LOW CARBON ENERGY SYSTEMS

ROLE OF HYDROGEN

Current Hydrogen Research and Technologies

HYDROGEN TECHNOLOGY CENTER

December 10, *2020*

RG 360 - Blending Renewable Hydrogen into the Natural Gas Pipeline: Key Opportunities and Challenges

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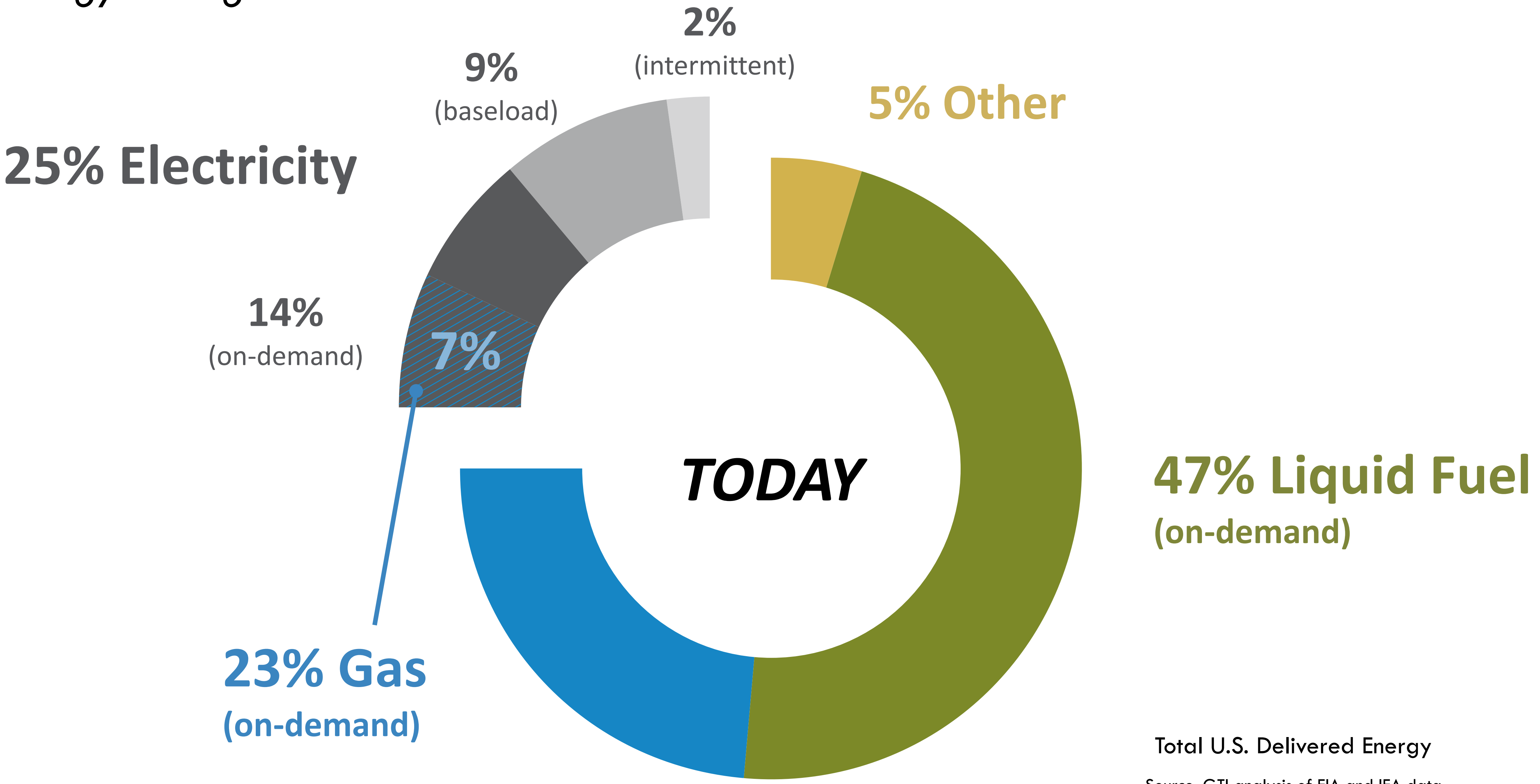
Hydrogen ...

- is an energy carrier that can be used to store energy over long periods of time and to transport energy over large distances
- provides a zero-carbon emissions fuel
- offers a beneficial use of excess electricity produced by renewables

US Energy System

Energy Storage

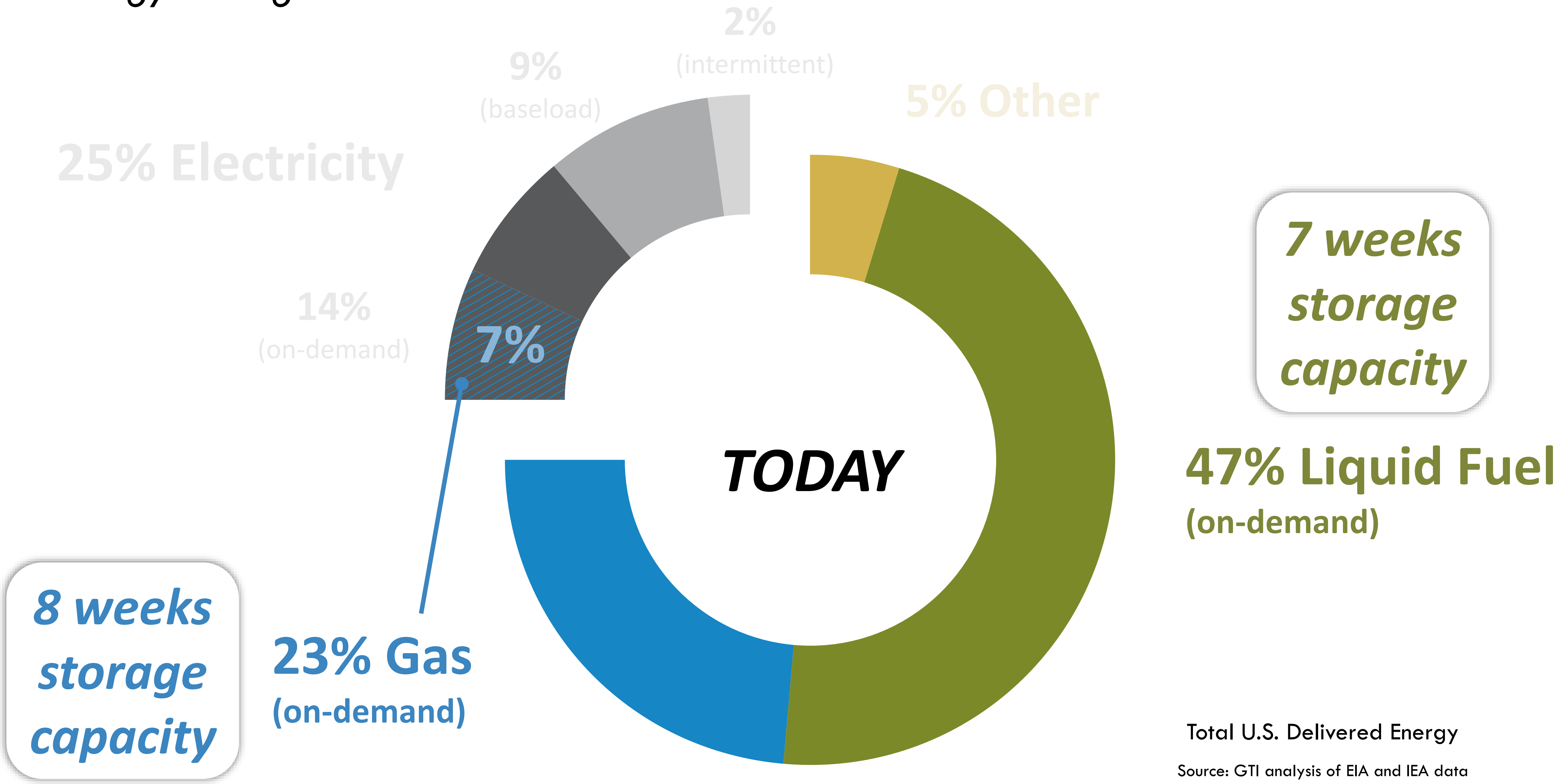


Total U.S. Delivered Energy

Source: GTI analysis of EIA and IEA data

US Energy System

Energy Storage



Total U.S. Delivered Energy

Source: GTI analysis of EIA and IEA data

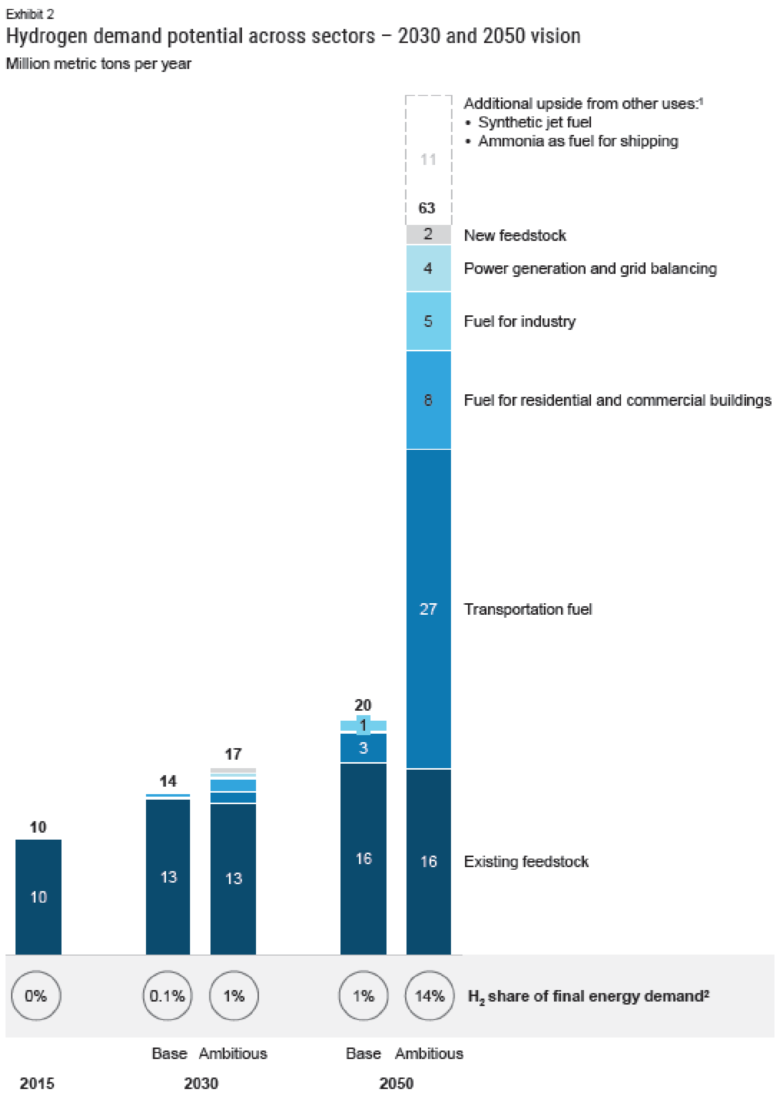
THE MOMENT FOR HYDROGEN IS NOW

Global Competitiveness

Accelerated Corporate Commitments

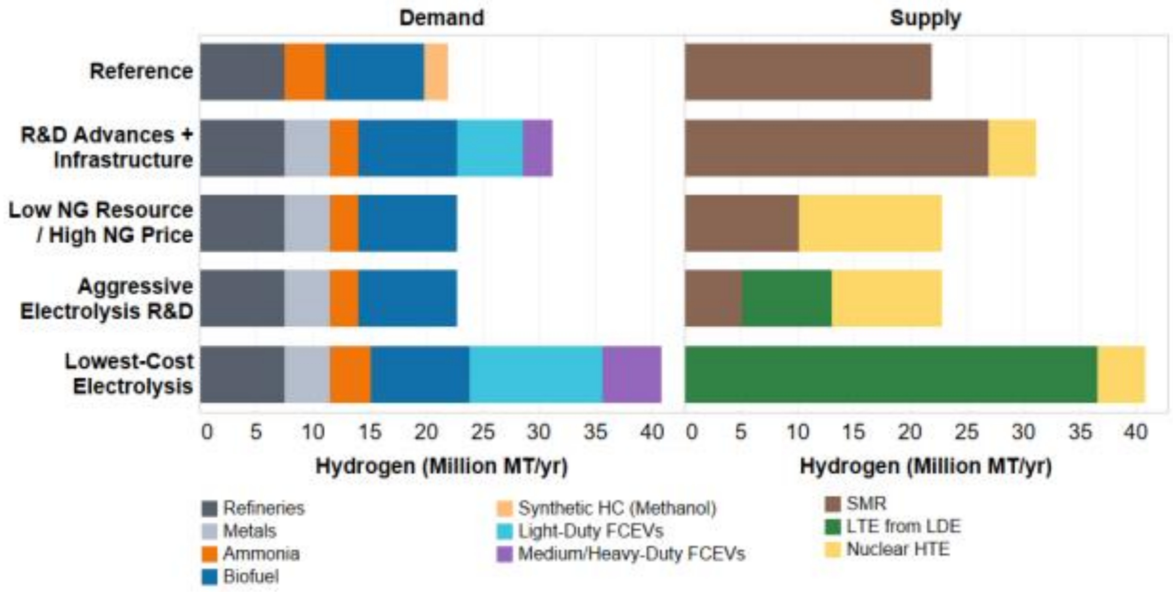
Growing Sources of Capital

ROBUST DEMAND FOR HYDROGEN



Hydrogen Demand Potential

Source: Roadmap to a US Hydrogen Economy



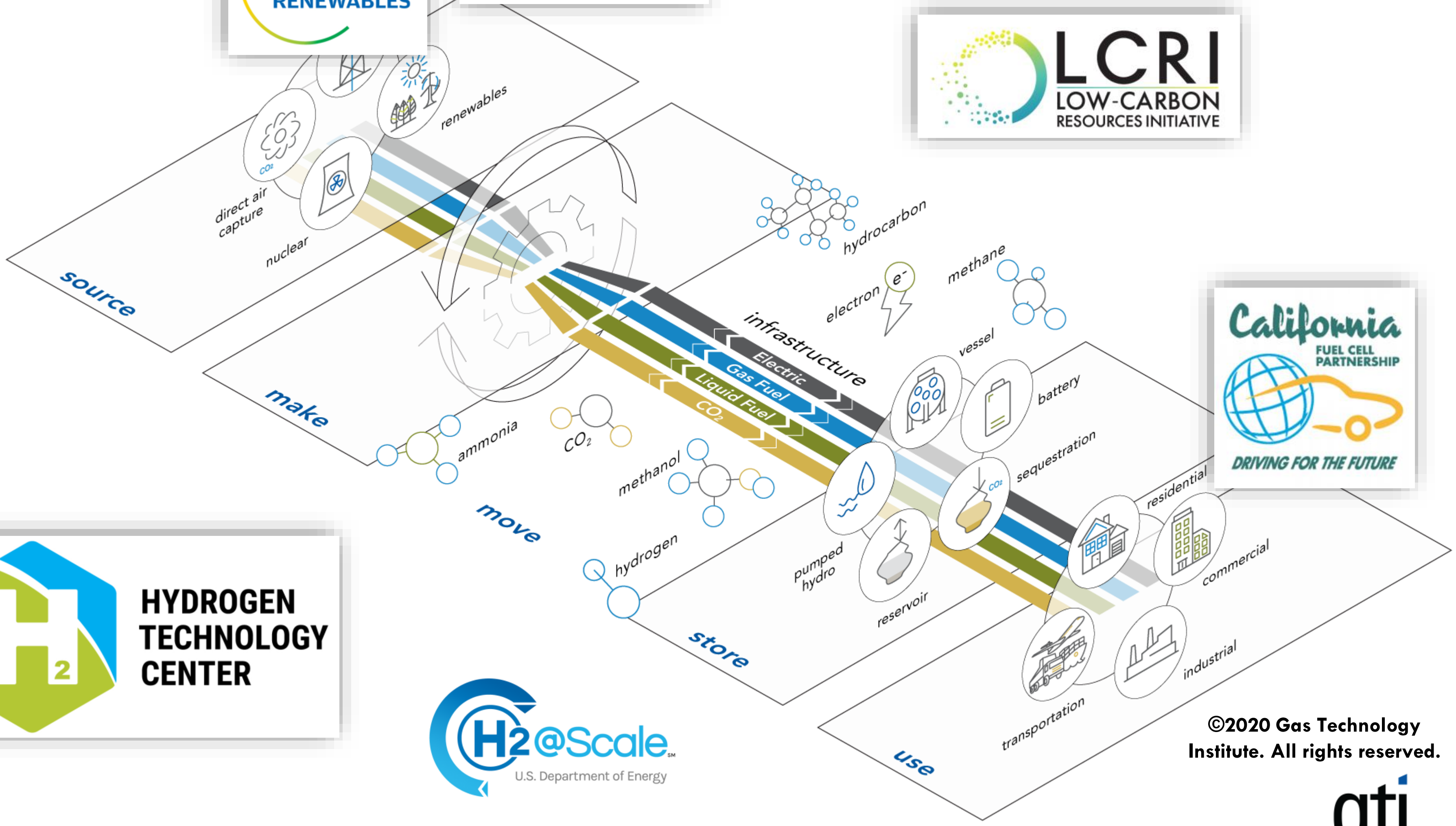
Economic Hydrogen Potential

Source: NREL The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States

LOW-CARBON HYDROGEN FUTURE

Integrated Energy System

GTI's Hydrogen Technology Center researches components of a hydrogen future to convert our vision for low-carbon energy systems into a reality.



SunGas RENEWABLES

HyPER

LCRI LOW-CARBON RESOURCES INITIATIVE

California FUEL CELL PARTNERSHIP DRIVING FOR THE FUTURE

HYDROGEN TECHNOLOGY CENTER

H2@Scale U.S. Department of Energy

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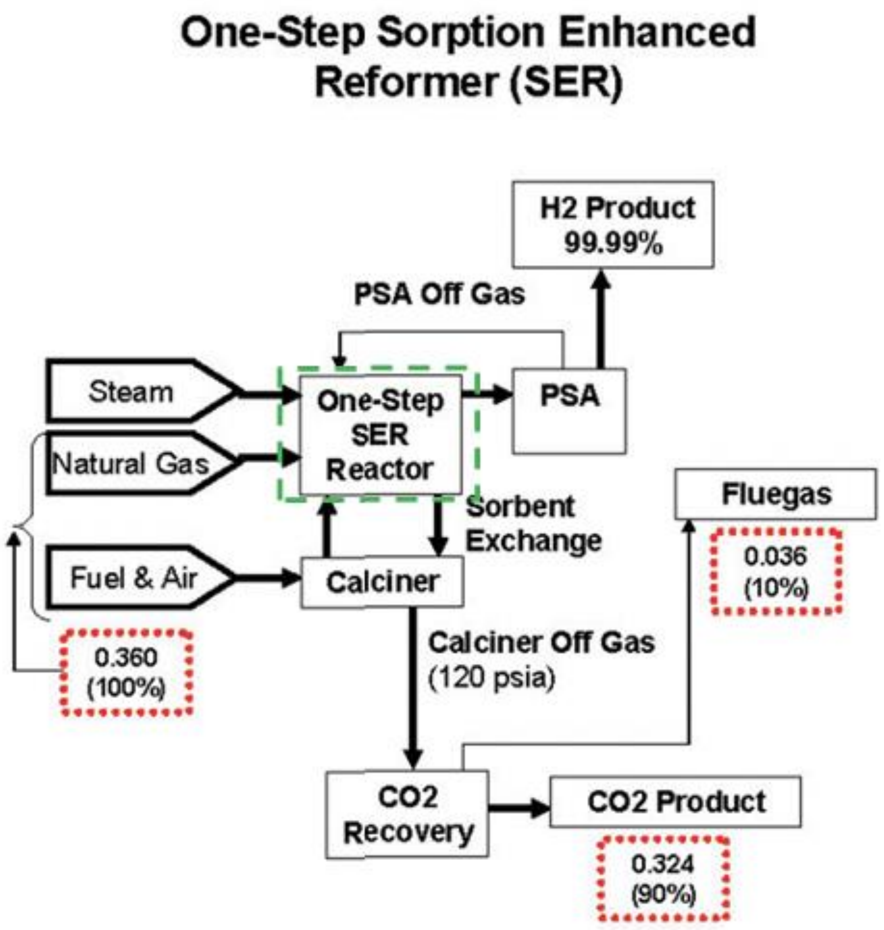
COMPACT HYRODGEN GENERATOR

Blue Hydrogen

- Steam-neutral alternative to traditional steam methane reforming (SMR)
- Reduces associated capital and operating expenditures
- Industrial-scale generation process yields near-zero carbon emissions power generation when combined with new turbine technologies
- Pilot-scale plant located at GTI's Illinois facilities
- 1.5 MW_{th} Pilot-scale plant located in the UK - HyPER Project



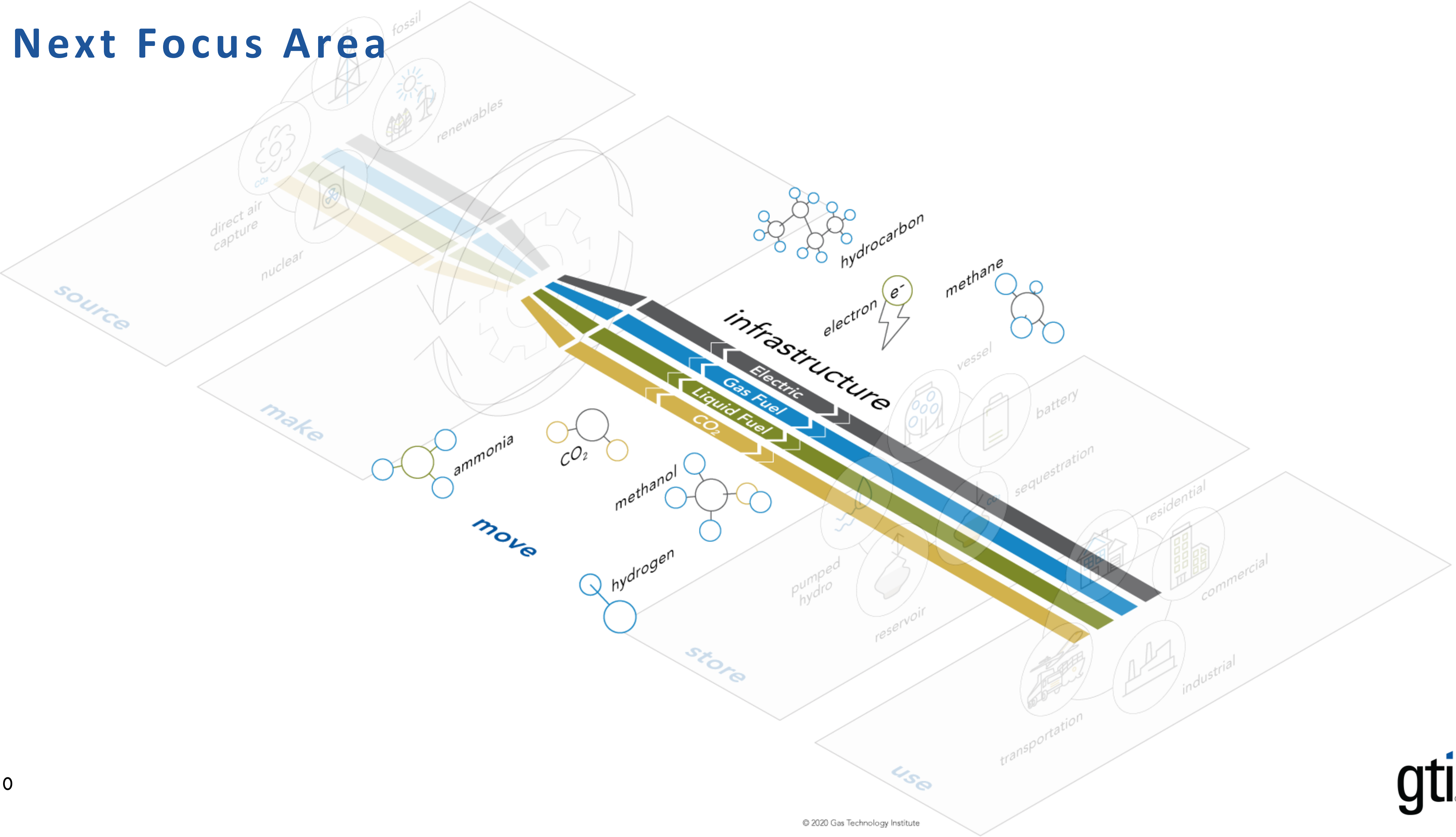
SUNGAS RENEWABLES

Renewable Hydrogen

SunGas converts the sun's energy from woody biomass at large scale into renewable syngas—producing low-carbon gaseous and liquid biofuels.

Transforming technological discoveries into commercial solutions

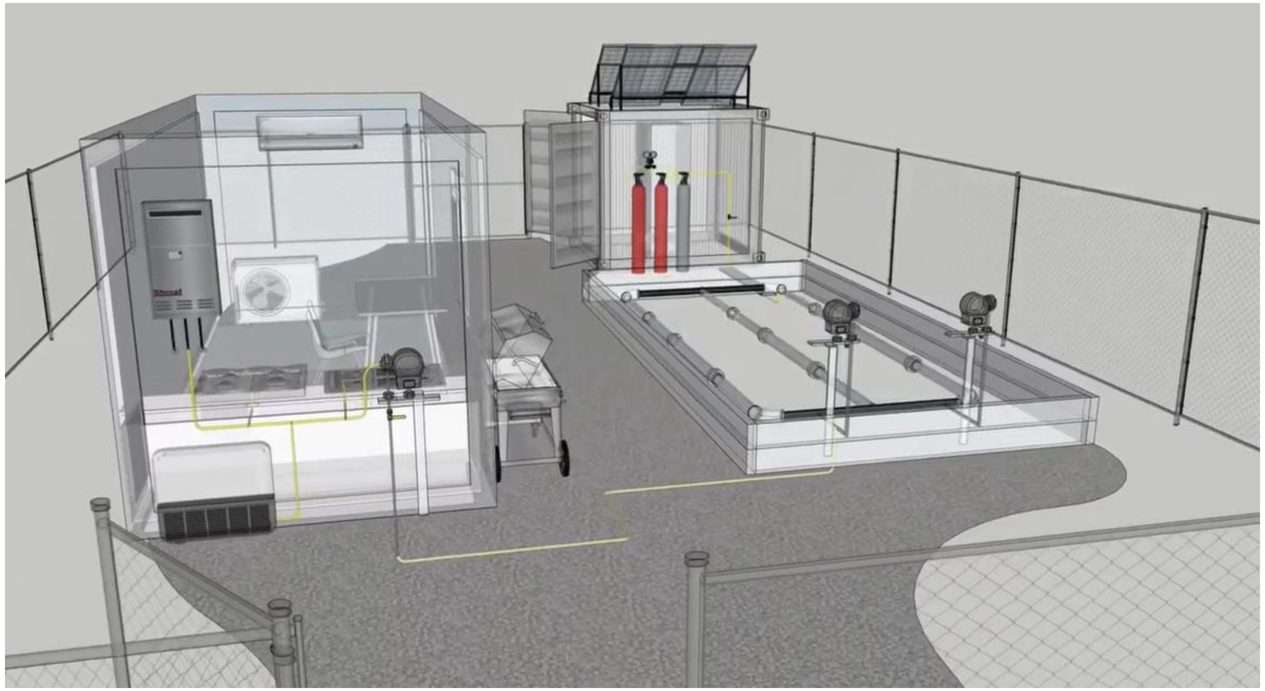
Next Focus Area



Enabling Gas Infrastructure for a Hydrogen Economy

Near Term R&D Opportunities

- Quantitative Risk Assessment of System
- Hydrogen Blending Test Facility
- Engineering and Safety Tools
- Standards and Codes
- Customer Focus, Outreach, Education
- Pilots



Evaluating Impacts of Hydrogen on Infrastructure and End Use Applications

R&D Portfolio

- SMP Development of Hydrogen Embrittlement Model for Steel Piping – Phase 1
- OTD 7.19. h Hydrogen Working Group
- OTD 6.14.b Effects of Hydrogen Blending in Natural Gas on Material Properties and Operational Safety Ph1 and Ph 2
- NYSEARCH Hydrogen Blend Impacts on Elastomer Materials
- CPUC Modeling of H2 Blending Impacts on Leak Rates and Pipeline Components
- SMP Hydrogen/Natural Gas Mixture Impacts on Legacy and Advanced Res/Com Combustion Equipment
- UTD 1.20.h High Hydrogen-Content Fuel in Residential/Commercial Combustion Equipment
- SMP Embedded Hydrogen Microsensor

Assessing Compatibility with Natural Gas Delivery Infrastructure

Scope of current research

- Evaluated effects of a 5% hydrogen-natural gas blend on non-metallic material properties and operational safety
- Determine safety factors for hydrogen gas systems need to be established based on materials tests
- Develop **engineering tools** to allow an integrity assessment and a safety margin determination of hydrogen blended gas use
- Determine operational impacts of a hydrogen blend in pipelines, such as leak detection, surveys, emergency response

Factors on Hydrogen Embrittlement Susceptibility
Environmental Factors
Role of Microstructure
Hydrogen Traps
Inclusions and Precipitates
Texture and Grain Boundary
Effects of Alloying Elements

Material Properties most affected by HE
Toughness
Reduction in Area
Crack Growth Resistance

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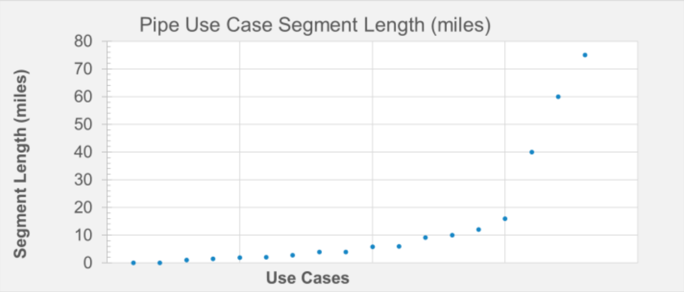
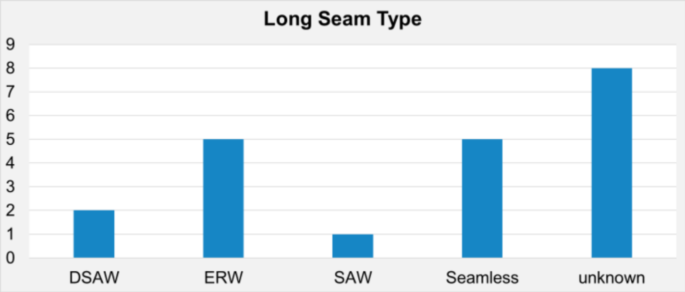
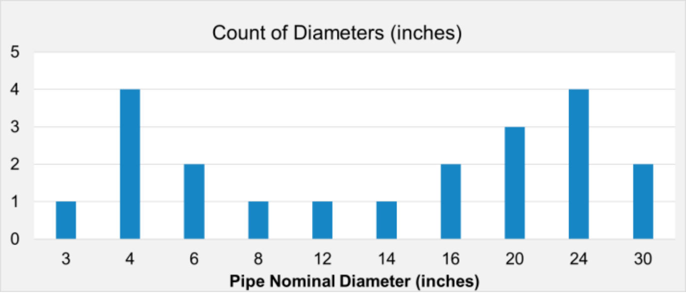
Hydrogen Blending Use Cases

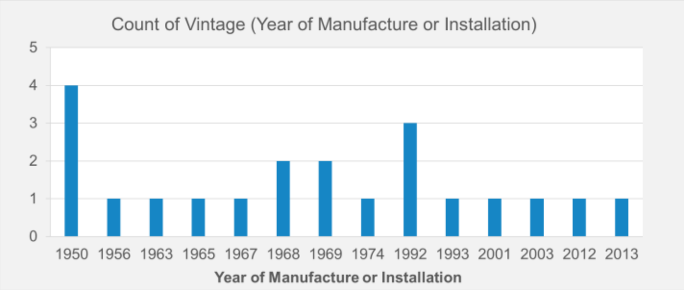
Survey Responses from Utility Project Sponsors

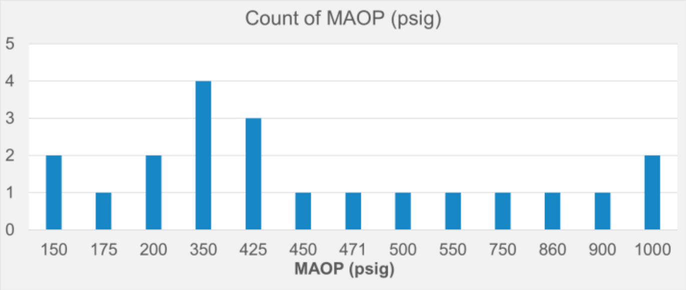
Min Temp	Ave Temp	Max Temp	Pressure Cycle Amplitude	Percent Hydrogen Desired	Depth of Cover
40F	58F	64F	Minimal to +/- 20 psig	5-15% (most use cases 5%)	1.7 to 6.8+ feet

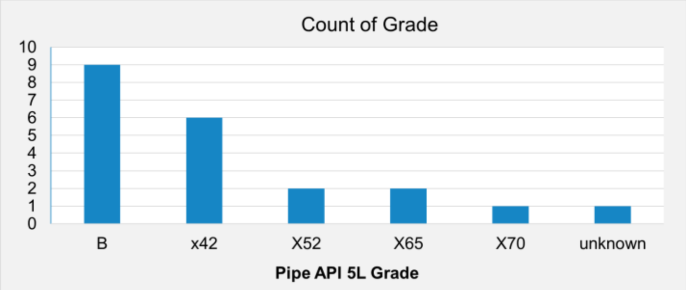






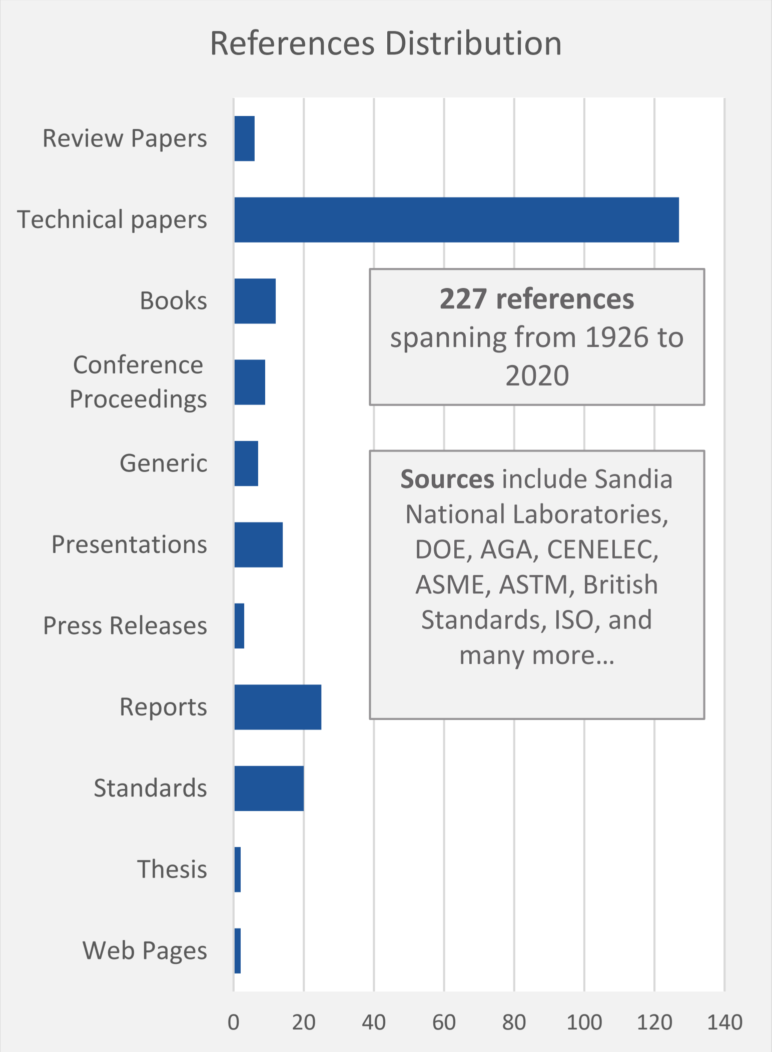






Studies on Hydrogen Impacts on Steel

Results from Comprehensive Literature Review



Factors on HE Susceptibility	
Environmental Factors	Xu, K. (2012). 14 - Hydrogen embrittlement of carbon steels and their welds
Role of Microstructure	Sha, Q. and Li, D. (2013). "Microstructure, mechanical properties and hydrogen induced cracking susceptibility of X80 pipeline steel with reduced Mn content."
Hydrogen Traps	Matsumoto, R., et al. (2009). "Atomistic simulations of hydrogen embrittlement."
Inclusions and Precipitates	Qin, W. and Szpunar, J. A. (2017). "A general model for hydrogen trapping at the inclusion-matrix interface and its relation to crack initiation."
Texture and Grain Boundary	Yao, J. and Cahoon, J. R. (1991). "Experimental studies of grain boundary diffusion of hydrogen in metals."
Effects of Alloying Elements	Huang, F., et al. (2010). "Effect of microstructure and inclusions on hydrogen induced cracking susceptibility and hydrogen trapping efficiency of X120 pipeline steel."

Material Properties most affected by HE	
Toughness	Hejazi, D., et al. (2012). "Effect of manganese content and microstructure on the susceptibility of X70 pipeline steel to hydrogen cracking."
Reduction in Area	Bueno, A. H. S., et al. (2008). Assessment of stress corrosion cracking and hydrogen embrittlement susceptibility of buried pipeline steels.
Crack Growth Resistance	Cialone, H. J., Holbrook, J. H., (1985). "Effects of gaseous hydrogen on fatigue crack growth in pipeline steel."

Hydrogen Blending Impacts on Steel

Plans for future tests

- Develop Design of Experiments Plans
- Proposed Physical and FEA Tests
  - Burst Testing
  - Tensile Testing
  - Notched Bar Impact Testing
  - Incremental Step Loading
  - Slow Strain Rate Testing
  - Fracture Toughness (Many Methods)
  - Fatigue Crack Initiation and Growth Rates
  - Threshold Stress Intensity Factor Determination
  - Hydrogen Uptake, Permeation, and Transport

Engineering Tools to Characterize Effects of Hydrogen Blending in a Pipeline System

Expected Deliverables

- Failure Assessment Diagram
  - Provide failure vs. safe condition for pipe system in the hydrogen environment.
- Critical Flaw Curves
  - Provide the length vs. depth relationship for flaws that would lead to pipe failure, therefore it will determine/inform inspection criteria of ongoing integrity assessments, as well as fitness for service decisions.
- Crack Growth Rate Plots
  - Provide expected time to failure based on crack growth rates in hydrogen blend environment.

Enabling Hydrogen Use for Residential/Commercial Applications

Terminology and Basics

Blending Impacts on Building Equip.:

While impacts will vary across product designs, generalized blending levels are:

- **Low Blending:** < 10% H_2 by vol.
  - No or minor equipment adjustments
- **Medium Blending:** 10% - 30% H_2 by vol.
  - Adjustments necessary with components and combustion controls
- **High Blending:** > 30% H_2 by vol.
  - Specially-designed equipment are required (e.g. Hydrogen Boiler)

THyGA

Classifications based on consensus of EU *THyGA* Project, w/ GTI as advisor

Feature	Compared to Methane	Possible Equipment Issues
Flame Temperature	Adiabatic flame temperature is about 500°F hotter than methane	Flame burns hotter, can lead to uneven heat transfer and material degradation
Flame Speed	Methane/air has a laminar flame speed of ~38 cm/s, however increasing H_2 volumes can increase over 2X (see Figure below)	Can lead to flame stability issues, ignition problems and flashback
Flammability Range	Hydrogen has an extremely wide flammability range (4% LEL to 75% UEL) compared to methane (5% LEL to 15% UEL)	H_2 portion can ignite prematurely in rich pockets of fuel/air mixture, leading to pre-ignition
By Products	Produces only water vapor when oxidized (no CO_2)	Flue gas dew point will be higher, leading to unwanted condensation/corrosion, also many products are calibrated to stack CO_2 which will be off
Visibility / Ionization	Hydrogen burns invisibly	Safety equipment to detect flame (flame rod, etc.) and technicians/operators will updating/training

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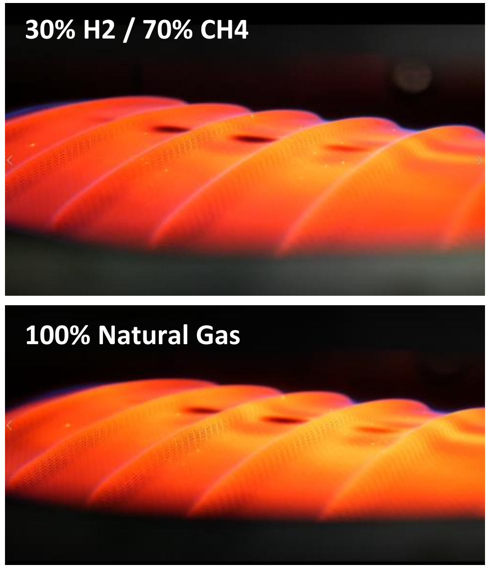
Enabling Hydrogen Use for Residential/Commercial Applications

Current Projects

- Demonstrate solutions to utilize high hydrogen blends in residential and commercial combustion equipment
- Performance testing of appliances with varying hydrogen blends
- Quantify the ability of appliances to retain normal operations (emissions, efficiency, cycling)
- Hydrogen sensor development for "behind the meter" applications and in-situ sensing



Engagement with Industry Partners

WEIL-McLAIN

BRADFORD WHITE WATER HEATERS

AOSmith

Rheem

TRANE TECHNOLOGIES

DGC Danish Gas Technology Centre

gwi Gaswärme-Institut e.V. Essen

TOKYO GAS

engie

DVGW

le gaz naturel

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Hydrogen Use in Transportation

Current Projects

Reducing Air Pollution With FAST TRACK Fuel Cell Truck Project for Zero-Emission Heavy-Duty Vehicles

- Deploying heavy-duty fuel cell-electric hybrid trucks in Southern California near Ports of Los Angeles and San Diego
- Extensive performance data and analysis from real-world conditions to determine the impact of broadly deploying zero-emission Class 8 trucks on local air quality
- Training and local community outreach

Improving Cost and Efficiency of Hydrogen Vehicle Fueling Infrastructure

Low maintenance cost—only one moving part

- Free-piston linear drive expander for H_2 cooling counteracts heating effects that occur when fuel cell vehicles are fueled
- Substantial capital and operating cost savings anticipated

California FUEL CELL PARTNERSHIP

DRIVING FOR THE FUTURE

GTI International subsidiary Frontier Energy has managed the CaFCP since inception 20 years ago

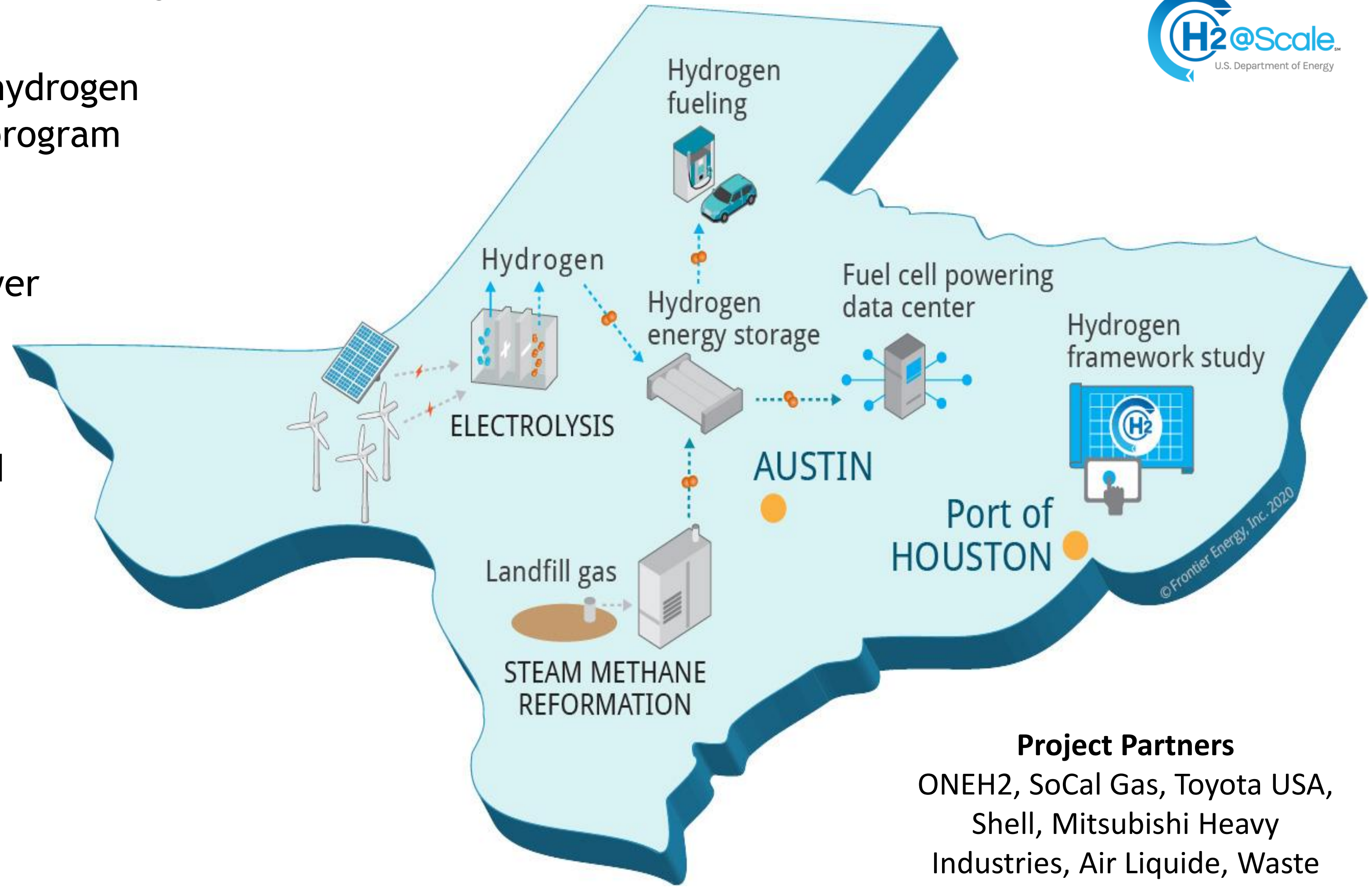
Demonstration and Strategic Planning for H2@Scale in Texas

Building a Framework for Hydrogen Integration

Design, build, and operate the first dedicated hydrogen infrastructure network under DOE's H2@Scale program

Hydrogen Framework Study - Port of Houston

- Analysis of the integration of Texas wind power and natural gas resources and infrastructure
- Actionable 5-year framework for the Port of Houston to enable used to enable the deployment of stationary fuel cell power and hydrogen-fueled vehicles
- Viability of "renewable hydrogen" opportunities
- Ways to increase resiliency of the power grid by low or zero-emissions, on-site power generation using hydrogen or natural gas/ hydrogen blends for fuel



Project Partners
ONEH2, SoCal Gas, Toyota USA, Shell, Mitsubishi Heavy Industries, Air Liquide, Waste Management, Chart Industries, ONEGas

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Enabling the Pathway to Economy-Wide Decarbonization

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Low Carbon Resources Initiative

LCRI LOW-CARBON RESOURCES INITIATIVE

The **Low-Carbon Resources Initiative** is a five-year, collaborative R&D commitment to reveal the pathway to advance low-carbon technologies for large-scale deployment approaching **2030.** Led by and funded through **EPRI and GTI**, the vision is to enable a risk-informed understanding of options and technologies for deep, economy-wide decarbonization, and advance these through applied engineering and technology acceleration.

$82M
+$10M EPRI

Funding
$100M

27

Members
50

WHY H_2 and related, low-carbon resources

Enabling infrastructure for future low-carbon fuel options

Hard-to-decarbonize sectors such as bulk transportation, large industries, and heating networks in cold climates

Large-scale clean power utilizing combustion turbines

Hydrogen Ammonia Biofuels Synthetic Fuels

Low-carbon Resource Production
- Hydrogen
- Biofuels

Low-carbon Power Gen.
- CCUS
- Hydrogen Turbines

Transmission, Delivery & Storage
- Existing Infrastructure
- New

End Use
- Industrial
- Transportation
- Buildings

VALUE CO_2

Individual commitment to environmental, social, and governance (ESG) efforts

Increase optionality of low-carbon solutions

Leverage investments across relevant sectors

Identify approaches to mitigate stranded assets

American Electric Power · aps · LA DWP Los Angeles Department of Water & Power · Missouri River Energy Services · GE · Duke Energy · Southern Company · Dominion Energy · ppl · Consumers Energy Count on Us · NOMAC · LES · Oglethorpe Power · Mitsubishi Power · conEdison · Exelon · Alliant Energy · CenterPoint Energy · New York State of Opportunity NY Power Authority · Portland General Electric · Southern California Edison · SRP · TVA · Nebraska Public Power District · National Fuel · SoCalGas A Sempra Energy utility · WEC Energy Group

WHAT'S NEXT

The Future – an Integrated Energy Systems Approach

Planning, investment, and R&D must consider:

- **the whole energy SYSTEM**

  not just a particular energy product, sector, or source

- **gas and liquid fuels will evolve and play a vital role**

  grid-scale, long-duration storage, long-distance energy transport, and difficult-to-decarbonize sectors

- **INFRASTRUCTURE is fundamental and near-term decisions have long-term impact**

  enable energy systems integration to deliver energy where we need it, when we need it

- **storage must balance both demand and supply**

  address seasonal variations, reliability, resiliency, and price volatility

Collaboration and Scale will Drive Progress

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Q&A

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