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

Industrial Decarbonization Roadmap and Context

Joe Cresko, Chief Engineer
Industrial Efficiency and Decarbonization Office

ITIAC Meeting
March 21st, 2024 | Washington, D.C

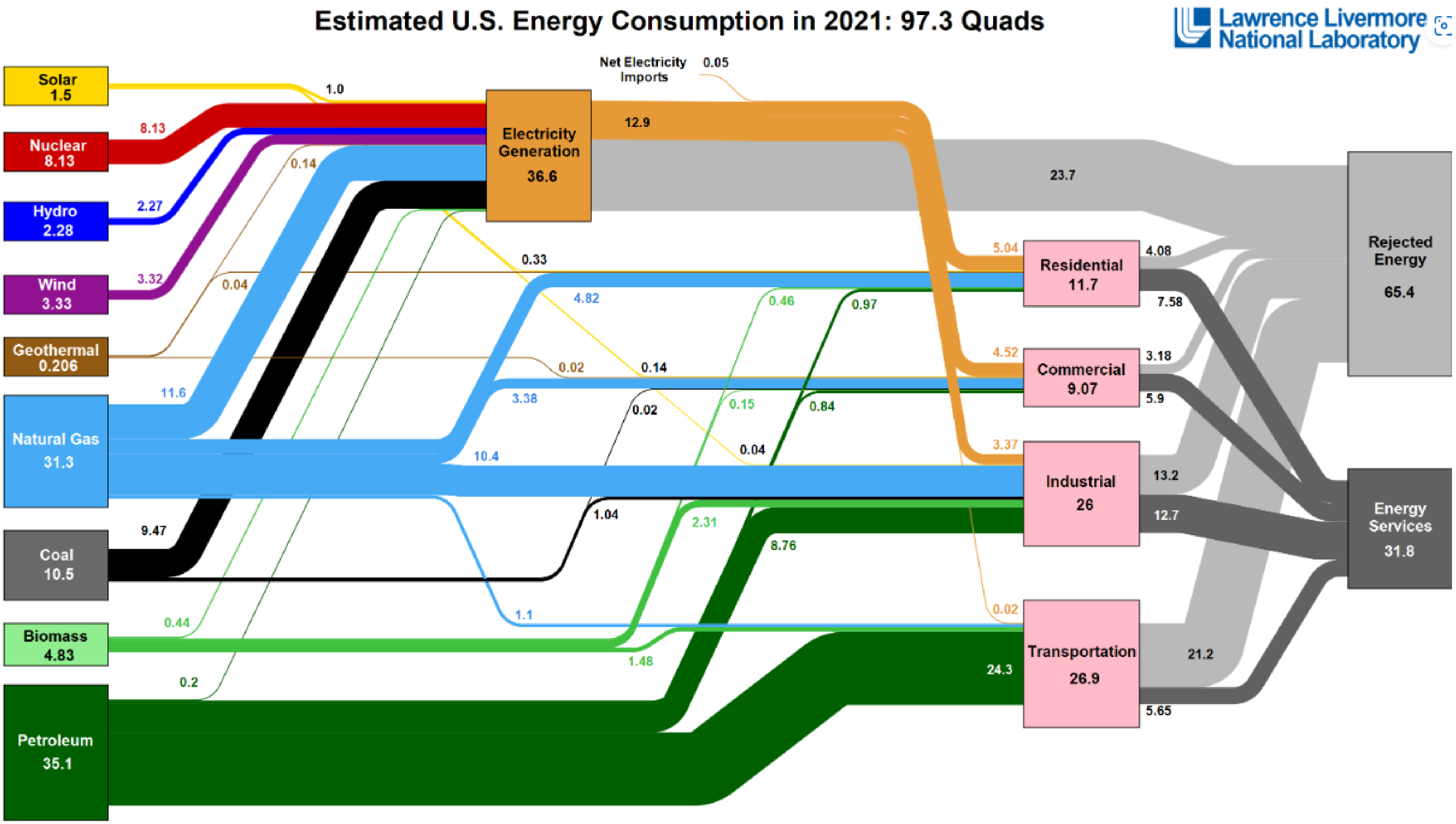
Argonne National Laboratory | NREL Transforming ENERGY | Oak Ridge National Laboratory | Berkeley Lab Lawrence Berkeley National Laboratory | energetics Clean Energy Consulting

- **Background and Context – Industrial Energy and Emissions**
- **Industrial Decarbonization Roadmap**
- **Ongoing Analysis – Look Ahead**

Vision: An efficient and competitive industrial sector with net-zero greenhouse gas emissions by 2050.

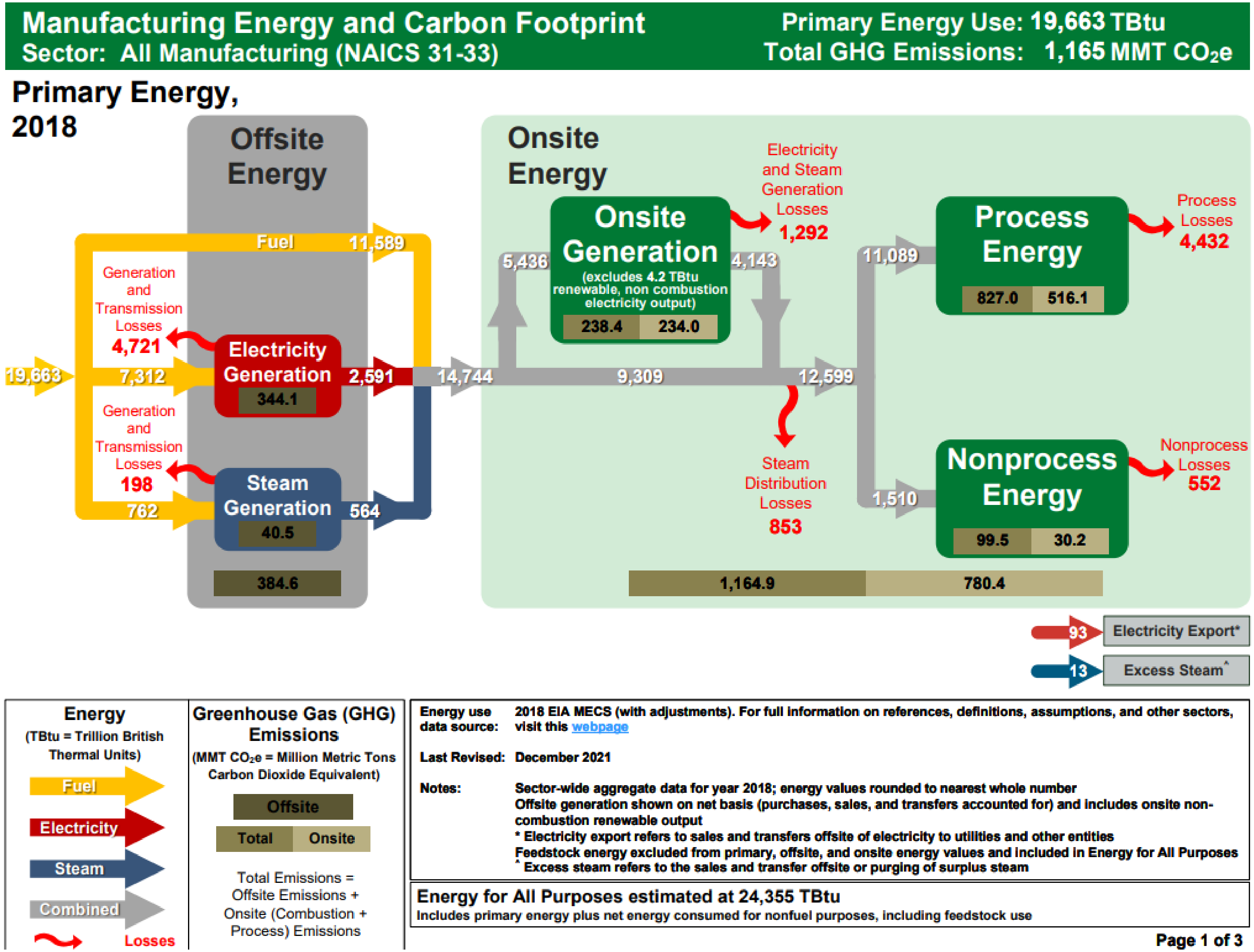
Mission: Accelerate the innovation and adoption of cost-effective technologies that eliminate industrial greenhouse gas emissions.

Energy Demand in the U.S.



U.S. Energy Flow Chart for 2022 (LLNL) - https://flowcharts.llnl.gov/commodities/energy

Energy & Emissions in Manufacturing



Manufacturing Energy and Carbon Footprints

The flow of energy supply, demand, and losses as well as greenhouse gas (GHG) emissions for end uses in 15 manufacturing subsectors.

https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf

Thermal Energy Systems

No One-Size-Fits-All Solution

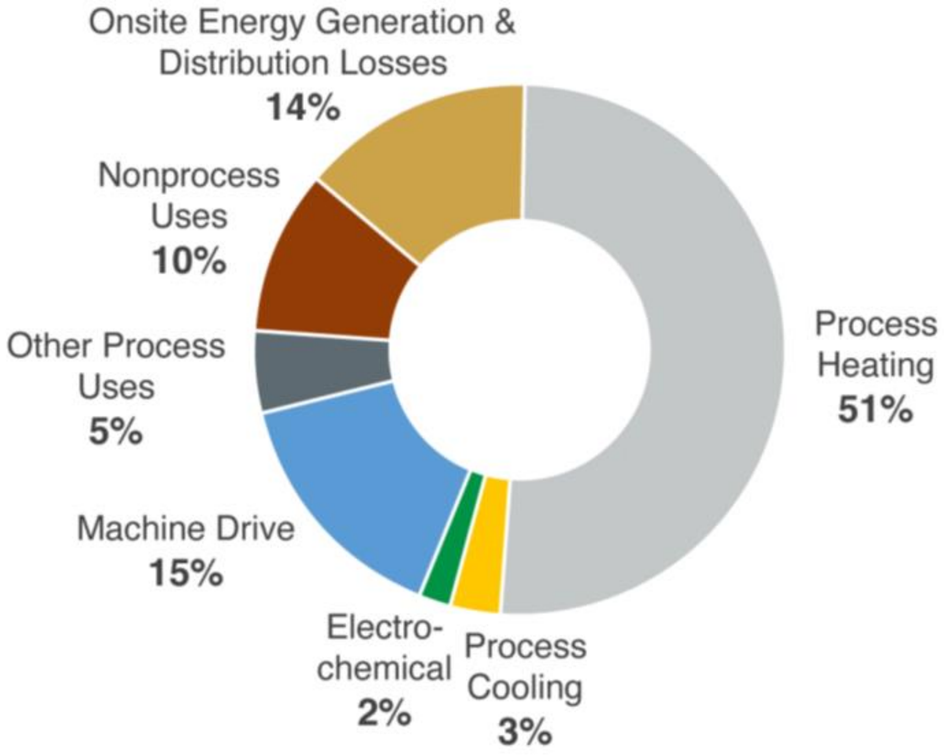


Figure source: DOE [Industrial Decarbonization Roadmap](#)
Data source: [Manufacturing Energy and Carbon Footprint](#) for 2018

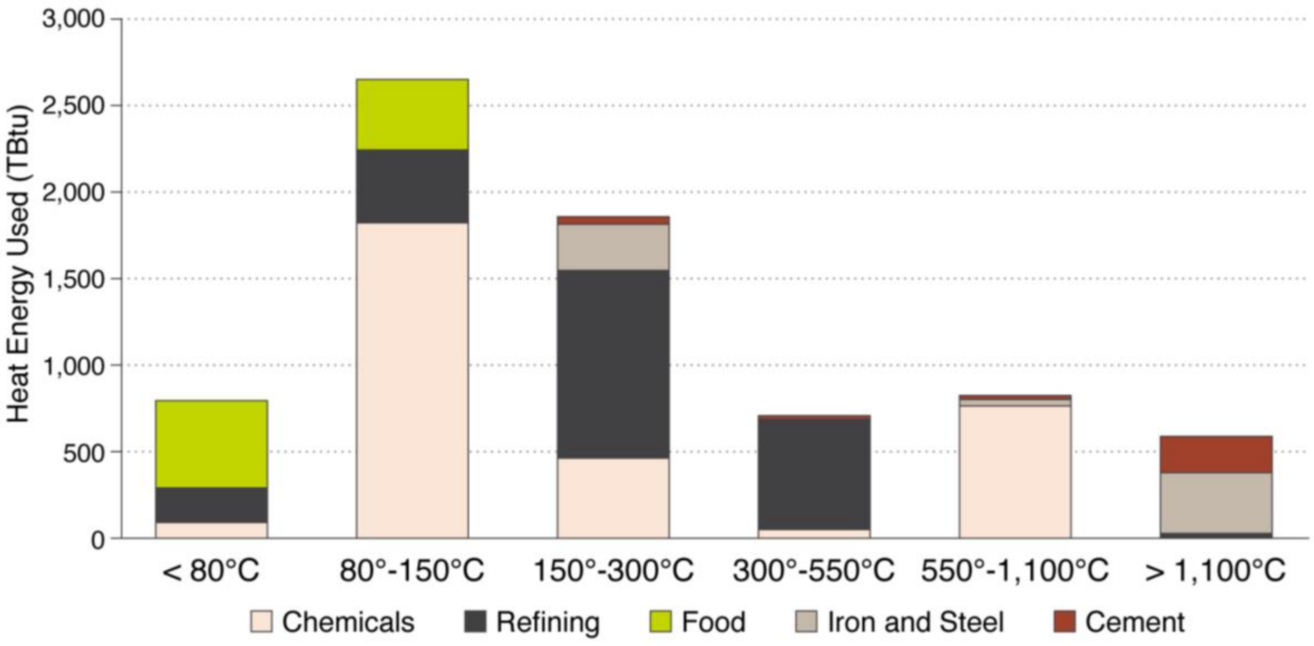
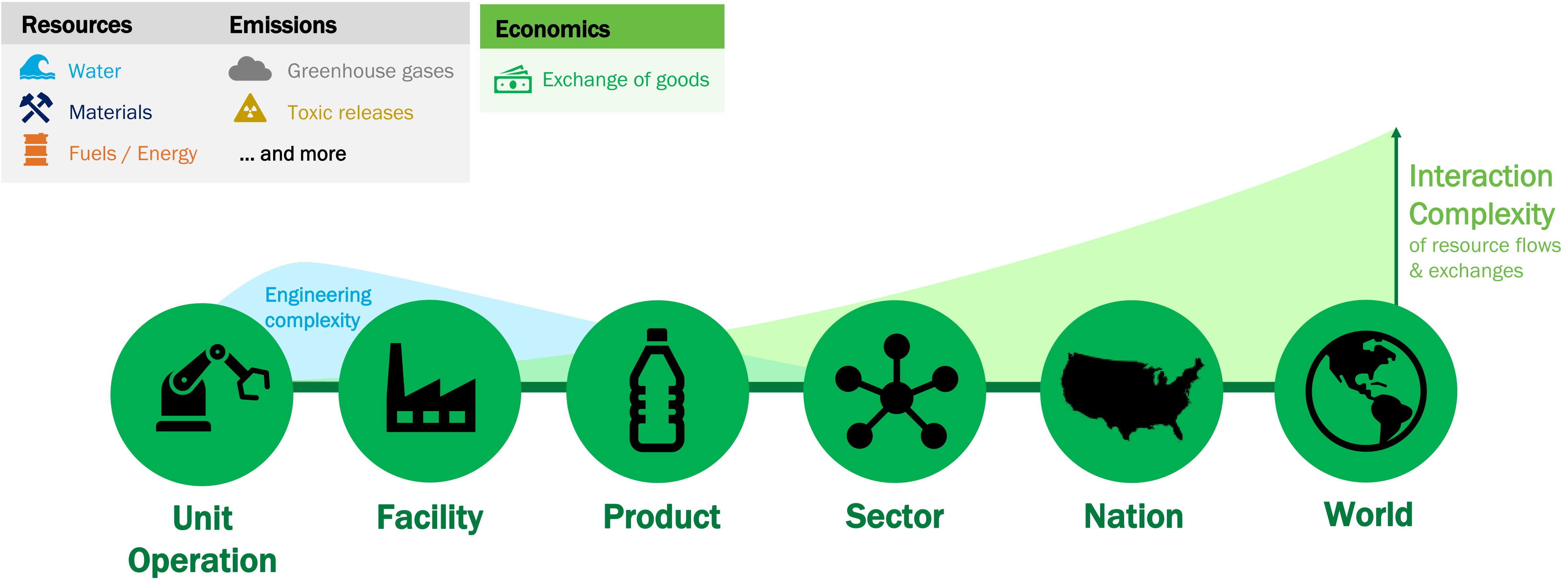
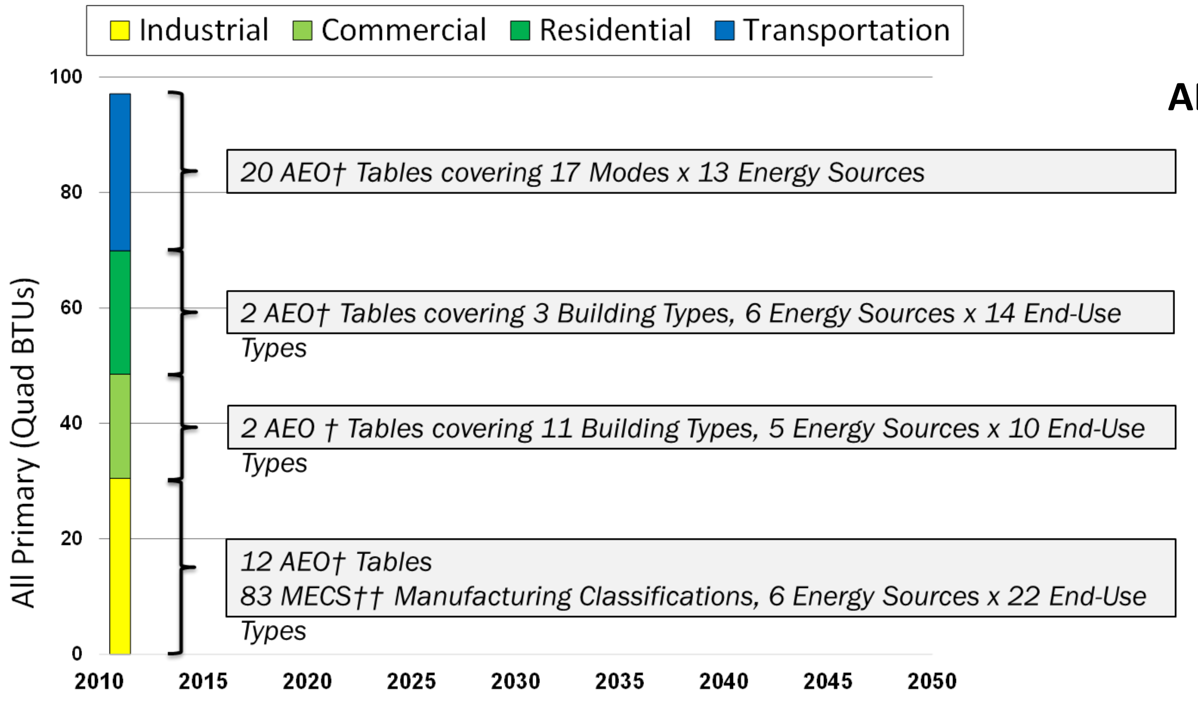


Figure source: DOE [Industrial Decarbonization Roadmap](#)
Data source: [McMillan 2018](#)

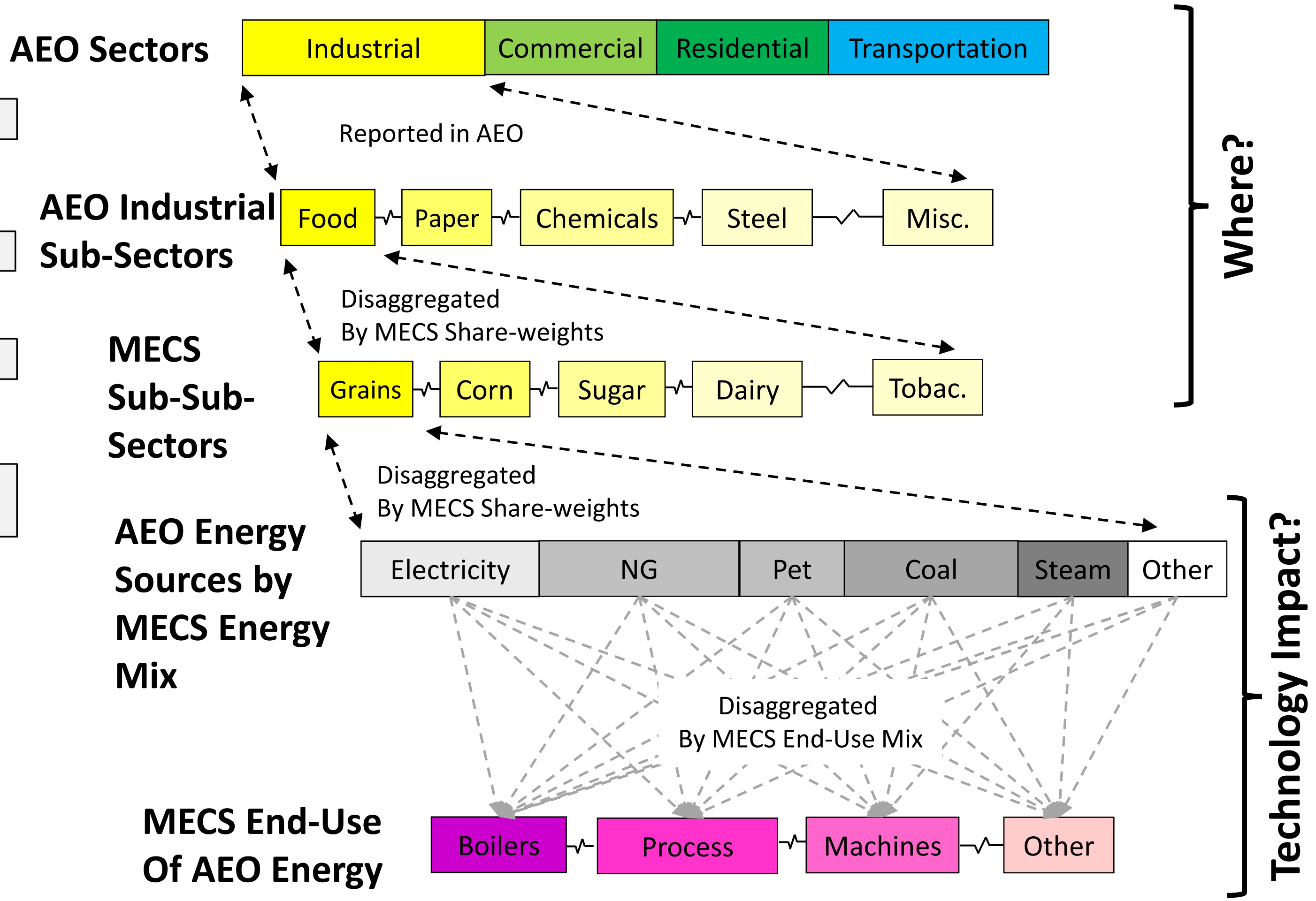
Complex interactions across scales



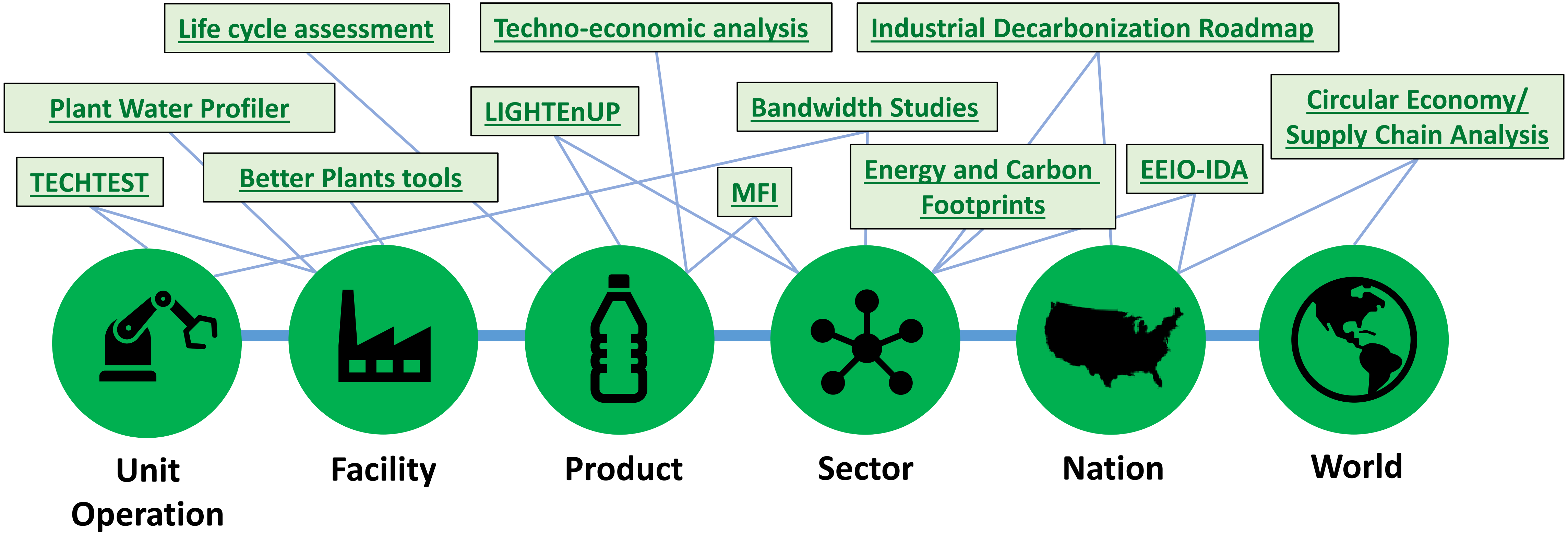
Integrating Data Across Scales



† Annual Energy Outlook (AEO) Tables
†† Manufacturing Energy Consumption Survey



IEDO analysis methodologies and tools



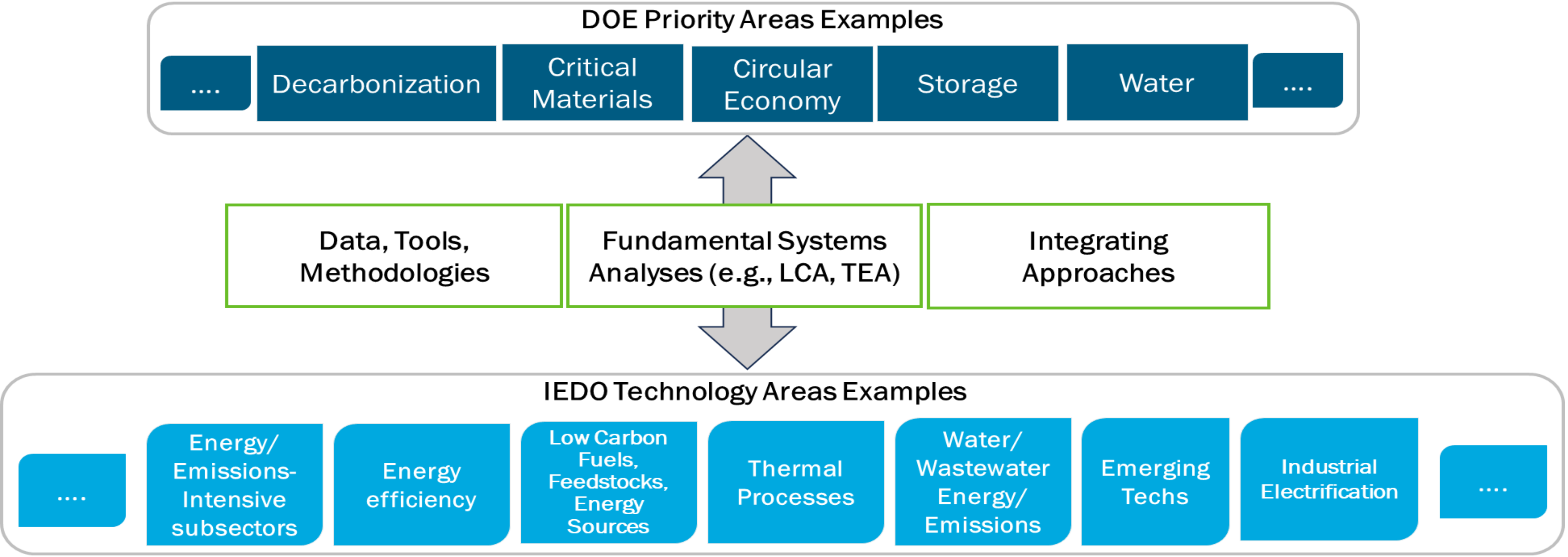
MFI (Materials Flows through Industry): an NREL tool for environmental and material flow analysis of industrial supply chains

EEIO-IDA (Environmentally Extended Input/Output for Industrial Decarbonization Analysis): an IEDO-developed model for analysis of emissions accrual through industry supply chains

TECHTEST (Techno-economic, Energy, and Carbon Heuristic Tool for Early-Stage Technologies): an IEDO-developed Excel tool for simplified life cycle assessment (LCA) and technoeconomic analysis (TEA) of low-TRL technologies

LIGHTEnUP (Lifecycle Industry GreenHouse gas, Technology, and Energy through the Use Phase): an LBNL developed tool for forecasting product and sector life-cycle energy and emissions across the US economy

IEDO Strategic Planning in Context with DOE



Analysis Informed Resources

Foundational
- Technology Assessments
- Energy & Carbon
- Technology Adoption

Roadmaps
- Decarbonization
- Energy Storage
- Critical Materials
- Circular Economy

Workshops
- Energy Storage
- Critical Materials
- Thermal Intensification
- Ind. Heat Shot

Planning
- FOAs
- Prizes
- WFD Programs
- MYPP
- Big Ideas Summit
- Goal setting

Portfolio
- Peer Review
- Annual Report
- Introspective
- Technology Tracking
- TEA/LCA

Conferences, journal articles etc.

- Background and Context – Industrial Energy and Emissions
- **Industrial Decarbonization Roadmap**
- Ongoing Analysis – Look Ahead

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

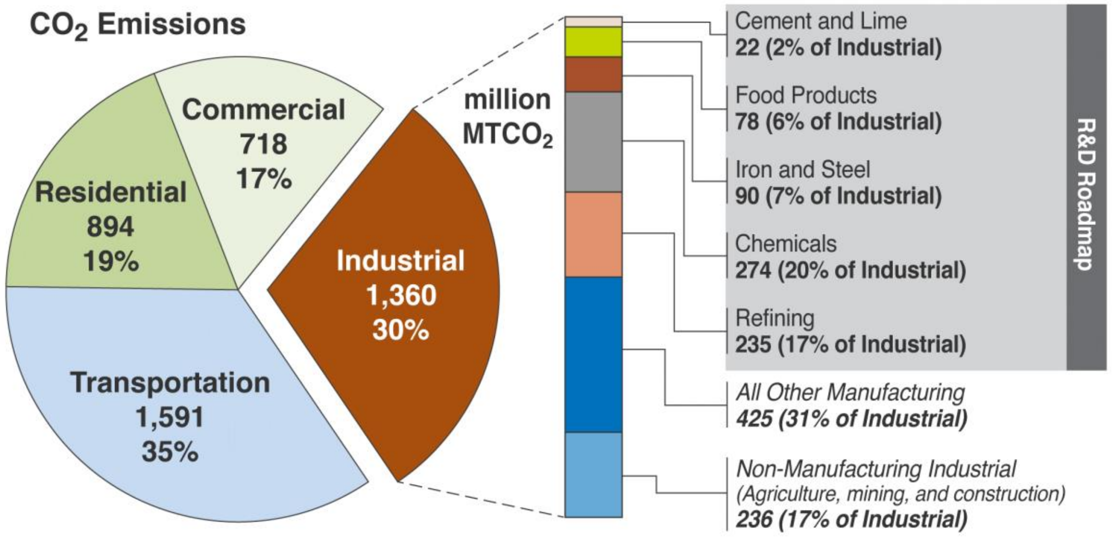
https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap

U.S. Industry Emissions

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

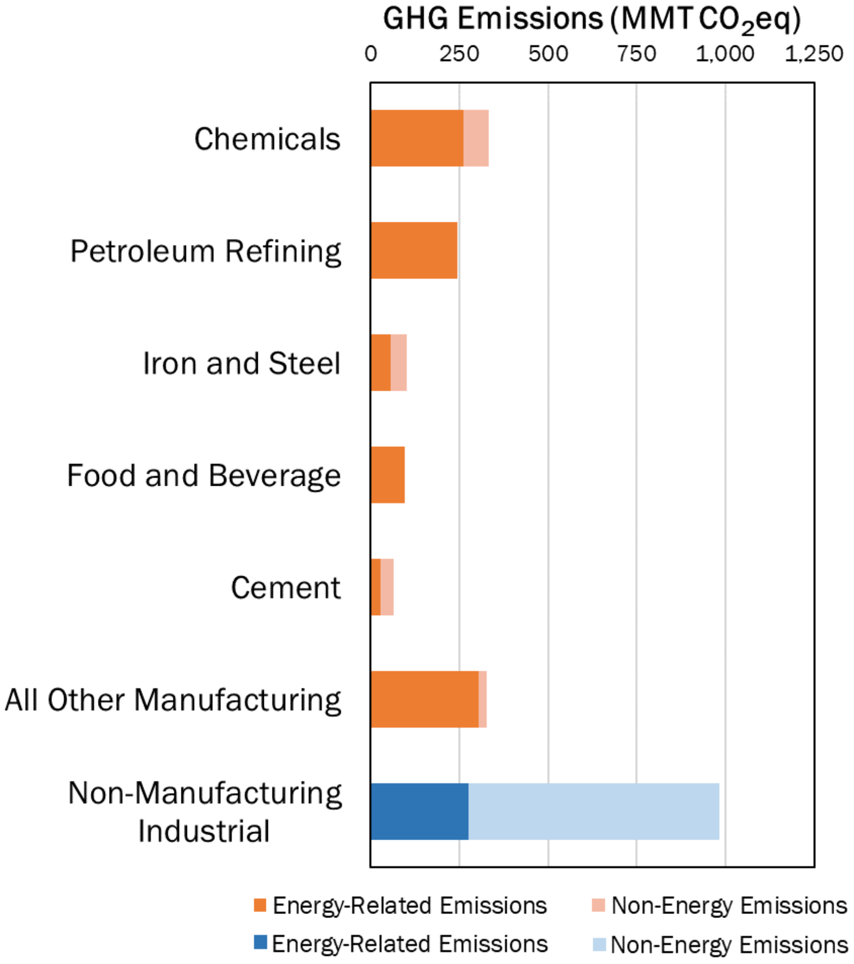
ACCOUNTS FOR **30%** of energy-related CO_2 emissions

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



EIA, *Annual Energy Outlook 2020 with Projections to 2050*. Source: [Industrial Decarbonization Roadmap](#).

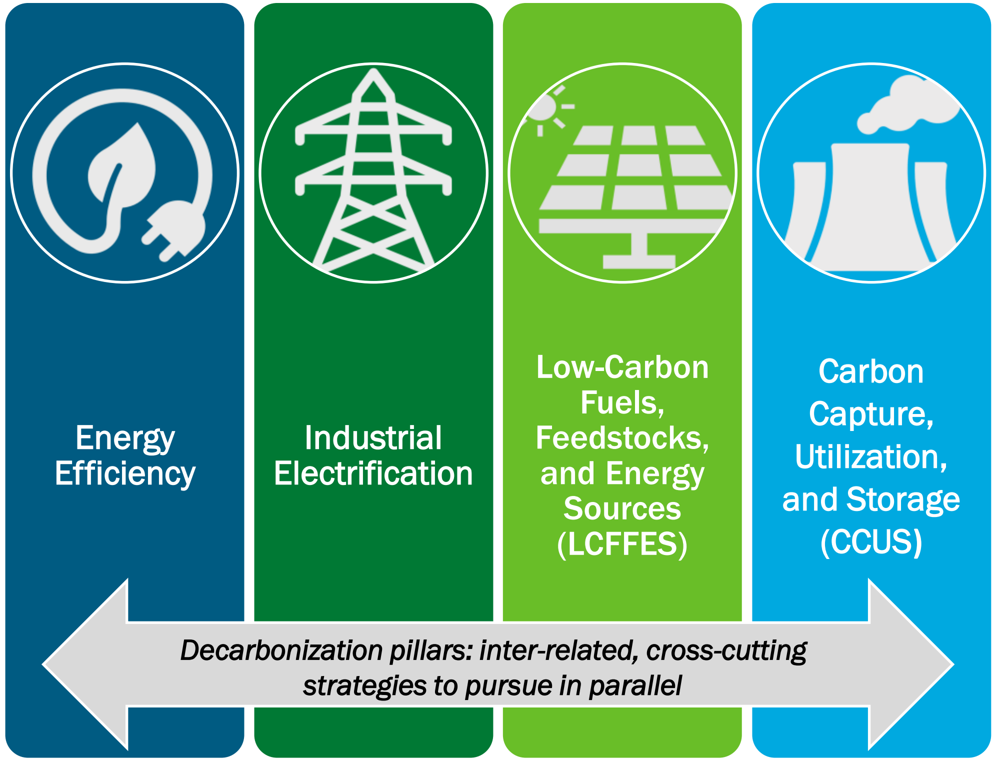
Total Industry Emissions, 2018
(energy-related + non-energy; million metric tons CO_2eq)

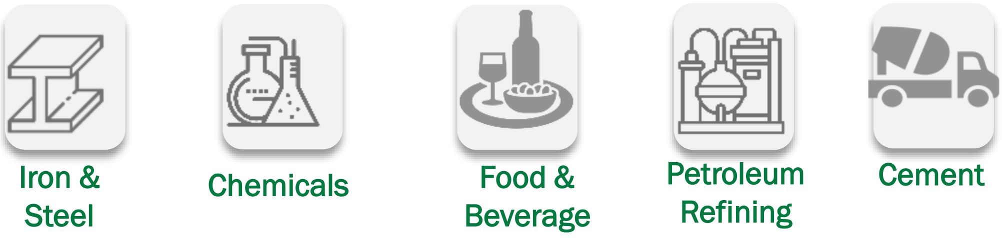


EIA Monthly Energy Review, Manufacturing Energy Consumption Survey; EPA GHGRP Inventory

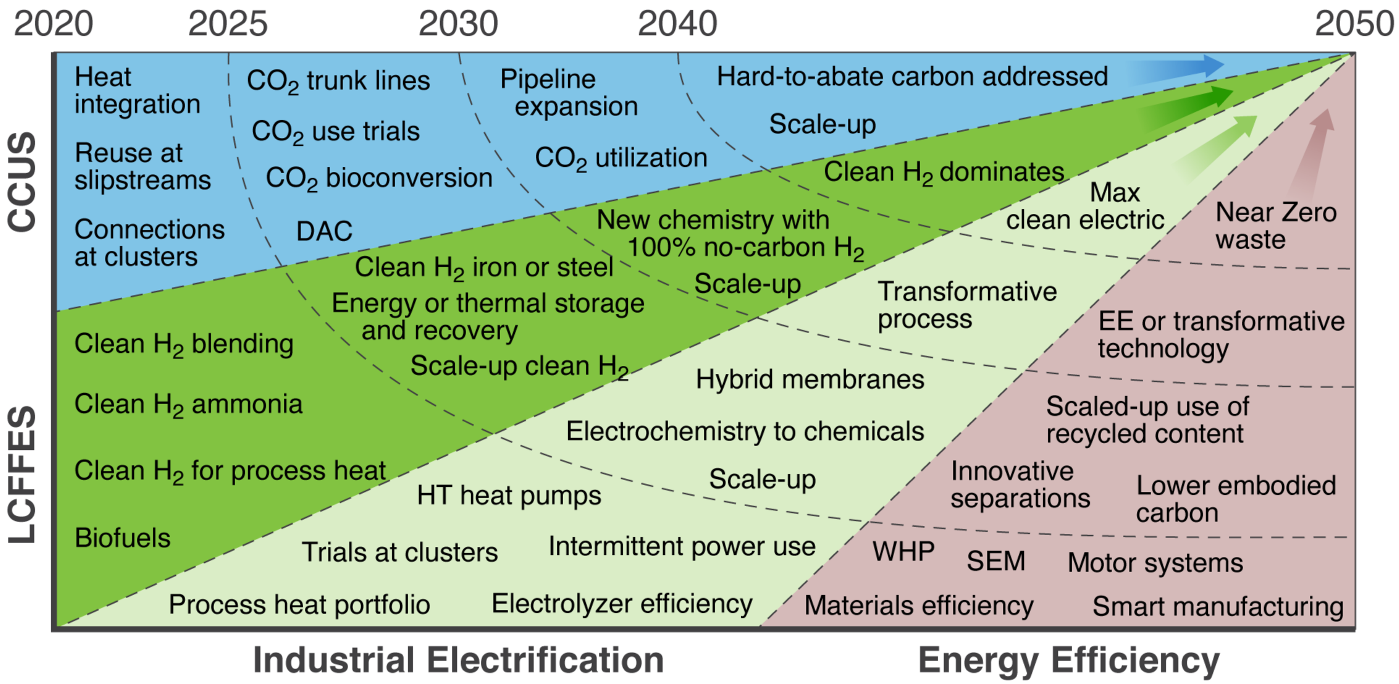
DOE Industrial Decarbonization – Pillars, Pathways and Technologies

Industrial Decarbonization Pillars





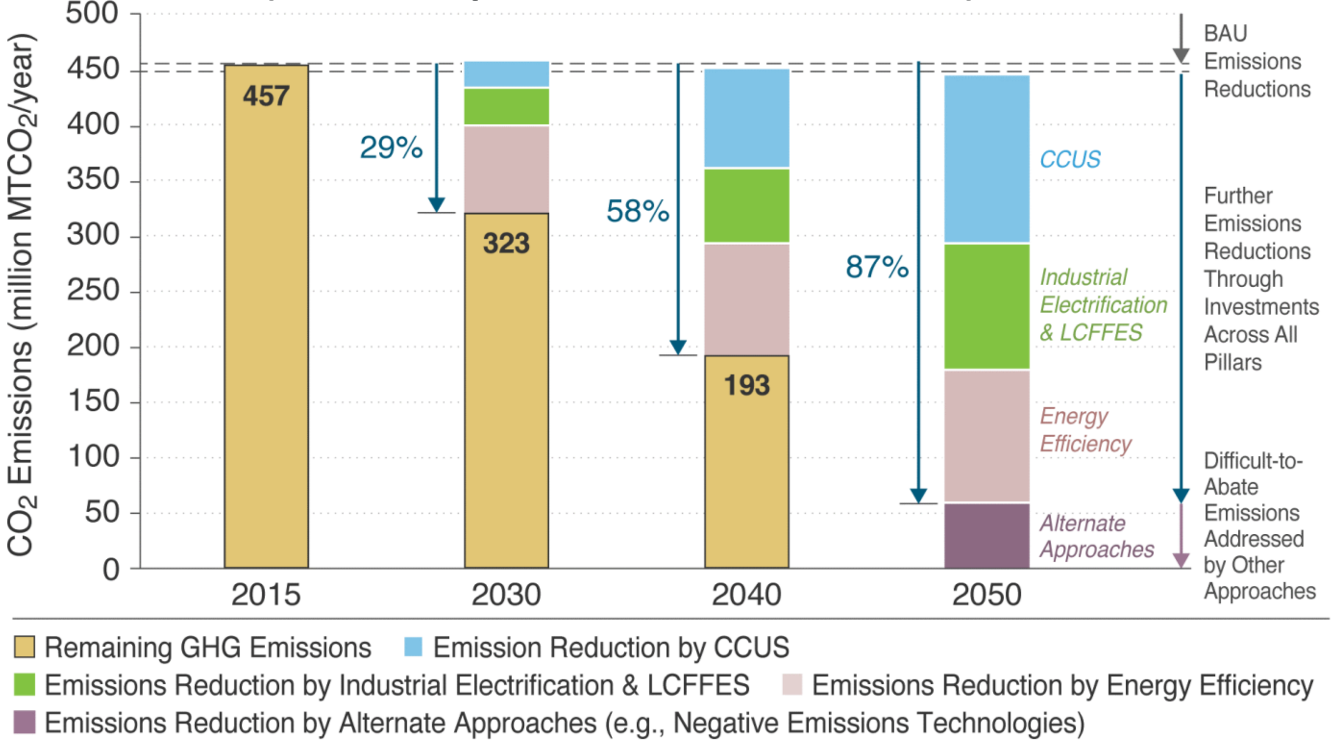
- **Invest in all pillars**
- **Leverage cross-sector approaches**
- **Interdependencies require systems solutions**
- **Strategies are needed to minimize implementation hurdles, address scale-up, and accelerate adoption**



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

2050 Industrial Emissions Reductions Potential

Near-Zero GHG Emissions Scenario
(for five representative subsectors*)



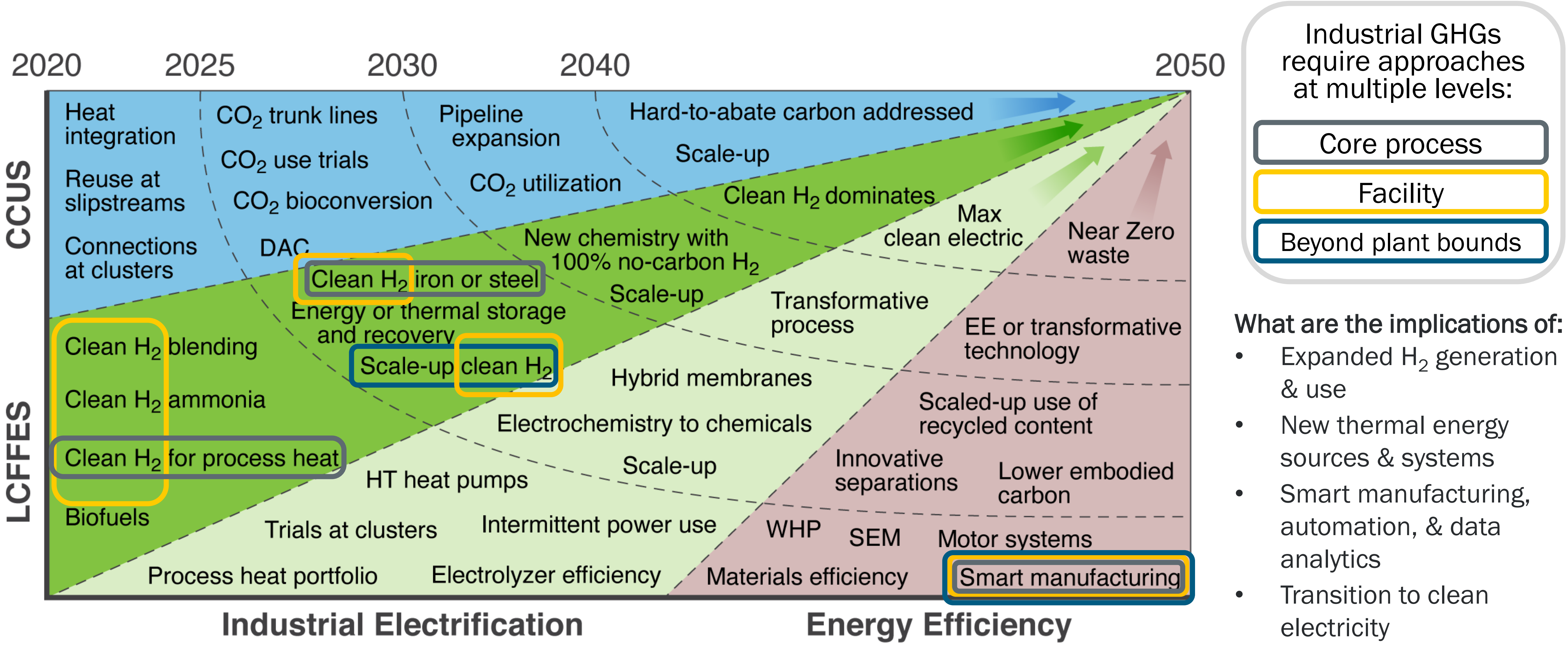
Roadmap Recommendations

- 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).*

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

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]

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

Pillar 1: Energy Efficiency

Foundational, cost-effective decarbonization strategy.

Example Opportunities for Energy Efficiency

- Improve process heating, steam, and motor systems efficiency (largest end-uses of energy in industry).
- Smart manufacturing and advanced data analytics to unlock energy efficiency opportunities at every level of system integration: equipment, facility, and supply chain.
- Research to address big data challenges related to data quality, storage, and computing; advanced analytical tools are needed to process the data and improve cybersecurity.
- Demonstrate plant automation systems that provide real-time energy performance data.
- Data integration to facilitate utility efficiency programs that reward manufacturers for energy saved rather than equipment installed.

Pillar 1

Pillar 2: Industrial Electrification

Allow for the expanded use of low-carbon electricity

Example Opportunities for Industrial Electrification

- Scale-up electrified technologies
- Durability and reliability of electrified services
- Integration with intermittent energy sources (e.g., control systems and interfaces)
- Hybrid process heating (e.g., hybrid boilers)
- More efficient heat transfer at commercial scale
- Modular size-matching for application needs
- Analysis of tradeoffs between energy source and CO_2 reduction

Pillar 3: Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)

Substitute low-carbon inputs to reduce combustion related emissions

Example Opportunities for LCFFES

- Novel technologies for hydrogen use such as metal refining, synthetic fuels production, and stationary fuel cells can further enable nationwide emissions reductions

Renewable hydrogen

- Cost, efficiency, and durability improvements for electrolyzers.
- Reversible fuel cells that combine the functionality of electrolyzers and fuel cells.
- Hydrogen infrastructure advancements – compression, pipeline and chemical carrier transport, and bulk storage.

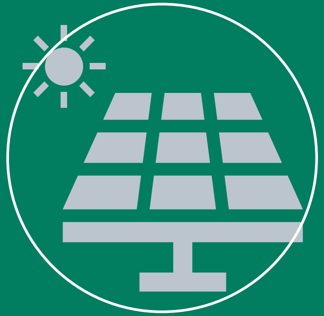
Bioenergy, biofuels, and bio-feedstocks

- Improve costs of conversion technologies for low-carbon feedstocks to fuels.
- Data science and process simulation for alternative low-carbon resources.
- Coordination across multiple sectors & industries for GHG accounting standards and net-zero accountability (to avoid burden-shifting).

Other low-carbon energy sources

- Renewable natural gas (RNG) for CHP and direct use in industrial processes.
- Modular and distributed processes for alternative sources of energy and fuels.
- Solar, including concentrating solar power hybrid systems.
- Modular nuclear power.

Pillar 3



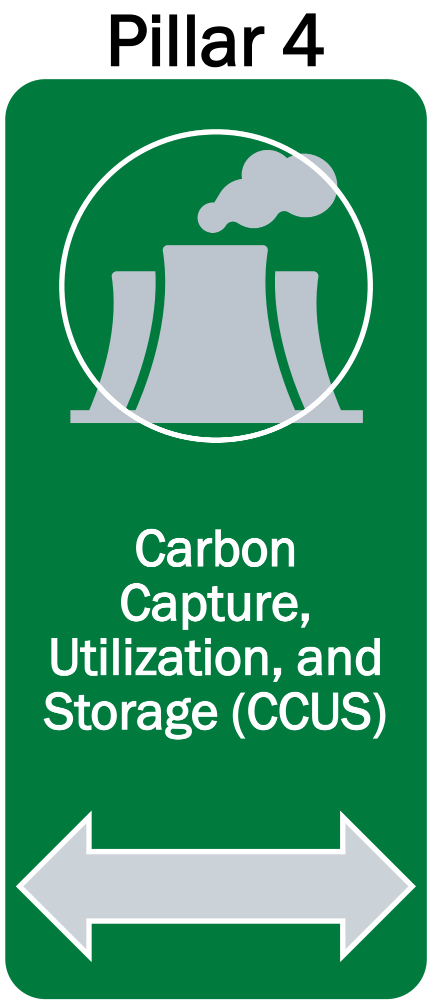
Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)

Pillar 4: Carbon Capture, Utilization, and Storage (CCUS)

Mitigate hard-to-abate emissions

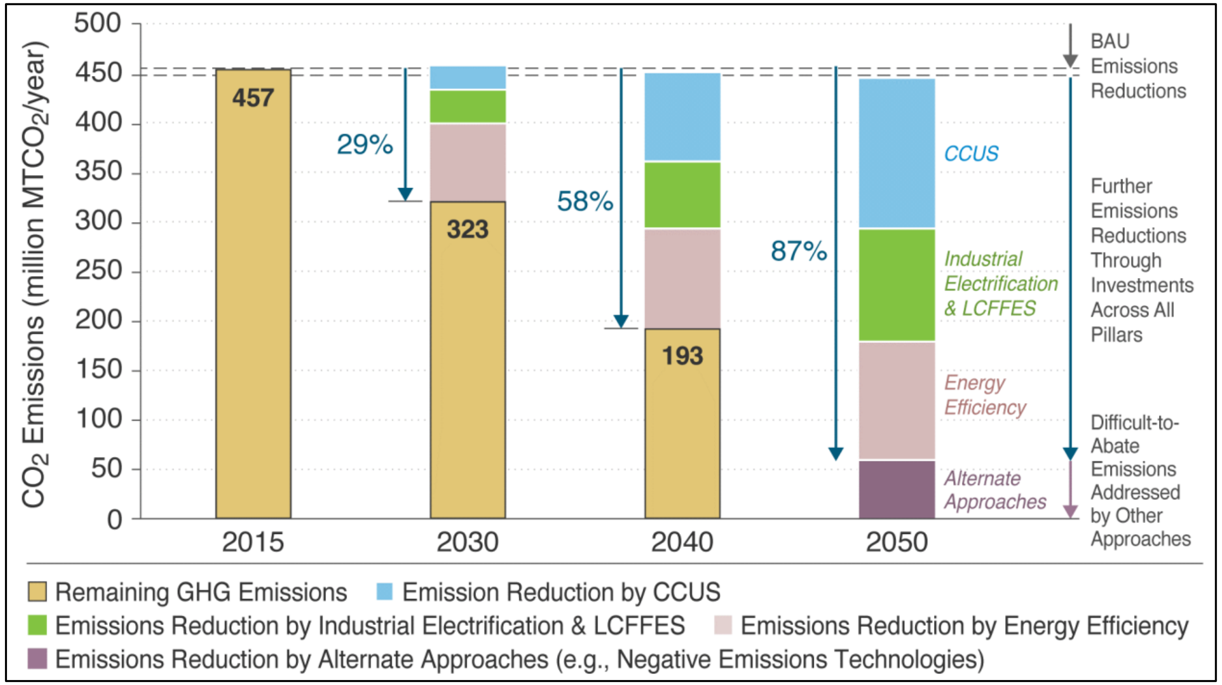
Example Opportunities for CCUS

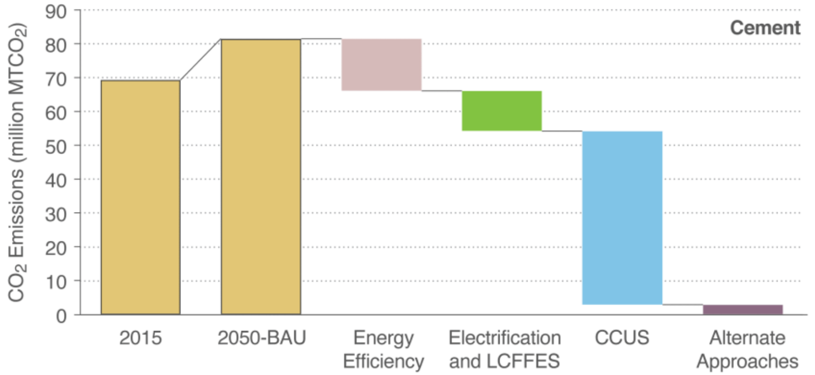
- Improve catalysts and better process designs → increase efficiency, lower costs, and lower material consumption/waste production.
- Optimize of the techno-economic performance of the technology and heat exchanger network (e.g., with calcium looping)
- Pilot-scale demonstrations for CCUS of heavy industries emissions; explore technological potential of storage near industrial plants.
- Research to address specific installation, operation, and maintenance requirements, ensure continuous operation at a given capture level is possible for specific plants.
- Continued research on other mitigation options, such as direct air capture and forest preservation.

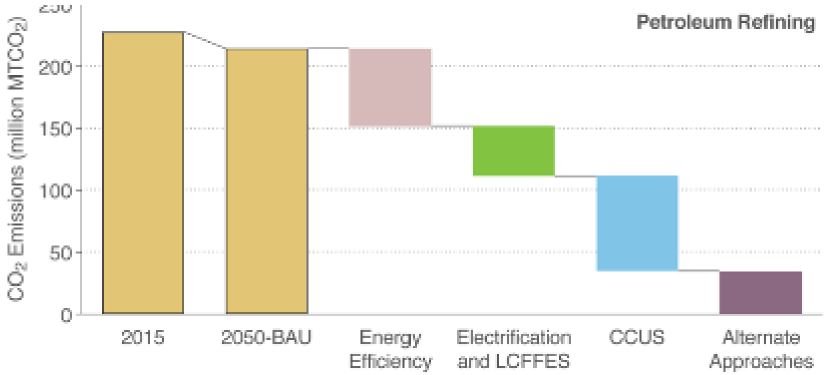


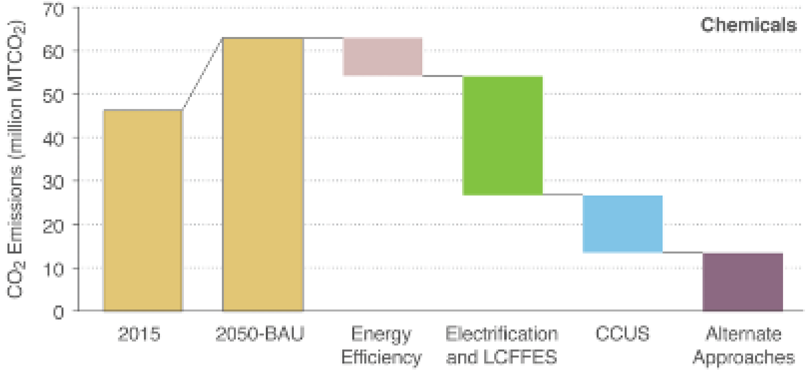
Roadmap Figures

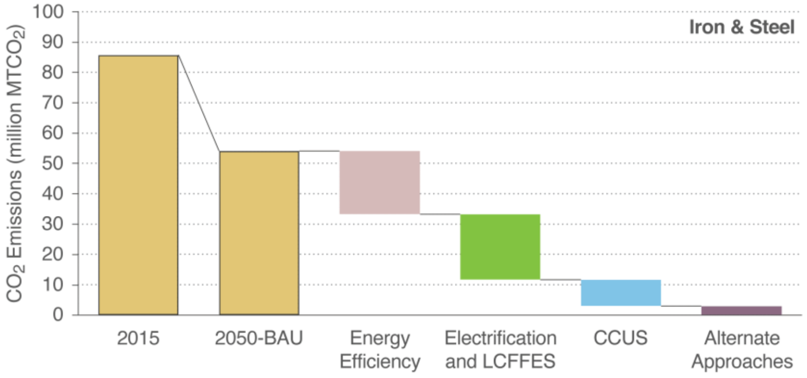
Aggregated results and individual results for five sectors studied. For details, see the assumptions, framing, and analysis in the DOE Industrial Decarbonization Roadmap: https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

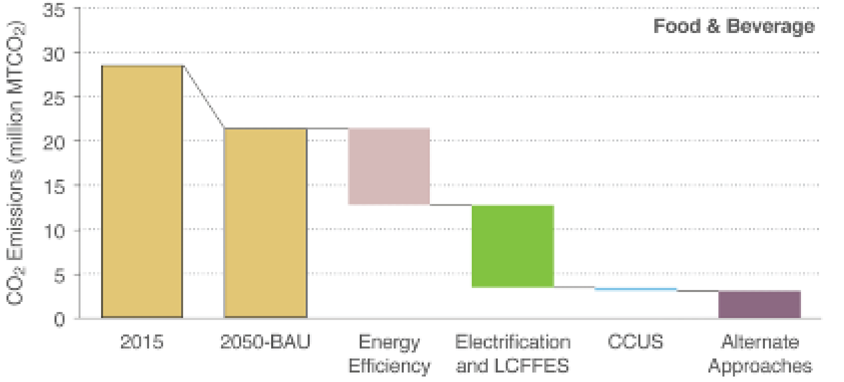












Barriers to Decarbonization - Examples

Cross-cutting barriers

Industrial heterogeneity. The industrial sector is diverse, with a wide range of processes and products. There are no "one-size-fits-all" technology solutions.

Incumbent technologies and practices. Existing infrastructure, capital investments, and workforce training favor incumbent technologies and practices.

High costs for low-carbon technologies. Low-carbon alternatives are often more costly than incumbent practices and materials.

Scale-up. Transitioning a technology from laboratory to commercial scale is costly and often introduces new technical challenges.

Sector-specific barriers

Iron and Steel: lower quality of scrap-based and "green" steel (produced with lower-carbon fuels)

Chemicals: high costs of low-carbon feedstocks compared to fossil fuel feedstocks; long-lived capital assets that limit adoption rates

Food and Beverage: food shelf-life and waste; lack of in-house uses of waste heat streams

Refining: by-product dependency; capital intensity constraints

Cement: regulatory barriers for blended cement; prevalence of hard-to-abate process emissions

Key Roadmap Recommendations

Pursue industrial heat decarbonization pillars in parallel.

- Generate heat from clean electricity
- Integrate clean heat from alternative sources
- Innovative low- or no-heat process technologies

Drive capital investment aligned with expansion of renewable energy and low-carbon assets.

- Leverage low-capital solutions to facilitate early adoption
- Technology integration into systems and supply chains
- Align industrial heat decarbonization strategies with infrastructure of the future

Develop robust RD&D portfolio and workforce for cross sectoral and innovative thermal processes.

- New low-carbon industrial heat technologies & pathways
- Analysis and modelling to measure energy, emissions, and cost impacts
- Spectrum of worker skill sets and diversity and inclusion

- Background and Context – Industrial Energy and Emissions
- Industrial Decarbonization Roadmap
- **Ongoing Analysis – Look Ahead**

Ongoing Industrial Decarbonization Analysis

IEDO Analysis & Goal Development

Energy & Emissions Intensive Industries

- Chemicals
- Iron & Steel
- Cement & Concrete
- Food & Beverage
- Forest Products
- Other Industries

Cross-Sector Technologies

- Thermal Processing
- Utilization of LCFFES
- Emerging Techs
- Water
- Cross-Cutting Assumptions: CCUS, Material Efficiency, H_2, Grid Emissions

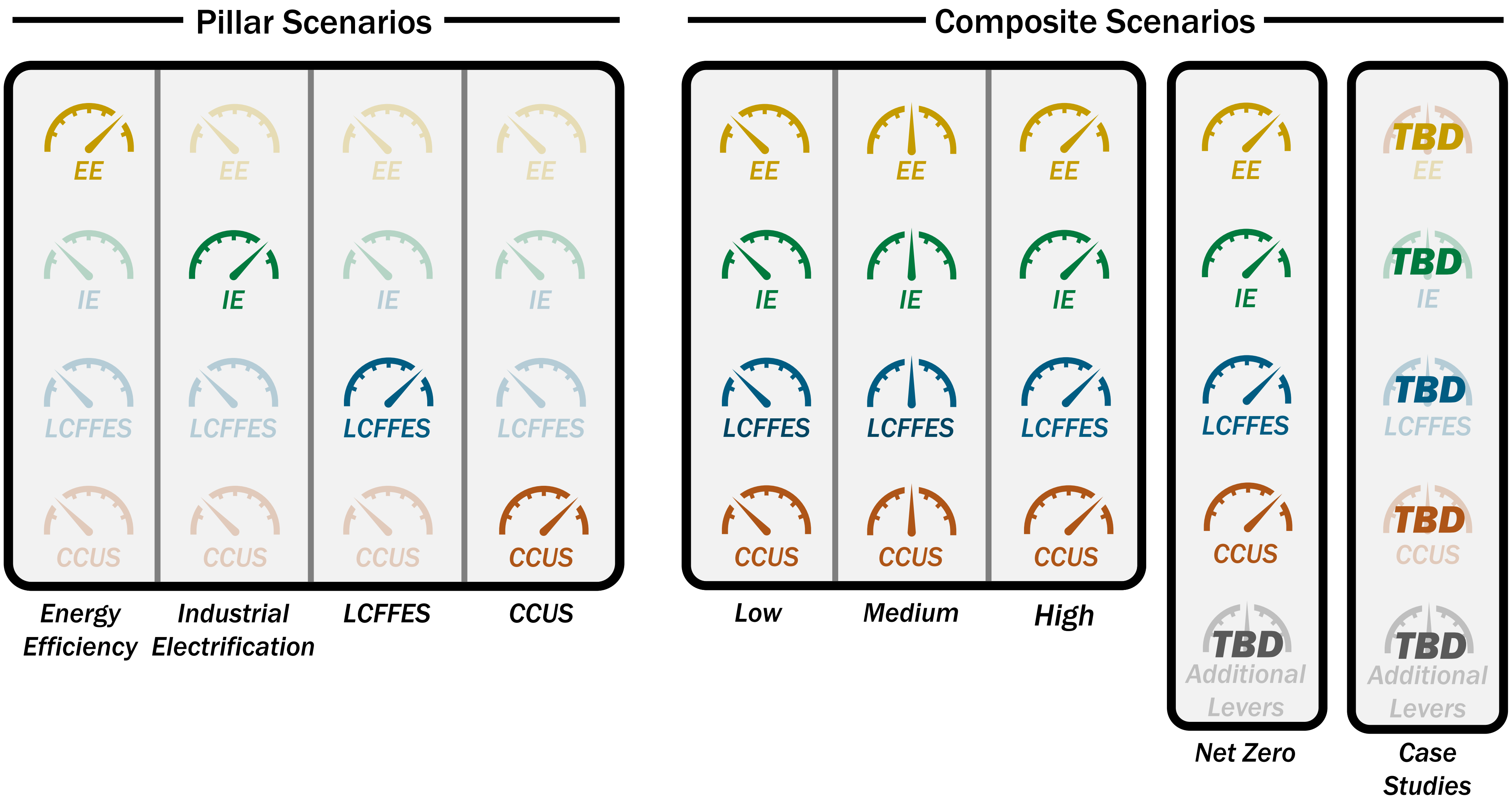
Industrial Decarbonization Modeling

- **Expanded bottom-up analysis** to capture specific technologies or process units
- Identify and standardize inputs and assumptions for **transparency now**, and **robust documentation and flexibility** going forward
- **Add resolution** - fuel sources, process emissions, and adoption rates by technology, electrification, onsite generation, etc.
- **Refine pillar breakdown** calculations to more accurately capture adoption of technologies and separate electrification from low carbon fuels, feedstocks, & energy sources (LCFFES)

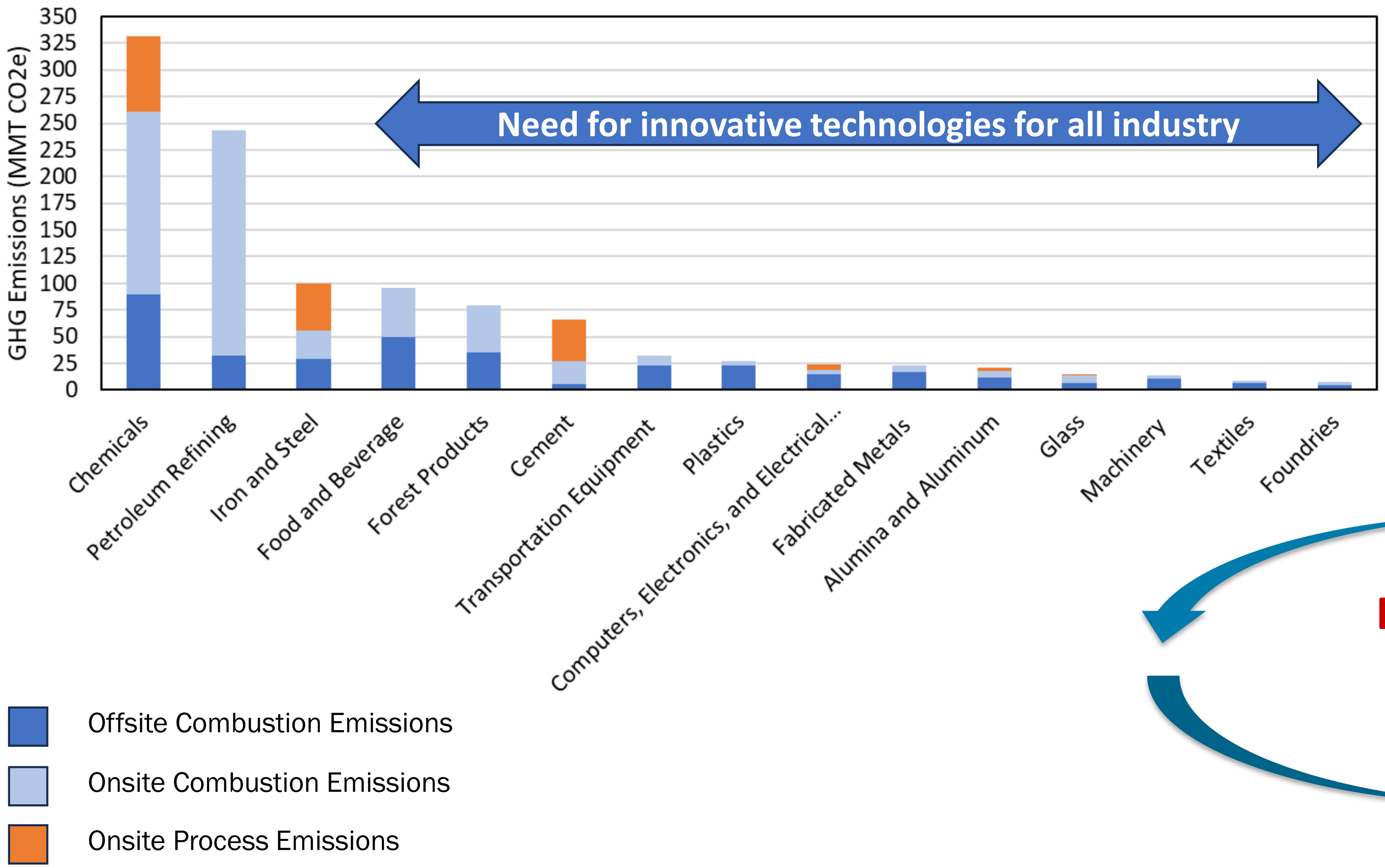
Building upon the Roadmap

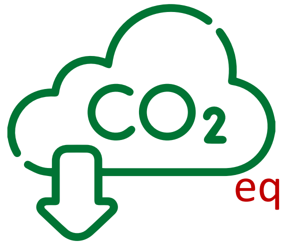
	EEII	Cross-Sectoral	Cross-Economy
Pillars	Roadmap	Roadmap + *Ongoing analysis*	*Ongoing analysis*
Levers	Roadmap + *Ongoing analysis*	*Ongoing analysis*	*Ongoing analysis*
Core Technologies	Roadmap + *Ongoing analysis*	*Ongoing analysis*	E.g., demand response & synergy between other areas of economy and industry

Example Roadmap Extension/Expansion work – Scenario Options



The Long Emissions Tail of the Industrial Sector





equivalents

All subsectors

All industrial emissions

The imperatives for U.S. industrial decarbonization

Incremental solutions are insufficient:

- The need for an industrial transformation

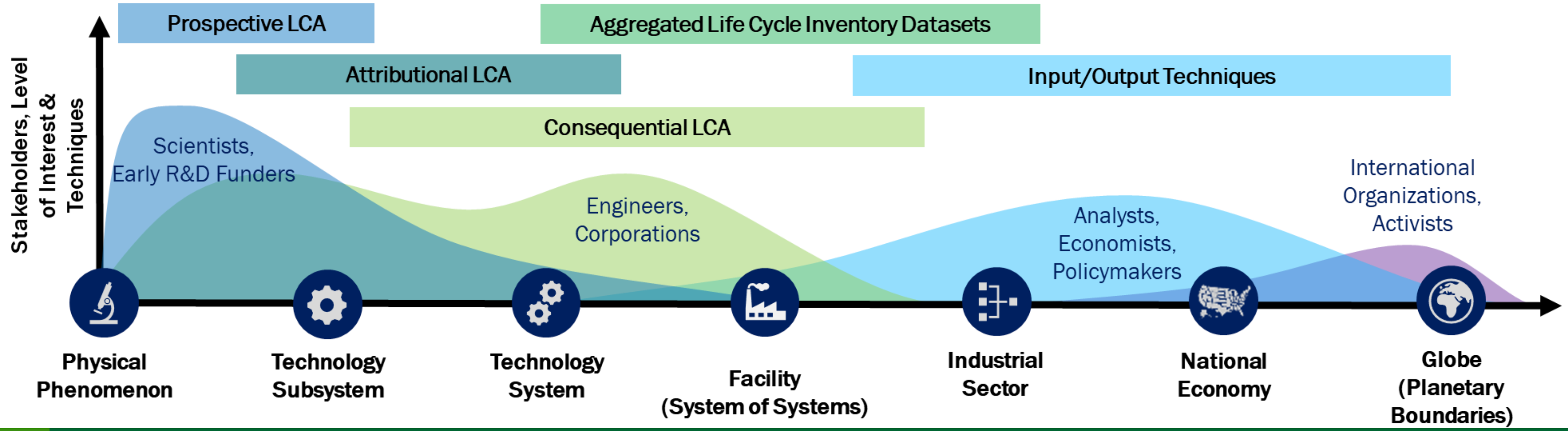
CO_2 emissions from inefficient materials flows are a problem:

- The opportunity for more thoroughly efficient production processes

GHGs are one environmental impact factor:

- The need for more thoroughly sustainable manufacturing

Industrial decarbonization is a complex systems challenge



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

Journal of Economic Dynamics and Control
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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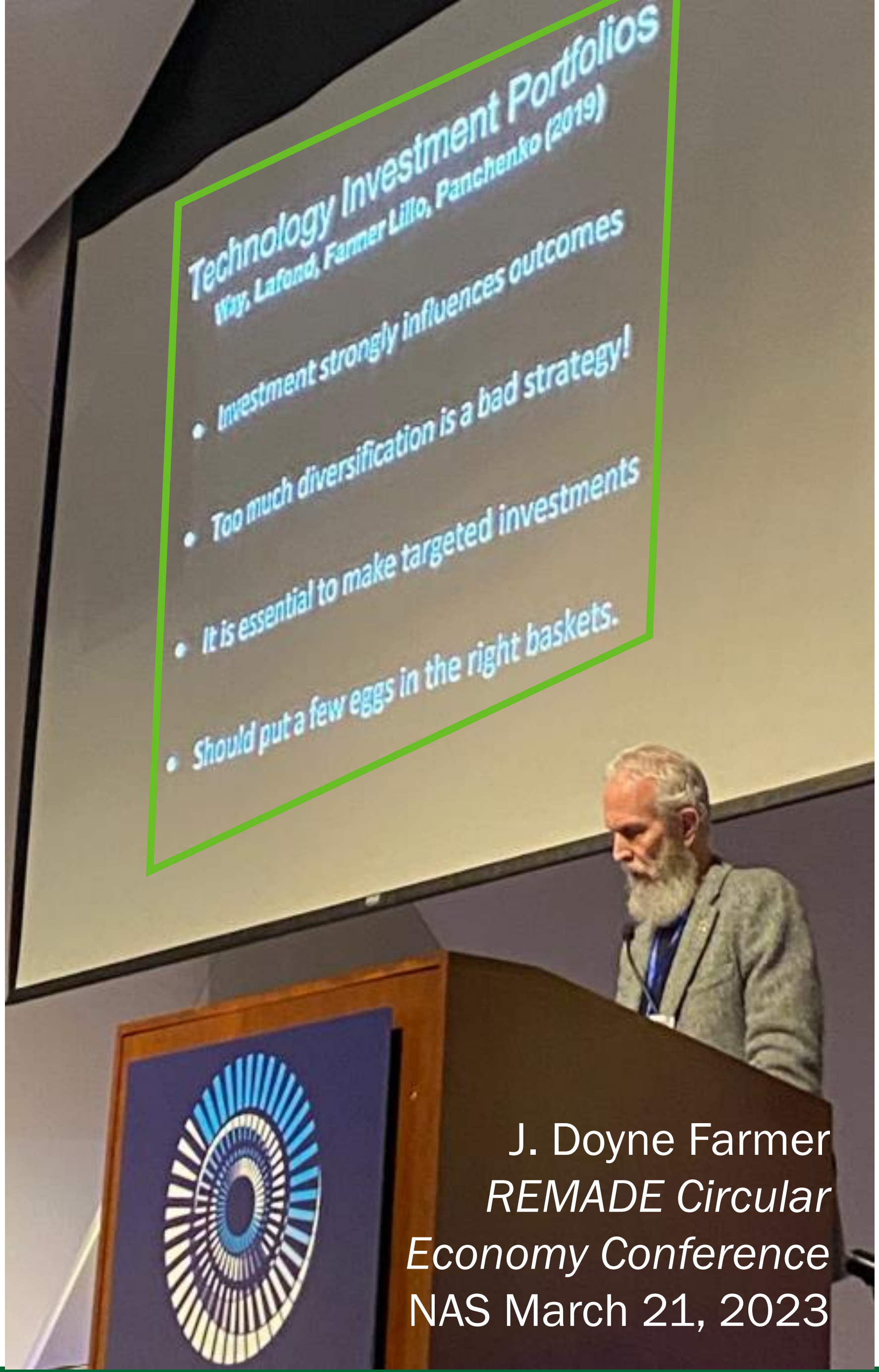

J. Doyne Farmer
REMADE Circular Economy Conference
NAS March 21, 2023

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

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Energetics – Caroline Dollinger, Heather Liddell, Sabine Brueske, Brian Ray

DOE – Zach Pritchard

Backup Slides

Ongoing Roadmap Analysis

- Original models are being expanded to address new scope, including:
  - Inclusion of original roadmap sectors (cement; chemicals; iron & steel; food & beverage; petroleum refining) **plus pulp & paper**
  - Modeling at **1-year increments**
  - More bottom-up analysis in each sector to capture specific technologies or process units
  - Identify & standardize inputs & assumptions for **increased transparency** and **extensibility**
  - **Adding significant resolution** (i.e., allowing differing fuel sources, process emissions, and carbon capture & storage (CCS) rates by technology; adding nuance to CCS, electrification, onsite electricity generation)
  - **Refinement of pillar breakdown** calculations to more accurately capture adoption of technologies and separate electrification from low carbon fuels, feedstocks, & energy sources (LCFFES) pillar
    - Built-out pillar-based scenarios
  - Further **aligned sectors** to ensure consistency & allow estimates to be summed within & across sectors

Strategic Analysis Posters – Full Versions Available Online

1. Energy & Materials Resource Flows
2. Sustainable and Circular Economy
3. Water-Energy-Carbon Nexus
4. Industrial Decarbonization: Extended Pathways Analysis
5. Industrial Decarbonization: Integrated Systems & Deep Dives Analyses
6. Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA)
7. Project & Portfolio Impact & Environmental Justice Analysis

Highlights Follow

IEDO Strategic Analysis Team

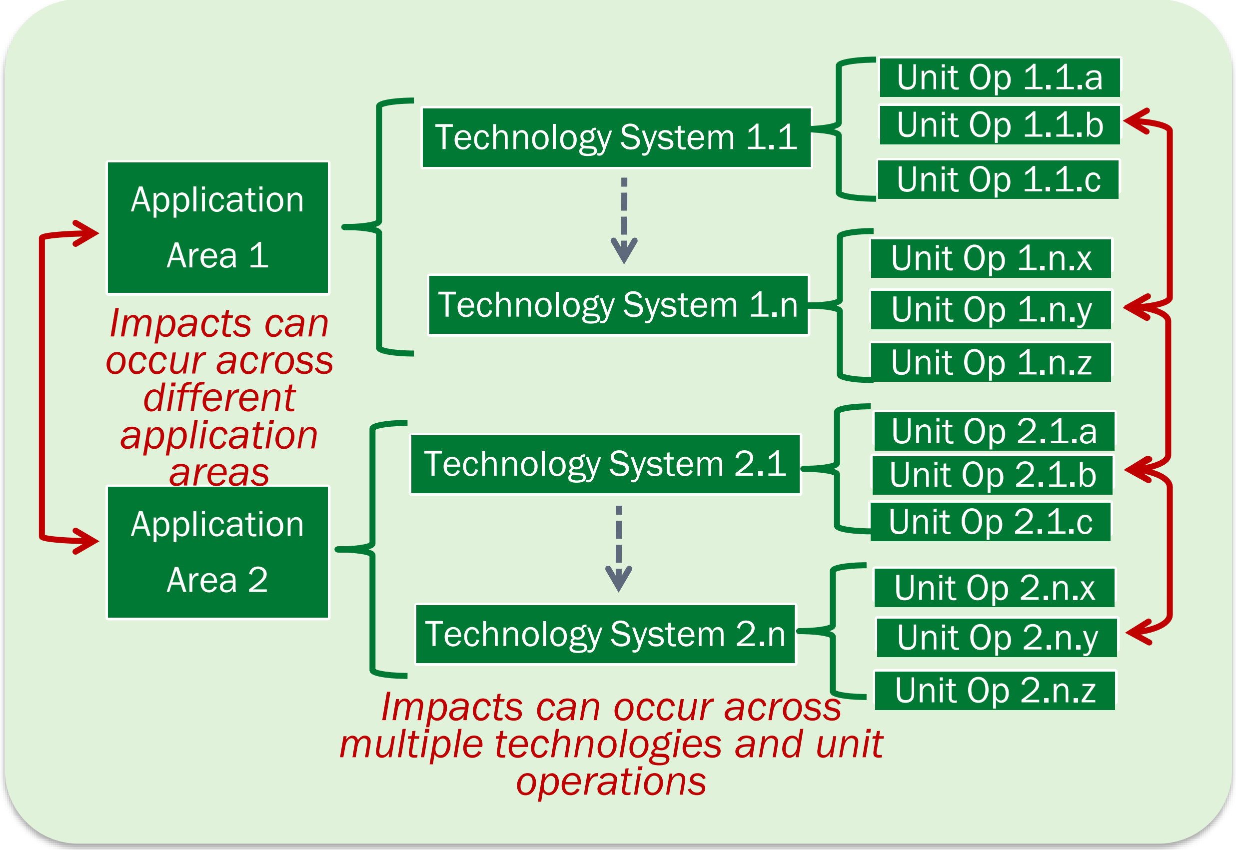
The multi-laboratory **IEDO Strategic Analysis (StA) Team** provides independent, objective, and credible information to inform decision-making.

Poster: Energy & Materials Resource Flows

Decarbonization of the Economy

<u>Life-Cycle Targets</u>

- Product life cycle emissions and energy use
- Life cycle resource consumption of industrial products
- Circularity



Decarbonization of the Industrial Sector

<u>Process-Level Targets</u>

- Manufacturing energy and process emissions
- Industrial energy efficiency
- Facility resource utilization

See full poster here:

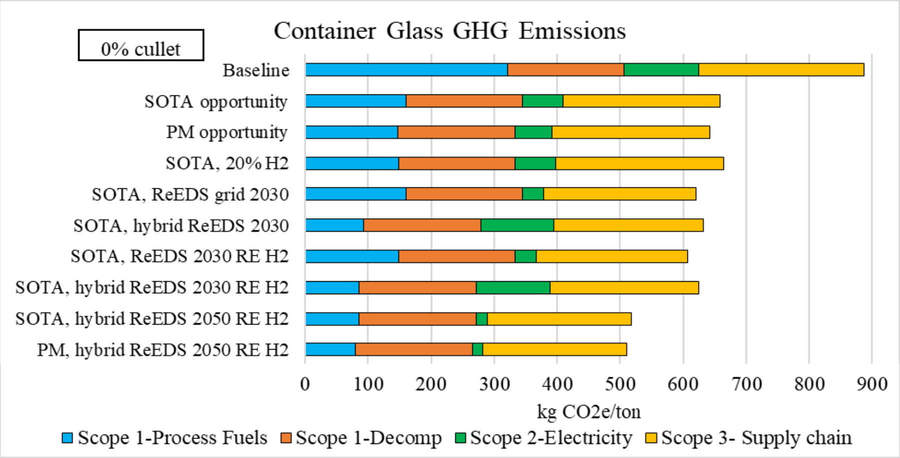
Poster: Resource Flows - Sustainable Manufacturing

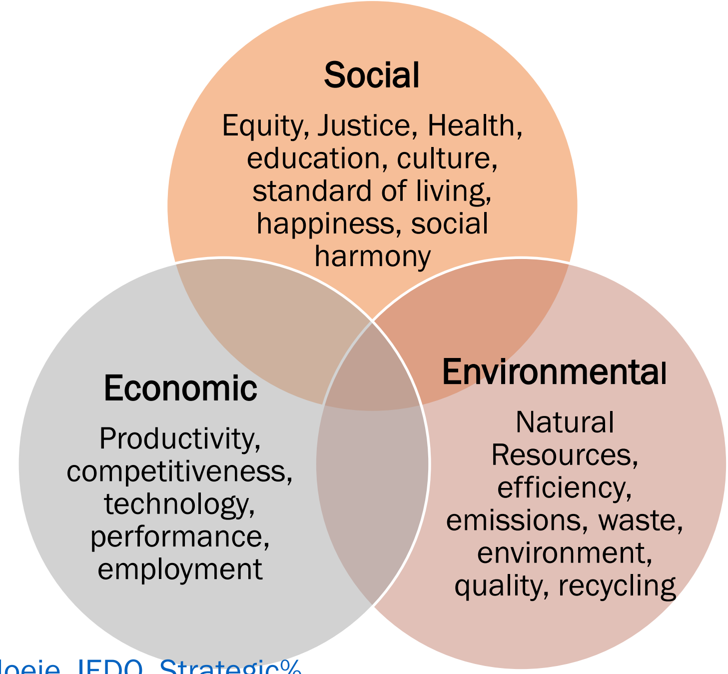
Sustainability is defined globally as "meeting the needs of the present without compromising the well-being of future generations" (United Nations General Assembly 1987, 41).

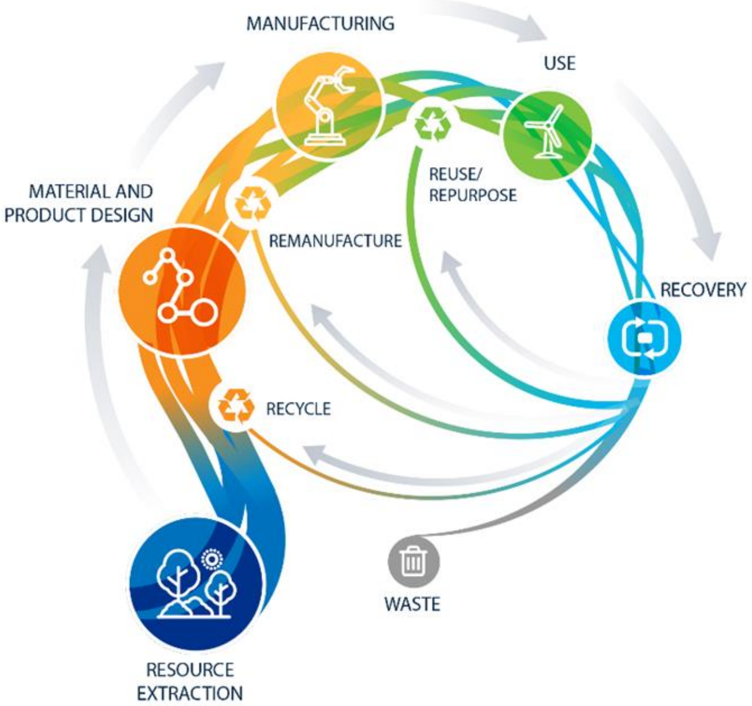
Sustainable manufacturing is the "creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources" (EPA 2021) and then extended to require safety for employees, communities, and consumers (DOC).

The ***circular economy*** is defined as an economic system that uses a systemic approach to maintain a circular flow of resources, by regenerating, retaining or adding to their value, while contributing to sustainable development (draft ISO standard).

Why are materials important?





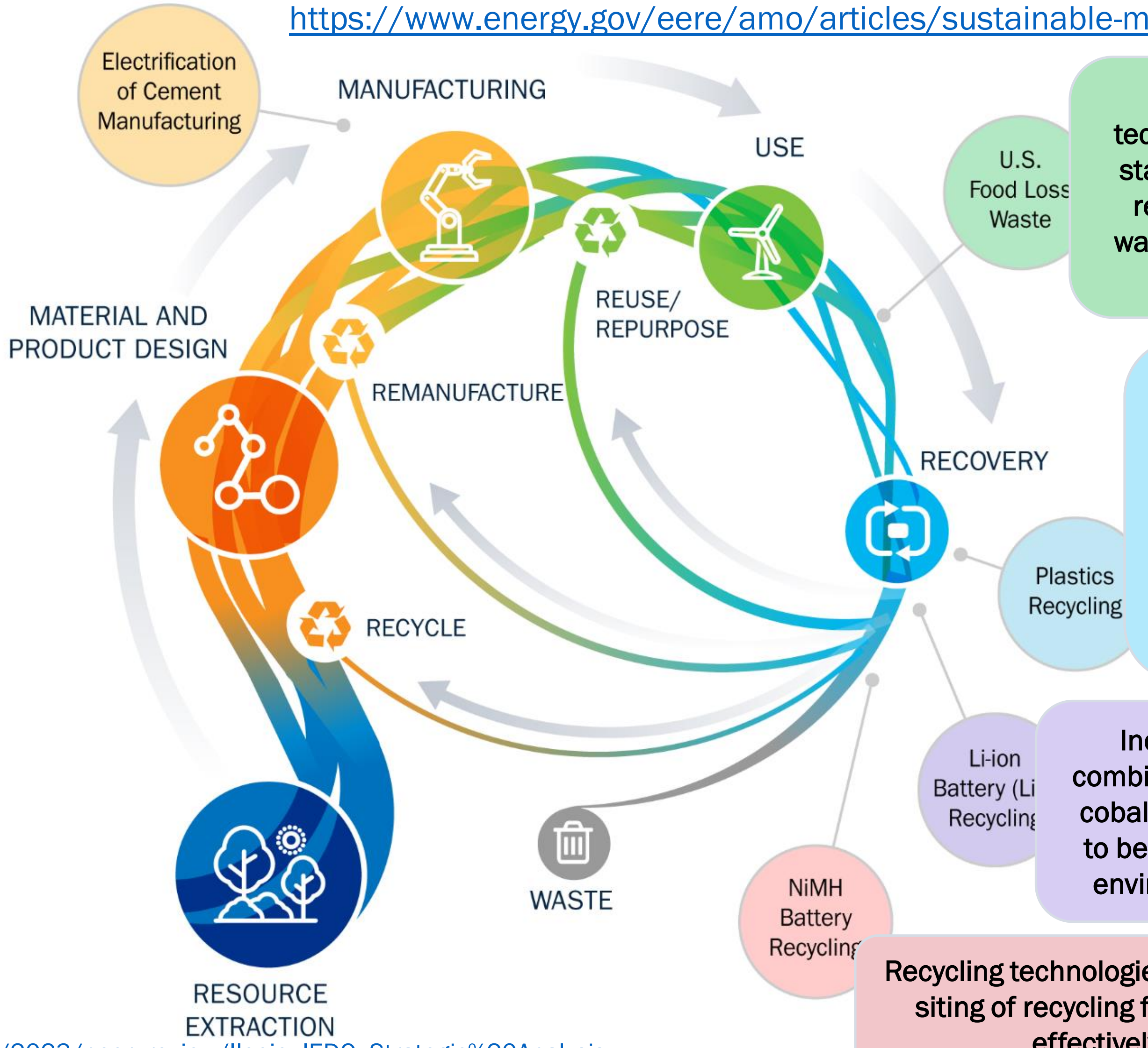


See full poster here:
https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Ilioeje_IEDO_Strategic%20Analysis_Poster_Sustainable%20and%20Circular%20Economy.pptx

Poster: Sustainable Manufacturing & the Circular Economy Report: Select case study observations

https://www.energy.gov/eere/amo/articles/sustainable-manufacturing-and-circular-economy

Renewable power can decarbonize the sector but unprecedented ramp-up of renewable energy systems would need abiotic resources at a rate significantly higher than today.



Improved packaging technologies and labeling standards are needed to reduce consumer food waste and the associated impacts.

Consideration of waste material collection levels and technology adoption characteristics are needed to properly assess novel technologies that convert plastic waste into functional materials.

Increased recycling combined with shift to low-cobalt chemistries seems to be the most promising environmental solution.

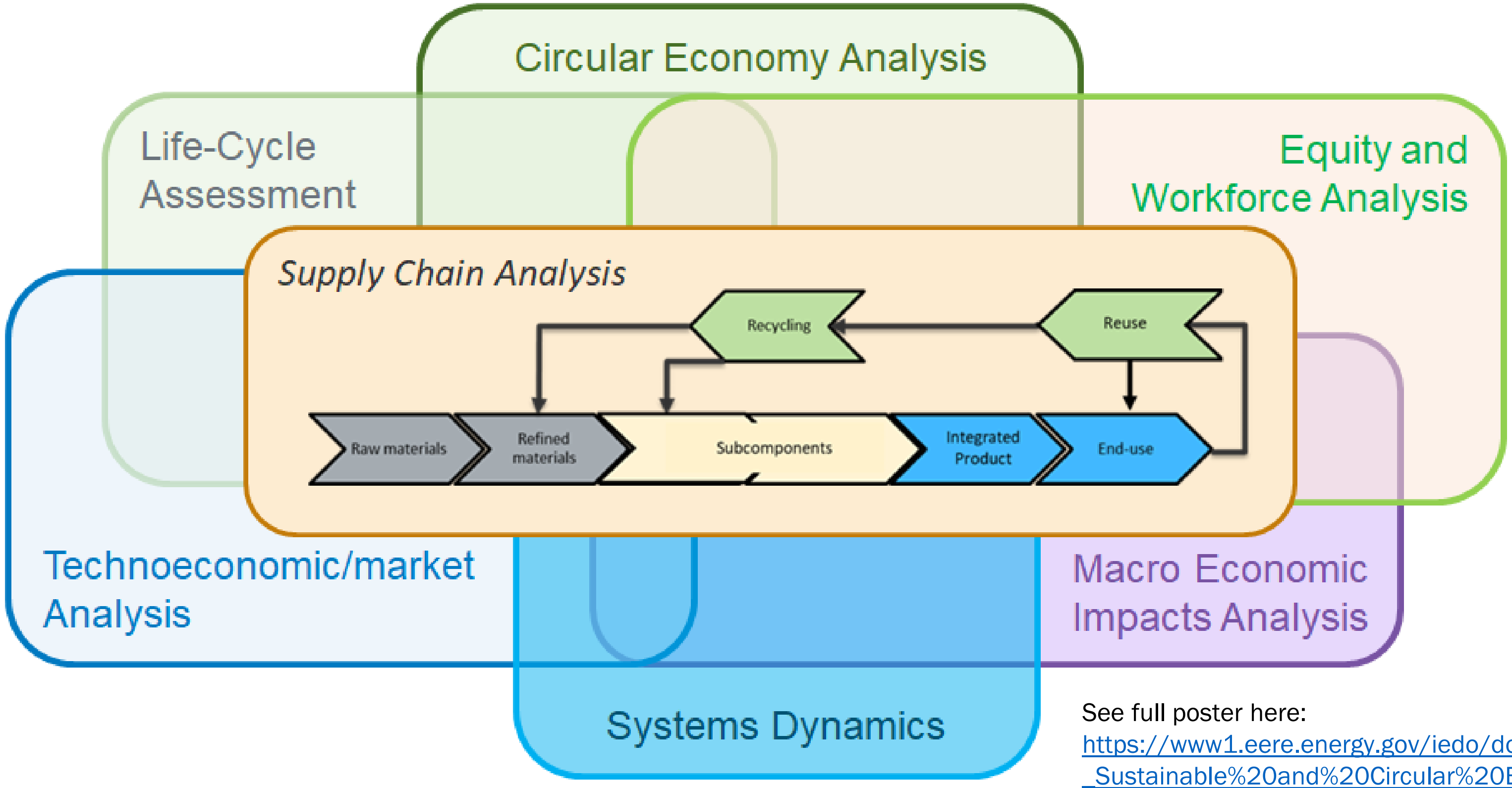
Recycling technologies with lower chemical intensities and strategic siting of recycling facilities are needed to sustainably and cost-effectively offset primary materials demand.

See full poster here:
https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Iloeje_IEDO_Strategic%20Analysis_Poster_Sustainable%20and%20Circular%20Economy.pptx

Poster: Sustainable and Circular Economy

Supply Chain Analysis requires a systems approach that is **dynamic** and **geospatially explicit**

- **Sustainability** Supply Chain Analysis seeks to understand the environmental implications
- **Competitiveness** Supply Chain Analysis seeks to understand global market competition, resiliency, vulnerabilities, and the capacity to evolve and grow



Sustainability objective is to minimize the environmental impacts from the supply chain

Competitiveness objective is to have supply chains that are flexible, resilient, and robust

See full poster here:
https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Iloeje_IEDO_Strategic%20Analysis_Poster_Sustainable%20and%20Circular%20Economy.pptx

Poster: Water-Energy-Carbon Nexus

See full poster here:
https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Rao_IEDO_Strategic%20Analysis_Poster_Water%20Energy%20and%20Carbon%20Nexus%20poster.pptx

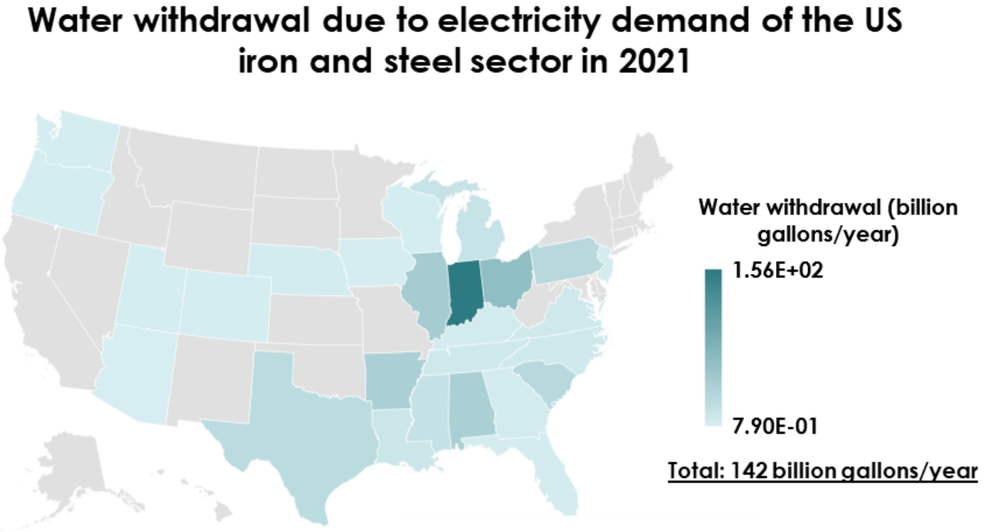
Strategic Analysis (StA) team has been evaluating water considerations in the U.S. manufacturing sector since 2016

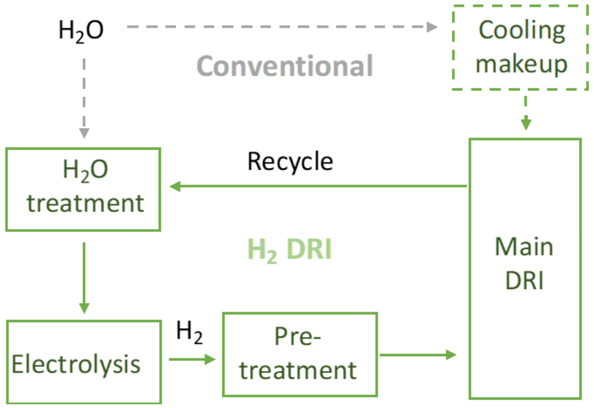
- Identified manufacturing need for water supply risk mitigation and resilience

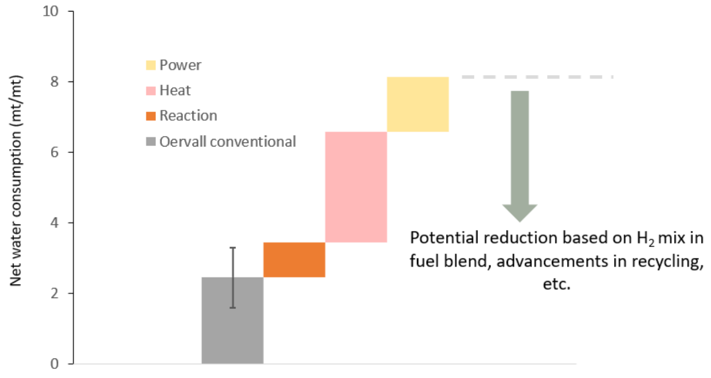
Recent work aims to understanding the water use/need impacts of manufacturing sector transformation to meet decarbonization goals (due to interconnectedness of water, energy and CO_2 emissions)

- Changes to manufacturing processes, supply chains, locations, or any other characteristic should be evaluated to better understand impacts on water supply, use, or wastewater discharge
- Emphasize development of technologies/strategies that are sustainable and within water resource limits

Example analysis: Water impacts of iron & steel decarbonization – Increased electrification & direct reduced ironmaking (DRI)







Results show that DRI produced with hydrogen via electrolysis (left) for steel making will result in significant increases in water use and consumption (right)

Poster: EEIO-IDA Scenario Modeling Tool

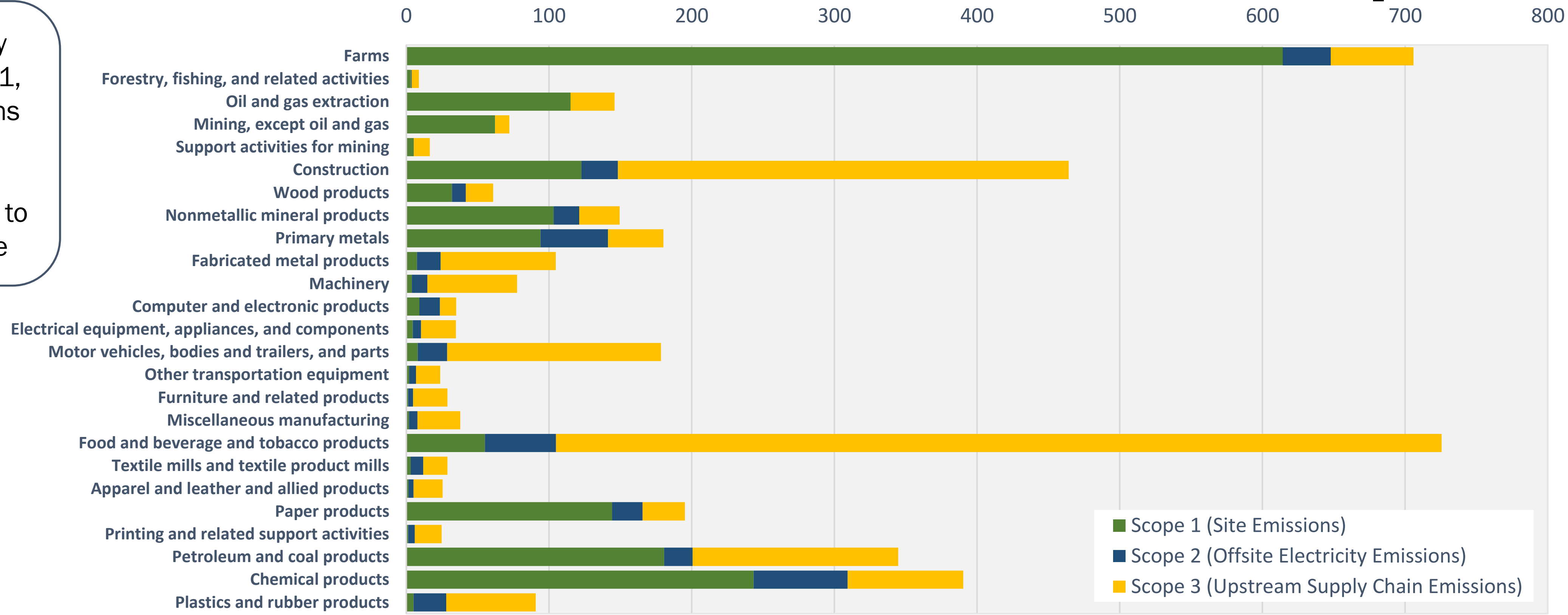
EEIO-IDA: Environmentally Extended Input-Output for Industrial Decarbonization Analysis

EEIO-IDA is a new Excel-based tool for rapid “what-if” analysis of sector-level industrial decarbonization opportunities, leveraging an environmentally extended input/output (EEIO) approach.

Tool automatically calculates scope 1, 2, and 3 emissions based on user assumptions and compares results to a 2018 base case

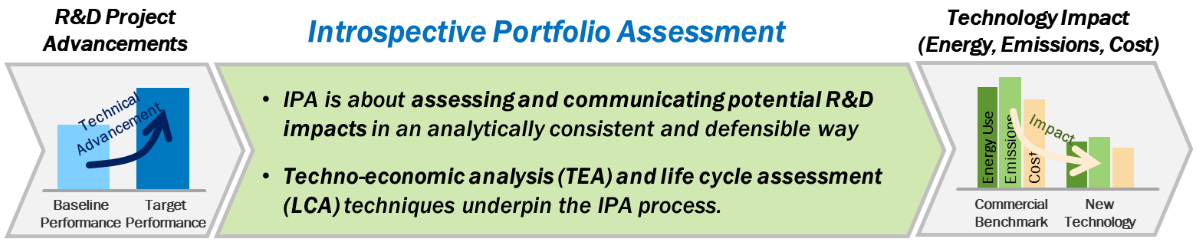
See full poster here: https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Liddell_IEDO_Strategic_Analysis_EEIO-for-Industrial-Decarb_POSTER-VERSION.pdf

U.S. Greenhouse Gas Emissions in 2018 (million metric tons CO_2eq)



Poster: Project & Portfolio Impact & Environmental Justice Analysis

Introspective Portfolio Assessment (IPA)



Resources

Training and resources to educate and improve communication with stakeholders

M&P

Clear methodologies & processes (M&P) for project and portfolio level assessment

Data

Data requirements and data management systems for project tracking.

Analysis

Analytical frameworks and tools to simplify and streamline assessment

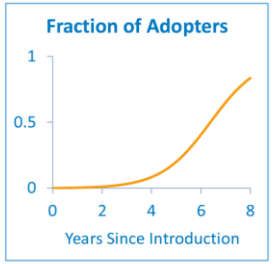
See full poster here:
https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Dollinger_IEDO_Strategic-Analysis_Poster_Project-and-Portfolio-Impact-and-Environmental-Justice-Analysis.pptx

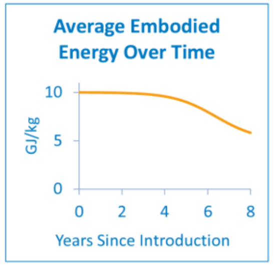
Portfolio-level Analysis

- Such as expanding technology adoption & savings analysis to industrial decarbonization technologies

Technology-specific data → Bass diffusion curves → Energy use over time

Technology Characteristic	Data
Payback period	3 years
Type of modification	Add-on
Lifetime	8 years
and other characteristics	





Manufacturing Environmental & Social Justice

- Contributing analysis on quantitative & qualitative social & environmental data to inform decarbonization studies

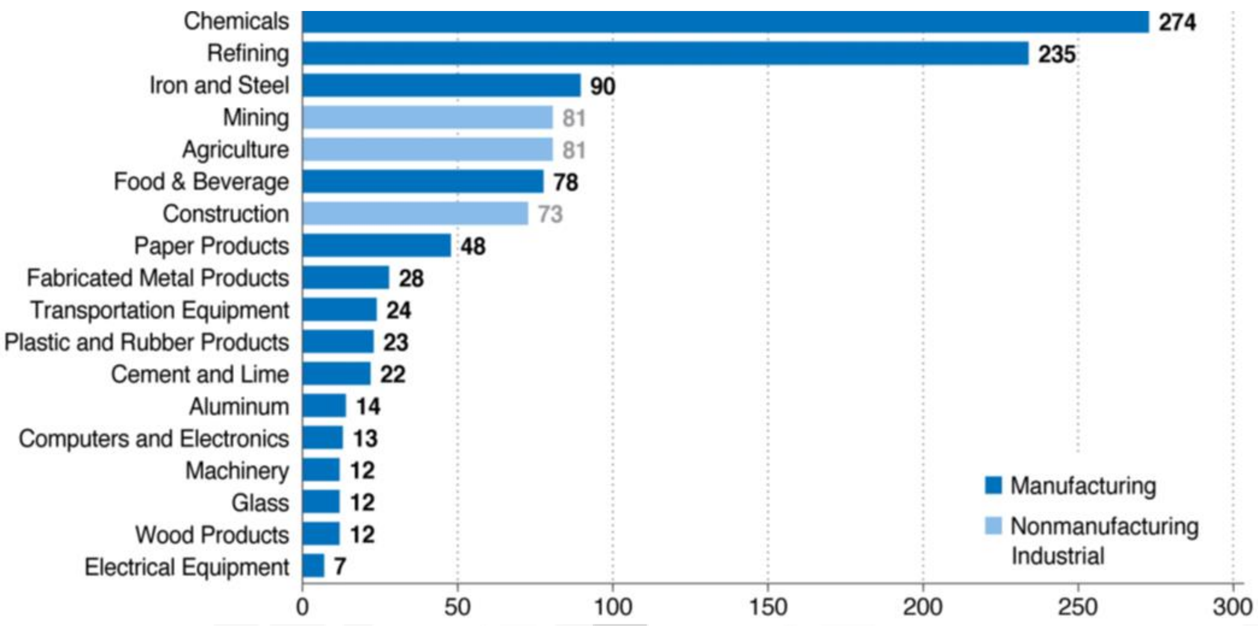
Decarbonizing Industry is an Opportunity for America’s Economy

U.S. manufacturing subsector…

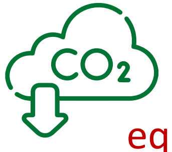
CONTRIBUTES
$2.79 trillion to the U.S. Economy

GENERATES
12% of U.S. GDP

SUPPORTS
11.2 million jobs



MMT CO_2



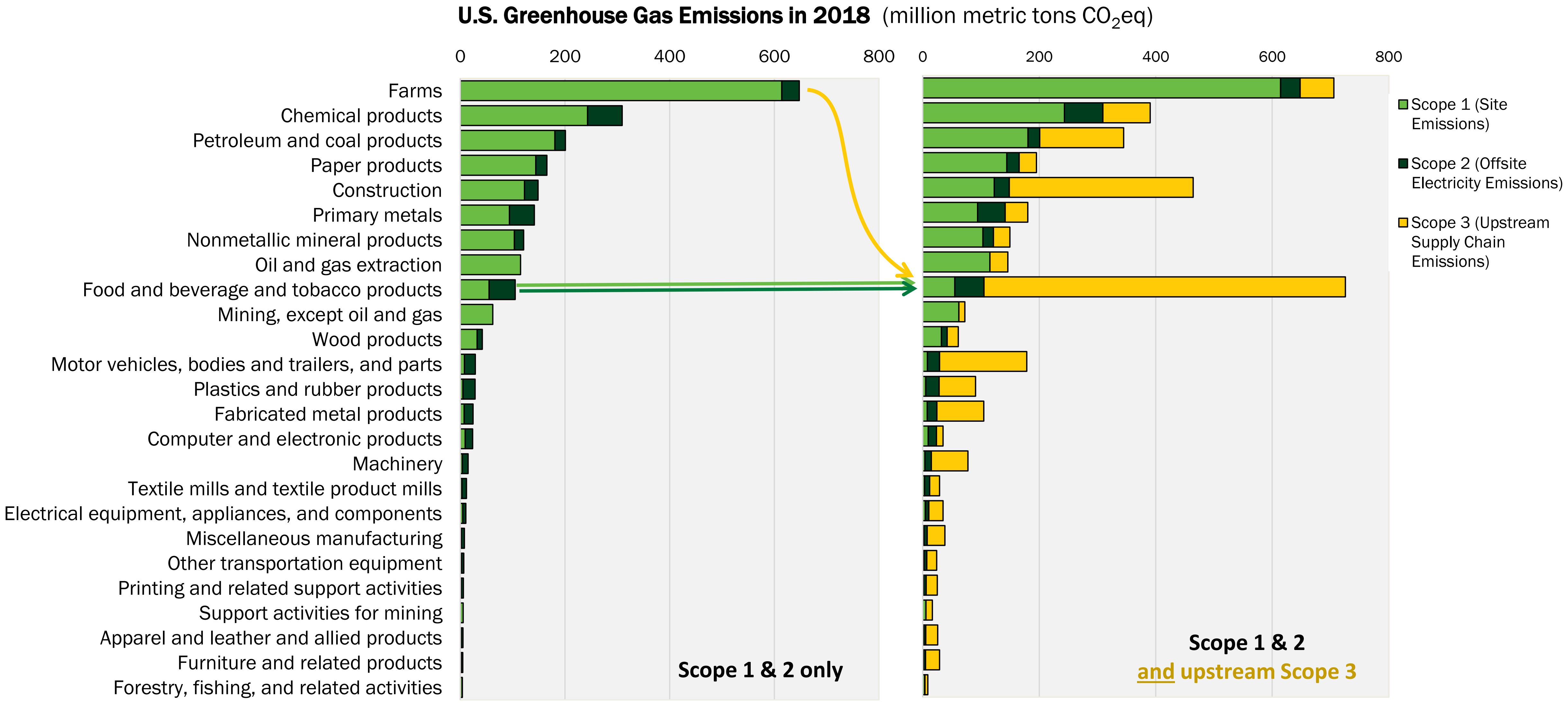
equivalents

All industrial emissions

All subsectors

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

GHG Emission in Context: Significance of Supply Chain Emissions



Data Source: DOE EEIO-IDA tool

For more information, see Strategic Analysis poster: https://www1.eere.energy.gov/iedo/downloads/2023/peer_review/Liddell_IEDO_Strategic_Analysis_EEIO-for-Industrial-Decarb_POSTER-VERSION.pdf

Buying Clean requires Making it Clean

THE WHITE HOUSE

MENU

- The **Department of Energy (DOE)** is supporting Buy Clean with training, technical assistance, and innovation grants. The Building Technology Office is building tools such as GREET ↗ for whole building lifecycle analysis and the Advanced Manufacturing Office is supporting with tools such as LIGHTEnUp ↗ and MFI ↗ to support standard-setting for specific products.

FACT SHEET: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century | The White House

NREL Transforming ENERGY

energetics Clean Energy Consulting

BERKELEY LAB Lawrence Berkeley National Laboratory

Materials Flow through Industry (MFI) Tool
Linear network model of the U.S. industrial sector. It can model a range of manufacturing scenarios, including the effects of changes in production technology and increases in industrial energy efficiency.

https://www.nrel.gov/manufacturing/mfi-modeling-tool.html

Environmentally-Extended Input/Output (EEIO) models
Input/output techniques to estimate the total impact of an industry's products on environmental metrics, such as greenhouse gas emissions.

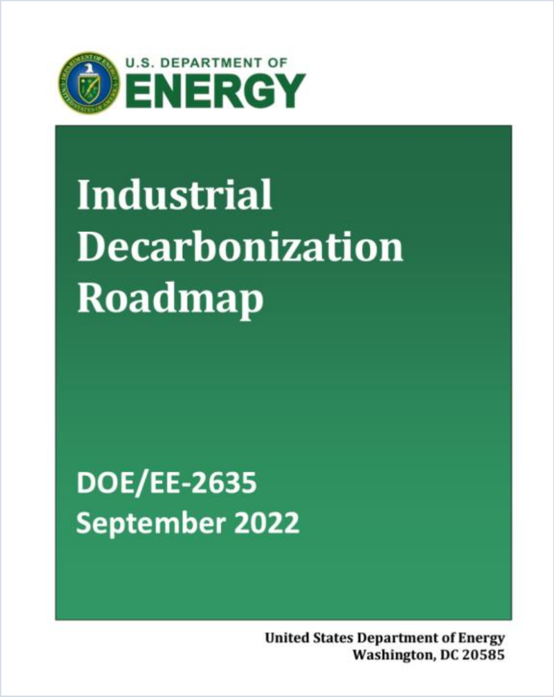
https://www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio

LIGHTEn-UP Tool
Scenario framework for assessing prospective net energy impacts of a technology/product, accounting for both manufacturing and end-use life cycle phases.

https://energyanalysis.lbl.gov/tools

LIGHTEn-UP: Lifecycle Industry GreenHouse gas, Technology and Energy through the Use Phase

DOE Industrial Decarbonization Roadmap

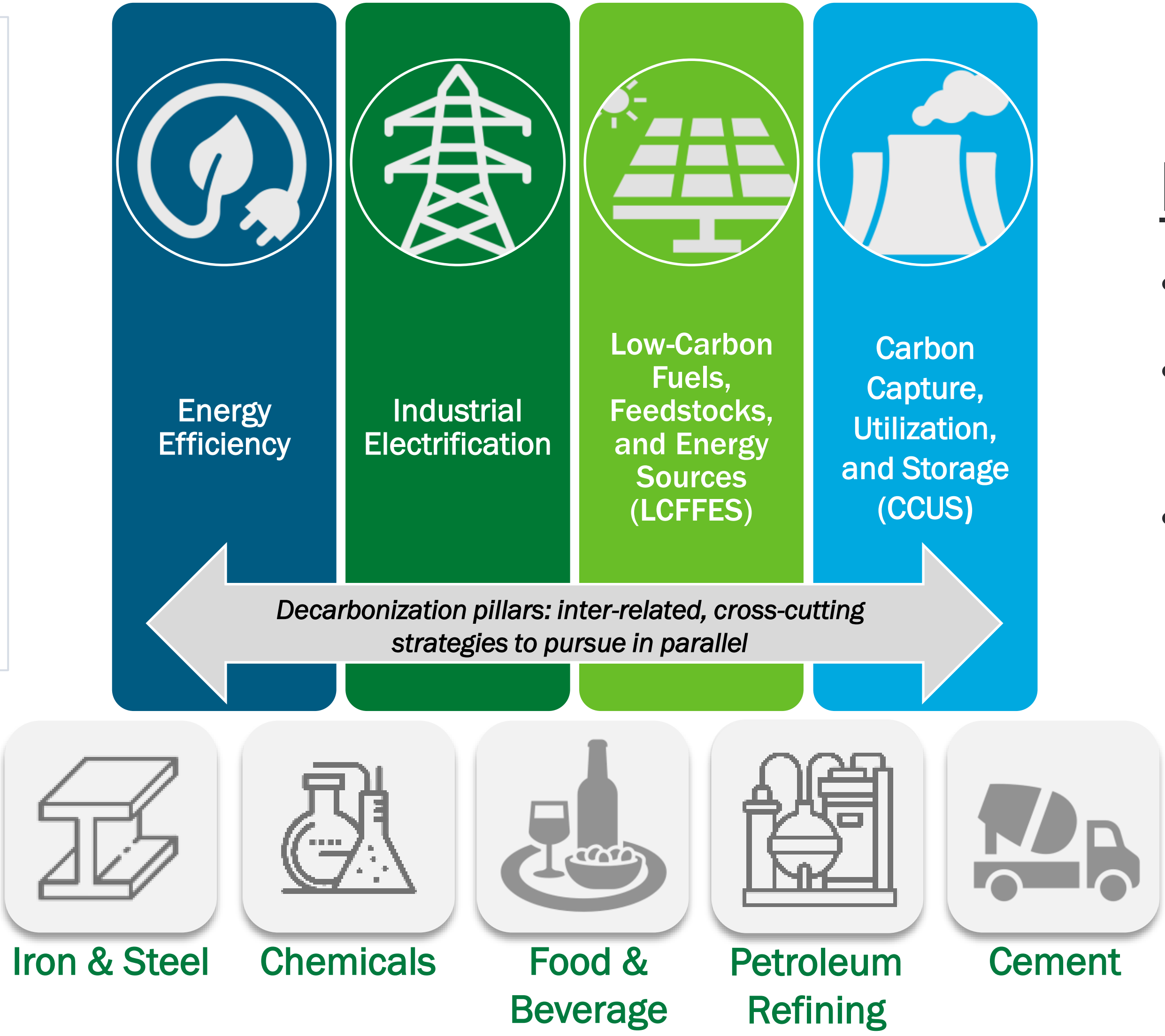

U.S. DEPARTMENT OF ENERGY

Industrial Decarbonization Roadmap

DOE/EE-2635
September 2022

United States Department of Energy
Washington, DC 20585

Industrial Decarbonization Pillars



Key Takeaways:

- Invest in all pillars
- Leverage cross-sector approaches
- Interdependencies require systems solutions

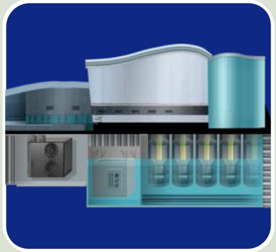
All-hands-on-deck effort (example research areas)

Office of Science

- Foundational R&D Capabilities at the User Facilities
- High Performance Computing for Manufacturing

Industrial Efficiency and Decarbonization Office

- RD&D in manufacturing processes, technologies, products, facilities, and supply chains



Nuclear Energy

- RD&D to expand nuclear energy to industrial, transportation, and energy storage applications

Bioenergy Technologies Office

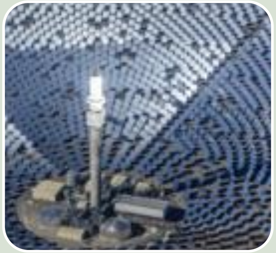
- RD&D development of processes using alternative feedstocks and low/no heat manufacturing options

Hydrogen and Fuel Cell Technologies Office

- RD&D of clean hydrogen technologies for low-carbon feedstocks and fuels

Fossil Energy and Carbon Management

- RD&D to convert captured carbon into products without the need for heat or using substantially less heat



Solar Energy Technologies Office

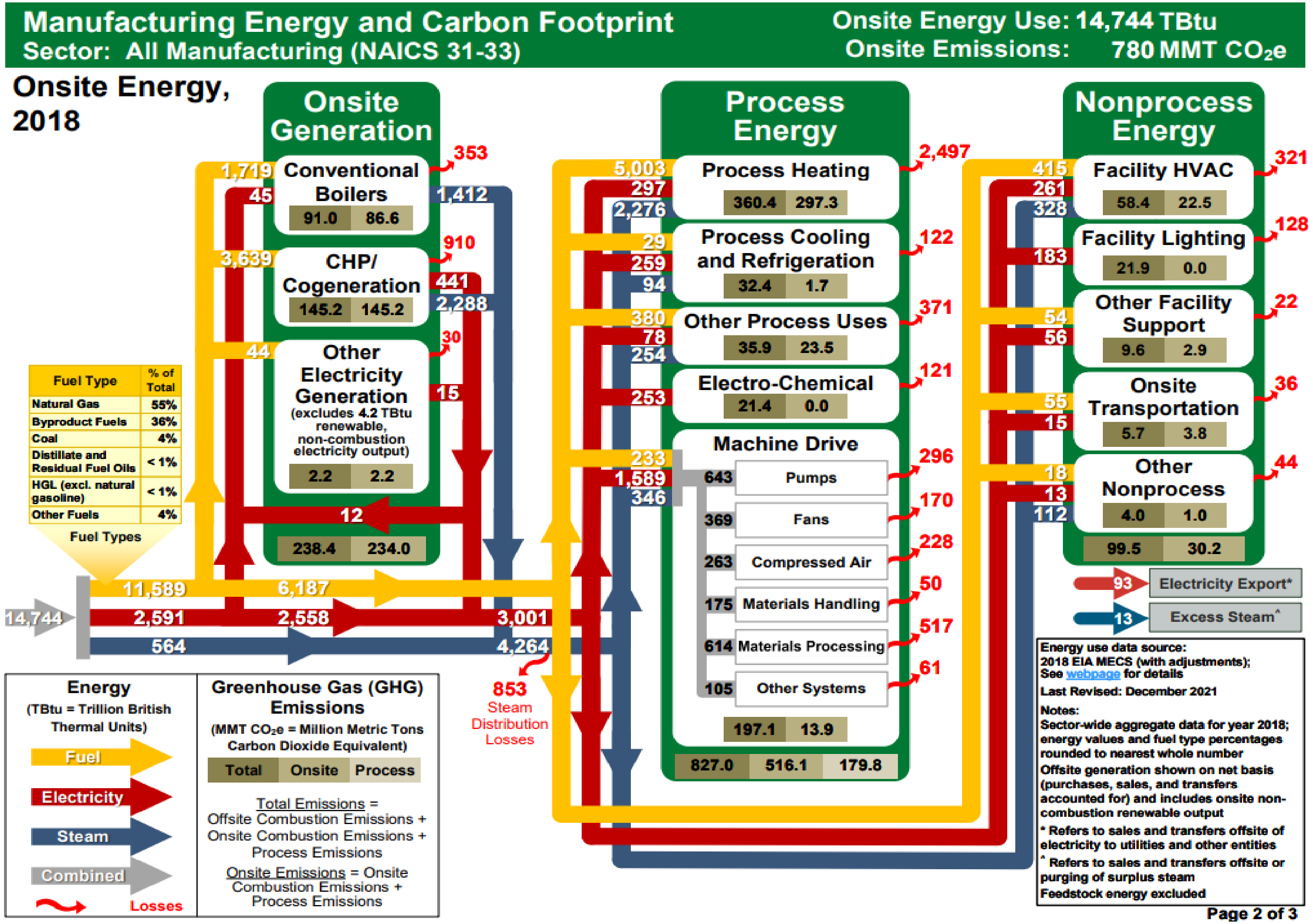
- RD&D in concentrated solar thermal and thermal storage technologies

Office of Clean Energy Demonstrations

- Industrial Decarbonization Demonstration projects

DOE National Laboratories RD&D

Energy & Emissions in Manufacturing

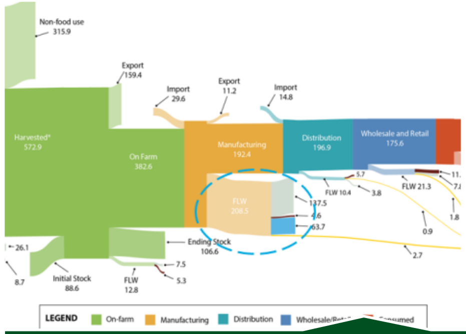


Manufacturing Energy and Carbon Footprints

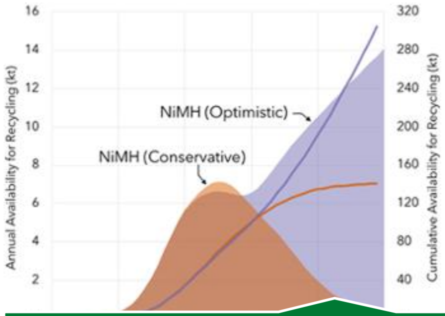
The flow of energy supply, demand, and losses as well as greenhouse gas (GHG) emissions for end uses in 15 manufacturing subsectors.

https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf

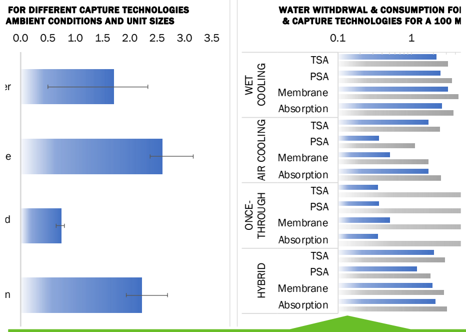
Strategic Analysis Deep Dives



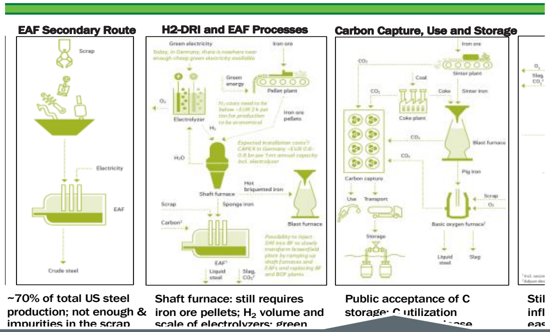
Energy & Materials Resource Flows



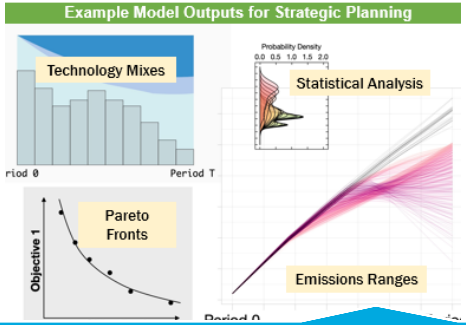
Sustainable & Circular Economy



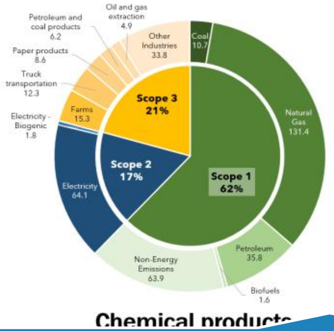
Water-Energy-Carbon Nexus



Industrial Decarbonization: Extended Pathways Analysis



Industrial Decarbonization: Integrated Systems & Deep Dives Analyses



Environmentally Extended Input-Output for Industrial Decarbonization Analysis

Project & Portfolio Impact & Environmental Justice Analysis