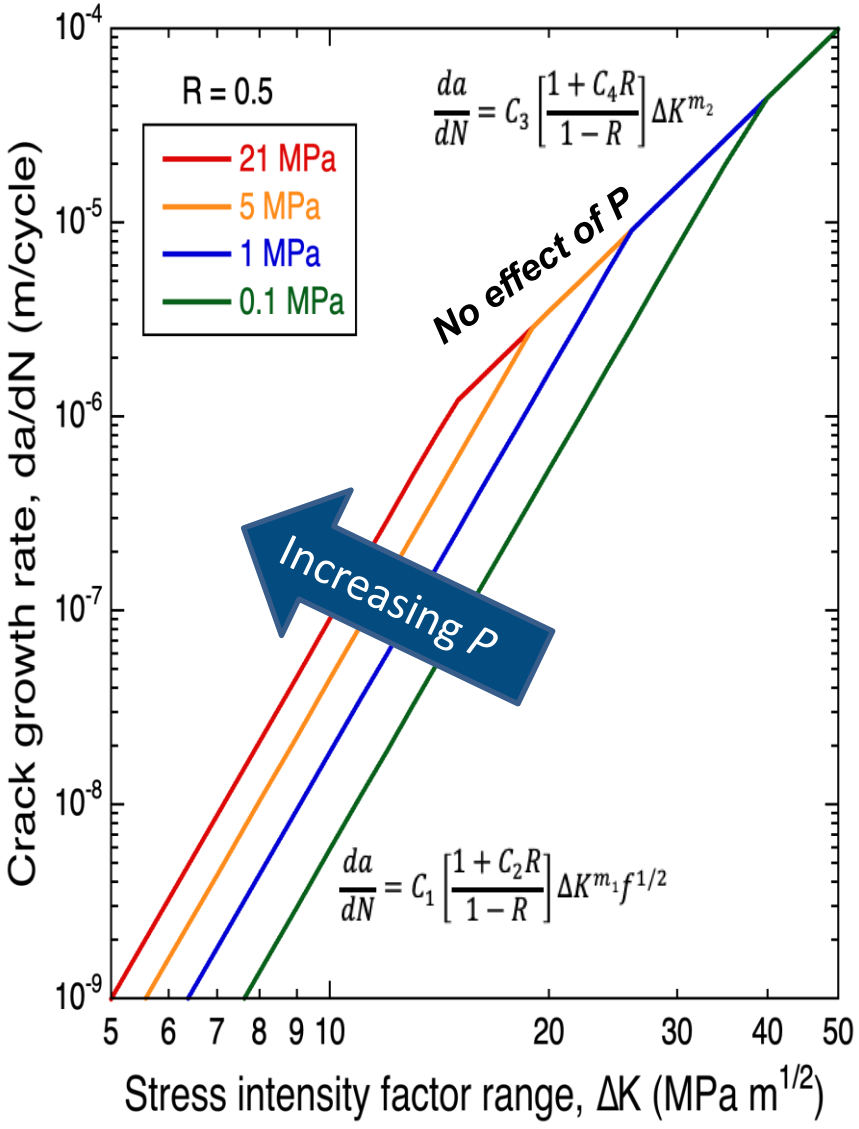
Effect of high-P H2 on Crack growth

Effects of Pressure and P-cycle Range

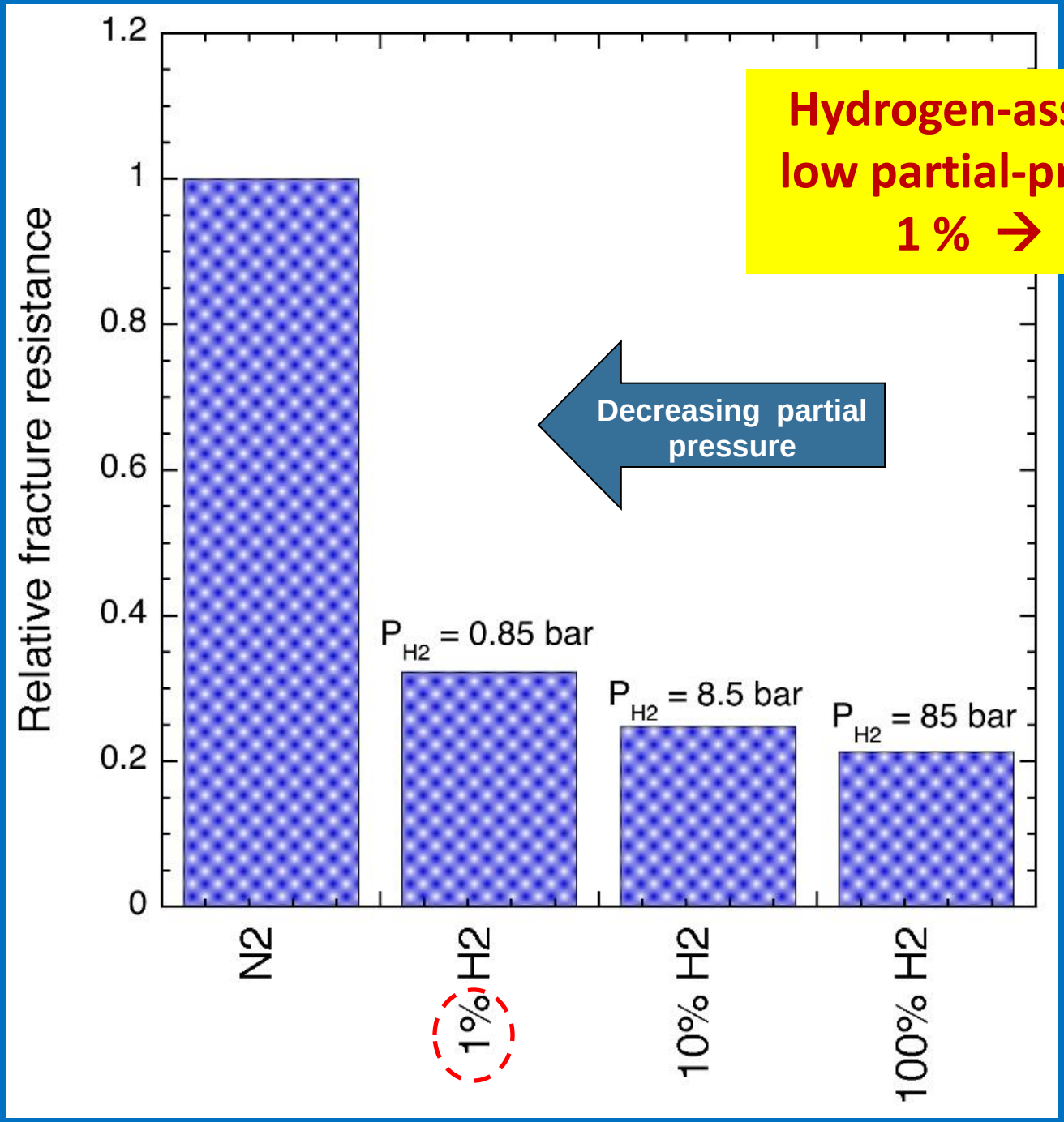
Effect of load ratio (R)



Effect of pressure (P)



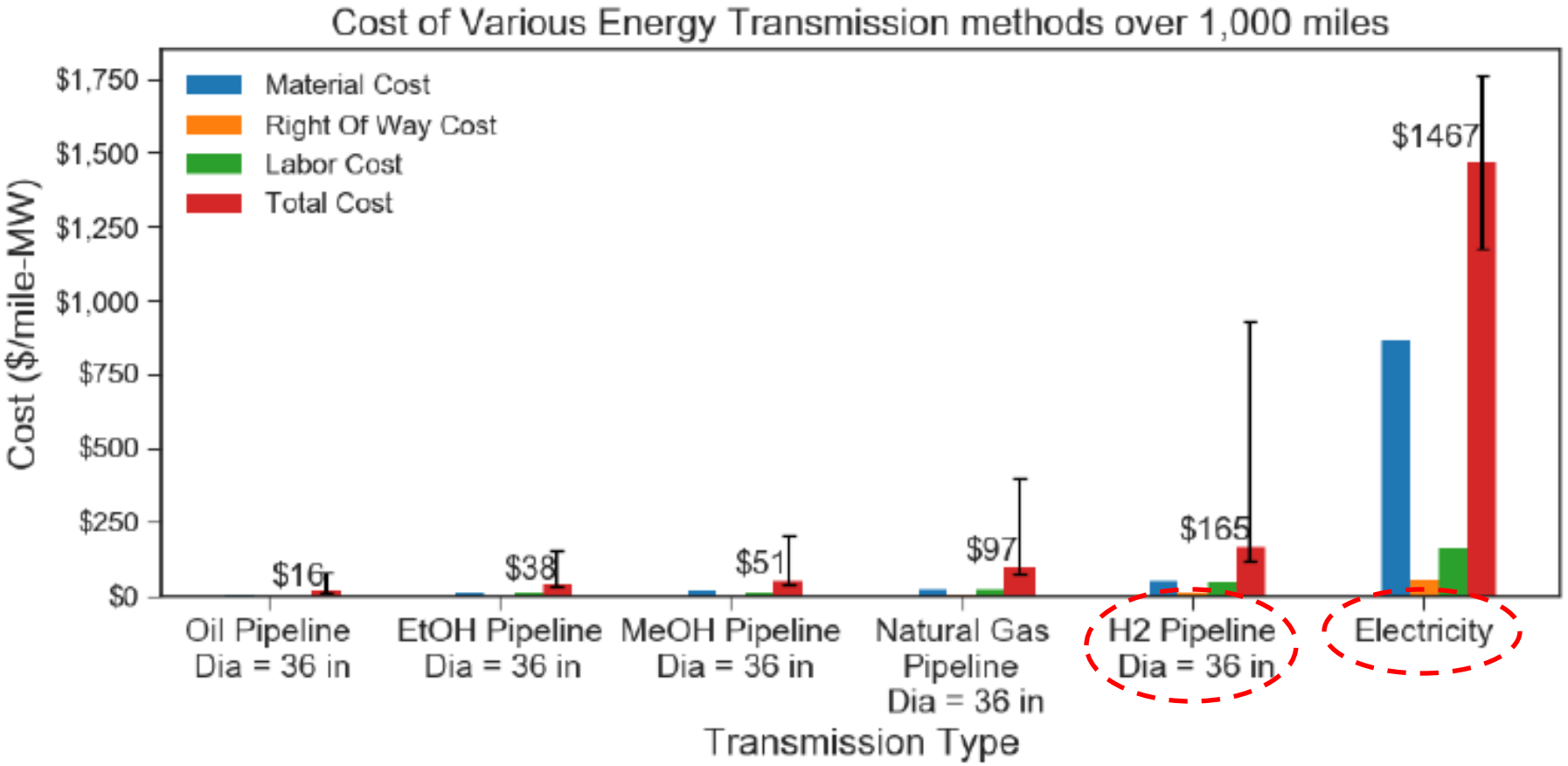
Hydrogen-assisted fracture in low partial-pressure hydrogen
1 % → 100 % GH2



Why pipeline H2 ?

- C-free energy carrier, storage medium, fuel
- Prevent catastrophic Climate Change
- Total de-carb, de-GHG-emission, entire human enterprise
- Transform world's largest industry
- SMR to refineries
- Blending in NatGas
- **Access GHG-emission-free sources:**
  "clean", "green", renewable, CO2-emission-free
- **Low-cost:**
  - **Transmission**
  - **Storage**
  - **Off-Grid H2 production**
- **"Whole system"**: gather, transmission, storage, distribution
  - Slow
  - "Free" storage
  - Underground: safer, low O&M

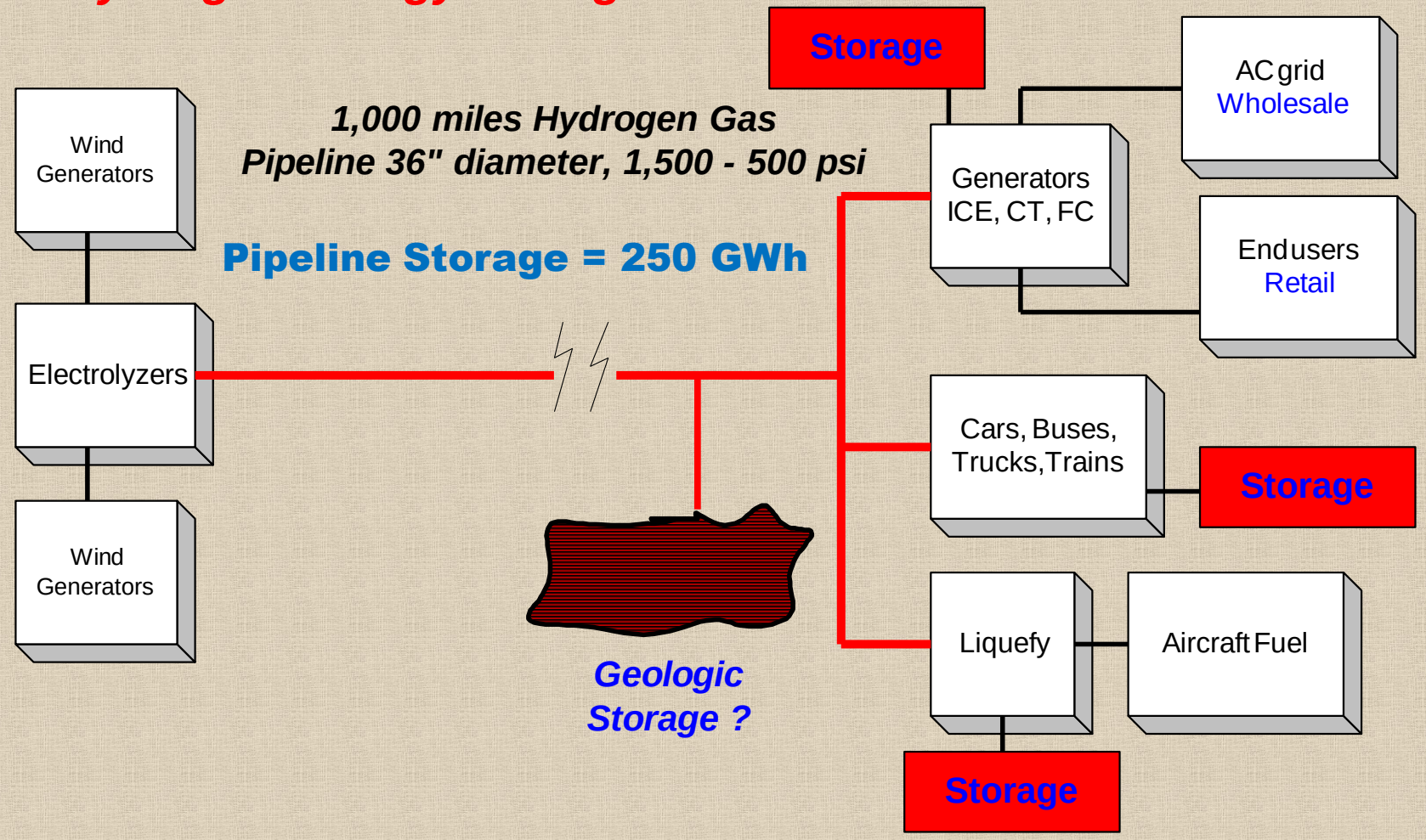
Transmission CAPEX per MW – mile, over 1,000 miles

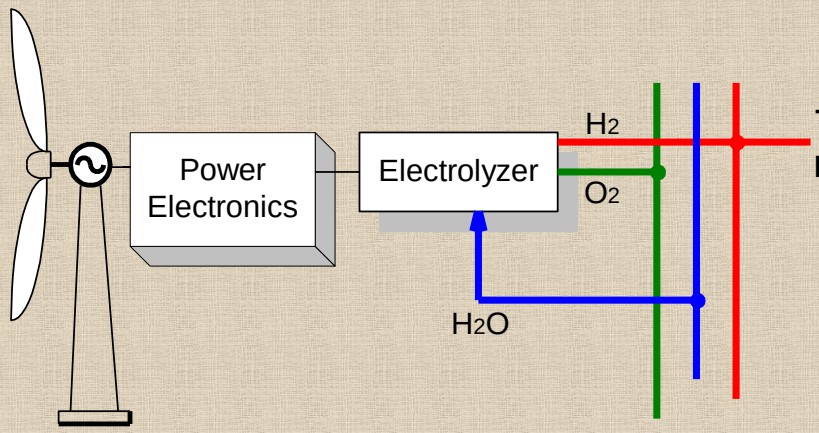


- **Liquid Pipelines :**
  - ► **Least expensive**
  - ► **High energy density, low pumping energy**
  - ► **Ammonia (NH_3) not considered**
- **Electrical :**
  - **> 10 x natural gas**
  - **> 90 x oil**

Off – Grid and / or On – Grid

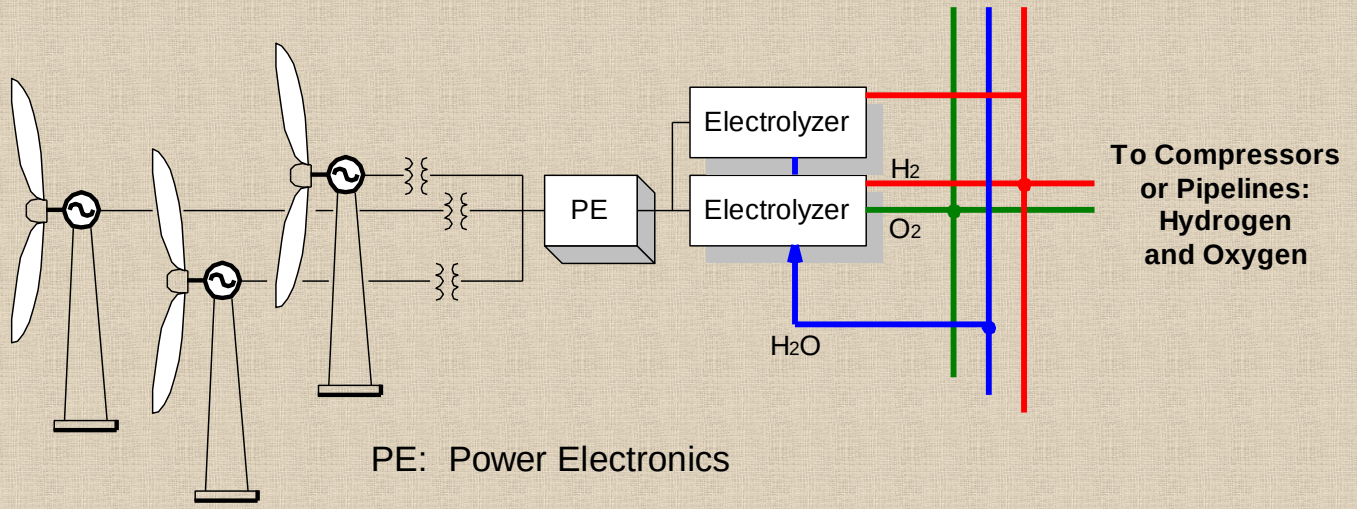
Hydrogen Energy Storage





Renewable-source Electricity Generation

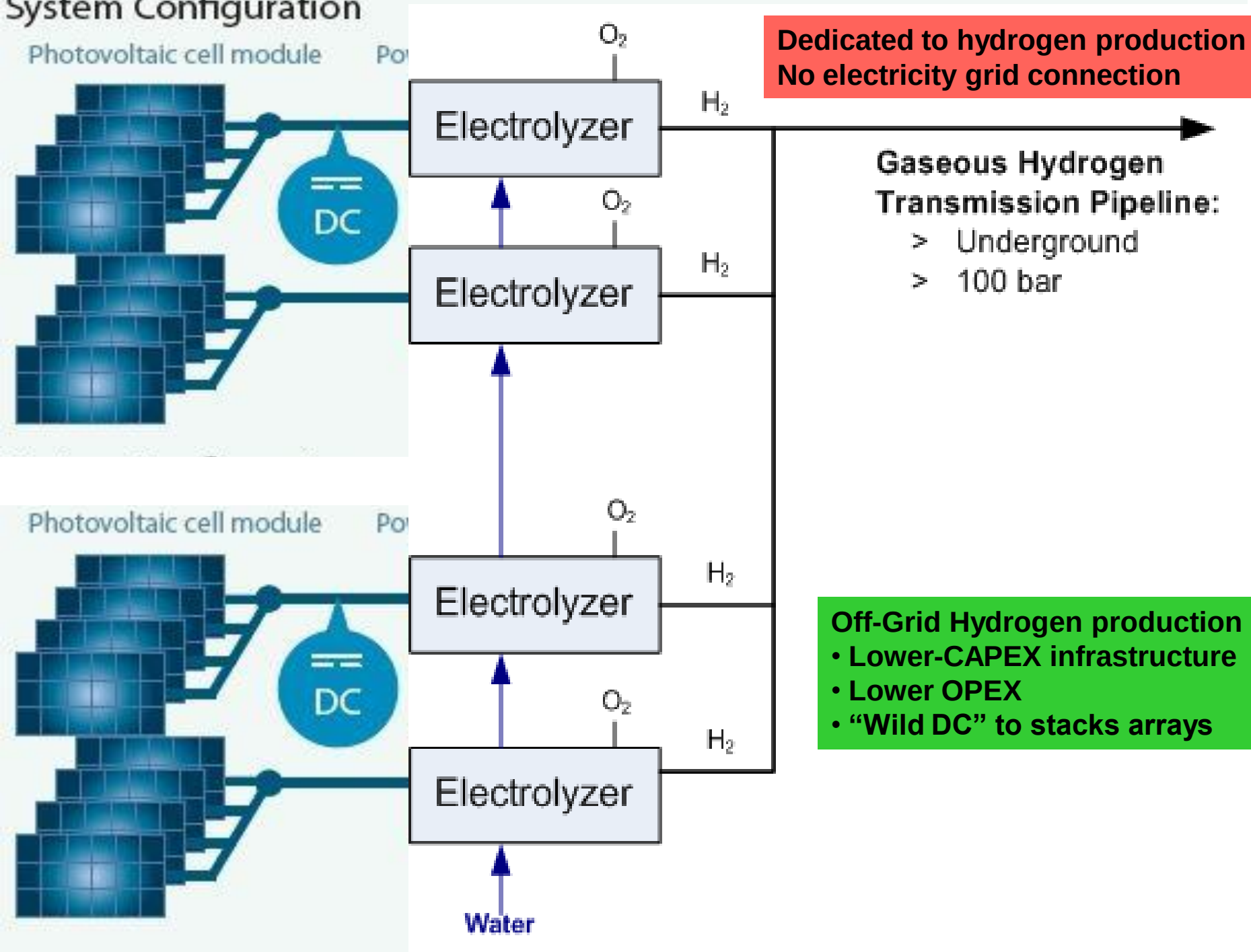
No grid connection



PE: Power Electronics

Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation

System Configuration



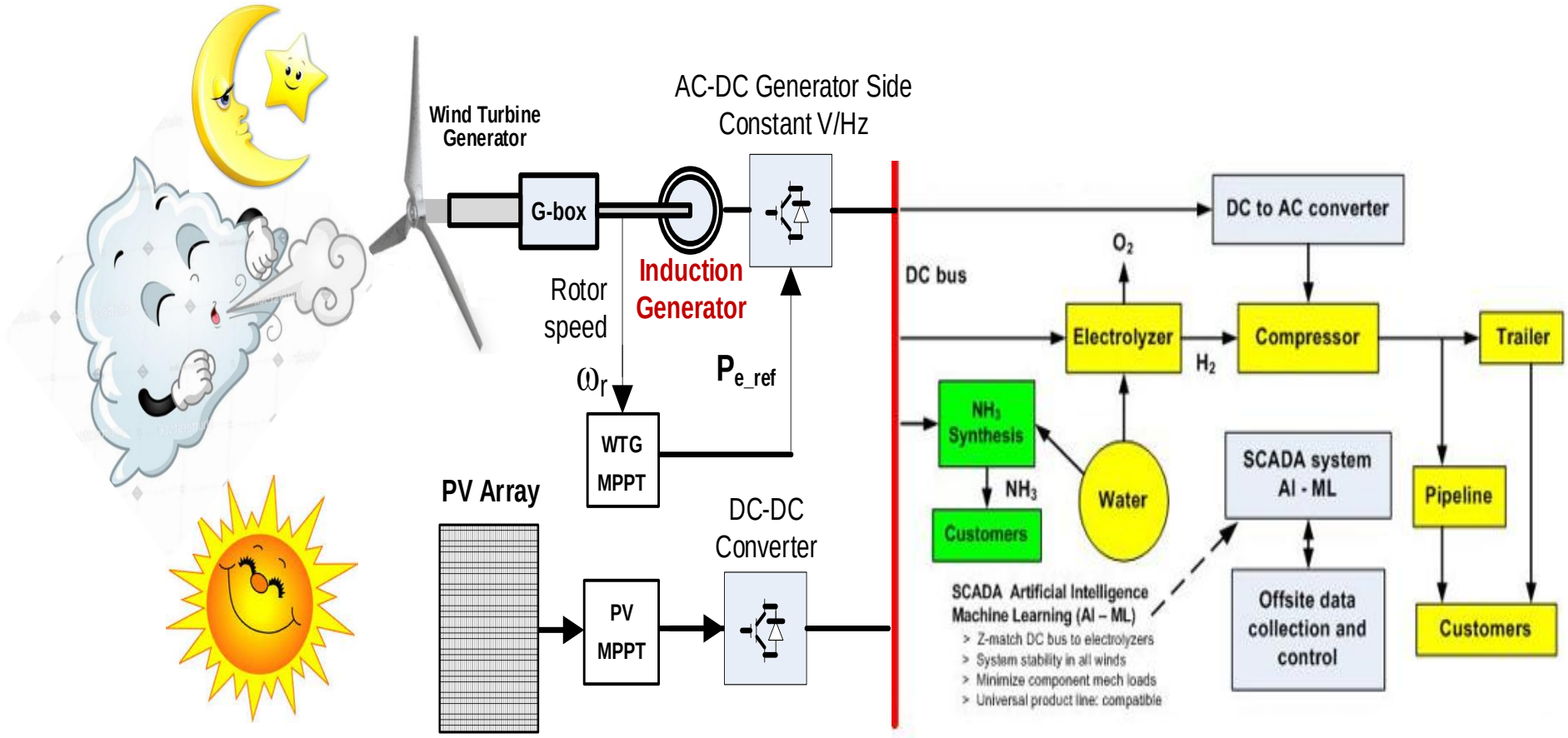
Dedicated to hydrogen production
No electricity grid connection

Gaseous Hydrogen Transmission Pipeline:

- Underground
- 100 bar

Off-Grid Hydrogen production

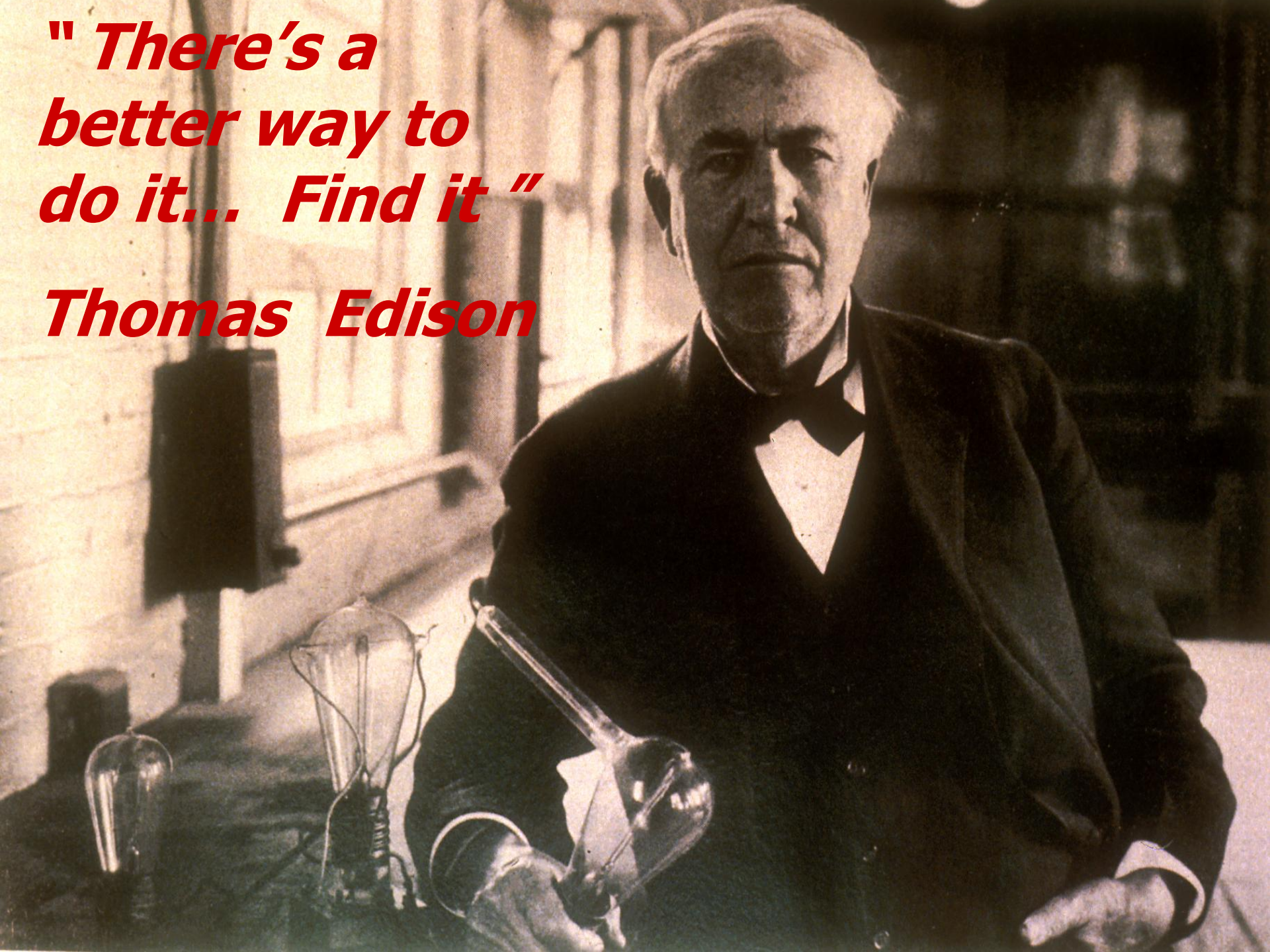
- **Lower-CAPEX infrastructure**
- **Lower OPEX**
- **"Wild DC" to stacks arrays**



Synergistic wind + PV

- **Co-located, co-generation, single plant**
- **No Grid connection; pipeline export**
- **Diurnal, seasonal**
- **Dedicated hydrogen, ammonia production**

Whole systems: Renewables, Electrochemical energy


" There's a better way to do it... Find it "
Thomas Edison

Why pipeline H2 ?

- C-free energy carrier, storage medium, fuel
- Prevent catastrophic Climate Change
- Total de-carb, de-GHG-emission, entire human enterprise
- Transform world's largest industry
- SMR to refineries
- **Blending in NatGas: "free" transmission + storage**
- Access GHG-emission-free sources: "clean", "green"
- Low-cost:
  - Transmission
  - Storage
  - Off-Grid H2 production
- "Whole system": gather, transmission, storage, distribution
  - Slow
  - "Free" storage
  - Underground: safer, low O&M

Pipelining Hydrogen:

Blend with NatGas or high-purity ?
Free “packing" storage ?
Continental scale ?
Salt cavern storage access ?
Repurpose old pipes or new-build ?

Bill Leighty
Director
The Leighty Foundation

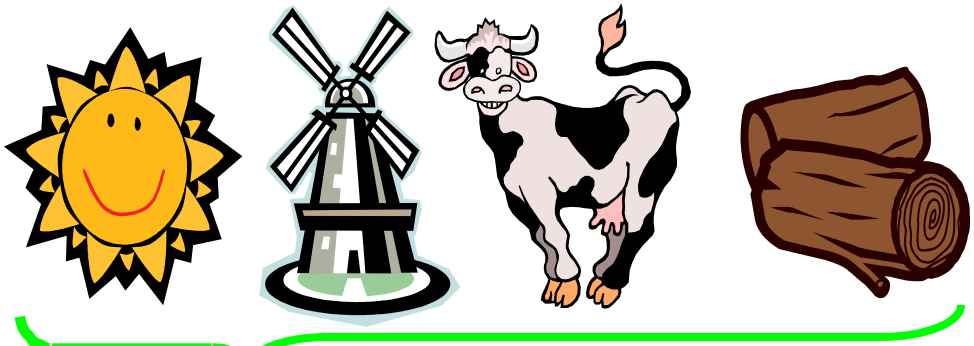
Why Blending ?

< 20% gaseous Hydrogen (GH2) (vol, mass, energy ?)
"Free" transmission
"Free" storage – "packing"
Build big market for "green" H2
Marginally decarbonize gas system → all downstream
But:

- **Cannot recover high-purity**
  - **Cannot "send" to customer**
  - **Costly separation → "five nines" 99.999 %**
- **Utility charges**
- **Gov't regulations**
- **Pipeline danger: HE, HCC**
- **Short-term strategy ?**
- **Need "RPS" for gas utility, as electric**

First: Power-To-Gas (PTG), Wind to Hydrogen, "Blending" in NatGas pipeline
E.ON, Uniper, Falkenhagen, DE 2020

2006: The NATURALHY approach: EC, R+D



" Power – to – Gas "

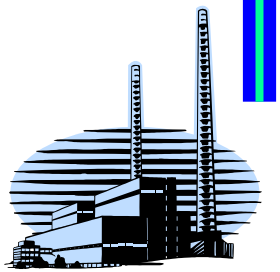
H_2

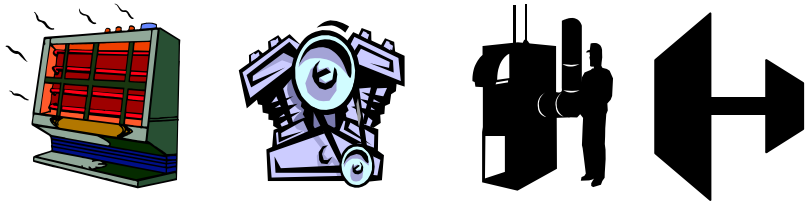
NG

Pure H_2

NATURALHY:

- ***Breaks "chicken-egg" dilemma***
- ***Bridge to sustainable future***

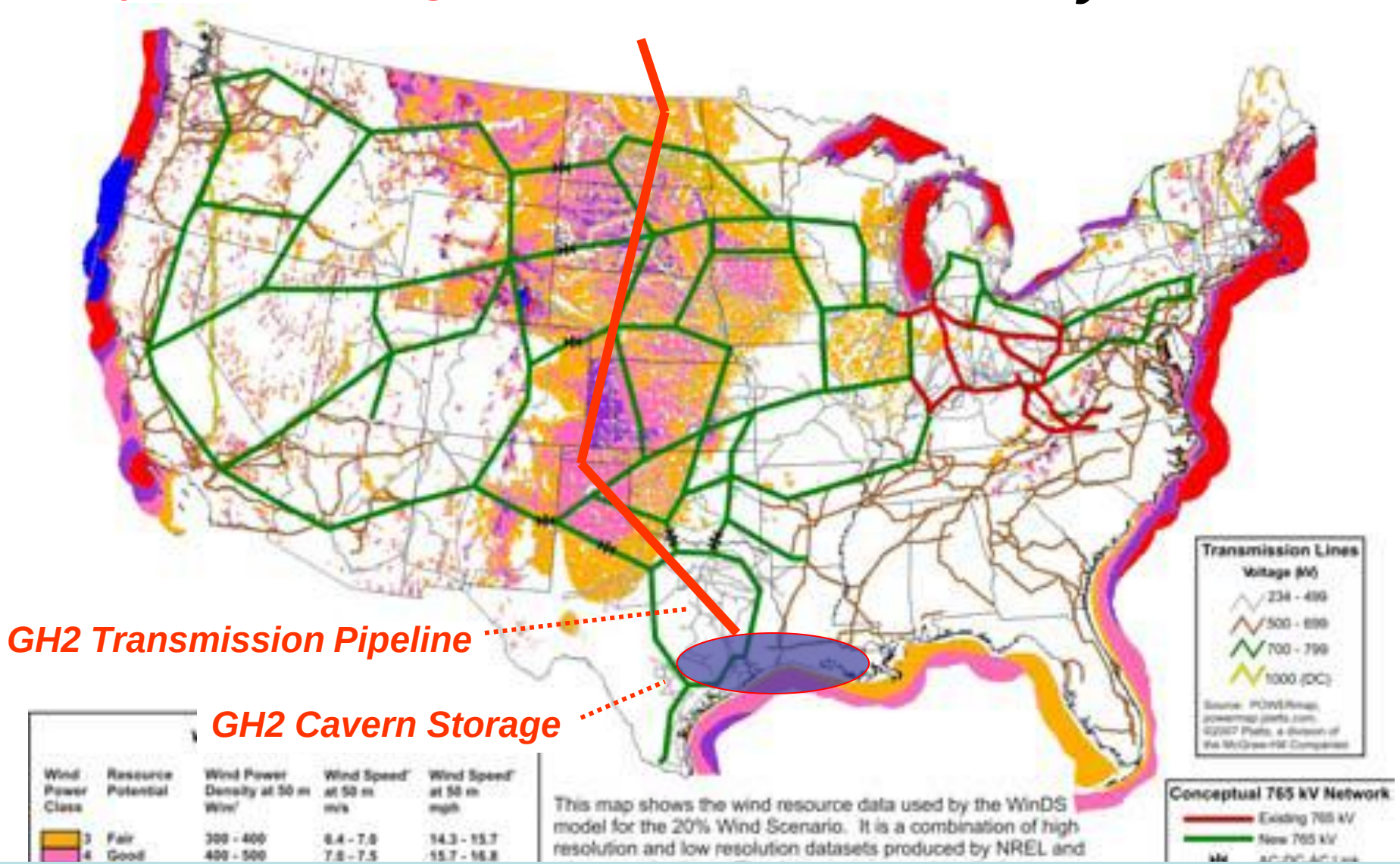




Prepared by
O. Florisson
Gasunie

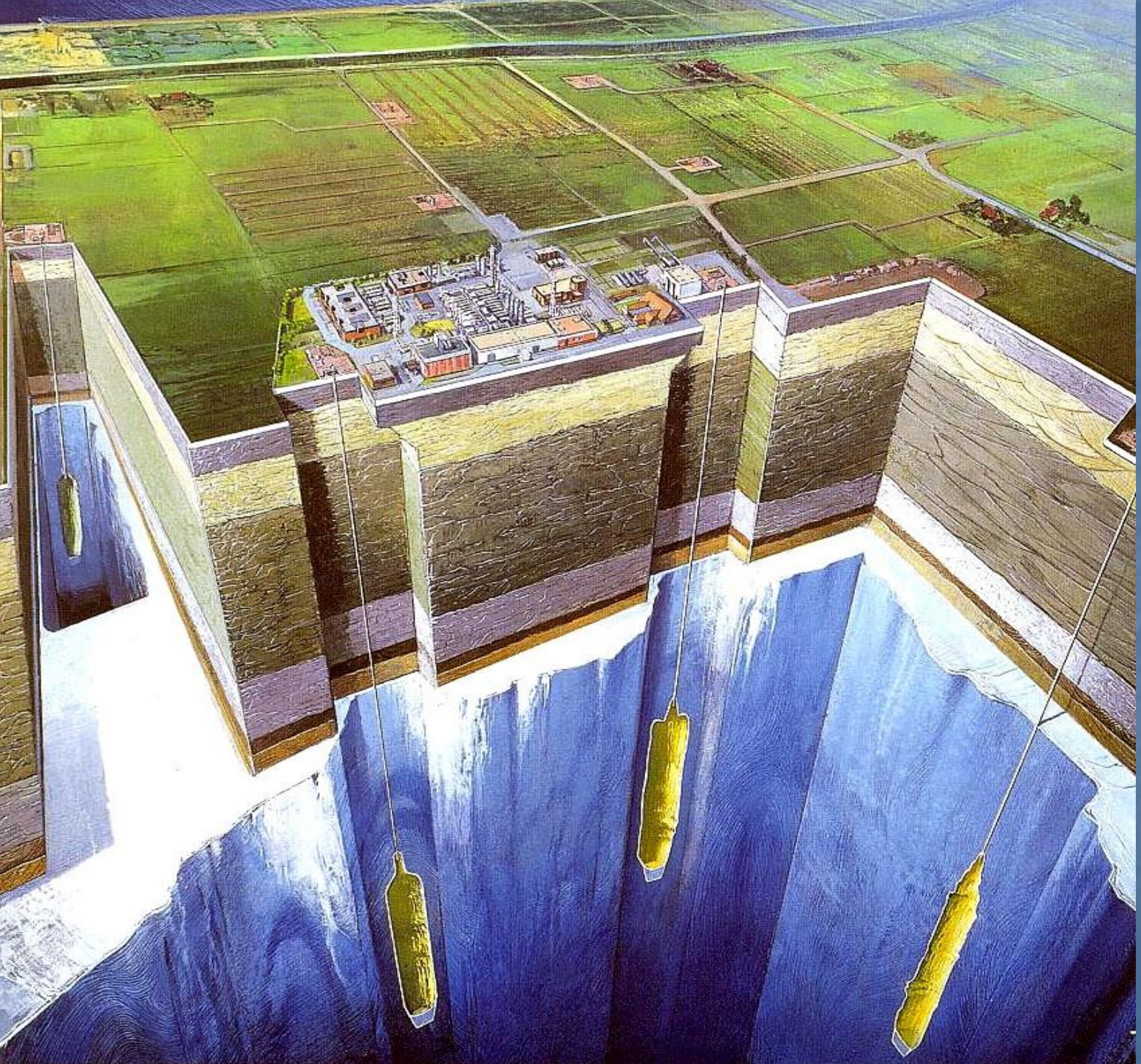
Beyond blending

AWEA 20% Wind by 2030

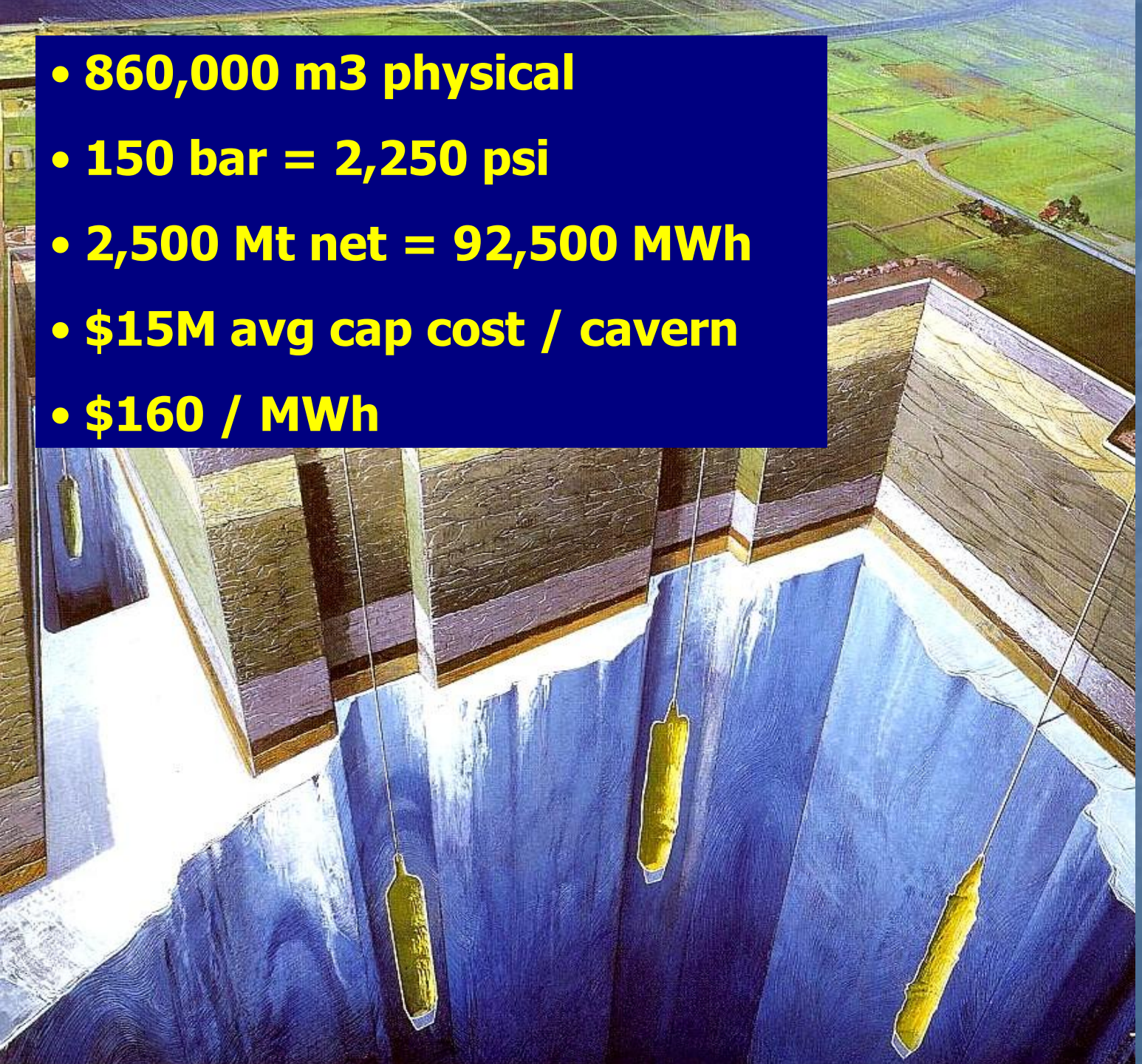


Wind Potential ~= 3,000 GW

12 Great Plains states



Domal Salt Storage Caverns



- 860,000 m3 physical
- 150 bar = 2,250 psi
- 2,500 Mt net = 92,500 MWh
- $15M avg cap cost / cavern
- $160 / MWh

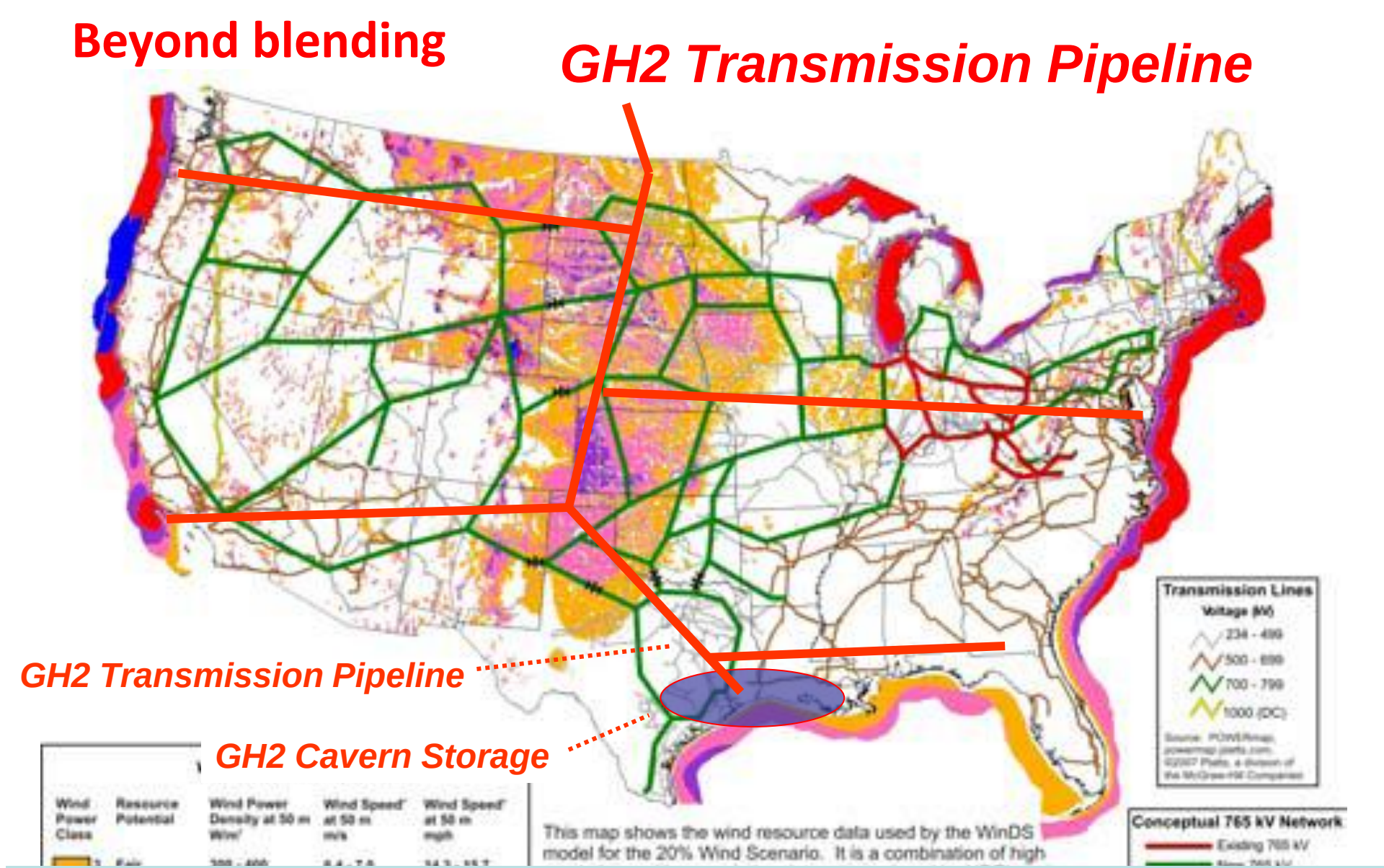
Domal Salt Storage Caverns

Texas

"Clemens Terminal"
Conoco Phillips

Praxair

Beyond blending

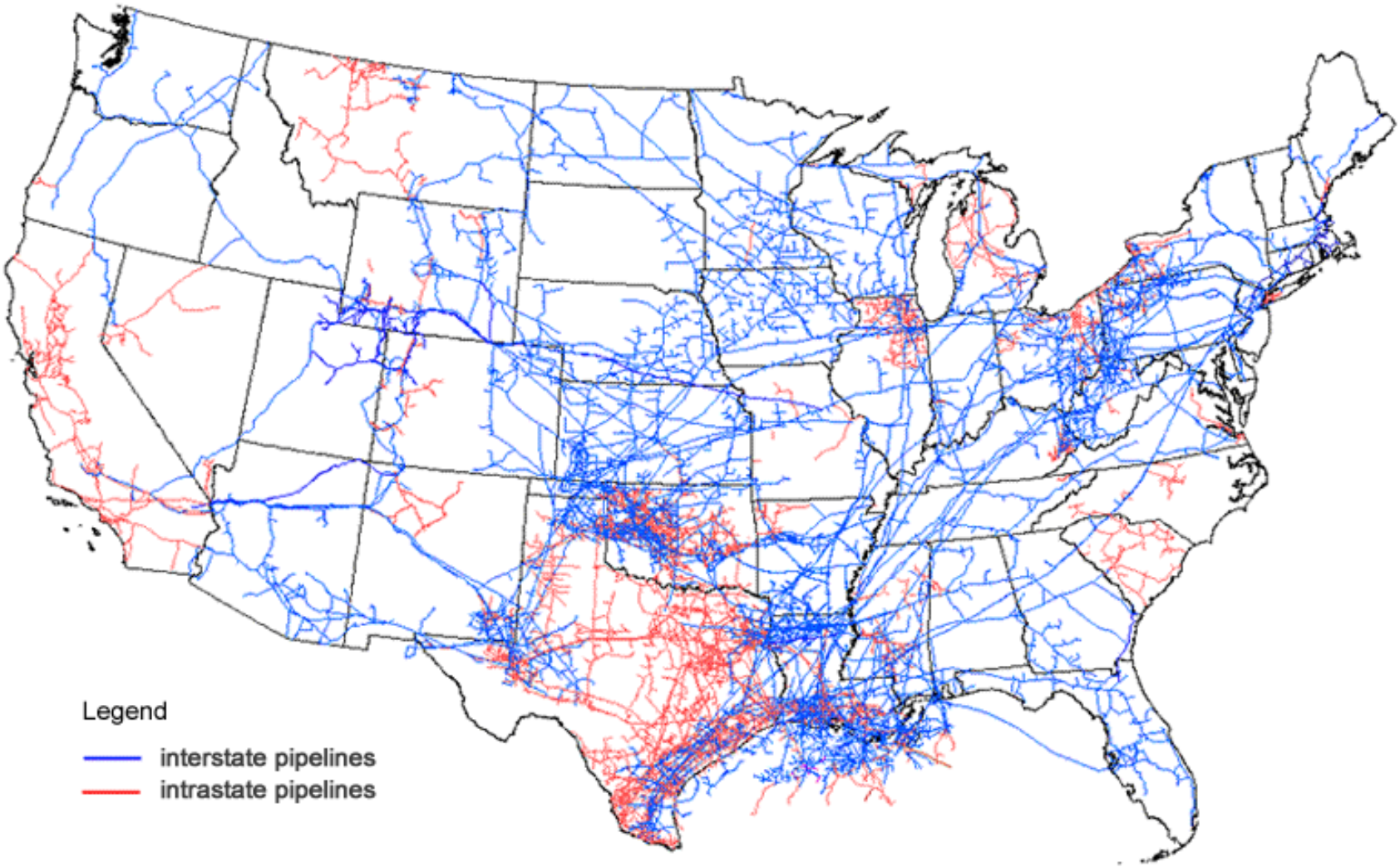


Wind Potential ~ 10,000 GW

12 Great Plains states

NatGas pipelines

Map of U.S. interstate and intrastate natural gas pipelines



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

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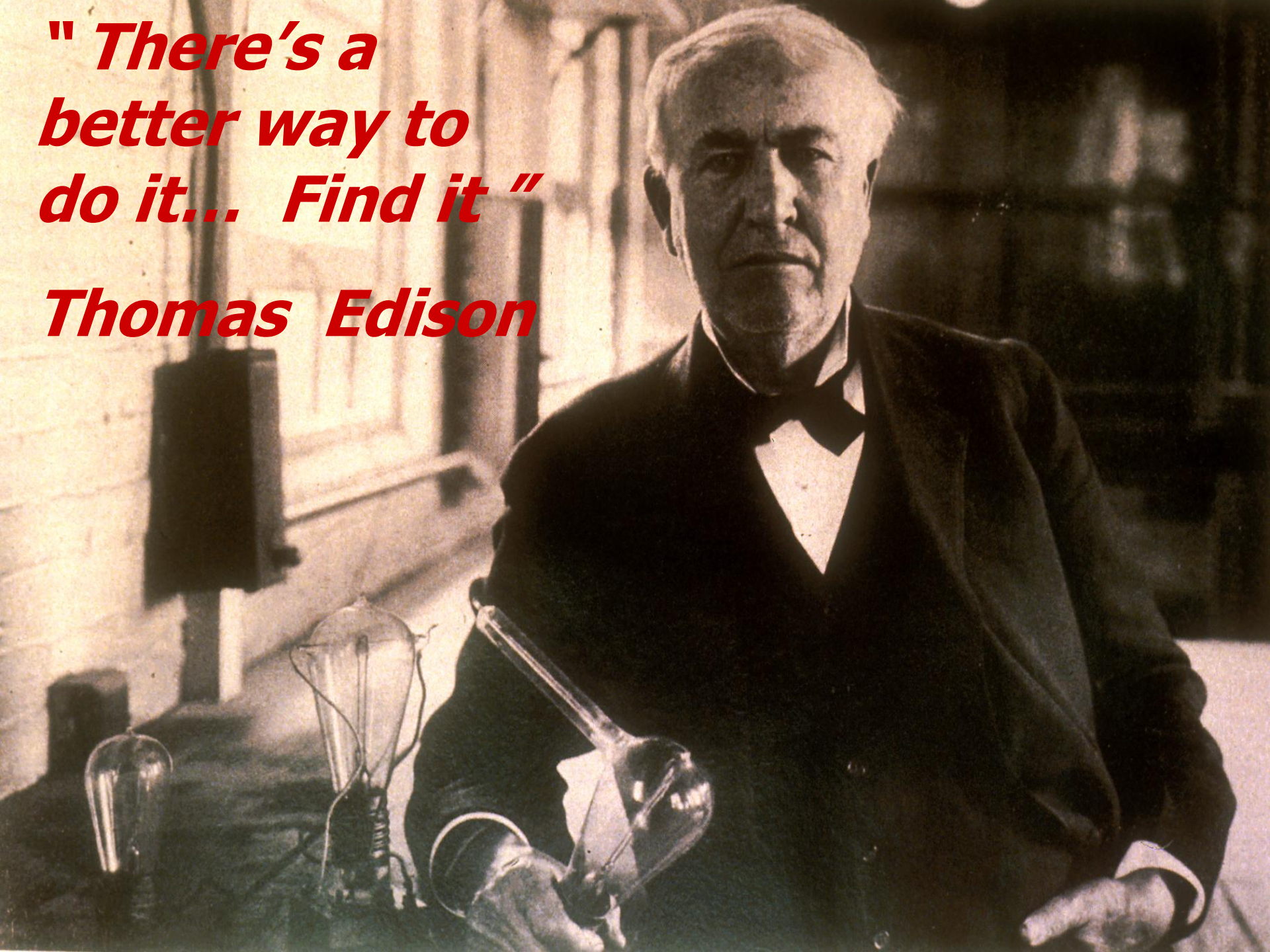
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Thomas Edison

Composite Reinforced Line Pipe (CRLP)

42” diameter
3,400 psi
.75” X70 steel
.75” composite

NCF Industries and TransCanada Pipelines

ASME International Pipeline Conference and Exposition, Calgary, AB, Canada, October 02.

Composite – Reinforced Line Pipe (CRLP)

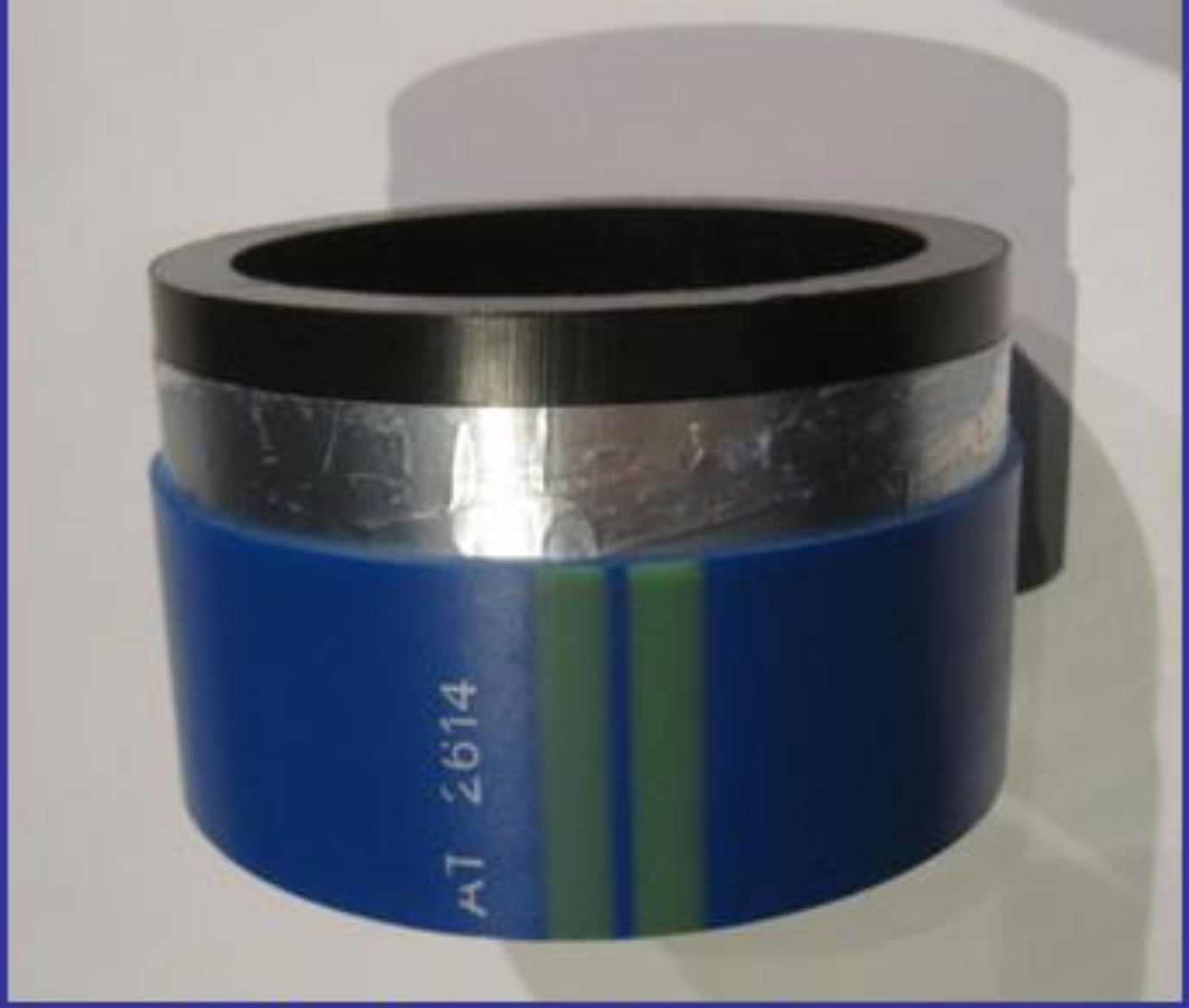
3,400 psi, .75” X70 steel plus .75” composite

NCF Industries and TransCanada Pipelines
ASME International Pipeline Conference and Exposition,
Calgary, AB, Canada, October 02.

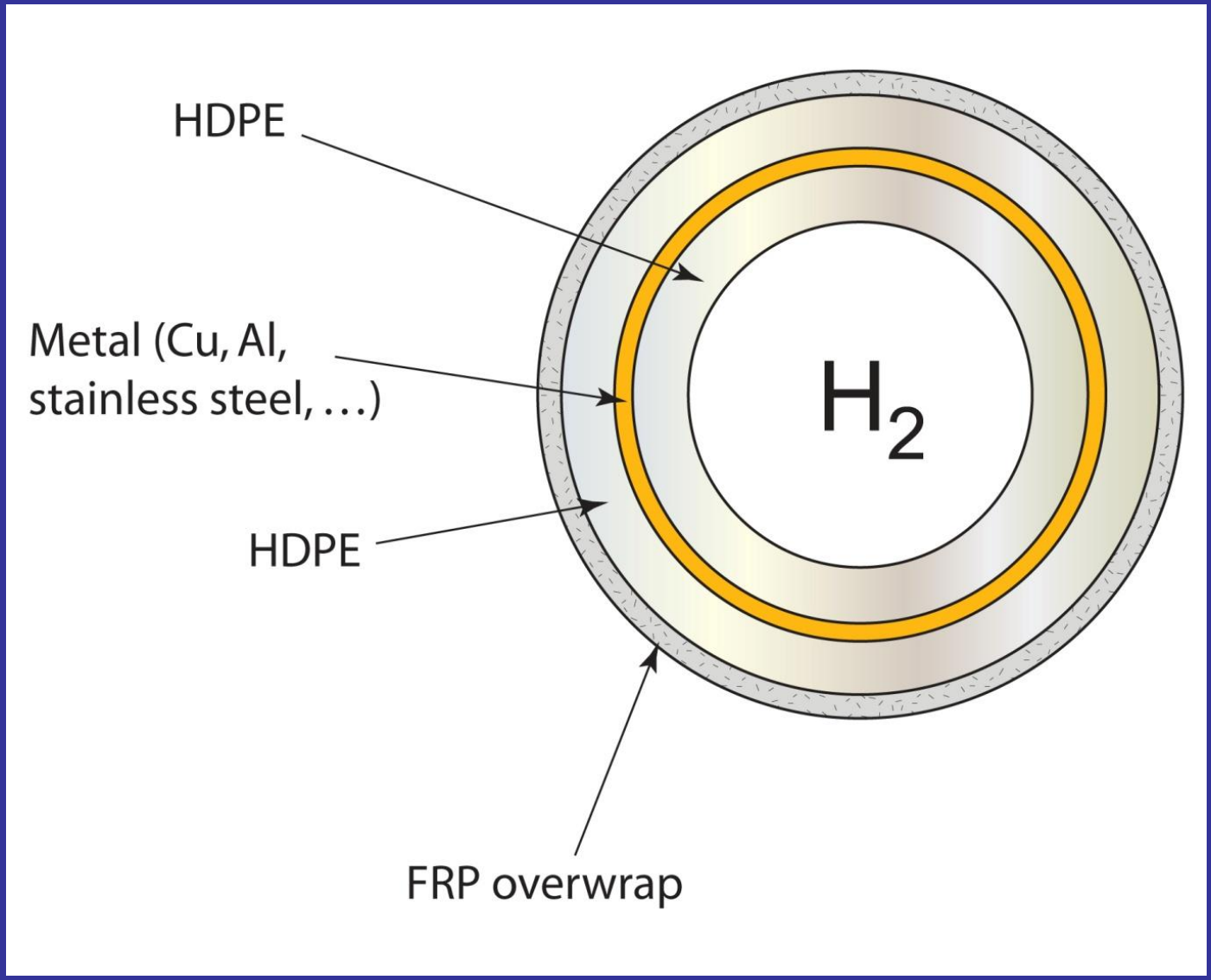
Gaseous Hydrogen (GH2)

36” diam,
800 km
No compression

8,000 MW



Engineering Concept Prototype
Polymer – metal line pipe avoids GH2 permeation and embrittlement



Polymer-metal linepipe avoids hydrogen embrittlement

Composite Pipe System For GH2 Delivery

Portable Assembly Plant

Set up at Job Site

Continuously Produces Smartpipe® in Long Continuous Lengths

Approximately 1 Mile per Day

Smart Pipe Company, Houston
On-site pipeline factory
Continuous process, unlimited length
Hydrogen-compatible: polymer-metal hybrid resists HE, HCC

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  - **Storage → access salt caverns**
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    - **Compression**
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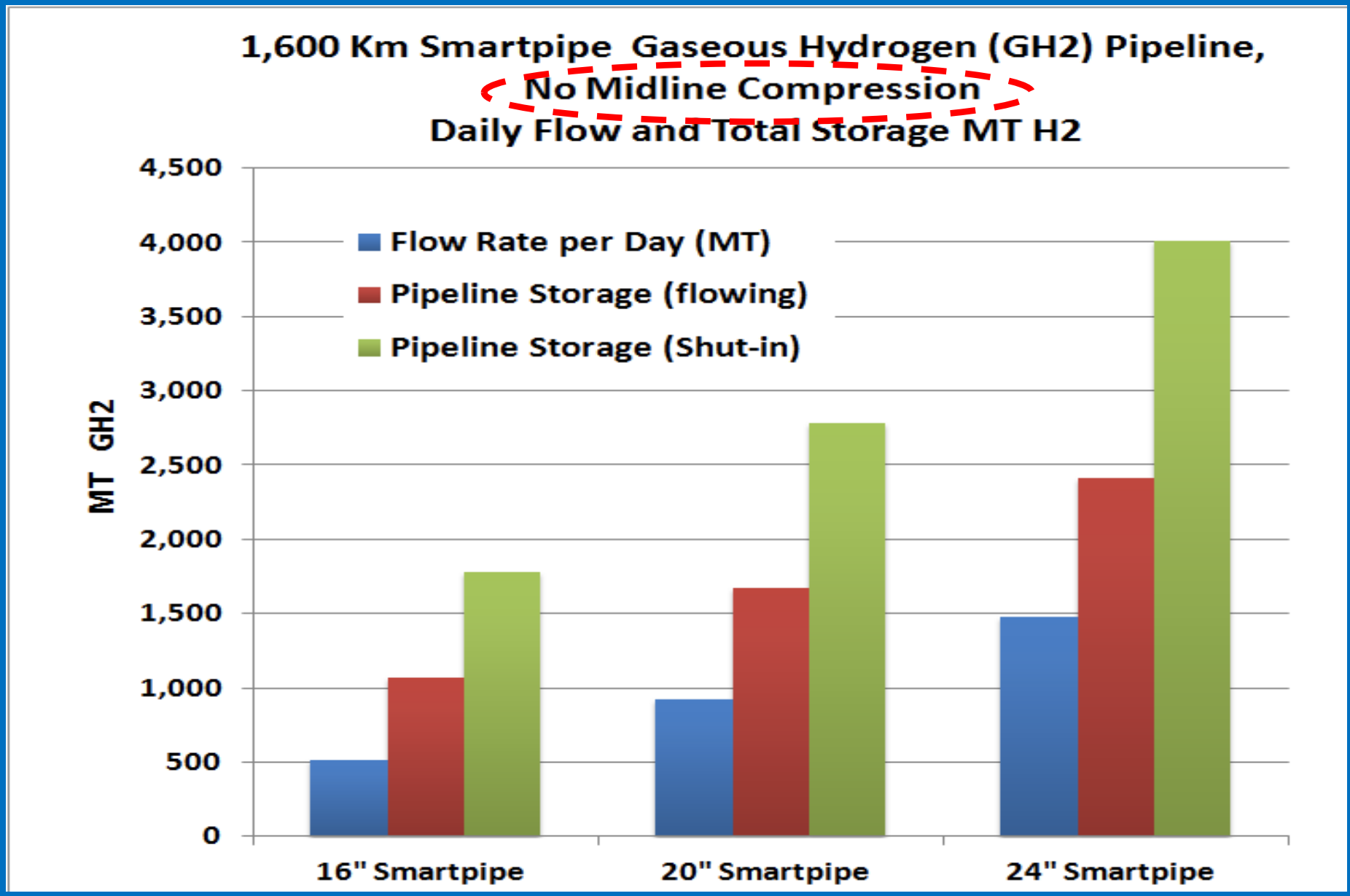
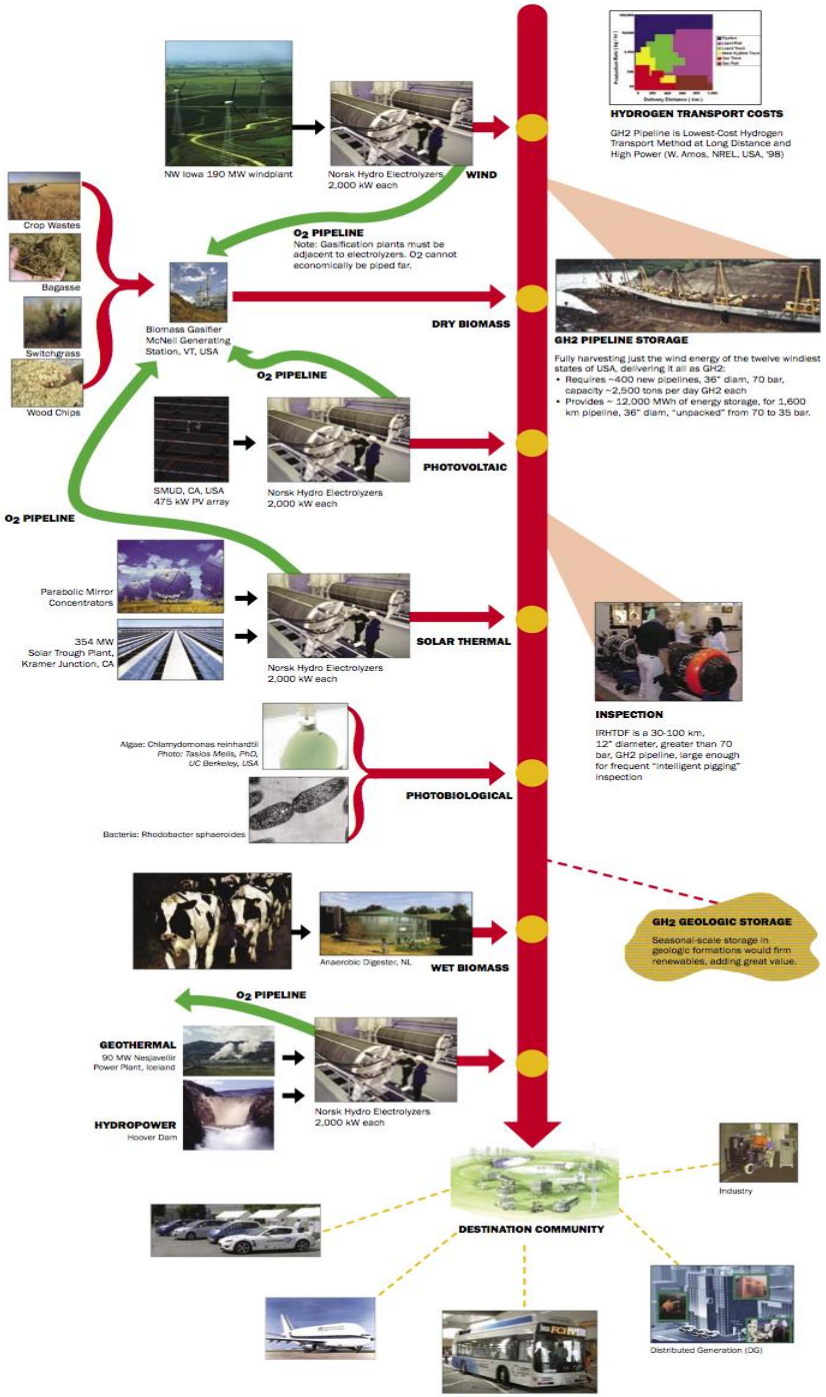


GH2 pipeline flow capacity (MT / day), storage capacity (MT)
MT = metric ton = 1,000 kg



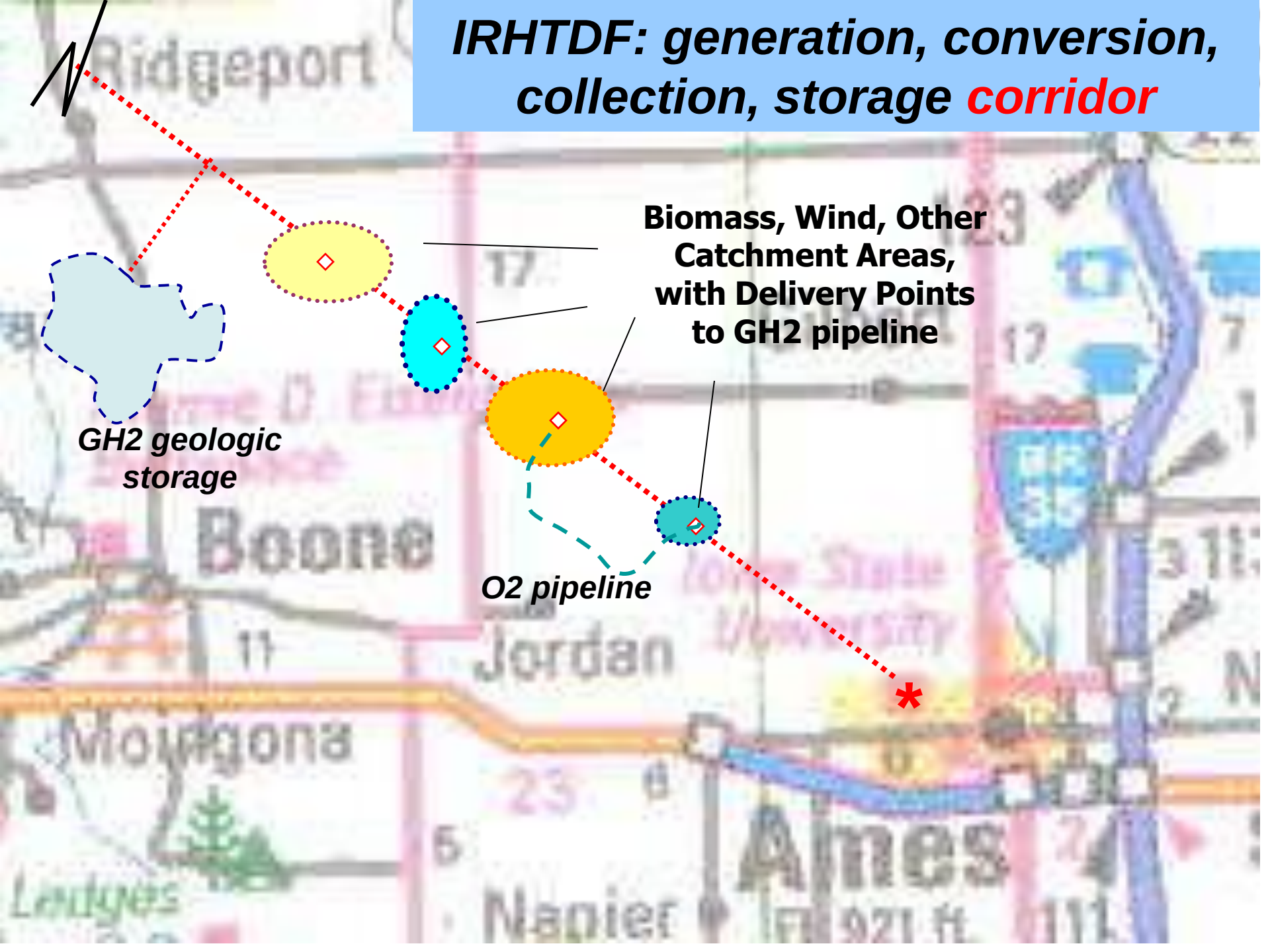
International Renewable Hydrogen Transmission Demonstration Facility

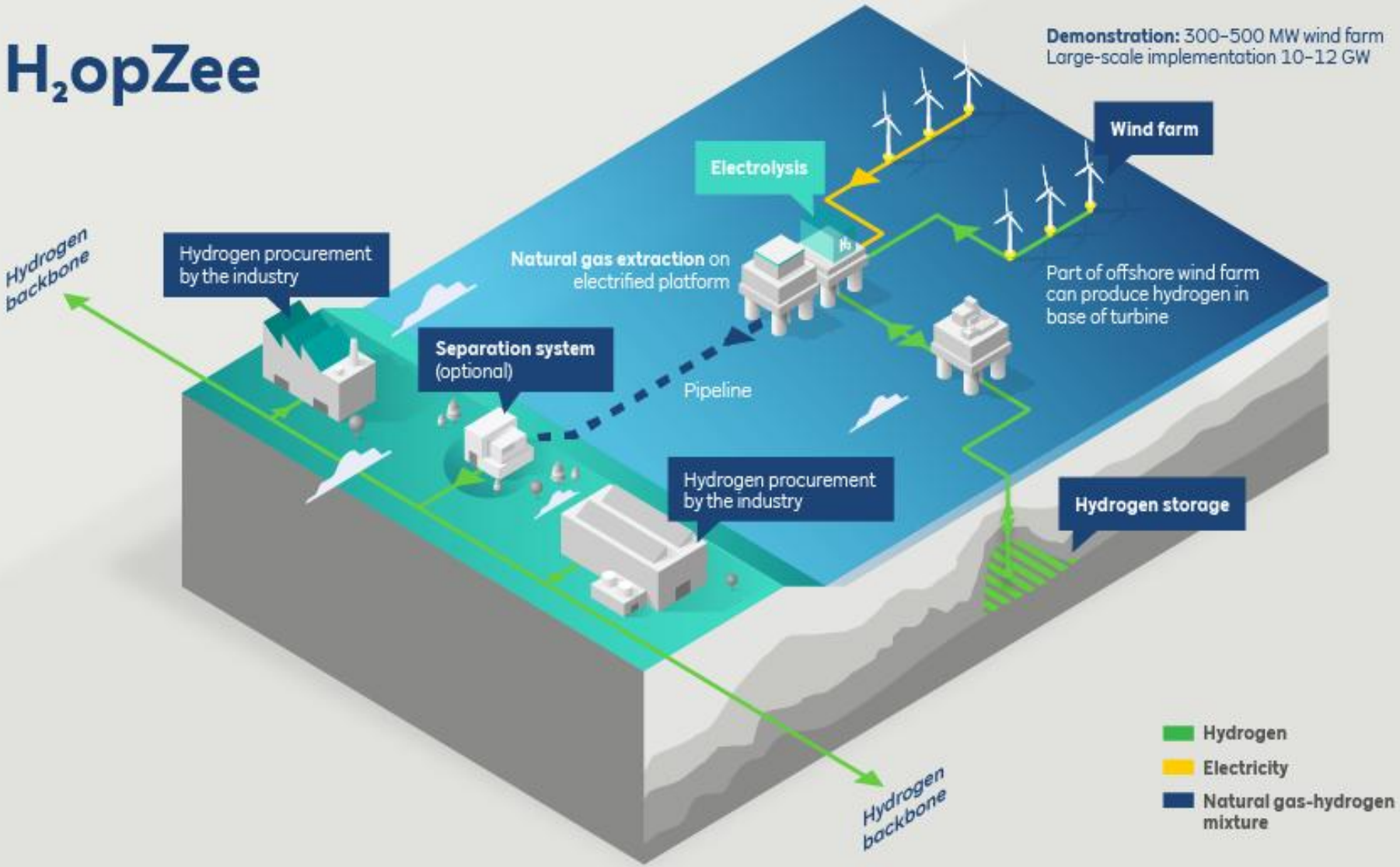
(IRHTDF)

Pilot plant

Global opportunity: IPHE project

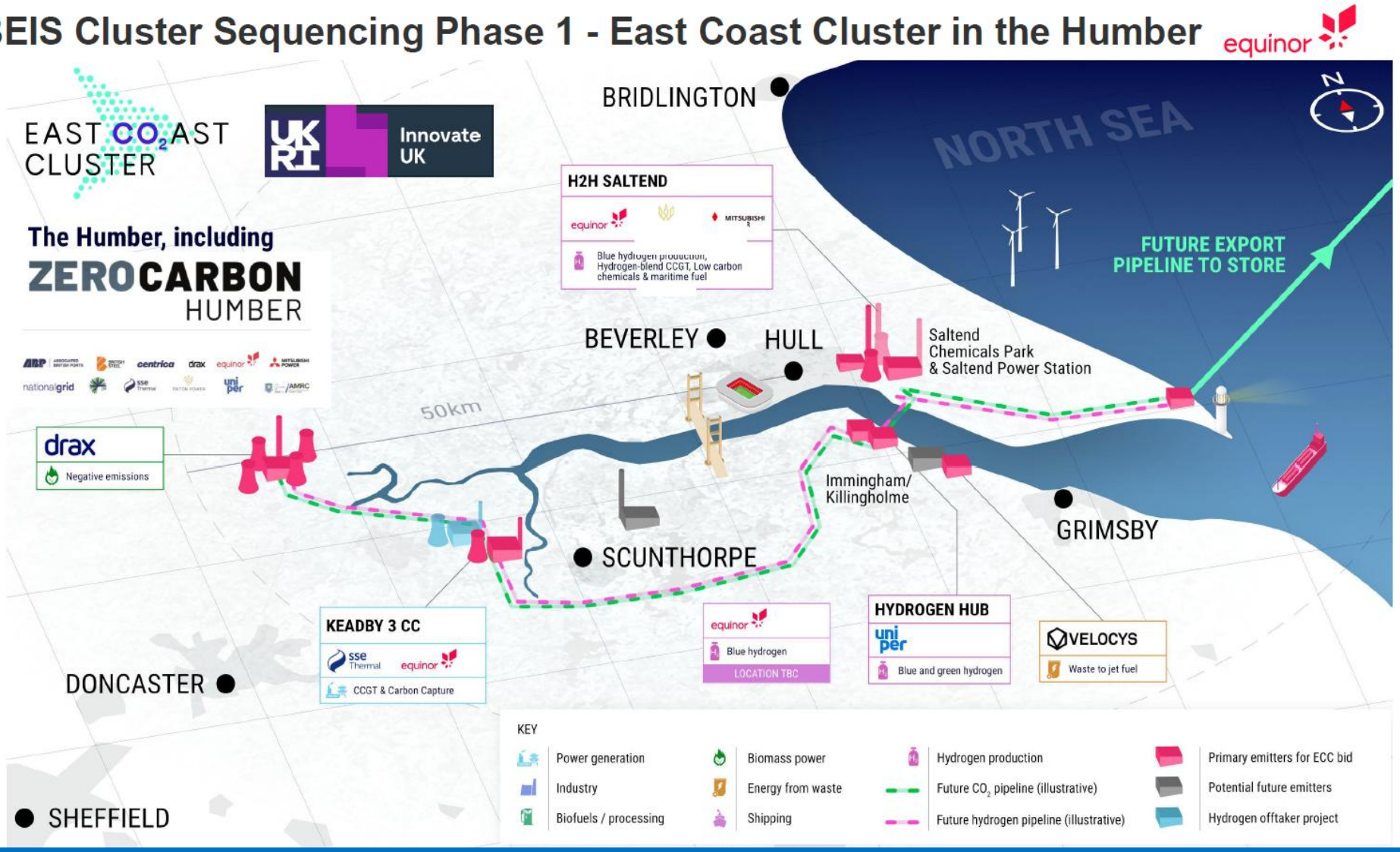
IRHTDF: generation, conversion, collection, storage corridor





Netherlands Hydrogen from Offshore Wind

BEIS Cluster Sequencing Phase 1 - East Coast Cluster in the Humber



North Of England

“Blue” NatGas–source Hydrogen Hub

North Sea CCS

Pipelining Hydrogen:

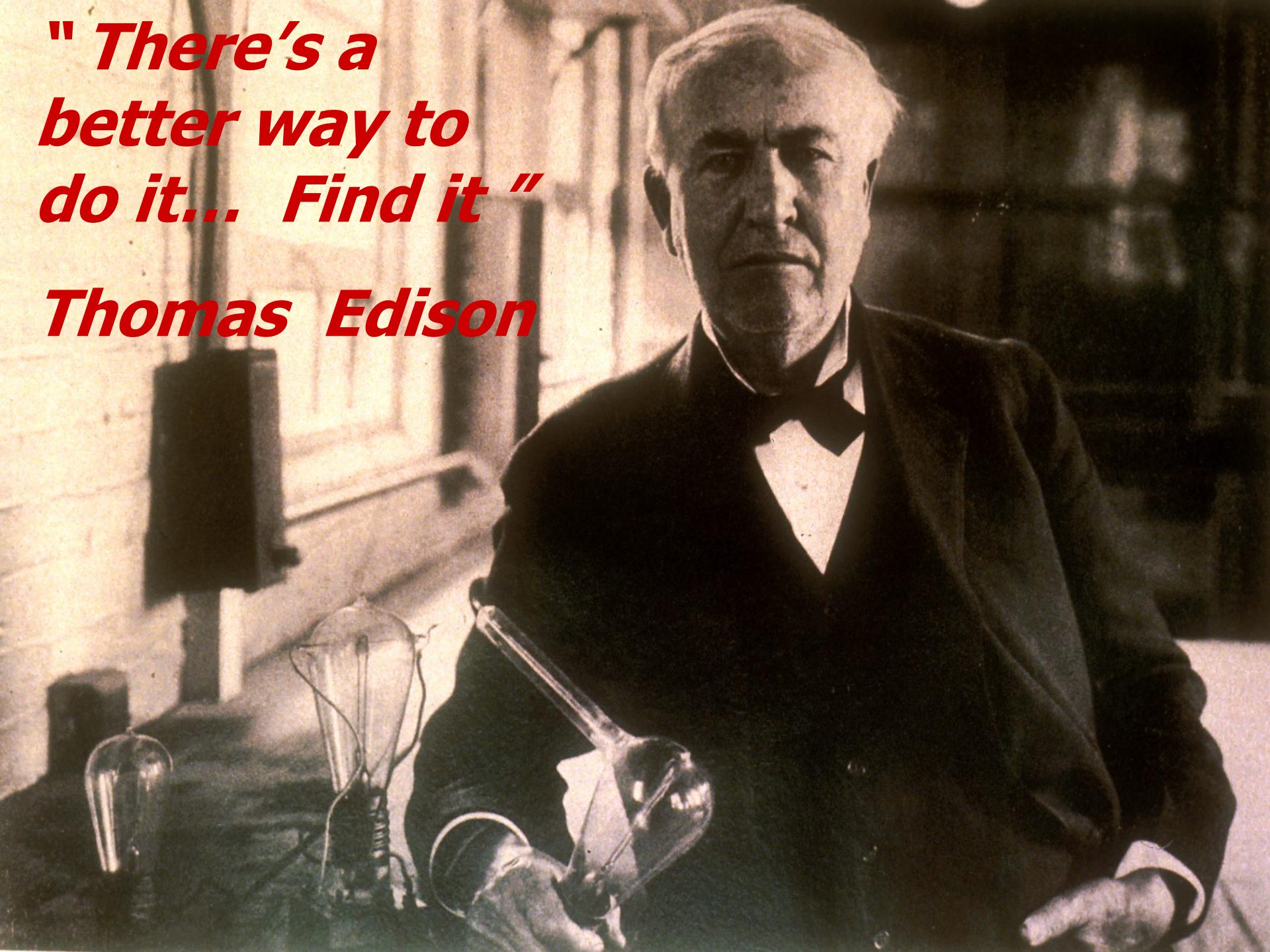
Gas or liquid ? (LH2)
Blend with NatGas or high-purity ?
Repurpose old pipes or new-build ?
Free “packing" storage ?
Continental scale ?
Salt cavern storage access ?

Bill Leighty
Director
The Leighty Foundation

Continental Supergrid – EPRI concept "Energy Pipeline"

~ 2005: Chauncey Starr, Paul Grant, Electric Power Research Institute (EPRI)

NASA LH2 Rocket Fuel Cryo storage and pipeline


" There's a better way to do it... Find it "
Thomas Edison

Pipelining Hydrogen:

Blend with NatGas or high-purity ?
Repurpose old pipes or new-build ?
Free “packing" storage ?
Continental scale ?
Salt cavern storage access ?
GH2 or LH2 or liquid NH3 (ammonia) ?

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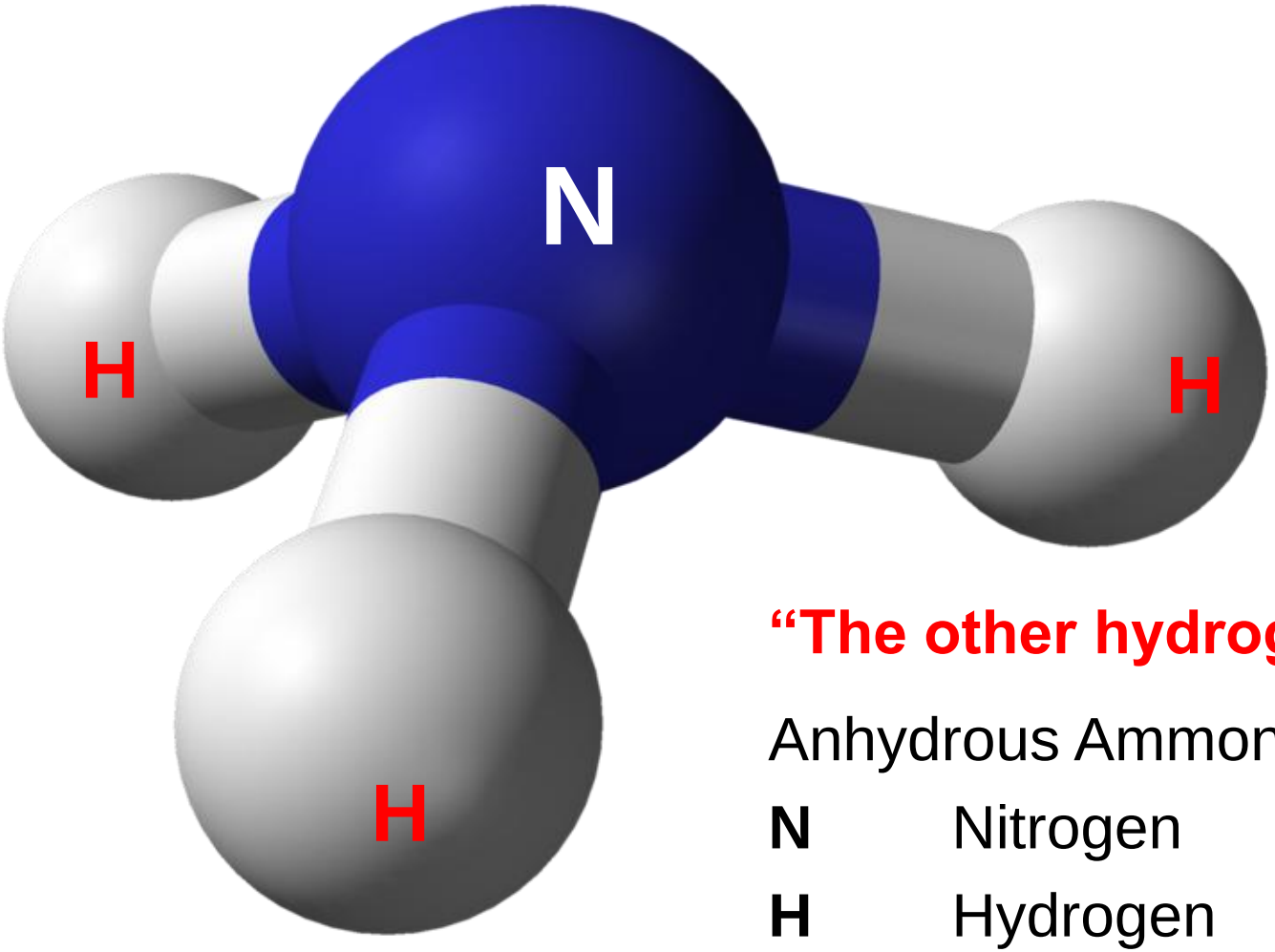


NH_3

“The other hydrogen”

Anhydrous Ammonia **NH_3**

N Nitrogen

H Hydrogen

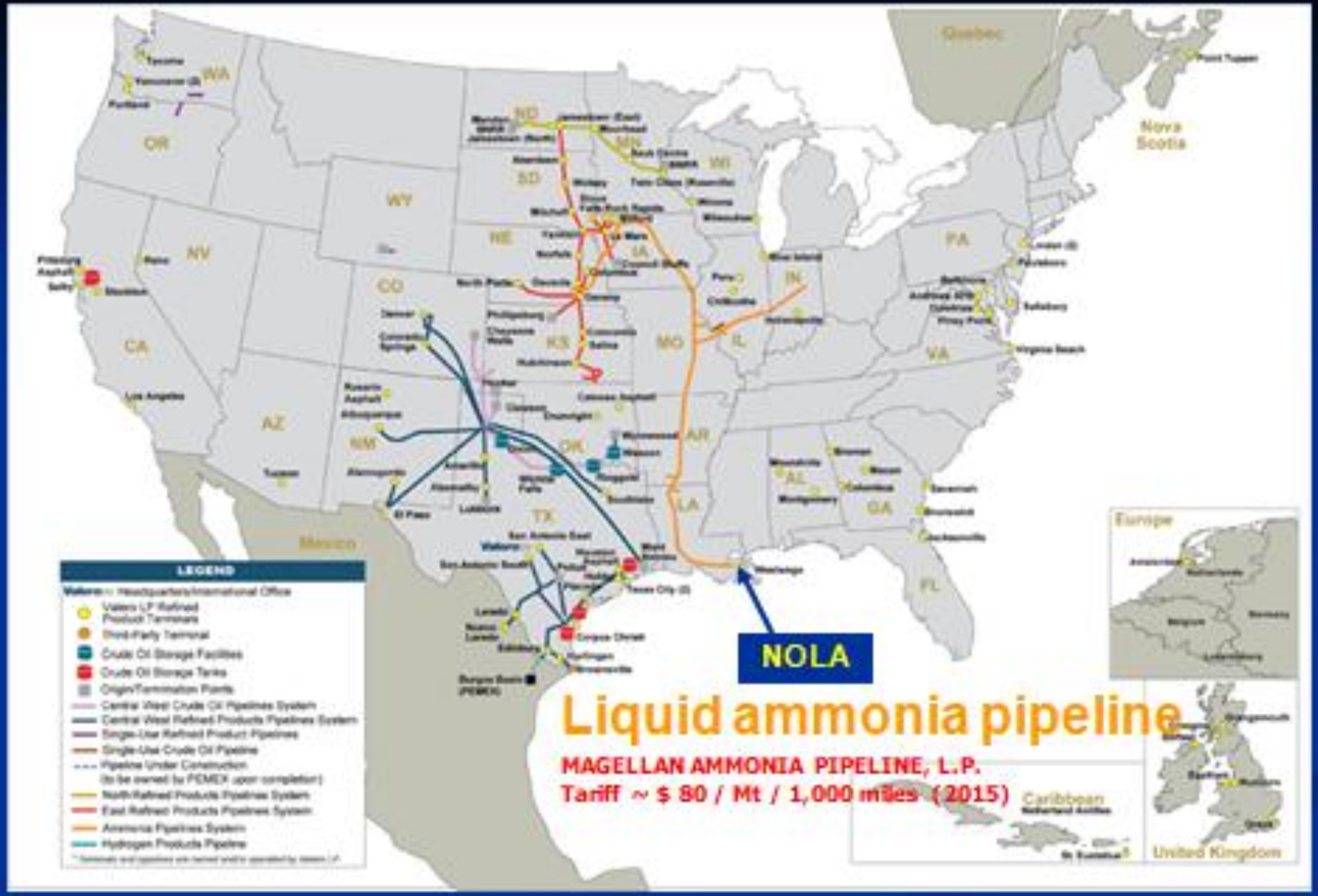
Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”

$NH_3 + O_2 = N_2 + H_2O$

Liquid Hydrogen – LH_2
100 H atoms

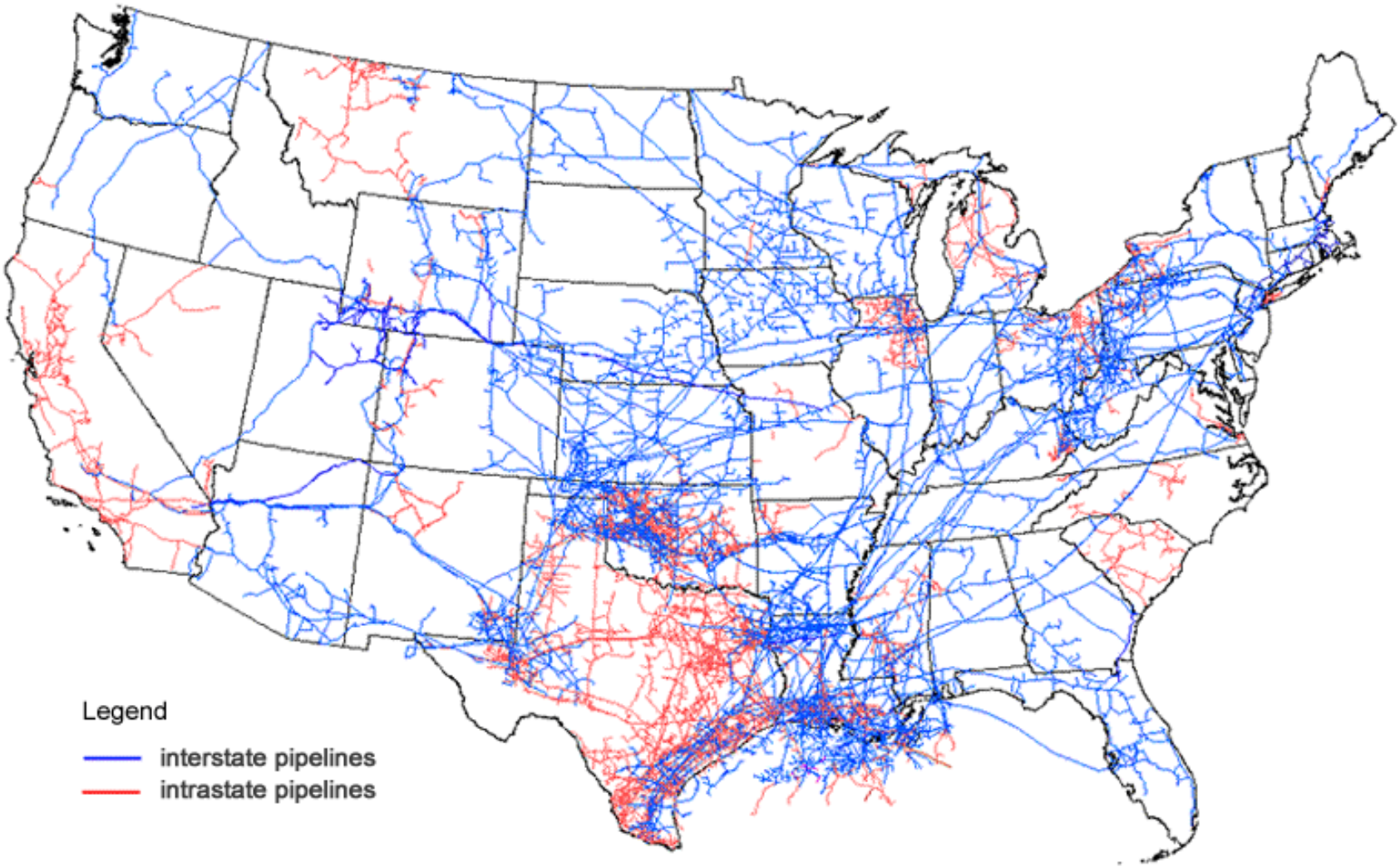
Liquid Anhydrous Ammonia – NH_3
170 H atoms



Valero LP Operations

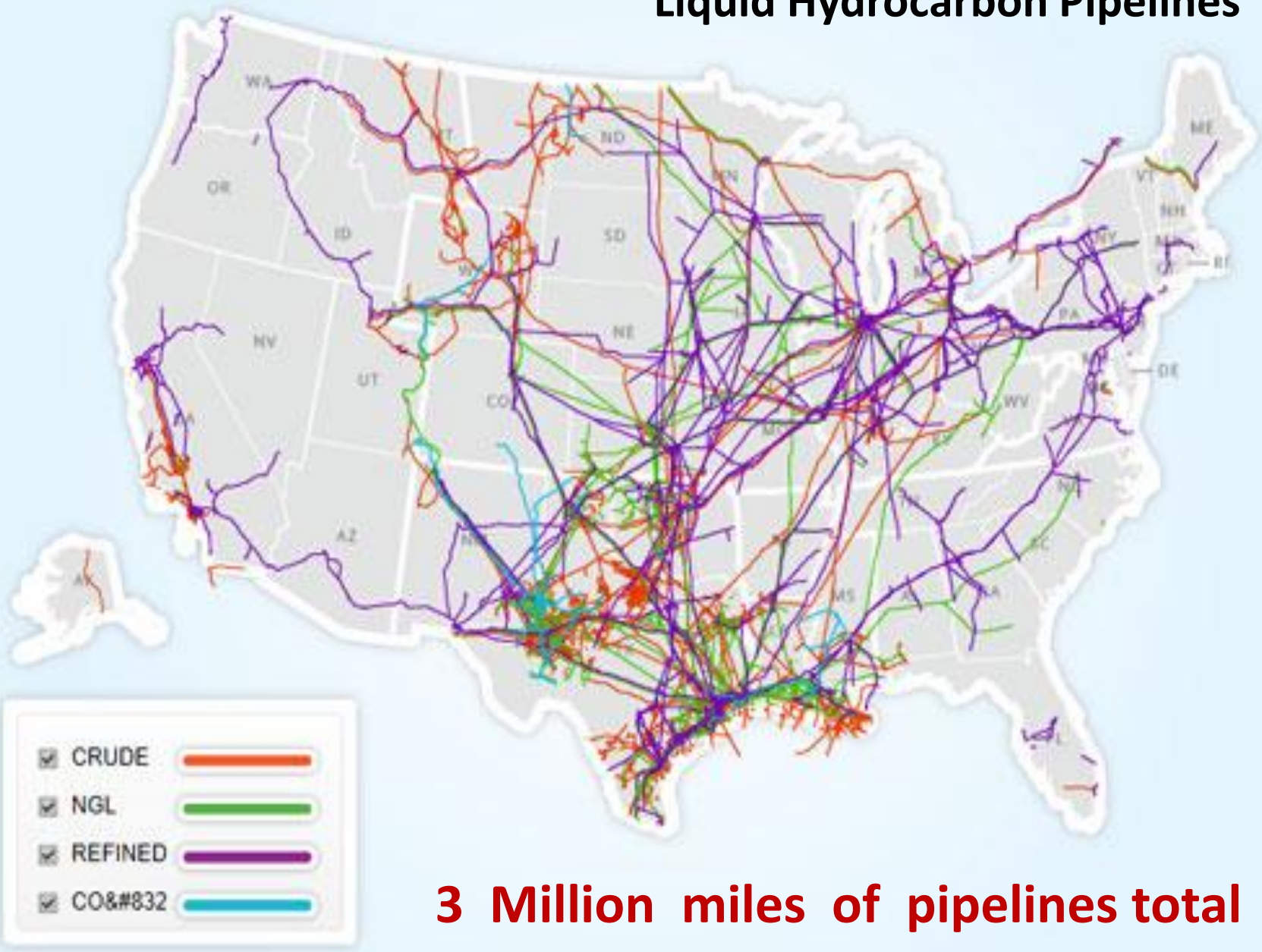
NatGas pipelines

Map of U.S. interstate and intrastate natural gas pipelines



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

Liquid Hydrocarbon Pipelines



3 Million miles of pipelines total

Source: American Energy Mapping (AEM) 2013

’09 ARPA-E “Grids” Goal: $100 / kWh capex

Total storage = 380 GWh

Storm Lake, IA

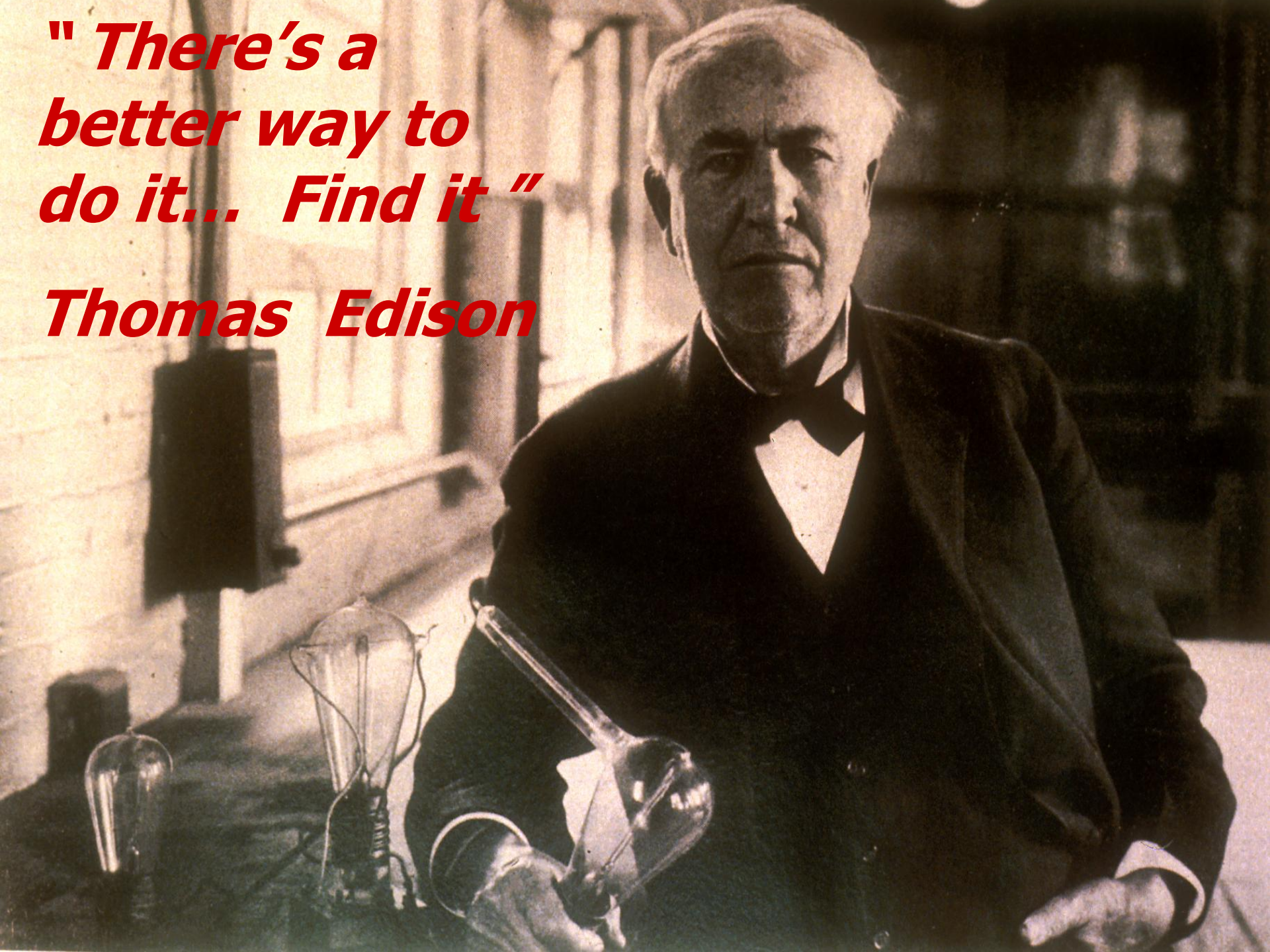
“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

Each: 30,000 Tons, 190 GWh $ 20 M turnkey

$ 100 / MWh = $ 0.10 / kWh capital cost


200 Ton “propane” tanks for liquid ammonia
~ 10 bar pressure
25 C

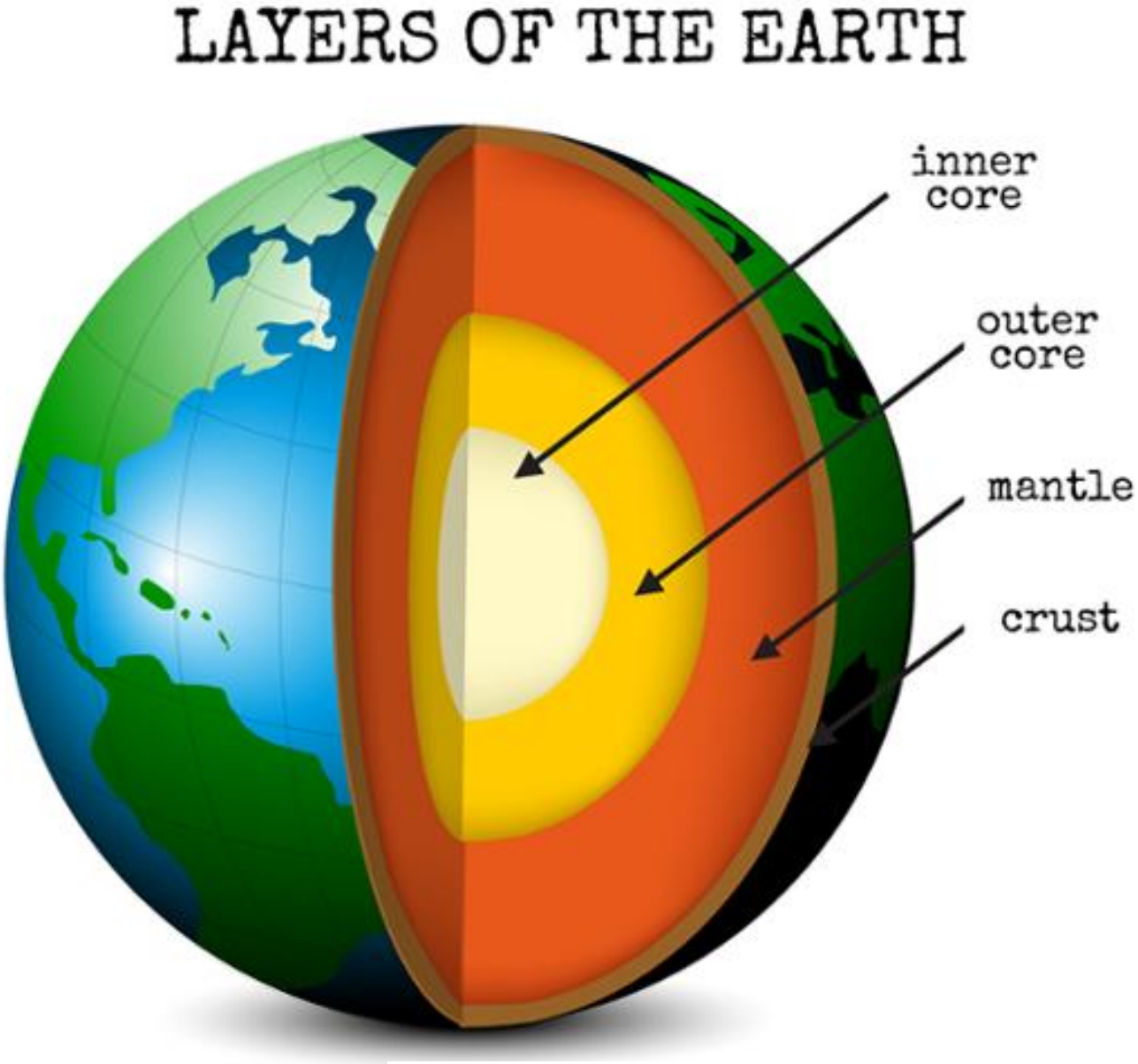

" There's a better way to do it... Find it "
Thomas Edison

"Hydrogen is hard" -- too hard ?

Pipelining Hydrogen:

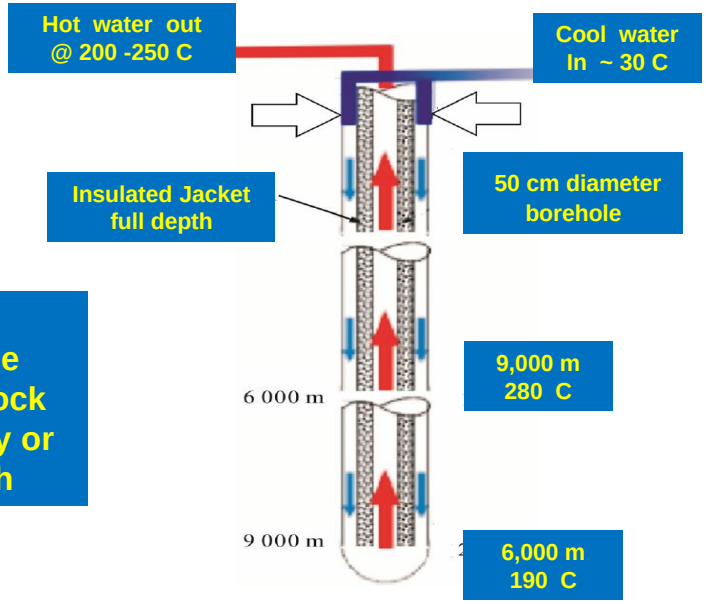
- Welcome disruption
- R&D&D success: complete system
- Energy + Industrial Feedstocks [E+IF]
- Entire human enterprise → Grid, energy
- Benign: GHG-emission-free
- Inexhaustible
- Baseload, firm, dispatchable
- Ubiquitous on Earth
- Equitable
- Affordable: competitive
- Free energy storage -- leave heat in ground

Deep Hot Dry Rock Geothermal



Deep Hot Dry Rock Geothermal

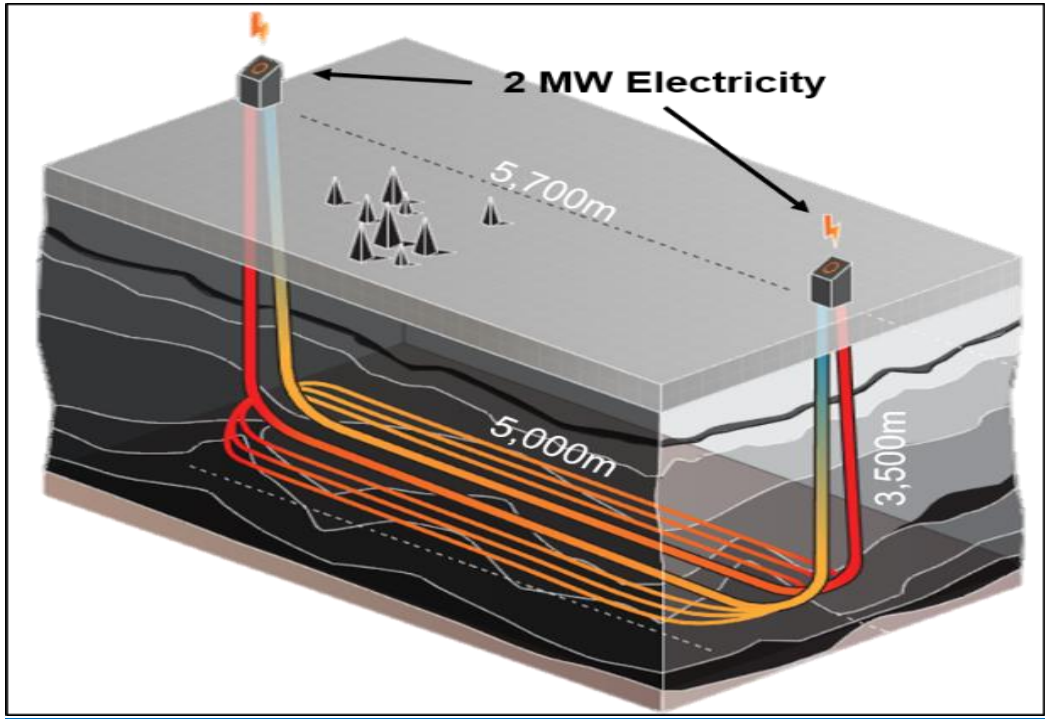
Borehead: 50 cm diameter
Electrode array: multiple fracture pathways for rock breaking in sedimentary or crystalline rock to depth



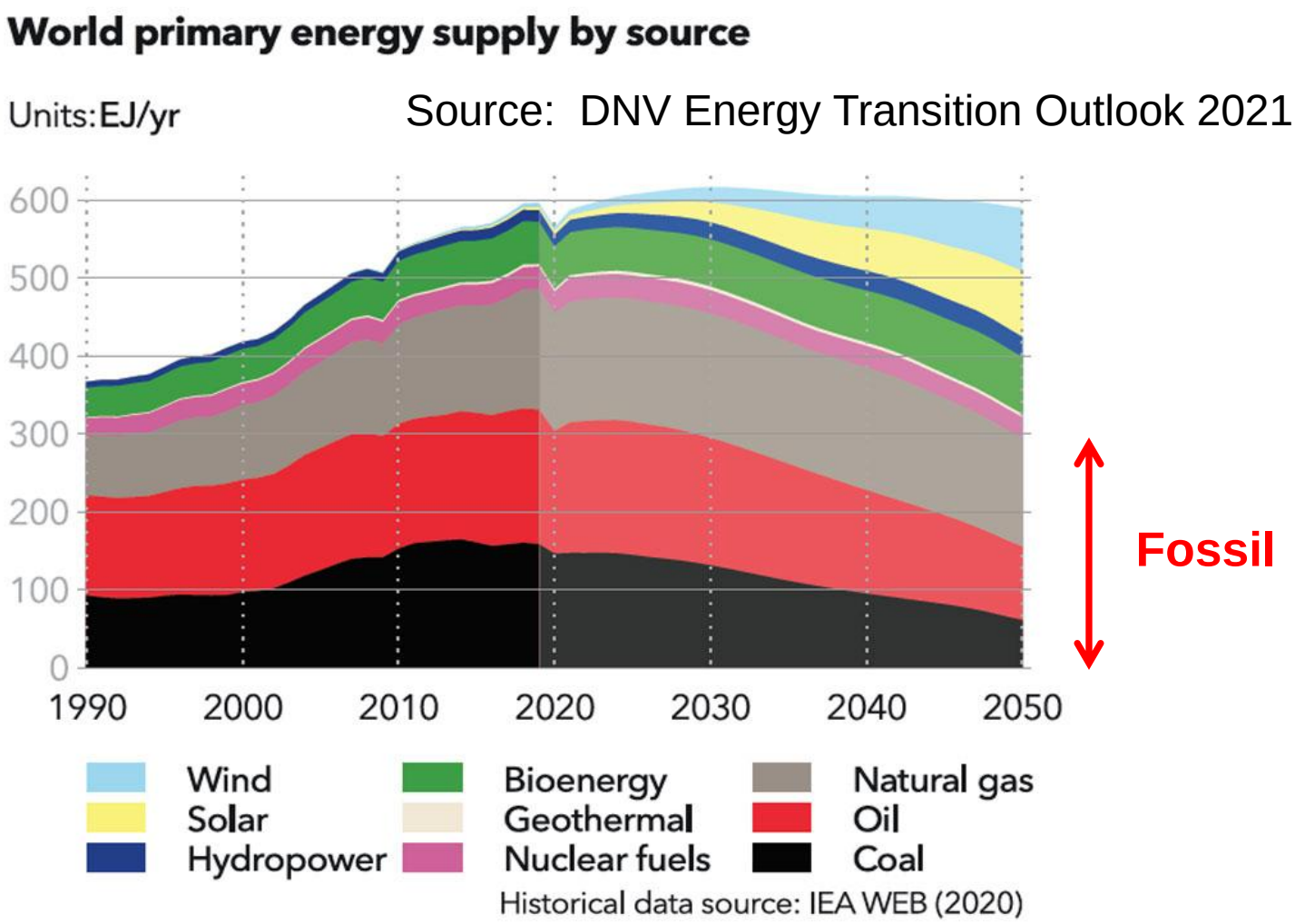
Bore deep enough, cheap enough

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**

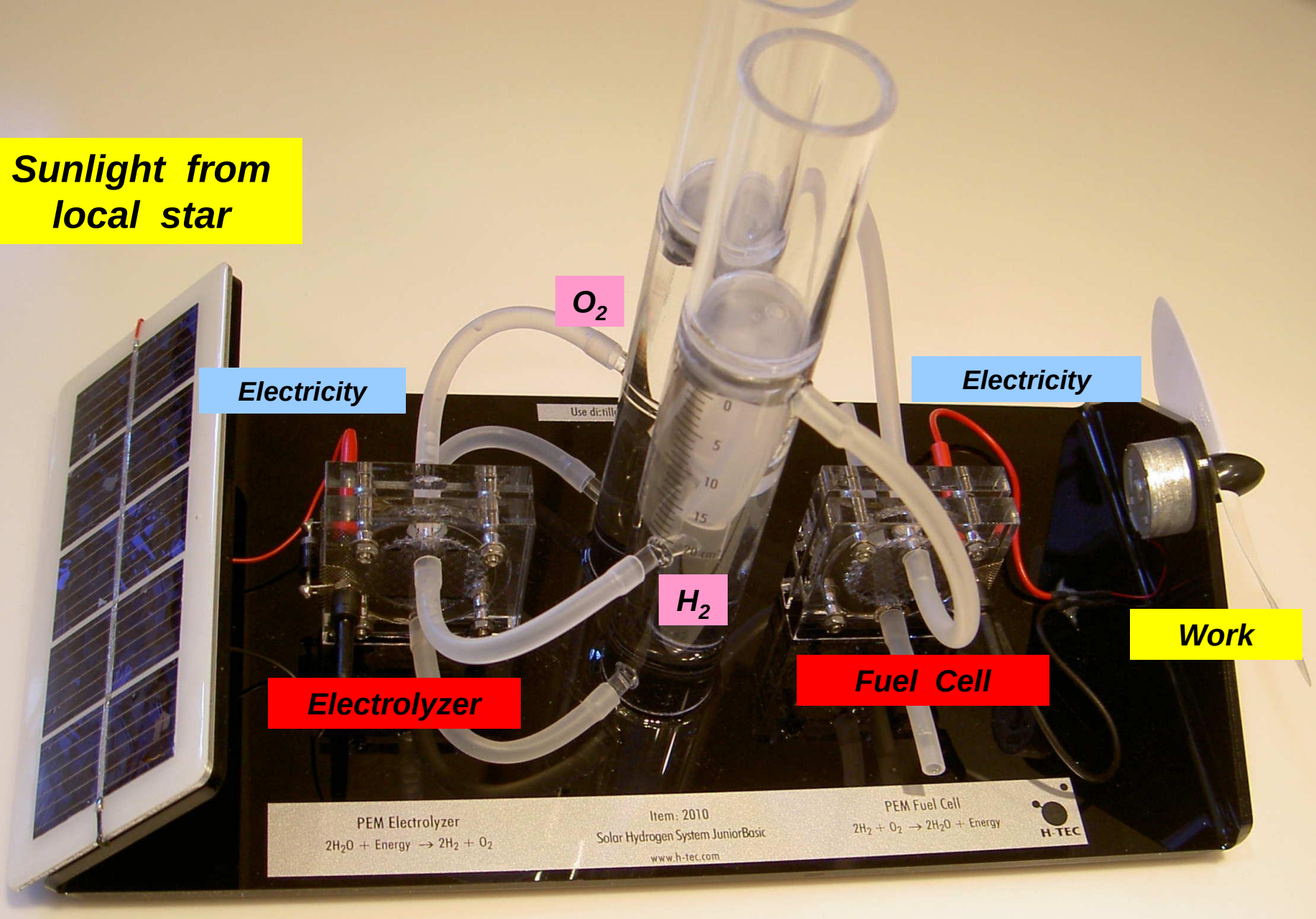
- **Benign**
- **Baseload**
- **Firm, dispatchable**
- **Inexhaustible**
- **Ubiquitous on Earth**
- **No transmission, storage**
- **Equitable**
- **Affordable**



Deep Hot Dry Rock Geothermal (DHDRG)



2050 : Total De-carb, de-GHG-emission: anthropogenic
Entire human enterprise: Energy + Industrial Feedstocks
Fossil 50 % → Zero
Geothermal insignificant
Roles: Legacy Gas, Nascent Hydrogen ?
Arrest: Climate catastrophe



Solar Hydrogen Energy System

Pipelining Hydrogen:

“Hydrogen is hard”

Why ?
Gas or liquid ?
Blend with NatGas or high-purity ?
Repurpose old pipes or new-build ?
Free “packing" storage ?
Continental scale ?
Salt cavern storage access ?
GH2 or LH2 or liquid NH3 ?
R&D&D now

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www.leightyfoundation.org/Earth.php
https://vimeo.com/711824309