Technology Pathways for Energy System Transformation

Industrial Processes Emissions Reduction Workshop

San Antonio, TX

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Global Status of CO_2 Emissions

37.2 Gigatons of CO_2 Emitted

Data Source: IEA

Energy Transformation Enabled by Innovation

Energy Transformation

Accelerate economy-wide, low-carbon solutions

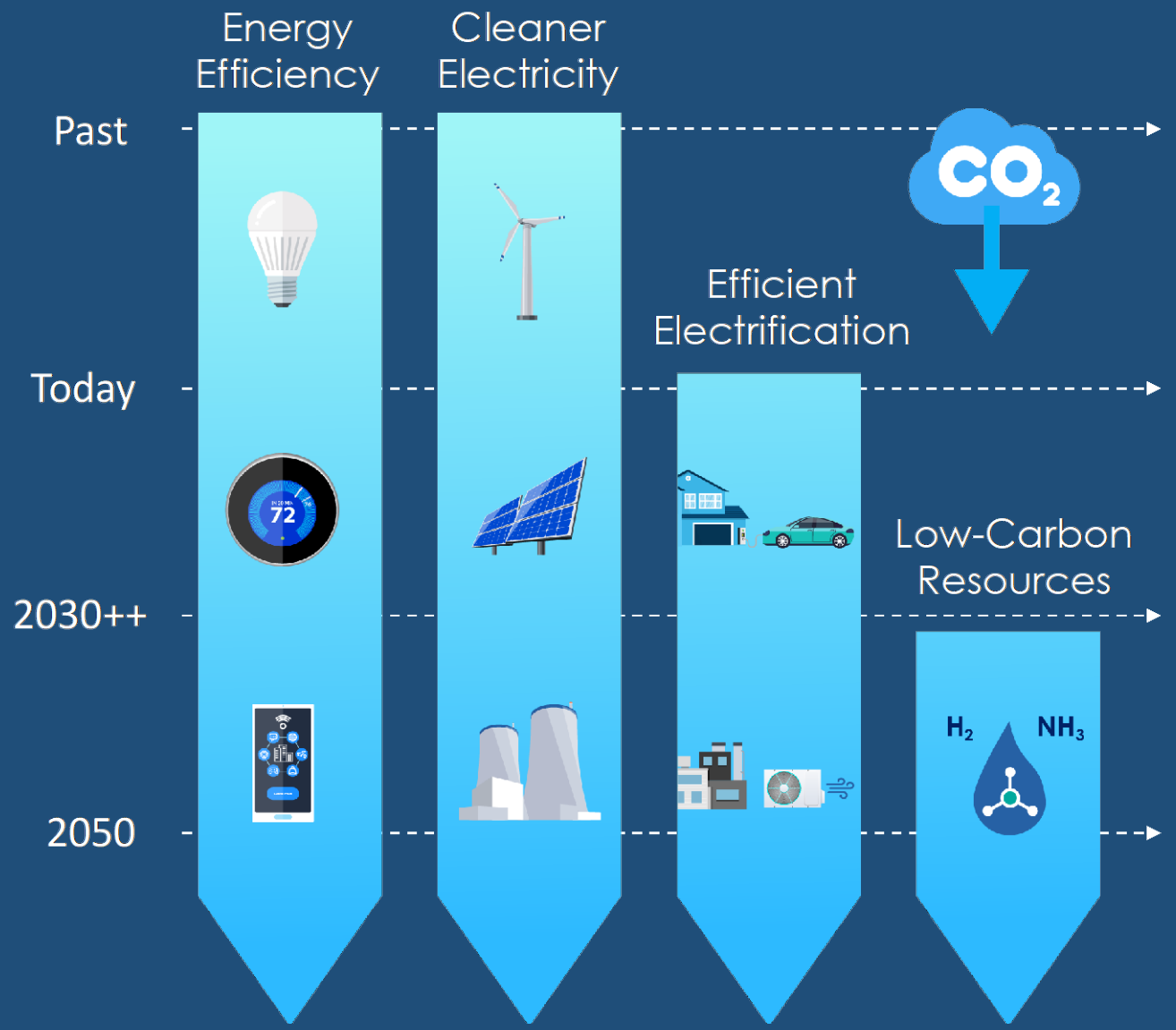
- Electric sector decarbonization
- Electric transmission and grid flexibility: storage, demand, EVs
- Efficient electrification and natural gas, hybrid systems
- Mitigate methane emissions

Achieve a net-zero clean energy system

- Ubiquitous clean electricity: renewables, advanced nuclear, CCS
- Negative-emission technologies
- Low-carbon resources: hydrogen and related, low-carbon fuels, biofuels, and biogas

~5-15 years

~15-30 years



LCRI's Global Collaboration

LCRI LOW-CARBON RESOURCES INITIATIVE

Electric Only

Gas Only

Dual Fuel

OEMs

EPC

Oil & Gas

2020 **2030** 2050+

LCRI
LOW-CARBON RESOURCES INITIATIVE

Hydrogen | Ammonia | Synfuels | Biofuels | CCS

Achieving **net zero emissions across the economy** by 2050 will require accelerating a safe, affordable, and reliable energy transition through advancements in a **variety of clean energy technologies and options**.

The LCRI evaluates pathways for deploying of **low-carbon technologies, fuels, and energy carriers** in support of decarbonization across the energy economy.

The LCRI is focused on a vision of the future global energy system that is **decarbonized, consumer-focused, sustainable, and resilient**.

Renewable & Synthetic Fuels

Hydrocarbon-Based Processes & Negative Emissions

Electrolytic Processes

Transport, Delivery, & Storage: H_2, Ammonia, CO_2

Power Generation

End Uses: Transportation, Industry, & Buildings

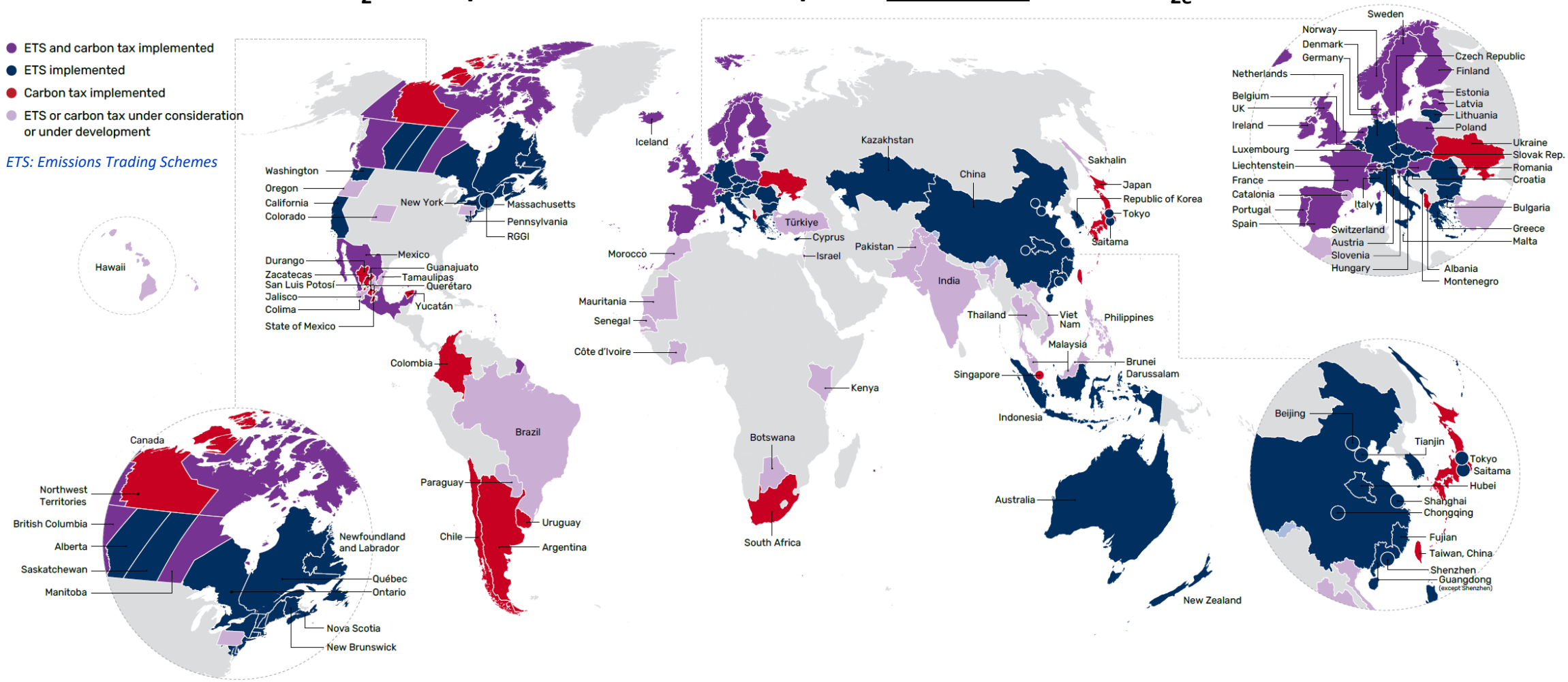
Safety and Environmental Aspects

Integrated Energy System Analysis

Global Status of Carbon Regulations

88% of global CO2 emissions are covered by targets or regulations

CO_2 tax required to limit climate impacts: $63 to 385/tonne CO_{2e}



Source: World Bank Group 2024 State and Trends of Carbon Pricing

Reflecting on learnings to date…

2019 Baseline	What we are finding…
Hydrogen	Hydrogen **& Sustainable Fuels**
Carbon Management	Carbon Management **& Carbon Removal: Biofuels & DAC**
Electricity plays a major role in 2050	Electric **&** gas underpin transition and have an important role in 2050
Emerging technologies take decades to deploy	Emerging technology deployment supported by global economy-wide collaboration
Risk-informed decision making	Proactive while being practical: **Reliability & Affordability / Low Cost**
Transitioning a 2018/2019 energy economy	Transitioning a **rapidly changing** global energy economy

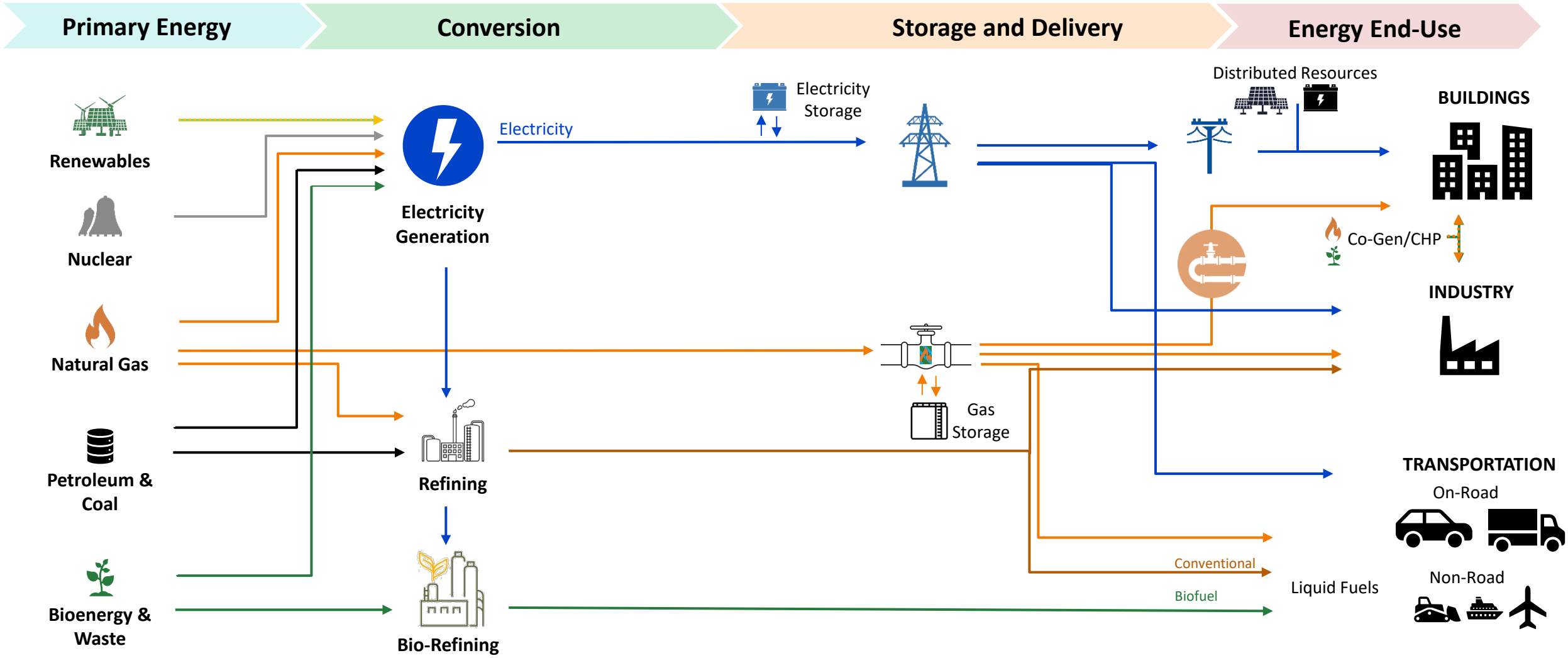
LCRI Continuously Staying Ahead of the Curve

Staying ahead of the curve in understanding low-carbon fuels and technologies is a cornerstone of the LCRI, which **drives innovation to meet ambitious climate and energy goals**. The LCRI plays a vital role in exploring how these technologies integrate into existing systems, enabling an **affordable and reliable transition to low-carbon energy solutions**.

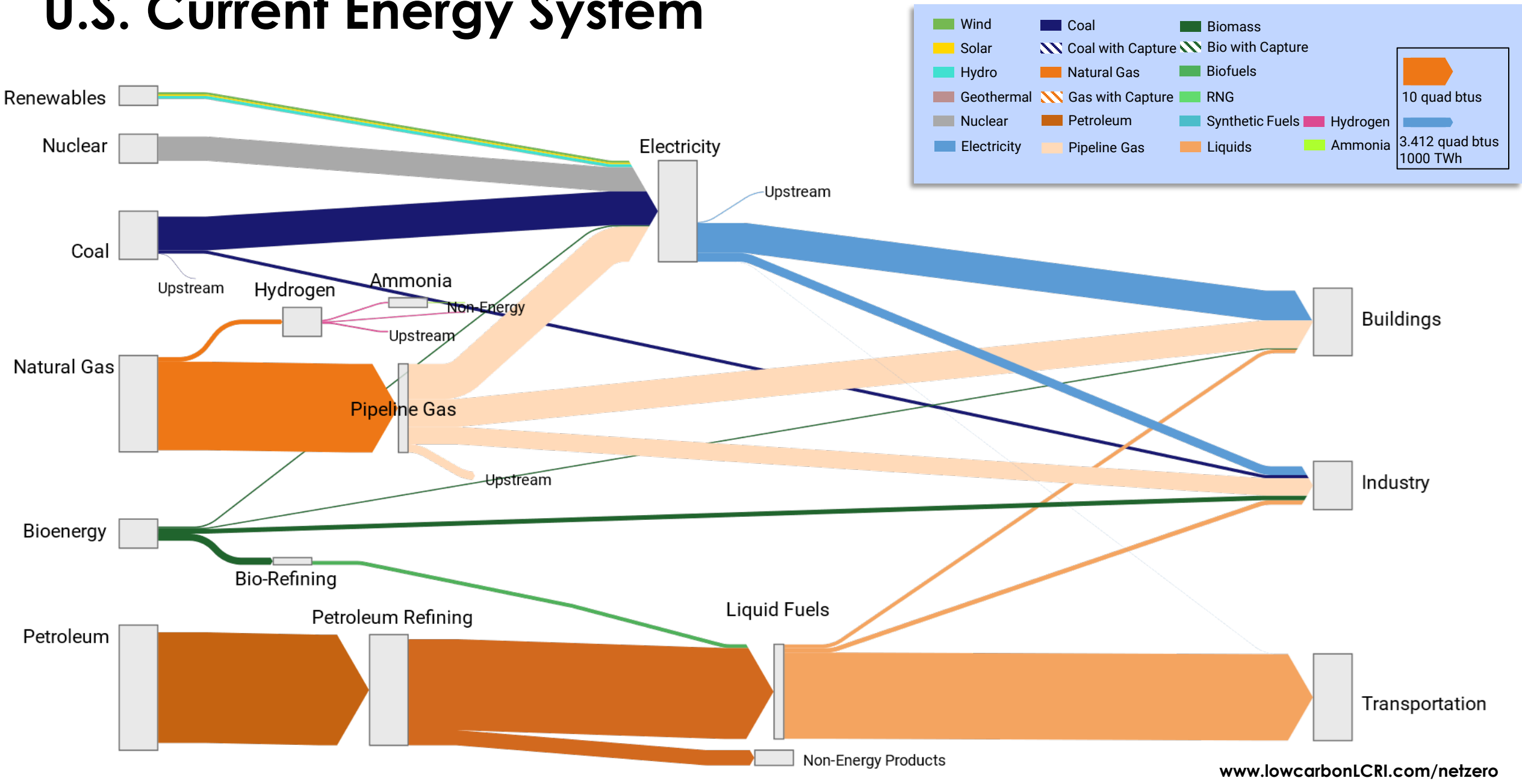
Through **demonstration projects**, the initiative evaluates the functionality, reliability, and scalability of emerging technologies, providing critical insights to inform their development.

By fostering **collaborative research** across industries, the LCRI leverages diverse expertise and resources to accelerate innovation, address integration challenges, and unlock transformative opportunities for decarbonization. This **forward-thinking approach** helps to ensure stakeholders are well-positioned to **lead in a sustainable energy future**.

Today's energy system

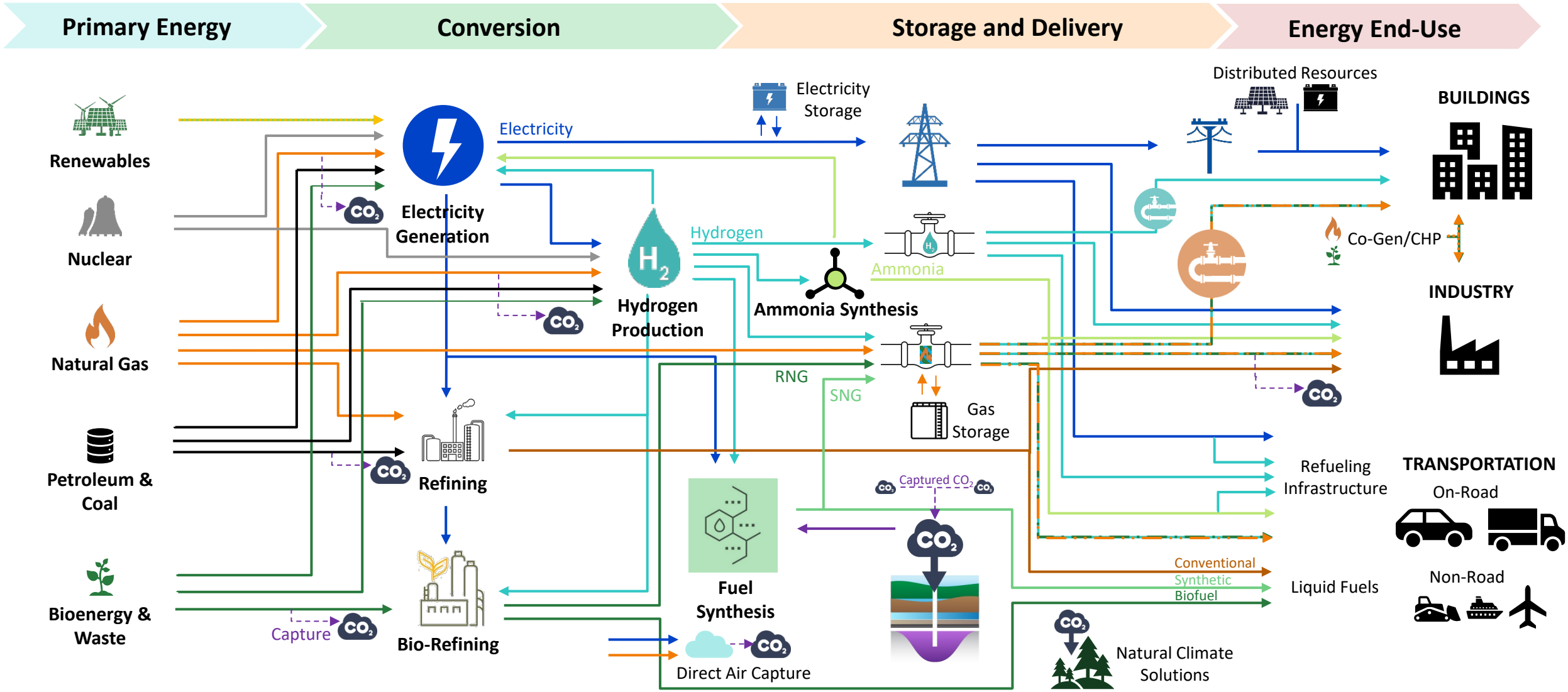


U.S. Current Energy System

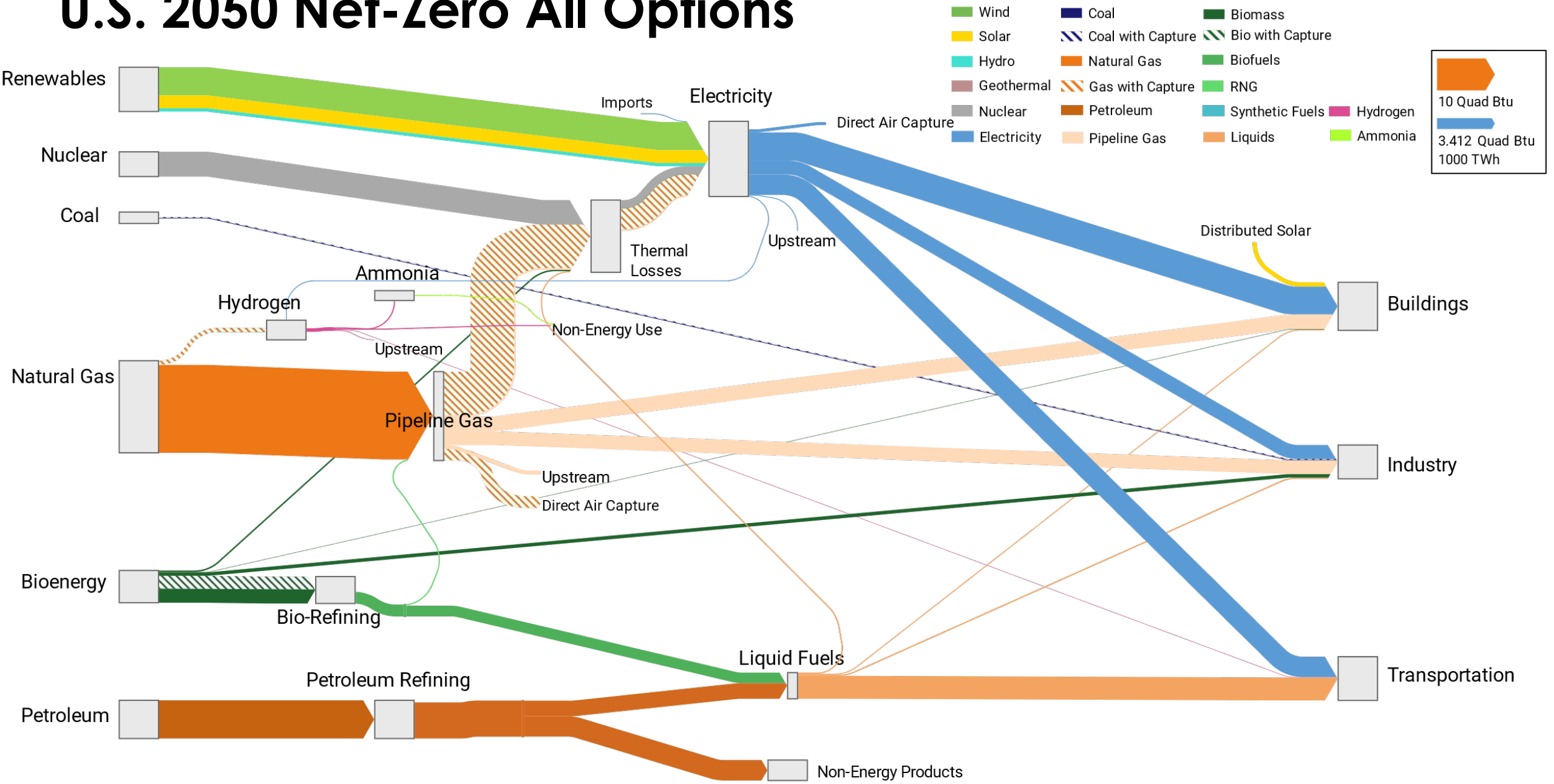


www.lowcarbonLCRI.com/netzero

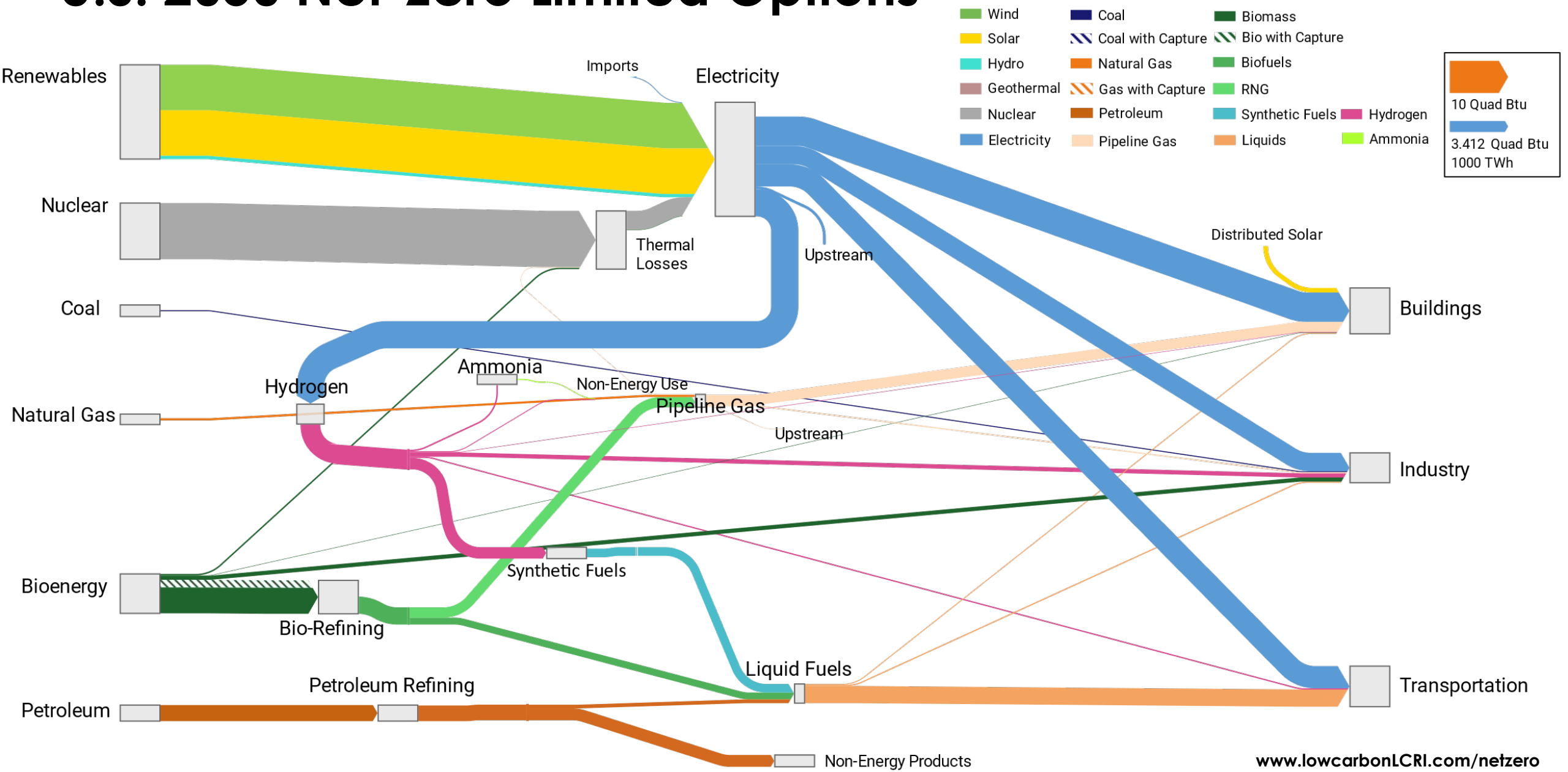
Future Energy System = More Integrated



U.S. 2050 Net-Zero All Options



U.S. 2050 Net-Zero Limited Options



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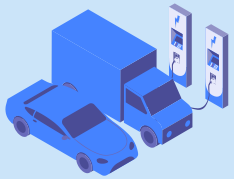
Technology Options by Sector

Optionality = Affordability

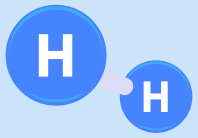
Clean Electricity


Buildings


Transportation


Industrial Processes

Short and Medium Duration Energy Storage

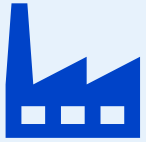


Electrolytic Hydrogen

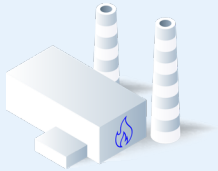
Hydrogen Direct


Refining & Chemicals


Ammonia

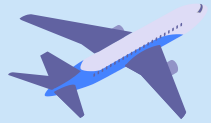

Steel


High Temp Process Heating


Power Generation & Seasonal Storage

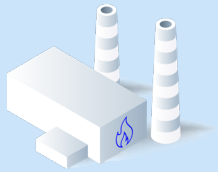

MD/HD Vehicles

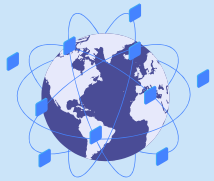
Hydrogen Derivatives & Biofuels


Aviation

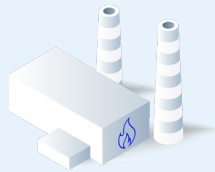

Marine Shipping

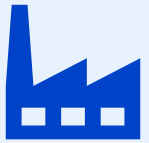

MD/HD Vehicles


Power Generation & Seasonal Storage


Bulk Import / Export

Carbon Capture


Power Generation

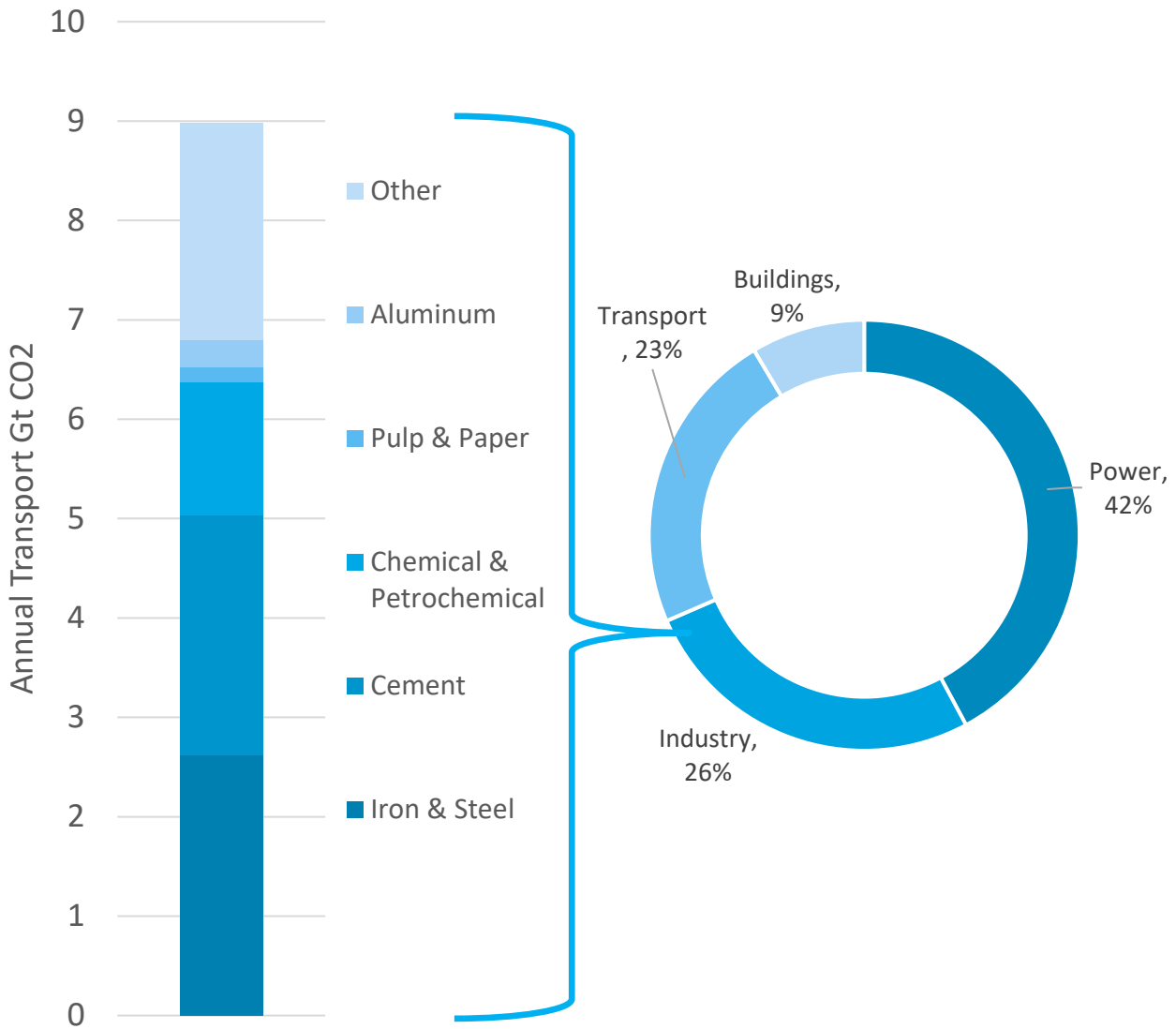

Cement & Concrete


Ammonia


Industrial Process Heating


Carbon Offset Technologies

Decarbonizing Industry



Data Source: IEA

Recycling, efficiency, & electrification improvements are key to reducing emissions from metals industry

CCS and/or hydrogen can be deployed to further reduce emissions in metals and cement industry

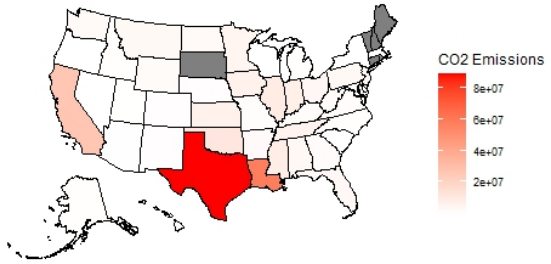
Chemical & refining industries are positioned to be early adopters of low-carbon hydrogen

Industrial facilities are suitable candidates to anchor net-zero hubs

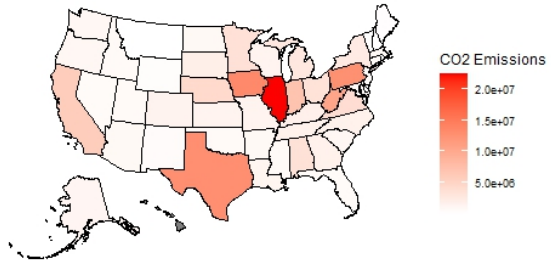
Geographical Distribution of Industries

Annual Industrial CO_2 Emissions (metric tons)

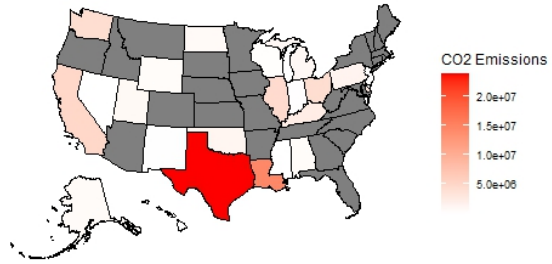
Chemicals



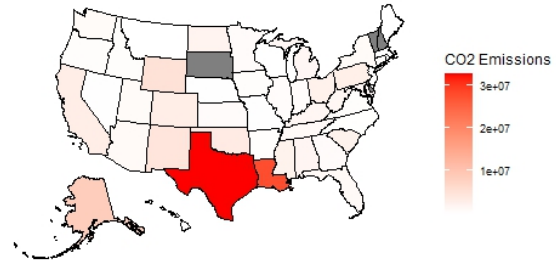
Other



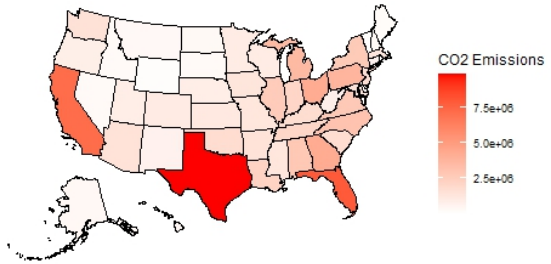
Petroleum Product Suppliers



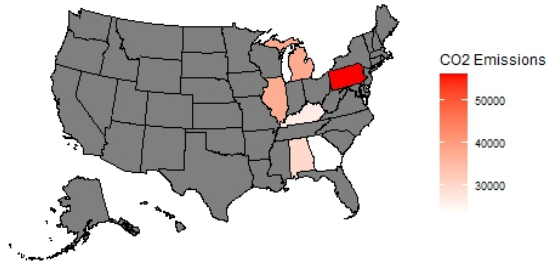
Petroleum and Natural Gas Systems



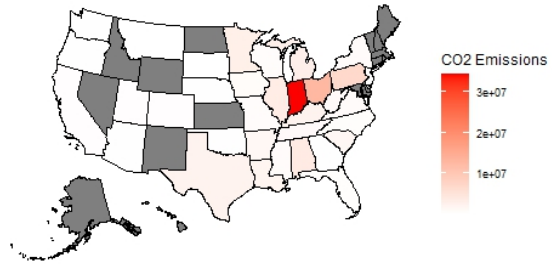
Waste



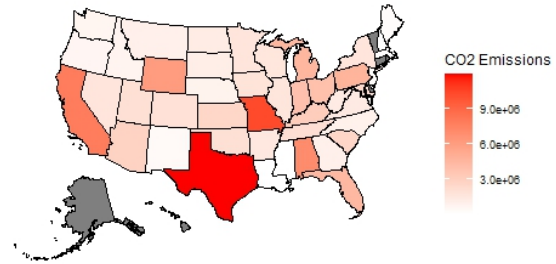
Import and Export of Equipment Containing Fluorintaed GHGs



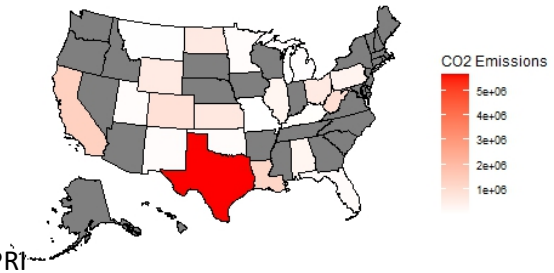
Metals



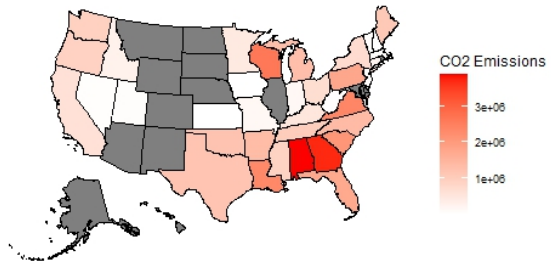
Minerals



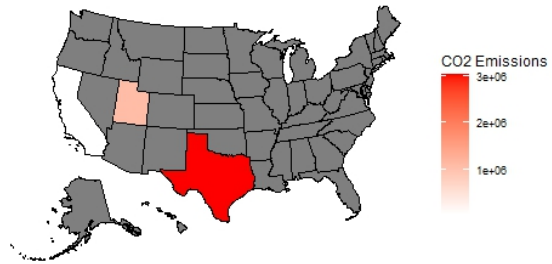
Natural Gas and Natural Gas Liquids Suppliers



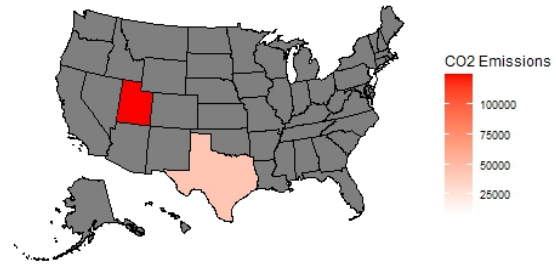
Pulp and Paper



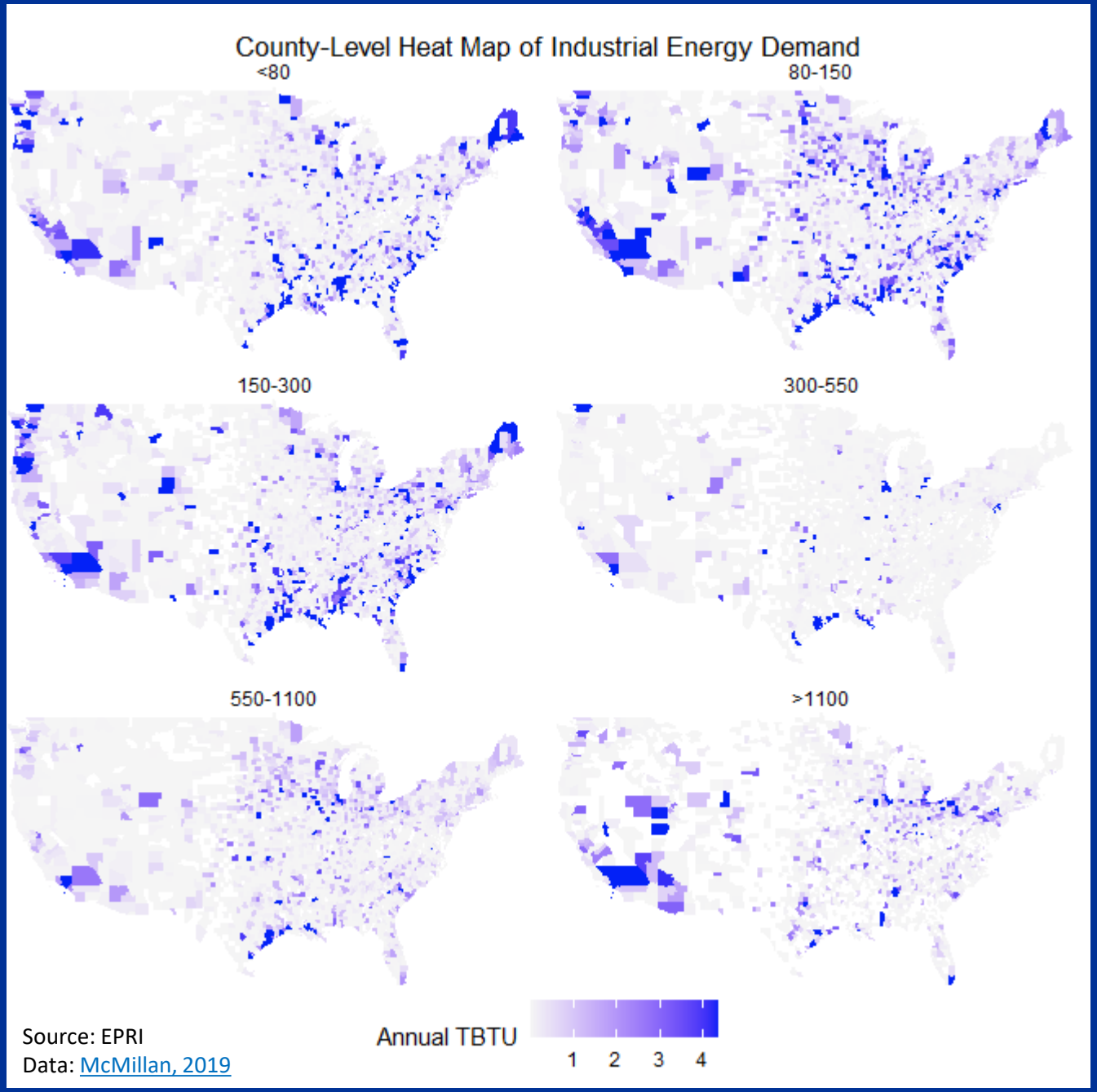
Refineries



Industrial Gas Suppliers



Source: EPRI
Data: US EPA



Source: EPRI
Data: McMillan, 2019

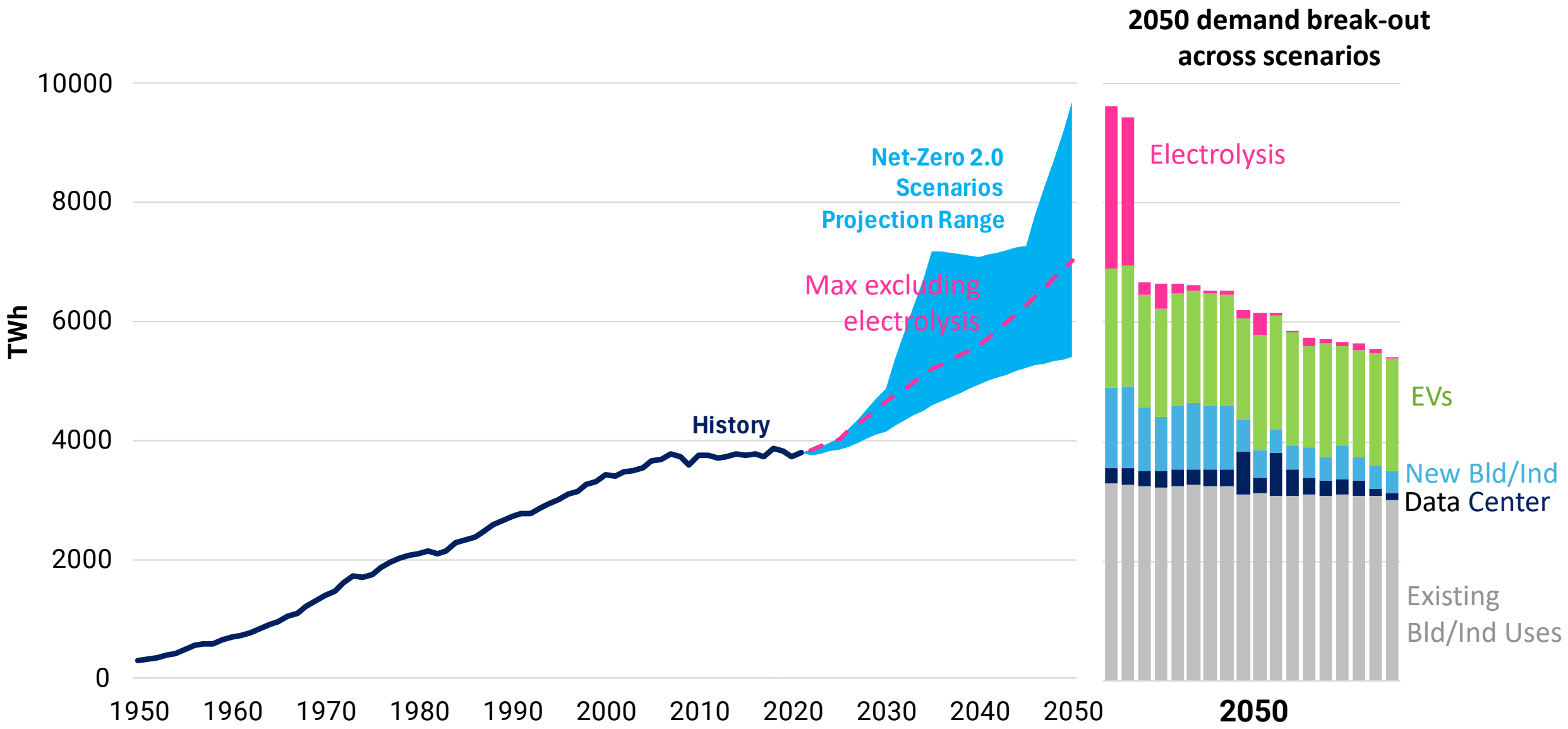
Industrial Energy Demands

Electrification

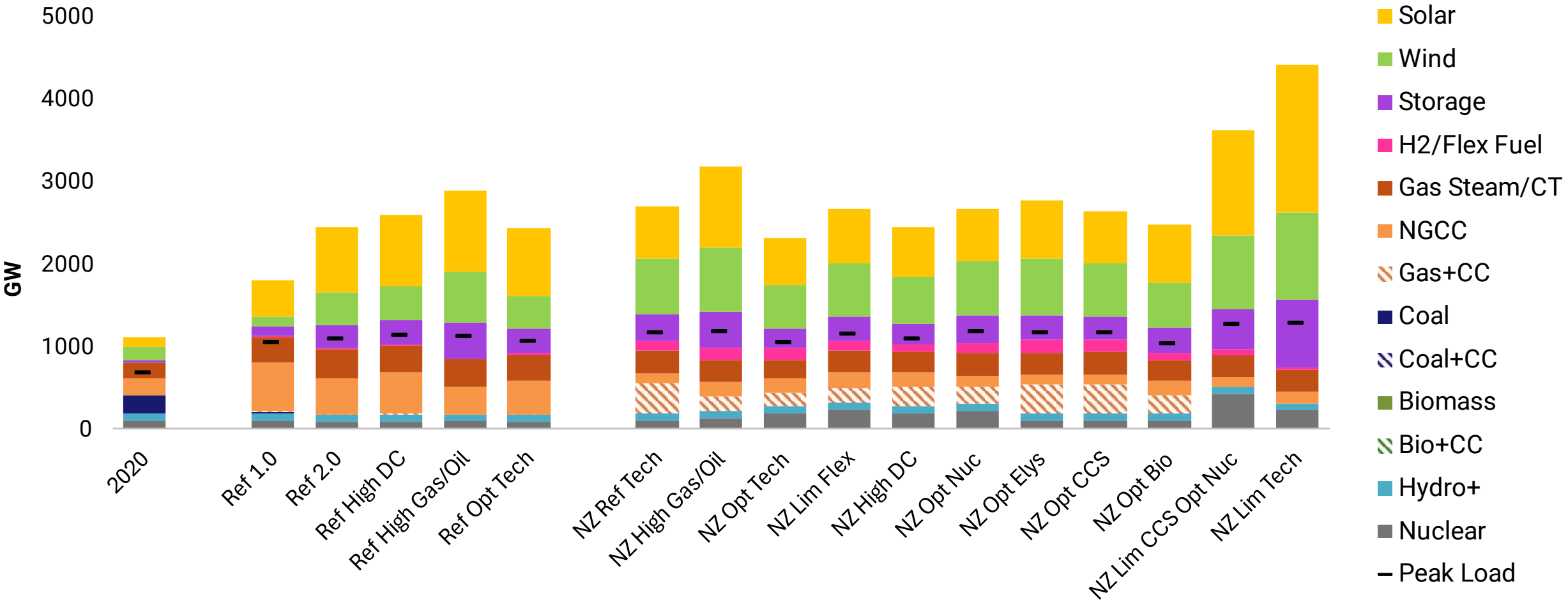
Electrification & Low-Carbon Fuels

Low-Carbon Fuels & Carbon Capture

Electricity Demand Grows in All Scenarios

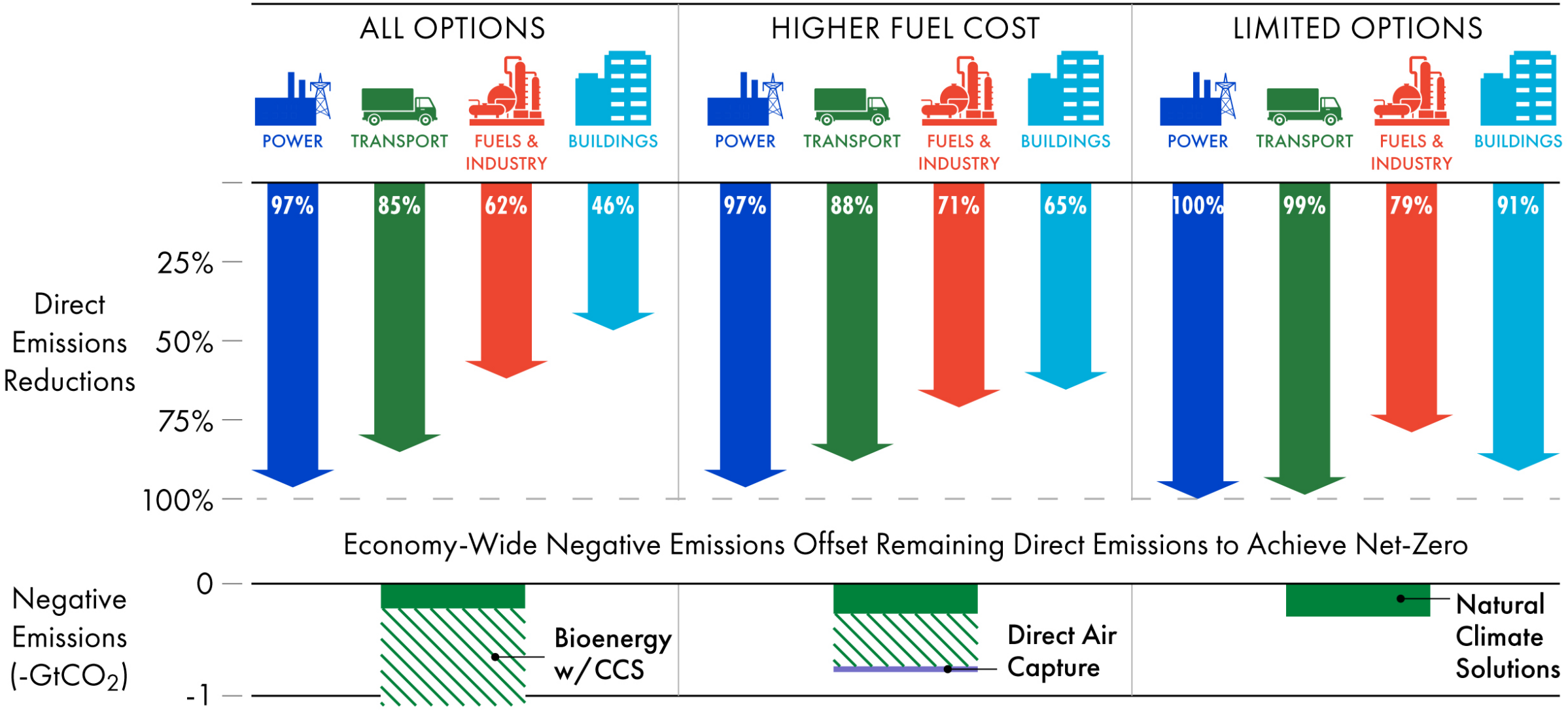


U.S. Total Electric Generation Capacity in 2050



CO_2 Emission Reductions by Sector, 2005–2050

Net-Zero 2050 Scenario Examples



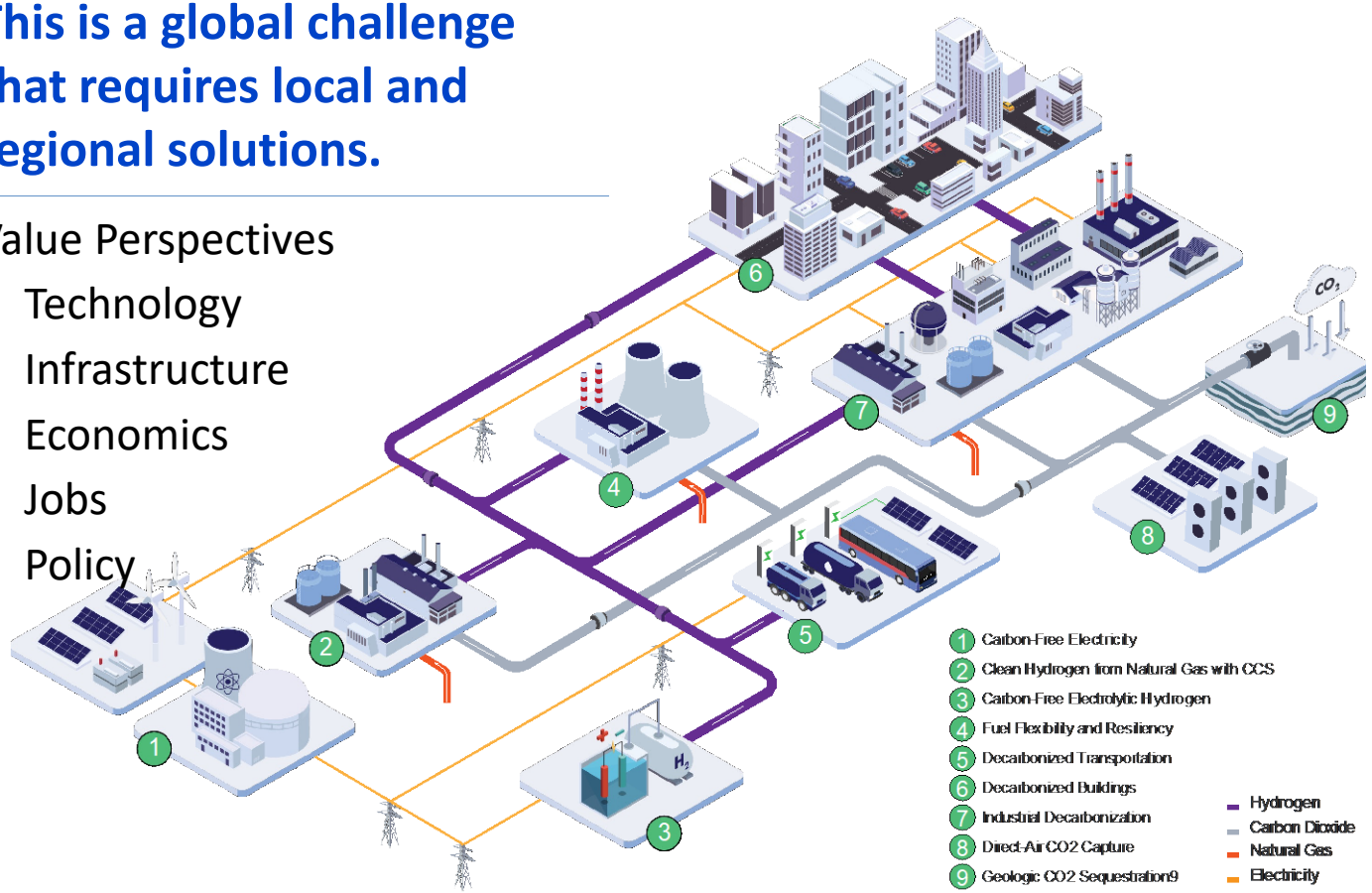
Integrated approach to decarbonization

LCRI is reducing risk and maximizing impact while prioritizing safety, reliability, and affordability.

This is a global challenge that requires local and regional solutions.

Value Perspectives

- Technology
- Infrastructure
- Economics
- Jobs
- Policy



Maximizing Emissions Reductions

Enhanced Economic Efficiency

Technological Synergies

Energy System Flexibility and Resilience

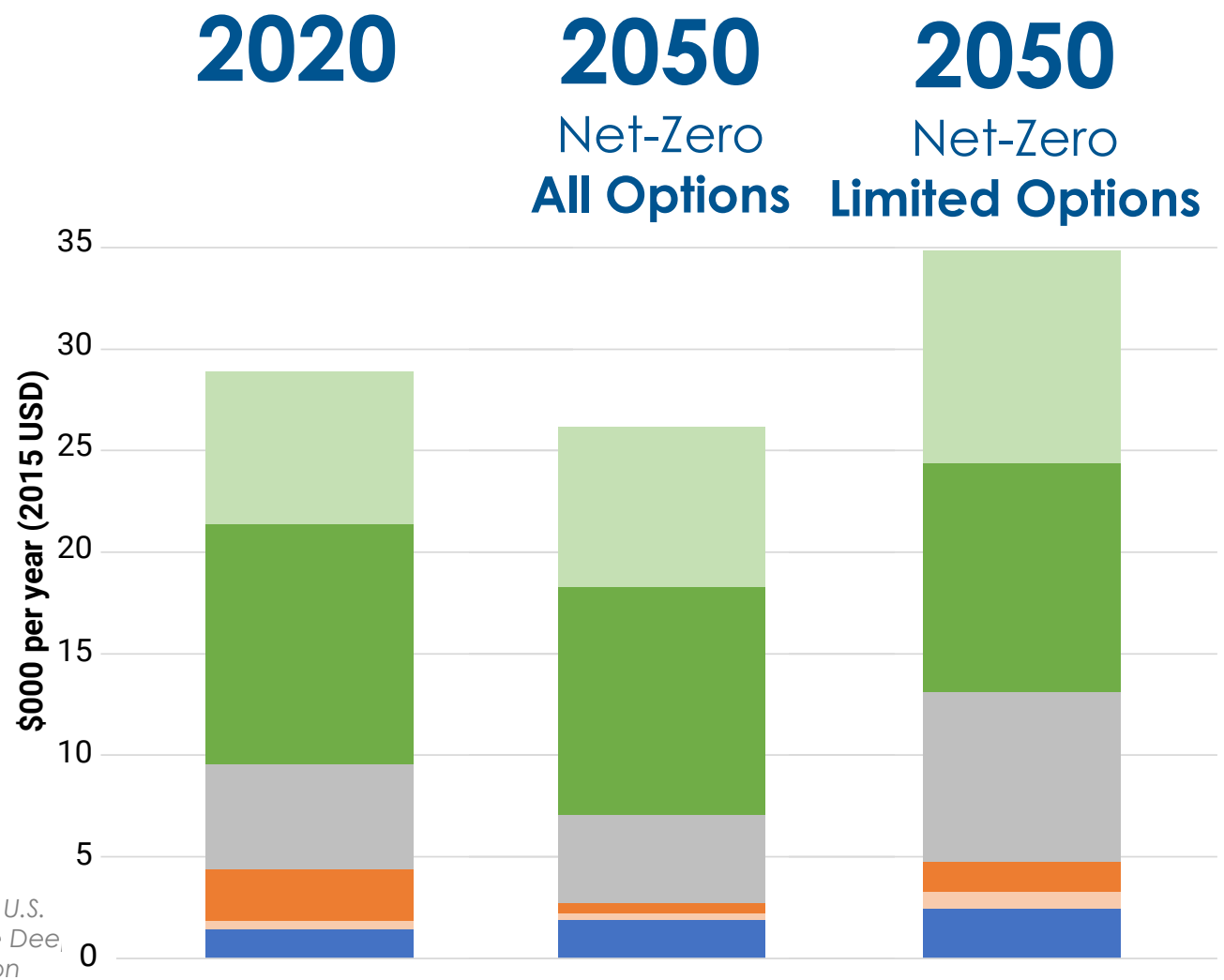
Policy and Regulatory Alignment

Environmental and Social Benefits

Long-Term Sustainability

Household Energy Expenditures

Technology Optionality Enables Affordability



Total Energy Services

Annual energy expenditures

Indirect by Firms non-energy expenditures related to energy end-use (e.g., embedded in price of goods and services)

Household non-energy expenditures related to energy end-use
(e.g., personal vehicles, appliances, charging)

Non-household Energy
(indirect to households - commercial buildings and transportation, industrial)

Liquids/Other

Pipeline Gas

Electricity

Direct Household Energy

Net-Zero 2050: U.S. Economy-Wide Dee Decarbonization Scenario Analysis

EPRI

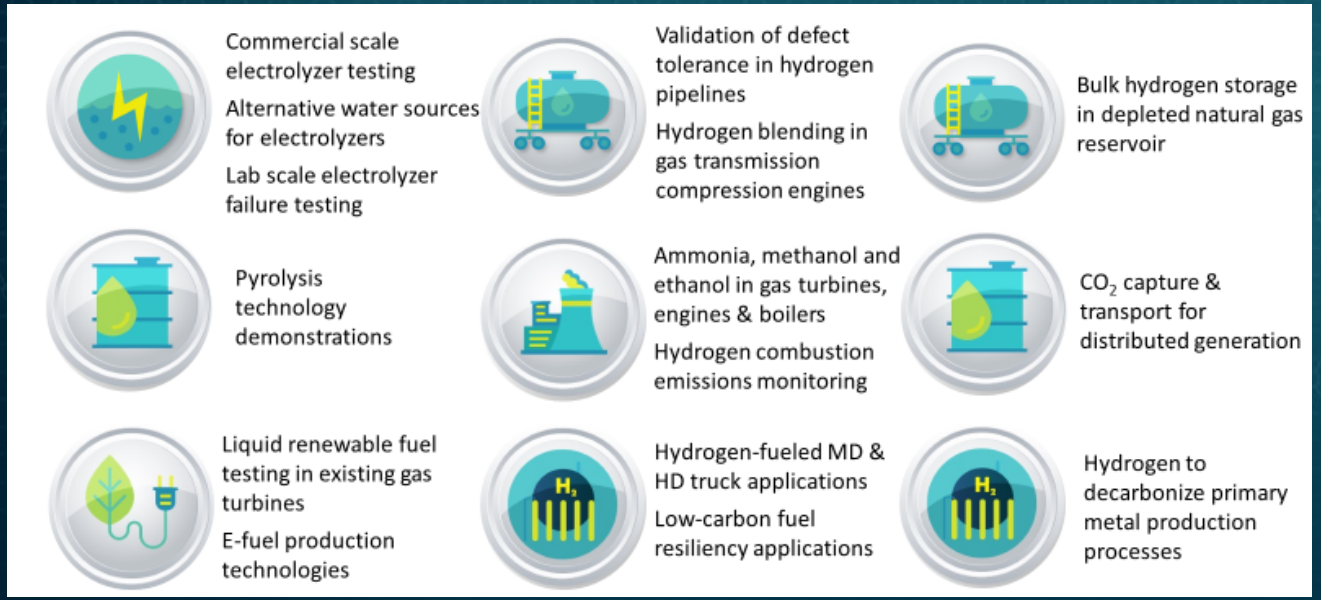
LCRI Efforts to Accelerate Technology Development

Completed & Ongoing LCRI Demonstrations

- **3** Electrolyzer demonstrations
- **4** Natural gas & bio-feedstock to hydrogen related demonstrations
- **6** Hydrogen in power generation demonstrations (4 gas turbines, 1 reciprocating engine, 1 fuel cell)
- **3** Fundamental tests of ammonia combustion
- **3** Carbon capture / direct air capture related demonstrations
- **4** Commercial & industrial decarbonization demonstrations
- **2** Transport application demonstrations
- **1** Jet fuel and gasoline production demonstration
- **3** Delivery and storage infrastructure related demonstrations

Upcoming LCRI Efforts to Accelerate Technology Commercialization

24 New Demonstration Projects Across the Low-Carbon Fuels Value Chain



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