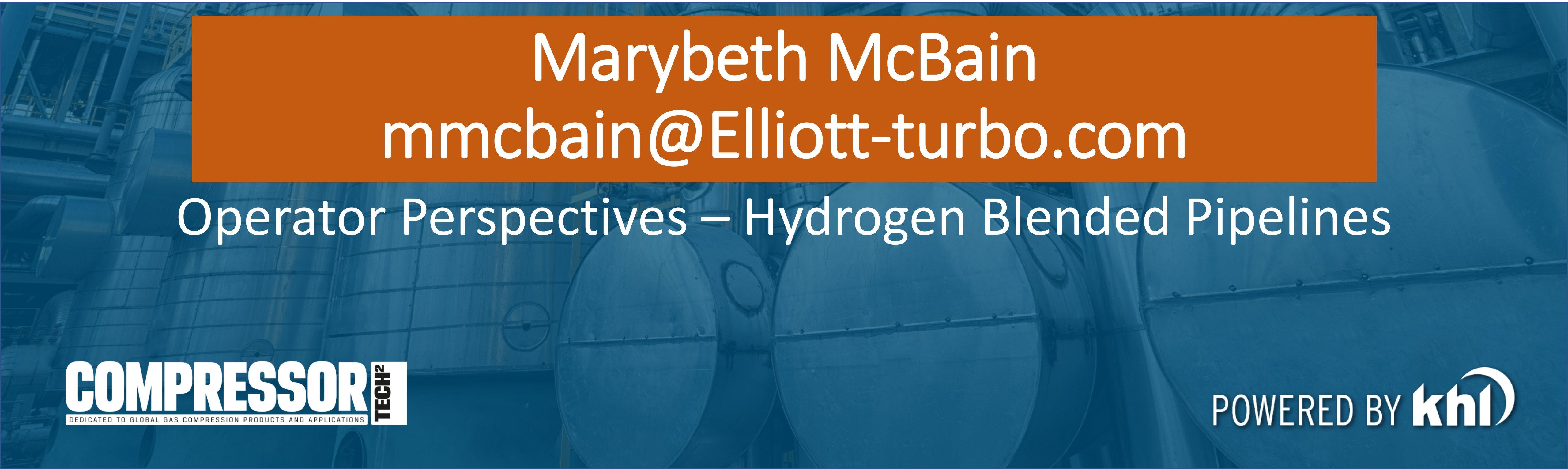
COMPRESSOR TECH² HYDROGEN SUMMIT

HOUSTON, TX
APRIL 25, 2023



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Operator Perspectives – Hydrogen Blended Pipelines

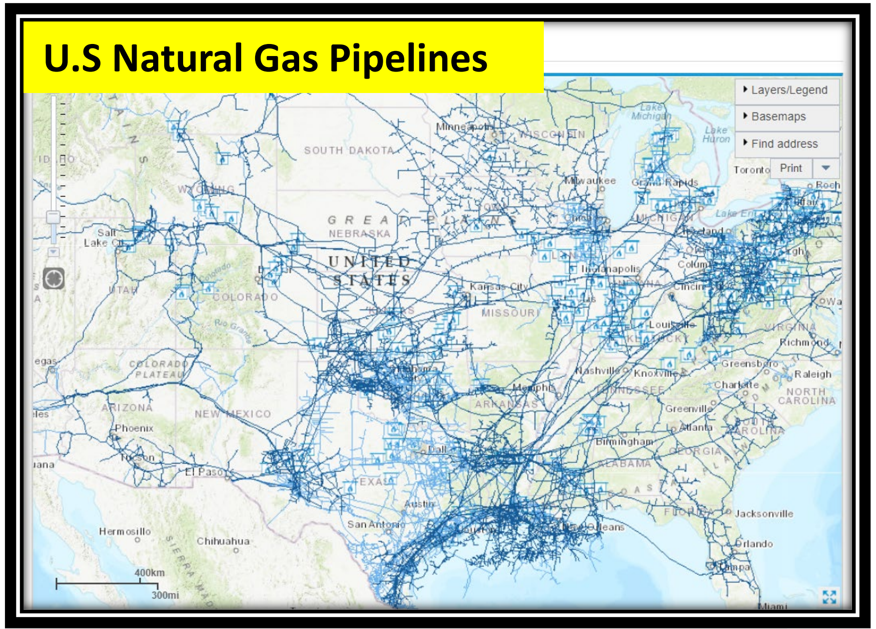
COMPRESSOR TECH²
DEDICATED TO GLOBAL GAS COMPRESSION PRODUCTS AND APPLICATIONS

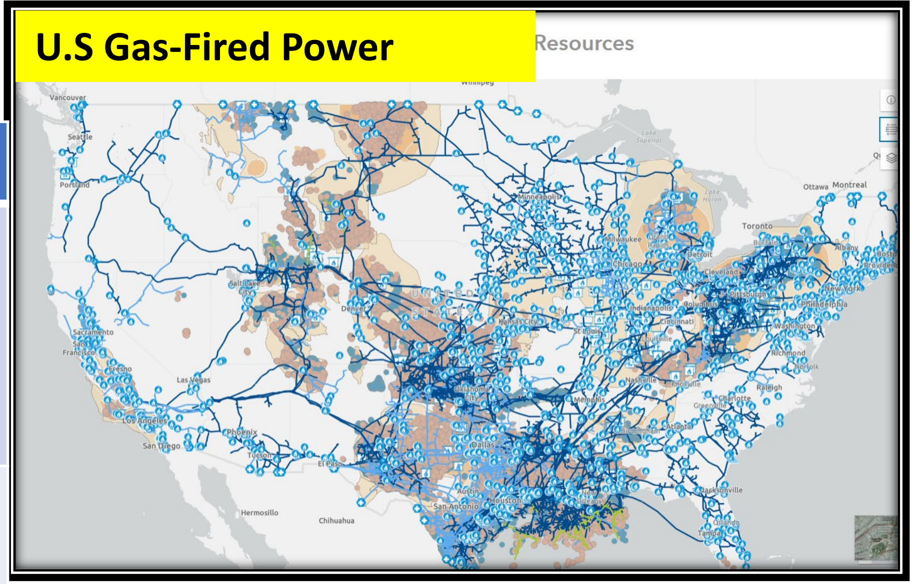
POWERED BY khl

Hydrogen vs Natural Gas

- **U.S. pipeline network is a superior backbone for development – leveraging gas and CO2 pipelines and availability of gas-fired power.**
- **For Green H2 - Must regard hydrogen as energy storage for usage / pricing. Must incorporate H2 storage in some form.**
- **For Blue H2 - Continuous hydrogen production w/ less storage required. Must include CO2 capture and pipelines for sequestrations.**

	Ads	Disads
Pure H2 pipelines	• Optimized size • Shorter lines to support blue / green production areas	• Cost of new lines • Electrical lines compete
Blended NG and H2 lines	• Steel in the ground already if repurposed • Can specify H2 limits	• Risks to using existing aging lines and equipment


U.S Natural Gas Pipelines


U.S Gas-Fired Power

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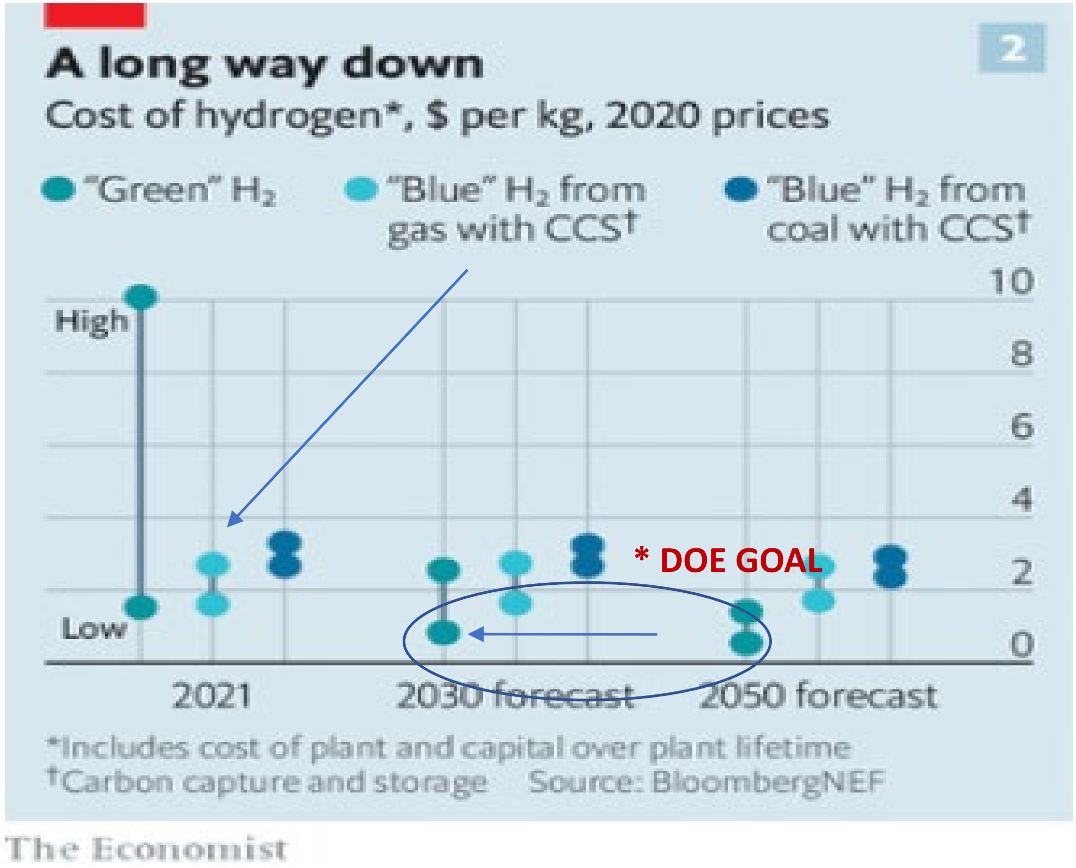
Types of Hydrogen Production – and the pipelines each produce for power gen



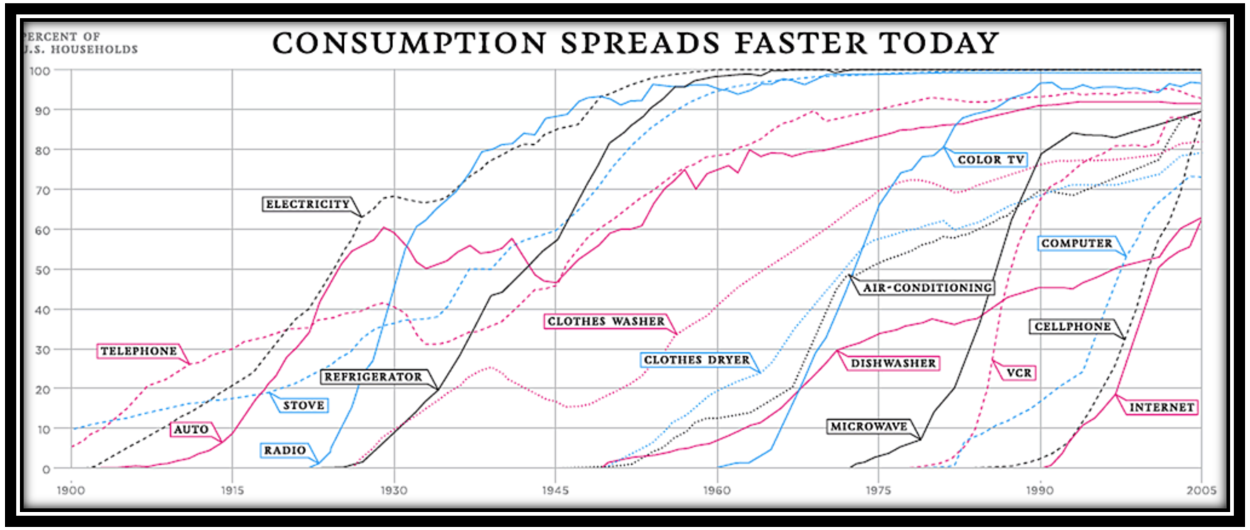
Source: The Economist, October 2021

- Currently Grey H2 $1.0 / kg
- **Blue H2 $2-2.5 / kg**
  DOE goal for blue H2 = $1 /kg by 2030
- **Blue Makes CO2 pipelines necessary.**
- Green Hydrogen: $5.0 / kg,
  DOE goal = $2 / kg by 2030
- **Pink H2 costs = ??**
- **Green hydrogen will likely require higher storage pressures and more intermittent production of hydrogen to match up to renewables cycles (ie when sun is shining and wind is blowing)**

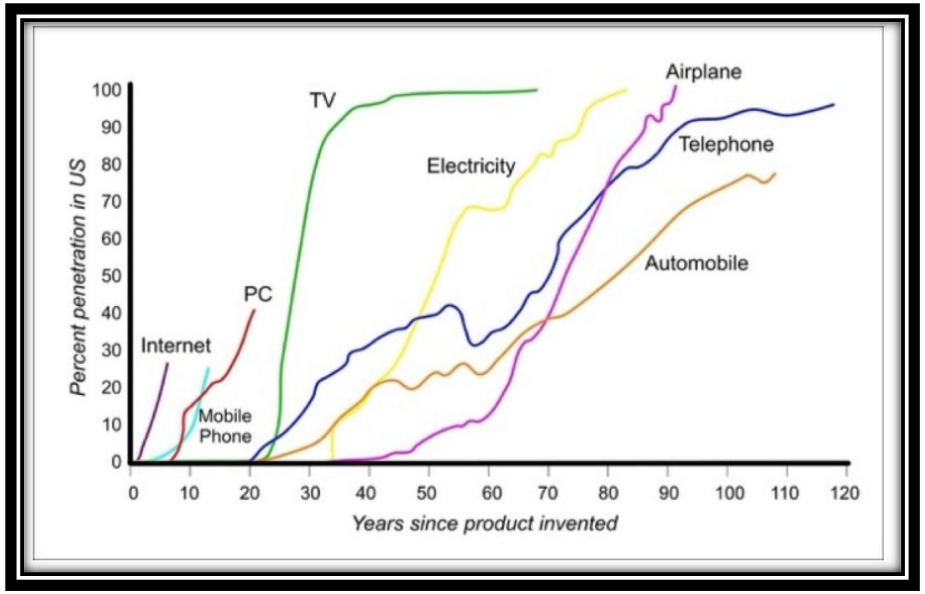
New Costs of H2 due to recent Inflation Reduction Act and Carbon Intensity

Production of Hydrogen – Amount of CO2 produced (per kg of H2)	Credit in $ / kg – tax credit on green or blue hydrogen	Range of Qualification – Net Cost for Blue and Green
2.5 – 4.0 kg of CO2	$0.60 / kg of H2	Likely Range for Blue hydrogen with measures on fugitive emissions = $1.50 production - $1 credit = $0.50 / kg net cost
1.5-2.5	$0.75 / kg of H2	
0.45-1.5	$1.0 / kg of H2	
0-0.45 kg of CO2	$3.00 / kg of H2	Green hydrogen will qualify for highest = $5 production - $3 credit = $2 / kg net cost

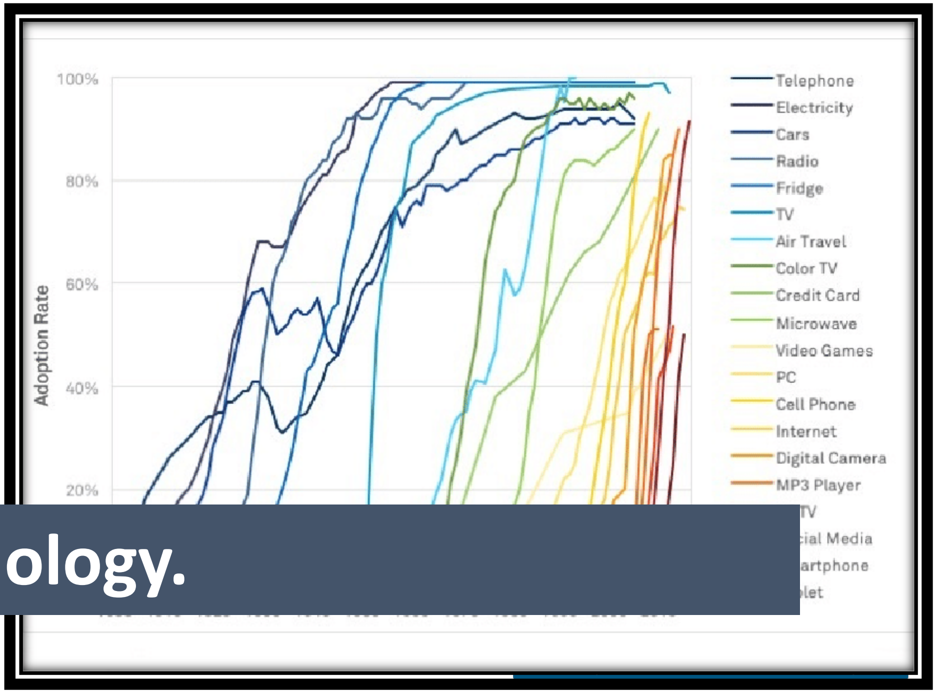
Technology Adoption Curves….



- Alternative low cost choice → Co-existence is often sustainable for decades
- Hydrogen fuel for power plants will also have localized adoption curves or "bubbles" (operator driven by environmental / political pressure).
- U.S. tends to have state regulated emissions = more bubble type behavior



- Exponential
- S-curves
- Flat S



Technology adoption curves depend on the technology.

Hydrogen Cost Analogy to LNG….

In 2013, Historical Review of LNG suggested capex costs were rising…

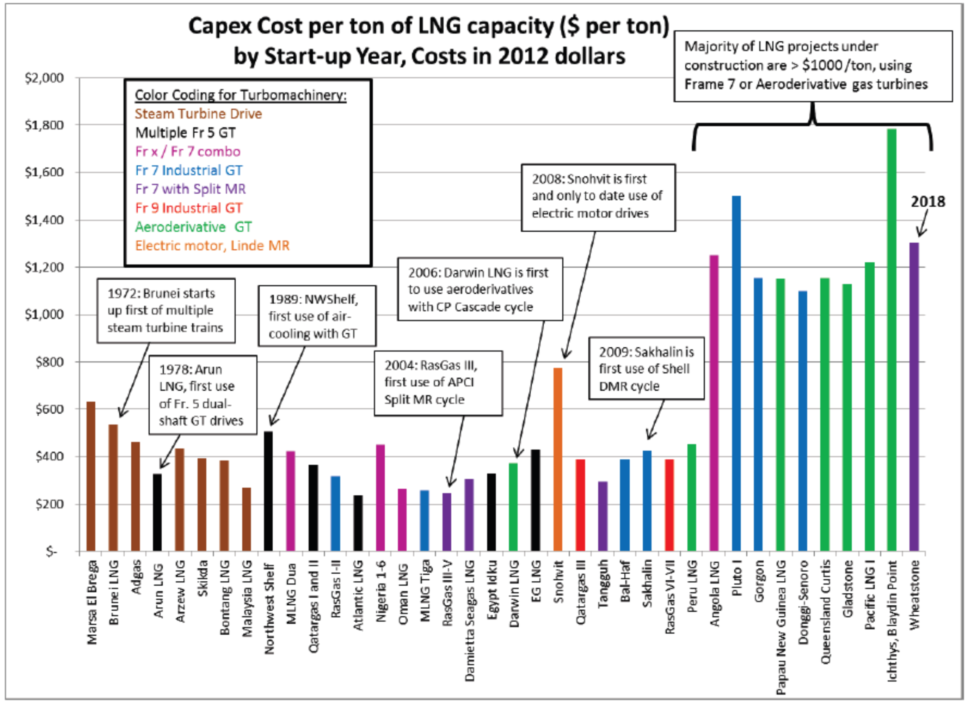
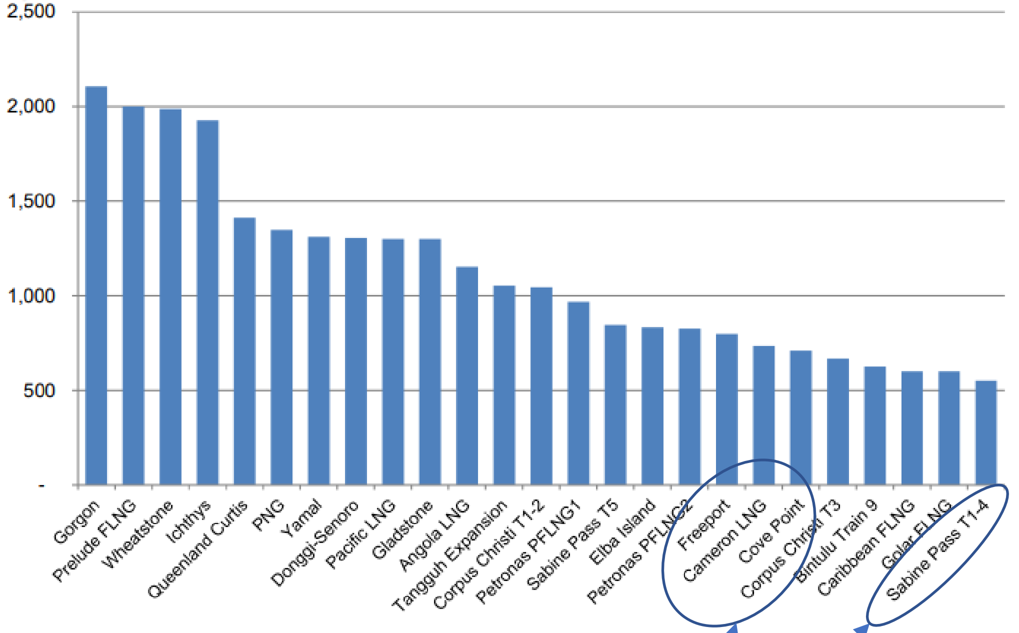


Figure 2. Historical LNG Capital Costs ($ per ton, 2012 dollars) for Major Export LNG Plants, organized by start-up year

Source: "A Historical Review of Turbomachinery for LNG Applications," Marybeth Nored and Andrew Brooks, Apache Corporation, LNG17, Houston, Texas.

By 2018, LNG cap costs fell dramatically due to leveraging infrastructure, economies of scale and standardization….

Figure 3: Liquefaction Plant Capital Costs $/tpa Constructed 2014–18



Source: Oxford Energy – LNG Plant Cost Reduction 2014-2018. The Oxford Institute for Energy Studies

Cost of Texas, Louisiana and Maryland plants are lowest at $700-$1000 / tpa, siting factors such as taking advantage of infrastructure, standard equipment usage, economies of scale on multiple trains.

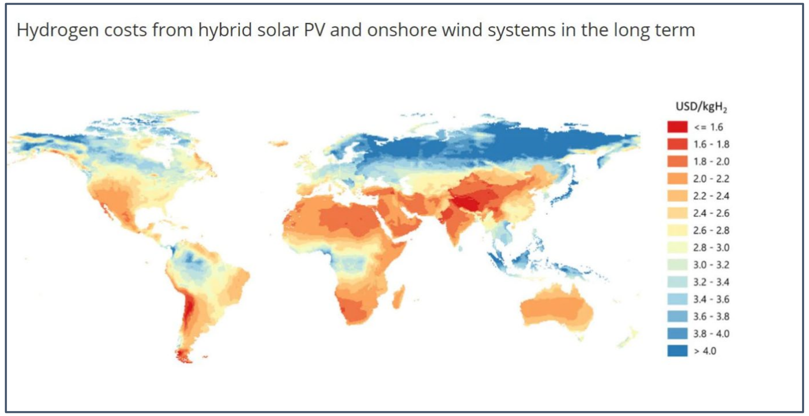
Six Pathways to Blue / Grey / Green Hydrogen

Method of Producing	**Reaction**	**Exothermic or Endothermic**	**Ratio of H2 : CH4 *High Ratio is more favorable**	**Ratio of H2:CO *High CO ratio will be more costly for blue hydrogen**
Steam Methane Reforming	CO + 3 H2	**Endothermic – Needs Energy**	**3:1**	**3:1**
Water Gas Shift	CO2 + H2	**Releases heat**	**1:1**	**1:1**
Partial Oxidation	2 CO + 4 H2	**Releases heat**	**2:1**	**2:1**
CO2 Reforming	2 CO + 2 H2	**Endothermic – Needs Energy**	**2:1**	**1:1**
Methane Pyrolysis	2H2 + C	**Endothermic – Needs Energy**	**2:1**	
Water Electrolysis “Green Hydrogen”	2 H2 + O2	**Endothermic – Needs Energy**	*** Current best available electrolysis designed at 20-30 bar H2 discharge**	

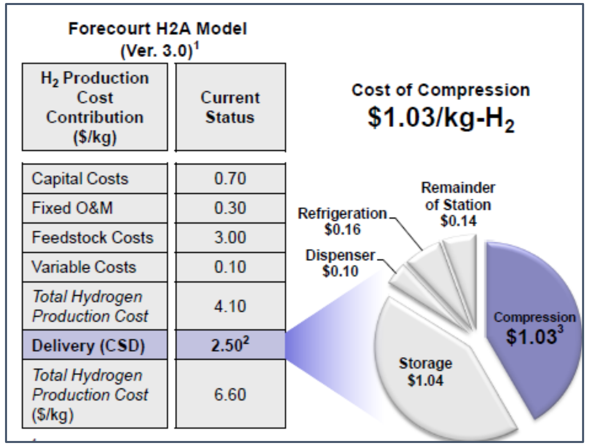
H2 Production – Process Effects on Compression / Storage

Hydrogen Type	**Production Process**	**Likely Duration**	**Compression Profile**	**Storage Medium**
Green Hydrogen	Use curtailed renewable electric power to run electrolysis	Daily on / off	PEM @ 20-30 bar delivery pressure → high ratio to storage	Liquid tanks, H2 linepack, ammonia, methanol
Blue Hydrogen	Use one of various reformer processes to produce H2 from hydrocarbons, **requires CCS**	Continuous	Near Atm → fuel pressure for GT	Natural gas - existing storage fields and linepack
Pink Hydrogen	Use nuclear power to run electric driven electrolysis process	Continuous	Same as Green – PEM @ 20-30 bar	?? Likely H2 or batteries

Green Hydrogen Costs Worldwide:


Hydrogen costs from hybrid solar PV and onshore wind systems in the long term

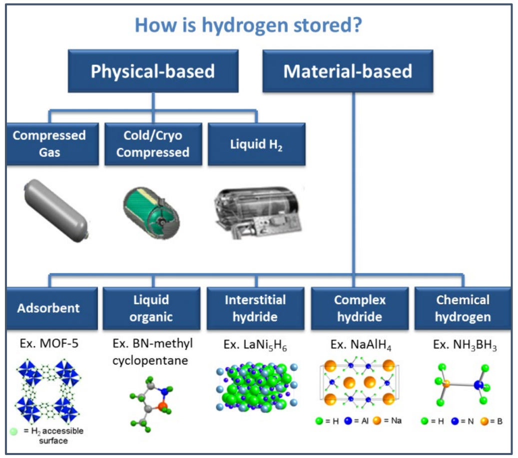
H2 Compression Cost Breakdown (2014):


Forecourt H2A Model (Ver. 3.0)[1]

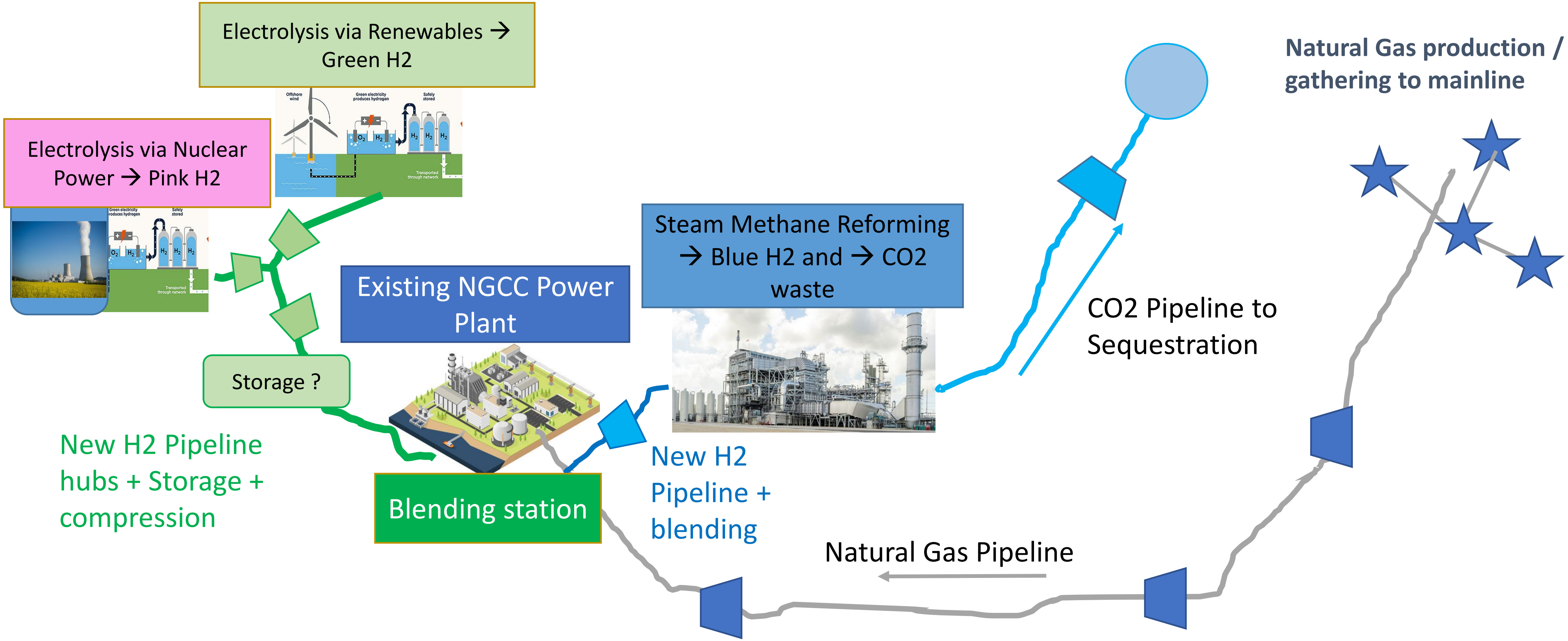
H_2 Production Cost Contribution ($/kg)	Current Status
Capital Costs	0.70
Fixed O&M	0.30
Feedstock Costs	3.00
Variable Costs	0.10
Total Hydrogen Production Cost	4.10
Delivery (CSD)	**2.50[2]**
Total Hydrogen Production Cost ($/kg)	6.60

Cost of Compression
$1.03/kg-$H_2$

Hydrogen Storage Forms:



Likely H2 and CO2 pipeline routes



Electrolysis via Renewables → Green H2

Electrolysis via Nuclear Power → Pink H2

Storage ?

New H2 Pipeline hubs + Storage + compression

Existing NGCC Power Plant

Blending station

Steam Methane Reforming → Blue H2 and → CO2 waste

New H2 Pipeline + blending

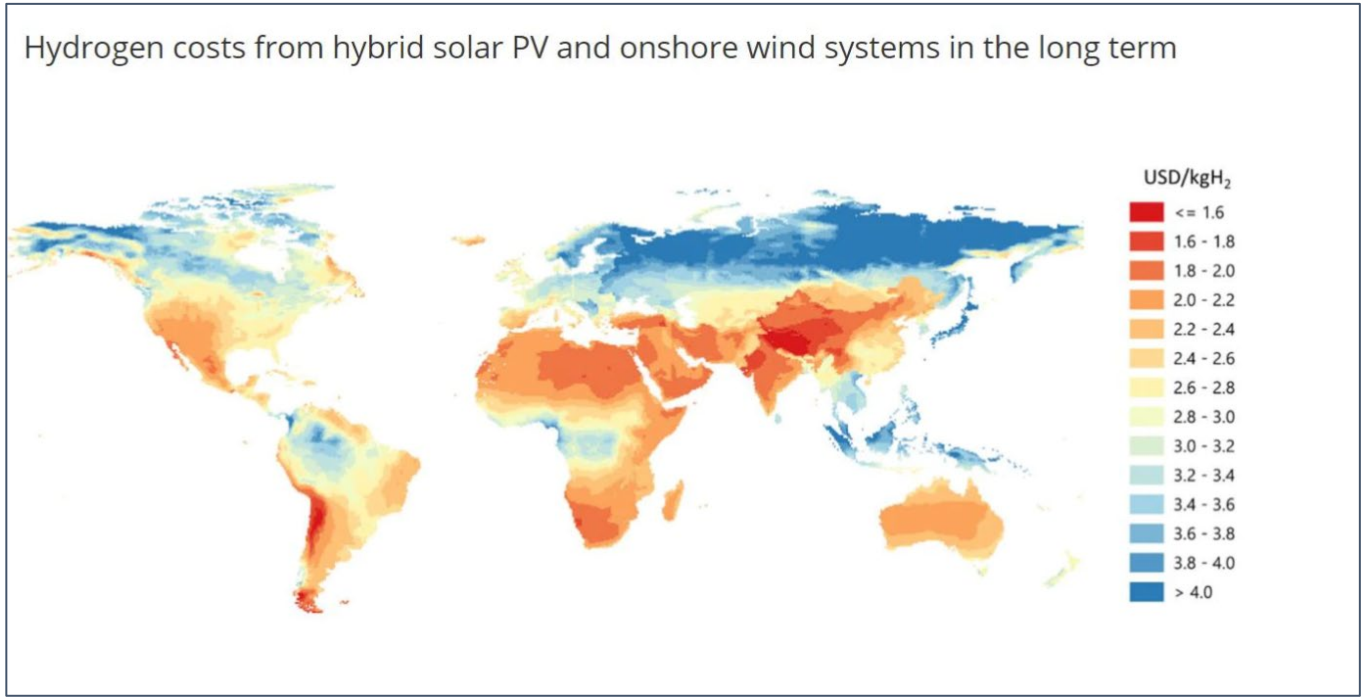
CO2 Pipeline to Sequestration

Natural Gas production / gathering to mainline

Natural Gas Pipeline

Hydrogen Hubs – Favored in Concentrated Wind and Solar Areas – Buildout Expectations?

Green Hydrogen Costs Worldwide:


Hydrogen costs from hybrid solar PV and onshore wind systems in the long term

- Likely to see green hydrogen pipelines in usage where Solar and Wind power is at a lower cost.
- However, blue hydrogen hubs are possible anywhere with readily available natural gas.
- Ammonia and methanol as carriers for green hydrogen allow further reach beyond solar / wind areas.

When Hydrogen Starts to Blend Into Natural Gas Streams…

"You're gonna need a bigger boat." -
Chief Brody in Jaws

Due to the volumetric flow increase and specific heat changes with hydrogen =
All Horsepower with Hydrogen gets Bigger!

Pressure Ratio and Head – Compression Formula

To keep the same pressure ratio, Head Hact term must increase in proportion to the high cp value

$$\frac{P_2}{P_1} = \left[1 + H_{act} * \frac{n}{c_p * T_1}\right]^{\frac{\gamma}{\gamma-1}} = \left[1 + \frac{\omega * (r_2 c_2 - r_1 c_1)}{c_p * T_1}\right]^{\frac{\gamma}{\gamma-1}}$$

Can achieve the higher head required with either:

1) More speed, w
2) Larger diameter, r
3) More stages of compression

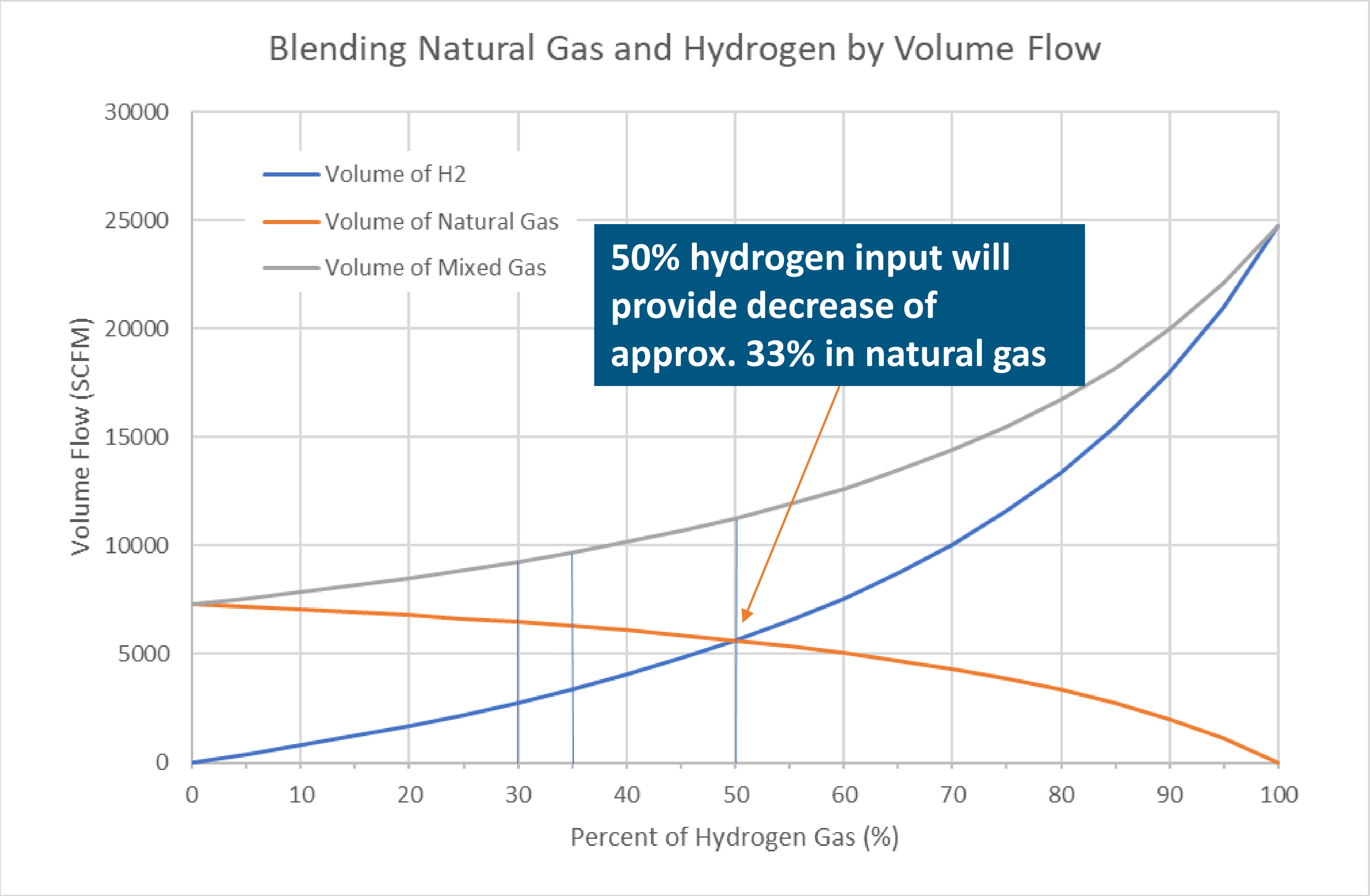
	Hydrogen	Natural Gas	CO2
Heat Capacity (cp, kJ/kgK)	14.3	2.3	0.839
Ratio of Heat Capacities (γ)	1.4	1.3	1.3

Source: Brun K., Kurz R., Allison, T. "Pipeline Compression for the Hydrogen Economy", DOE Seminar 2021

Design Challenges of Pure Hydrogen Compression

- Light gas compression
  - Volumetrically high flow for equivalent energy to NG
  - Many stages (mechanical/rotordynamic) or high speed (high stress, novel materials)
  - Equation of state
- Sealing
  - Dry gas seal design utilizes different materials / more filtration to ensure high reliability
  - Higher speeds = greater challenge for DGS
- Materials and coatings
  - Hydrogen embrittlement (material loses ductility due to H_2 penetration)
  - Coating loss and disbonding
- Safety
  - Explosivity, wide flammability range, dispersion and impact radius, leak detection

LM6000 Fuel Flow to Gas Turbine – 50 MW ISO Power



50% hydrogen input will provide decrease of approx. 33% in natural gas

Hydrogen Transport via Pipeline

- Hydrogen Compressors are completely different due to:
    - 10x Head increase – power and speed increase for typical pipeline ratios
    - Multiple impellers required & speed material limitations
    - 3x flow increase (for equivalent energy) due to lower Btu/scf
    - Hydrogen embrittlement and cracking at pressures lower than yield strength
    - Leakage and sealing of very low density gas
    - Speed of sound 3x higher – over 3000 ft/sec > 1000 psi
- Other Compressor station differences:
    - Regulator and filter design
    - Threaded fittings
    - Treatment / monitoring and capture of vented gas
- **Likely: Adding new purpose-built H2 stations more favorable.**

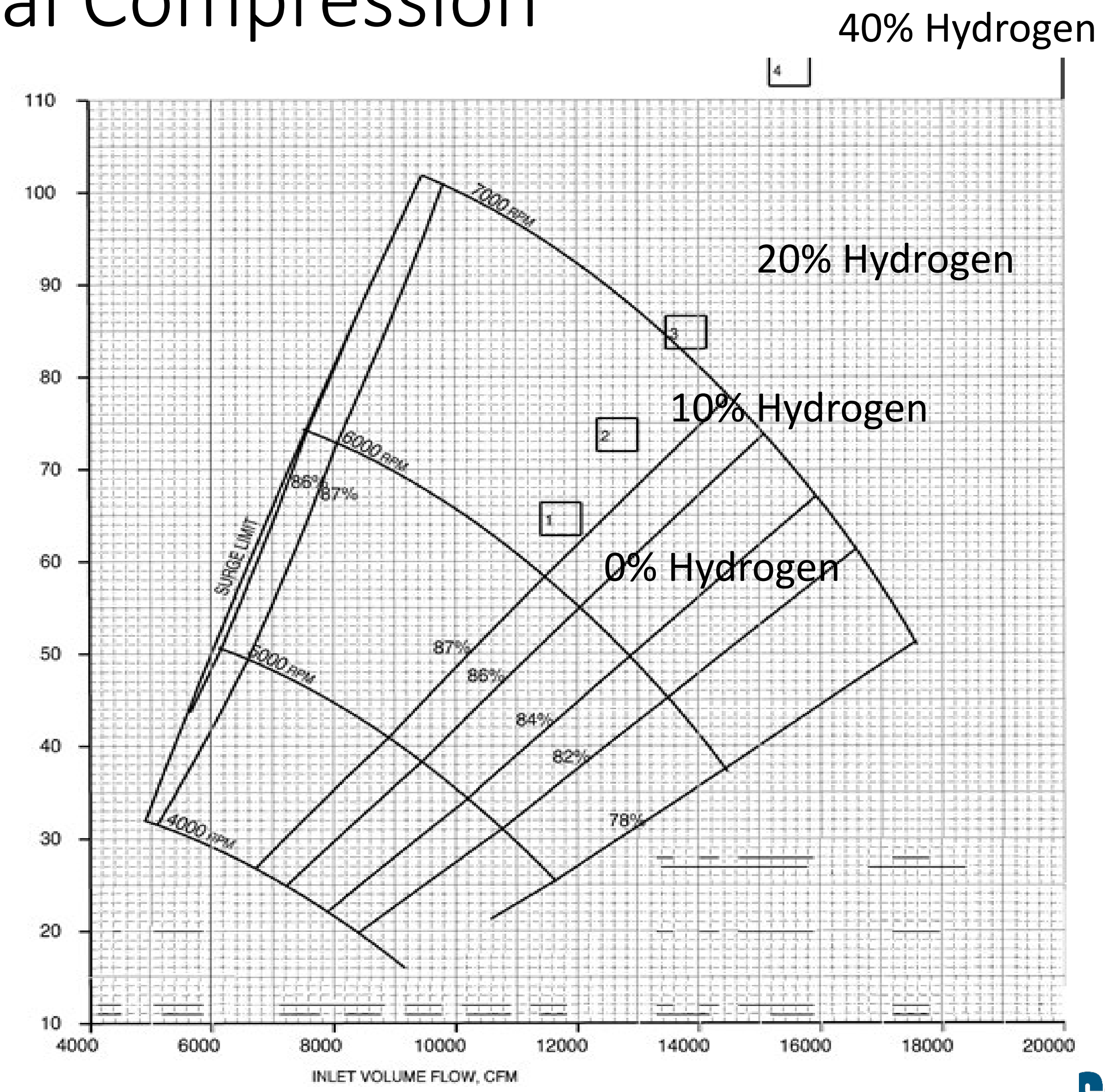
Figure 1: Elliott hydrogen hydrocracker compressor used in refinery processes. This unit processes a low mole weight gas (4.0 MOL) that is approximately 91.5% hydrogen. It has five impeller stages, an inlet pressure of 2,335 psia, maximum continuous operating speed of 12,027 rpm, and can process 1,692 ICFM through its 10-inch inlet nozzle.

Source: Gas Compression Magazine, January 2022 and Turbomachinery International, "Special Report: Hydrogen Compression", Nov / Dec. 2020

Blending Impact on Centrifugal Compression

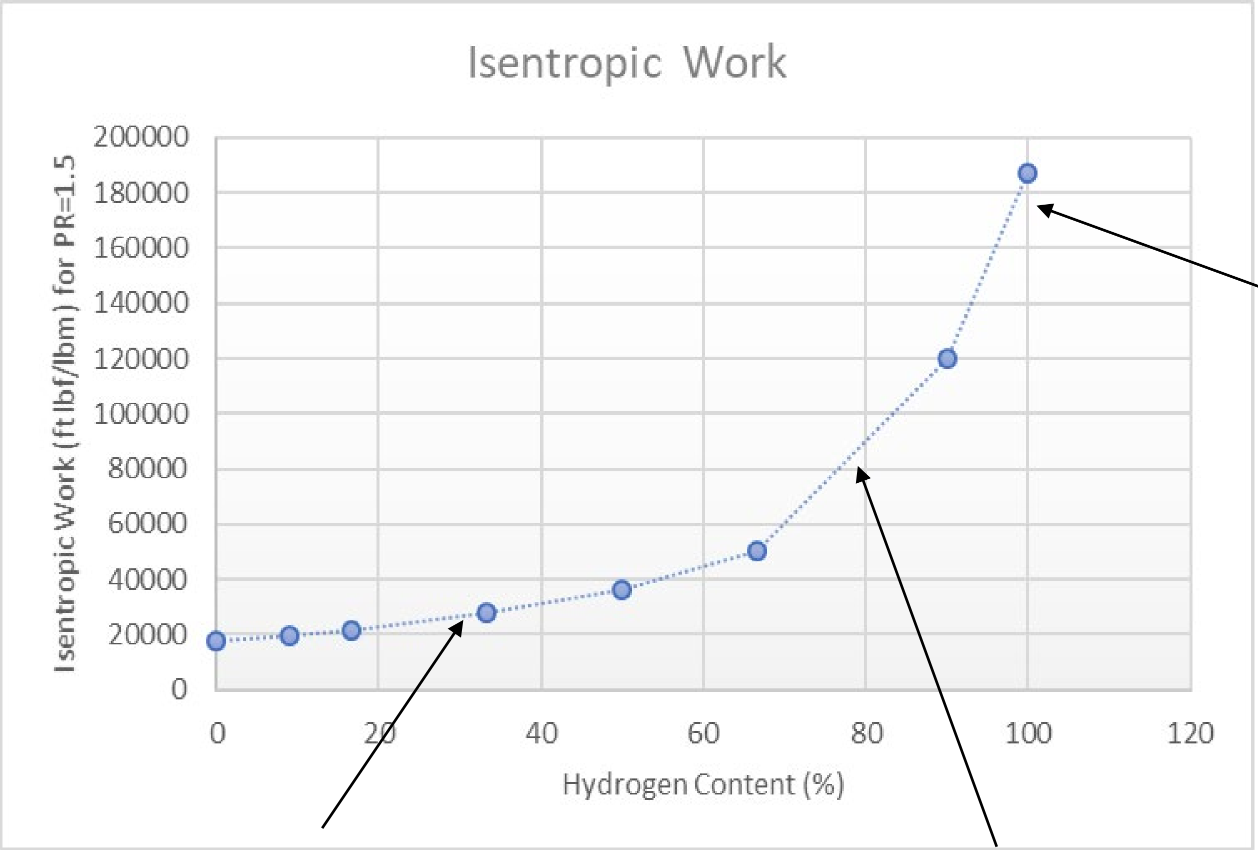
- Operating points for constant inlet conditions and discharge pressure
- As hydrogen blended into natural gas – higher head required – exponentially.
- For blending > 20% hydrogen, likely need multiple compressor casings.

Source: Brun K., Kurz R., Allison, T. “Pipeline Compression for the Hydrogen Economy”, DOE Seminar 2021

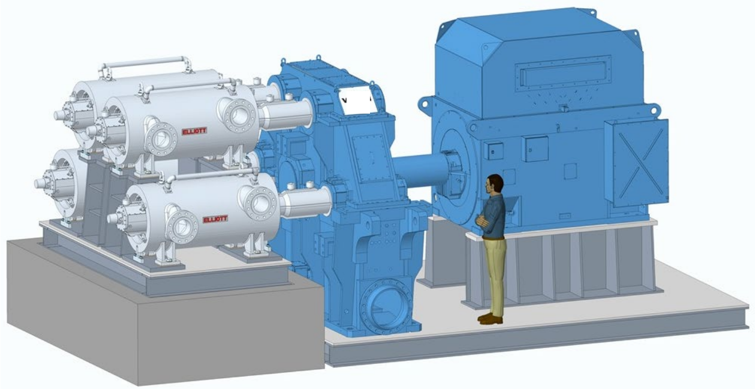


NG Blending with Increasing Hydrogen

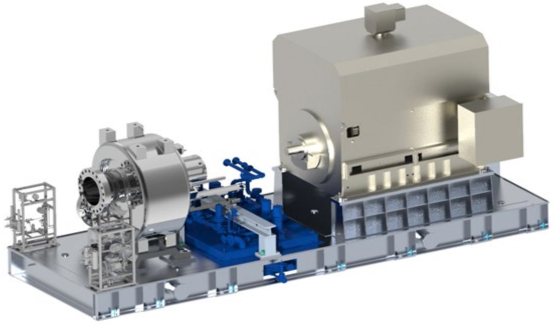
Source: Kurz R., Allison, T., Brun, K. “Pipeline Compression for the Hydrogen Economy”, DOE Seminar 2021



Multiple Compressor Bodies



Conventional Pipeline Compressor



Single Body Process Compressor

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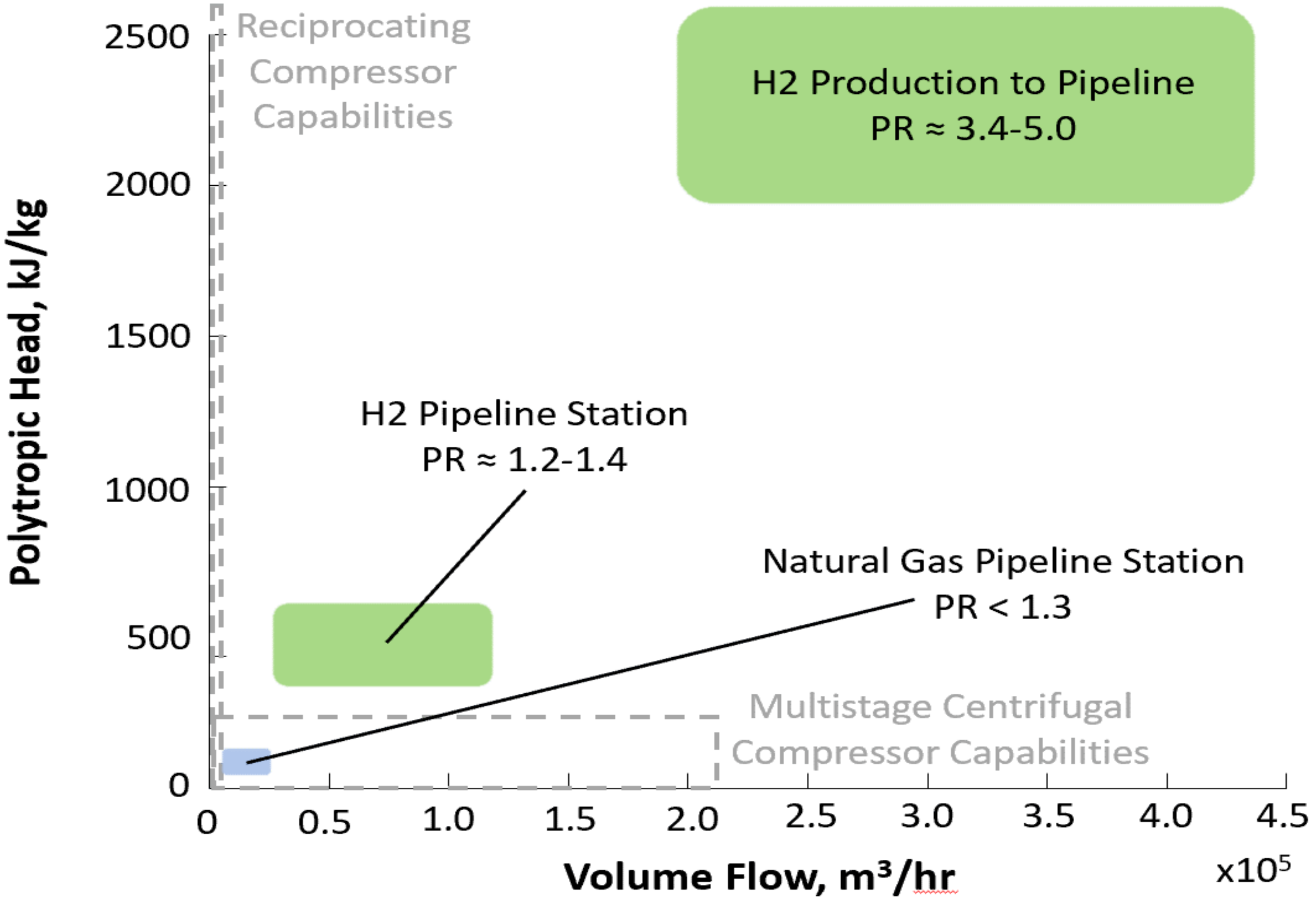
Flow vs Head for Hydrogen



Hydrogen Effects on Carbon Steel – Expected Effects on Aging U.S. Pipelines

- Studies of hydrogen effects on mechanical degradation of carbon steels ongoing.
- Effects are dissimilar and vary widely depending on steel composition.
- Mechanisms of degradation include:
  - HE decohesion
  - HE local plasticity
  - Stress induced vacancies
  - Absorption induced dislocation emissi
- Researchers able to better predict correlation in degradation based on steel composition

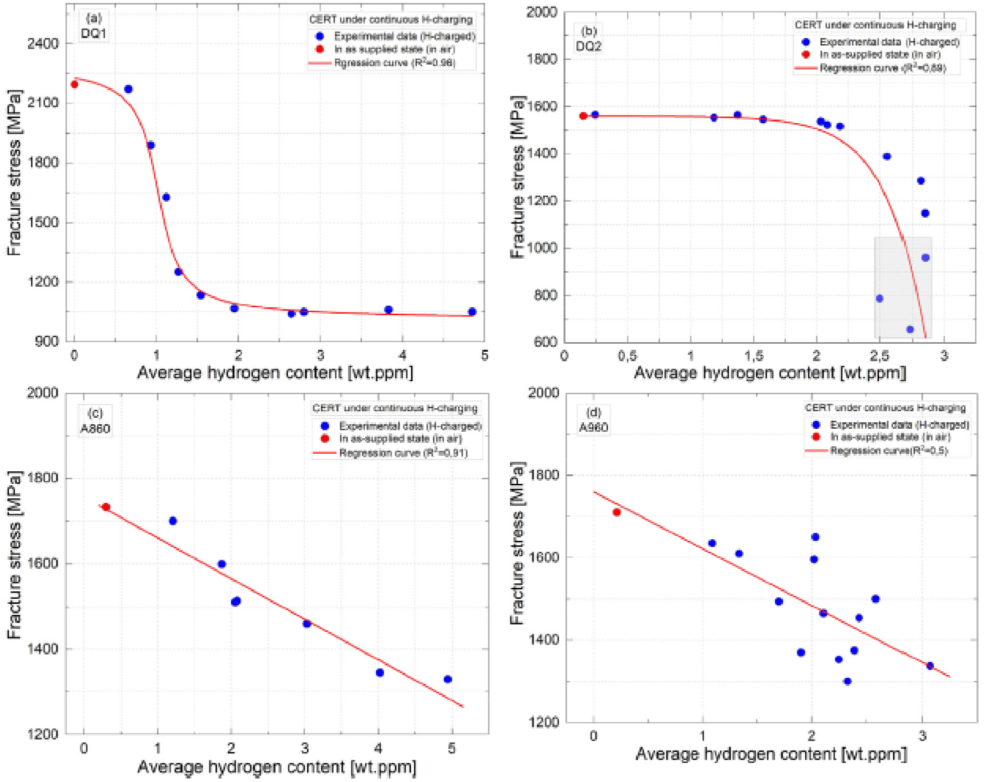


Fig. 6 – Fracture stress as a function of hydrogen concentration for (a) DQ1, (b) DQ2, (c) A860, and (d) A960.

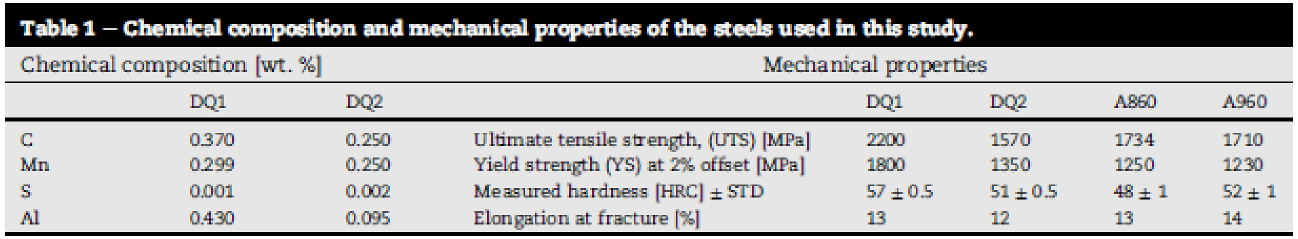


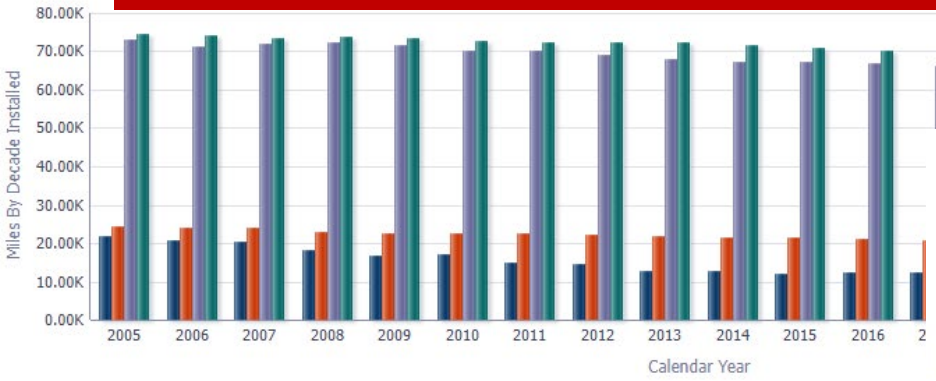
Table 1 – Chemical composition and mechanical properties of the steels used in this study.

Chemical composition [wt. %]			Mechanical properties				
	DQ1	DQ2		DQ1	DQ2	A860	A960
C	0.370	0.250	Ultimate tensile strength, (UTS) [MPa]	2200	1570	1734	1710
Mn	0.299	0.250	Yield strength (YS) at 2% offset [MPa]	1800	1350	1250	1230
S	0.001	0.002	Measured hardness [HRC] ± STD	57 ± 0.5	51 ± 0.5	48 ± 1	52 ± 1
Al	0.430	0.095	Elongation at fracture [%]	13	12	13	14

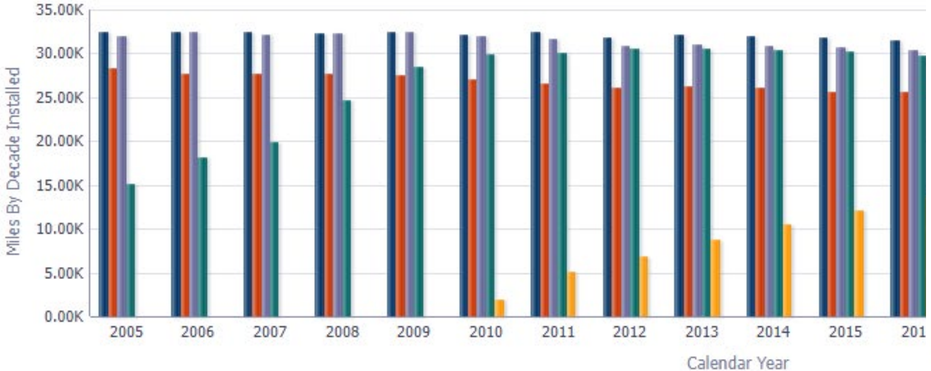
Figures above from:
Fangnon, Eric, Malitckii, E. , Latypova, R., Vilaca, P. "Prediction of hydrogen concentration responsible for hydrogen induced mechanical failure in martensitic high strength steels," Dept. of Mechanical engineering, Aalto University, Finland, International Journal of Hydrogen Energy, 2023.

Aging Gas Pipelines in U.S. - % by Decade

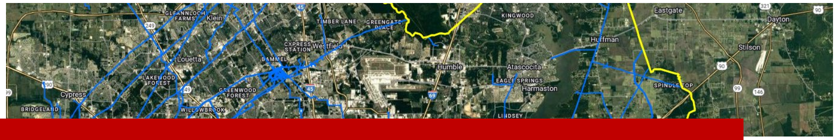
INSTALLED NATURAL GAS TRANSMISSION LINES BY DECADE



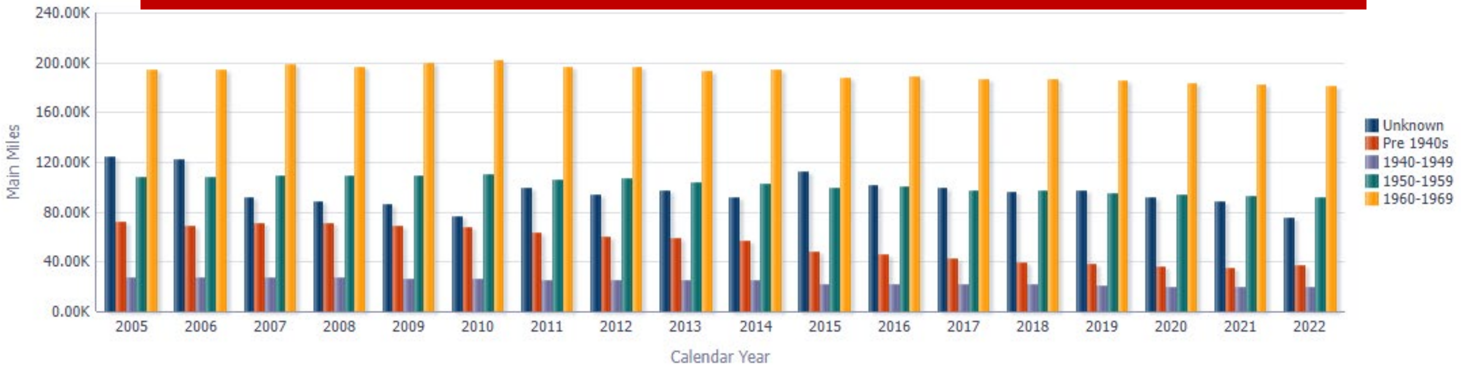
Post-1970 Miles by Decade



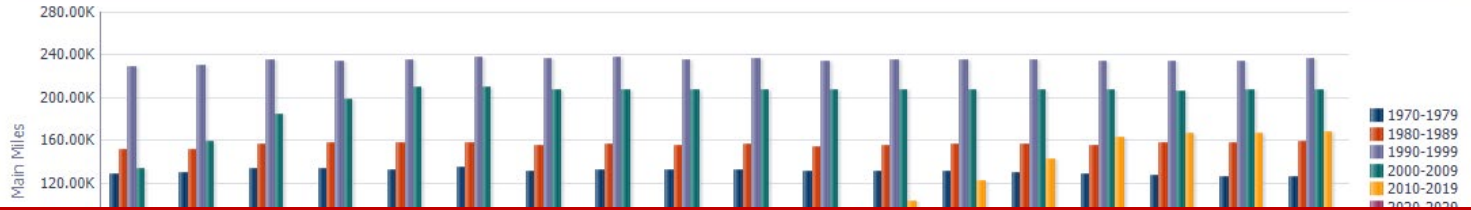
Harris County PHMSA regulated (non distribution) gas lines



INSTALLED NATURAL GAS DISTRIBUTION LINES BY DECADE



Post-1970 Mains by Decade



Overwhelming majority of U.S. gas transmission and distribution lines were installed prior to 1970 – with different steel compositions over time and with varying levels of corrosion exposure. Further, each decade has shown development and steel compositions will vary based on region, supplier and materials available at the time.

Two Case Studies - Operating Parameters

	Case A – Low Flow / High Ratio	**Case B – High Flow / Lower Ratio**
Flow Rate	150 mmscfd	500 mmscfd
Suction Pressure	169 psia (11.6 bar)	363 psia (25 bar)
Discharge Pressure	1440 psia (99 bar)	1087 psia (75 bar)
Pressure Ratio	8.52	3.0
Suction Temp	87 degF	87 degF

Case A – 150 mmscfd low flow case

Design Criteria	Case A – Low Flow / High Ratio
Q	150 mmscfd
Ps	169 psia (11.6 bar)
Pd	1440 psia (99 bar)
Pratio (Pd/Ps)	8.52
Ts	87 degF

	Recip Compressor A	Recip Compressor B	Recip Compressor C	Centrifugal Option A
# of Units	2 units in parallel	5 units in parallel	5 units in parallel	2 units in series – ext. geared
# of Stages / Intercoolers	2 stages / 1 intercooler & an aftercooler	3 stages / 2 intercoolers & an aftercooler	3 stages / 2 intercoolers & an aftercooler	4 casings / 2-3 intercoolers
Target Speed RPM	**360 RPM**	**713 RPM**	**1200 RPM**	**15,100-15,900 RPM**
Compressor / Motor Selection	6-cylinders – 13.5" & 22.75" bore x 14.0" stroke / 2 x 13,200 hp motor	6-cylinders – 9.125"-17.875" bore x 6.0" stroke / 5 x 5,000 hp motor	6-cylinders – 10.0"-13.0" bore x 6.0" stroke / 5 x 5,700 hp motor	15"-20" impellers x 40 impeller count per unit / 2 x 13,500 hp induction motors
Block / Skid Mount?	**Block Mount**	**Skid Mount**	**Skid Mount**	**Skid-Mount**

Case B – 500 mmscfd High Flow Case

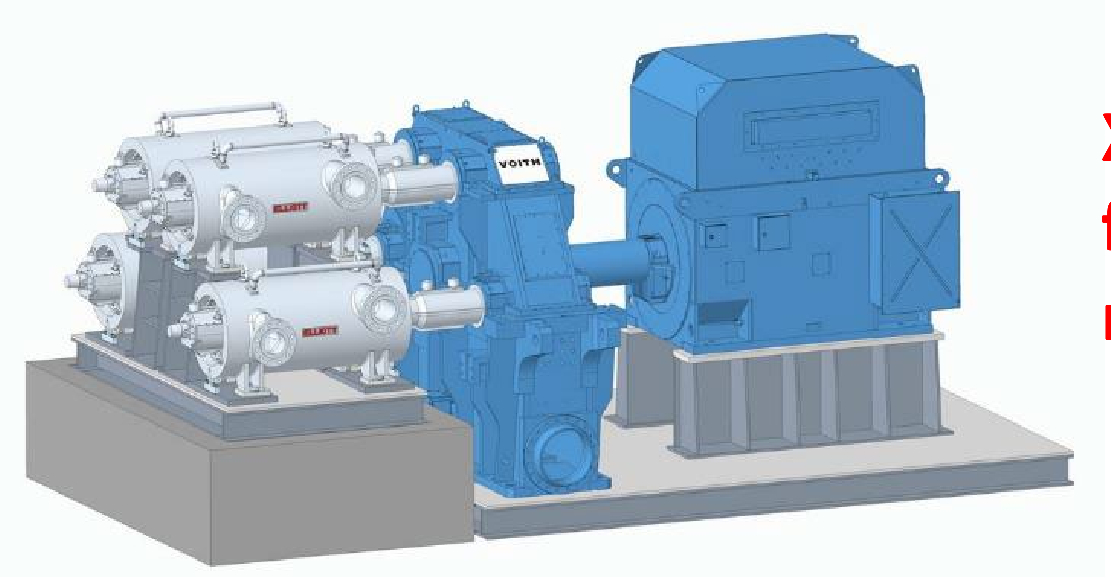
Design Criteria	Case A – Low Flow / High Ratio
Q	**500 mmscfd**
Ps	**363 psia (25 bar)**
Pd	**1087 psia (75 bar)**
Pratio (Pd/Ps)	**3.0**
Ts	**87 degF**

	Recip Compressor A	Recip Compressor B	Centrifugal Opt.A	Centrifugal Opt.B
# of Units	3 units in parallel	1 unit	2 units – externally geared – in parallel	2 units – 2 x double-ended motors - series
# of Stages / Intercoolers	2 stages / 1 intercooler & an aftercooler	2 stages / 1 intercooler & an aftercooler	4 stages – 3 intercoolers	LP stage: 2 casings HP stage: 2 casings
Target Speed RPM	**360 RPM**	**450 RPM**	**7500-9200 RPM**	**7500-8500 RPM**
Compressor / Motor Selection	5-cylinders – 19.75" & 20.5" bore x 14.0" stroke / 3 x 13,200 hp motor	8-cylinders – 22.5" & 30.5" bore x 12.0" stroke / 38,000 hp sync motor	25" - 32" impellers / 2 x 22,000 hp induction motors	25" + 29" + 32" +38" impellers / 2 x 22,000 hp induction motors
Block or skid Mount?	**Block**	**Block**	**Skid-mount**	**Skid-mount**

Centrifugal – Case A at 150 mmscfd

- Two units - Externally geared – In series – Four casings per unit

Elliott Compressor selection	No of intercooling stages	Motor + Gear?	# of casing	HP total	Poly efficiency	Speed RPM	Config options	Footprint	Approx Weight
20MB10 + 15MB10 + 15MB10 +15MB11	3	Ind. Motor + GB	4	13416	76.6-82.8%	15050 - 15874	FLEX OP	27' x 14' x 11'	320,000 lb

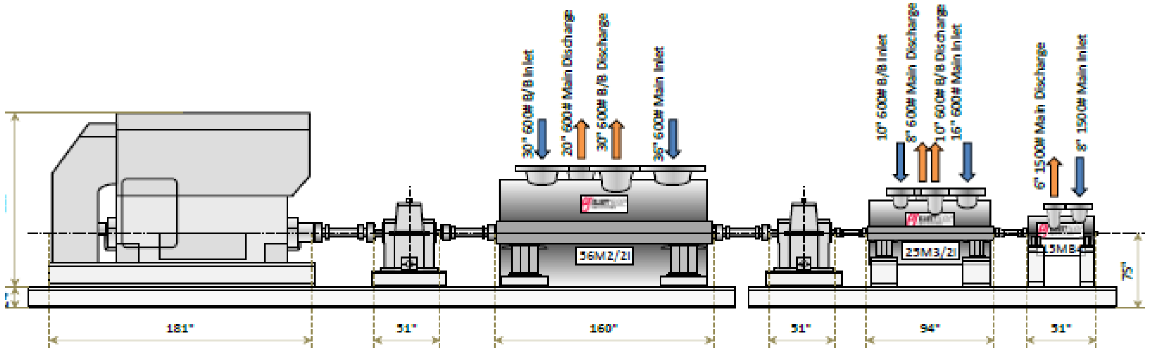


X2 units in series for total pressure range

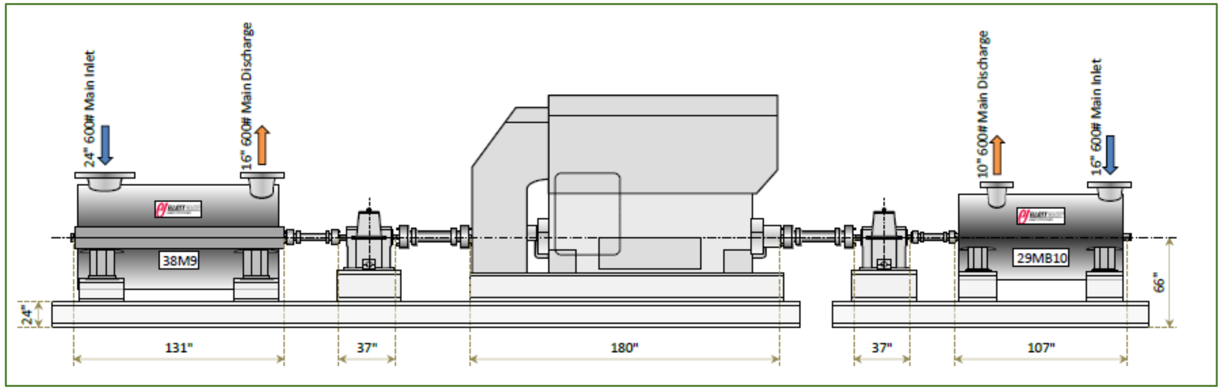
Centrifugal – Case B at 500 mmscfd

Elliott Compressor selection	No of intercooling stages	Motor + Gear?	# of casing	HP total	Poly efficiency	Speed RPM	Config options
38MB10 + 32MB10 + 32MB8	2	2 x Ind. Motor + GB	3	31037	82.5-83.2%	7398 - 8630	2 units in series = (1+2)

Can utilize single train with three casings + 2 gears



Or…. Single casing unit feeding a double ended motor arrangement ….



General Ads and Disads of Each Technology

Style of Compressor	Applications	Ads	Disads
Conventional In-line Multi-body	**Up to 16,000 RPM, High Ratio applications (CO2, H2, gas storage, injection)**	- High reliability - Robust surge control - High flow with VFD option - Incorporates barrel style case	- Longer footprint - Torsionally complex if drive thru - Limited to 3-4 bodies (head limits)
Externally Geared Multi-body	**Up to 16,000 RPM, Designed for Hydrogen Service**	- Optimize speed by stage - Designed for high head apps - Clutch in and out - Compact design - VFD / VSD option	- Limited # of bodies - Physical size limit on casings limits flow rates - Flow rate < 180 mmscfd
Two Body DE **(Double ended motor)**	**Mid-size Option for Natural Gas / CO2 / H2 pipeline,** **Up to 12,000 RPM**	- Fits well for certain PR - High Reliability - High pressure casings	- DE Motor lead times - Limited on pressure ratio
IGCC (Integrally geared centrifugal compressor)	**Up to 30-50k RPM** **Air compression, cleaner services**	- Typically open impeller design - Optimized speed by stage - Higher head per stage typically - Compact single casing	- Surge issues can be catastrophic - High # of Dry gas seal components - High thrust loads on start-up - Sensitive to fouling - Capital sparing differences
Reciprocating Compressors	**Up to 1,200 RPM upstream + Gathering applications, Smaller flows < 100 mmscfd**	- High pressure ratios - Dirtier gases - Accommodates intercooling well	- Flow rate limits - Some use Lubricated for optimum performance - Potential Pulsation + Vibration issues

Why H2 Blending for Pipelines Makes Less Sense

- Need > 10% Hydrogen to start to make a difference on carbon emissions due to the energy content difference
- Likely need > 30% to be economic for H2 hub and production costs to gain appreciable credit in CO reduction.
- Compressors for hydrogen will require completely different designs.
- Material “recipe” for carbon steel line can be customized for pure hydrogen to generate less susceptible steel for hydrogen degradation effects – if building new.
- Retrofit stations with blends introduce leakage risks at > 6-10% H2.
- Aging U.S. gas lines and unknown compositions / corrosion effects are a major concern for blended lines.
- Blended ratio for power delivery is tighter and easier to control if on a shorter blended line (in a H2 hub) → blending at point of use.
- Point of use blending for hydrogen into natural gas offers significantly less risk and can be blended for higher hydrogen content for lower emissions.

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THANK YOU !!! QUESTIONS ? COMMENTS?

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