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

Pathways for U.S. Industrial Transformations: Unlocking American Innovation

Executive Summary

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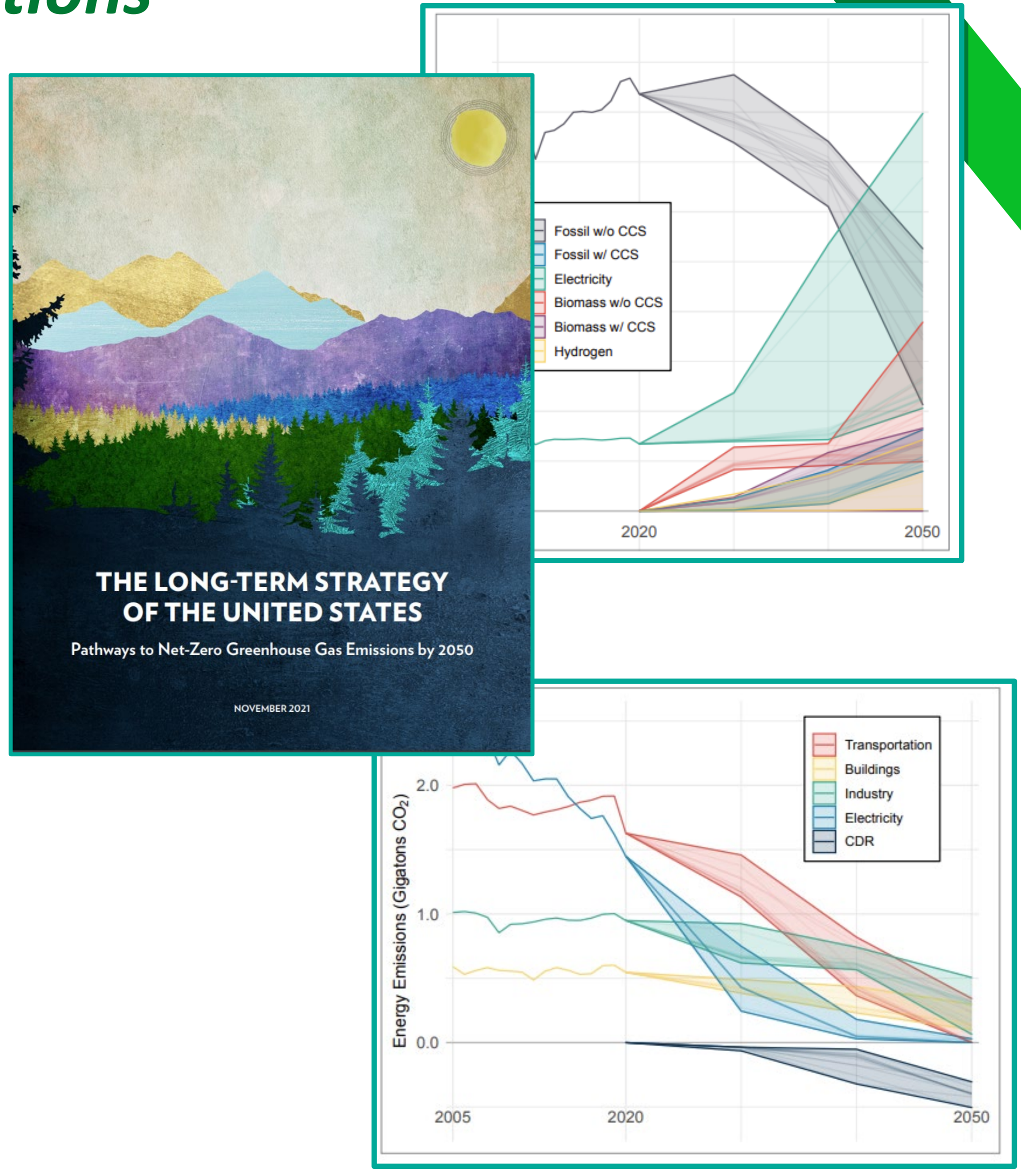
Context: *Pathways for U.S. Industrial Transformations*

Alignment With Departmental and USG Goals, e.g.

- Energy Earthshots
- Energy & Environmental Justice Priorities
- Long-term Strategy of the U.S.
- Nationally Determined Contributions (NDCs)*

DOE Approach

- Coordinate with industry, academia, NGOs, National Labs and all public and private stakeholders.
- Identify potential technological solutions, key decisions that determine implementation, and barriers to adopting no/low-emission solutions.
- Consider impacts and opportunities beyond the plant bounds.
- Map out pathways to overcome these barriers and achieve net-zero industrial emissions by mid-century.

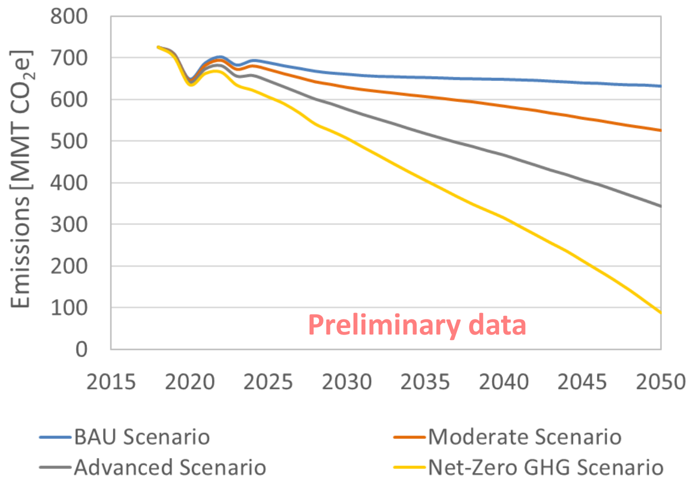


** "… so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century."*
Paris Climate Agreement

Approach for an Industrial Pathways Vision Study

Elucidate pathways to decarbonize U.S. industry by 2050

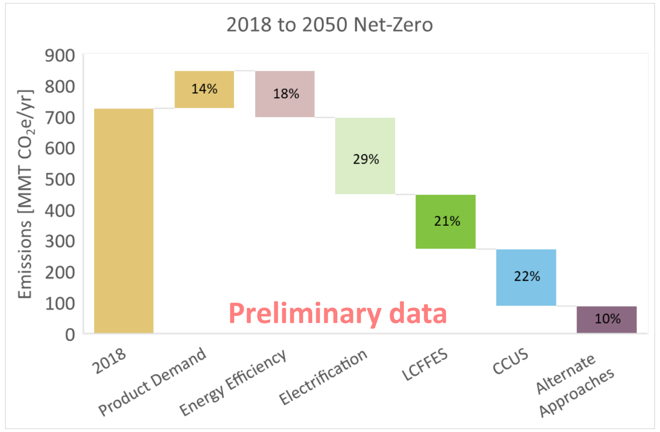
- Expand and extend Industrial Decarb Roadmap approach
- Thorough assessment of barriers
- Decision tree and solutions space frameworks
- Increase resolution of analysis to chart pathways options



CO_2e emissions (million MT/year) forecast for six U.S. manufacturing subsectors by scenario, 2018-2050.

Decarbonizing industry is a systems challenge

- From unit operations to facilities to beyond the plant boundaries
- Many pathways require coordination across and outside of industry
- Engage broader cross-section of stakeholders and issues

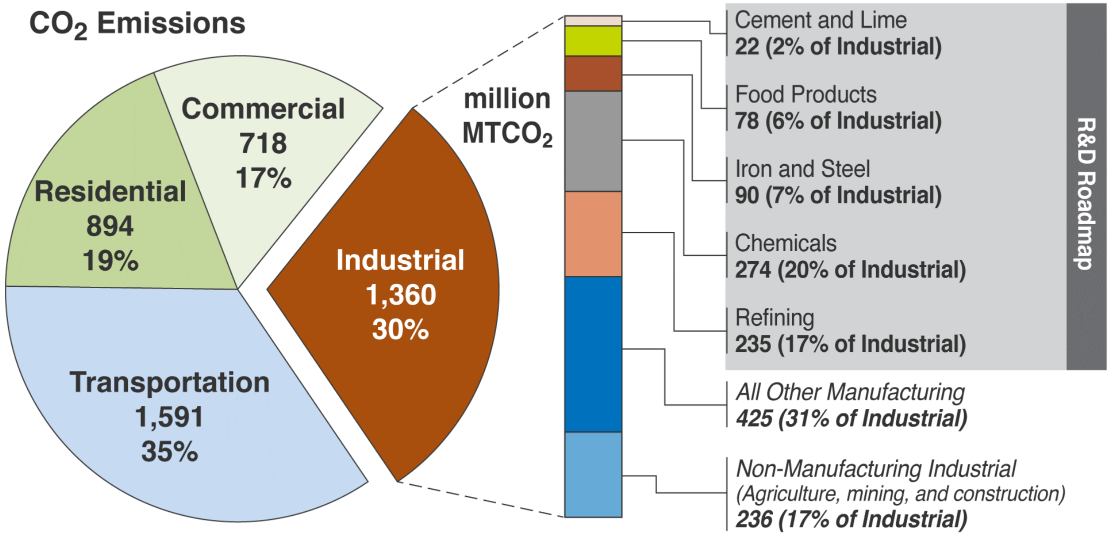


Impact of decarbonization pillars on CO_2e emissions (million MT/year) for six U.S. manufacturing subsectors, 2018-2050 under Net-Zero GHG scenario.

U.S. Industrial GHG Emissions

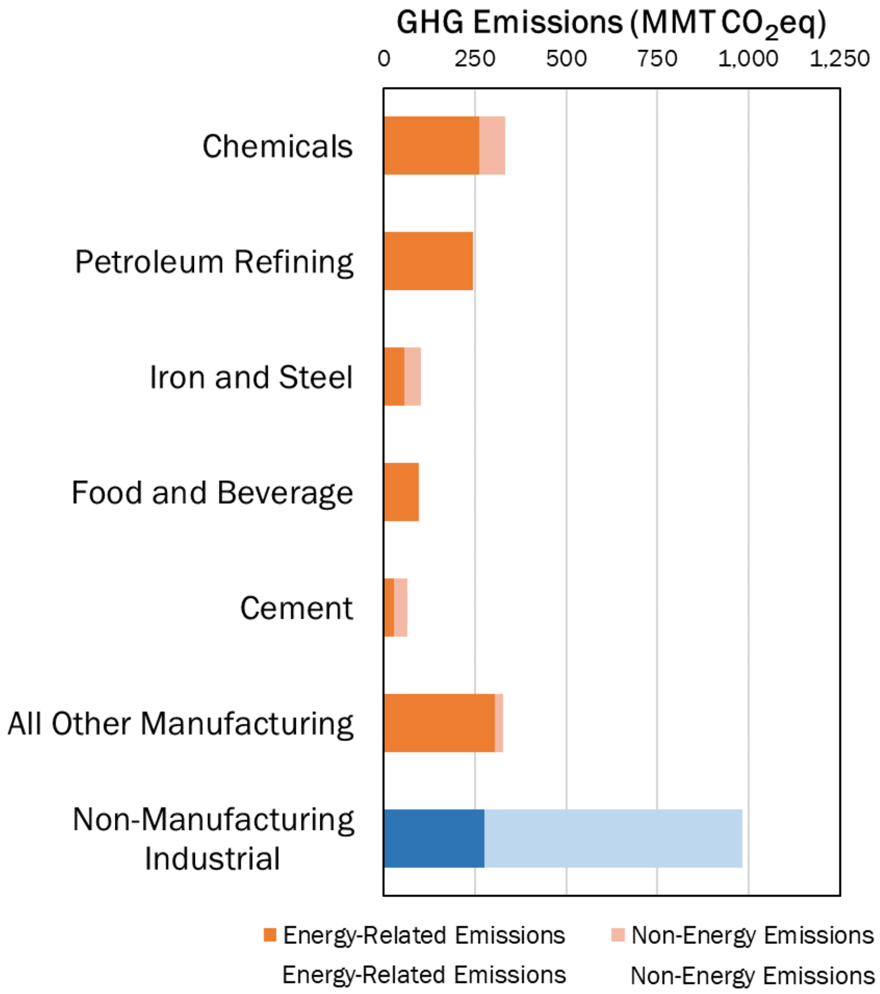
Industrial sector is comprised of
manufacturing | agriculture | mining | construction

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



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

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

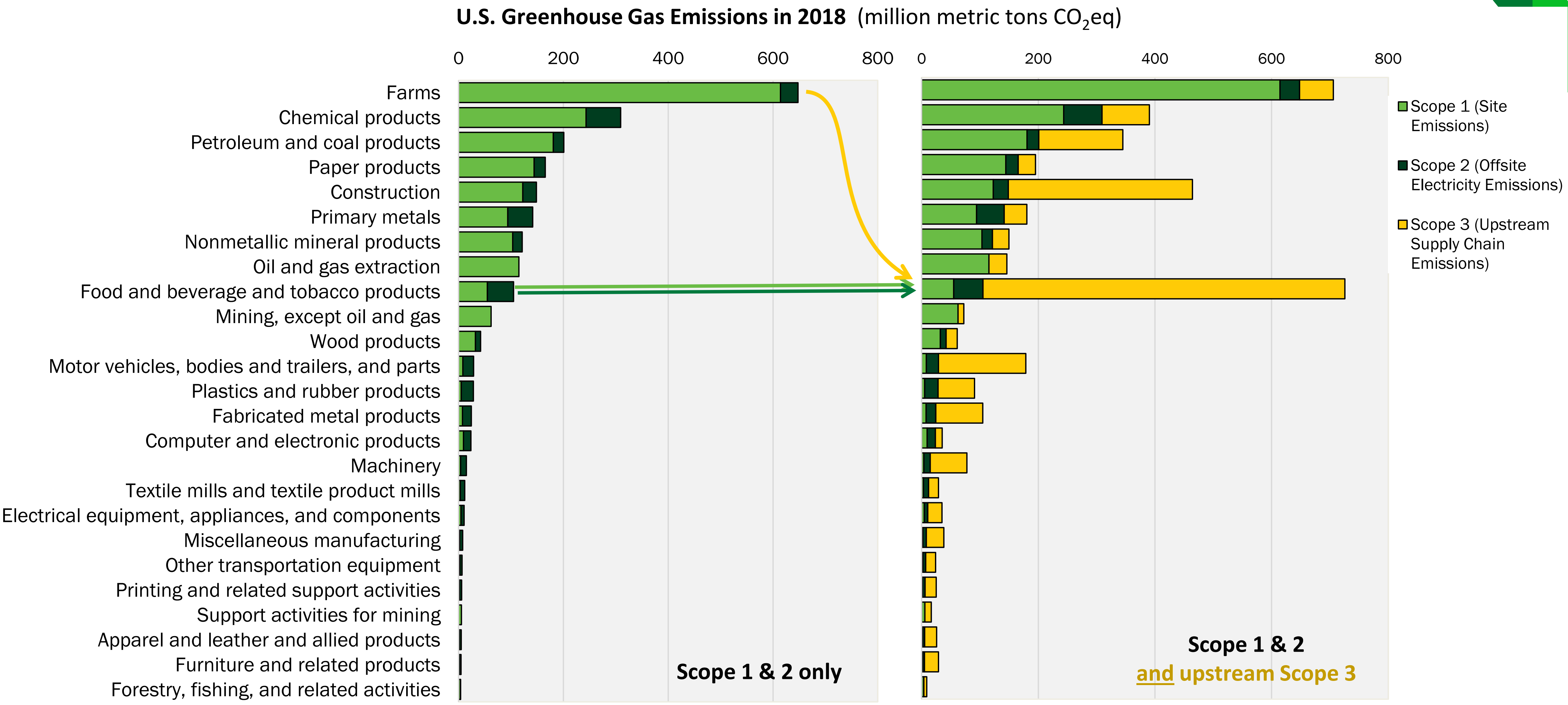


Energy-Related Emissions Non-Energy Emissions

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

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

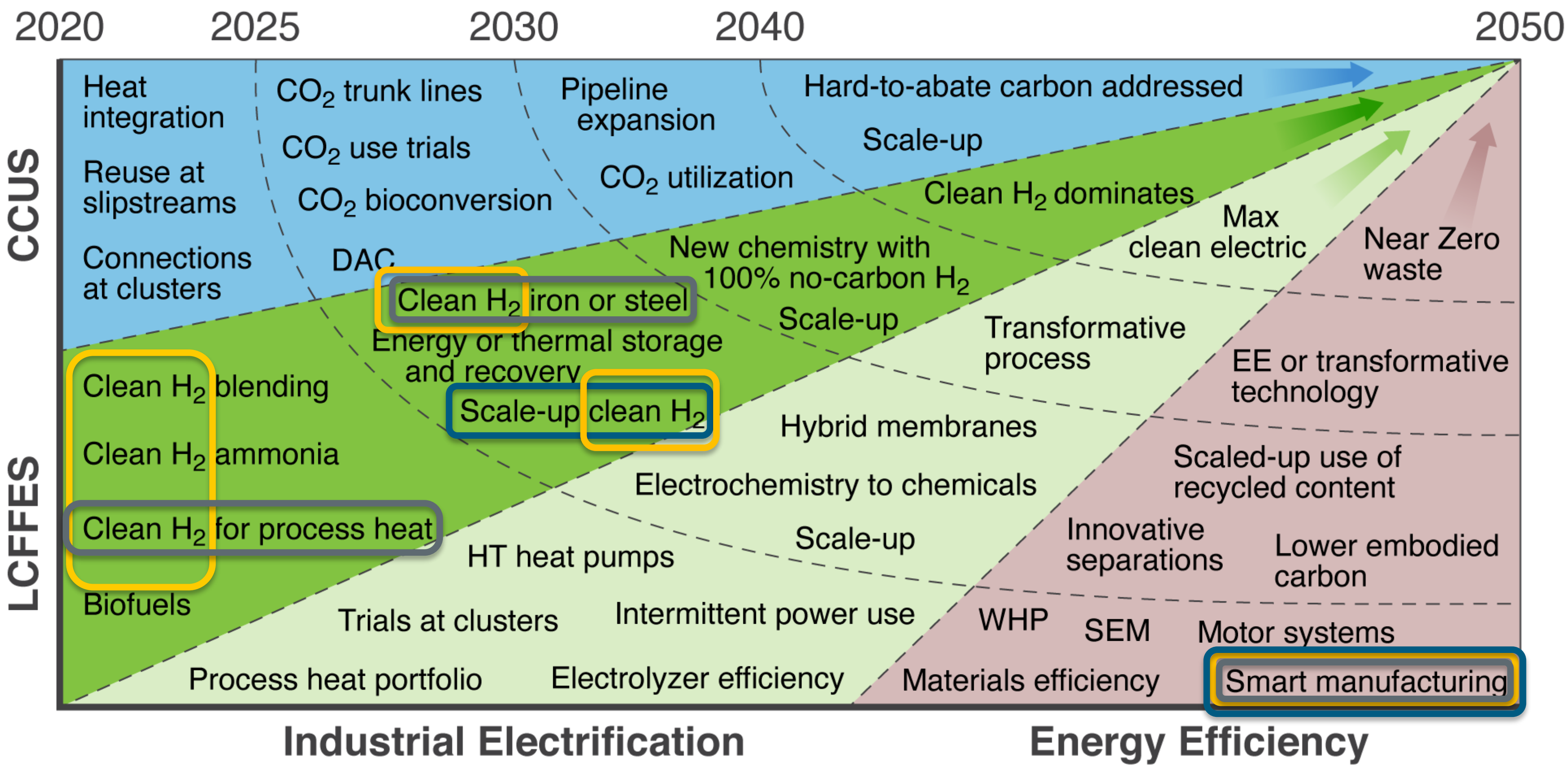
Significance of Supply Chain Emissions



Data Source: DOE EEIO-IDA tool

For more information, see IEDO Peer Review poster on the EEIO-IDA tool

Industrial Decarbonization: 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

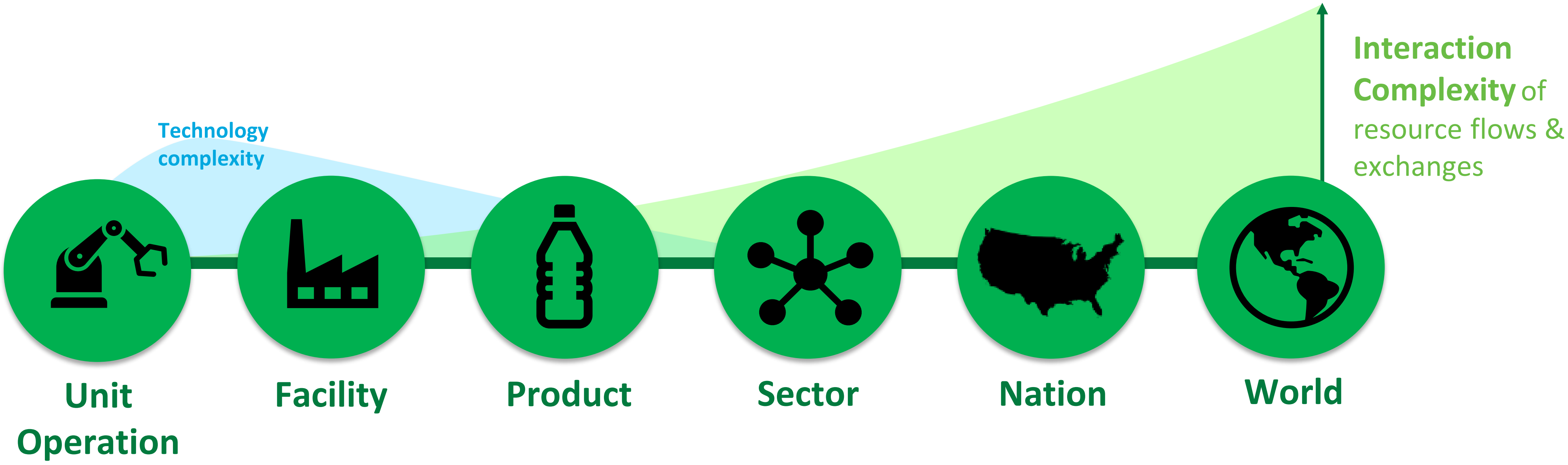
Industrial GHGs require approaches at multiple levels:

- 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

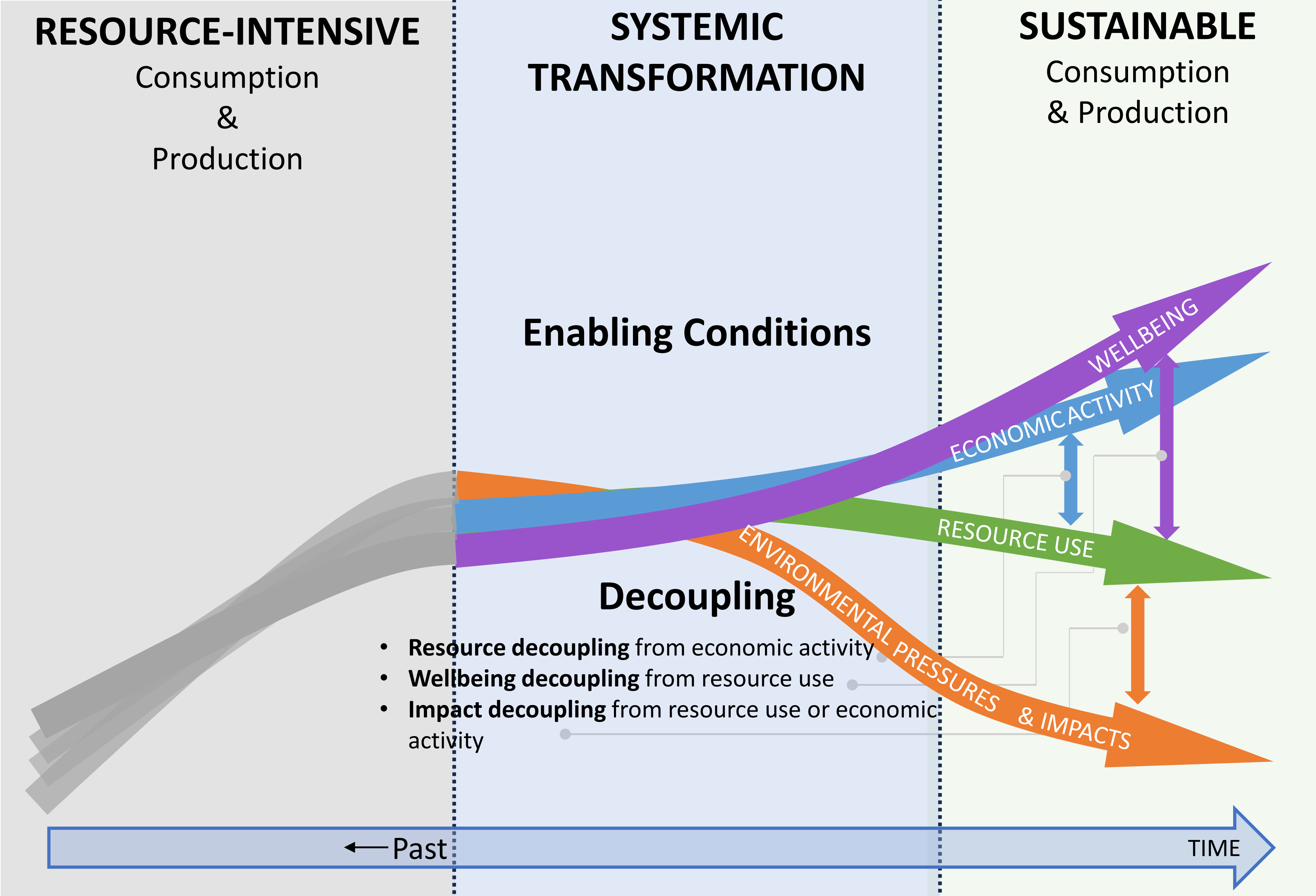
Understanding Impacts and Complex Interactions



- **What** are (collective) anticipated impacts?
- **Where** will (collective) impacts occur?
- **When** will impacts occur?

Resources	Emissions	Economics
Water	Greenhouse gases	Exchange of goods
Materials	Toxic releases	
Fuels / Energy	**… and more**	

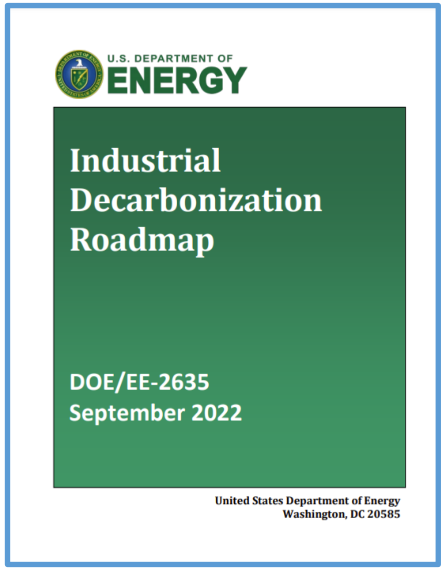
An equitable industrial transformation requires **resource decoupling**.



Adapted from Global Resources Outlook 2024 | UNEP - UN Environment Programme

A Strategy Built Upon Prior DOE Work

- Prioritized near- and mid-term objectives
- Provided limited resolutions for 60% of emissions where cost-effective solutions do not yet exist



- Brought opportunity space into focus
- Highlighted a range of opportunities without charting a course with multiple pathways

New Vision Study: *Pathways for U.S. Industrial Transformations* will…

- Expand solutions for 60% of emissions where cost-effective technologies don't yet exist
- Provide frameworks for pursuing multiple pathways in parallel
- Identify barriers to pursuing pathways
- Address potential impact on health, workforce, and environment.

Scope: Where the *Pathways* Vision Study builds upon the *Roadmap*

	Energy- and Emissions-Intensive Industries	Cross-Sectoral
Pillars	*Roadmap*	*Roadmap + Pathways*
Production Routes, Core Technologies	*Roadmap + Pathways*	*Pathways*

Industrial Decarbonization Analysis and Goal Development Efforts

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 Pathways Modeling

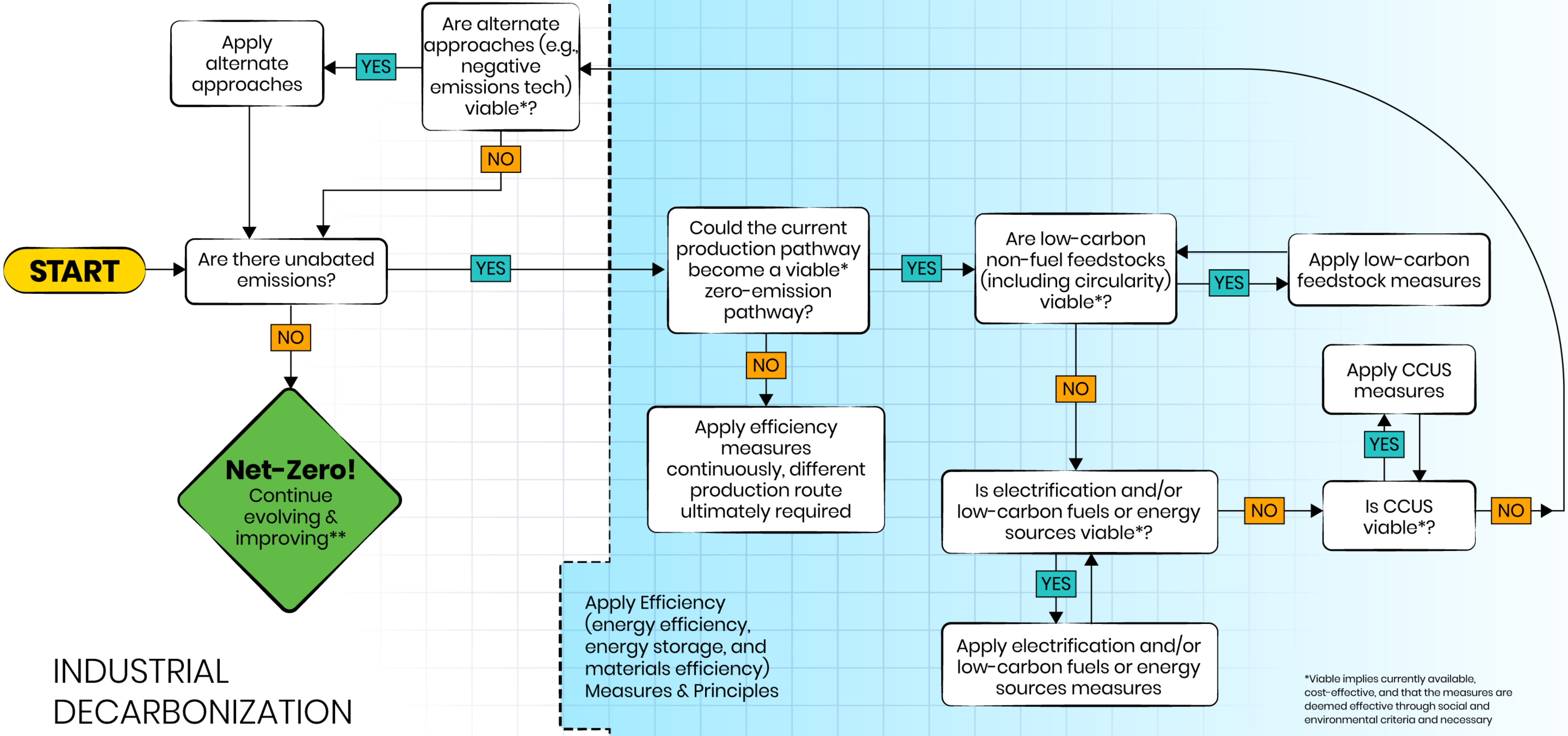
- **Expanded bottom-up analysis** to capture specific technologies or process units
- Identify and standardize inputs and assumptions for **transparency now,** and **future-proofing** going forward
- **Add resolution** - fuel sources, process emissions, and adoption rates by technology, electrification, 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)
- **Develop decision tree frameworks** to capture and communicate technology and production options represented in models

Decision Trees in Context with IEDO Industrial Decarbonization Modeling

Decision trees are frameworks that represent options available to industry as represented in the models. They are intended to be:

- **A starting point** for more targeted use cases depending on factors applicable to the "user" of the decision tree.
- **Adaptive**: While the outputs of our models use assumptions about, for example, anticipated changes and aggregated uptake of technologies over time for a given industrial subsector, decision trees can be adapted.
- **Iterative**: Decision trees evolve over time as technologies evolve, as barriers are overcome, etc.

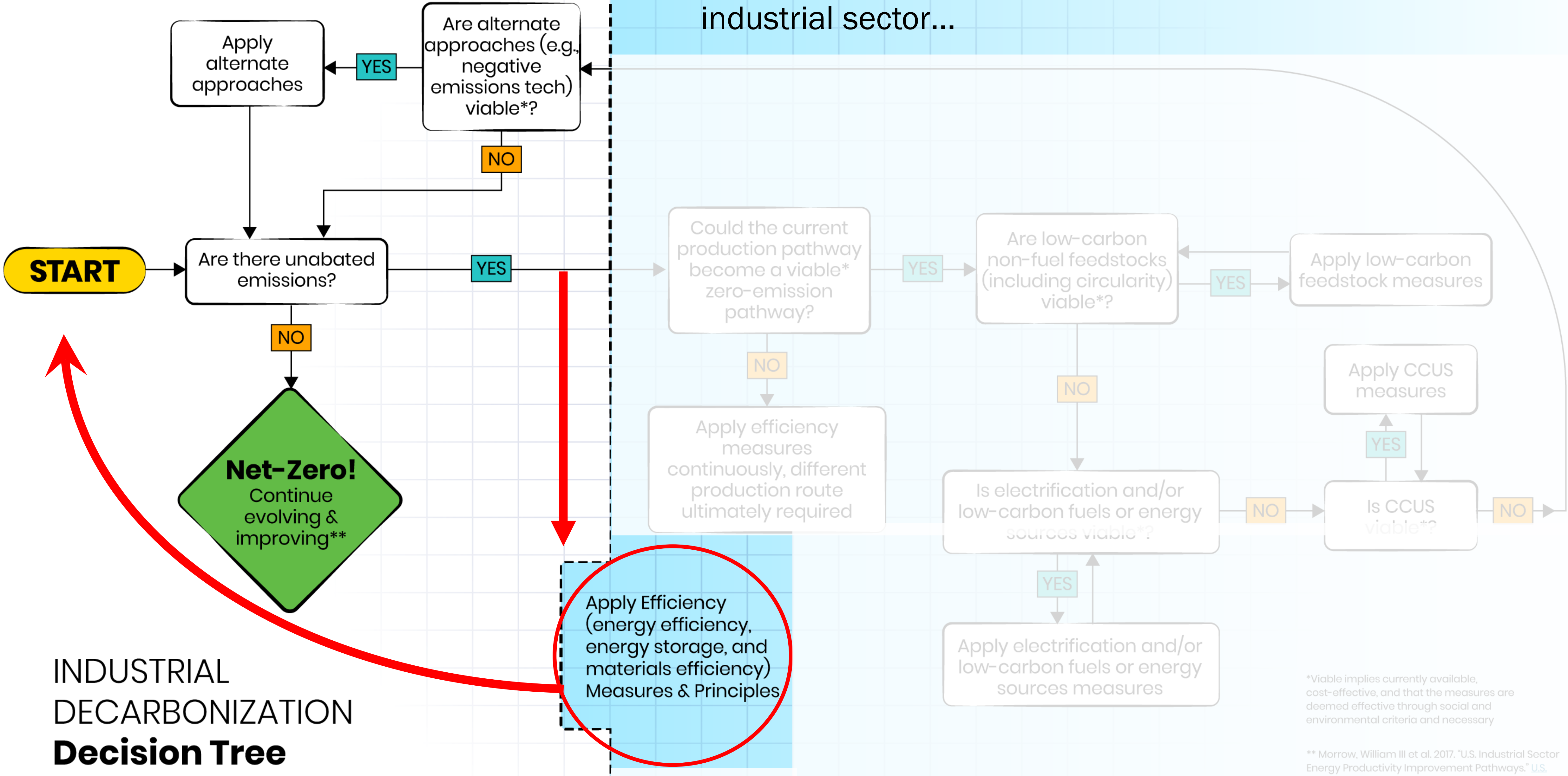
INDUSTRIAL DECARBONIZATION **Decision Tree**



*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)

Efficiency measures alone will **not** fully decarbonize industrial sector...



INDUSTRIAL DECARBONIZATION **Decision Tree**

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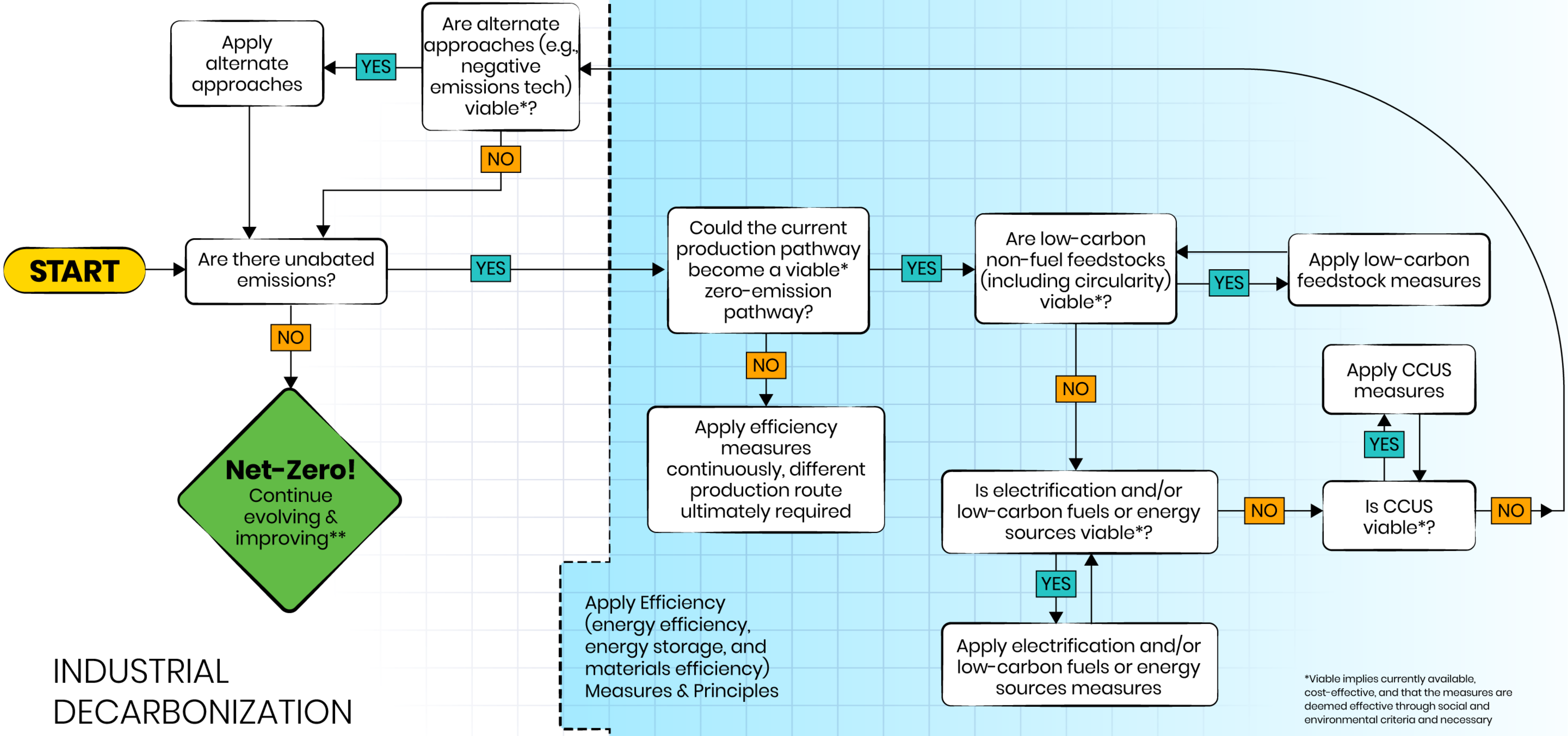

INDUSTRIAL DECARBONIZATION **Decision Tree**

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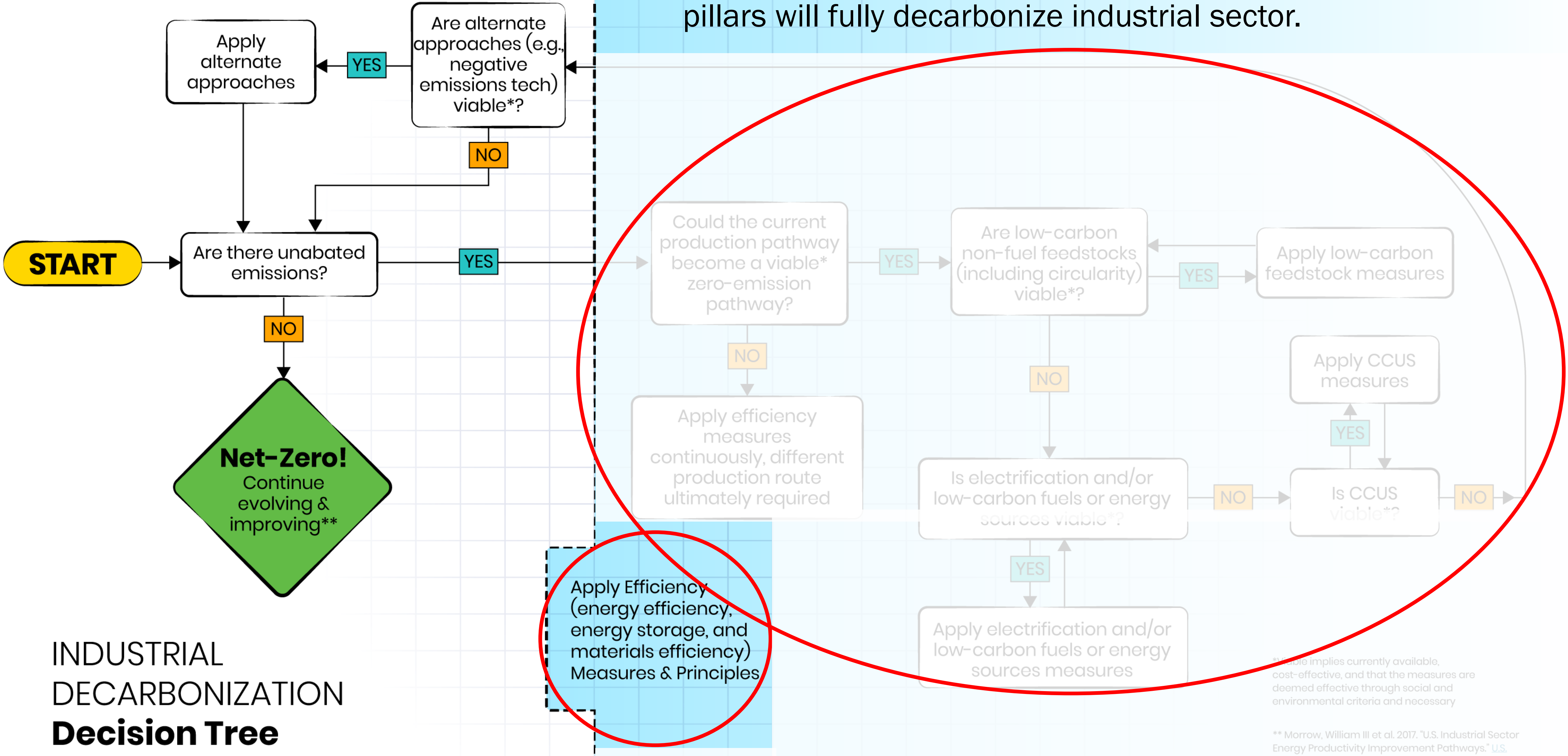
Efficiency measures **and** other industrial decarbonization pillars will fully decarbonize industrial sector.

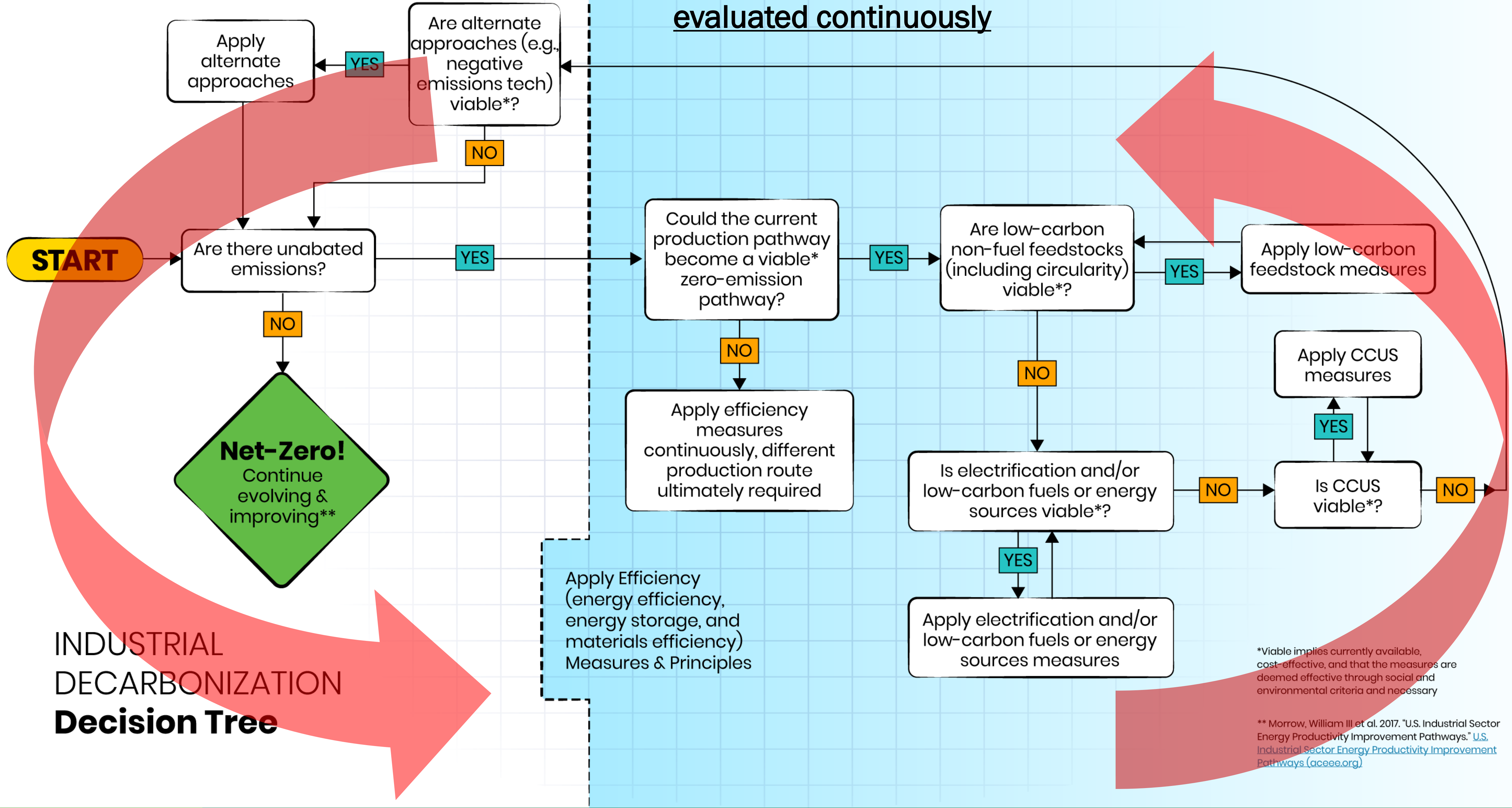


INDUSTRIAL DECARBONIZATION
Decision Tree

*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)

Pillars of industrial decarbonization must be **pursued and evaluated continuously**



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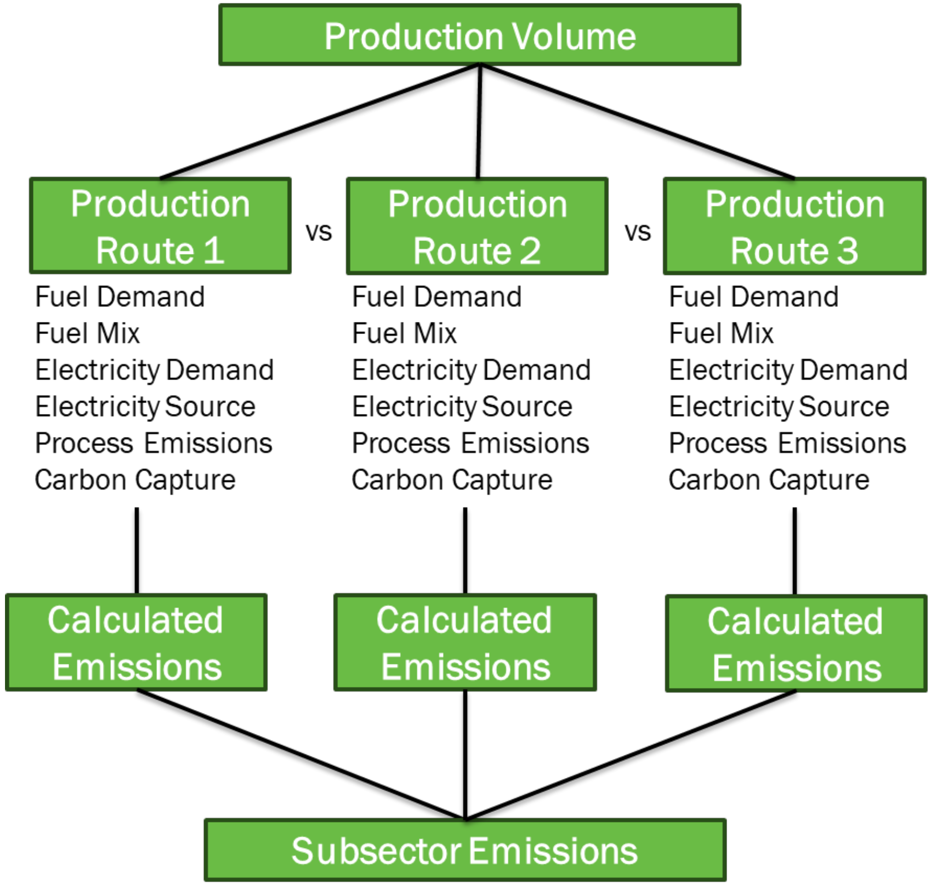
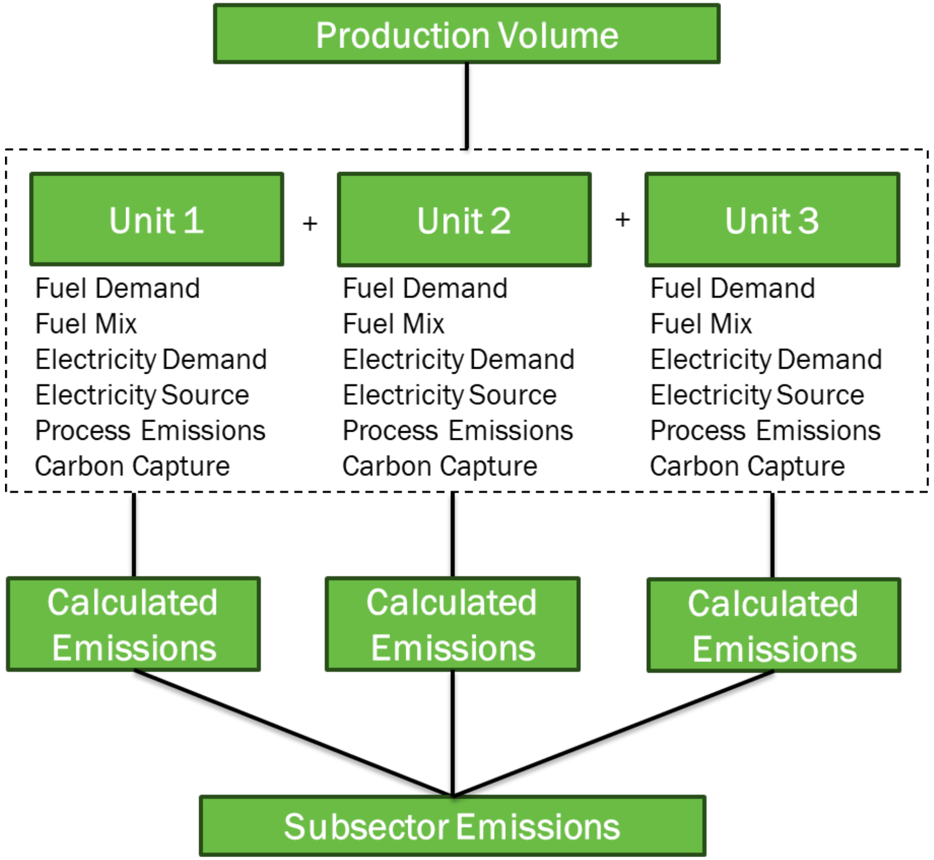
Net-Zero Pathway Modeling Structure

By alternate production route



Chemicals, cement, and iron & steel

By higher resolution of a production route



Petroleum refining, pulp & paper, and food & beverage

Net-Zero Pathway Models

Annual forecast of production volume

2018 Traditional Technologies

2050 Next-Generation Technologies

Excel-based models estimate energy- and process-related emissions for select industrial processes based on assumed feedstocks, manufacturing technologies, energy intensities, and energy sources tailored for each subsector

- Facilities and technologies are defined as a baseline, and promising technologies are characterized.
- Calculates the aggregate **subsector energy and emission impact** based on adoption rate, energy source, in context with other included technologies.
- As technology characteristics evolve over time, models can easily run new scenarios

Modeled Decarbonization Scenarios

Customized spreadsheet template for each sector

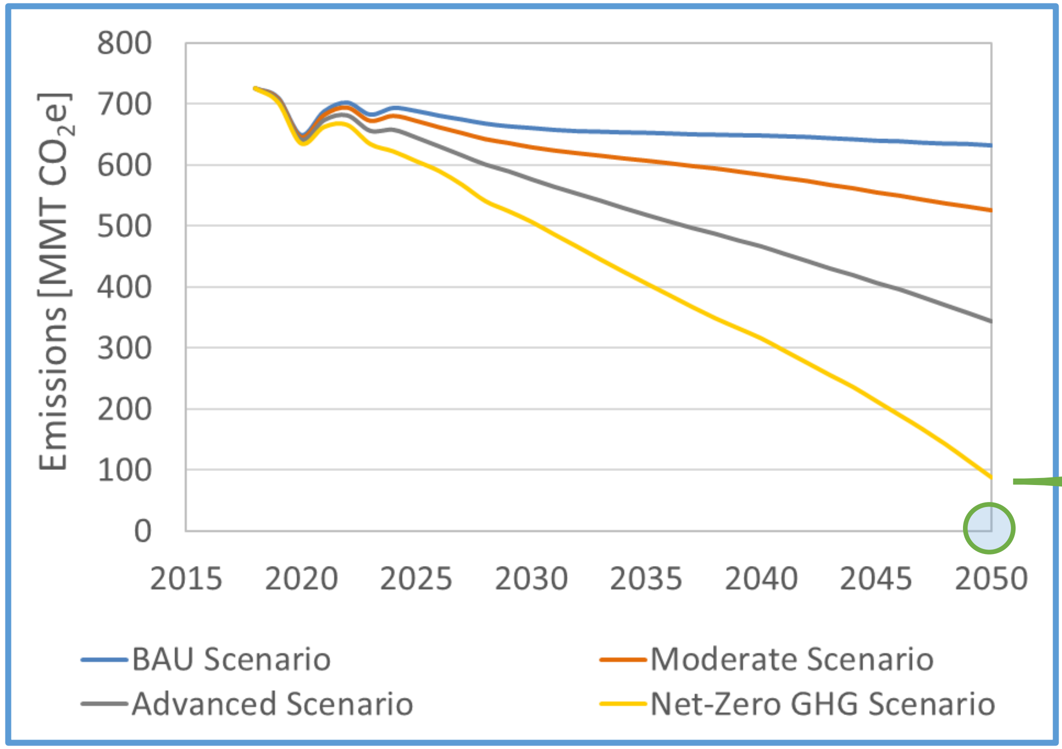
- Chemicals
- Petroleum Refining
- Iron & Steel
- Cement & Concrete
- Food & Beverage
- Pulp & Paper

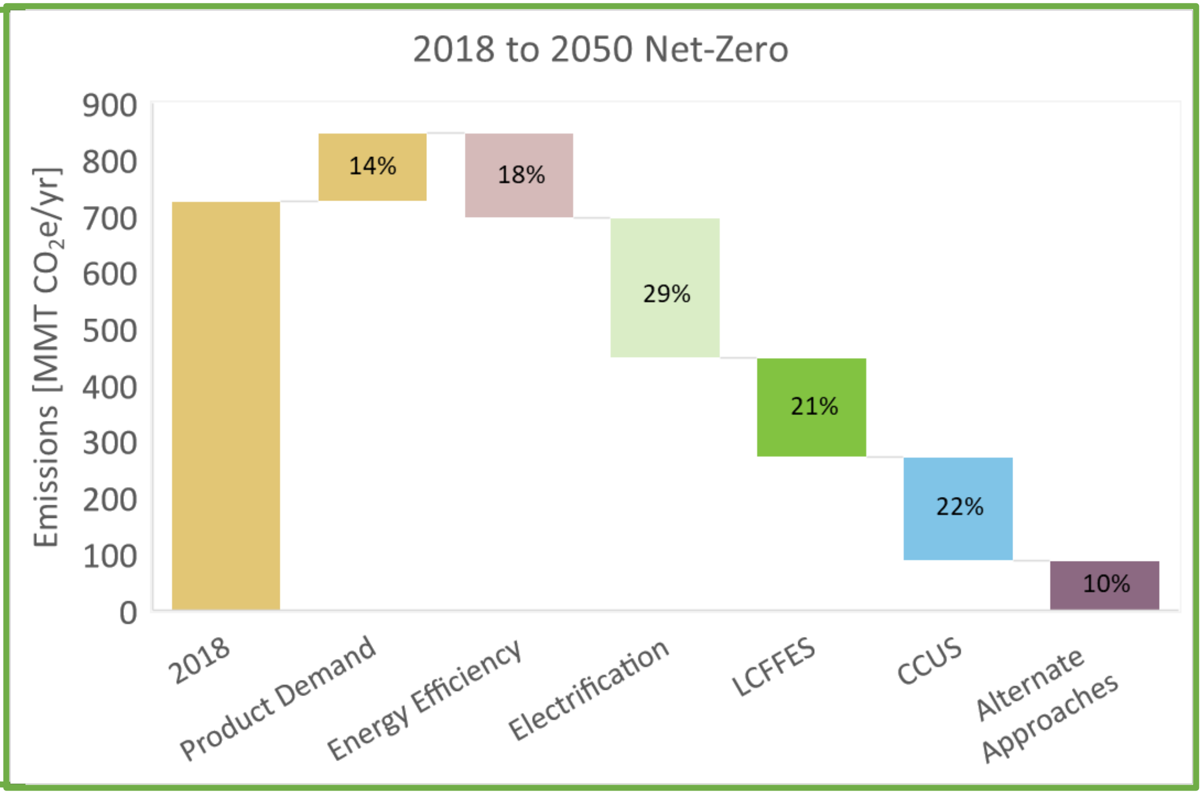
Scenarios

- Business as Usual (“BAU”)
- Moderate Technology and Policy (“Moderate”)
- Advanced Technology and Policy (“Advanced”)
- **Net-Zero GHG Emissions (“Net-Zero”)**

Most aggressive change

Net-Zero Scenario Detail



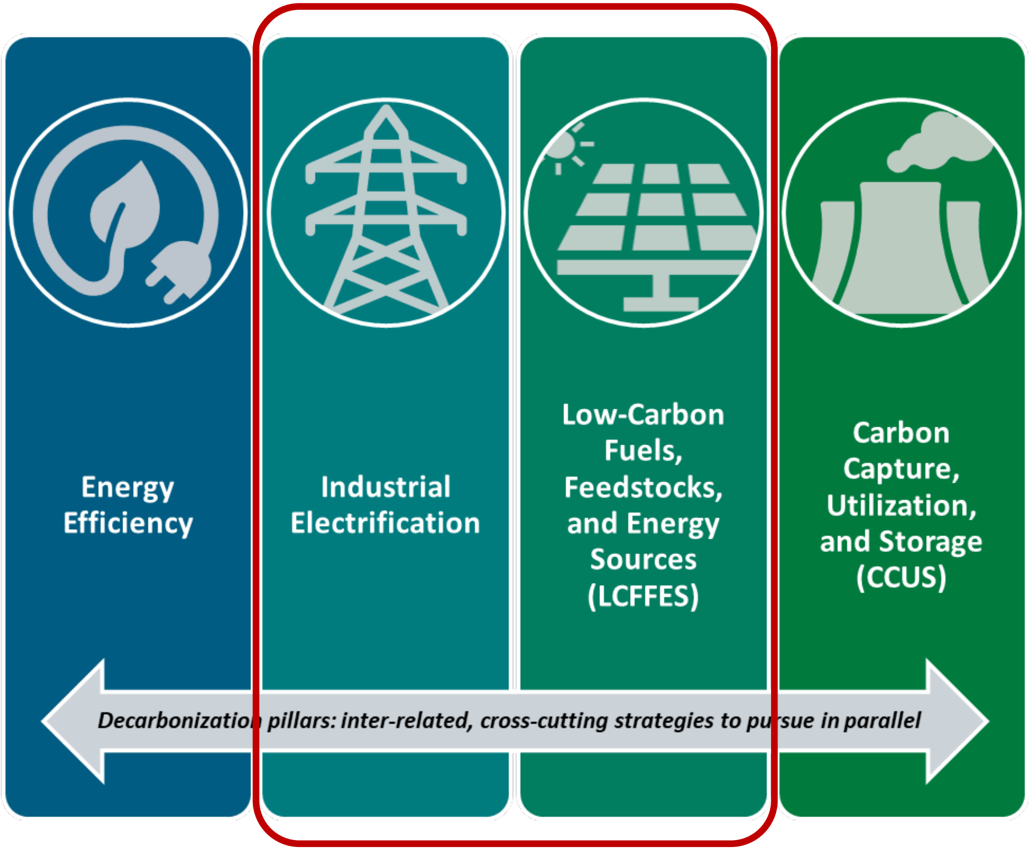


PRELIMINARY DATA. DO NOT CITE.

Example decarbonization scenarios with impact of decarbonization pillars on CO_2e emissions (million metric tons (MMT)/year) for six U.S. manufacturing subsectors*, 2018–2050

***Subsectors included in pathways analysis:** Iron & Steel, Petroleum Refining, Cement, select chemicals (ethylene, propylene, butadiene, BTX (benzene, toluene, xylenes), chlor-alkali, chlorine, sodium hydroxide (caustic soda), sodium carbonate (soda ash), ethanol, methanol, and ammonia), pulp & paper, and select food & beverage subsectors (grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages). *This figure may differ to the associated Roadmap figure due to additional modeling considerations included.*

Scenario representation – RM vs. Pathways Vision Study



Tiered approach

Tier 1 - Industrial Decarbonization Pillars

Tier 2 - Sub-category disaggregation / RD&D priority, e.g.:

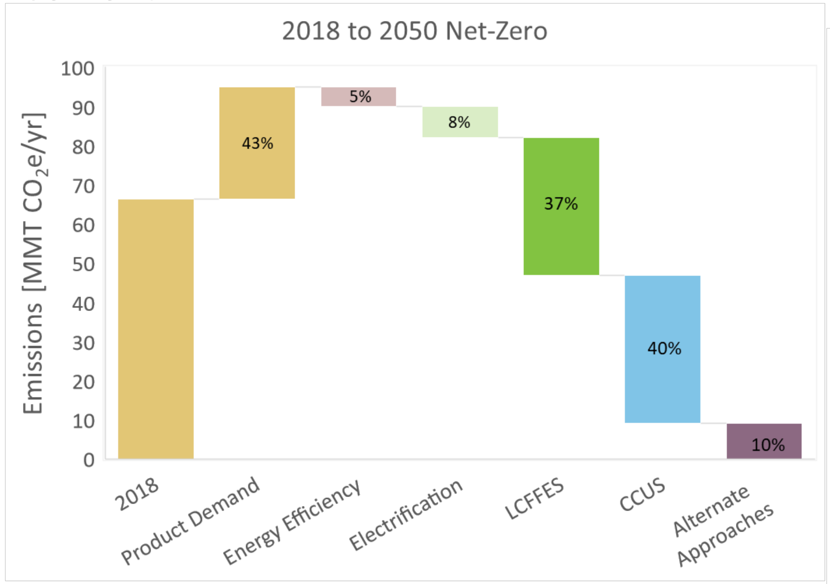
- Carbon utilization vs. storage
- Low-carbon feedstock vs. fuel

Tier 3 - Specific technologies

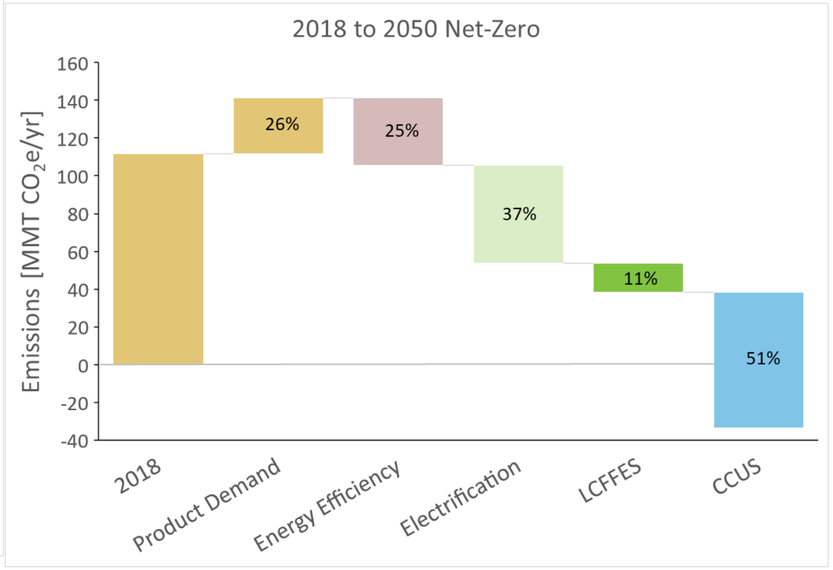
Represented in Roadmap → *Represented in Pathways Vision Study*

Net-Zero Pathway – Preliminary Modeling Results

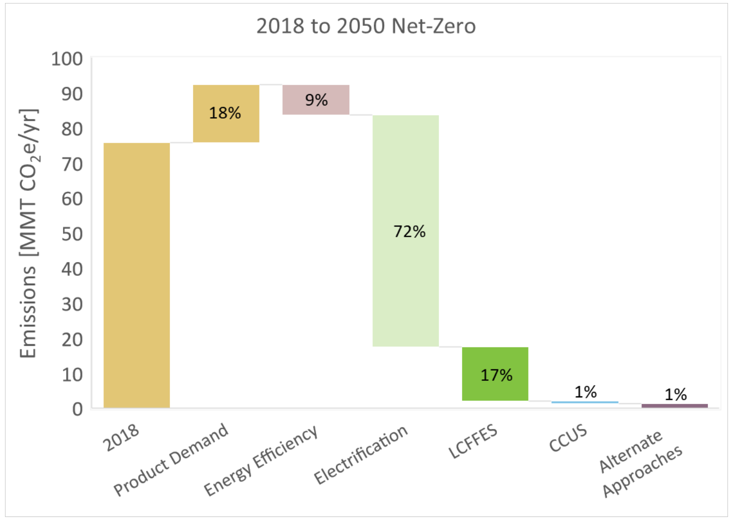
Cement



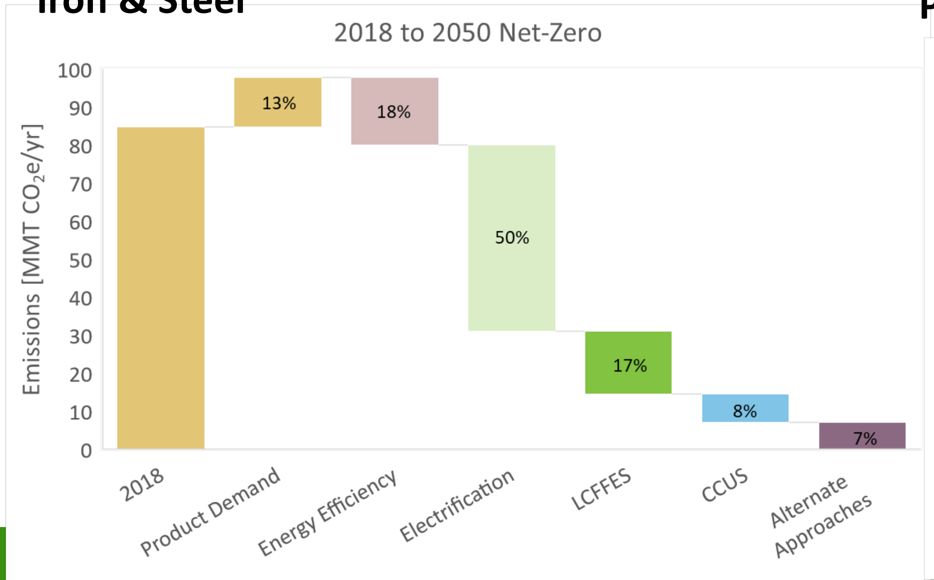
Chemicals



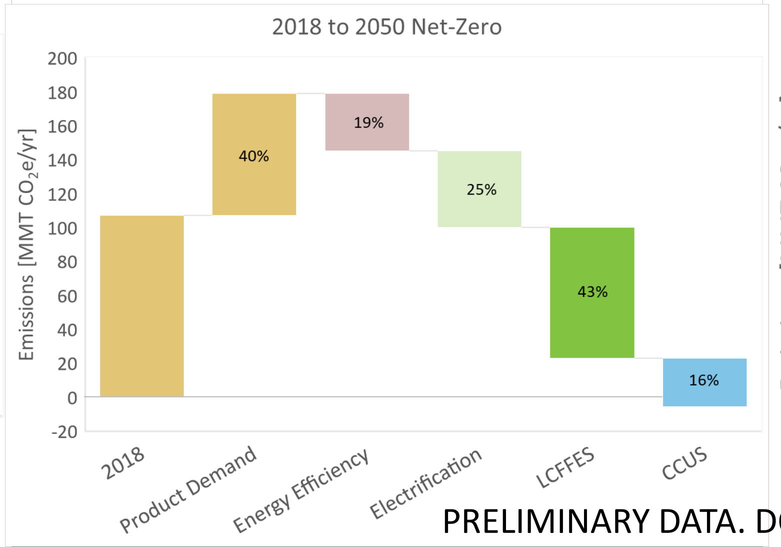
Food & Beverage



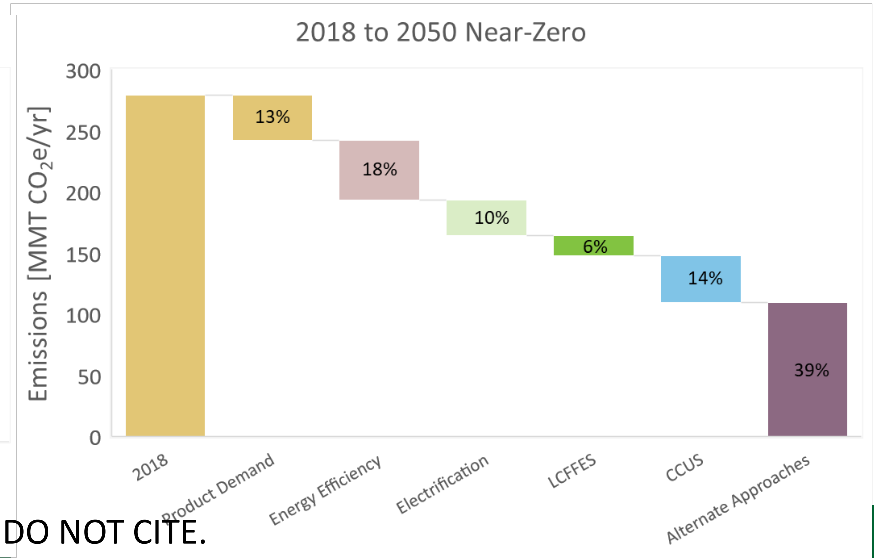
Iron & Steel



Pulp & Paper



Petroleum Refining

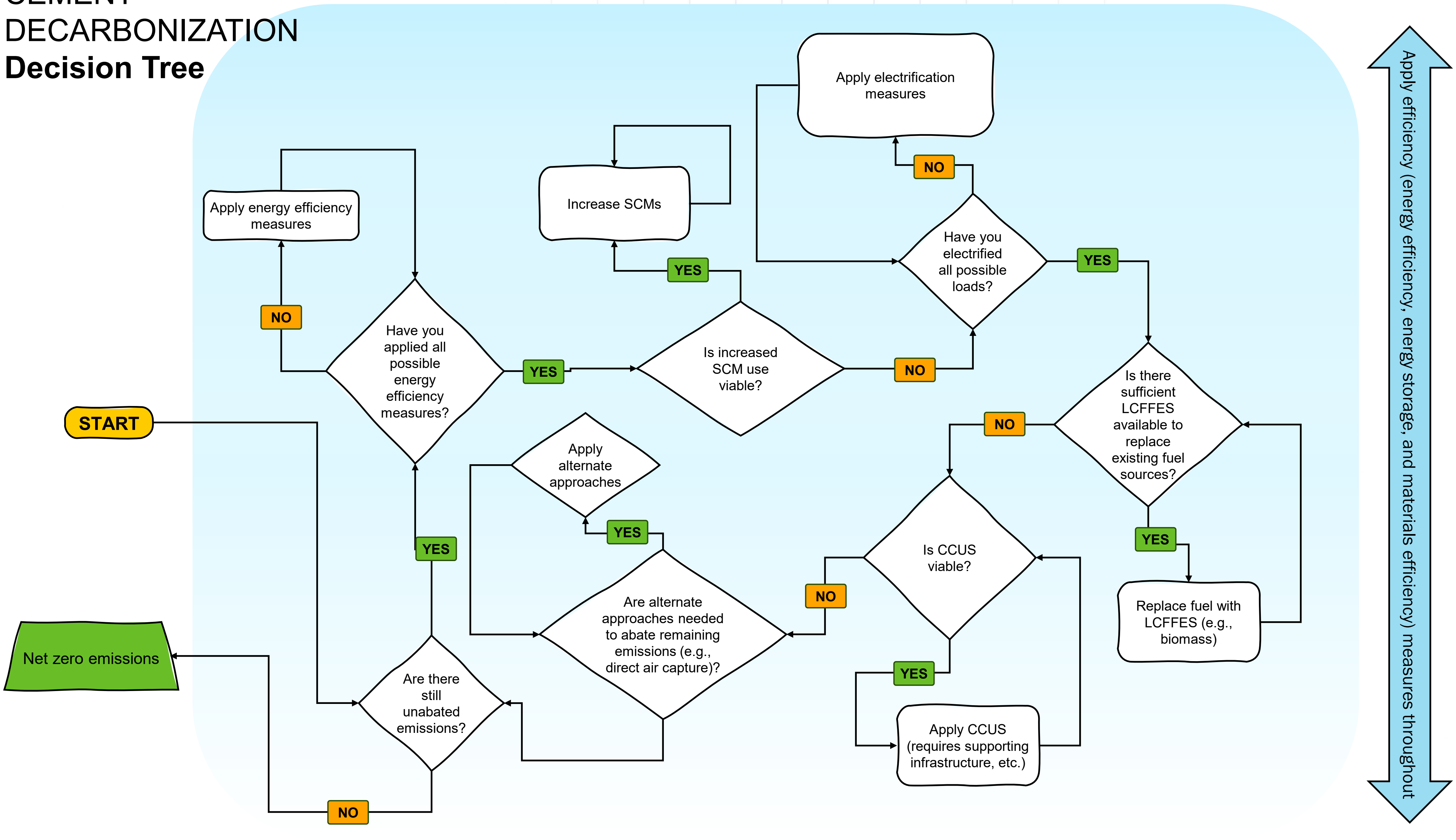


PRELIMINARY DATA. DO NOT CITE.

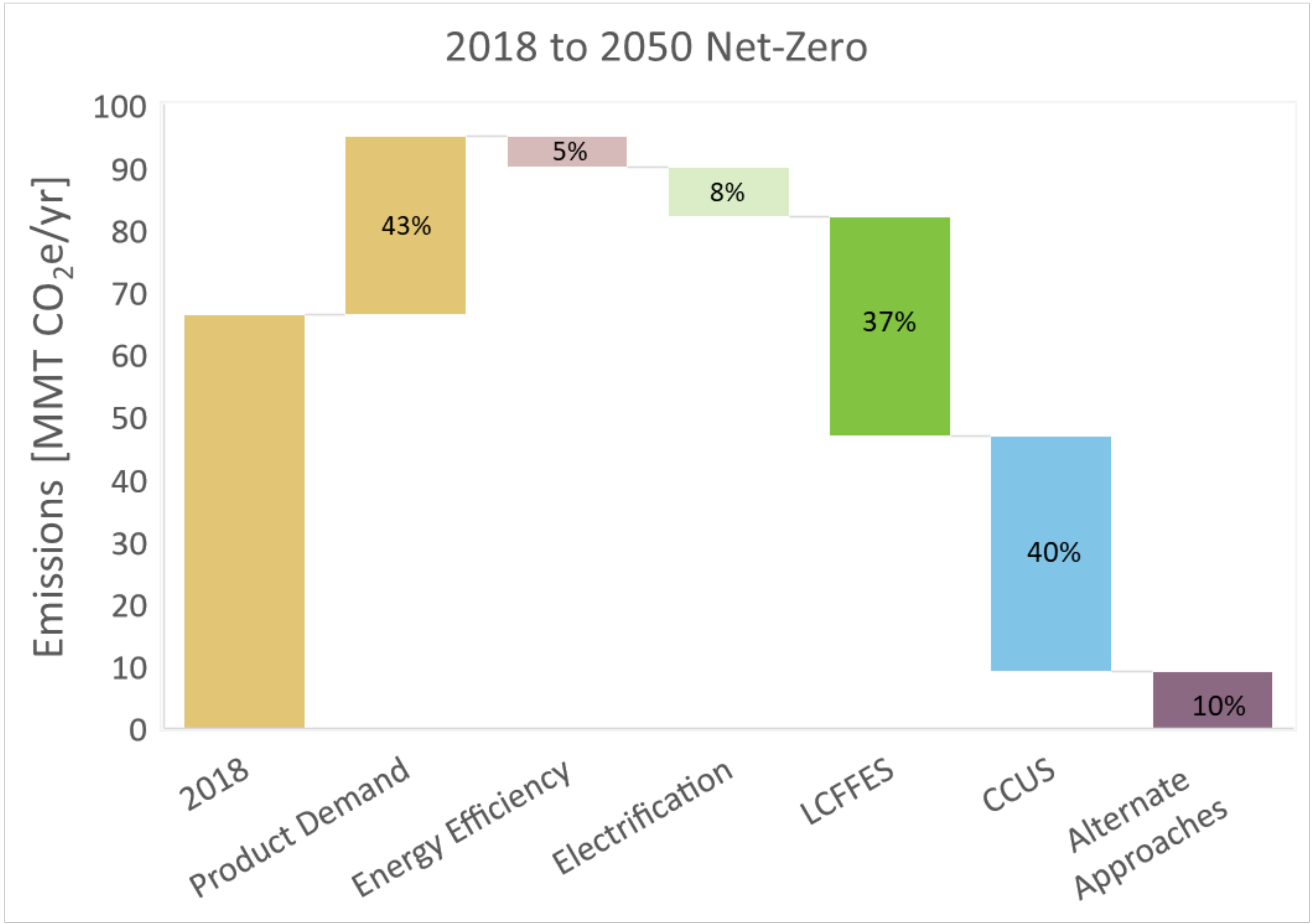
Summary of Major Decarbonization Approaches for 6 Subsectors Modeled

Manufacturing Subsector	Important Context	Major Decarbonization Strategies
Iron and Steel	2/3 U.S. steel already electrified (electric arc furnace)	• Address primary iron/steel emissions through low-carbon, iron ore reductants; electrolytic RD&D • Transition heating operations to low-carbon solutions • Improved heat management and waste recovery
Cement	CO_2 Emissions sources: 60% process; 40% energy	• CCUS to capture both emissions sources • Alternative heating/fuel switching; new processes/cement materials
Food and Beverage	Wide geographic diversity; grain/oilseed milling and meat largest emitters	• Electrify thermal energy needs when possible and implement efficiency measures • Transition remaining heating operations to low carbon solutions • Reduce food loss and waste throughout the supply chain
Chemicals	Largest GHG footprint; diverse – 70K chemicals	• Electrification or low-carbon fuel process heat • Low carbon feedstocks (bio, H2, etc.); CO2 utilization • Advanced catalysts, process intensification, biological processes
Pulp and Paper	Substantial existing use of biomass-based fuels (e.g., pulping liquor, waste wood)	• Increased biomass consumption and bioenergy with carbon capture and storage • Increased electrification (with more aggressive deployment of electric boilers) and reduced biomass use
Petroleum Refining	Evolution of end-use fuel demand and impact on refinery product slate	• Electrification, low carbon fuels and clean hydrogen production • Advanced catalysts, process intensification, biological processes • CCUS

CEMENT DECARBONIZATION **Decision Tree**



Net-Zero Pathway: Cement



Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions

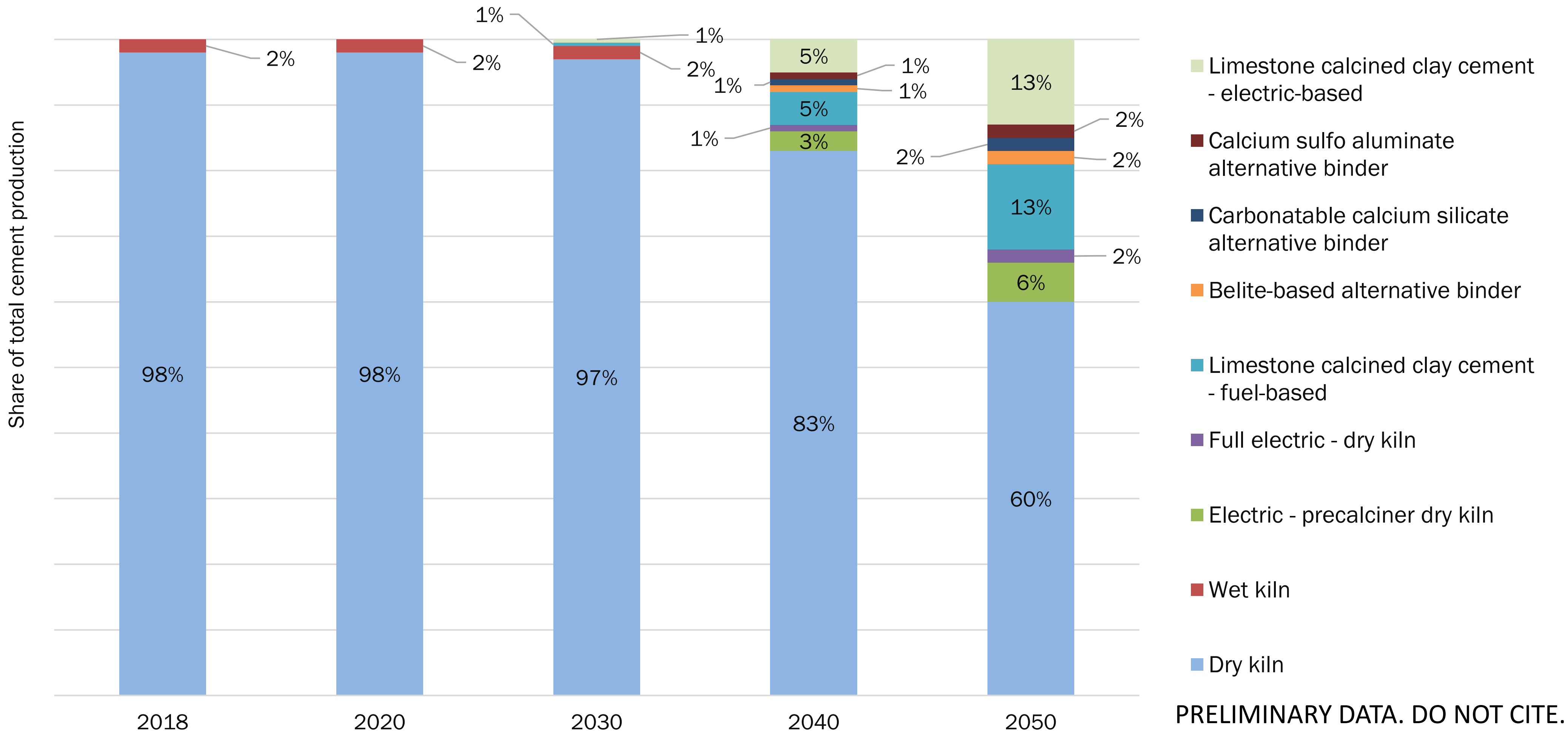
(million metric tons (MMT)/year) for U.S. cement manufacturing, 2018–2050

This representation is based on preliminary modeling and does not rely on actual facility data. This figure may differ to the associated Roadmap figure due to additional modeling considerations included here. Source: This work.

PRELIMINARY DATA. DO NOT CITE.

Net-Zero Pathway Production Routes: Cement

Example U.S. cement manufacturing production route share by decade under a net-zero emissions scenario, 2018–2050



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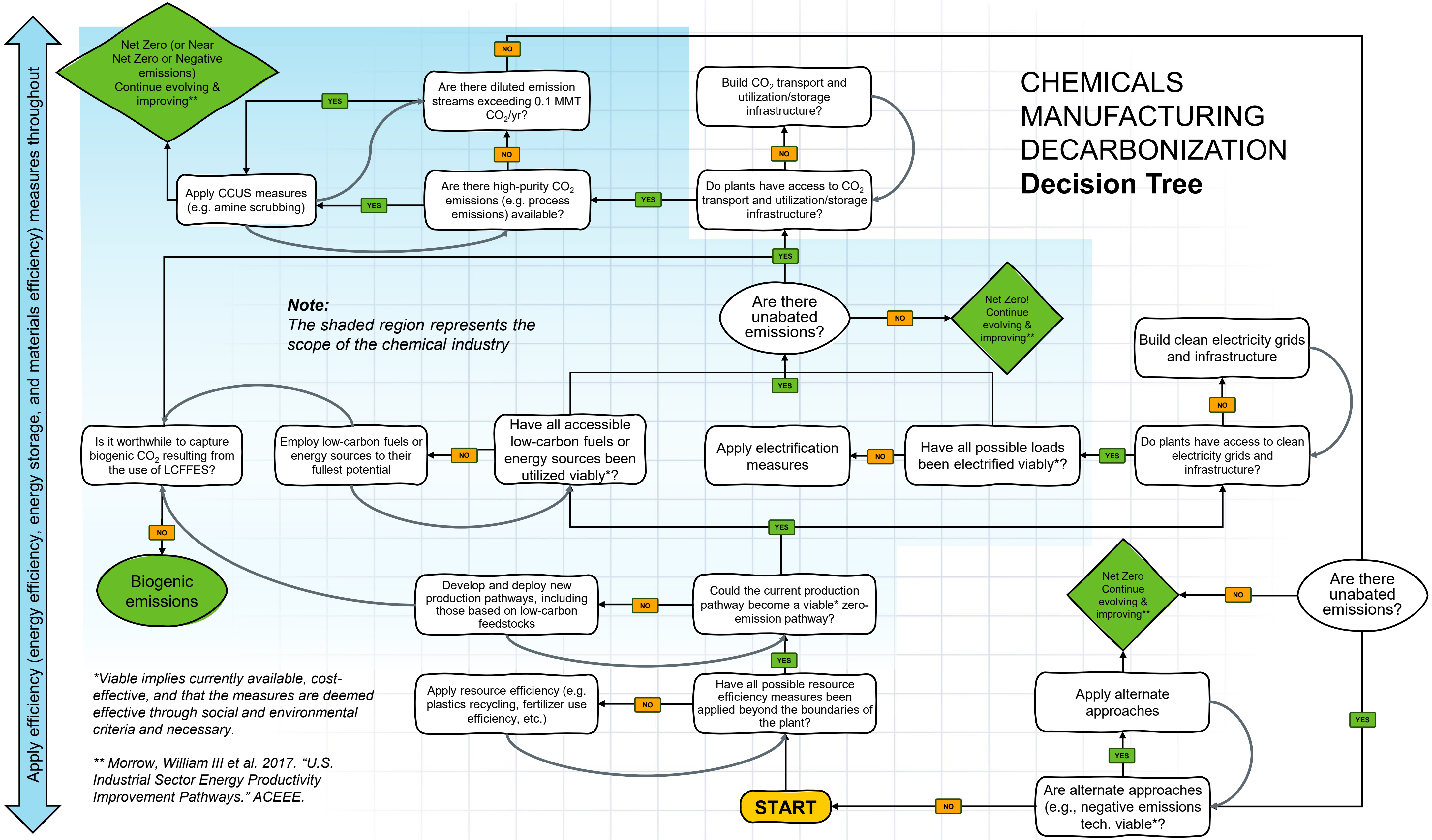
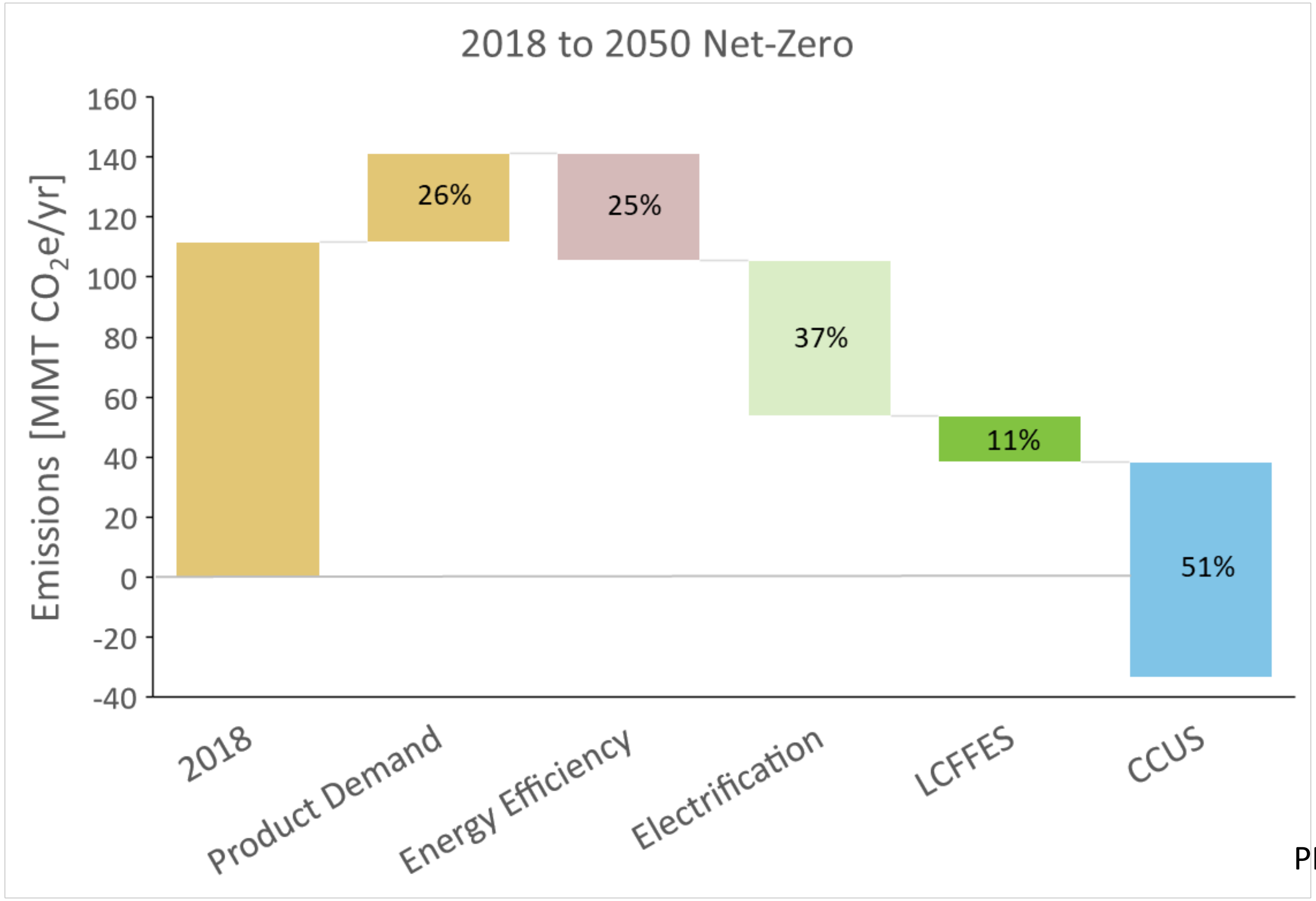


CHEMICALS MANUFACTURING DECARBONIZATION
Decision Tree
Apply efficiency (energy efficiency, energy storage, and materials efficiency) measures throughout
Net Zero (or Near Net Zero or Negative emissions) Continue evolving & improving**
Are there diluted emission streams exceeding 0.1 MMT CO_2/yr?
Build CO_2 transport and utilization/storage infrastructure?
Apply CCUS measures (e.g. amine scrubbing)
Are there high-purity CO_2 emissions (e.g. process emissions) available?
Do plants have access to CO_2 transport and utilization/storage infrastructure?
Are there unabated emissions?
Net Zero! Continue evolving & improving**
Note:
The shaded region represents the scope of the chemical industry
Build clean electricity grids and infrastructure
Is it worthwhile to capture biogenic CO_2 resulting from the use of LCFFES?
Employ low-carbon fuels or energy sources to their fullest potential
Have all accessible low-carbon fuels or energy sources been utilized viably*?
Apply electrification measures
Have all possible loads been electrified viably*?
Do plants have access to clean electricity grids and infrastructure?
Biogenic emissions
Develop and deploy new production pathways, including those based on low-carbon feedstocks
Could the current production pathway become a viable* zero-emission pathway?
Net Zero Continue evolving & improving**
Are there unabated emissions?
Apply resource efficiency (e.g. plastics recycling, fertilizer use efficiency, etc.)
Have all possible resource efficiency measures been applied beyond the boundaries of the plant?
Apply alternate approaches
START
Are alternate approaches (e.g., negative emissions tech. viable*?
YES
NO
*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.” ACEEE.

Net-Zero Pathway: Chemicals



Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions

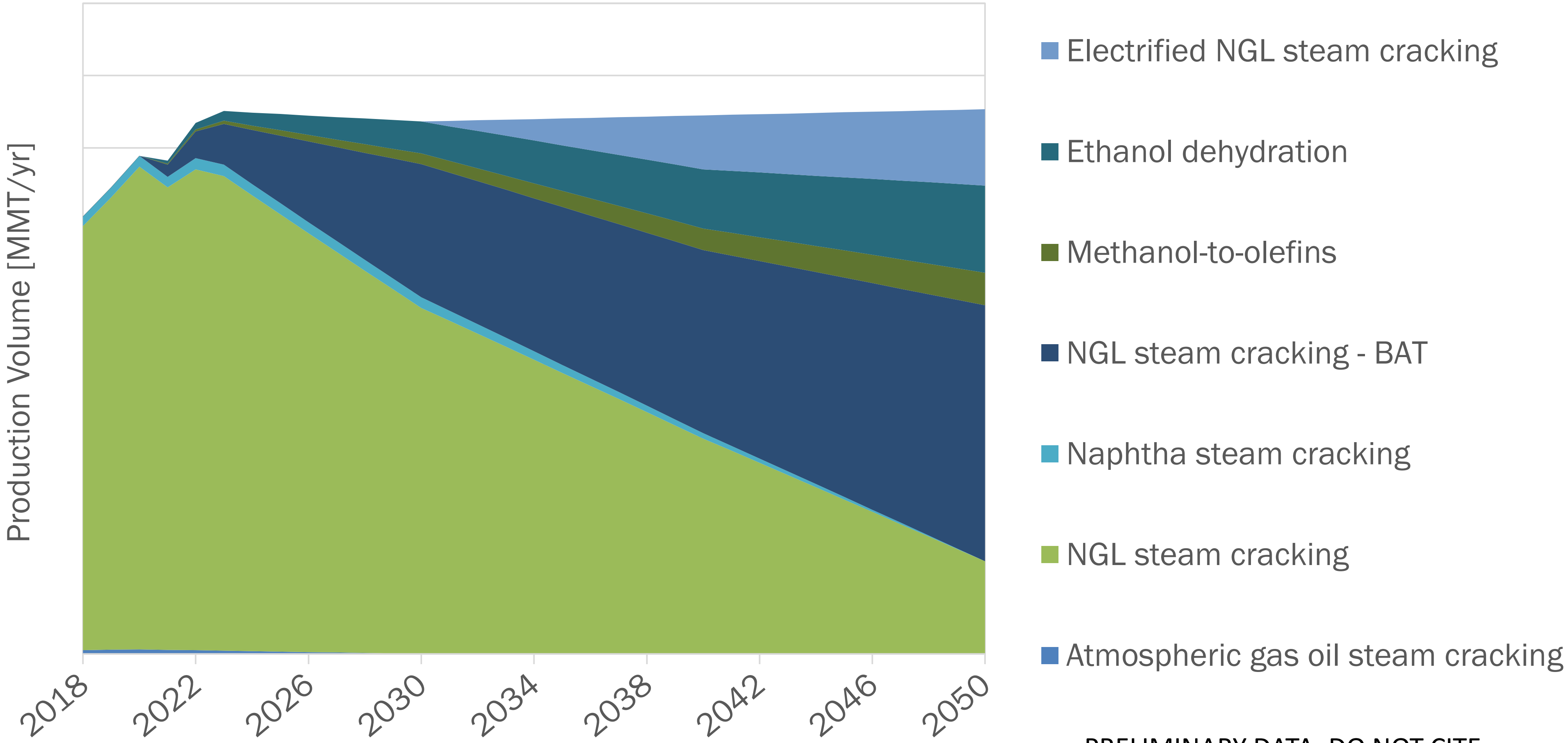
(million metric tons (MMT)/year) for modeled U.S. chemicals*, 2018–2050

PRELIMINARY DATA. DO NOT CITE.

*This representation is based on preliminary modeling and does not rely on actual facility data. *The chemicals modeled and included in this figure are lower olefins (ethylene, propylene, butadiene), benzene-toluene-xylenes (BTX) aromatics, chlorine and sodium hydroxide (chlor-alkali), sodium carbonate (soda ash), ethanol, methanol, and ammonia. These subsectors account for 40% of the chemical manufacturing subsector's total emissions in 2018. . The chemicals modeled and included in this figure are lower olefins (ethylene, propylene, butadiene), benzene-toluene-xylenes (BTX) aromatics, chlorine and sodium hydroxide (chlor-alkali), sodium carbonate (soda ash), ethanol, methanol, and ammonia. These subsectors account for 40% of the chemical manufacturing subsector's total emissions in 2018. This figure may differ to the associated Roadmap figure due to additional modeling considerations included here. Source: This work.*

Net-Zero Pathway Production Routes: Chemicals (Ethylene)

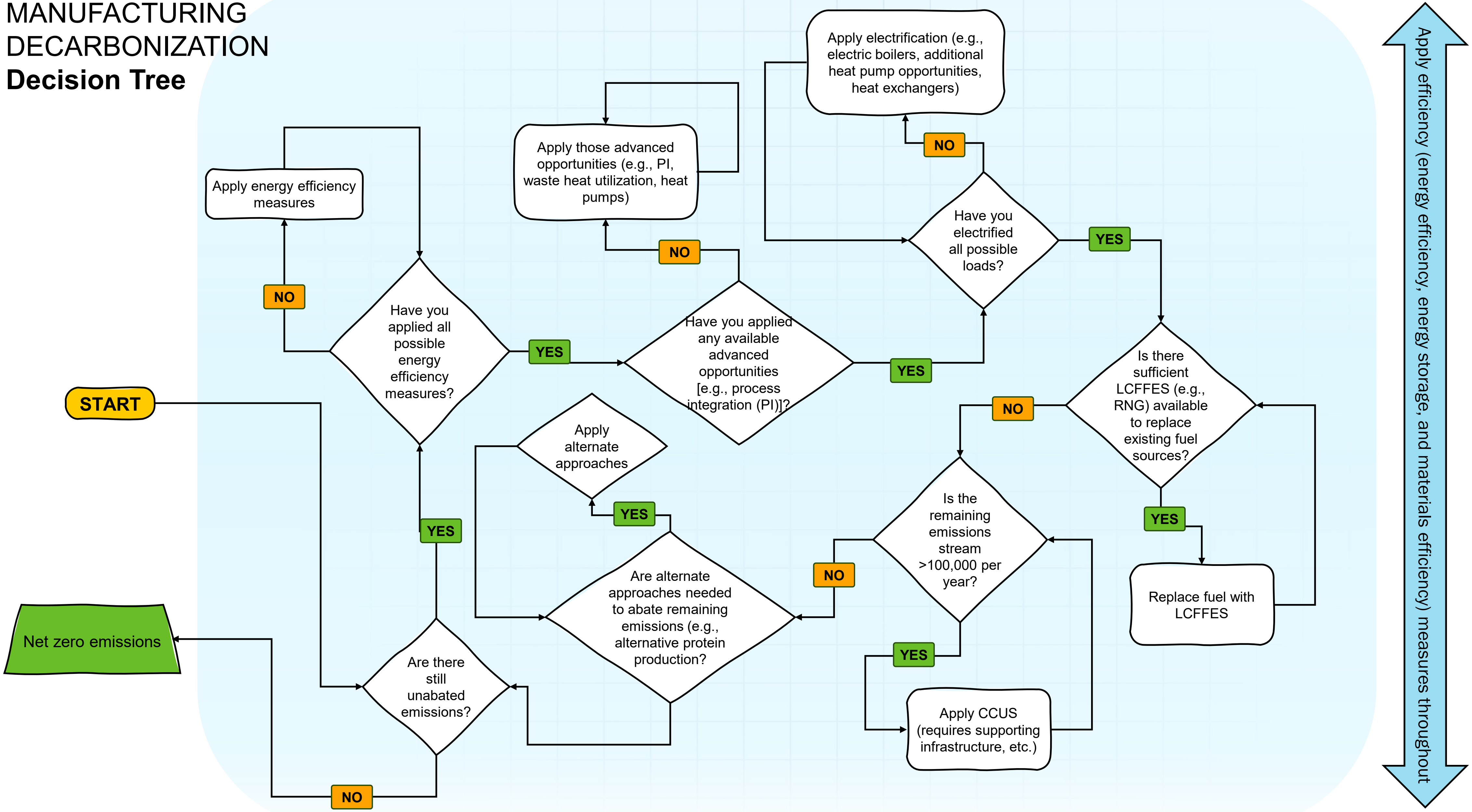
Example U.S. ethylene manufacturing production route share under a net-zero emissions scenario, 2018–2050



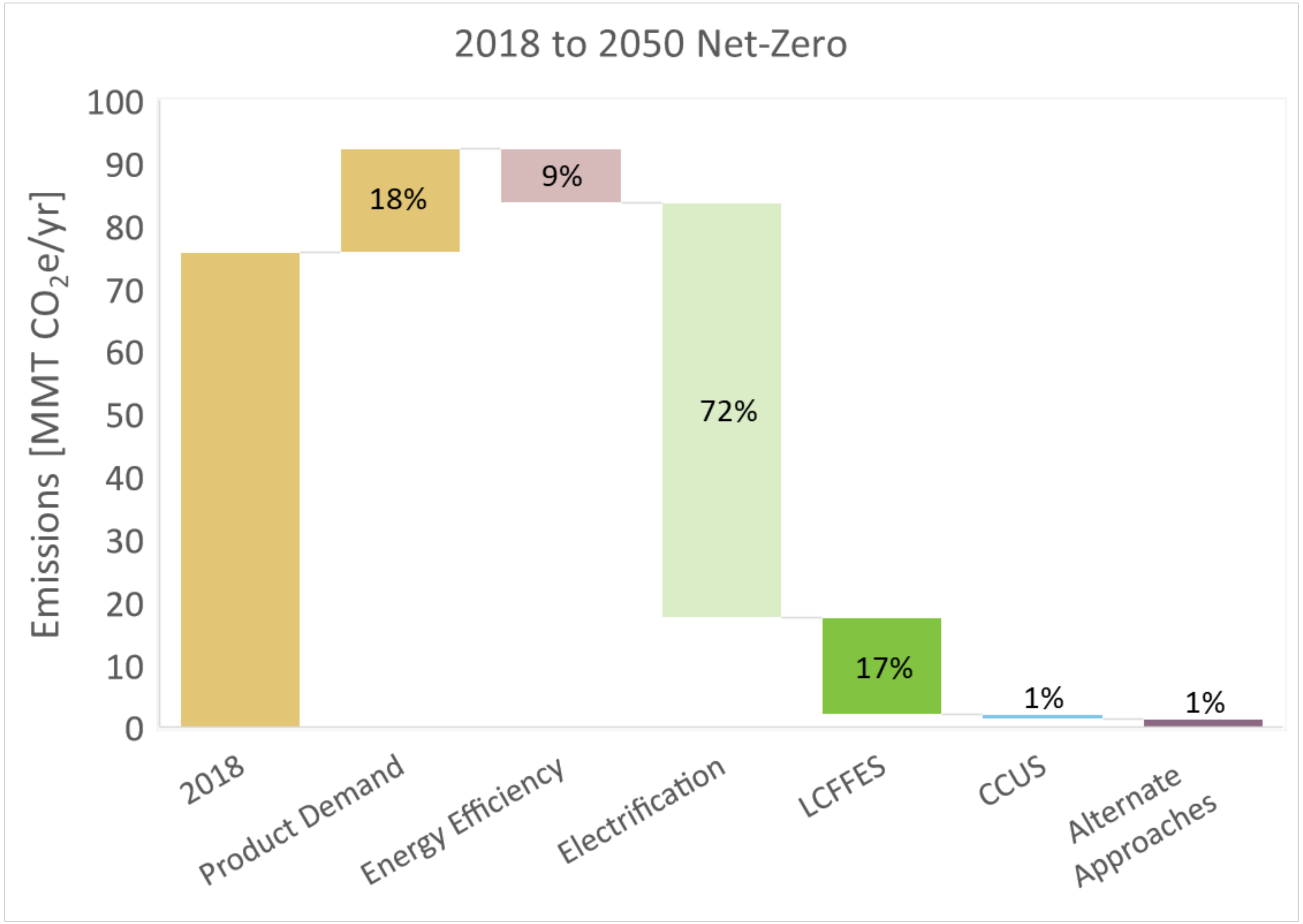
PRELIMINARY DATA. DO NOT CITE.

This representation is based on preliminary modeling runs and does not rely on actual facility data. Acronyms: NGL (natural gas liquids), (BAT) best available technology

FOOD & BEVERAGE MANUFACTURING DECARBONIZATION
Decision Tree



Net-Zero Pathway: Food & Beverage



Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions

(million metric tons (MMT)/year) select U.S. food and beverage manufacturing subsectors. 2018–2050

PRELIMINARY DATA. DO NOT CITE.

This representation is based on preliminary modeling and does not rely on actual facility data. The subsectors modeled are grain and oilseed milling; sugar manufacturing; fruit and vegetable preserving and specialty food manufacturing; dairy product manufacturing; animal slaughtering and processing; and beverage manufacturing. These subsectors account for 79% of energy consumption and 78% of emissions for food and beverage manufacturing in 2018. This figure was created by applying energy efficiency and industrial electrification technologies first in each subsector. This figure may differ to the associated Roadmap figure due to additional modeling considerations included here. Source: This work.

Modeled Technologies: Food & Beverage

Technology	Process
Energy Efficiency	
Boiler energy efficiency measures	Facility HVAC
Air Compressors energy efficiency measures	Machine Drive
Chillers energy efficiency measures (Motors/VFD)	Process Cooling and Refrigeration
Dryers/ovens energy efficiency measures	Low/High temp Convective hot air dryers
Fans and Blowers energy efficiency measures	Machine Drive
Process Integration	Low/High temp Convective hot air dryers Low/High temp Direct/Indirect hot water Process Cooling and Refrigeration
Pumps energy efficiency measures	Machine Drive
LCFFES	
Low-carbon fuels switching	Processes with remaining fuel demand
CCUS	
Post-combustion carbon capture and storage (amine absorption)	Remaining combustion emissions (grain and oilseed milling, beverages only)

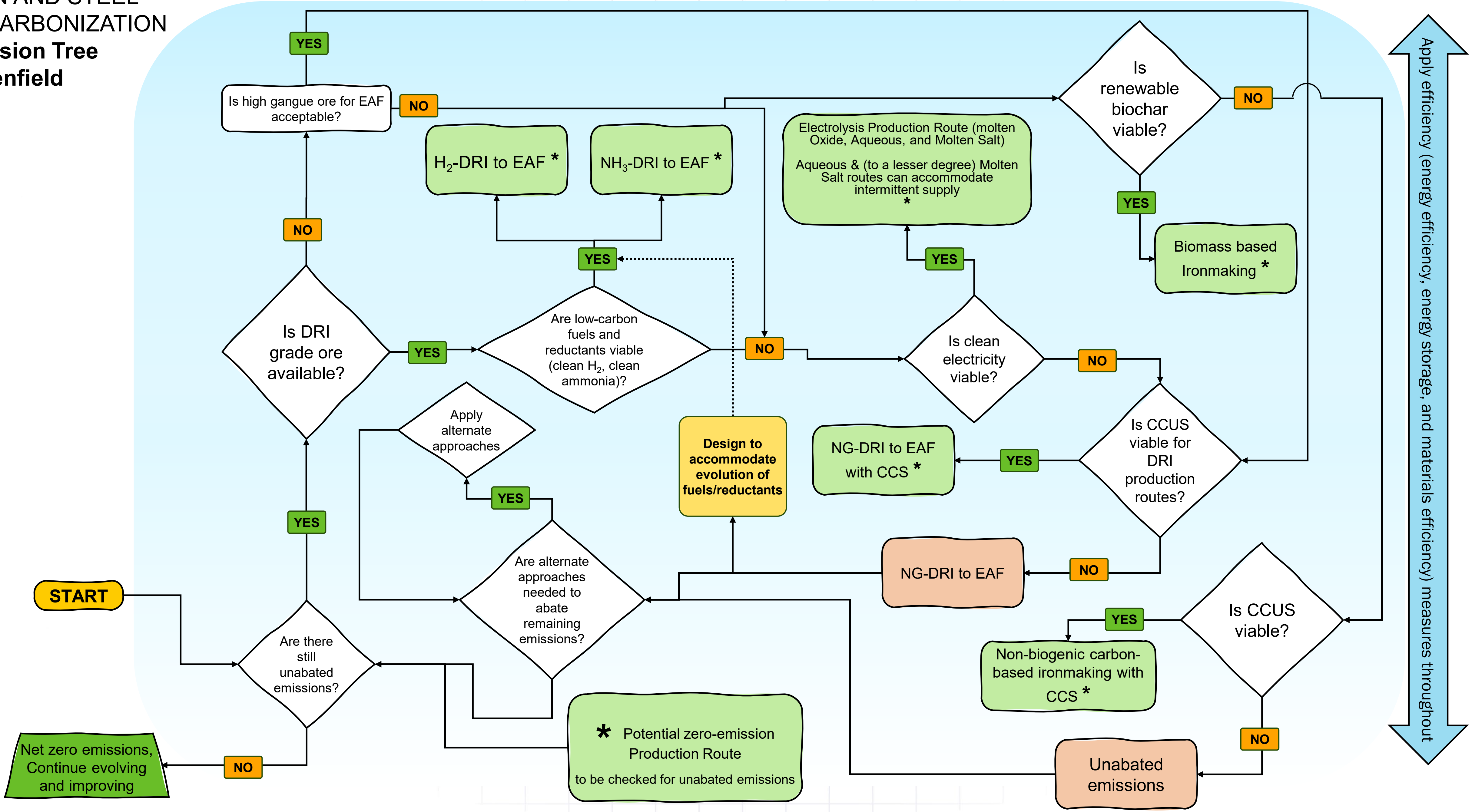
Subsectors modeled:

- Grain and oilseed milling
- Sugar
- Fruit and vegetable preserving and specialty food
- Dairy products
- Animal slaughtering and processing
- Beverages

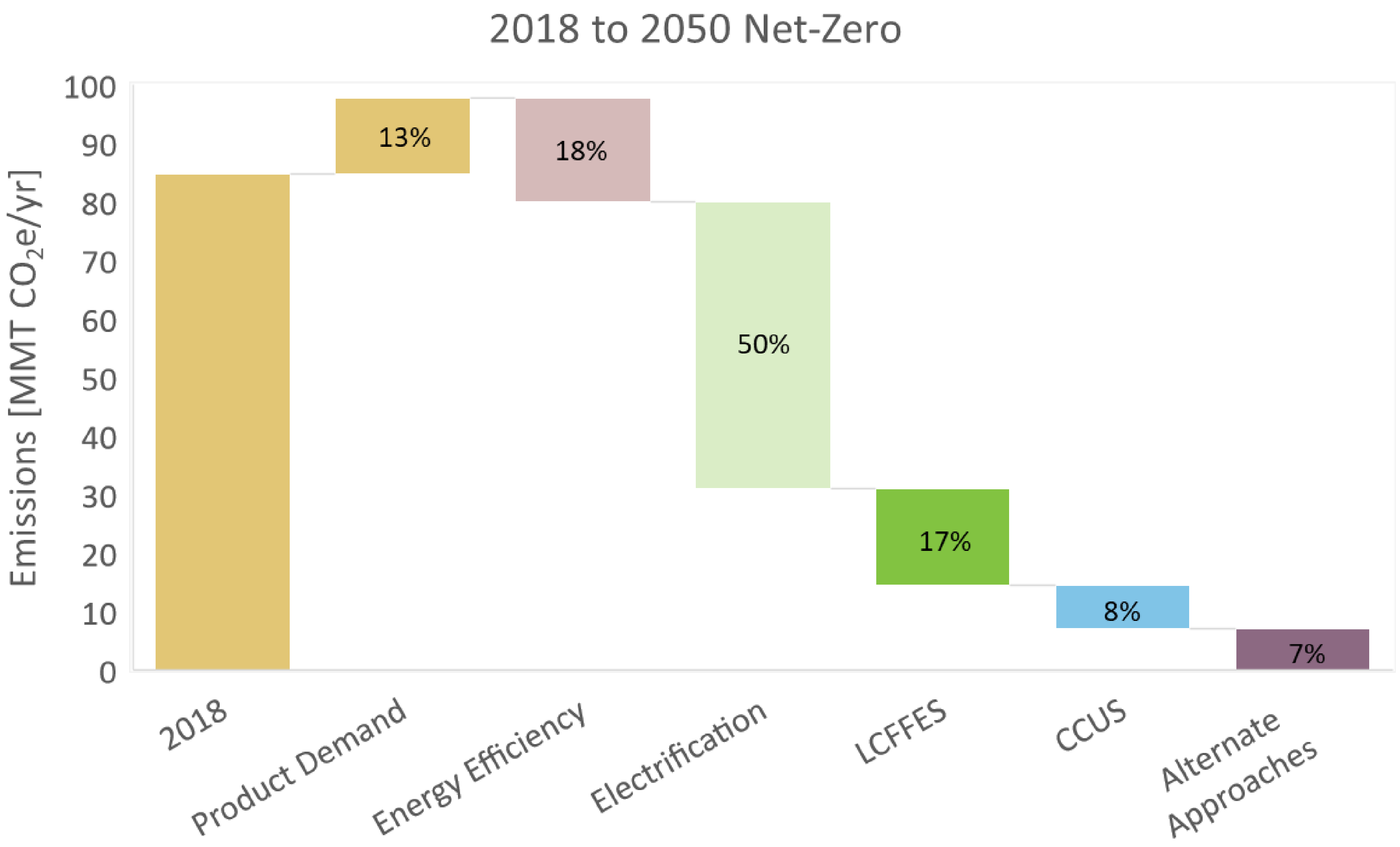
Account for 78% of energy and 79% of emissions total for food & bev subsector

Technology	Process
Electrification	
Electric Boiler	Low/High temp Direct/Indirect hot water/Steam
Hot water heat pump	Facility HVAC Low/High temp Direct/Indirect hot water
Membrane Pre-concentrators	Low/High temp convective hot air dryers
Steam generating heat pump	Low/High temp convective hot air dryers Low/High temp Direct/Indirect steam
Advanced electroheating technologies	Low/High temp Convective hot air dryers

IRON AND STEEL DECARBONIZATION
Decision Tree Greenfield



Net-Zero Pathway: Iron & Steel



Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions

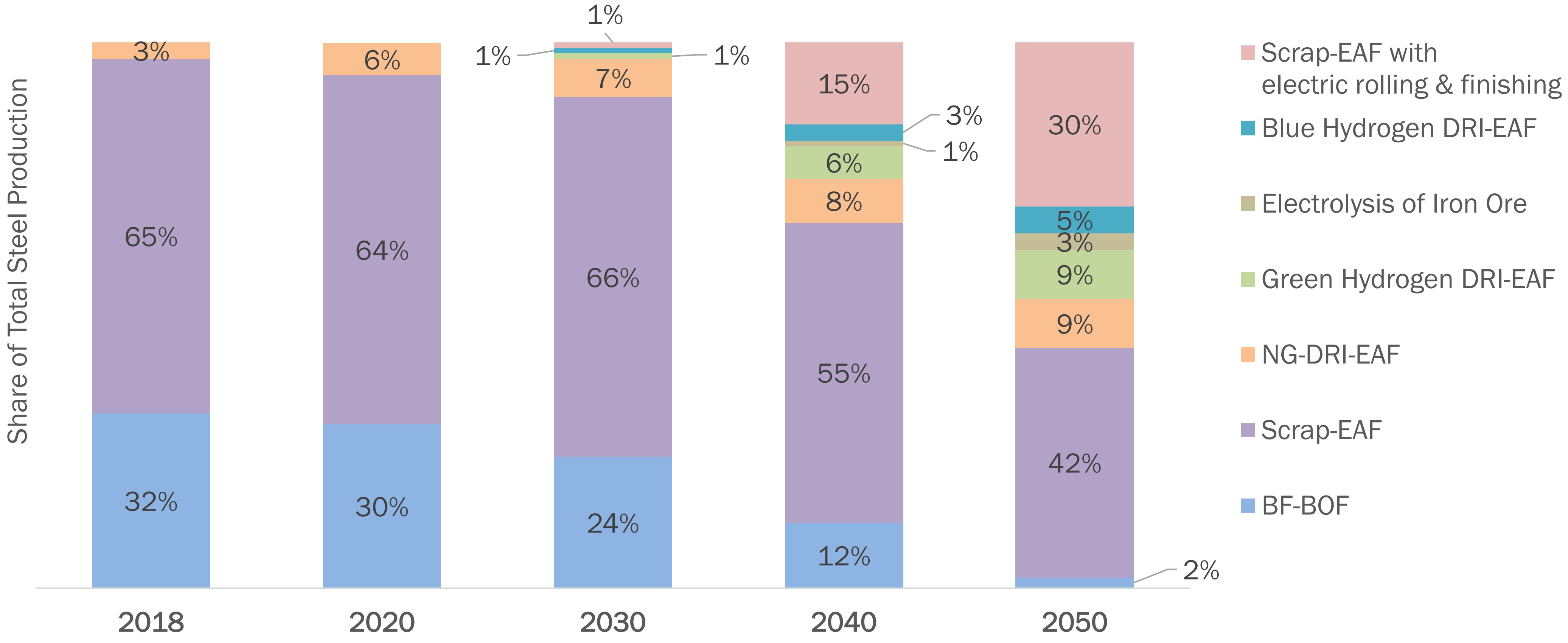
(million metric tons (MMT)/year) for U.S. iron and steel manufacturing, 2018–2050

This representation is based on preliminary modeling and does not rely on actual facility data. This figure may differ to the associated Roadmap figure due to additional modeling considerations included here. Source: This work.

PRELIMINARY DATA. DO NOT CITE.

Net-Zero Pathway Production Routes: Iron & Steel

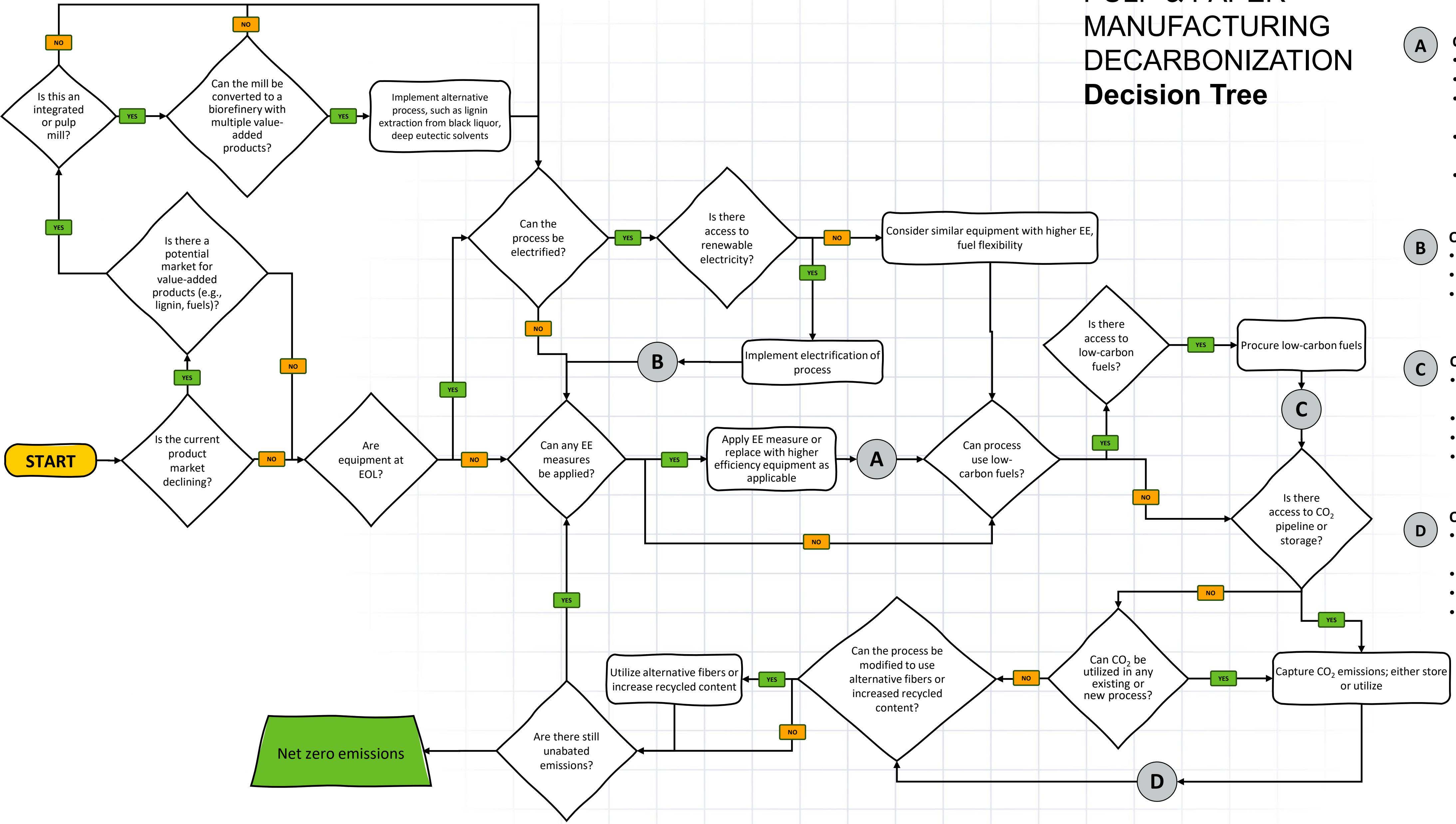
Example U.S. iron and steel manufacturing production route share by decade under a net-zero emissions scenario, 2018–2050



PRELIMINARY DATA. DO NOT CITE.

This representation is based on preliminary modeling runs and does not rely on actual facility data. Acronyms: BF (blast furnace), BOF (basic oxygen furnace), DRI (direct reduced iron), EAF (electric arc furnace), NG (natural gas).

PULP & PAPER MANUFACTURING DECARBONIZATION **Decision Tree**



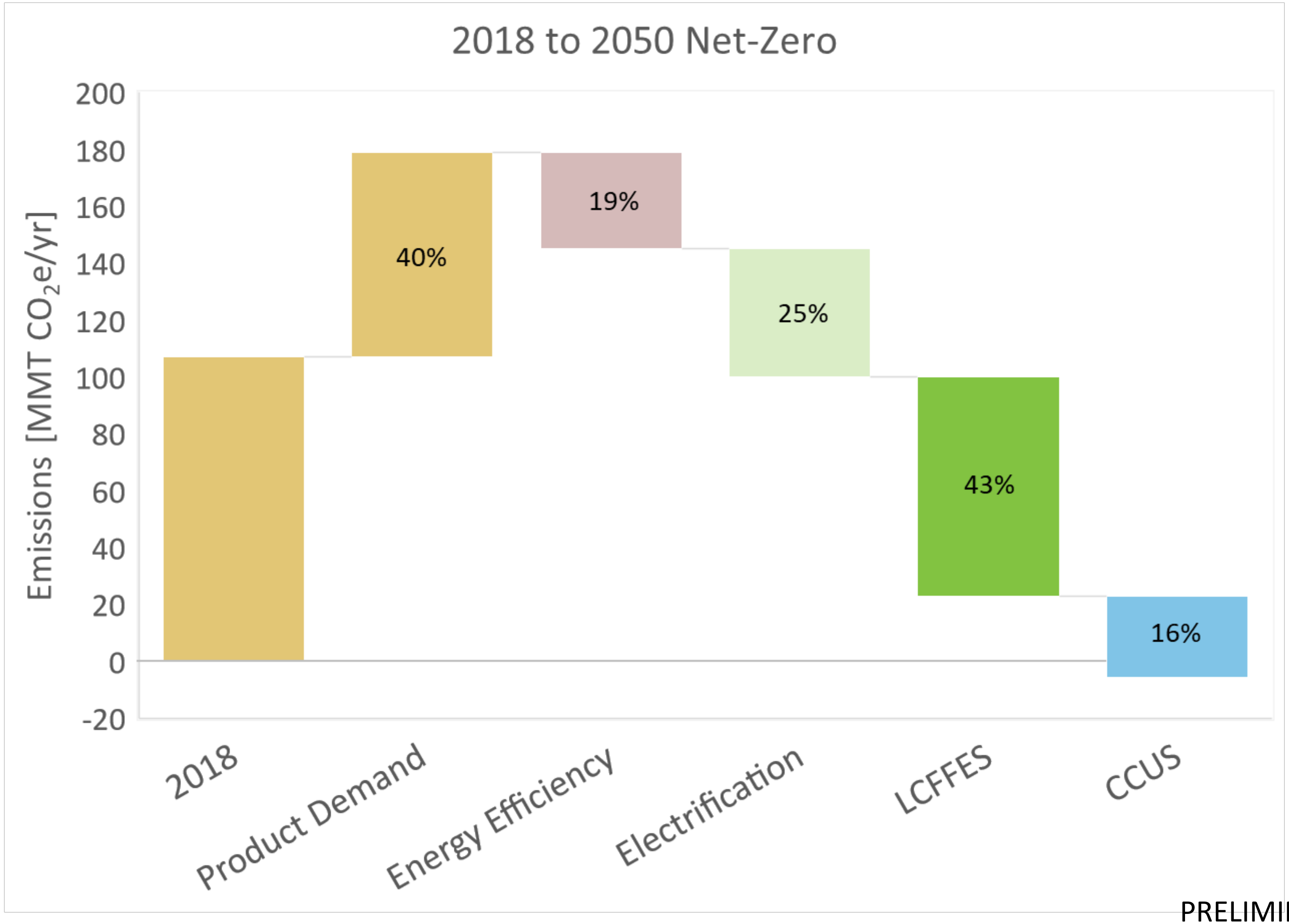
A **Options available:**
- Waste heat recovery
- Drying process changes
- Advanced monitoring controls, digitalization
- Combined heat and power technology
- Membrane Concentration of BL

B **Options available:**
- Drying process changes
- Electric boilers
- Steam generating heat pumps

C **Options available:**
- Switching coal, oil, etc. to natural gas (NG)
- Switching NG to renewable NG
- Switching to green H_2 (if available)
- Switching to solid biomass, if available

D **Options available:**
- Post-combustion amine-based CCS
- Calcium looping
- CCS for lime kiln alone
- Multiple stacks considered together

Net-Zero Pathway: Pulp & Paper



Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions

(million metric tons (MMT)/year) U.S. pulp and paper manufacturing. 2018–2050

PRELIMINARY DATA. DO NOT CITE.

This representation is based on preliminary modeling and does not rely on actual facility data. Source: This work.

Modeled Technologies: Pulp & Paper

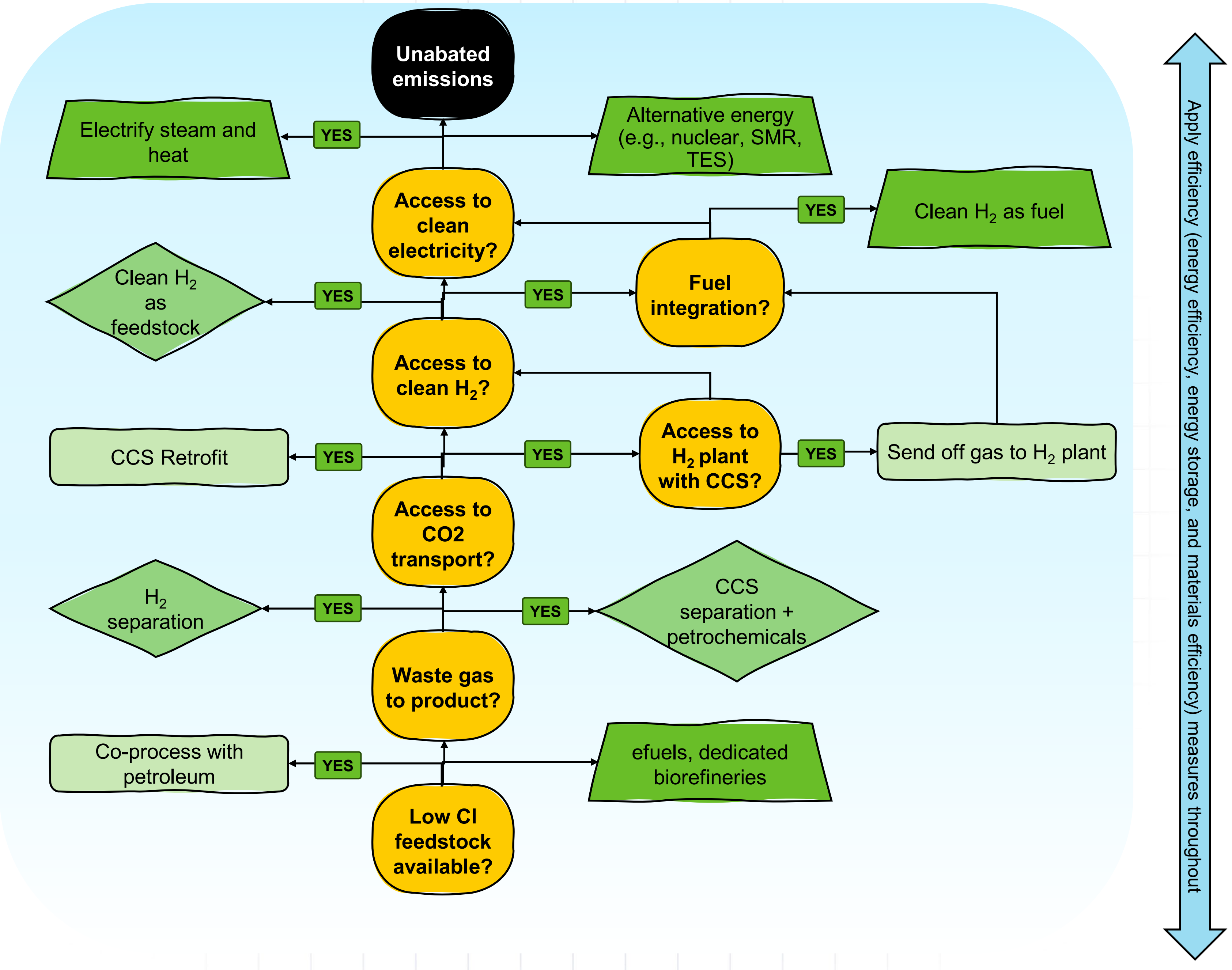
Technology	Process
Energy Efficiency	
Autonomous energy efficiency improvement	All processes
Equipment upgrades	Wood prep (debarking)
	Refining/ screening (refiner)
	Forming/ pressing (high consistency forming)
	Forming/ pressing (press section upgrades)
	Drying (improved drying technologies)
	Chemical prep (lime kiln modifications)
	Evaporation (additional evaporation effects)
Waste heat recovery	Wood prep
	Pulping/ Cooking
	Boilers
	Bleaching
Chip screening and conditioning	Wood prep
Advanced digestion additives	Pulping/ Cooking
Optimization	Stock prep (batch stock)
	Forming/ pressing (air supply, paper machine vacuum)
Through air drying	Drying (improved drying technologies)
Recovery boiler temperature monitoring	Chemical prep

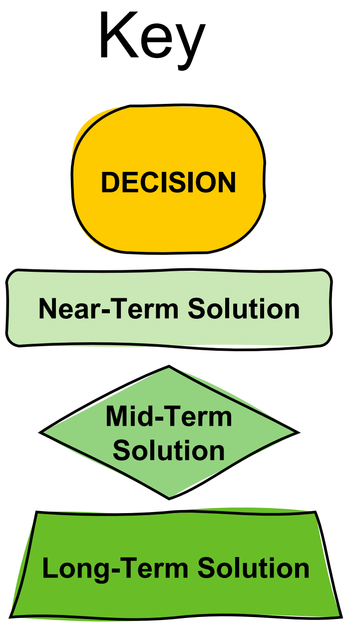
Mill types modeled:

- Market pulp mill
- Tissue mill
- Specialty mill
- Recycled mill
- Bleached integrated mill
- Unbleached integrated mill

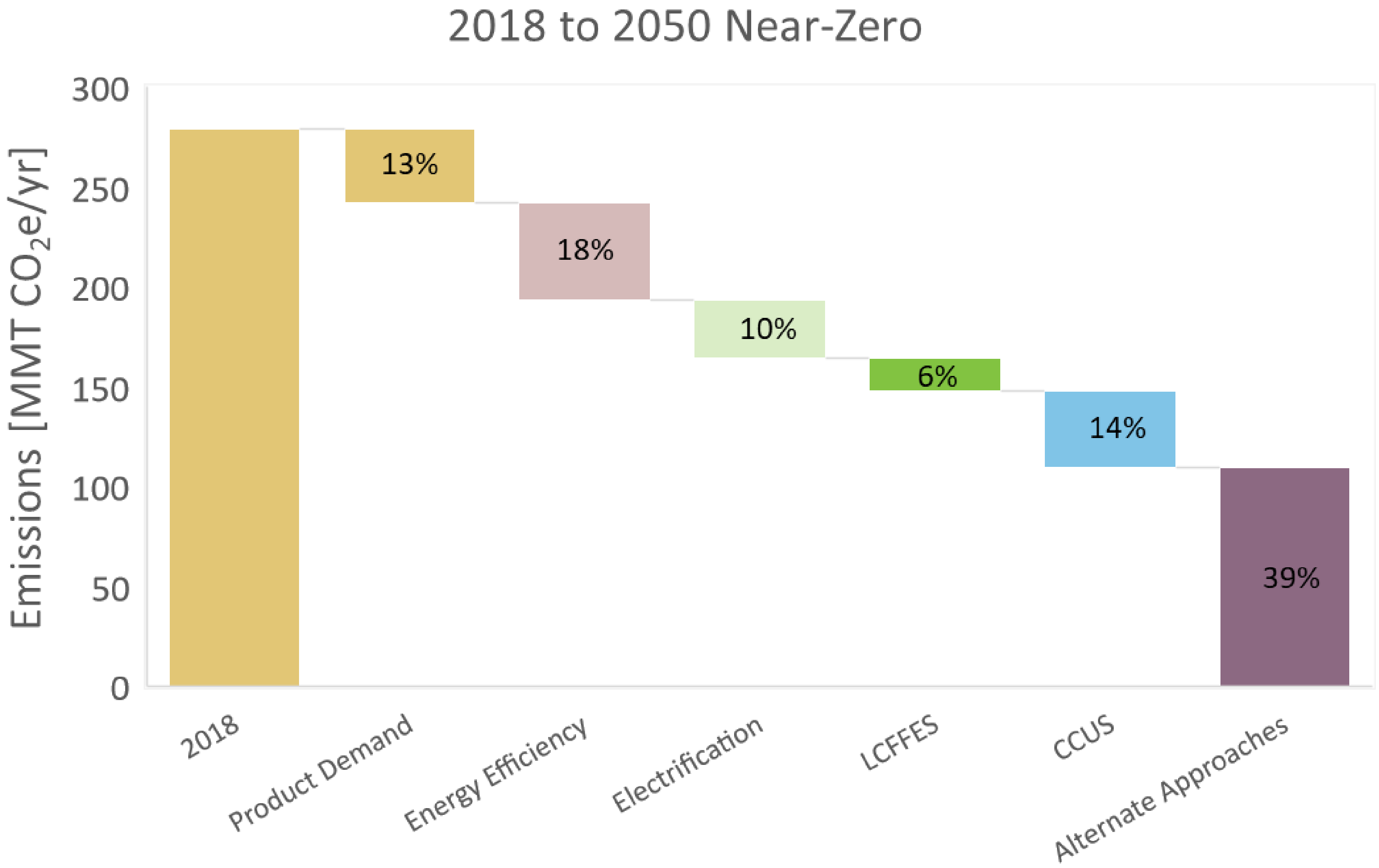
Technology	Process
Electrification	
Electric Boiler	Auxiliary boilers
LCFFES	
Fuel switching to biomass	Auxiliary boilers, chemical prep (lime kilns)
Fuel switching to hydrogen	Drying (Yankee dryers)
CCUS	
Post-combustion carbon capture	Recovery and auxiliary boilers, lime kilns

REFINING
DECARBONIZATION
Decision Tree





Net-Zero Pathway: Petroleum Refining



Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions

(million metric tons (MMT)/year) for U.S. petroleum refining, 2018–2050

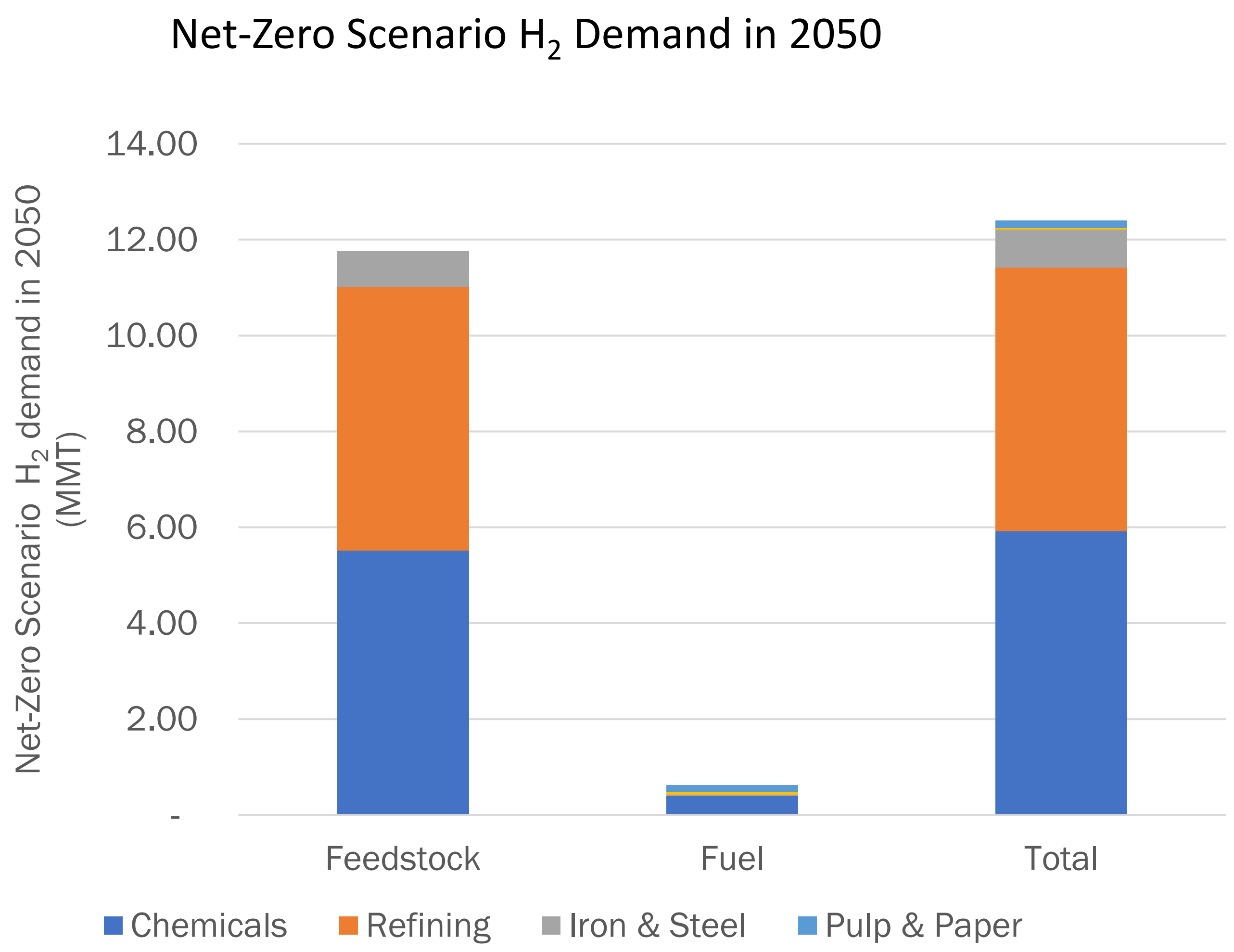
This representation is based on preliminary modeling and does not rely on actual facility data. This figure may differ to the associated Roadmap figure due to additional modeling considerations included here. Source: This work.

PRELIMINARY DATA. DO NOT CITE.

Cross-Sectoral Approaches

- Hydrogen
- CCUS
- Electric grid
- Material efficiency & demand reduction

U.S. Hydrogen Demand Estimates



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

Current hydrogen production is ~10 MMT

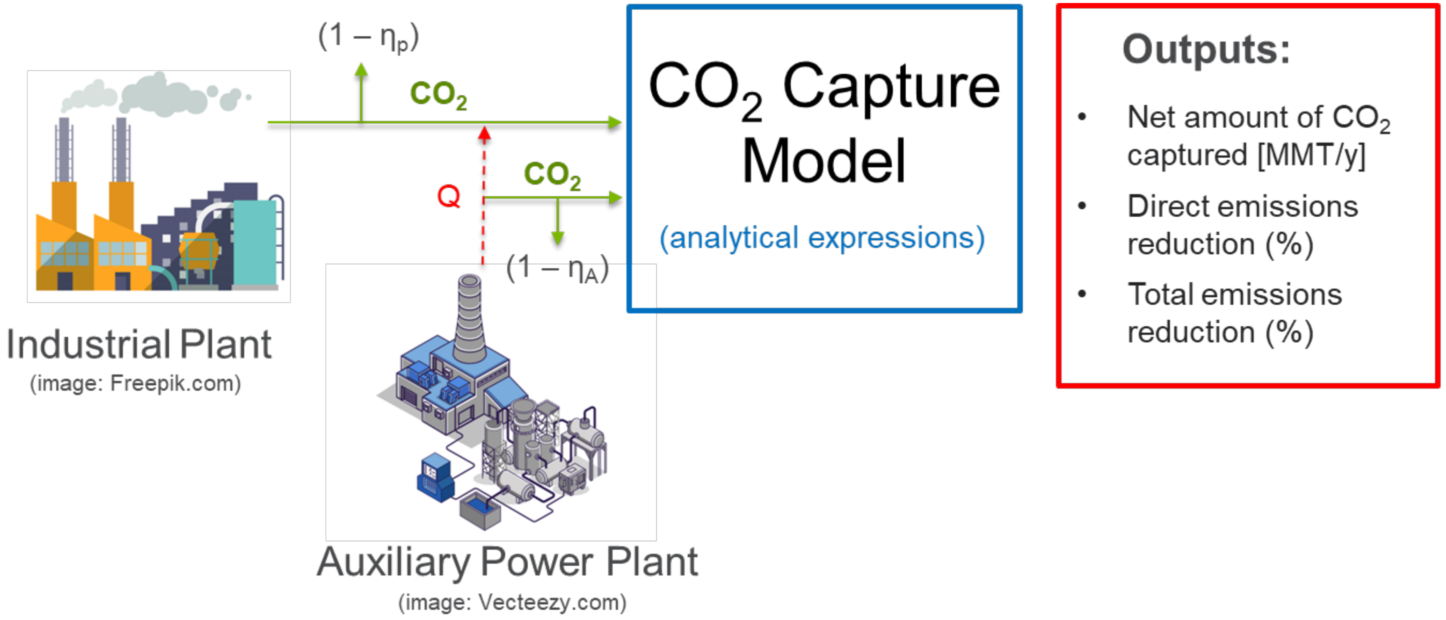
U.S. National Clean Hydrogen Strategy and Roadmap forecast 50 MMT hydrogen production in 2050.

- Total 2050 Net-Zero Hydrogen Demand for 6 modeled 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

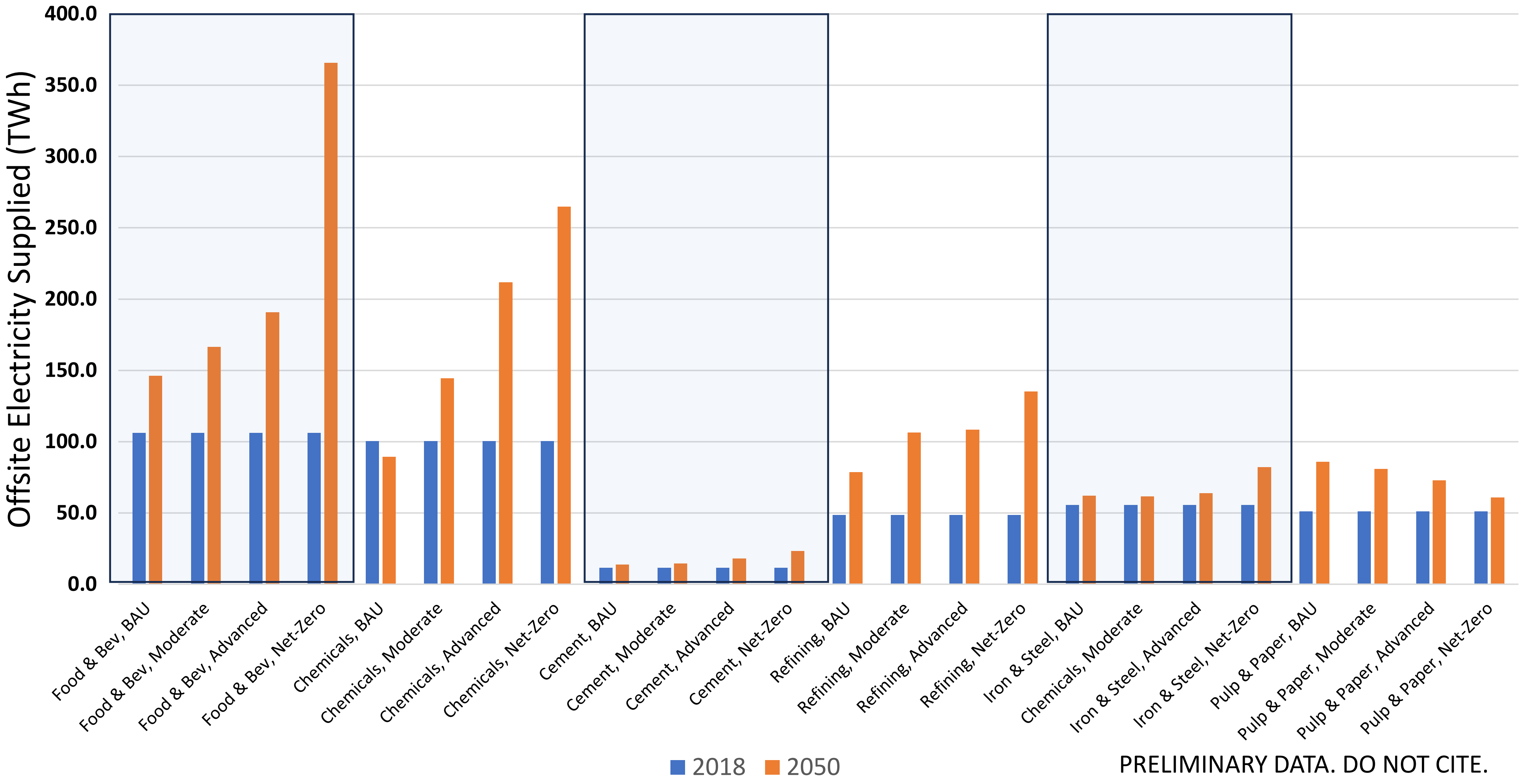
PRELIMINARY DATA. DO NOT CITE.

CCUS in the Pathways Models

- Model assumes the user gives a **<u>time series of "capturable" CO_2 emissions</u>** (MMT-CO_2/y) out of which ~80-90% can be captured
- Other model inputs include heat and electricity **<u>energy demands</u>**, **<u>CO_2 capture efficiencies</u>**, etc. obtained from the literature
  - Can be changed, but it is not expected from the user
- Model assumes that heat for the capture energy is provided by an auxiliary plant using natural gas as fuel
  - Emissions from the auxiliary plant are also captured
  - Auxiliary plant consists of boiler + steam turbine that provide low-pressure steam and electricity, OR direct heat from combustion

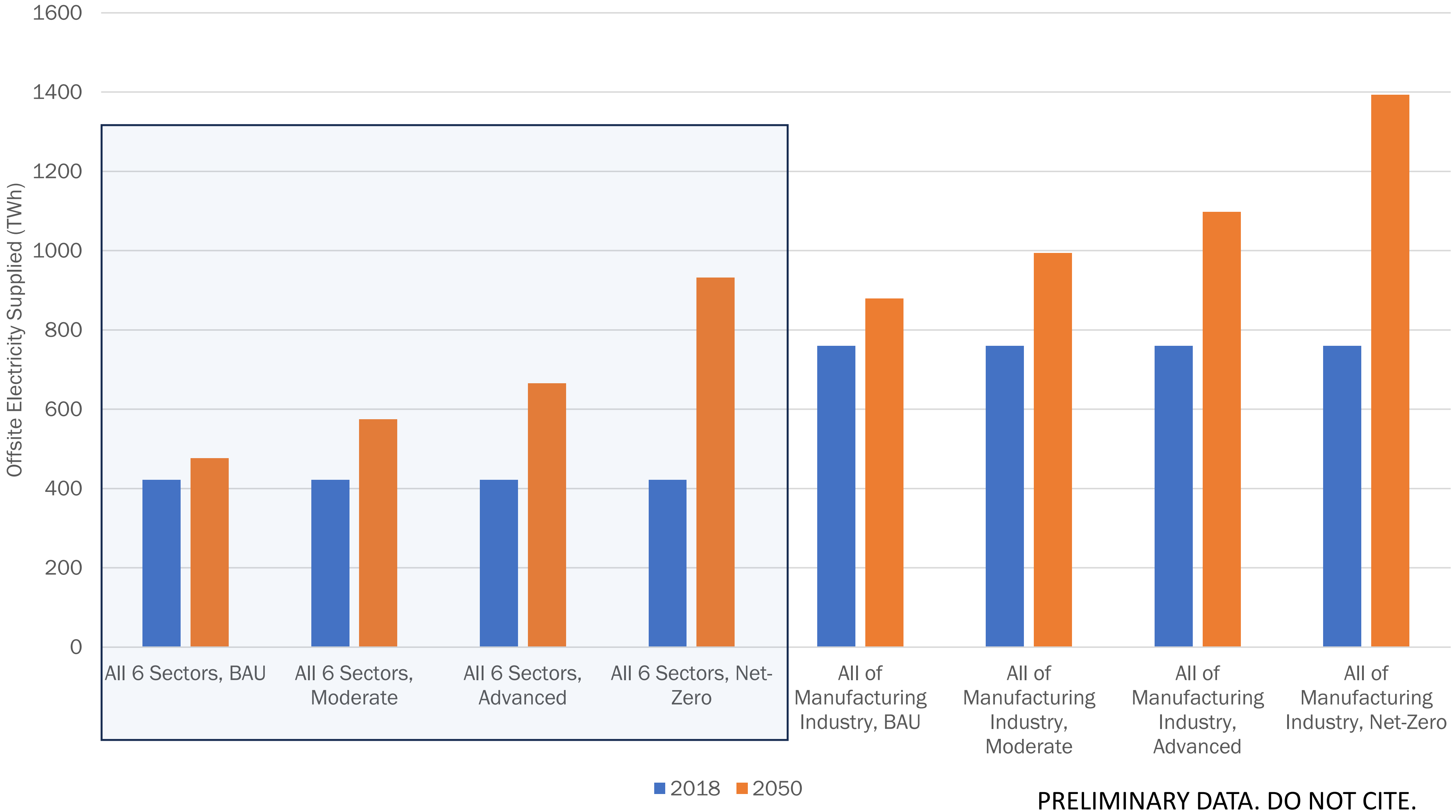


Industrial Electrification: Electricity Demand for Modeled Subsectors



PRELIMINARY DATA. DO NOT CITE.

Industrial Electrification: Total Electricity Demand for Modeled Subsectors



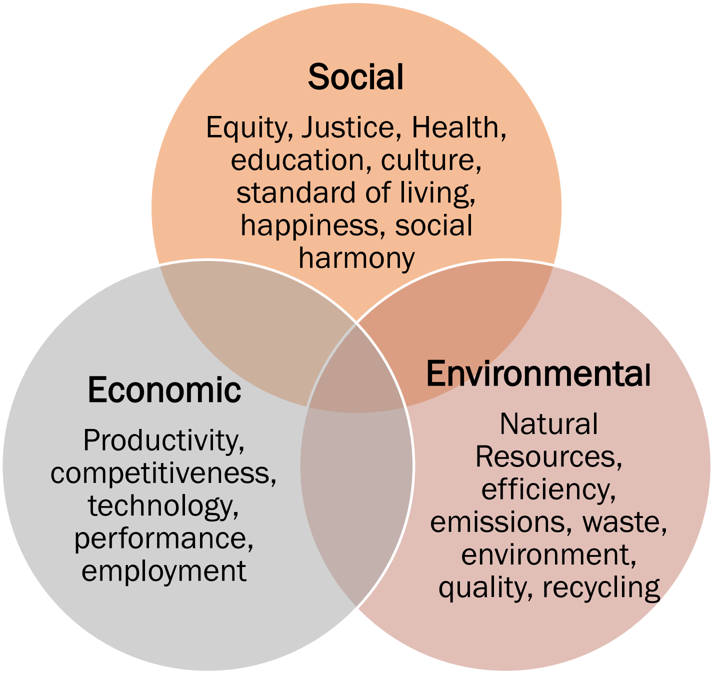
PRELIMINARY DATA. DO NOT CITE.

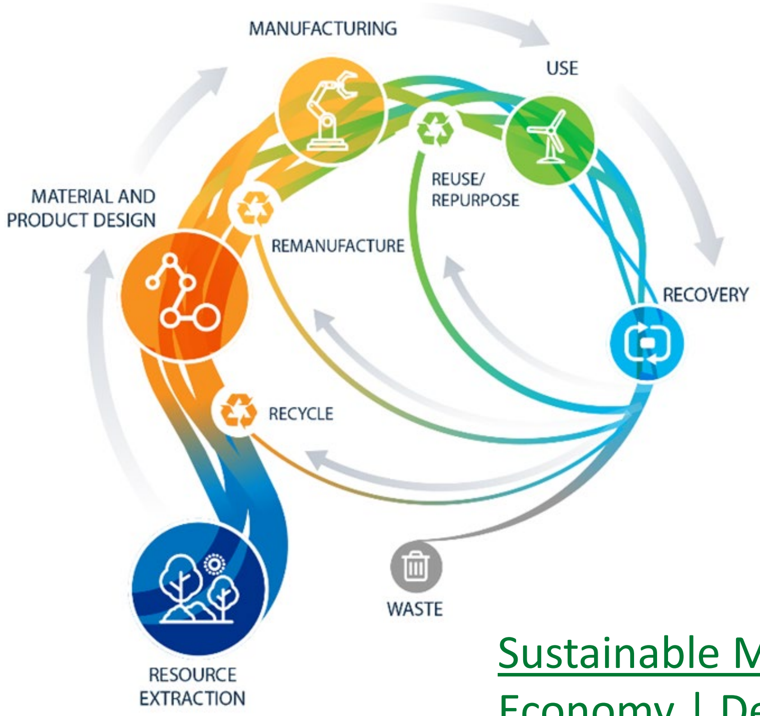
Resource Flows: Sustainable Manufacturing

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).





[Sustainable Manufacturing and the Circular Economy | Department of Energy]

Material Efficiency & Demand Reduction

Material efficiency looks to minimize the amount of raw materials required to manufacture products (dematerialization, yield improvements). **Demand reduction** looks to reduce the total demand for manufactured products (by example through increased product longevity or eliminating the product need)

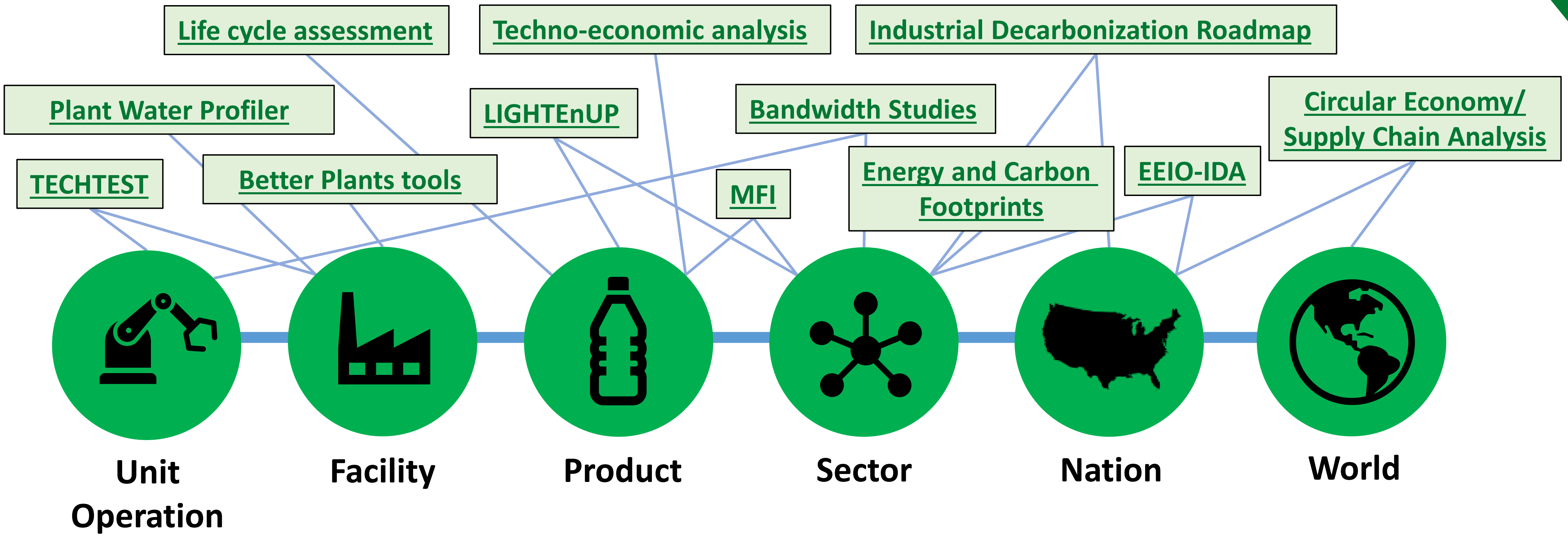
Why do we care?

- Supply chain security for critical materials and other commodity resources
- Long term sustainability and availability of resources
- Circular economy initiatives
- Large carbon and broad environmental impacts of material extraction and processing; producing less materials reduces Scope 1, 2 and 3 emissions

Challenges

- Cost of extracting materials and managing waste materials is generally minimal (except for hazardous materials)
- Many material efficiency/demand reduction strategies are both within and outside of the individual subsectors (i.e., replacing concrete/steel with wood framed buildings) and beyond Scope 1 and 2 boundaries (i.e., biobased substitutes)

IEDO analysis for energy environmental flows



Acronyms:

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

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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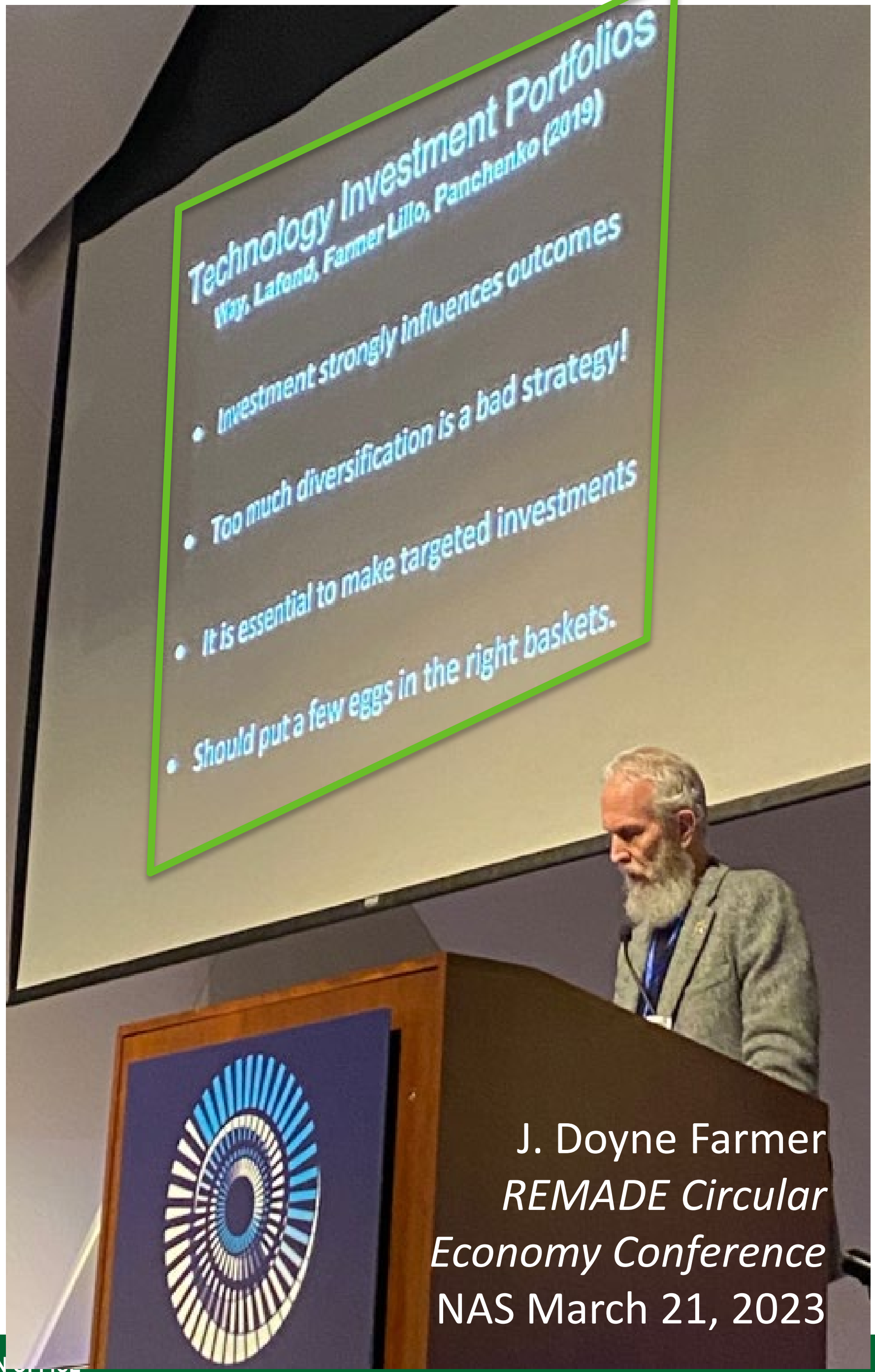

J. Doyne Farmer
REMADE Circular Economy Conference
NAS March 21, 2023

Transforming Industry: Strategies for Decarbonization RFI

The RFI will inform the ***Pathways for U.S. Industrial Transformations: Unlocking American Innovation*** study:

IEDO seeks input on the following categories:

- Industrial Decarbonization Barriers, Challenges, and Cross-Cutting Strategies
- Framework for Industrial Decarbonization Pathways
- Impacts and Evaluation Criteria for Industrial Decarbonization Pathways; and
- Net-zero Decarbonization Pathways for Specific Industrial Subsectors

www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

Deadline for responses: June 10, 2024, at 5:00pm ET