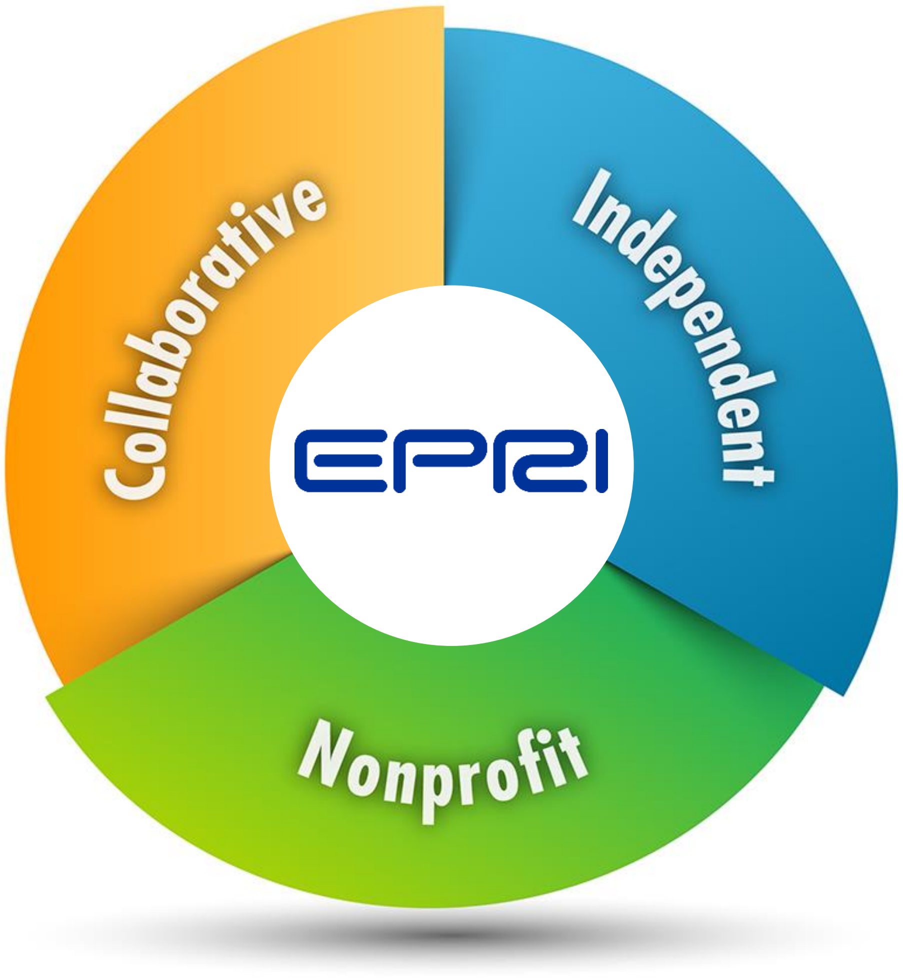
EPRI Research, Development and Demonstration Efforts

Low-Carbon Energy Carriers and Fuels

Tom Martz
Principal Project Manager, EPRI

NPPD / NDEE Power Summit
October 6, 2022

Three Key Aspects of EPRI



Independent

Objective, scientifically-based results address reliability, efficiency, affordability, health, safety, and the environment

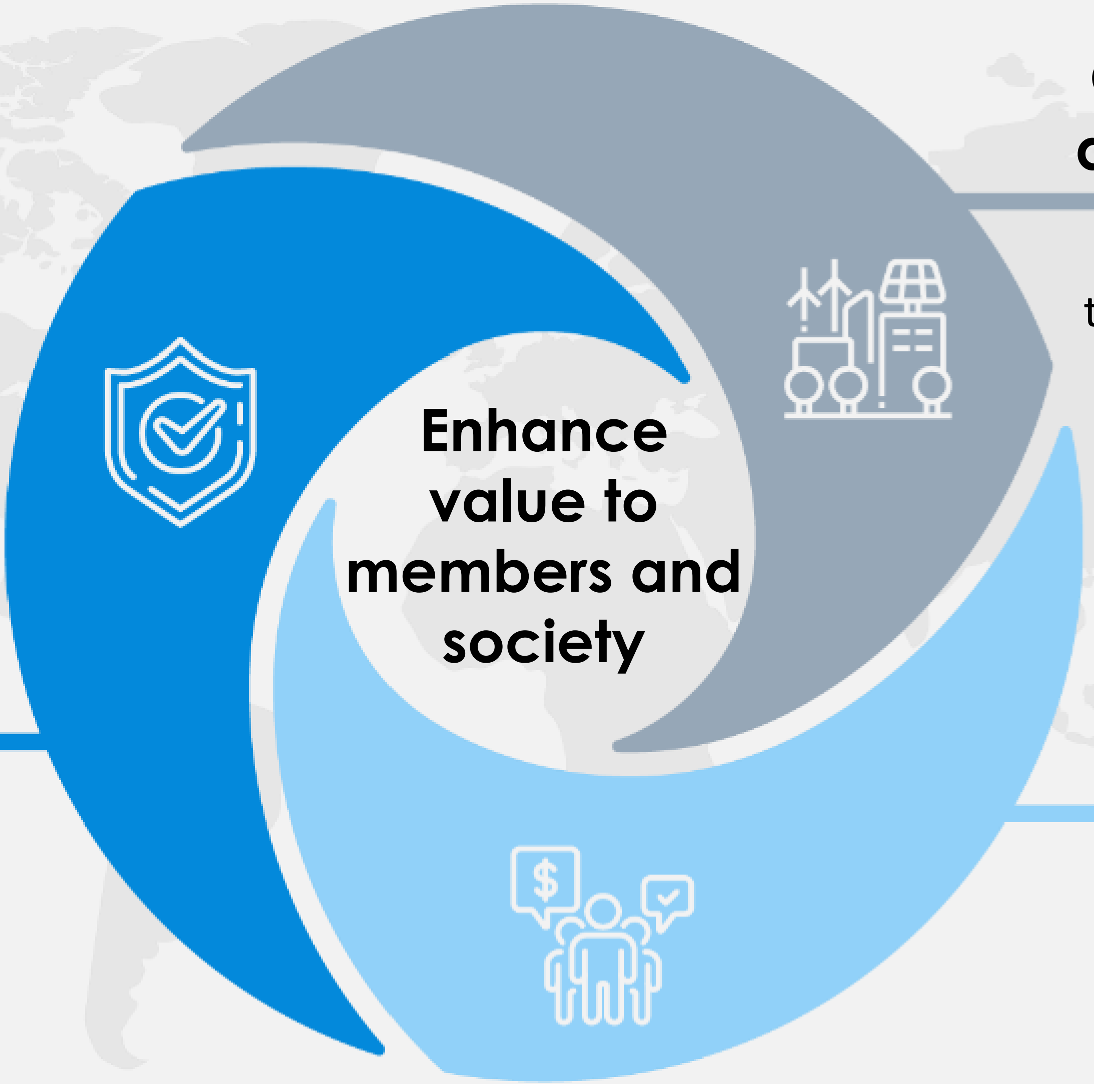
Nonprofit

Chartered to serve the public benefit

Collaborative

Bring together scientists, engineers, academic researchers, and industry experts

EPRI's Role



Pushing the technological frontier

Develop and evaluate solutions while engaging national labs, technical partners, and international stakeholders

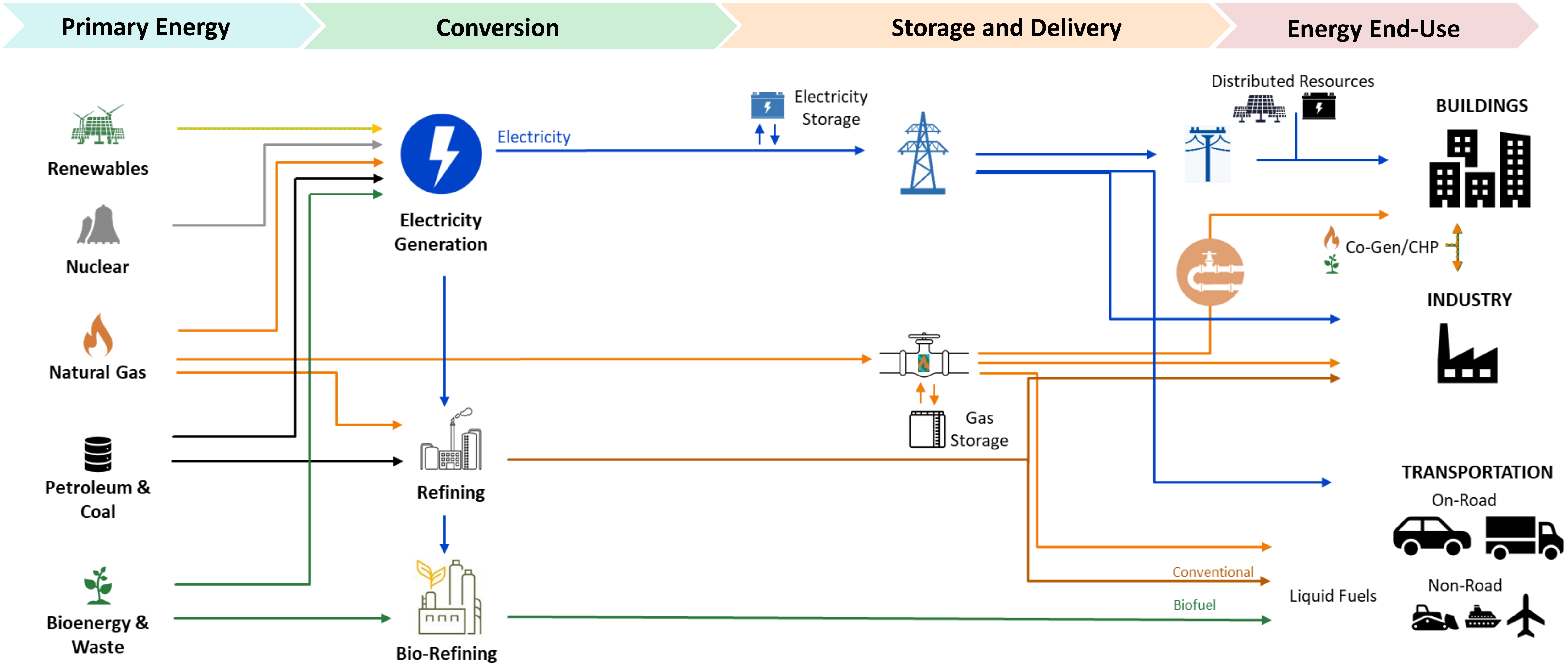
Guiding climate and grid strategy

Economy-wide modeling to optimize sustainability, reliability, and resiliency solutions

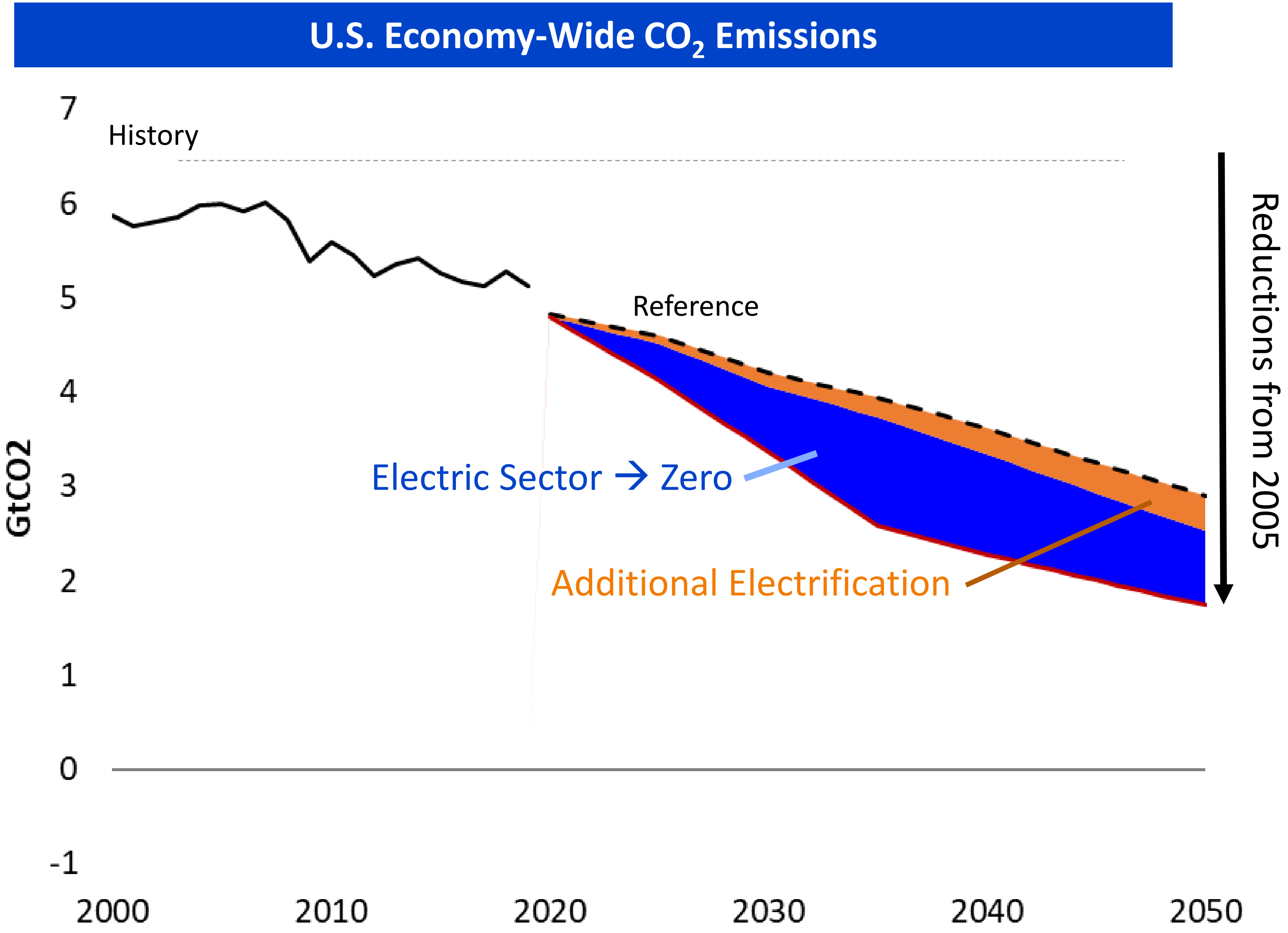
A trusted source of information

Industry, lawmakers, policymakers, thought leaders, regulators, financial community

Energy System is Becoming More Complex

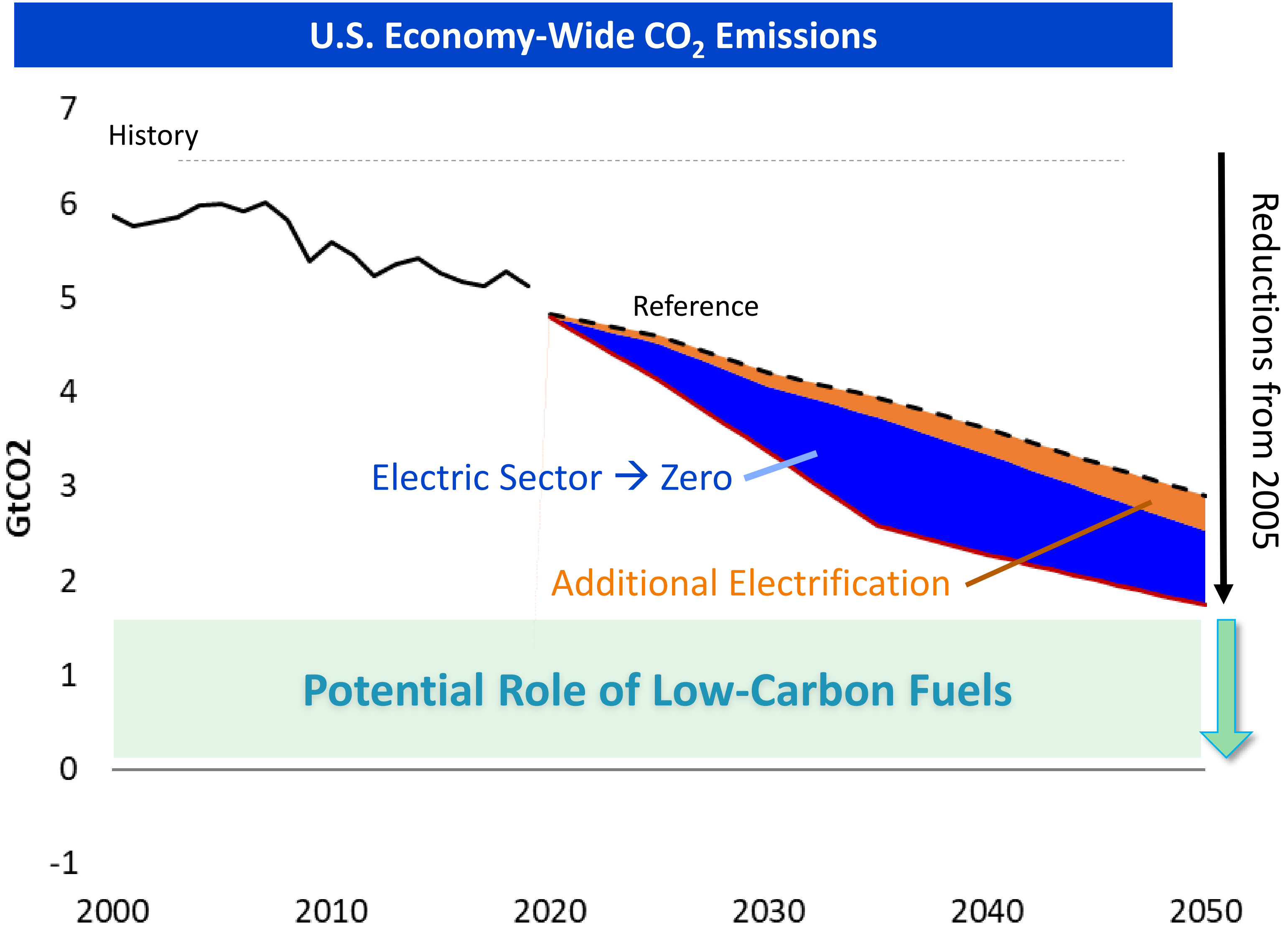


Reducing Economy-Wide CO_2 Emissions



EPRI Report 3002020700

Reducing Economy-Wide CO_2 Emissions



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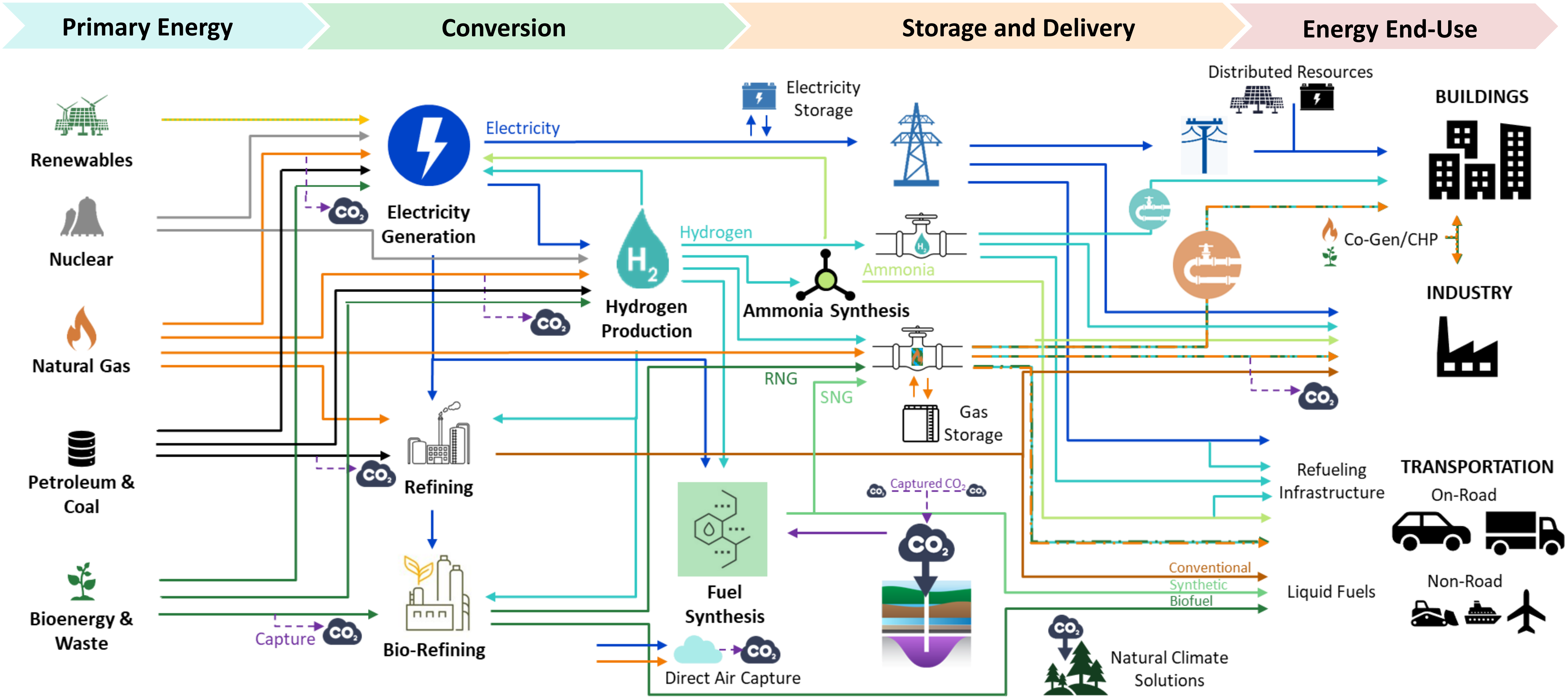
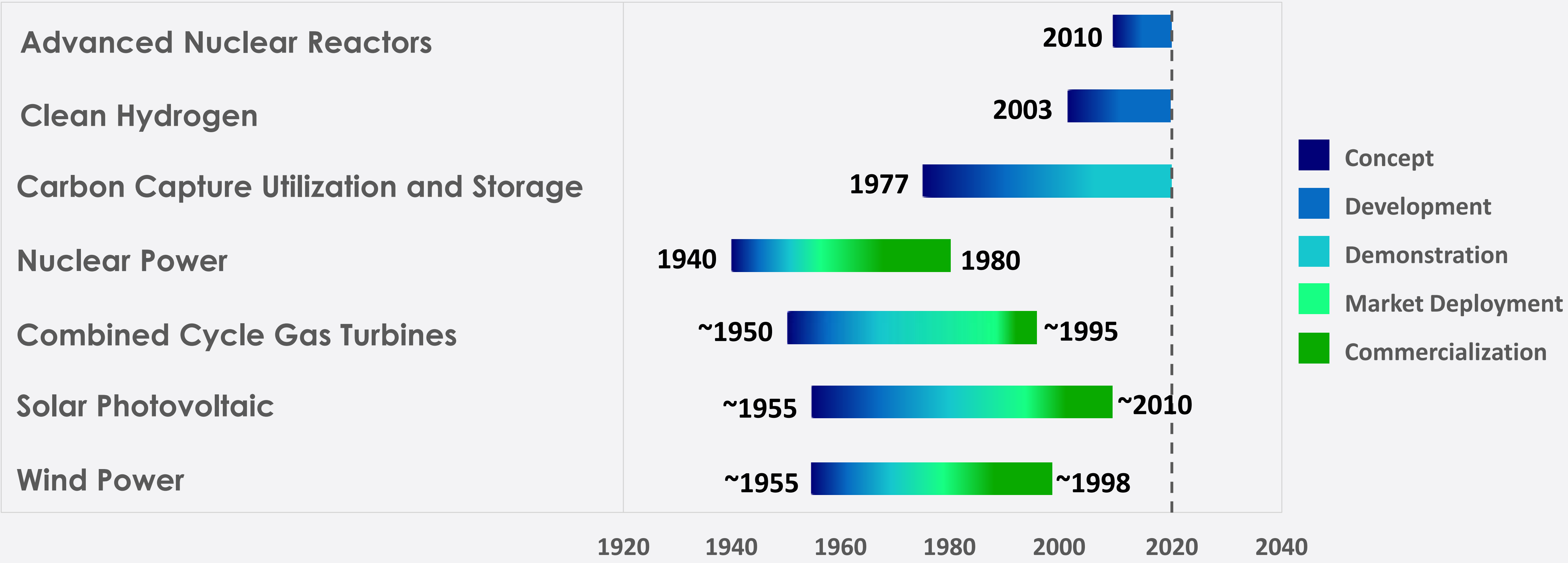
Energy System is Becoming More Complex



Concept to Commercialization Takes Decades



Notional timelines

Low-Carbon Resources Initiative

FOCUS

Multiple options and solutions to establish viable low-carbon pathways

Technologies for hard-to-decarbonize areas of the energy economy

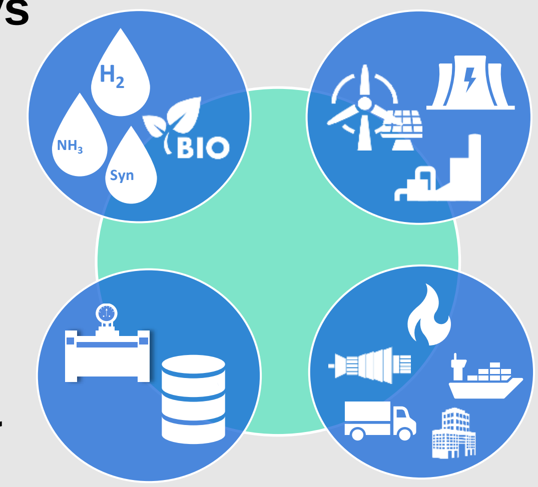
Affordable, reliable, and resilient integrated energy systems for the future

RESEARCH AREAS

Hydrogen | **Ammonia** | **Synthetic/ Derivative Fuels** | **Biofuels**

Production Pathways

Integrated Energy Systems



Storage & Delivery

End Use Applications

VALUE

Independent, objective research leveraged by global engagement and collaboration

Comprehensive approach to low-carbon value chain and technology analyses

High-impact results from technology evaluations, and safety, environmental, and economic assessments

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Beyond 2030 – Integration of Low-Carbon Energy Carriers

LCRI Focus: Hydrogen Ammonia Synthetic/ Derivative Fuels Biofuels

Production Sources

Next Gen Technologies

Integrated Clean Electricity

Integrated Nuclear (Current & Advanced)

Natural Gas with CCS

Delivery & Storage

Existing Natural Gas Pipeline through Blending and/or New Infrastructure

Shipping, Trucking, and Conversion/Intermediates Aboveground and Underground Storage

End Use Applications

Combustion

Heavy Duty Transportation

Electricity Generation

Advanced Fuel Cell

Large Industry

Chemical Processes

LCRI Research Vision Framework

LCRI Research Areas

- Renewable Fuels
- Hydrocarbon-Based Processes
- Electrolytic Processes
- Delivery & Storage
- Power Generation
- Transportation, Industry, & Buildings
- Safety and Environmental Aspects
- Integrated Energy System Analysis

RD&D Approach

Goals – Strategies – Actions – Activities

Technology Spectrum

Track – Participate – Lead

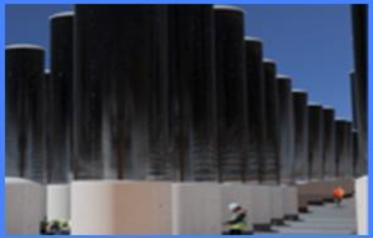
https://lcri-vision.epri.com/

Current LCRI Technology Demonstration Portfolio

LCRI LOW-CARBON RESOURCES INITIATIVE

H_2 Production from Nuclear

Advanced Oxy-Combustion



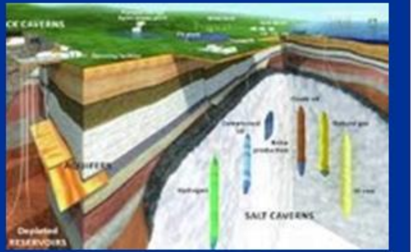
Direct Air Capture of CO_2

Flexible Gasification for Generation

Moving-Bed Gasifier Performance

H2@Scale Electrolyzer

H_2 Storage for Flex Fossil Power Gen

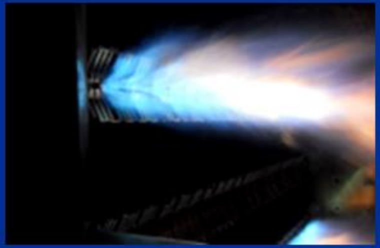


Integrated H_2 Energy Storage

H_2 Grid Integration and Scaling

HyBlend Pipeline Demos

H_2 Negative Emissions Demonstration



H_2 Storage for Load Following

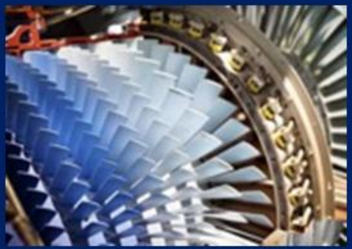
H2@Scale H_2 Fueling Station

H_2 Leak Monitoring

H2@Scale Fuel Cell Demo

H2@Scale SMR from Landfill Gas

H_2 Locomotive



H_2 in Combustion Turbines and RICE

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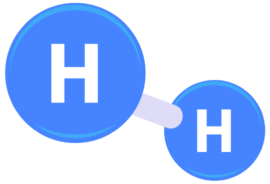
LCRI Value Chain Project Example

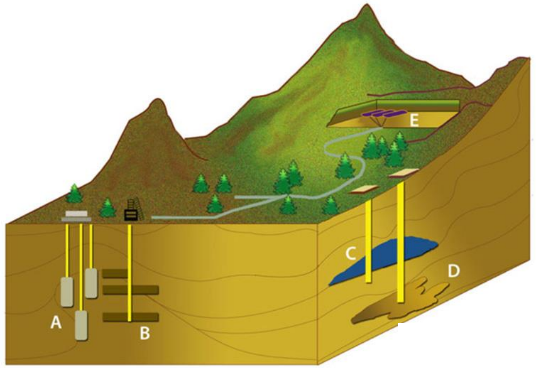
LCRI LOW-CARBON RESOURCES INITIATIVE

Variable Renewable Energy (VRE)

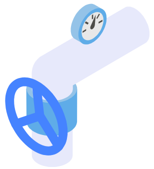
H_2 Production
(Electrolysis)



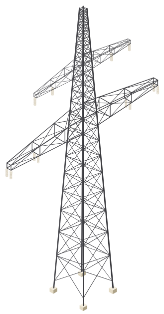
Underground H_2 Storage



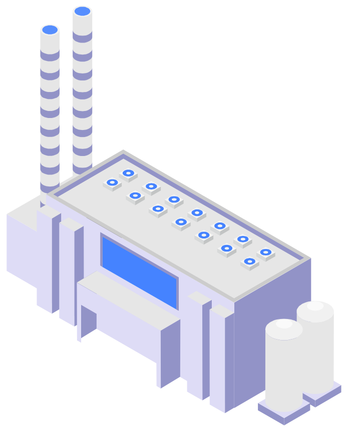
H_2 End Uses
(Sector coupling: transportation, industry, buildings)



Power Grid



Decarbonized, Dispatchable Power
(100% H_2-capable gas turbines)



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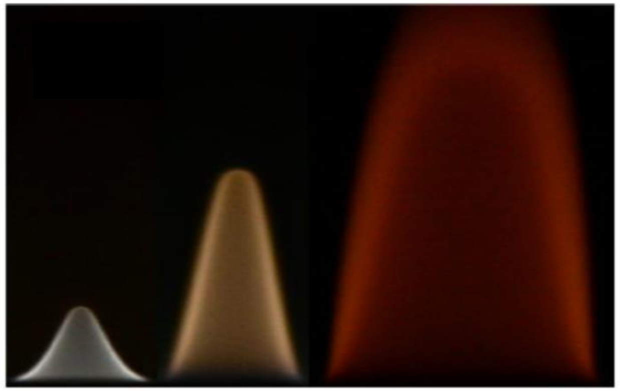
Power Generation TSC

Power Generation Research Priorities

TSC Research Objectives

1. Confirm the viability of **alternative energy carriers (AECs)** as fuels for power generation – both in pure or blended mixtures
2. Identify and lead efforts to accelerate advanced power generation technology development
3. Support large-scale technology and system integration



Research Impact

- Create an independently generated database of emissions characteristics resulting from the combustion of AEC fuels; **first priority is hydrogen and ammonia**
- Conduct power generation field demonstrations using AEC fuels in collaboration with LCRI member companies

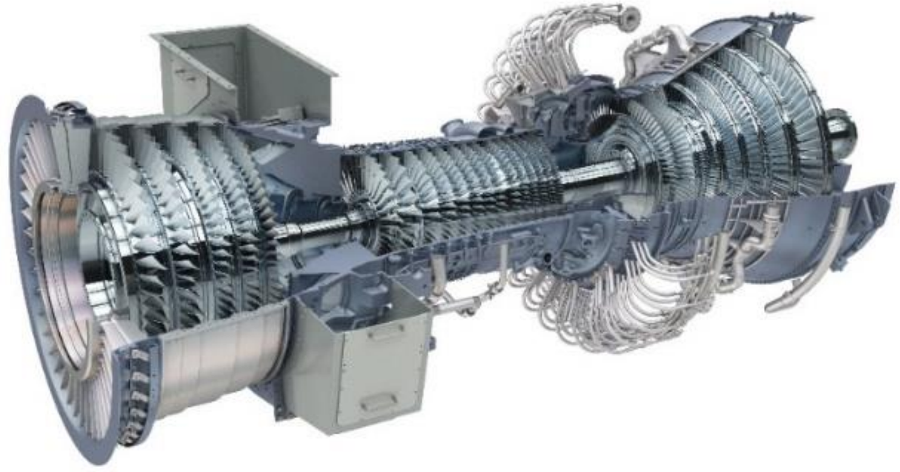
How Does CH_4 Stack Up to H_2 & NH_3?

Methane	Hydrogen	Ammonia
Lower Heating Value (LHV) Mass: 50 MJ/kg (21,500 BTU/lb) Volume: 915 BTU/scf	**Lower Heating Value (LHV)** Mass: 120 MJ/kg (51,600 BTU/lb) Volume: 275 BTU/scf	**Lower Heating Value (LHV)** Mass: 18.6MJ/kg (8,000 BTU/lb) Volume: 365 BTU/scf
Flame Speed (S_L) 37 cm/s (1.2 ft/s)	**Flame Speed (S_L)** 291 cm/s (9.5 ft/s)	**Flame Speed (S_L)** 7 cm/s (0.23 ft/s)
Flame Temperature (T_{ad}) 1950°C (3542°F)	**Flame Temperature (T_{ad})** 2110°C (3830°F)	**Flame Temperature (T_{ad})** 1800°C (3272°F)

Hydrogen burns 9 times faster than methane & 42 times faster than ammonia

Challenge for Hydrogen Combustion in Gas Turbines

- State of the art low NOx combustors are premixed
  - Compliant NOx
  - No water injection
- Today's premixed combustor concepts cannot accommodate high H_2 due to flashback
- Older diffusion technologies can handle H_2 but produce higher NOx
- Challenge: need low NOx combustor concepts for high H_2



Recent Technology Overview: State of the Art OEM Offerings

	Type	Notes	TIT °C [°F] or Class	Max H_2 % (Vol)
MHPS	Diffusion	N2 Dilution, Water/Steam Injection	1200~1400 [2192~2552]	100
MHPS	Pre-Mix (DLN)	Dry	1600 [2912]	30
MHPS	Multi-Cluster	Dry/Underdevelopment - Target 2024	1650 [3002]	100
GE	SN	Single Nozzle (Standard)	B,E Class	90-100
GE	MNQC	Multi-Nozzle Quiet Combustor w/ N2 or Steam	E,F Class	90-100
GE	DLN 1	Dry	B,E Class	33
GE	DLN 2.6+	Dry	F,HA Class	15
GE	DLN 2.6e	Micromixer	HA Class	50
Siemens	DLE	Dry	E Class	30
Siemens	DLE	Dry	F Class	30
Siemens	DLE	Dry	H Class	30
Siemens	DLE	Dry	HL Class	30
Ansaldo	Sequential	GT26	F Class	30
Ansaldo	Sequential	GT36	H Class	50
Ansaldo	ULE	Current Flamesheet™	F, G Class	40
Ansaldo	New ULE	Flamesheet™ -- Target 2023	Various	100

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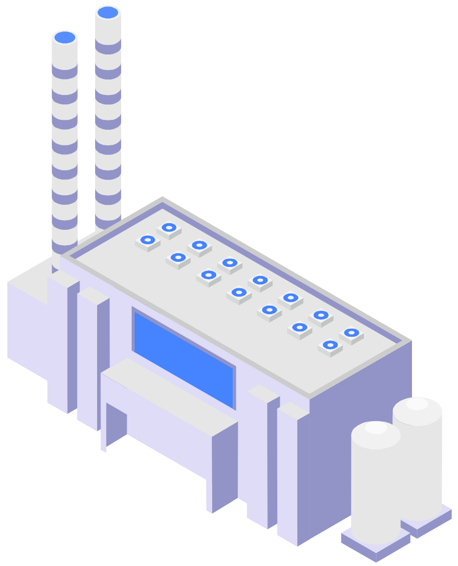
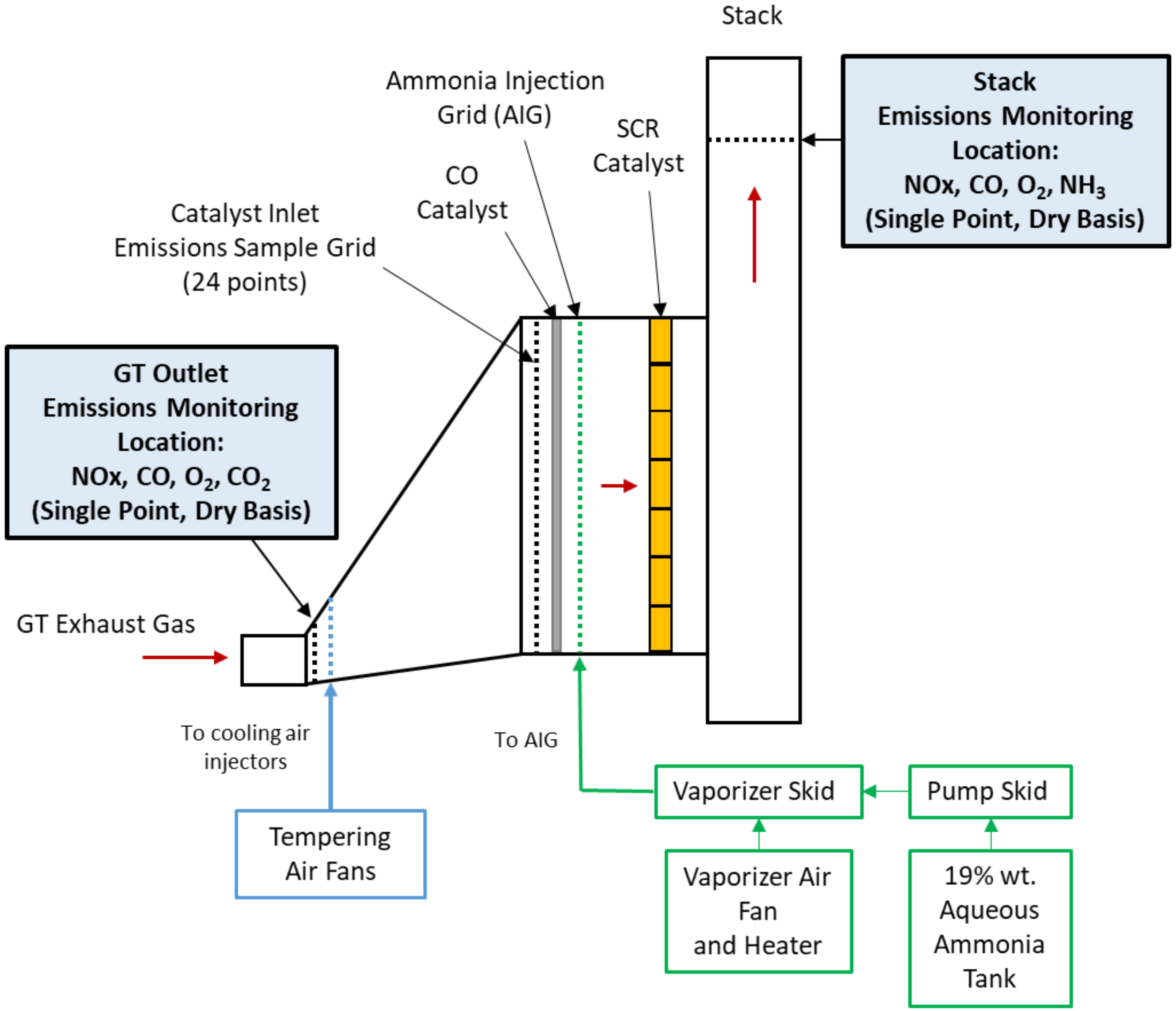
NOx Production, Monitoring and Control

- NOx production, monitoring and control are key considerations in the investigation of natural gas (NG), H_2 and NH_3 fuel blends as decarbonization options for gas turbines (GTs)
- Cross-cutting interest from **LCRI Power Generation and EA&S TSCs**
  - NOx Production
    - LCRI Technical Briefs 3002017544 and 3002020043 and LCRI GT technical report
    - LCRI work completed or in progress (Power Generation TSC)
      - **NYPA Brentwood GE LM6000PC Sprint gas turbine burning up to 44% H_2 by volume** (3002025167)
      - High H_2 Combustion Fundamental NOx Production Limit Study
      - Study of H_2 and NH_3 Blend Combustion Fundamentals
  - NOx Monitoring
    - **Investigation of dry ppmv (ppmvd) measurements and O_2 corrections with NG/H_2 fuel blending** (Georgia Tech / EPRI paper for ASME Turbo Expo GT2022)
    - Review of ppmvd to mass rate conversions (EPA Method 19 F Factor) with NG/H_2 fuel blending
  - NOx Control: SCR Design Considerations
    - LCRI Technical Brief 3002022688



NYPA Brentwood H_2 Co-firing Demonstration

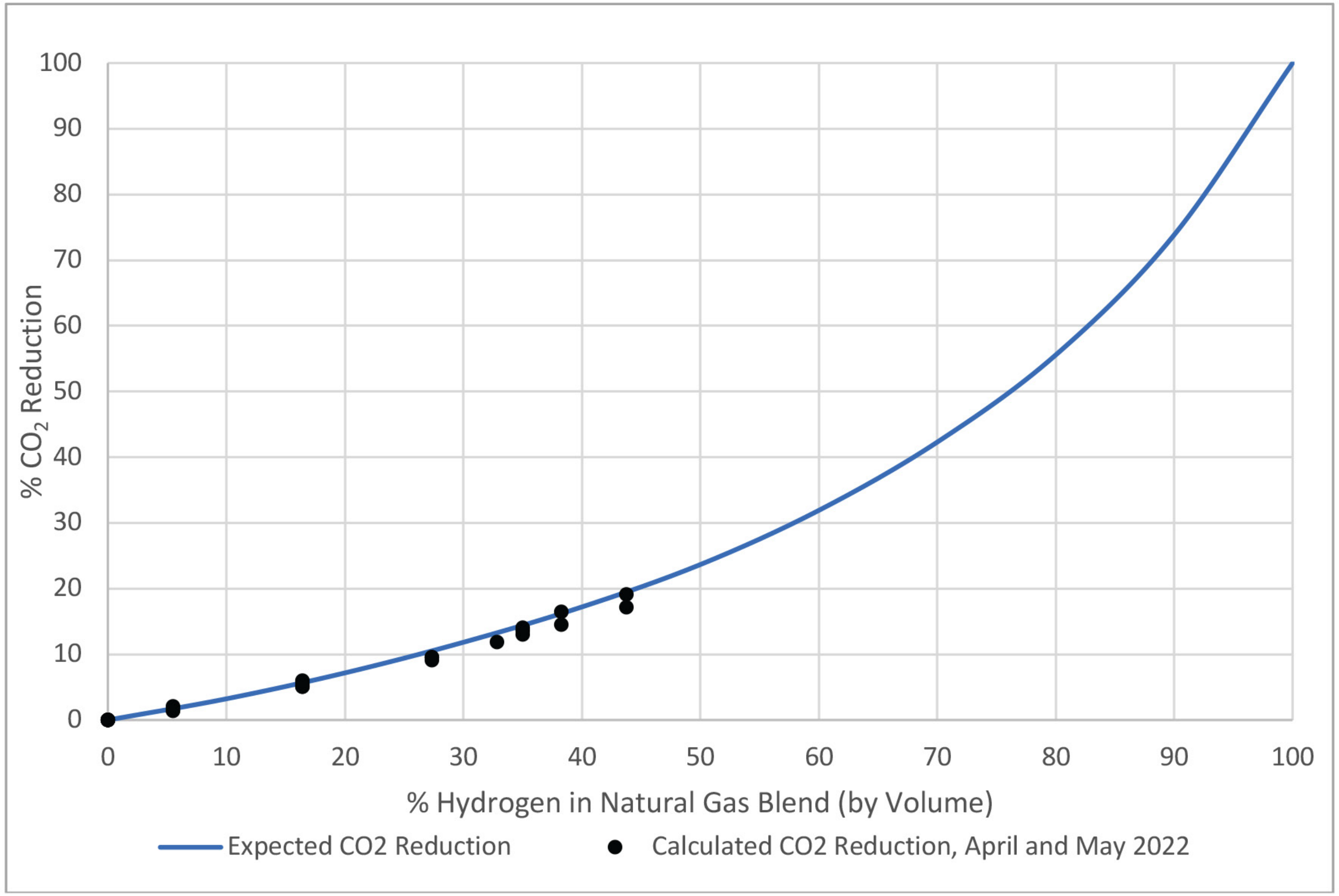
- **GE LM6000 GT** (47 MWg peaker) equipped with single annular combustion (SAC) technology
- Requires **water injection** for NOx control
- Also equipped with post-combustion catalyst systems for NOx and CO control
- Working with EPRI, GE, and other industry collaborators, **NYPA fired blends of 5–44% green hydrogen** (by volume) with NG
- Identified and documented the resulting **impacts on GT outlet emissions (CO_2, NOx, CO) and unit operation**



NYPA Brentwood: CO_2 Reduction

Observations

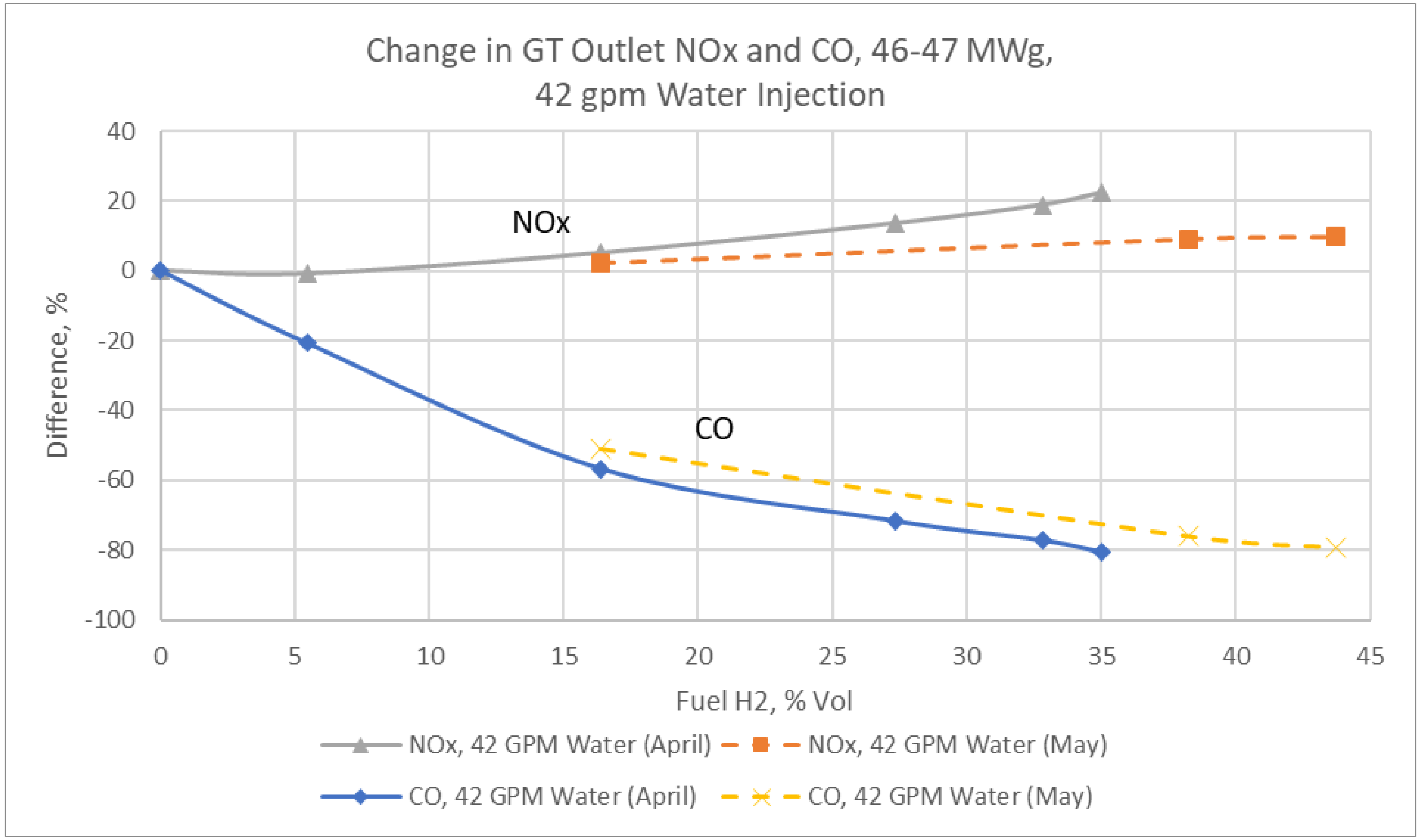
- CO_2 mass emission reductions followed expected trends, decreasing as H_2 increased
- At 47 MWg, CO_2 mass emission rates were reduced by ~14% at 35% H_2 (volume)



NYPA Brentwood: GT Outlet NOx and CO Impacts

Observations

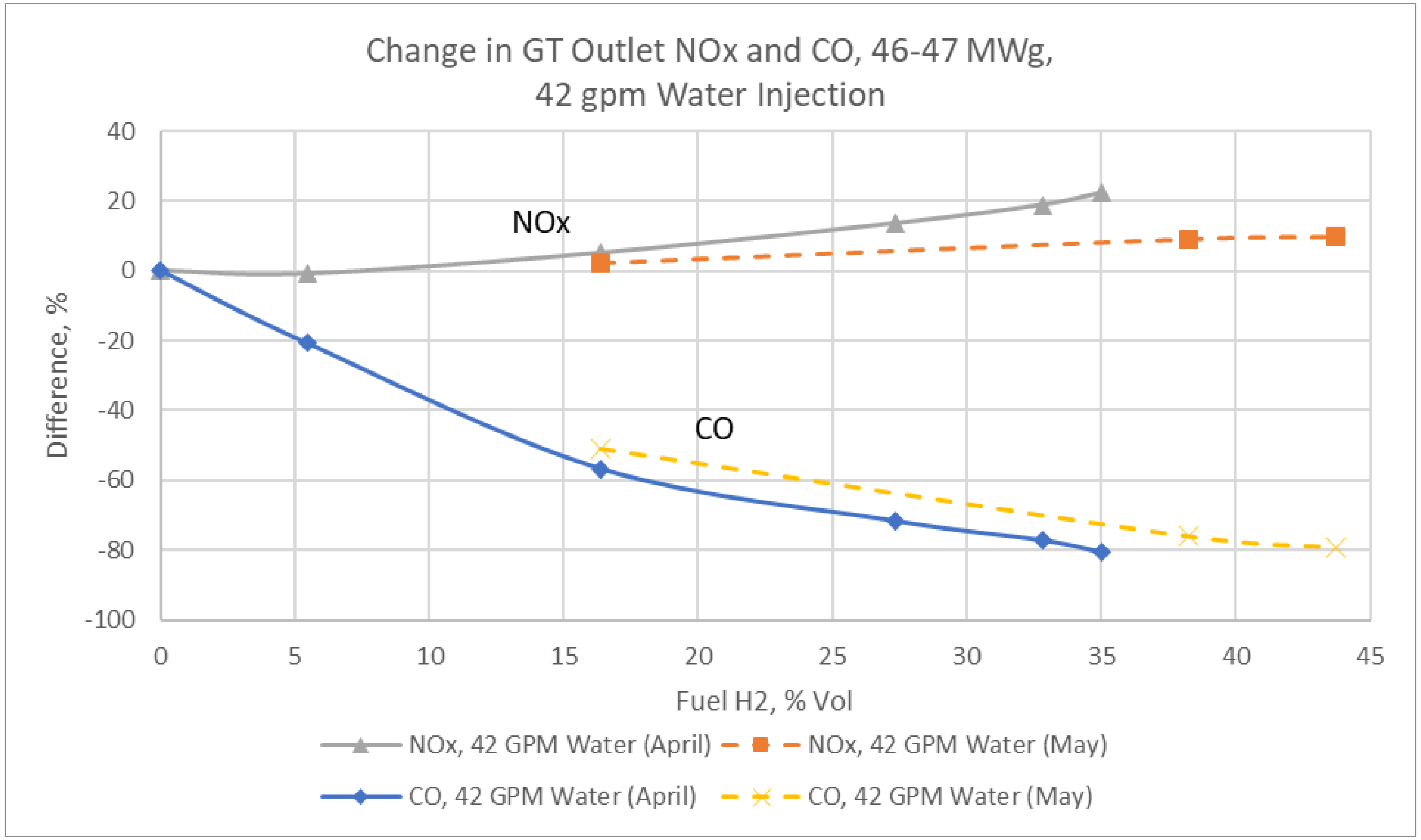
- At steady water injection rates, GT outlet NOx levels increased, and CO levels decreased as H_2 increased
- By increasing water injection rates less than 20%, GT outlet NOx levels were maintained at a constant level as hydrogen fuel increased
- Results are specific to LM6000 SAC technology and may not apply to dry-low emissions combustors



NYPA Brentwood: GT Outlet NOx and CO Impacts (Cont'd)

What it means…

- H_2 cofiring could require LM6000 operators to increase water injection to maintain steady GT outlet NOx levels
- H_2 cofiring could allow LM6000 units to operate across a wider load range (improved turndown) without CO oxidation catalyst or with reduced volumes of catalyst



Exhaust H_2O and O_2 Variability with NG and H_2 Fuel Blends

Issue

- With 100% NG fuel, exhaust H_2O and O_2 concentrations are relatively consistent
- As H_2 fuel % increases in a NG blend, exhaust H_2O and O_2 concentrations will increase
- As H_2 fuel % increases, higher sample H_2O% is removed in the CEMS sample system; dry NOx, CO ppmv and dry O_2% measurements artificially increase
- Artificial NOx and CO ppmvd @ 15% O_2 increase is below 10% up to 50% H_2, but increases to nearly 40% at 100% H_2

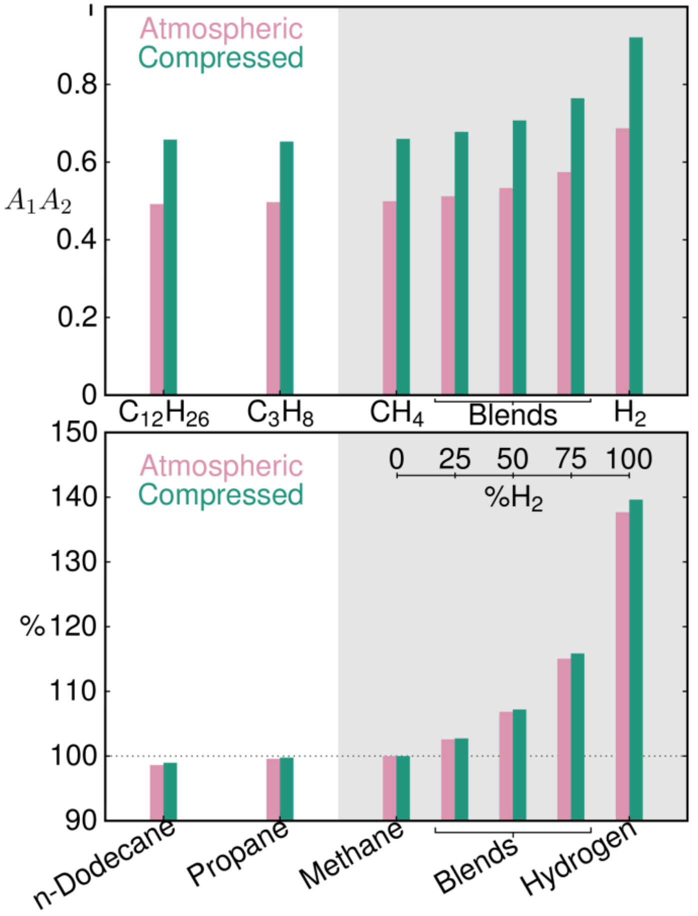
Solution

- Convert ppmvd measurements to a mass rate (lb/hr) before comparing emissions at different H_2 fuel percentages

Questions

- What are the stack permit implications for varying H_2% in a NG fuel blend?
- Real-time fuel blend composition monitoring technologies required? (H_2, CH_4 and possibly other natural gas components)

Impact of Drying Exhaust Samples and Correcting to 15% O2 with Increasing Fuel H_2 (% volume)



$$A_1 = \frac{1}{1 - \chi_{H_2O}}$$

$$A_2 = \frac{0.21 - 0.15}{0.21 - A_1 \chi_{O_2}}$$

From: Pollutant Emissions Reporting and Performance Considerations for Hydrogen Hydrocarbon Fuels in Gas Turbines

J. Eng. Gas Turbines Power. 2022;144(9). doi:10.1115/1.4054949

[1]Other Combustion Systems Investigated to Fire/ Co-Fire H_2

Combined Cycle (HRSG) Duct Burners

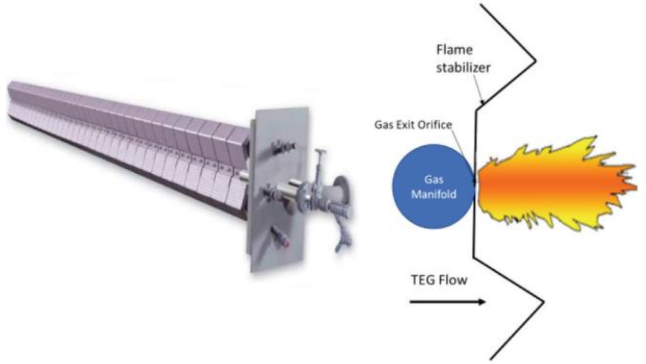
- Utility and industrial combined cycle applications
- Primarily designed for NG firing

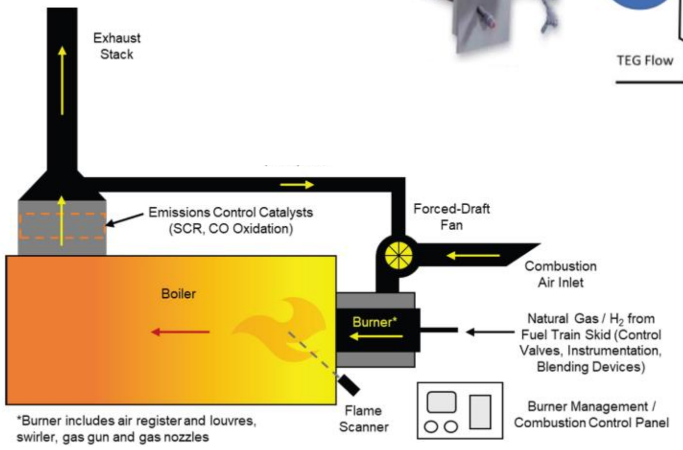
Industrial Boilers

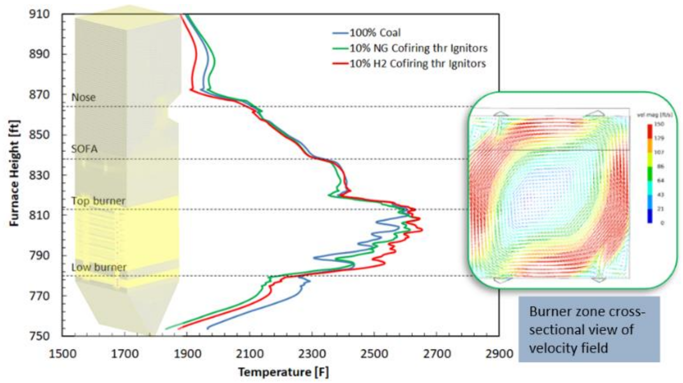
- Includes package and field erected units
- Primarily designed for natural gas (NG) firing

Utility Boilers

- Both tangential and wall applications
- Primarily designed for coal firing







(1) LCRI Report #3002020531, *Low-Carbon Fuel Pathways for Combustion-Based Boiler and Heat Recovery Steam Generation Applications*, contains detailed information on all 3 listed systems

Environmental Aspects and Safety TSC

Environmental Aspects & Safety "Mission Statement"

- Identify, quantify, and mitigate environmental and safety concerns with AECs, *including addressing environmental justice and community engagement*

Current Projects in EA&S Portfolio

Initial Projects

- EA&S "Landscape" Document (3002019994)
- EA&S Decision Support Tool
- Hydrogen **Codes & Standards** (3002025256)
- Application of **Quantitative Risk Assessment** to Hydrogen Systems
- **Power Plant Safety** Review and Assessment for Using Hydrogen
- Next Generation **Hydrogen Leak Sensor Technology** (with NREL)

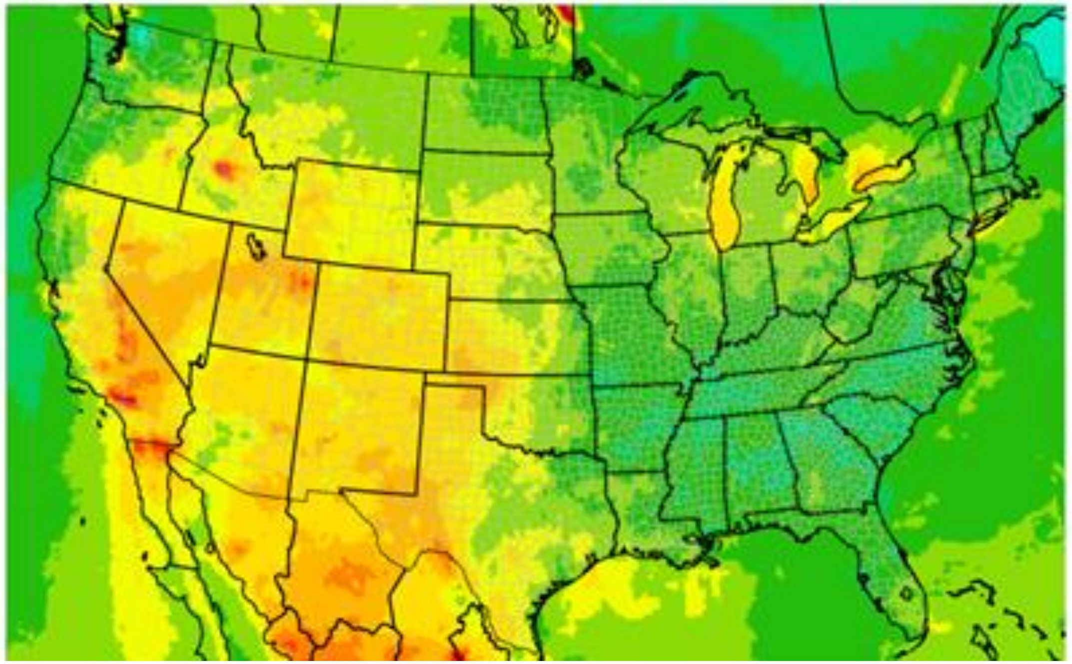
2022 Projects

- Modeling **Water Resiliency** in Decarbonization Scenarios
- White Paper: **Effluent and Brine Management** for Low-Carbon Technologies
- White Paper Series: The **Role of Water** in the Low-Carbon Energy Transformation
- Technoeconomic Evaluation of **Carbon Sequestration Brine Management**
- Potential Environmental Aspects of Key Alternative Energy Carriers (AEC) within **Power Generation**
- **Air Quality, Health, and Environmental Justice** in LCRI Scenarios

Air Quality, Health, and Environmental Justice in LCRI Scenarios

Objective

- Identify, quantify, and map impacts of future LCRI scenarios to air quality, health effects, and environmental justice metrics
  - Recalibrate REGEN model using data and tools from EPA's most recent air quality modeling platform
  - Conduct gap analysis to ensure all emissions associated with the use of AECs in future scenarios are captured



Example format of air quality modeling output – not an actual scenario.

Equity and Environmental Justice

LCRI LOW-CARBON RESOURCES INITIATIVE

EPA's definition

Environmental justice is the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies

Helpful resources

- EPRI's Equitable Decarbonization Interest Group (EDIG)
- DOE's energy justice mapping tool: https://energyjustice.egs.anl.gov/
- DOE's disadvantaged communities mapping tool: https://screeningtool.geoplatform.gov/en/#3.74/25.83/-93.2
- DOE's Justice 40 initiative: https://www.energy.gov/diversity/justice40-initiative

Report #: 3002023584
Just Transition: An Overview of the Landscape and Leading Practices

https://www.epri.com/research/products/000000003002023584

EPRI GTI ENERGY

White Paper Series: The Role of Water in the Low-Carbon Energy Transformation

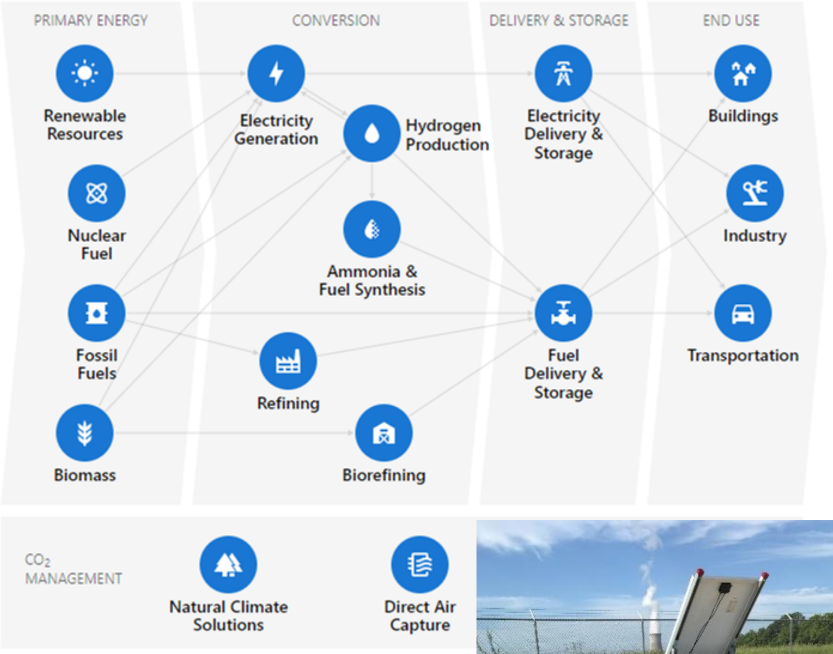
- Siting considerations for sustainable water use in low-carbon fuel production
- Outline the water needs for:
  - Electrolysis for H_2 production
  - Steam methane reforming for H_2 production
  - Bioenergy/renewable fuels
  - Carbon capture and sequestration

Air Products' Geismar hydrogen production facility

Image courtesy of Air Products and Chemicals, Inc.

White Paper: Effluent and Brine Management for Low-Carbon Technologies

- Outlines the water effluent streams from low-carbon technologies and the challenges they may impose to technology siting
- Brine management options
- Ecological constraints for effluent discharge
- Pathways to valorize brines
- Identify water reuse opportunities



The primary objective of this project is to provide thought leadership on how brine and effluent management considerations are a critical component of low-carbon technology deployment and achieving net zero carbon goals.

Renewable Fuels TSC

Renewable Fuels TSC Mission

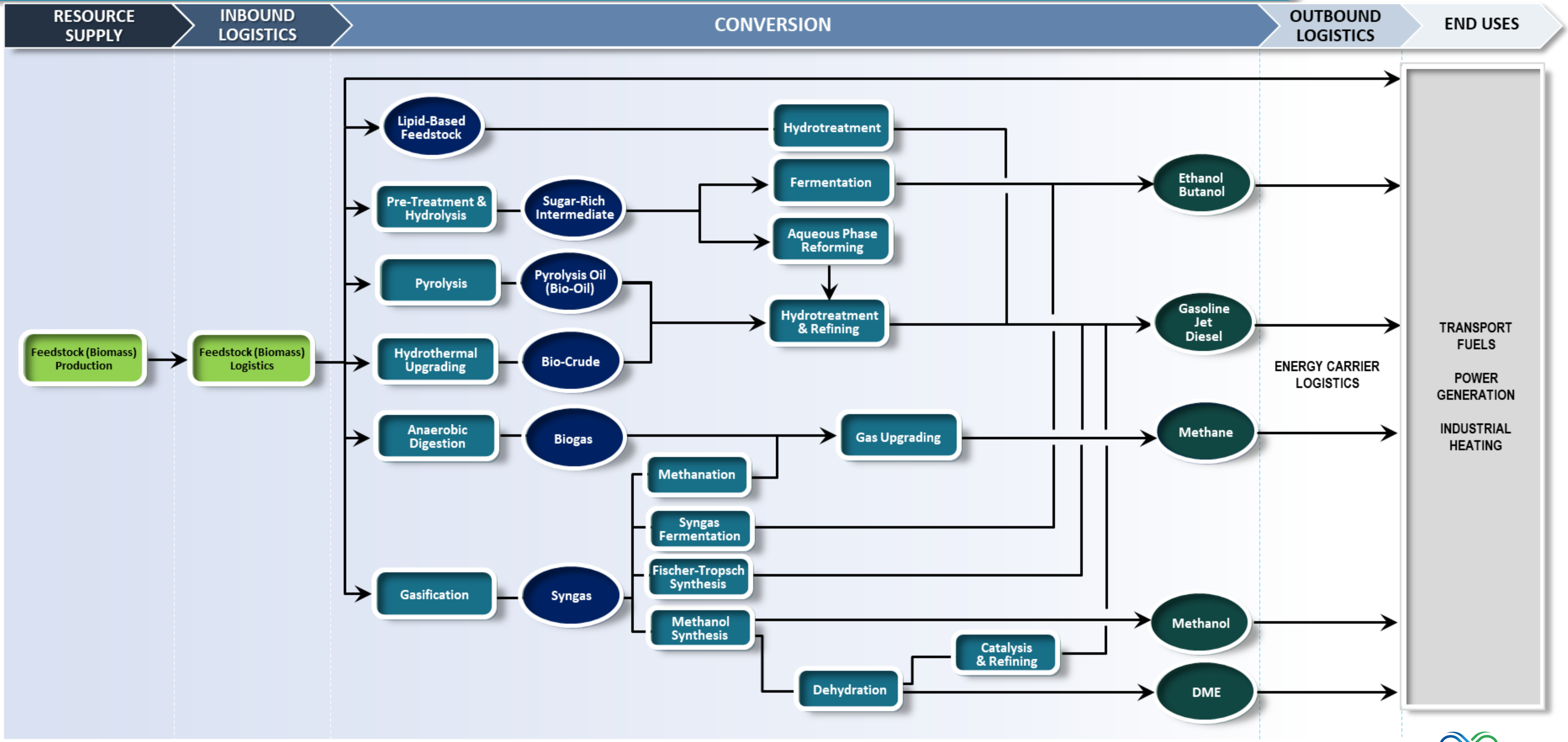
- Undertake and facilitate research on potential renewable fuel and bioenergy options for economy-wide deep decarbonization

- Inform our members and the public of how *incumbent* and *emerging* renewable fuels and bioenergy pathways can potentially enable, accelerate, and shape the global clean energy transition

- Apply and balance holistic value chain and deep technical approaches to comprehensively analyze biological, biochemical and thermochemical routes to produce renewable fuels and bioenergy from renewable biogenic feedstocks

Renewable Fuels enable <u>near-term</u> decarbonization and can play a unique and valuable role in energy <u>transition</u> and <u>transformation</u> of economies, businesses and communities

Renewable Fuels Value Chain



Renewable Fuels Current State Assessment

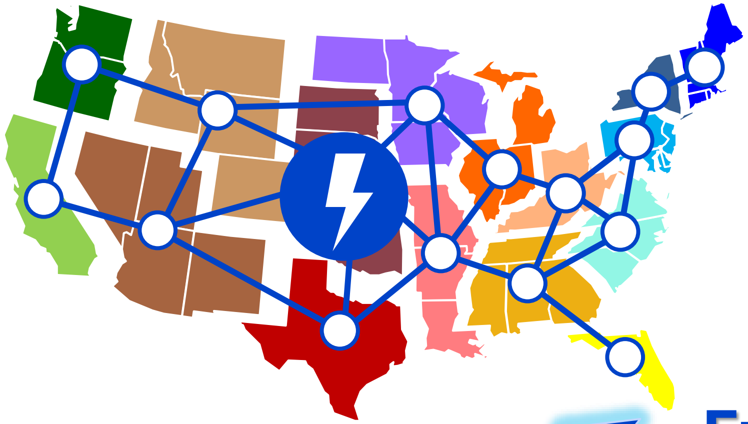
- Provide market insight into four prominent biofuels:
  SAF, RNG, RD, and Ethanol
- Define market via current production capacity, major production pathways, key players, etc.
- Baseline against fossil alternatives, climate goals, and energy system models
- Publish white paper + summary tech brief by end of Q1 2023

Integrated Energy Systems Analysis TSC

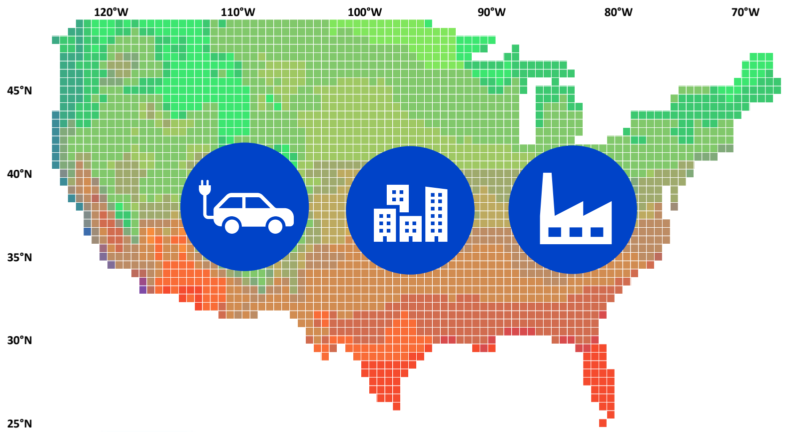
US-REGEN
Regional Economy, GHG, and Energy

Online documentation at us-regen-docs.epri.com
More information at esca.epri.com

Electric Generation

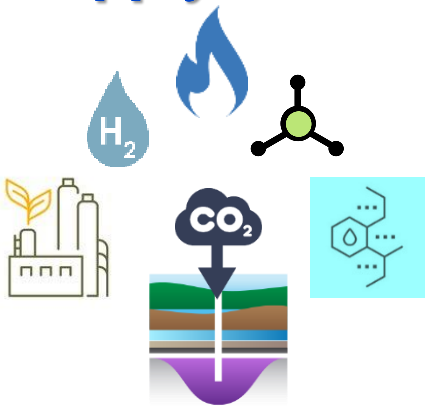


Energy Use



Synchronized prices/supply/demand

Fuel Supply/Conversion



Model Inputs:

Service demands, technology costs, resource availability, policy constraints, climate

Model Outputs:

Economic equilibrium across energy production and use

Emissions, air quality, and water

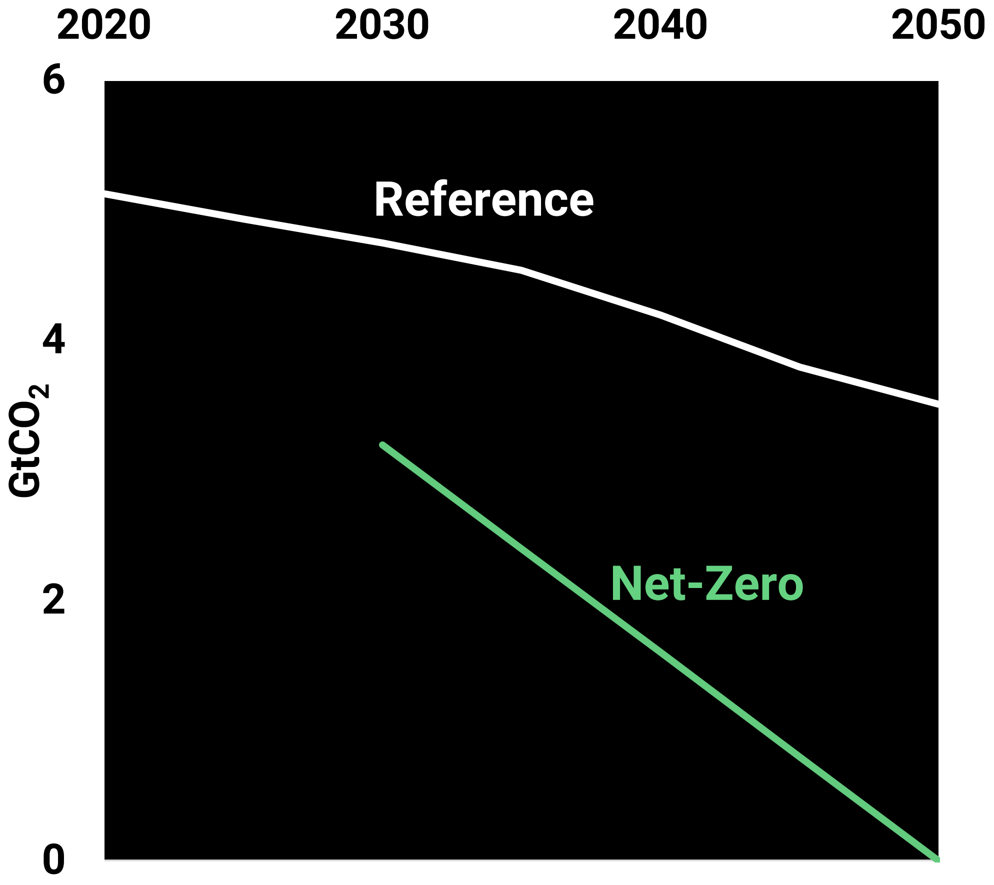
- Framework for understanding drivers of change in the electric sector and energy system
- Supported by EPRI engineering expertise and technology projections

EPRI GTI ENERGY

LCRI NET-ZERO 2050

Full report available at *lowcarbonlcri.com/netzero*

Reference with no new carbon policy, continued technology improvements



Net-Zero by 2050 with three core sensitivities around CCS, gas, bioenergy

	All Options	Higher Fuel Cost	Limited Options
Geologic Storage of CO_2	Lower Costs	Higher Costs	Not Available
Natural Gas Supply Costs	Lower Costs	Higher Costs	Lower Costs
Bioenergy Feedstock Supply	Full	Supply Limited	Supply Limited

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Key Messages and Takeaways

2020's — 2030's — 2040's

The Starting Point: Build on the 3 *Es*

Clean *electricity*, *efficiency*, and *electrification* are foundational to achieve substantial reductions

Grid Modernization & Investment Underpins Progress

Support reliability, resilience, electrification, flexibility, asset utilization, and customer choice

Existing Low-Carbon Resources Amplify Their Value

Maintaining nuclear, renewables, and energy storage is critical to realizing a net-zero energy future

Net Zero Requires Technology Advances

RD&D to enable clean, firm electric supply (e.g., advanced nuclear, CCS, biofuels, hydrogen) and low-carbon fuels

Technology Optionality High Value

Natural gas and biomass with CCS, along with direct air capture, are key to manage costs, while leveraging existing resources

Low-Carbon Fuels Fill Reduction Gaps

Scenarios show targeted use of a diverse portfolio of low-carbon fuels across power generation and end-use applications

Gas Infrastructure Enables Reductions

Gas capacity and infrastructure are useful in all scenarios, with varying capacity factor and differences in the *type of gas* used

Customer Adoption, Affordability & Equity

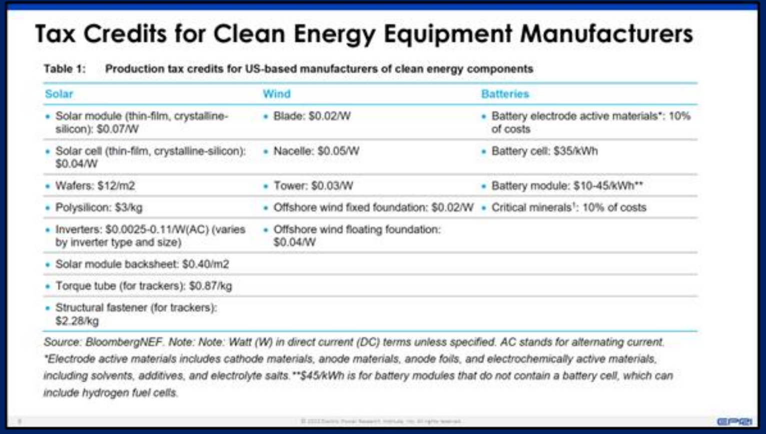
Reaching goals depends on 100M+ households and businesses participating and adopting low-carbon technologies

Regional Differences: Technology mix, electrification, and role of gas vary significantly by region, with climate as a key driver.

IRA Technology Cost Impact Analyses for 2023

Upstream/Manufacturing Tax Credit Impacts

- How do domestic sourcing and subsequent tax credits impact technology costs?



Tax Credits for Clean Energy Equipment Manufacturers

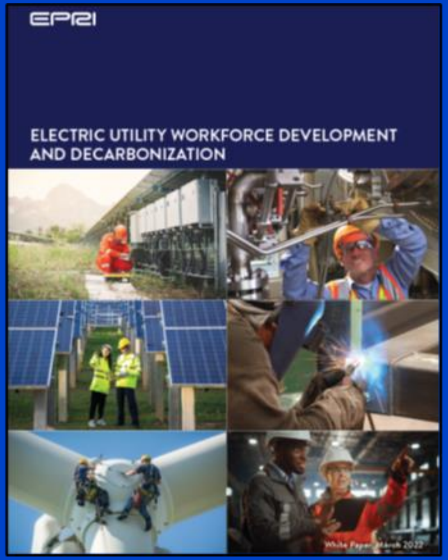
Table 1: Production tax credits for US-based manufacturers of clean energy components

Solar	Wind	Batteries
• Solar module (thin-film, crystalline-silicon): $0.07/W	• Blade: $0.02/W	• Battery electrode active materials*: 10% of costs
• Solar cell (thin-film, crystalline-silicon): $0.04/W	• Nacelle: $0.05/W	• Battery cell: $35/kWh
• Wafers: $12/m2	• Tower: $0.03/W	• Battery module: $10-45/kWh**
• Polysilicon: $3/kg	• Offshore wind fixed foundation: $0.02/W	• Critical minerals[1]: 10% of costs
• Inverters: $0.0025-0.11/W(AC) (varies by inverter type and size)	• Offshore wind floating foundation: $0.04/W	
• Solar module backsheet: $0.40/m2		
• Torque tube (for trackers): $0.87/kg		
• Structural fastener (for trackers): $2.28/kg		

*Source: BloombergNEF. Note: Note: Watt (W) in direct current (DC) terms unless specified. AC stands for alternating current. *Electrode active materials includes cathode materials, anode materials, anode foils, and electrochemically active materials, including solvents, additives, and electrolyte salts. **$45/kWh is for battery modules that do not contain a battery cell, which can include hydrogen fuel cells.*

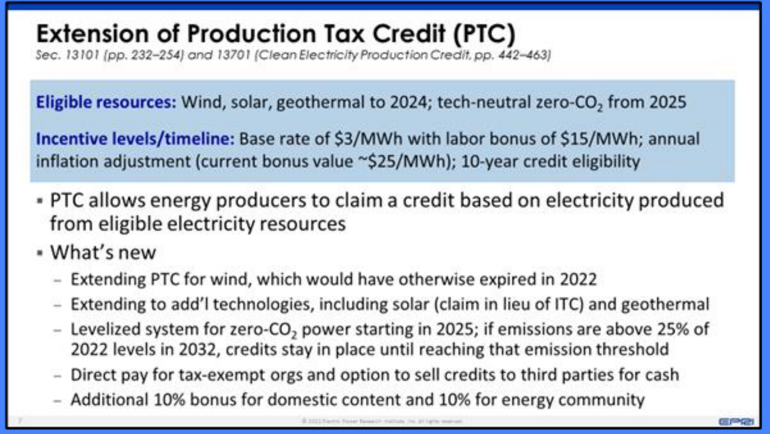
Construction Labor & Workforce Development

- Workforce and wage requirements for 'bonus' rates have a material impact on technology costs?



Investment, Production, H_2 Production, and CO_2 Capture Tax Credits

- How do these influence technology costs & rev req?
- How do these influence plant designs?



Extension of Production Tax Credit (PTC)

Sec. 13101 (pp. 232–254) and 13701 (Clean Electricity Production Credit, pp. 442–463)

Eligible resources: Wind, solar, geothermal to 2024; tech-neutral zero-CO_2 from 2025

Incentive levels/timeline: Base rate of $3/MWh with labor bonus of $15/MWh; annual inflation adjustment (current bonus value ~$25/MWh); 10-year credit eligibility

- PTC allows energy producers to claim a credit based on electricity produced from eligible electricity resources
- What's new
  - Extending PTC for wind, which would have otherwise expired in 2022
  - Extending to add'l technologies, including solar (claim in lieu of ITC) and geothermal
  - Levelized system for zero-CO_2 power starting in 2025; if emissions are above 25% of 2022 levels in 2032, credits stay in place until reaching that emission threshold
  - Direct pay for tax-exempt orgs and option to sell credits to third parties for cash
  - Additional 10% bonus for domestic content and 10% for energy community

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