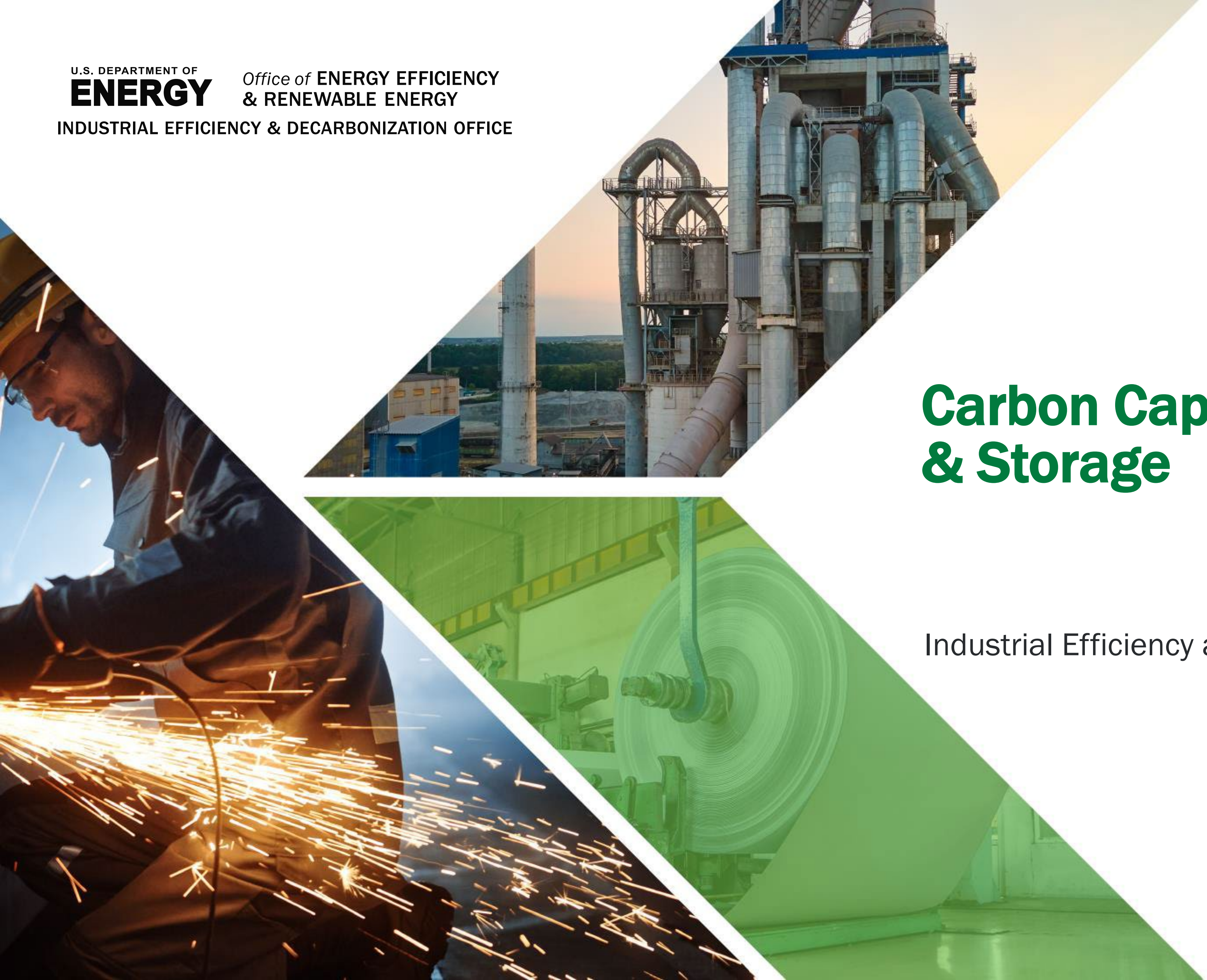
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Cross-Cutting Strategies Breakout Sessions

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

INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE



Carbon Capture, Utilization, & Storage

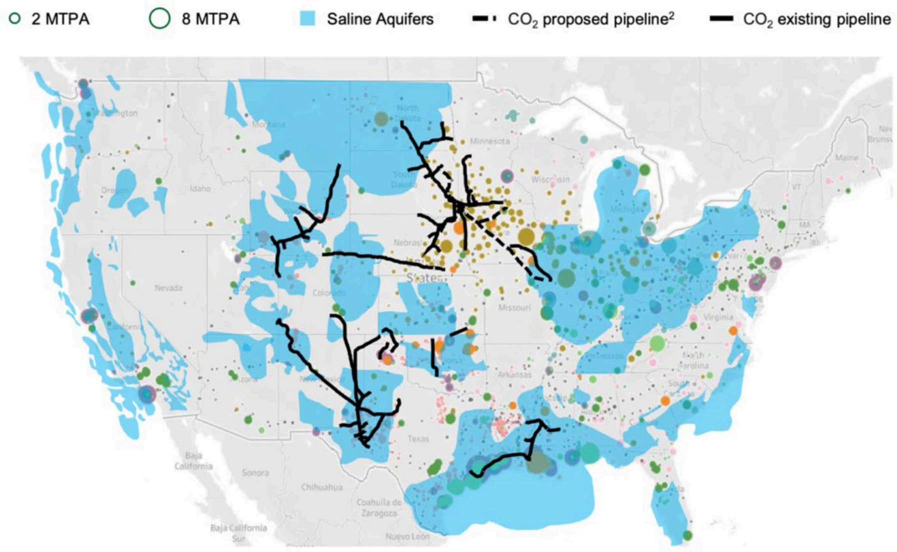
Industrial Efficiency and Decarbonization Office

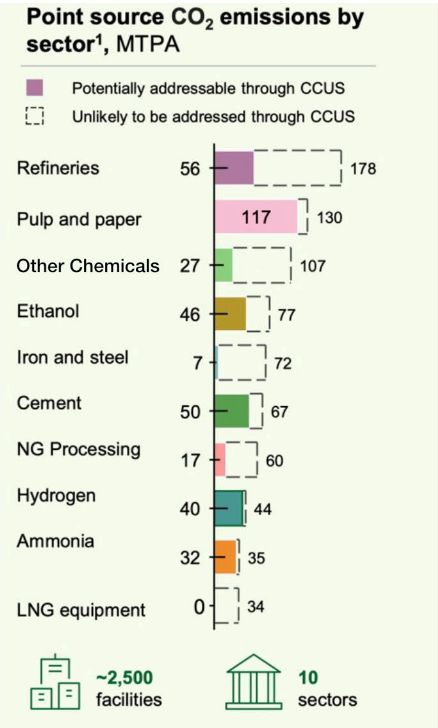
May 14, 2024

CCUS may be necessary in a significant capacity to achieve net-zero emissions in industry

Point sources that offer higher purity streams of CO_2 are the lowest hanging fruit

- Nearly 400 MMT CO_2/yr of industrial carbon capture potential identified.
- Only a fraction of higher purity industrial point sources currently capture their CO_2.
- The vast majority of captured CO_2 is expected to be sequestered in geologic storage and a small fraction will likely need to be utilized in developing sustainable fuels, chemicals, and other relevant industrial products.
- Carbon capture will likely come with significantly higher cost, energy, land, water, and other burdens in many facilities.





Note: Not all emissions are addressable through carbon capture alone. Plant by plant feasibility studies are required.

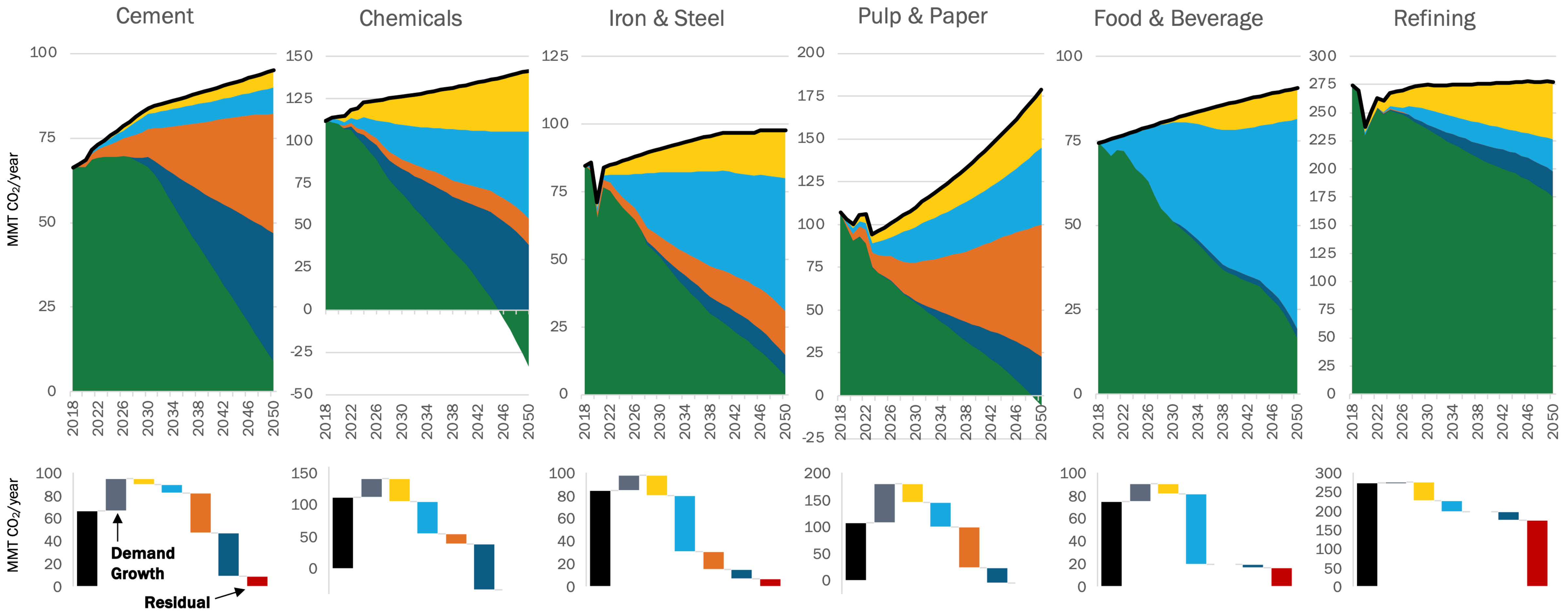
1 High purity and process CO_2 streams are solid, with total CO_2 emissions shown by dotted line. Waste, non-industrial sectors, and some petroleum and NG emissions amounting to ~500 MTPA are not shown on the map and in the MTPA breakdown
2 Includes Summit, Navigator, ADM, and Tallgrass proposed CO_2 pipelines from project websites
3 Exploration of capture on NG transmission and distribution facilities (including LNG terminals) is out of the scope of this report, though there are expected to be CCUS-addressable emissions in that sector

Source: EPA GHGRP FLIGHT database 2019 including biogenic CO_2 for pulp and paper sector, additional public information on smaller point source emitters, and estimated additional emissions from ethanol facilities in EIA ethanol plant database; Summit, Navigator, ADM, and Tallgrass CO_2 pipeline project websites; NatCARB Atlas V Database; Estimates on proportion of CCUS-addressable emissions compiled from EPA FLIGHT database, DOE Industrial Decarbonization Roadmap, and McCoy et. al (2016) for Ethanol, Sagues Et. al (2020) for Pulp and Paper

Adapted from: U.S. Department of Energy, Pathways to Commercial Liftoff: Carbon Management, 2023.

Projections for CCUS in decarbonizing major energy and emissions-intensive industries

Uptake of CCUS projected to vary considerably across industries

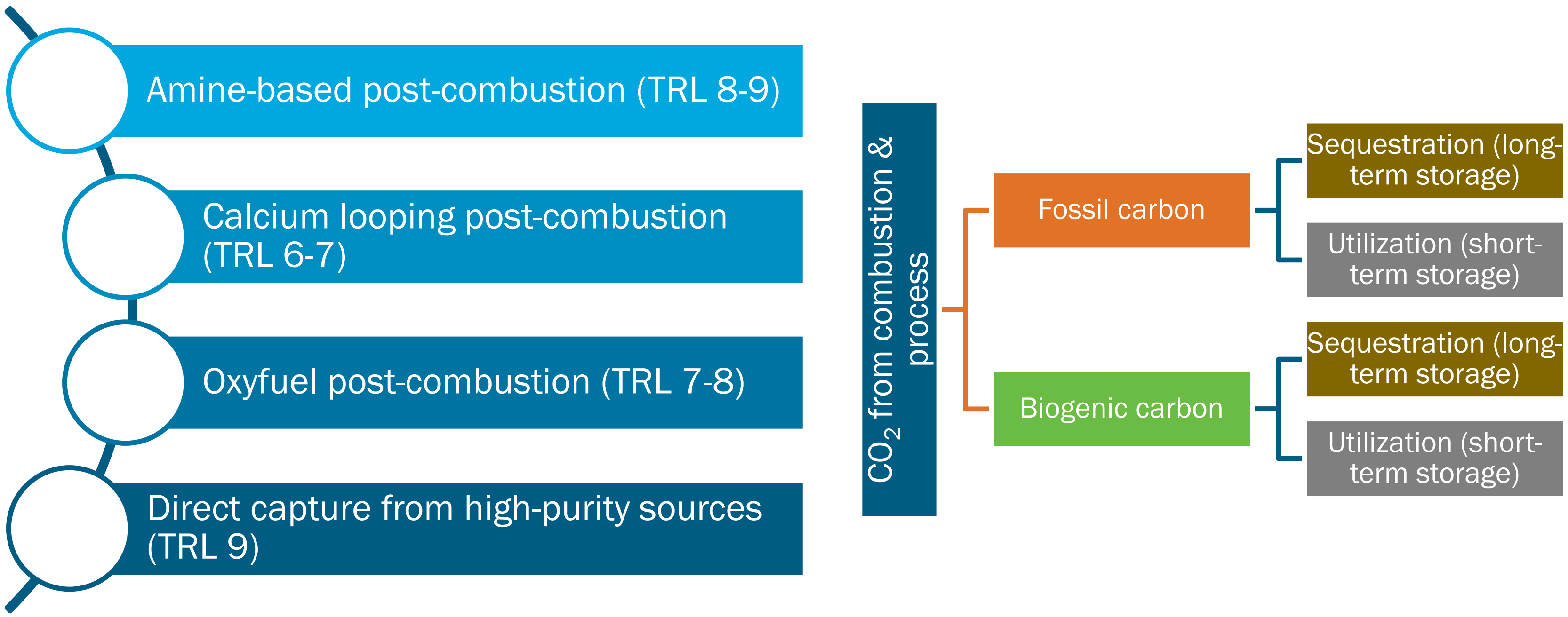


Source: IEDO Decarbonization Roadmap Extension & Expansion (RM 2.0) Analysis

Our models looked primarily at carbon capture technologies with higher commercial maturity

Significant RD&D opportunities exist at the lower end of the TRL spectrum

CO_2 capture technologies, sources, and fates in RM 2.0



Other capture technologies

- Gasification
- Membrane capture
- Cryogenic capture
- Reactive capture
- ?

Challenges and barriers for CCUS

Understanding technical and engineering challenges outside of the well-established ones around energy and cost penalties may help guide future RD&D focus areas

- Considerations outside of cost may determine the viability of CCUS as a decarbonization approach, including considerations outside of the industrial sector.
- Metrics for determining the applicability of CCUS technologies, particularly given significant variability in capture plant design across facilities within an industry.
- Emissions verification programs and carbon accounting guidelines may be insufficient for companies to consider CCUS and have several pitfalls that need to be addressed.
- Uncertainties around markets, infrastructure, and related supply chains for end use of captured CO_2 (whether geological sequestration or utilization).

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

INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

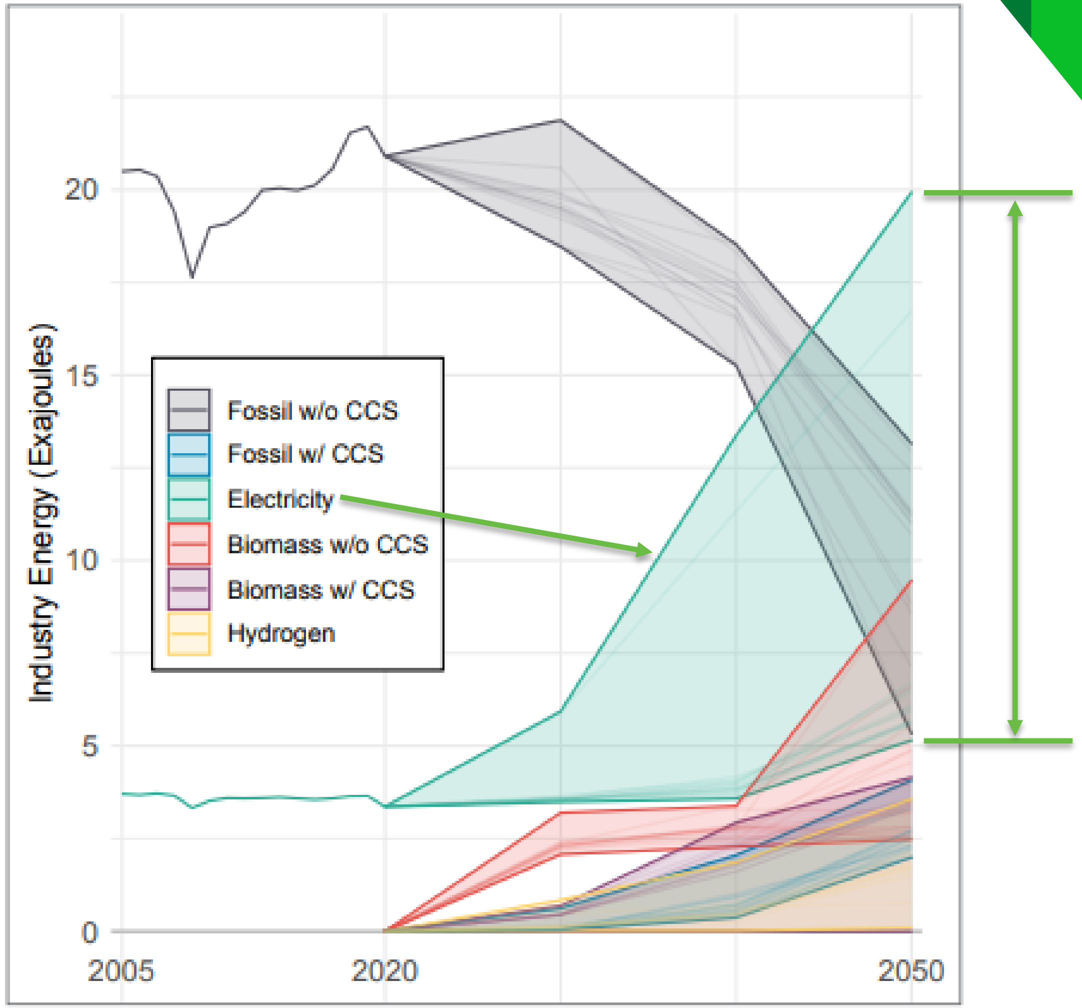
Industrial Electrification and the Grid

Industrial Efficiency and Decarbonization Office

May 14, 2024

Context of Industrial Electrification

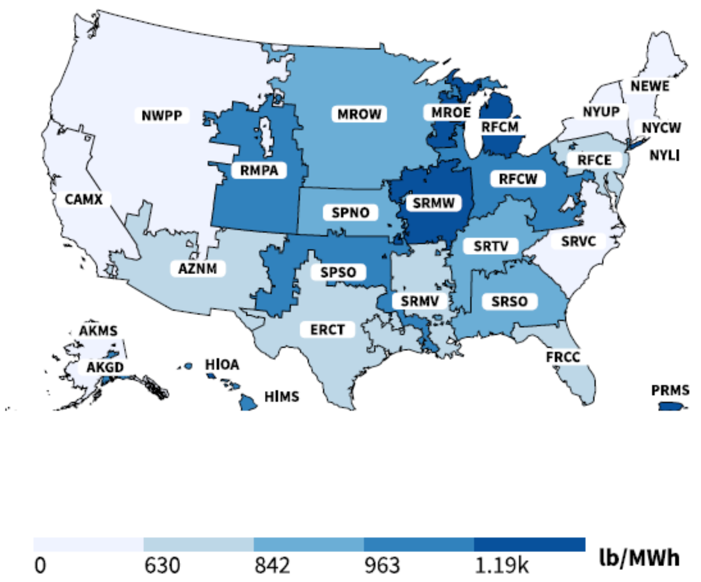
- Industrial Electrification, by energy end-use, from MECS 2018 survey
  - ~15% of energy end-use
  - ~1000 TWh of consumption (out of 4000 TWh supplied by the grid, AEO 2023)
- According to recent strategies
  - LTS – GCAM modeling shows range from 400 - 4000 TWh increase by 2050. Note high-end accounts for electrolytic hydrogen production with industry end-use.
- Current analyses supporting this vision study anticipate 500 – 1000 TWh of additional manufacturing industrial electrification by 2050 for manufacturing
  - With assumption that for many mid- to high-temperature processes, electrification is not considered a viable, cost-effective solution



The Long-Term Strategy of the United States

High Variability in Grid Emission Factors

CO_2 total output emission rate (lb/MWh) by eGRID subregion, 2022

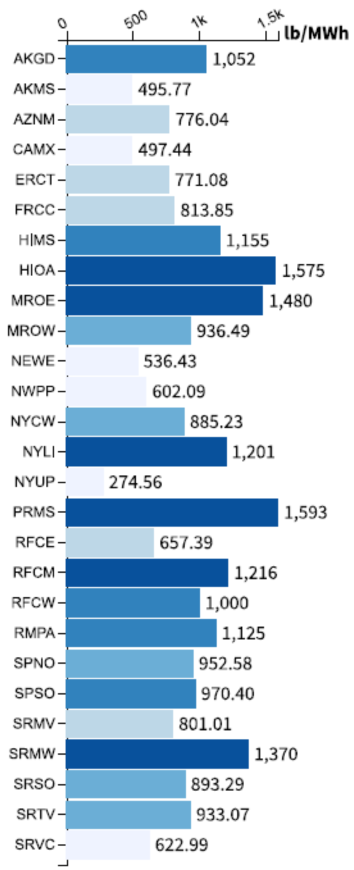


Trend, CO_2 total output emission rate (lb/MWh), by eGRID subregion, 2018–2022

Select an eGRID subregion in the map above or the graphs at the right to see its trend here.

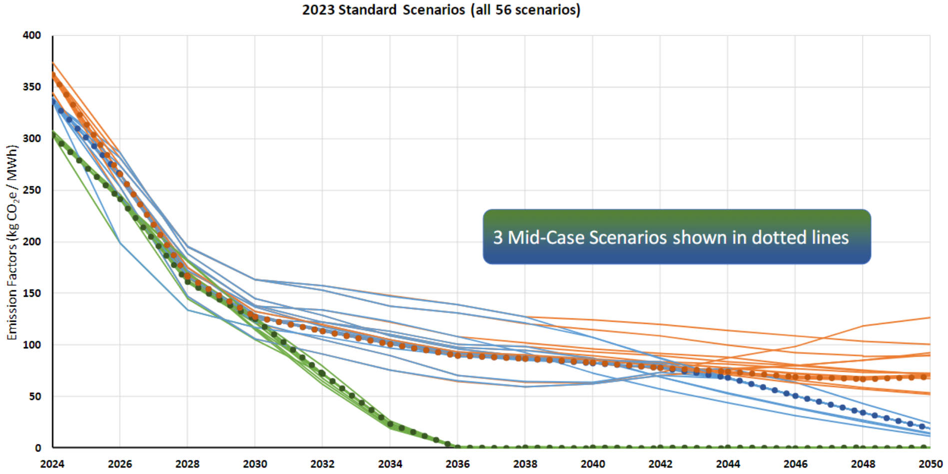
Regional Variability

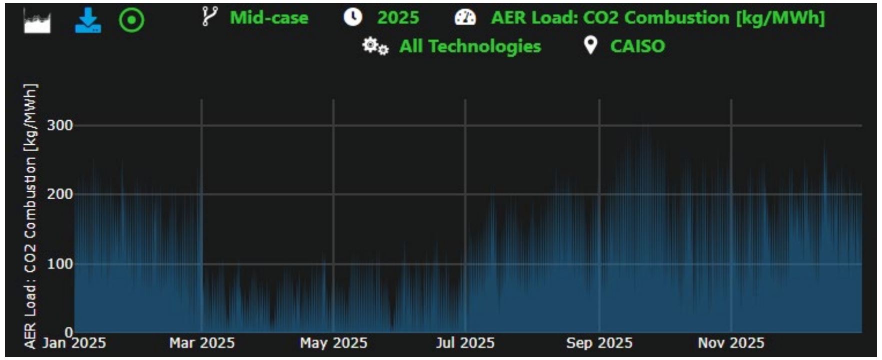
US: 823.15 (lb/MWh)



Uncertainty in Projections

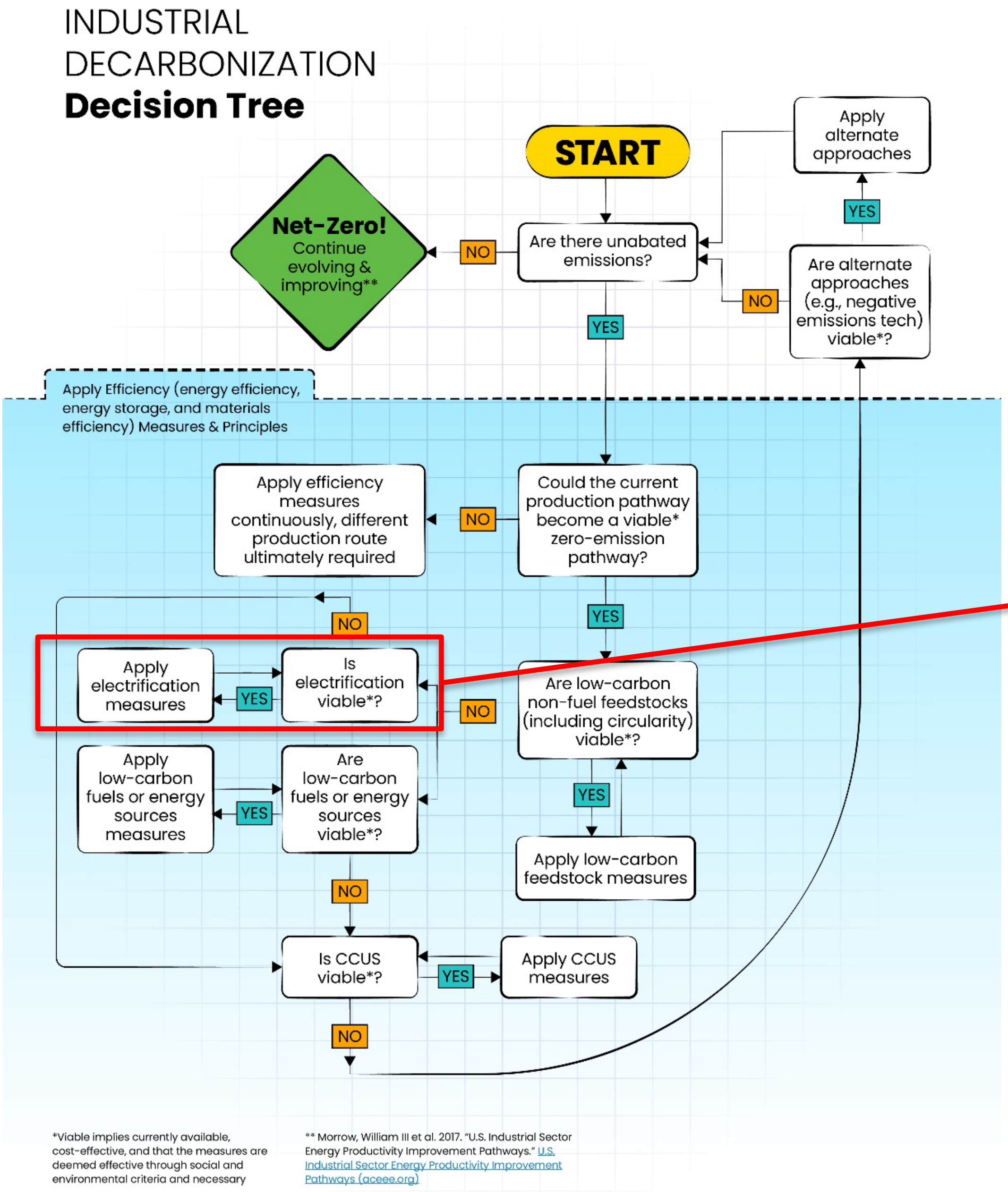
2023 Standard Scenarios, NREL





Temporal Variability

NREL Scenario Viewer, Cambium 2023



Industrial Electrification is a fundamental pillar in decarbonization strategies, often viewed in parallel with low-carbon fuels or energy sources opportunities

Challenges and Barriers

Key challenges and barriers to broadly implement industrial electrification

- R&D for process specific systems-level technologies
- Grid emission factors
  - Forecasts: temporal, regional, and marginal
- Systems Integration
  - Demand response, load shifting
- Electrification Infrastructure Build-out
  - Generation
  - Transmission & Distribution
  - Availability, regional, temporal & power quality
- Costs
  - $/MWh projections
  - High Capital costs
  - Risk mitigation
- Social
  - Reliability of grid for local communities
  - Workforce development for new processes

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

Energy Efficiency for Decarbonization

Industrial Efficiency and Decarbonization Office

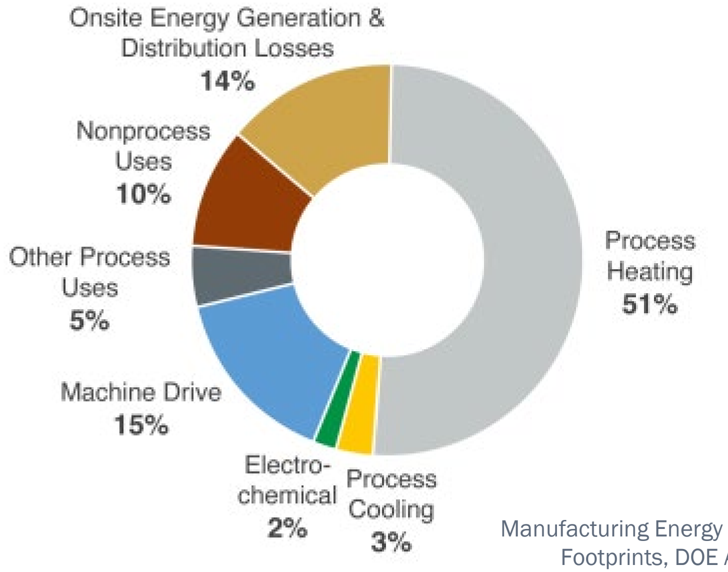
May 14, 2024

Energy Efficiency as a Decarbonization Pathway

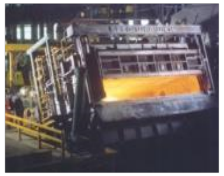
Energy efficiency measures and system design are fundamentally important at all industrial decarbonization stages since they apply to incumbent and future technologies.

- Often the "lowest-hanging fruit"; EE practices can directly reduce GHG emissions by minimizing industrial energy demand from fossil fuel combustion (scope 1) and electricity (scope 2).

Distribution of energy end-uses at U.S. manufacturing facilities (2018)



Manufacturing Energy and Carbon Footprints, DOE AMO, 2022.

Process Heating/ Steam Systems	Electric Motor Systems	Pumping Systems	Compressed Air Systems	Other*
				* *Other ancillary energy usages such as lighting represent less than 2% of energy consumption*
10% to 30%	5% to 10%	10% to 20%	10% to 20%	5% to 10%

← **Potential Energy Saving Opportunities** →

Broadly Strategic energy management, Material and life cycle efficiency, Smart manufacturing, CHP

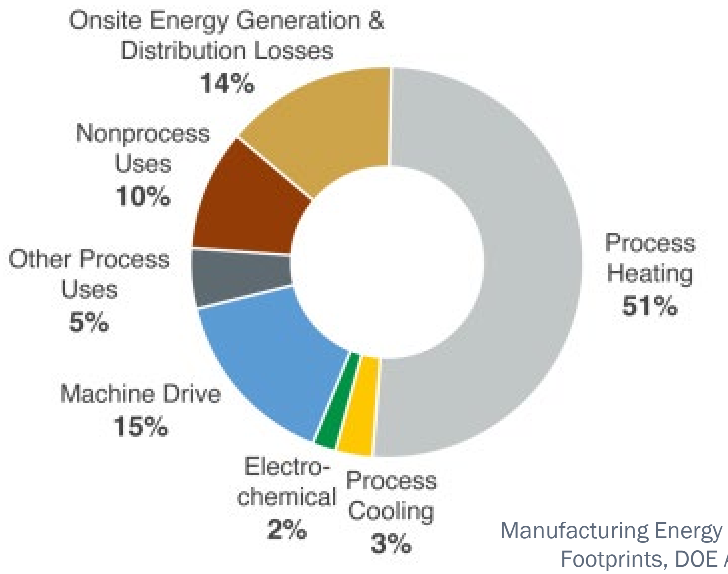
https://betterbuildingssolutioncenter.energy.gov/webinars/better-plants-online-learning-series-webinar-9-process-heating-and-waste-heat-recovery

Energy Efficiency as a Decarbonization Pathway

Energy efficiency measures and system design are fundamentally important at all industrial decarbonization stages since they apply to incumbent and future technologies.

- Often the "lowest-hanging fruit"; EE practices can directly reduce GHG emissions by minimizing industrial energy demand from fossil fuel combustion (scope 1) and electricity (scope 2).

Distribution of energy end-uses at U.S. manufacturing facilities (2018)



Manufacturing Energy and Carbon Footprints, DOE AMO, 2022.

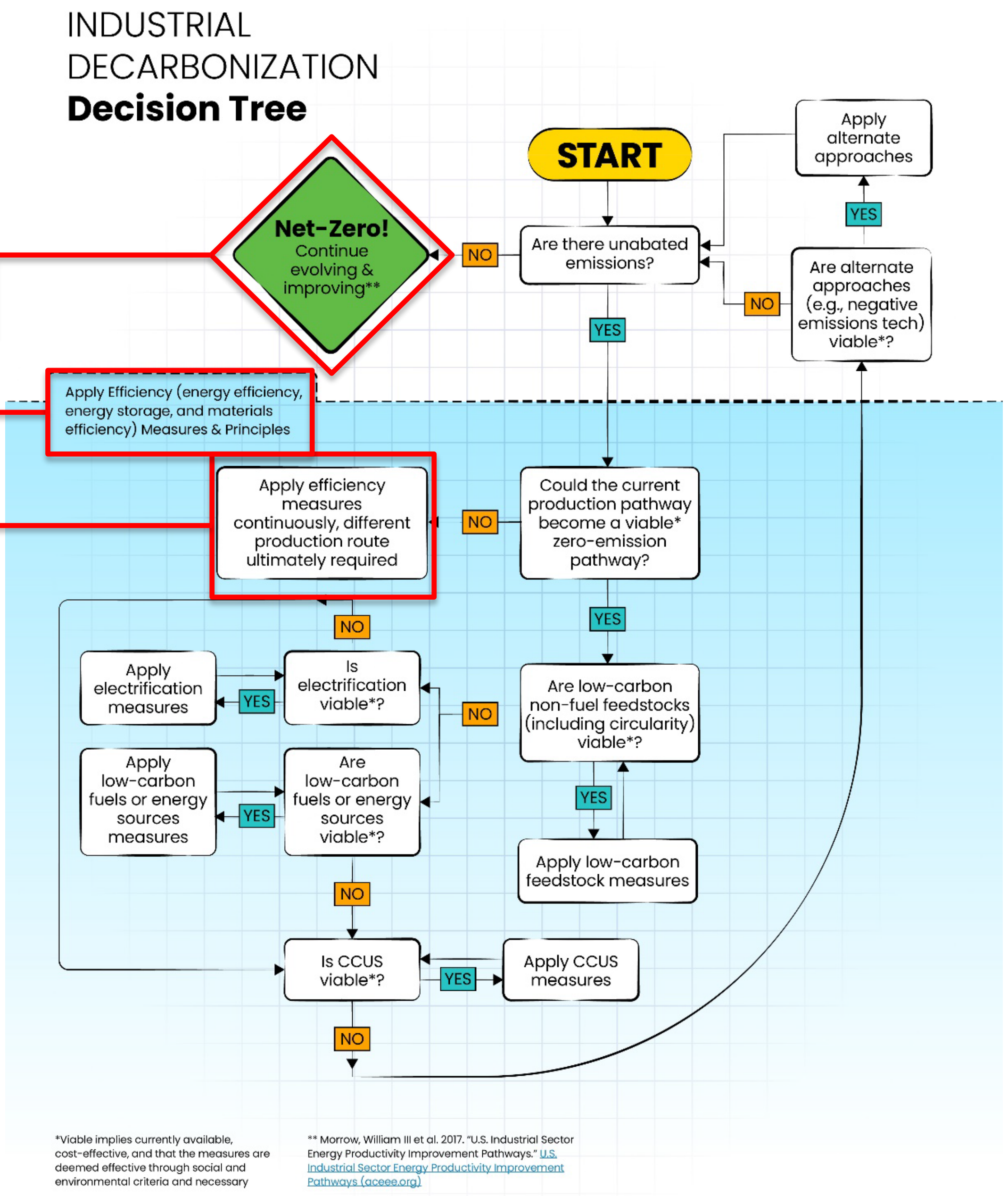
Key Energy Efficiency Approaches

- Strategic energy management
- Material and Life Cycle Efficiency
  - System efficiency improvements, e.g., process intensification, process integration
  - Waste heat recovery, waste heat to power
- Smart Manufacturing
  - Digitalization, IoT, AI/ML, flexible modular manufacturing and operations design
- Combined Heat and Power

Even after Net-Zero, energy efficiency should be utilized to continue evolving and improving processes.

Regardless of other cross-cutting strategies, energy efficiency must be leveraged in parallel.

In addition, energy efficiency must be applied continuously to existing production routes, until a net-zero pathway is implemented.



Challenges

Primary challenges for the energy efficiency technology adoption

- Inadequate awareness of efficiency measures and incentives and the resources to implement them.
- Unfavorable return on investment due to low fossil fuel energy costs and or high additional equipment cost.
- Disruptions to operation during retrofits.
- Engineering constraints for existing processes, e.g., waste heat integration.
- Lack of strategic energy management to ensure improvements persist.
- Rebound effects – increased energy consumption due to improved energy efficiency.

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


Hydrogen and Other LCFFES

Industrial Efficiency and Decarbonization Office

May 14, 2024

Hydrogen and Other LCFFES

	Approaches	Examples
Fuels and energy sources	Combustion of hydrogen and hydrogen carriers	H_2, ammonia
	Combustion of biofuels and biomass	Ethanol, biodiesel
	Integration of Renewable/clean sources of heat	Nuclear, solar-thermal, geothermal
Feedstocks	Hydrogen as a feedstock or reductant	H_2
	Waste, scrap, and synthetic feedstocks	Circular economy, steel scrap, alternative SCMs and binders.

Hydrogen

- Current H_2 production: 10 MMT (U.S.); 90 MMT (global)
- 2030 H_2 demand: 200 MMT (global projected)

MMT = million metric tons

Clean

- Water and excess O_2 are the only combustion products
- No carbonaceous residue as with biomass fuels

Compatible

- **High flame temperature**: enables decarbonization of hard-to-electrify industrial processes
- **Similarity to natural gas**: easier operator training and lower switching costs than biomass
- **Multi-functional**: transportation fuel, energy storage medium, and industrial fuel and feedstock

Biofuels

- **Biomass conversion into biofuels via:**[1]
  - Deconstruction
  - Upgrading: biological and/or chemical processing to produce a finished product.
- **Most common types of biofuels:**[1]
  - Ethanol
  - Biodiesel
  - Hydrocarbon "Drop-In" Fuels

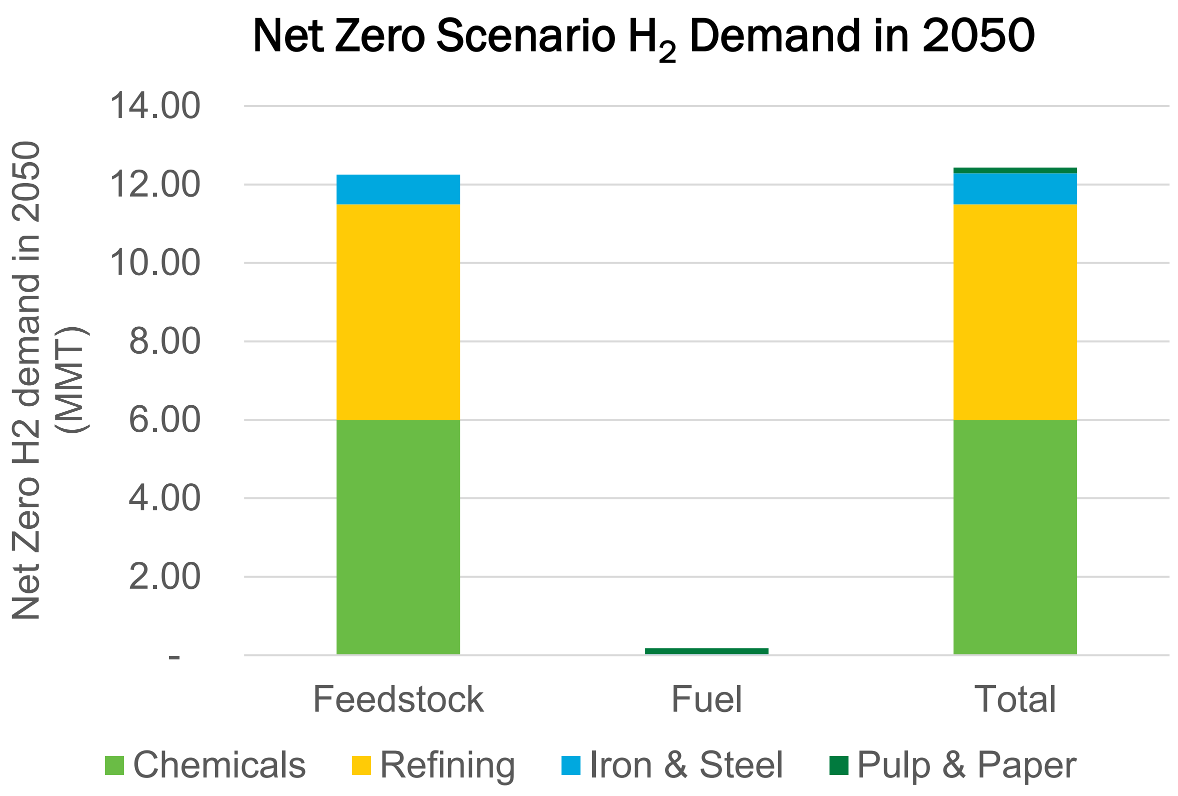
Safe

- Greater stability
- Safer and easier to store compared to petroleum fuels
- Easy transport in pipelines
- Reasonably non-explosive

Energy Dense

- High combustibility
- High energy to mass ratio

Hydrogen Demand and Specific Assumptions



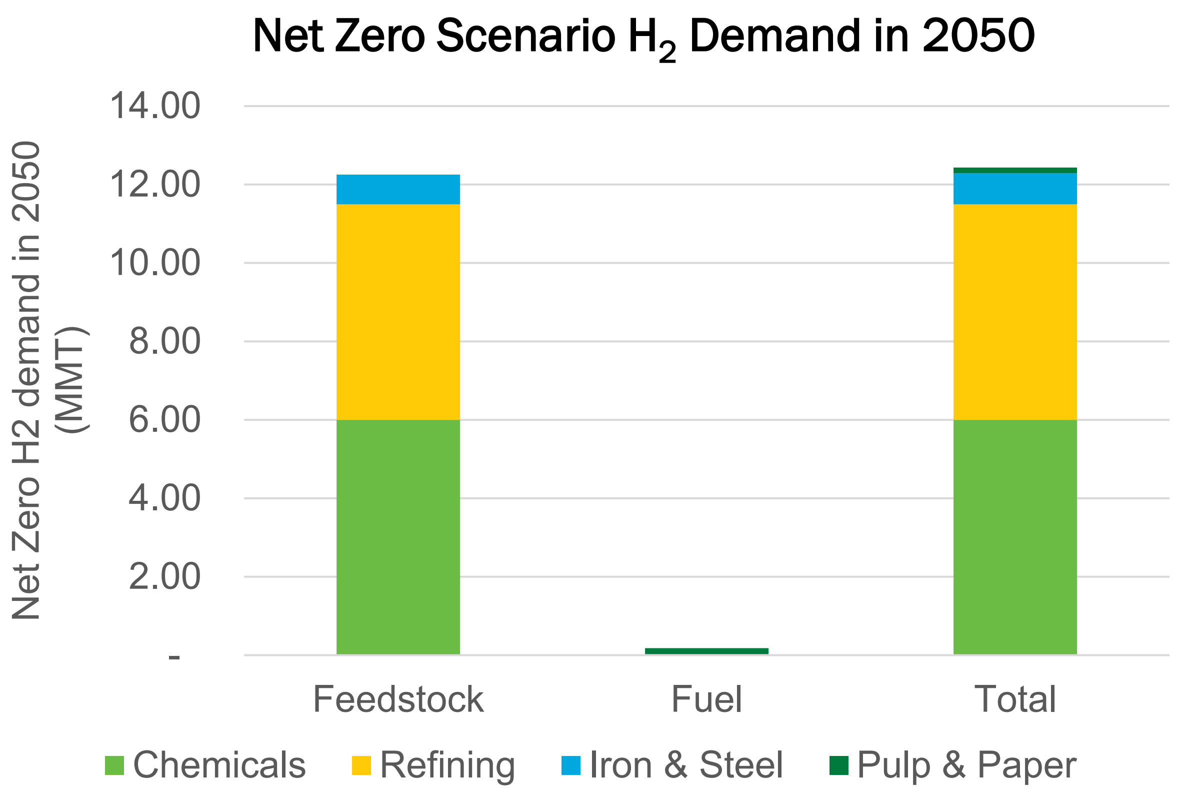
**Note that food & beverage and cement report negligible hydrogen demand under the net-zero scenario*

U.S. National Clean Hydrogen Strategy and Roadmap forecast 50 MMT hydrogen production in 2050 (current hydrogen production is ~10 MMT)

- 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

PRELIMINARY DATA. DO NOT CITE.

Hydrogen Demand and Specific Assumptions



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

Sector-Specific Assumptions*

***Chemicals*: Assumes complete replacement/switching to lower-carbon hydrogen feedstocks for BTX production.**

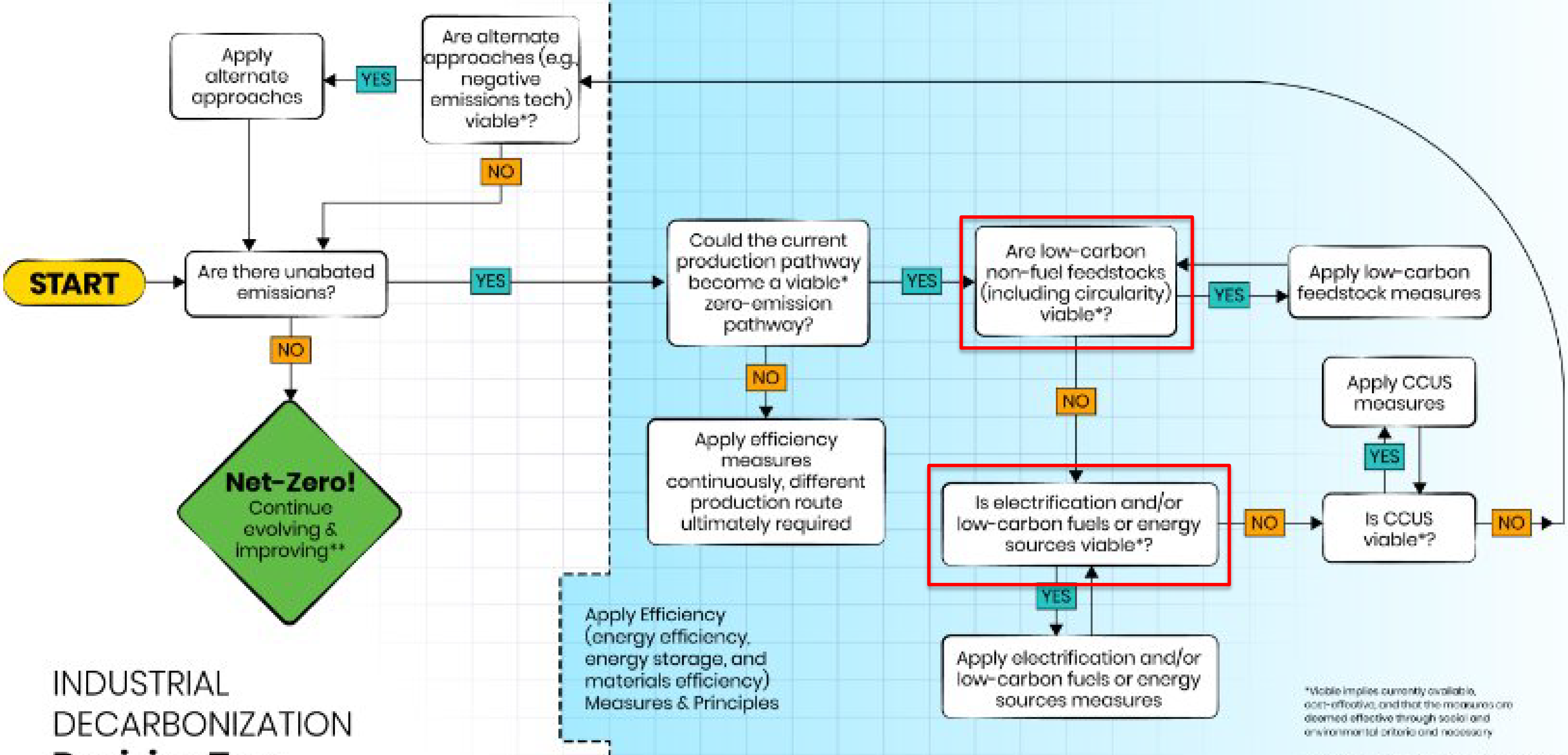
***Petroleum Refining*: The net-zero scenario assumes grey hydrogen capacity is switched to blue and green hydrogen by approximately 50% and 30%, respectively (~80% of total feedstock demand).**

***Iron and Steel*: Aggressive adoption of clean H_2 DRI is assumed for the net-zero scenario.**

***Pulp and Paper*: Low-carbon hydrogen is considered as a possible fuel source for the yankee dryers in tissue mills.**

PRELIMINARY DATA. DO NOT CITE.

INDUSTRIAL DECARBONIZATION **Decision Tree**



*Viable implies currently available, cost-effective, and that the measures are deemed effective through social and environmental criteria and necessary

** Morrow, William III et al. 2017. "U.S. Industrial Sector Energy Productivity Improvement Pathways." U.S. Industrial Sector Energy Productivity Improvement Pathways (aceee.org)

Challenges

Hydrogen

Expensive:
Must meet or exceed Hydrogen Shot Target $1/kg H_2 (~$7.50/MMBtu H_2)

Equipment:
Flame detection, sensors & controls, and compressors, exhaust control

Infrastructure:
New materials to prevent corrosion and embrittlement, pipeline permitting and buildout

Lack of analysis to inform H_2 *end use:*
technoeconomic and lifecycle analyses are needed

Biofuels

Expensive:
Production of biofuels often cost-prohibitive for industrial applications.

Water Intensive:
Can further exacerbate the water supply.

Monoculture:
Growing one crop can have negative environmental impacts in agriculture.

Supply Limited:
Biogenic feedstock availability may limit biofuel potential to fully replace transportation and industrial needs.

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

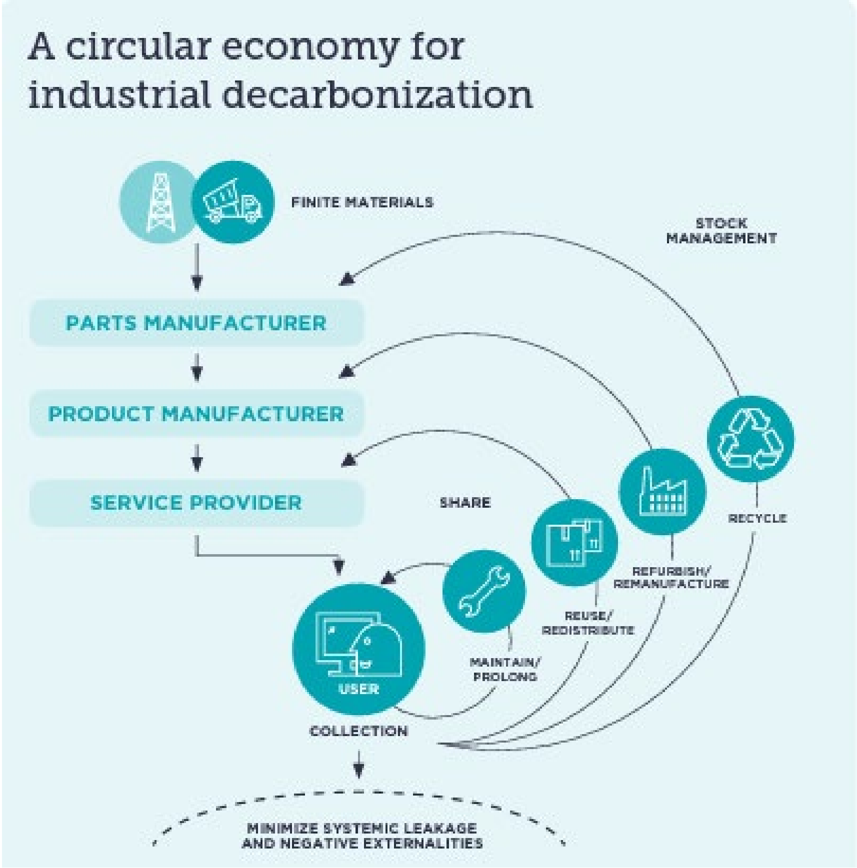
Demand Reduction / Resource Efficiency, Material Efficiency and Circular Economy

Industrial Efficiency and Decarbonization Office

May 14, 2024

Context

- For an integrated and material efficient economy, the industrial ecosystem must consider the full life cycle of products, from mine to manufacturing to use to end of life.
- According to Circle Economy, 85% of emission reductions needed to limit global warming below 2ºC could come from CE (Circle Economy, 2021).
- Scope 3 emissions are the largest contributors to corporate emissions, and materials from the supply chain are a large part of that.
    - Reducing total demand through material efficiency or circular economy strategies can help to reduce scope 3 emissions and decarbonize the industrial sector.



Ellen MacArthur Foundation

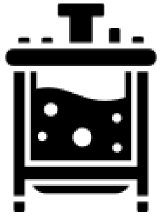
Demand Reduction/Resource Efficiency, Material Efficiency, and Circular Economy Strategies

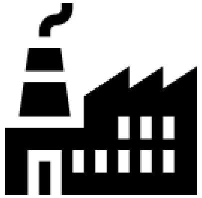
Strategy	Pathways
Alternative material approaches	Critical material substitution
	Biomass substitution
	Energy intensive material substitution
Use products for longer	Property improvement for increased productivity or longer life
	Re-sale
	Design for longer life
	Design for repair or re-manufacture
	Modularity
	Re-use

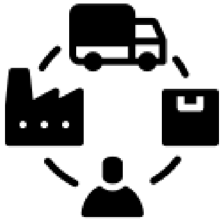
Strategy	Pathways
Do without or with less products or resources	Lightweighting
	Dematerialization
	Yield improvement
	Distributed manufacturing
	Recycling / recovery
	Operation at or near capacity
Use products more intensively	Shared use
	Products as service

Scale Matters

ME approaches have different impacts and challenges at different scales.







	Process	Facility	System/Supply Chain
Impacts of ME approaches	Well characterized.	Well characterized.	Not well understood.
Challenges and barriers (examples)	• Scale-up risks and performance or quality trade-offs with alternative substitutes. • Impurities in scrap or impurity build up. • Modifications to existing processes to accommodate new inputs.	• Absent or inadequate data to transition towards ME practices. • Lack of expertise to implement ME practices. • Lack of technology options.	• Absent or inadequate reverse supply chain infrastructure. • Higher costs relative to linear supply chains. • Regionality of available materials/suppliers. • Availability of scrap. • Risk adverse nature of industry. • Re-thinking business models.

Source: Flaticon

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

INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Natural Resources

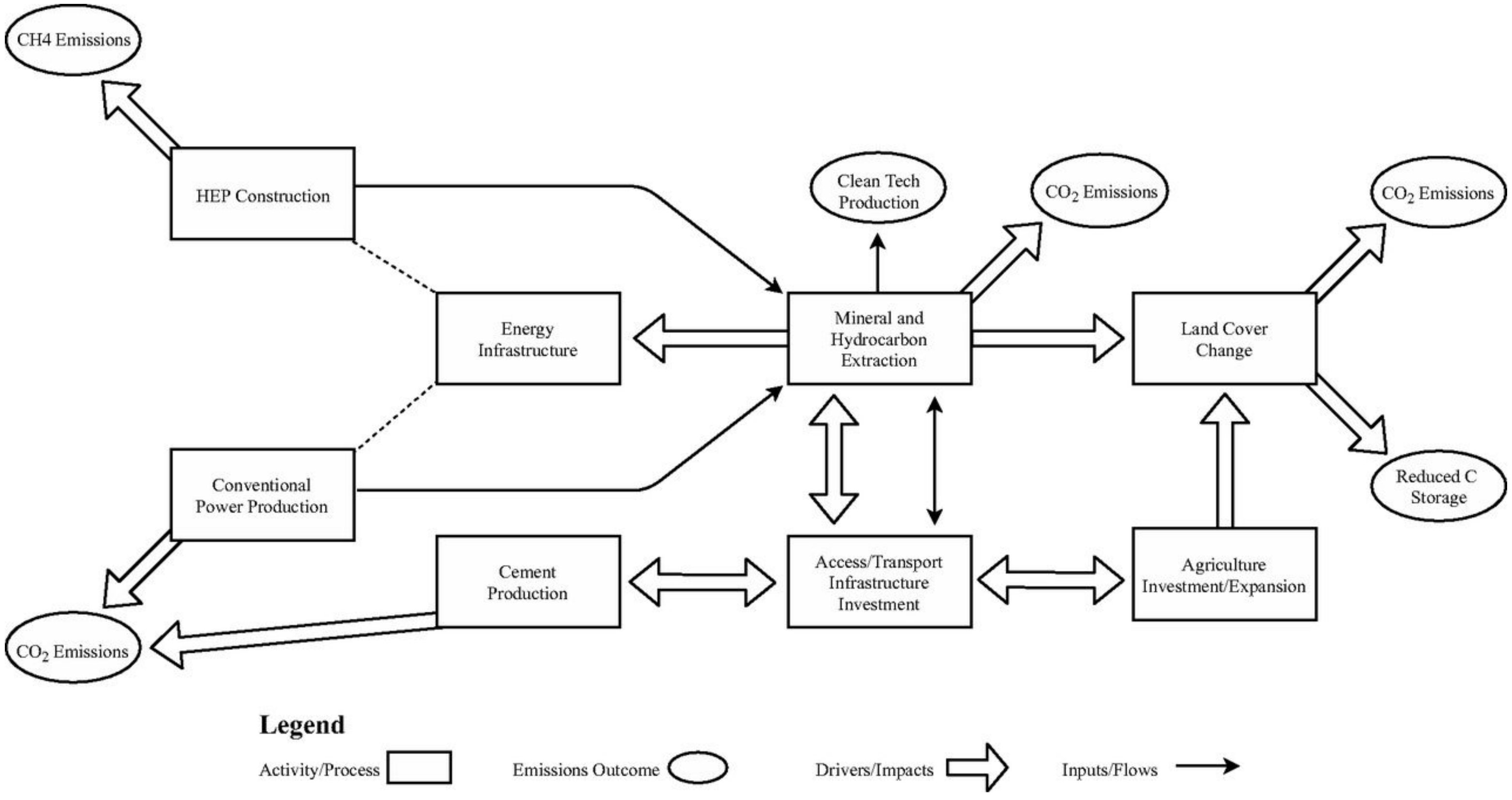
Industrial Efficiency and Decarbonization Office

May 14, 2024

What do we mean by natural resources

Connection between natural resources and industrial decarbonization

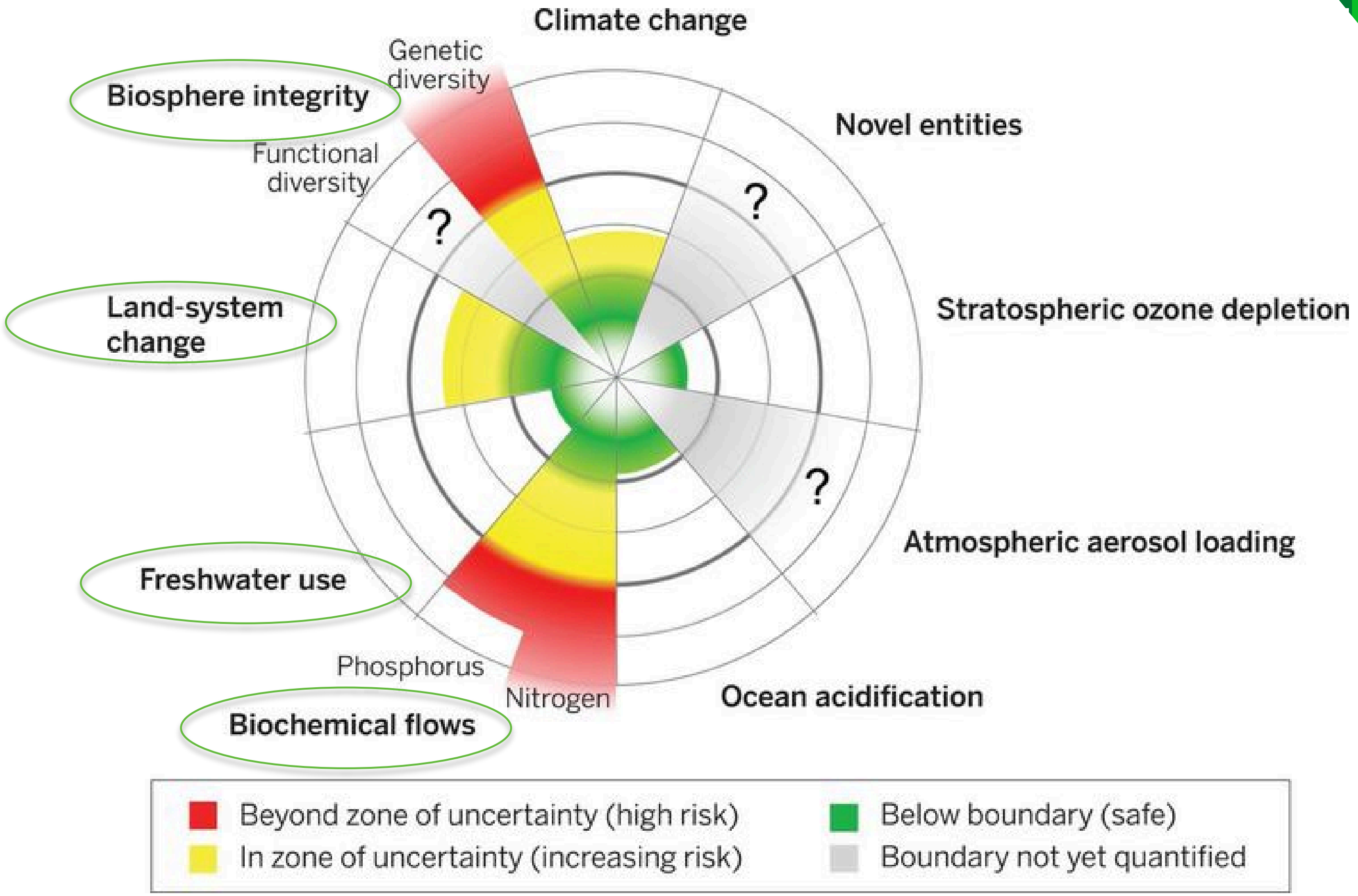
- Water (availability and quality),
- Minerals/materials (critical and otherwise),
- Land use/availability
- Soil health,
- Biodiversity (pharma, food, paper),
- Climate (in terms of uncertainty in availability),
- Oil/gas (particularly as feedstocks)



Bebbington et al. 2018. PNAS. 115 (52) 13164-13173

Implications of natural resources on decarbonization

- Impose limits on the availability of a technology
  - Scarcity
  - Security
  - Substitutability
- Can cause detrimental environmental impacts, e.g.,
  - Soil contamination
  - Water stress
  - Land use changes
- Use for industrial decarbonization limits its use for other activities (see right)

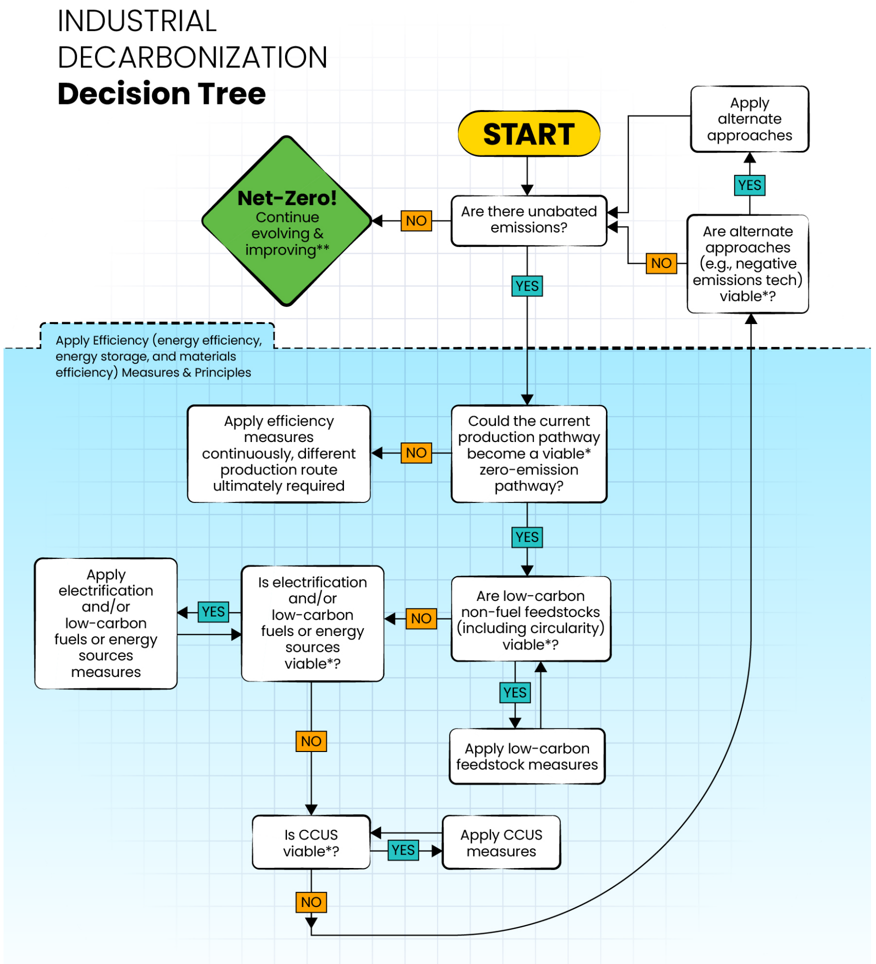


Planetary boundaries: Guiding human development on a changing planet, Volume: 347, Issue: 6223, DOI: (10.1126/science.1259855)

Science | AAAS

Impact for each decarbonization pillar

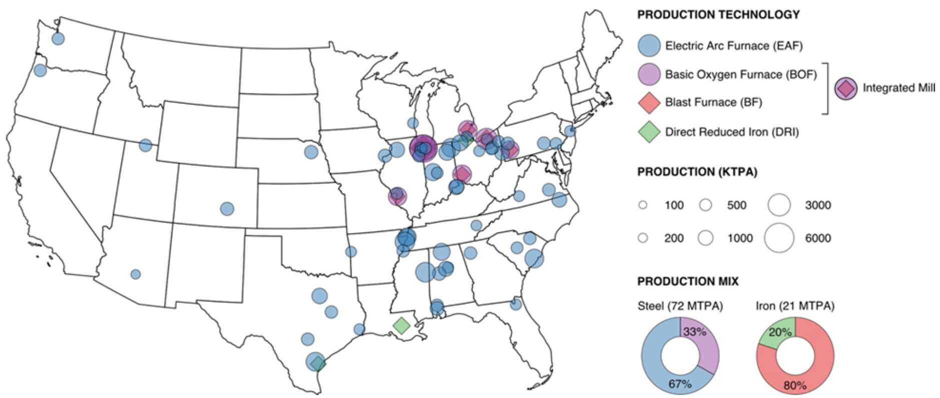
- Viability of any option is dependent on natural resources:
  - Land availability and water for bio-based energy sources and feedstocks
  - Water availability for H_2
  - Land availability for onsite clean electricity generation
  - Water and land availability for CCUS
  - Mineral availability for alternate pathways, e.g., high grade iron ore for H2 DRI steelmaking, SCMs



*Viable implies currently available, cost-effective, and that the measures are deemed effective through social and environmental criteria and necessary

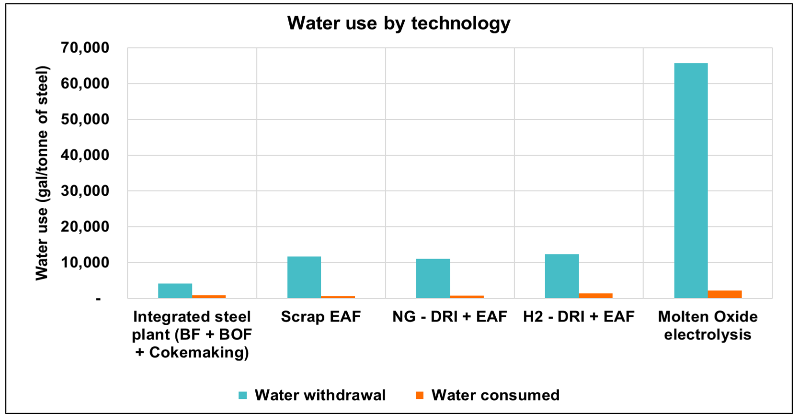
** Morrow, William III et al. 2017. "U.S. Industrial Sector Energy Productivity Improvement Pathways." U.S. Industrial Sector Energy Productivity Improvement Pathways (aceee.org)

Ex: Water impacts of steel decarbonization

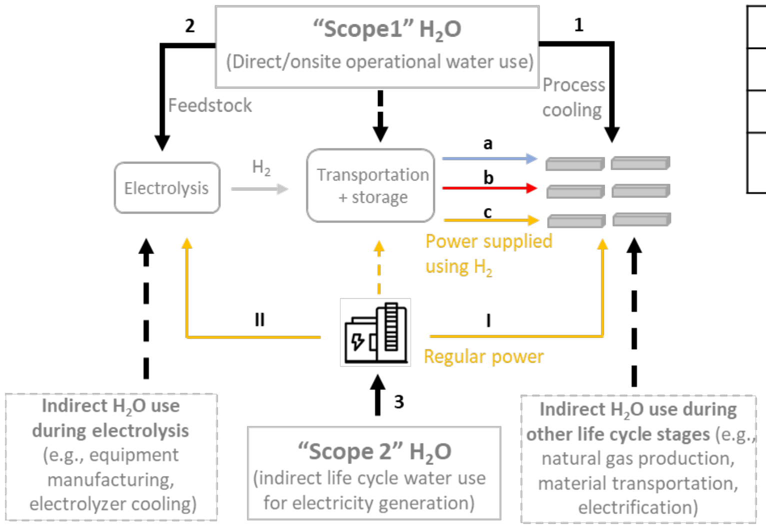


Iron and Steel production, 2021 - BAU

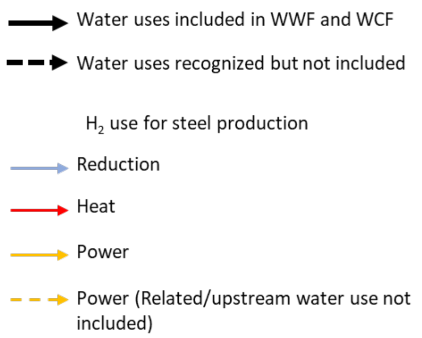
Source: EERE DECARB 2a Sprint Study

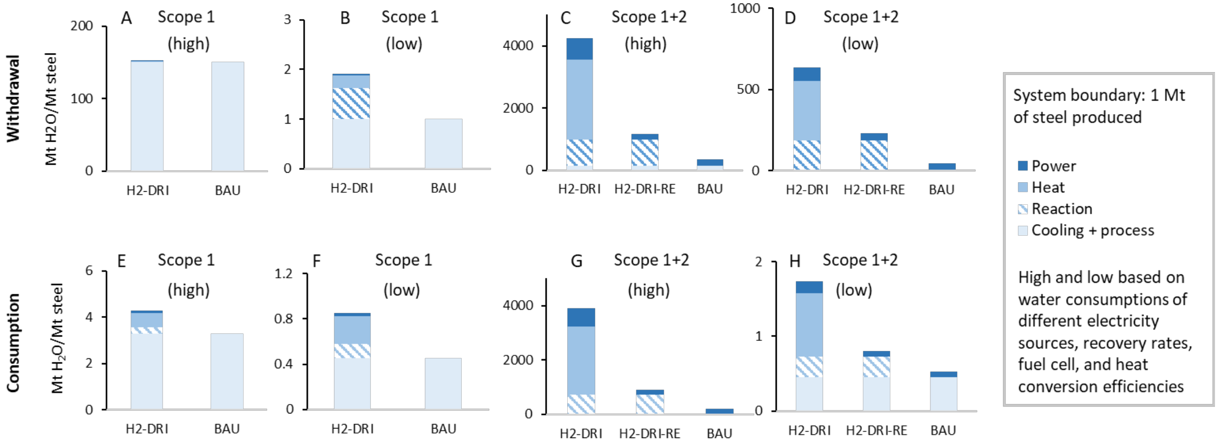


Preliminary Results: Water demand of electric technologies can exceed the water demand of existing integrated iron and steel production technologies to manufacture steel.



Scenario	Scope 1	Scope 2
BAU	1	3-I
H2-DRI-RE	1, 2-a	3-I , 3-II-a
H2-DRI	1, 2-a, 2-b, 2-c	3-I, 3-II-a, 3-II-b, 3-II-c





Under review. Do note cite or reproduce.

Some challenges

- Quantification:
  - Data to track resource availability (domestically and globally) and utilization (by industry but also across economy)
  - Metrics of merit to understand and track natural resource utilization by industrial decarbonization technologies
  - Lack of transparency further up a supply chain to where and how much natural resources are being used
- Lack of LCA-thinking
  - Impacts may be on natural resources not physically tied to manufacturer of technology
- Decision-making under deep uncertainty