U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Industrial Decarbonization Pathways to Net-Zero

Joe Cresko, Chief Engineer
Industrial Efficiency and Decarbonization Office

Hydrogen Program Annual Merit Review
May 8, 2024 | Crystal City, VA

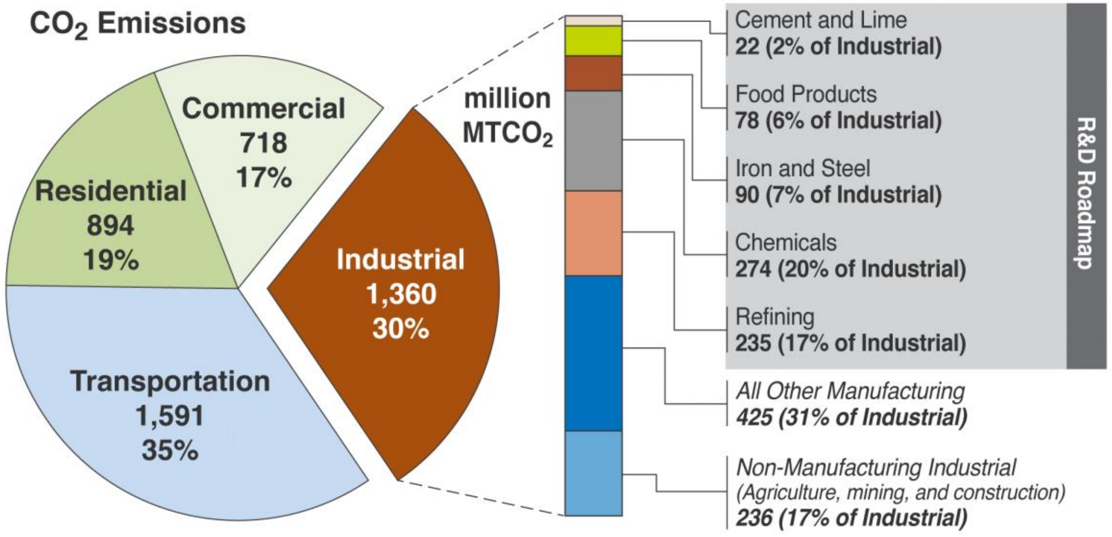
Industrial Efficiency & Decarbonization Office (IEDO):
https://www.energy.gov/eere/iedo/industrial-efficiency-decarbonization-office

Argonne NATIONAL LABORATORY | NREL Transforming ENERGY | OAK RIDGE National Laboratory | BERKELEY LAB Lawrence Berkeley National Laboratory | energetics Clean Energy Consulting

U.S. Industrial CO_2 Emissions

Industrial sector is comprised of
manufacturing | agriculture | mining | construction

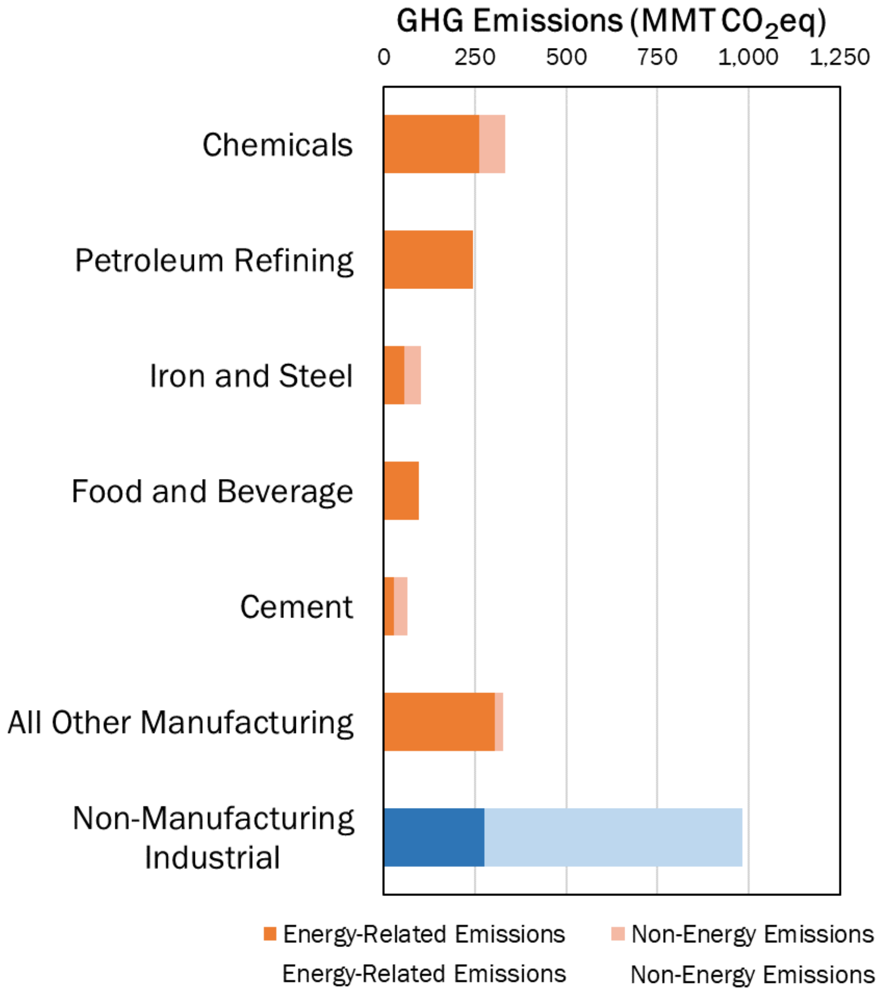
ACCOUNTS FOR **30%** of energy-related CO_2 emissions



Energy-Related CO_2 emissions, 2020
(million metric tons)

EIA, *Annual Energy Outlook 2020 with Projections to 2050*. Source: Industrial Decarbonization Roadmap.

Total Industry Emissions, 2018
(energy-related + non-energy; million metric tons CO_2eq)



EIA Monthly Energy Review, Manufacturing Energy Consumption Survey; EPA GHGRP Inventory

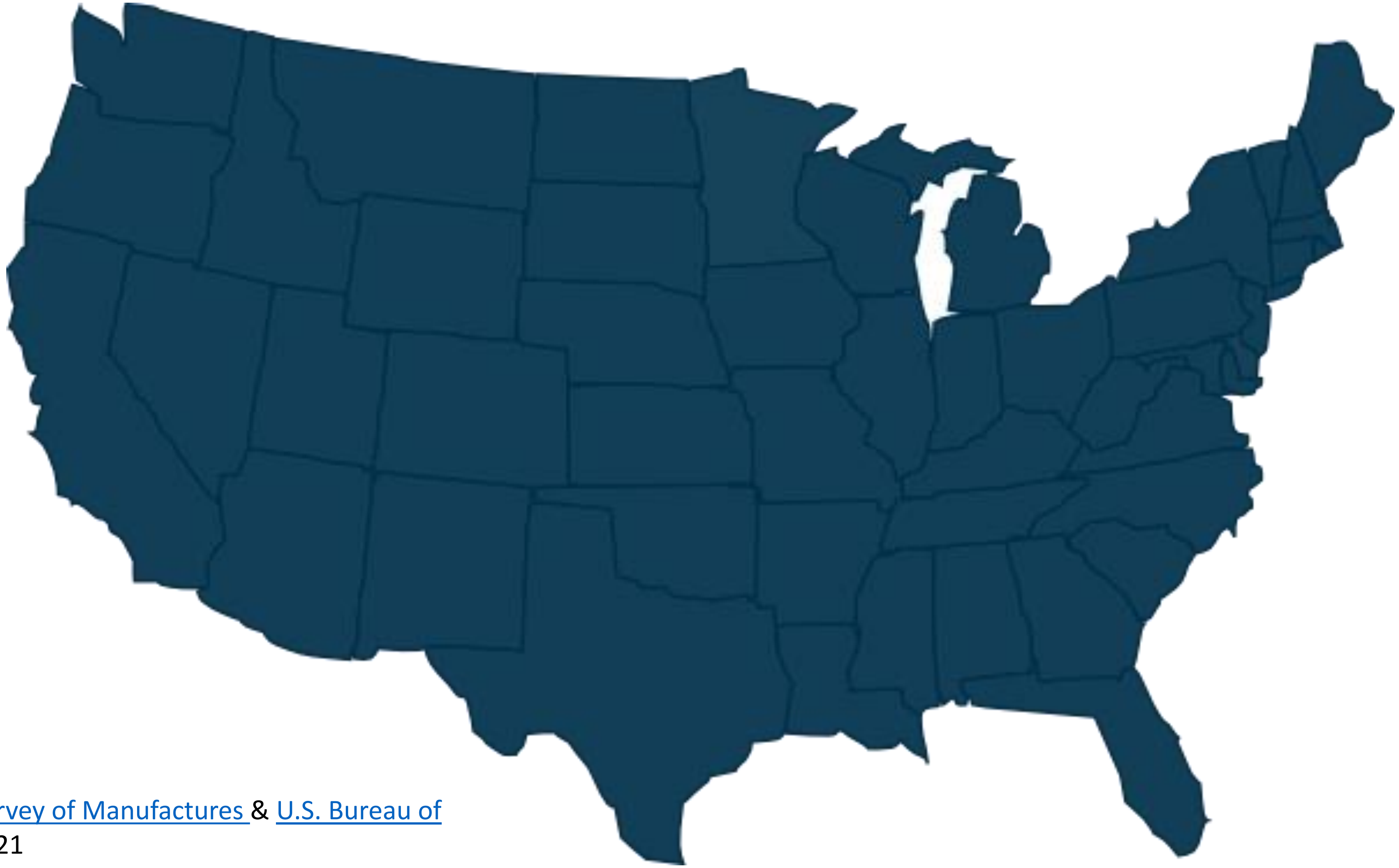
Decarbonizing Industry is an Opportunity for America's Economy

U.S. manufacturing subsector…

CONTRIBUTES
$2.79 trillion to the U.S. Economy

GENERATES
12% of U.S. GDP

SUPPORTS
11.2 million jobs



U.S. Census Bureau Annual Survey of Manufactures & U.S. Bureau of Economic Analysis data for 2021

Decarbonizing Industry is an Opportunity for America's Economy

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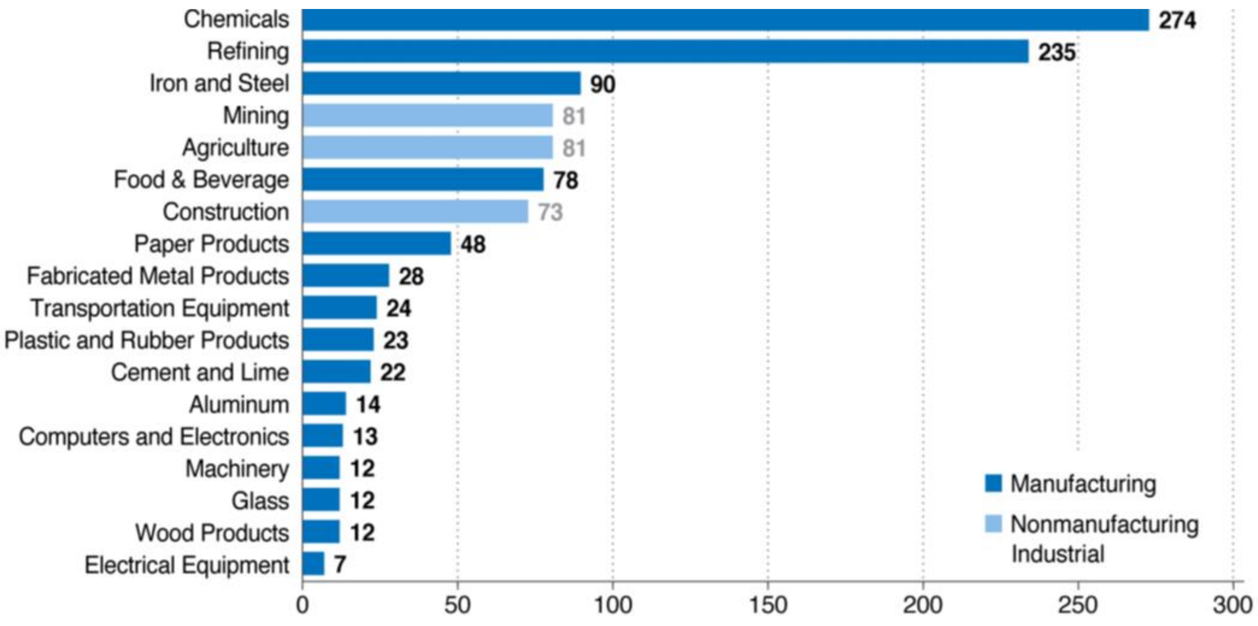


CO_2 equivalents

All industrial emissions

All subsectors

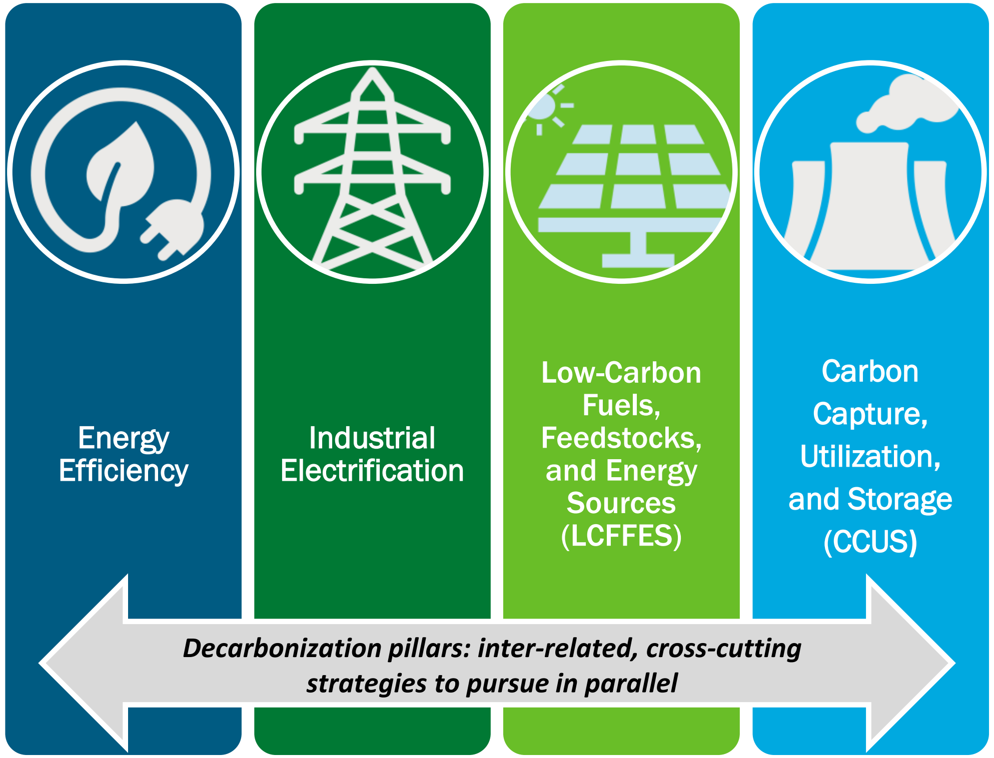
U.S. Census Bureau Annual Survey of Manufactures & U.S. Bureau of Economic Analysis data for 2021

DOE Industrial Decarbonization Roadmap

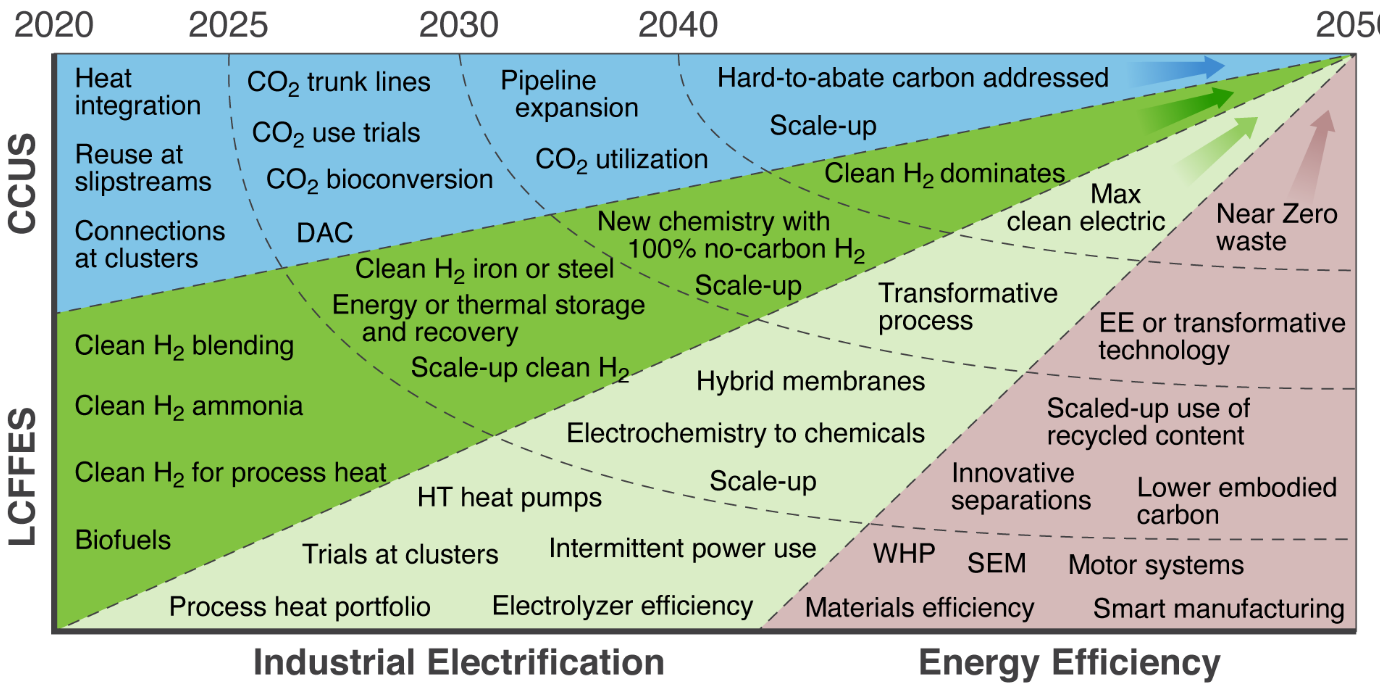
- Pillars, and associated pathways to net-zero GHG emissions by 2050 for high-emitting industrial subsectors
- Rethink the opportunity for RDD&D and robust technology solutions
- Innovations for more sustainable manufacturing

DOE Industrial Decarbonization Roadmap, Sept. 2022. https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

Industrial Decarbonization Pillars

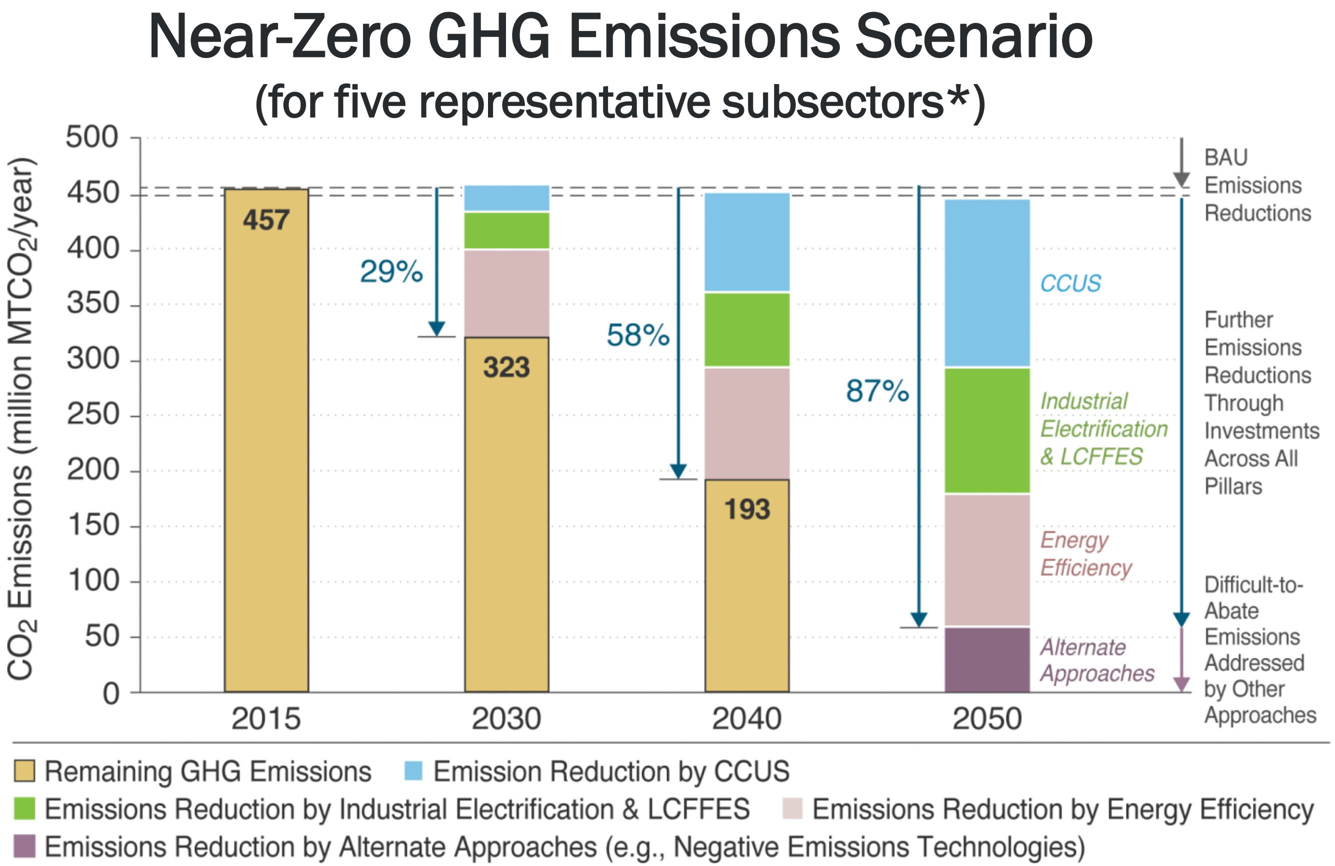


- **Invest in all pillars**
- **Leverage cross-sector approaches**
- **Interdependencies require systems solutions**
- **Strategies are needed to minimize implementation hurdles, address scale-up, and accelerate adoption**



Source: DOE Industrial Decarbonization Roadmap, Sept. 2022. https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

Industrial Decarbonization Recommendations



Roadmap Recommendations

- Advance Early-Stage RD&D
- Invest in Multiple Process Strategies
- Scale through Demonstrations
- Address Process Heating
- Decarbonize Electricity Sources
- Integrate Solutions
- Conduct Modeling and System Analyses
- Engage Communities, Develop a Thriving Workforce

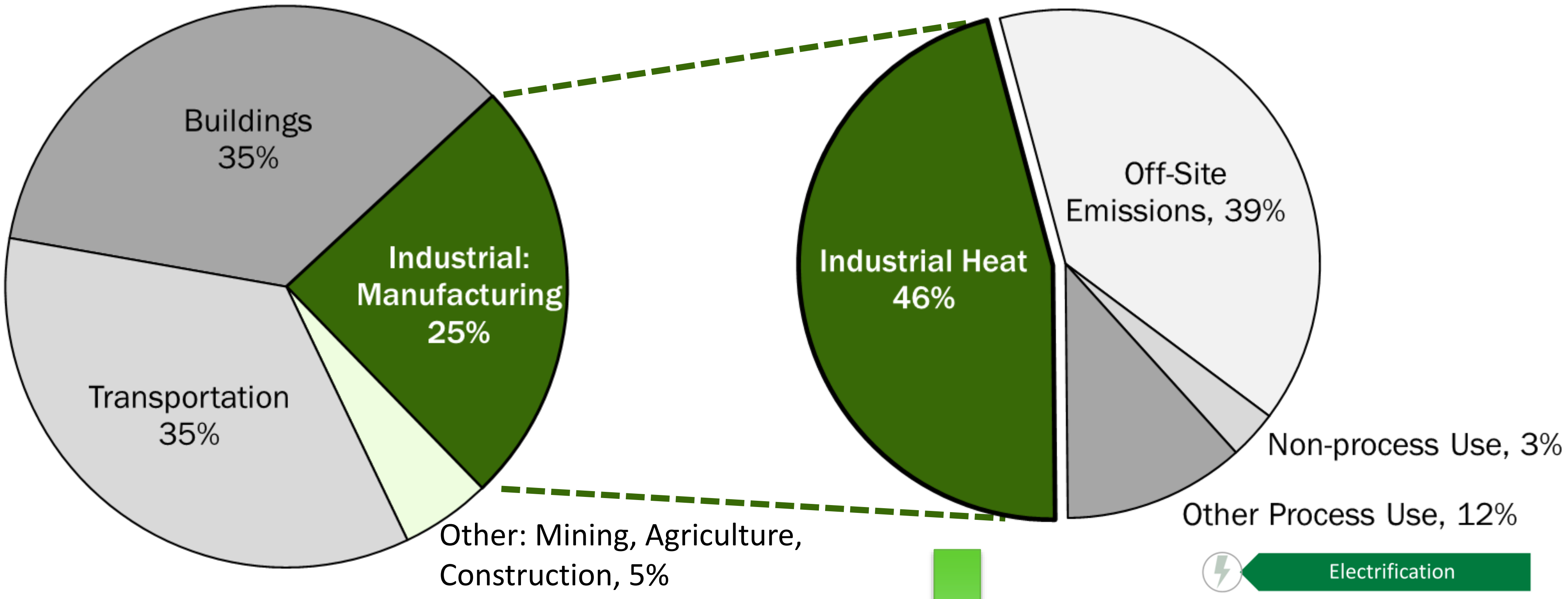
***Subsectors included in Roadmap analysis:** Iron & Steel, Chemicals, Food & Beverage, Petroleum Refining, and Cement. *(Near zero GHG scenario, excluding feedstocks.*

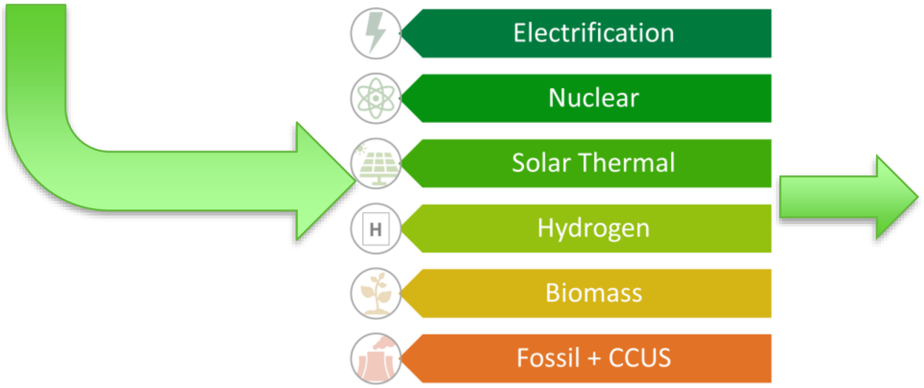
DOE Industrial Decarbonization Roadmap, Sept. 2022. https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

11% of All U.S. Energy-Related GHG Emissions are from Industrial Heat

2020 Energy-Related CO_2 Emissions by U.S. Economic Sector

2020 Estimated Industrial: Manufacturing Energy-Related CO_2 Emissions by Source





Opportunity for improved energy productivity and reduced emissions

Sources: EIA Annual Energy Outlook (2021); IEDO 2018 Manufacturing Energy and Carbon Footprints (2022)

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Industrial Heat Shot

Develop cost competitive industrial heat decarbonization technologies with **at least 85% lower greenhouse gas emissions by 2035**

>85% Lower Emissions

2035

Baseline	65 kg CO_2 equivalent per MMBtu	Current Average GHG Emissions Intensity of Industrial Heat
2035 Target	8.8 kg CO_2 equivalent per MMBtu	Aligned with Clean Hydrogen (1 kg CO_2 per kg H_2)

Industrial Heat Shot – Pathways to Reduce Emissions from Thermal Systems

Goal: Reduce the amount of heat and/or emissions from heat to make cleaner products

Generate Heat from Clean Electricity

Reduce Emissions:
electrify equipment & use clean electricity, improve energy efficiency

Examples:
heat pumps, microwave heating, resistive heating, etc.

Integrate Clean Heat from Alternative Sources

Reduce Emissions:
switch to low-emissions heat sources and increase thermal storage

Examples:
solar thermal, nuclear, geothermal, hydrogen, some sustainable fuels, etc.

Innovative Low- or No-Heat Process Technologies

Reduce Emissions:
new chemistry and emerging approaches to reduce heat demand

Examples:
advanced separations, electrolysis, ultraviolet curing, biobased manufacturing, etc.

Enabling technologies and systems: e.g. energy storage, materials, modeling, data analytics, etc.

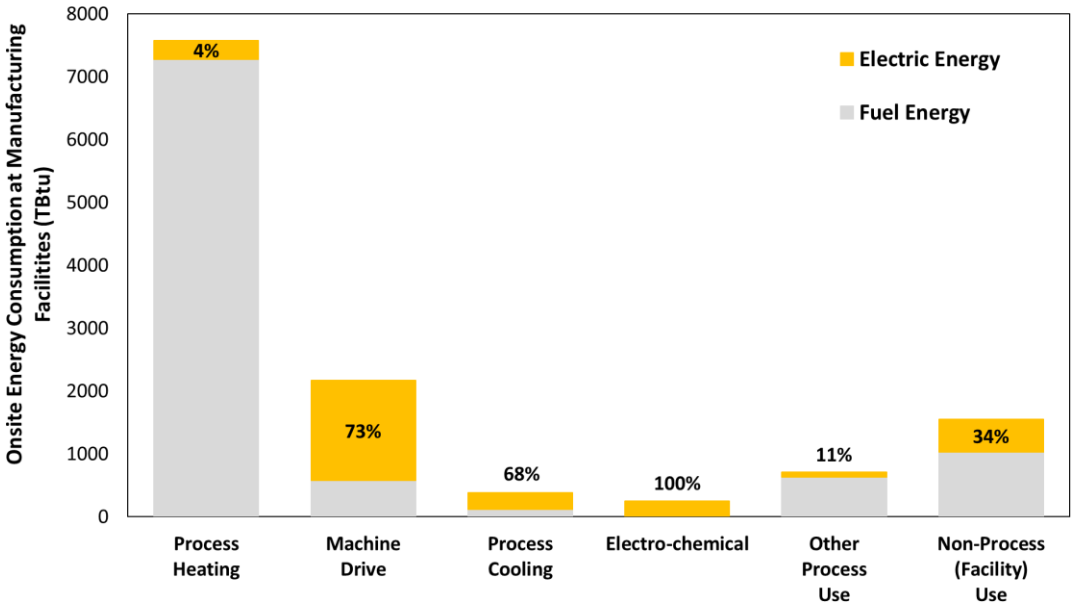
www.energy.gov/eere/industrial-heat-shot

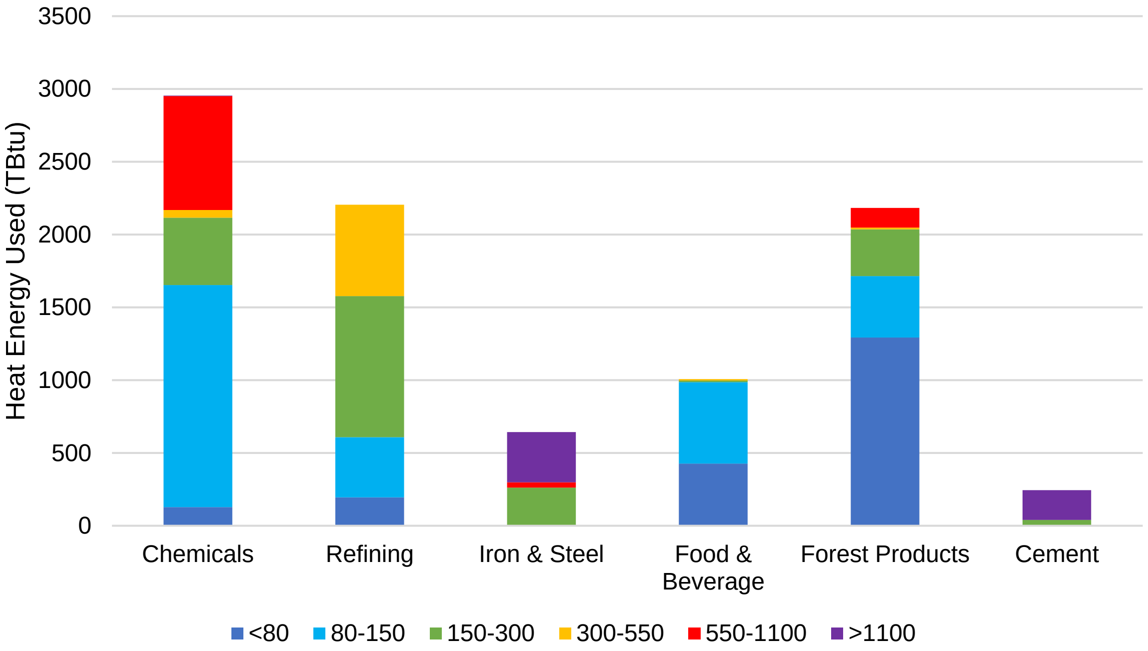
Cross-Sector Industrial Heat Demand

Decarbonization of process heating will require a multi-modal strategy.

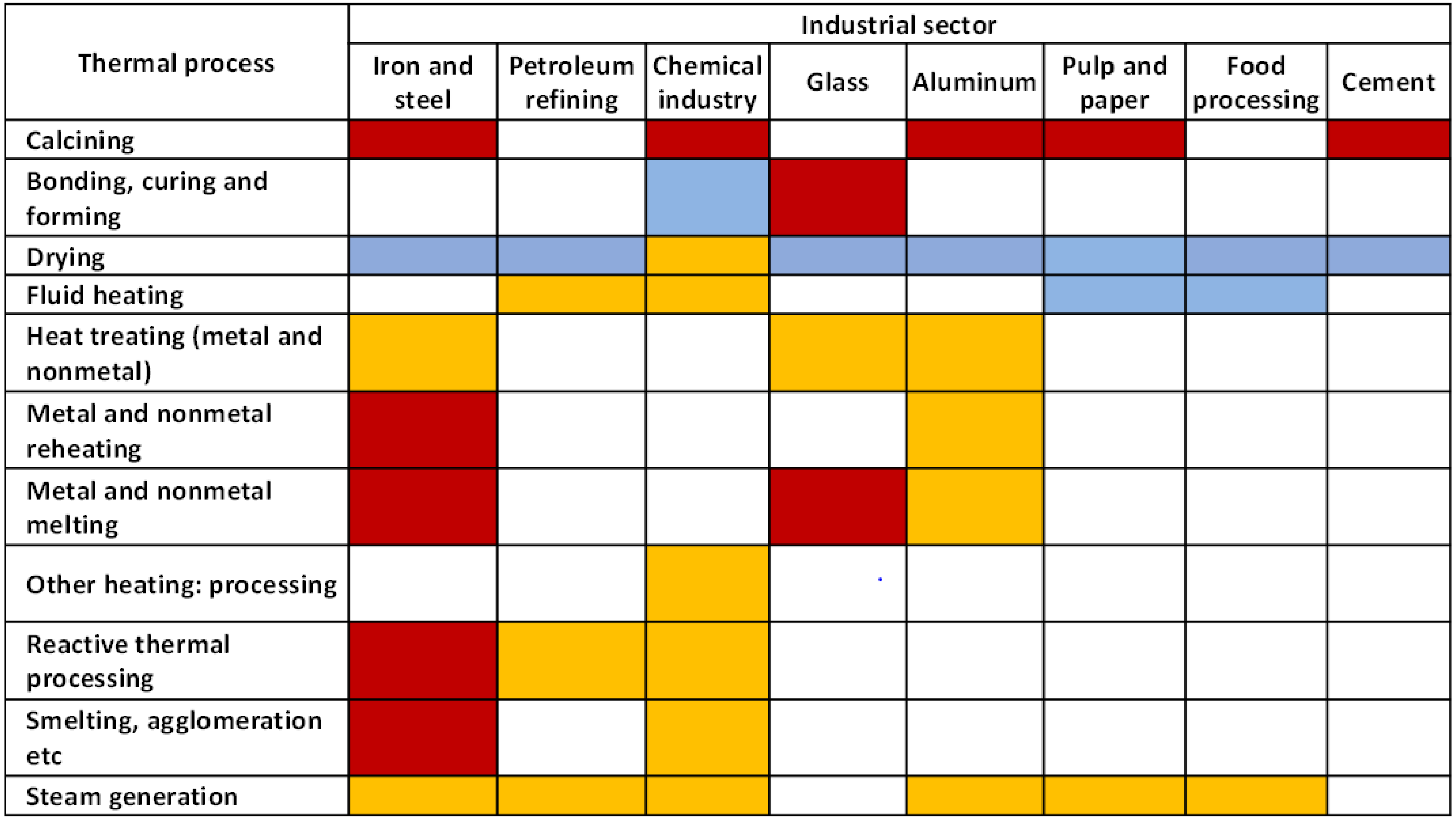
Process heating represents more than 50% of manufacturing end-use energy, but less than 5% of process heating is electrified.

Over 50% of process heating demand is low temperature (<150°C) – prime candidate for electrification, while other high temperature process heat needs will require alternative thermal processing technologies.





Data sources: DOE *Manufacturing Energy and Carbon Footprint*, based on EIA Manufacturing Energy Consumption Survey (MECS) data for 2018; C. McMillan, Manufacturing Thermal Energy Use in 2014. 2019. National Renewable Energy Laboratory. dx.doi.org/10.7799/1570008.



Blue = low temperature (<800°F);

Orange = medium temperature (800°F to 1,400°F);

Red = high temperature (>1,400°F).

Thermal considerations:

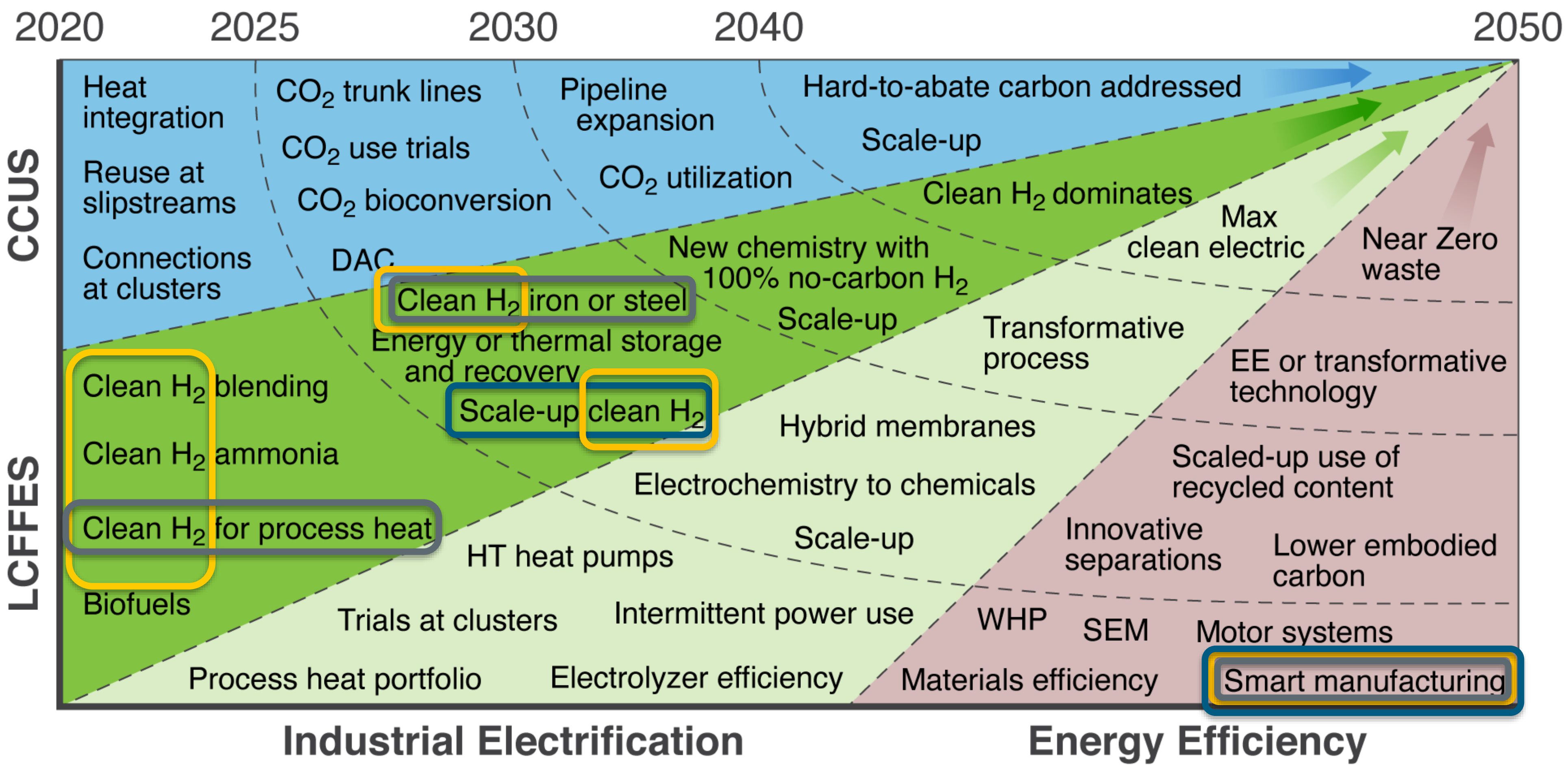
- Higher process heat needs requiring combustion fuel?
  - Cement
- Are alternative heating technologies (e.g. electrification) technically challenging or cost-prohibitive?
  - Glass

Process considerations:

- Is this a process that traditionally requires direct-fired heating?
  - Melting and forming

***Source**: Decarbonization Options for Process Heating, Arvind Thekdi, 2022*

Industrial Decarbonization is also a systems challenge



Landscape of major RD&D investment opportunities for industrial decarbonization between now and 2050.

LCFFES = Low Cost Fuels, Feedstocks, and Energy Sources; **CCUS** = Carbon Capture Utilization and Storage

Source: Industrial Decarbonization Roadmap

Industrial GHGs require approaches at multiple levels:

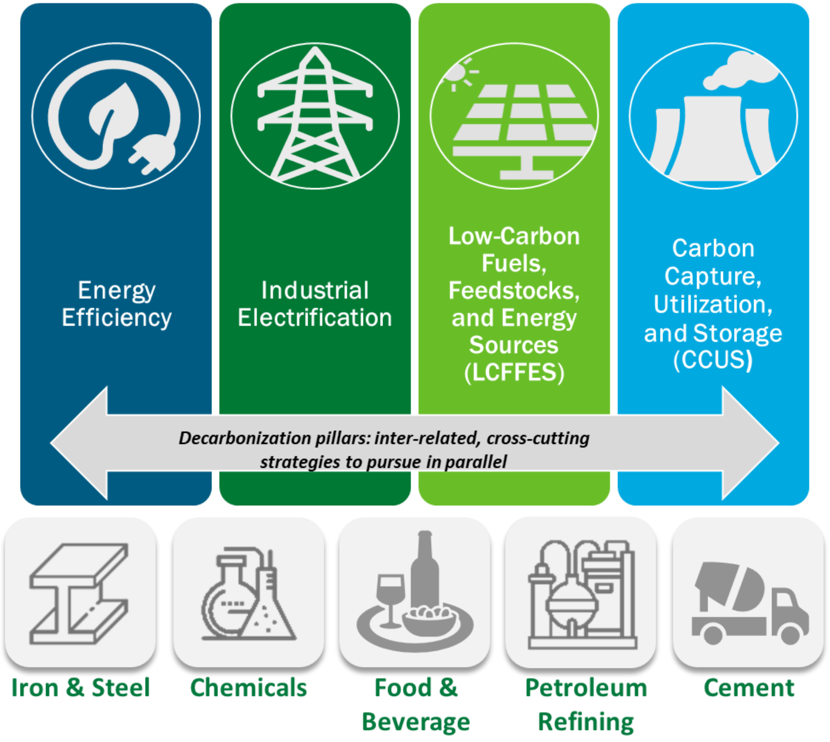
- Core process
- Facility
- Beyond plant bounds

What are the implications of:

- Expanded H_2 generation & use
- New thermal energy sources & systems
- Smart manufacturing, automation, & data analytics
- Transition to clean electricity
- Policies

DOE Industrial Decarbonization – Clean Hydrogen Opportunities

Industrial Decarbonization Pillars



Intersectoral Collaboration

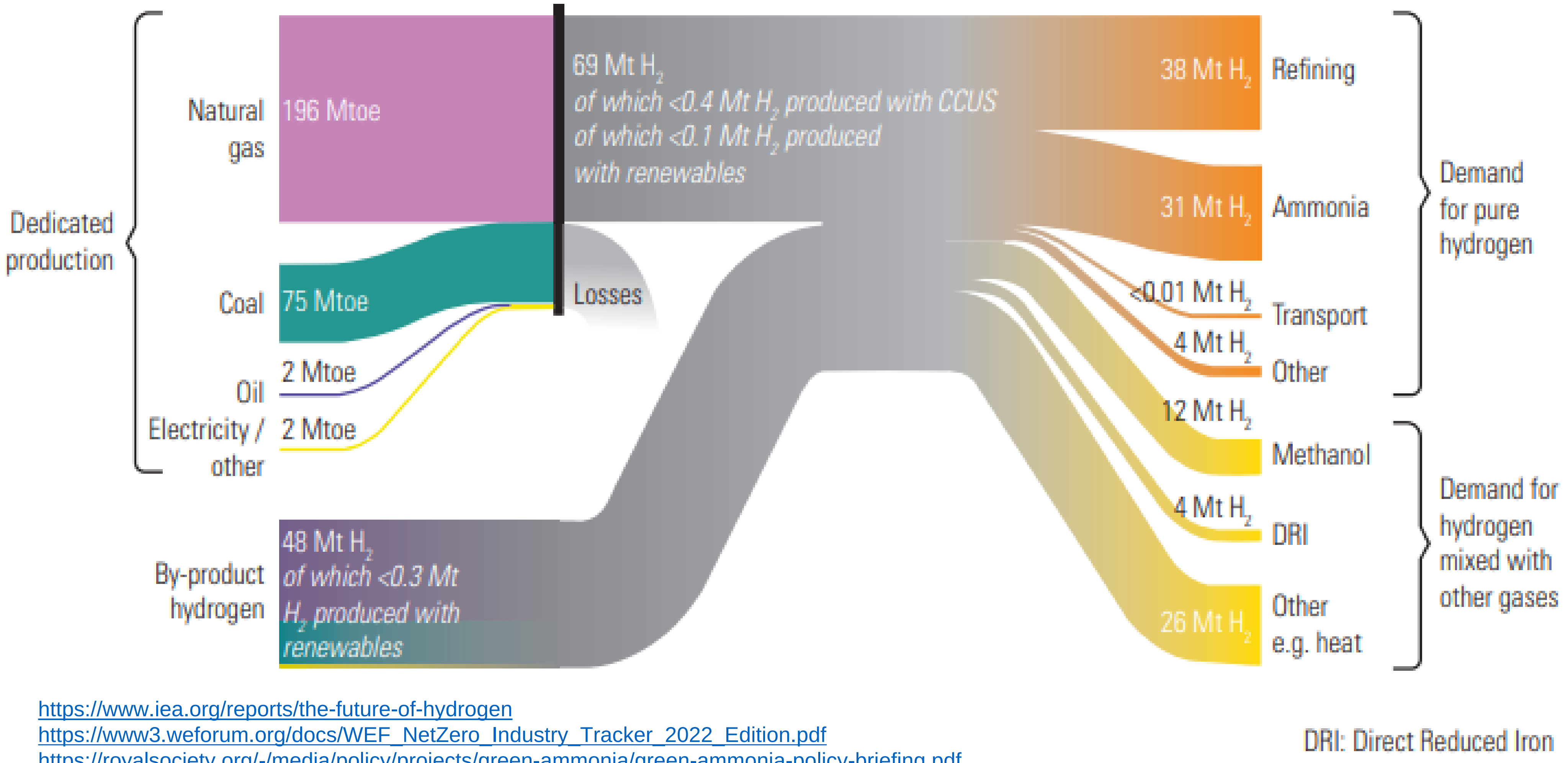
- **Clean H_2 generation** - renewables, nuclear power, or fossil resources with carbon capture can reduce emissions of existing demand sectors.
- **Clean H_2 and low-carbon electricity demand -** will increase significantly by 2050. R&D efforts will be needed to improve the efficiency of electrolyzers.
- Novel technologies for H_2 use - heavy-duty vehicles, metal refining, synthetic fuels production, and stationary fuel cells can further enable emissions reductions.
- H_2 supply for grid services - to increase resiliency.
- H_2 infrastructure advancements – e.g. compression, pipeline and chemical carrier transport, and bulk storage

Examples of hydrogen us by industrial subsector:

Iron & Steel	Chemicals	Food & Beverage	Refining	Cement
Alternative reductants – e.g., Clean H_2 in direct reduced iron (DRI) and blast furnaces	Clean H_2 use as fuel or feedstock	Clean H_2 use for med temp process heat	Desulfurization using clean H_2	Clean H_2 as fuel

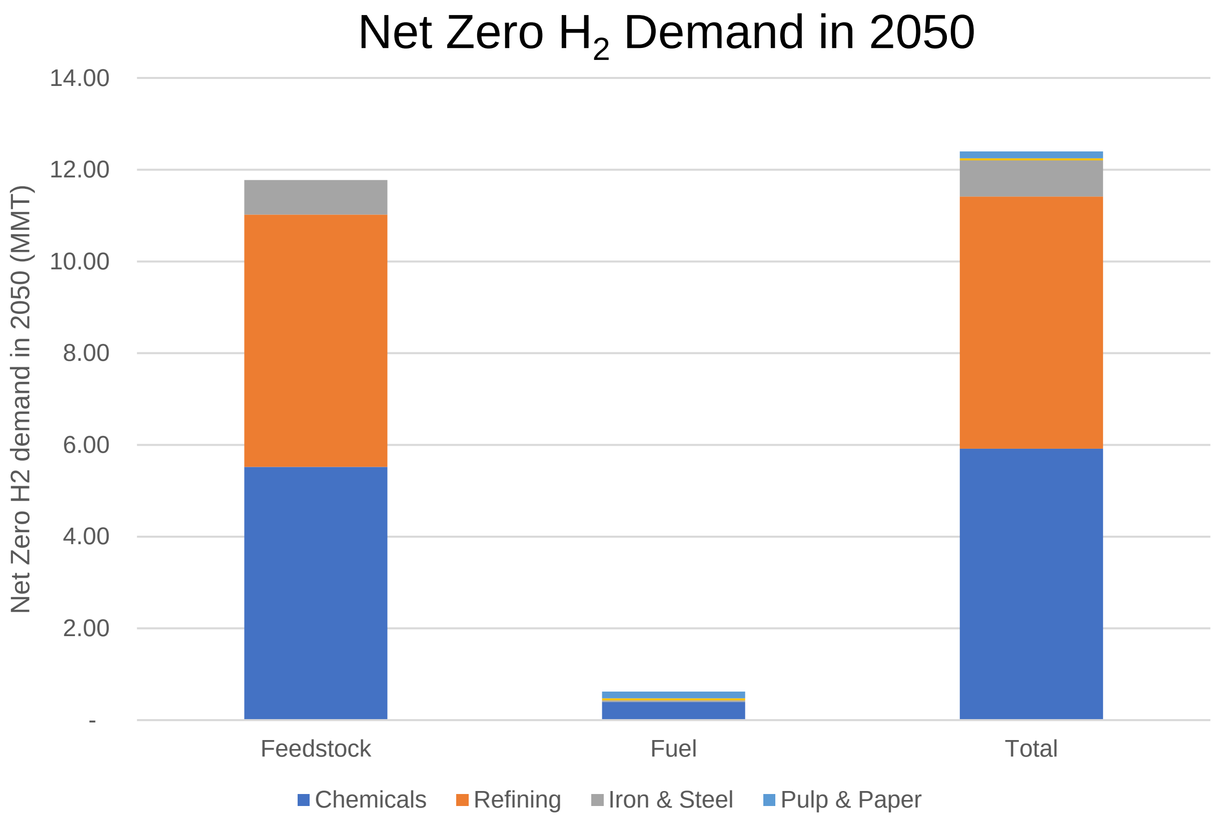
Global Hydrogen Value Chains

Current H_2 demand ~ 90 MMT
2030 forecast demand: 200 MMT



https://www.iea.org/reports/the-future-of-hydrogen
https://www3.weforum.org/docs/WEF_NetZero_Industry_Tracker_2022_Edition.pdf
https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf
https://industrialinnovation.org/wp-content/uploads/2023/05/The-Landscape-of-Clean-Hydrogen.pdf
https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf

U.S. Hydrogen Demand Estimates



Current hydrogen production is ~10 MMT

U.S. National Clean Hydrogen Strategy and Roadmap forecast 50 MMT hydrogen production in 2050.

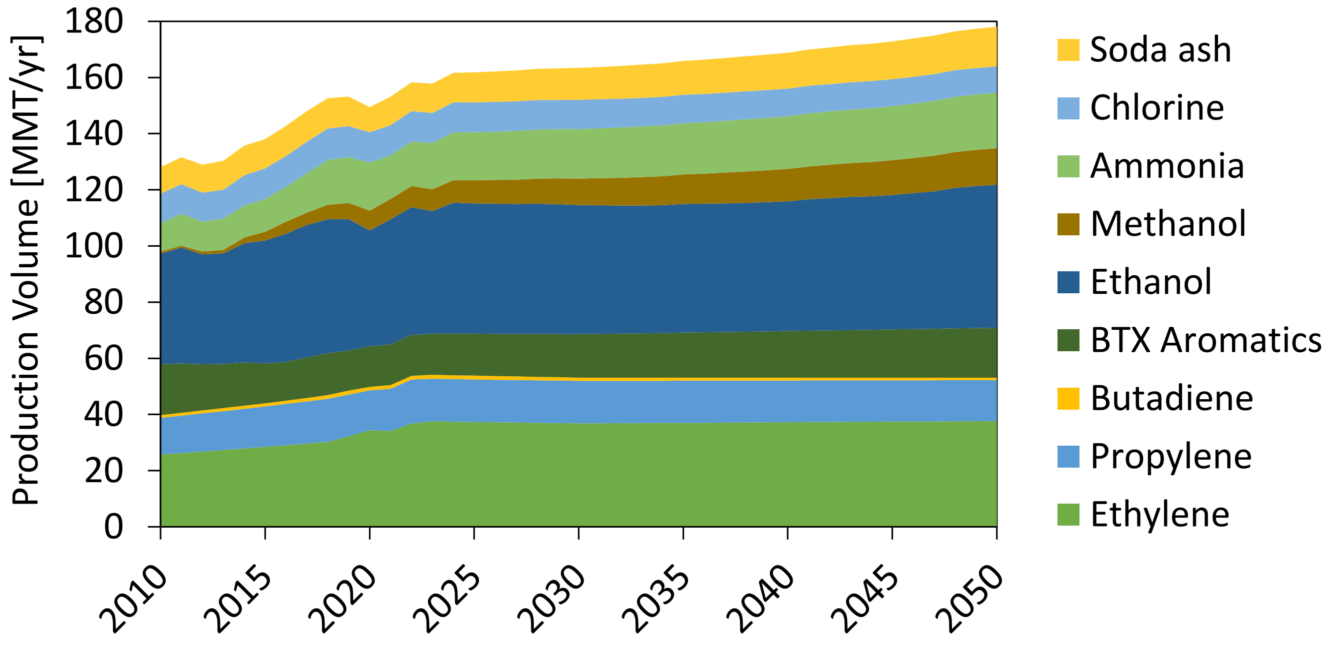
- Total 2050 Net Zero Hydrogen Demand for 6 EEII sectors is over **12 MMT**
- Chemicals and Refining are largest consumers
  - >90% of total industrial hydrogen use
- In 2050 hydrogen remains more valuable as a feedstock than as a combustion fuel

Note: food & beverage and cement report negligible hydrogen demand under the net-zero scenario

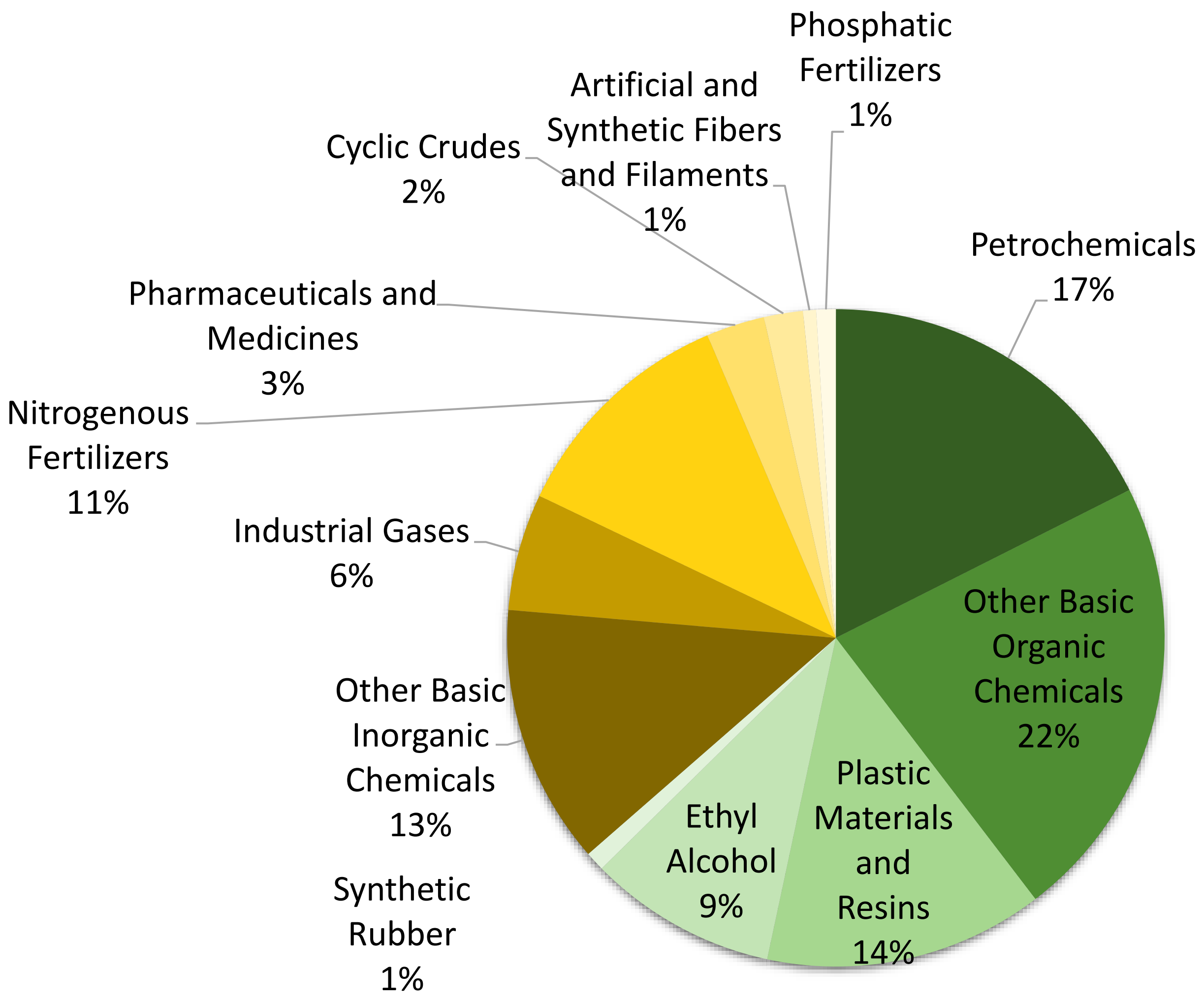
PRELIMINARY DATA. DO NOT CITE.

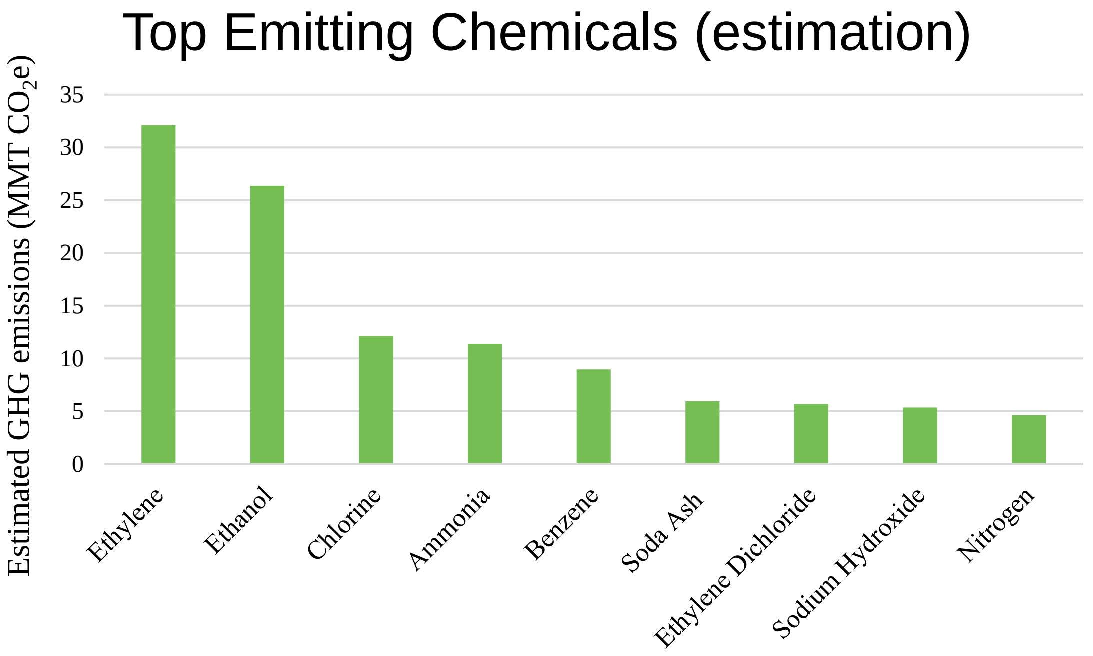
The U.S. Chemicals Sector

- The U.S. chemical industry contributed over 25% to the total GDP in 2022, valued at $486 billion.
- It manufactures **70,000+ distinct products across 11,000+ facilities**.
- In 2022, the **U.S. ranked as the world's second-largest chemical producer**, meeting nearly 13% of global demand.
- The sector **employs approx. 4.1 million individuals**, directly or indirectly.
- It consumes **25% of total primary energy** within U.S. manufacturing.
- Responsible for **28% of GHG emissions in U.S. manufacturing**.
- Historical data shows a **16% growth in chemical production from 2010 to 2020 …**
- … and projections **suggest a further 20% growth** in basic chemical production between 2020 and 2050.



Emissions Across Chemicals Sector





Manufacturing Energy and Carbon Footprints: https://www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs
Manufacturing Energy Bandwidth Studies: https://www.energy.gov/sites/default/files/2015/08/f26/chemical_bandwidth_report.pdf

Early Uses

- ✓ Process heat (especially high temperature)
- ✓ Blending with current H_2
- ✓ Ammonia (if energy for H_2 decarbonized)

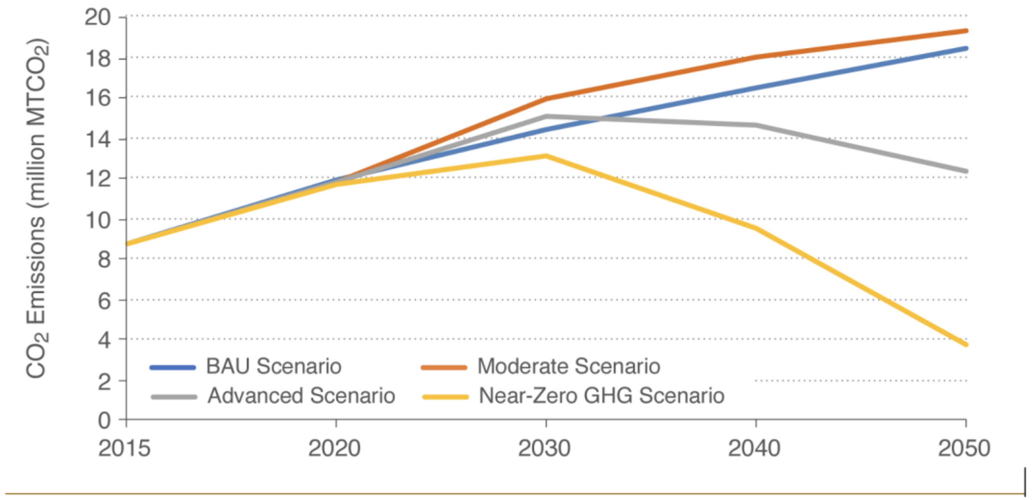


FIGURE 23. CO_2 EMISSIONS (MILLION MT/YEAR) FORECAST FOR THE U.S. AMMONIA INDUSTRY BY SCENARIO WHEN ELECTROLYSIS HYDROGEN IS ADOPTED MODESTLY IN 2030-2050. SOURCE: THIS WORK.

Later Uses

- ✓ Methanol
- ✓ Ethylene
- ✓ Ammonia (H_2 from energy via decarbonized grid)

Chemicals

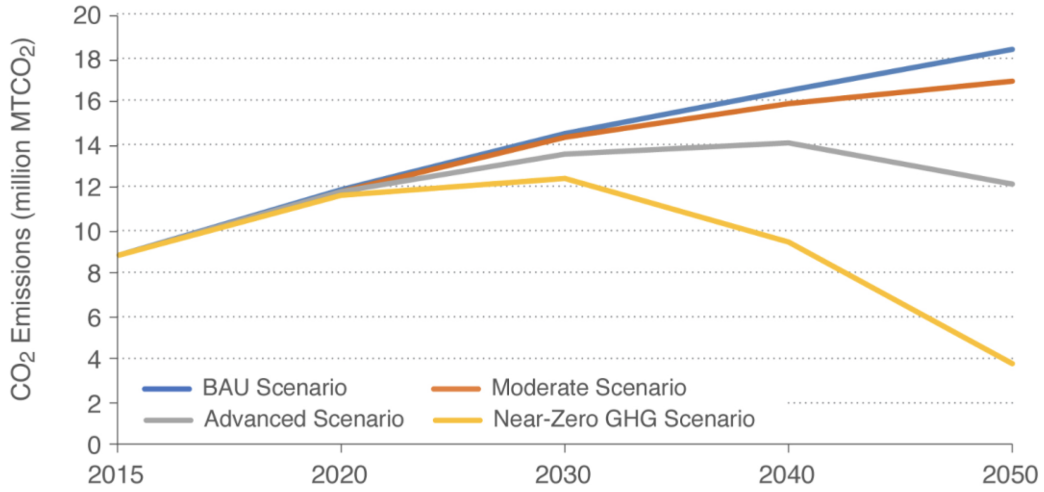
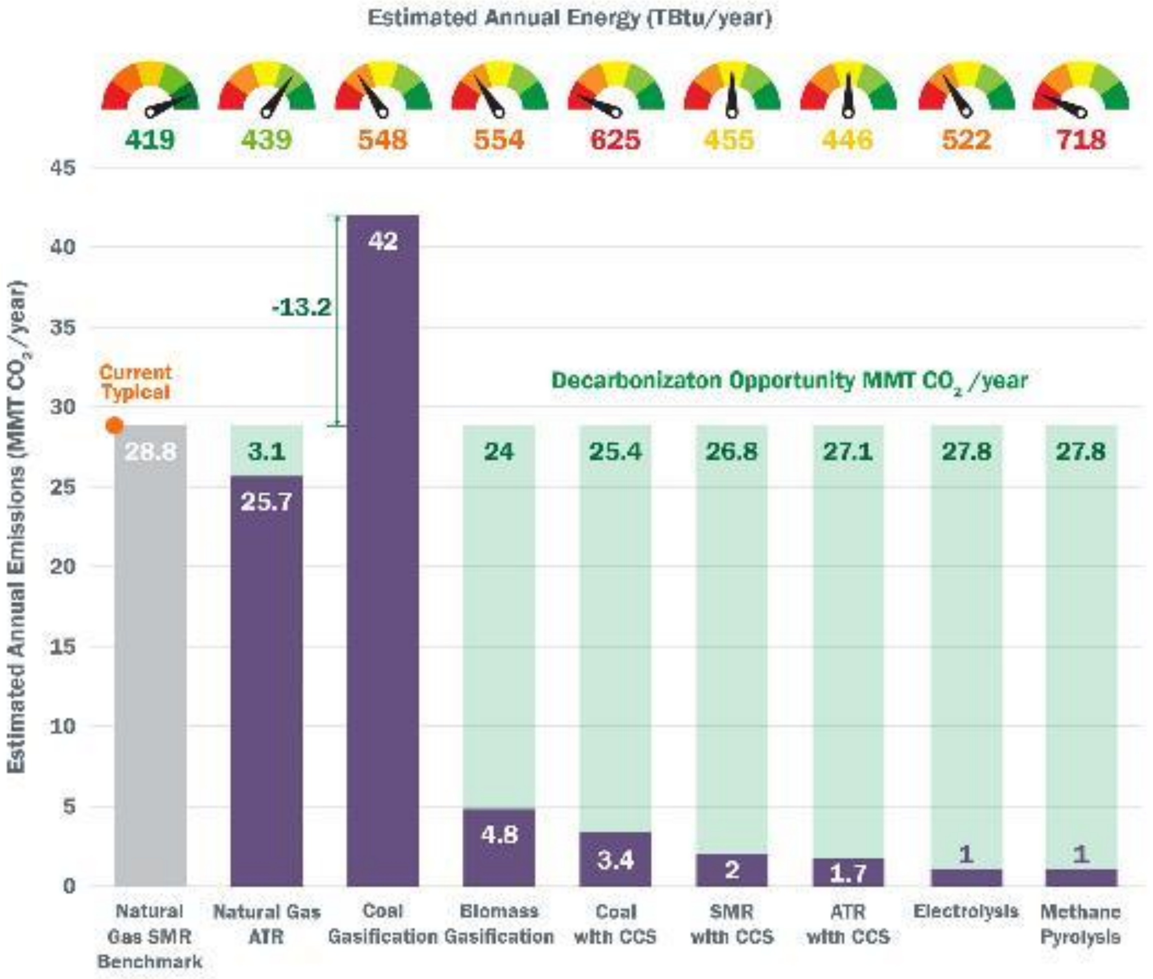


FIGURE 24. CO_2 EMISSIONS (MILLION MT/YEAR) FORECAST FOR THE U.S. AMMONIA INDUSTRY BY SCENARIO WHEN ADOPTION OF ELECTROLYSIS-H_2 IS DELAYED UNTIL THE ELECTRIC GRID IS DECARBONIZED. SOURCE: THIS WORK.

Key message: If electrolysis – H_2 using grid-based electricity is applied too rapidly as a feedstock by 2030, CO_2 emissions could increase above BAU, whereas if its use as a feedstock is delayed until the electric grid is fully decarbonized, the increased emissions above BAU could be avoided. Direct use of renewable energy to supply the energy for H_2 generation could also avoid this issue.



Benchmark

Fossil-based emissions

Decarbonization opportunity (avoided emissions)

Approximately 90% of ammonia emissions are from the generation of H_2 as feedstock

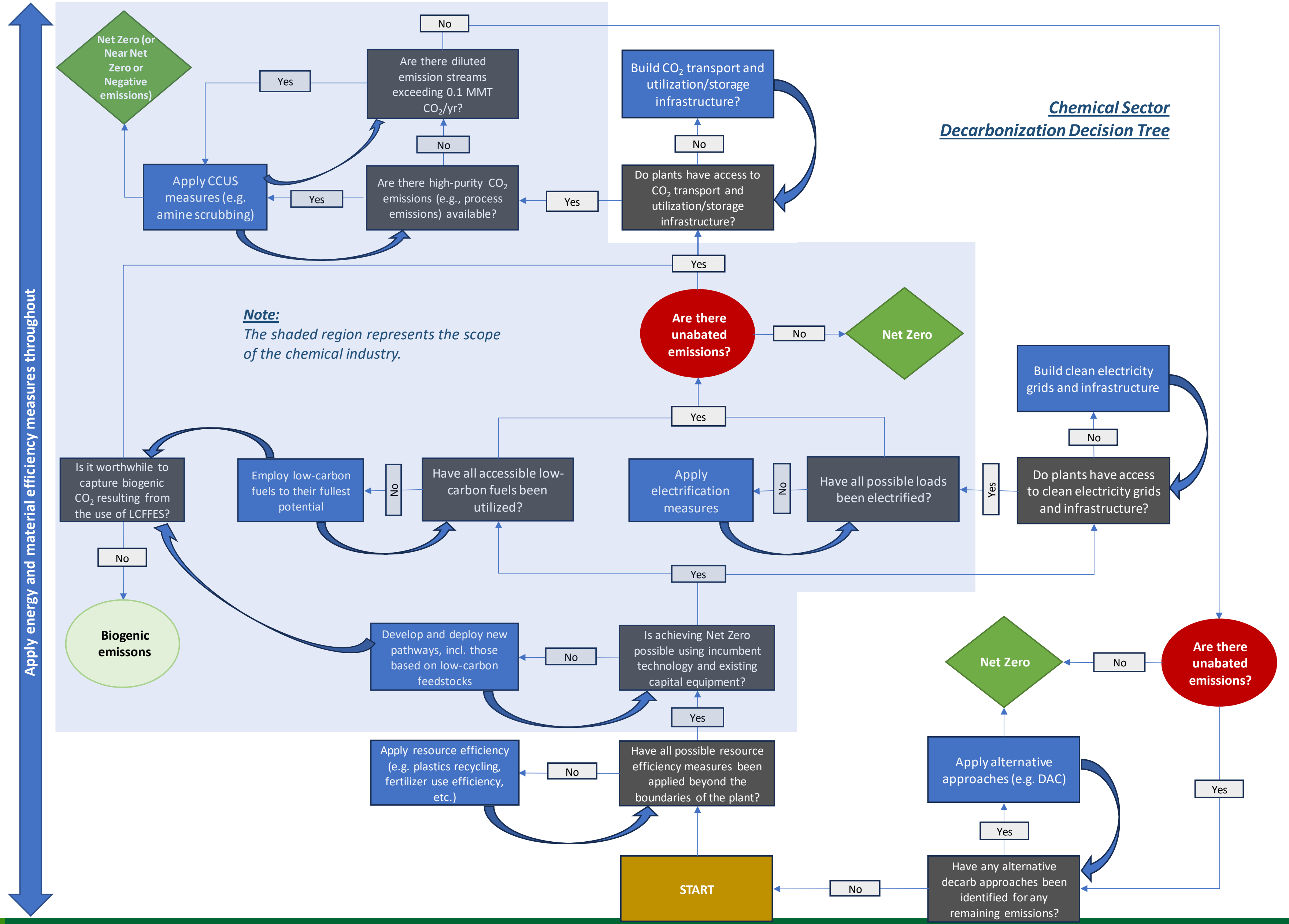
- Natural gas steam methane reforming (SMR) is the primary production route in the U.S.
- Autothermal reforming (ATR) and coal gasification are also commercial pathways to H_2 production.
- IEA's Ammonia Technology Roadmap provides a comprehensive list of late-TRL technology approaches to low-carbon hydrogen for ammonia production.
  - ➢ **Energy and emissions analysis presents interesting trade-offs**

PRELIMINARY DATA. DO NOT CITE.

Sources:

- RSC Policy Briefing, Ammonia: zero-carbon fertilizer, fuel and energy store, 2020, https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/
- IEA, Ammonia Technology Roadmap, 2021, Table 1.2, https://www.iea.org/reports/ammonia-technology-roadmap
- EPA, Inventory of U.S. Greenhouse Gases and Sinks: 1990 – 2019, https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf.
- INL, Nuclear-Integrated Ammonia Production Analysis, 2010, https://art.inl.gov/

Chemical Sector Decarbonization Decision Tree



Substantial Investments are Required to Meet Net-Zero Goals

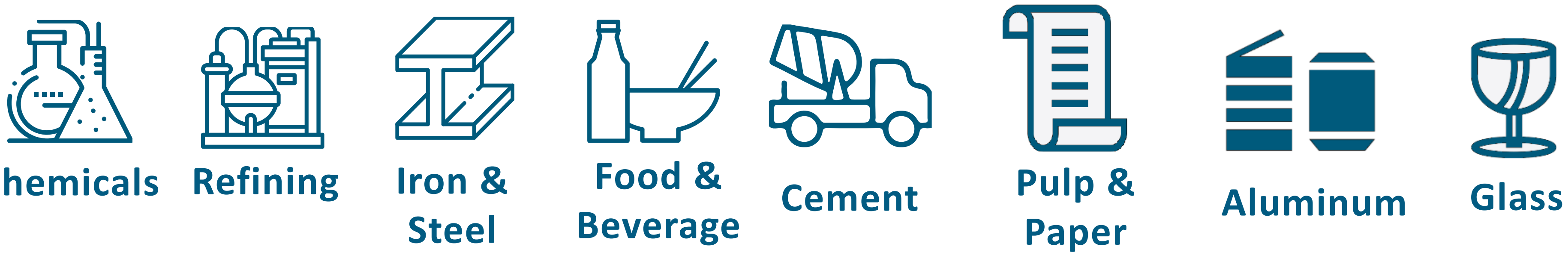
Investment scale → In the range of

$0.7 – $1.1T

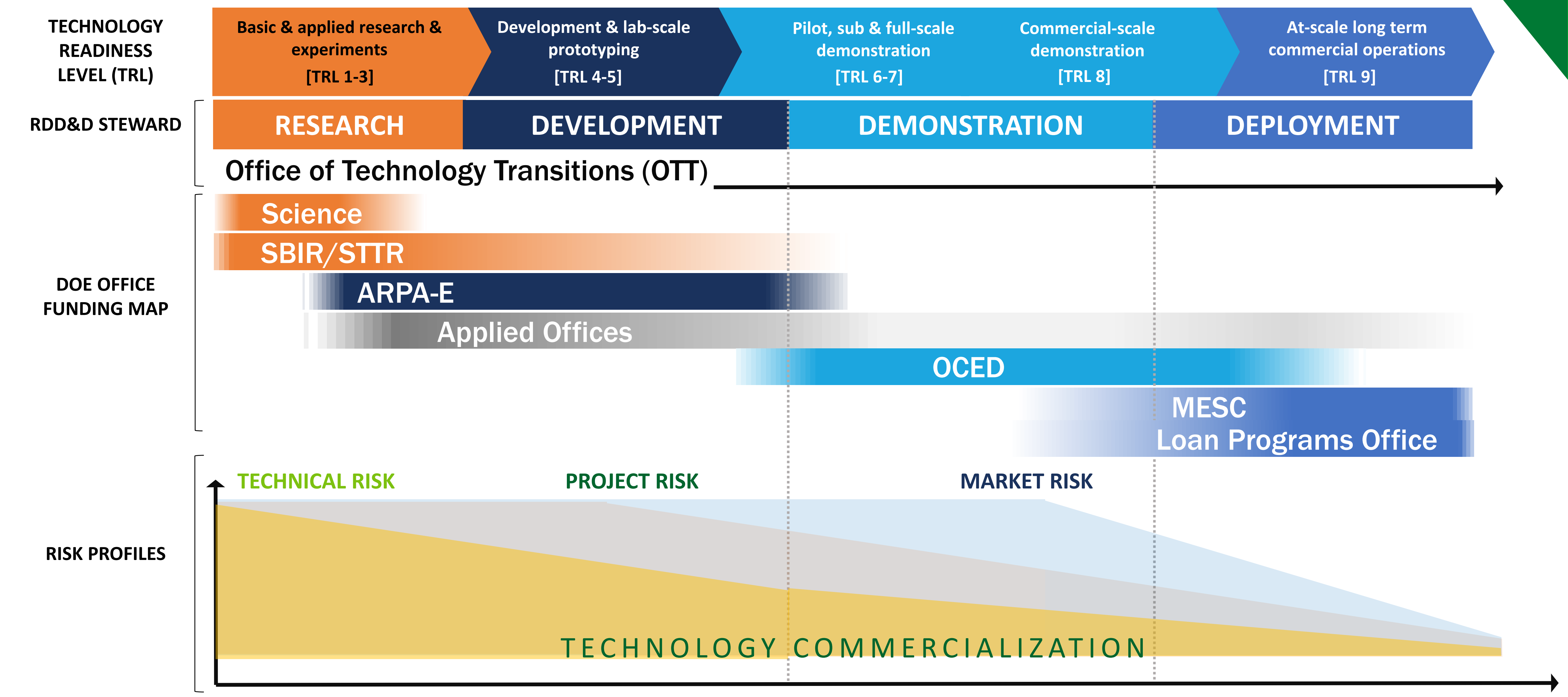
for 8 industrial sector of focus in the IRA :

Source: DOE Pathways to Commercial Liftoff; Industrial Decarbonization

https://liftoff.energy.gov/industrial-decarbonization/



Research, Development, Demonstration & Deployment (RDD&D) Continuum



Industrial Technologies across DOE:

https://www.energy.gov/industrial-technologies/industrial-technologies

Closing Thoughts

Technology Investment Portfolios

- Investment strongly influences outcomes
- Too much diversification is a bad strategy
- It is essential to make targeted investments
- Should put a few eggs in the right baskets

ELSEVIER
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Volume 101, April 2019, Pages 211-238

Wright meets Markowitz: How standard portfolio theory changes when assets are technologies following experience curves

Rupert Way [a b], François Lafond [a b c], Fabrizio Lillo [d e], Valentyn Panchenko [f], J. Doyne Farmer [a g h]

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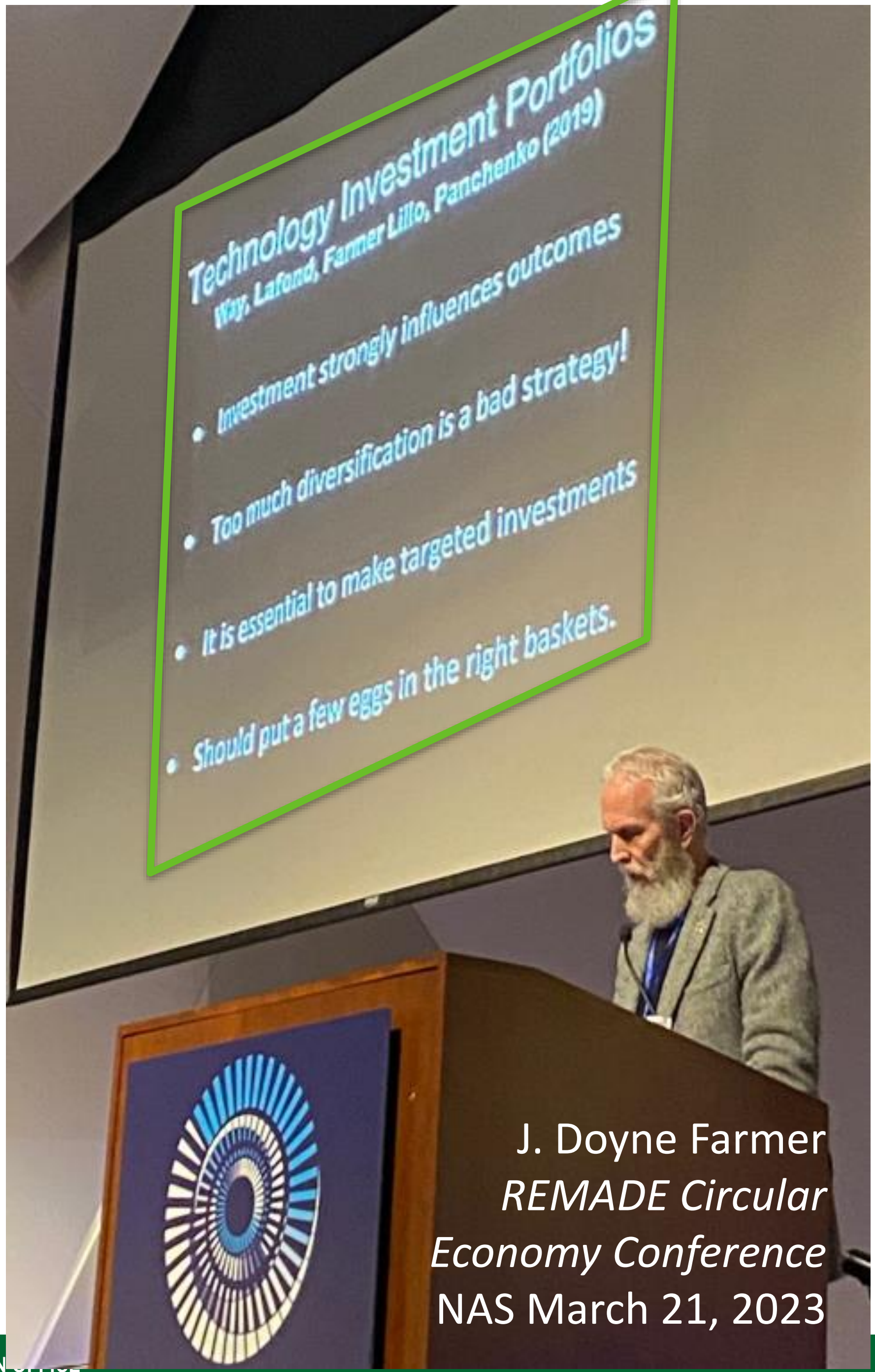

J. Doyne Farmer
REMADE Circular Economy Conference
NAS March 21, 2023

Thank you

Special Thanks to the IEDO Strategic Analysis Team

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Energetics – Caroline Dollinger, Sam Gage, Brian Ray

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For additional information:

https://www.energy.gov/eere/iedo/energy-analysis-data-and-reports