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INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Sector-Specific Strategies Breakout Sessions

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INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

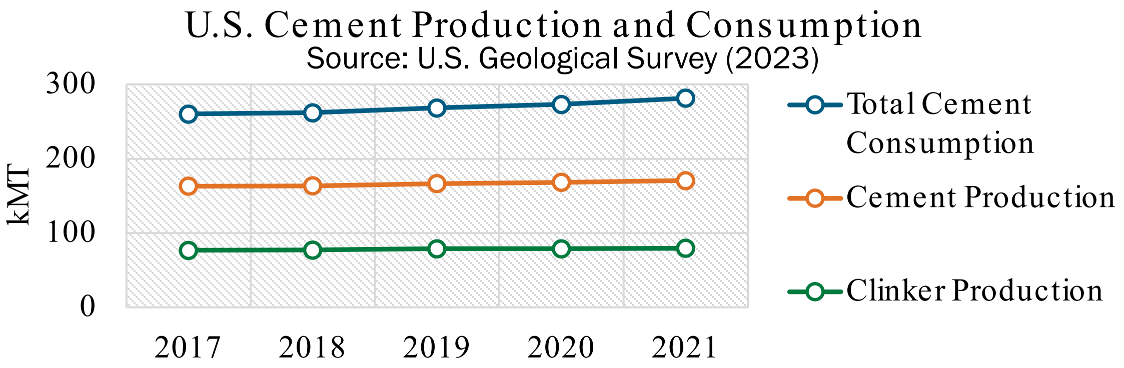
Cement and Concrete Strategies and Analysis Summary

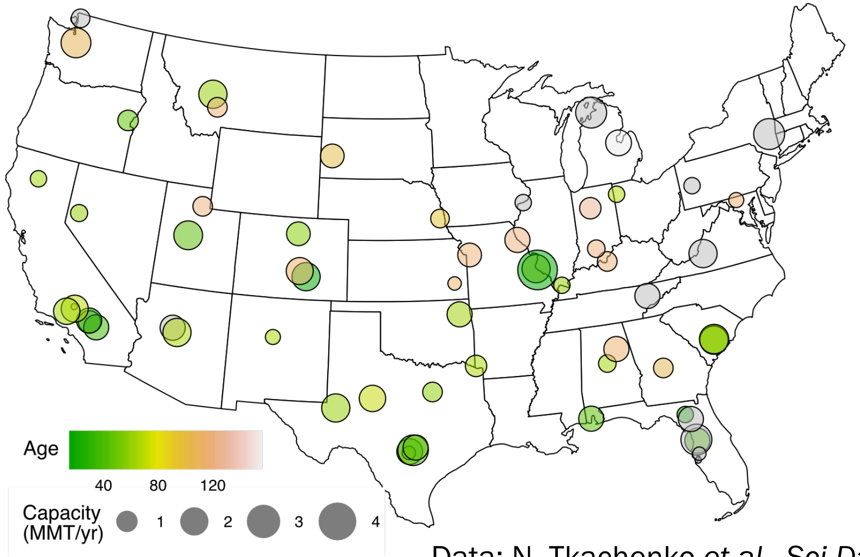
Industrial Efficiency and Decarbonization Office

May 15, 2024

U.S. Cement industry: At a glance

- The U.S. produced 95 million metric tons of Portland and masonry cement in 2022, ranking as the world's fourth-largest cement producer.
- Most U.S. cement plants utilize dry process kilns, with two-thirds featuring modern pre-heater and pre-calciner.
- The U.S. cement industry, with 96 plants and two in Puerto Rico, generated $14.6 billion in value of shipments and employed about 13,000 people.
- The clinker-to-cement ratio in the United States has slightly decreased over the past five years.
- Ready-mixed concrete producers are the primary consumers of U.S. cement, accounting for 75% of domestic shipments.
- U.S. cement production is projected to grow by 43% by 2050 compared to 2018 level.





Data: N. Tkachenko *et al.*, *Sci Data*. **10**, 696 (2023).

U.S. Cement industry: Energy use and emissions

- U.S. cement plants consume about 2% of the total fuel used in U.S. manufacturing industry.
- Coal is the predominant fuel source for U.S. cement plants, accounting for 43% of total fuel consumption, followed by natural gas (22%) and petcoke (19%).
- The production of clinker, an intermediate product in cement manufacturing, is the most energy-intensive process, consuming almost all fuels and about 60% of a plant's electricity.
- The U.S. cement industry contributes approximately 66 million metric tons of CO_2 annually, representing about 1% of total U.S. CO_2 emissions.

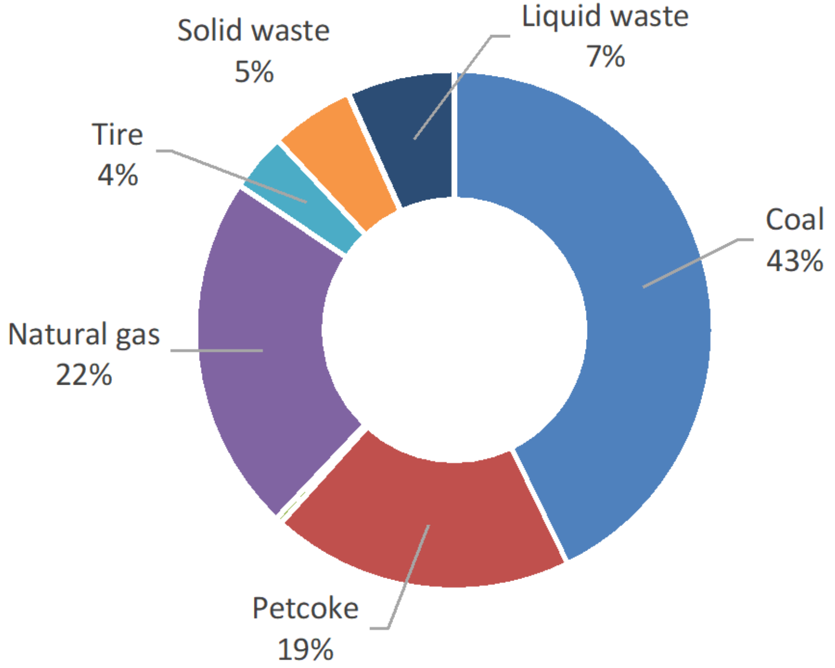
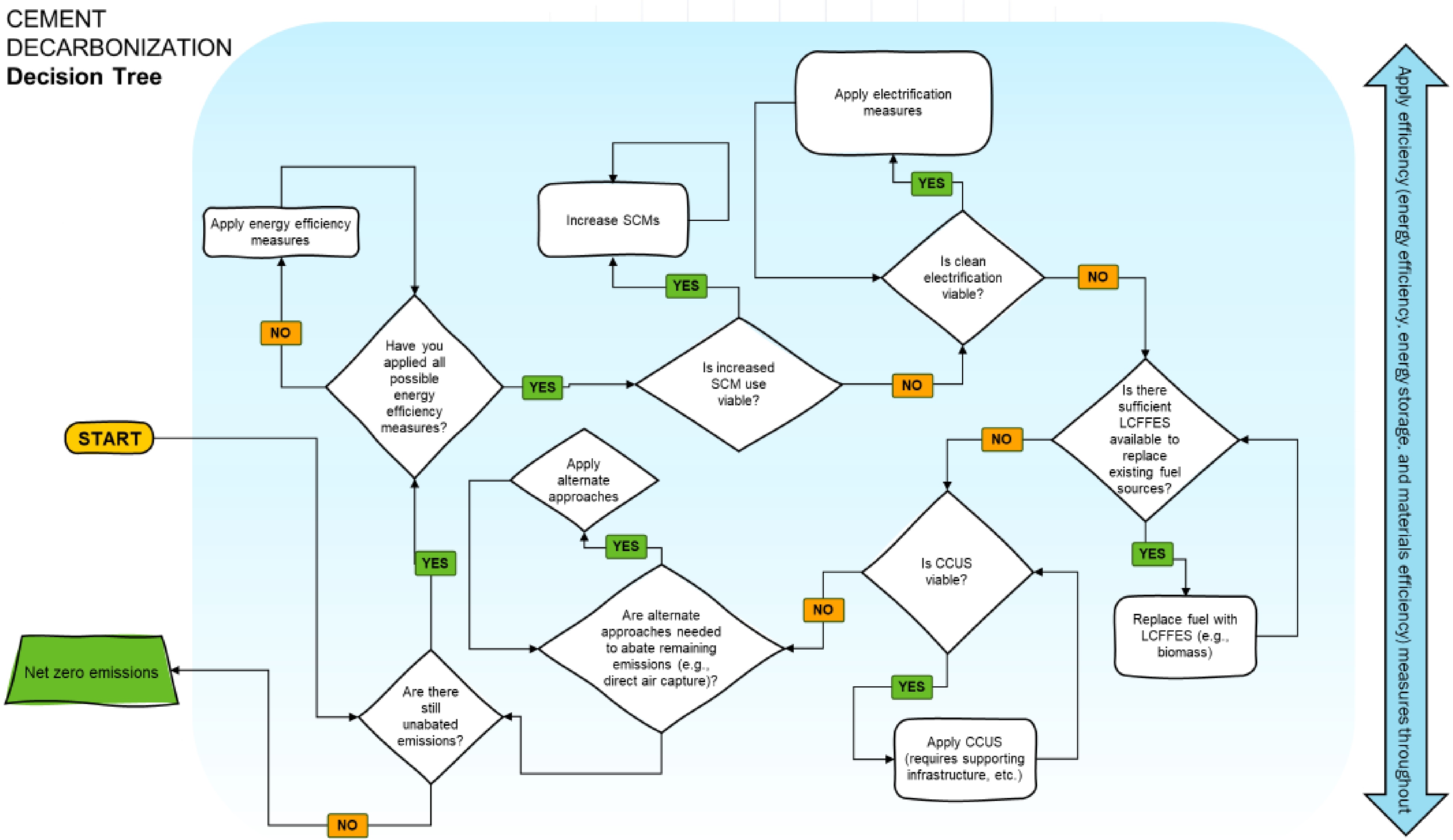


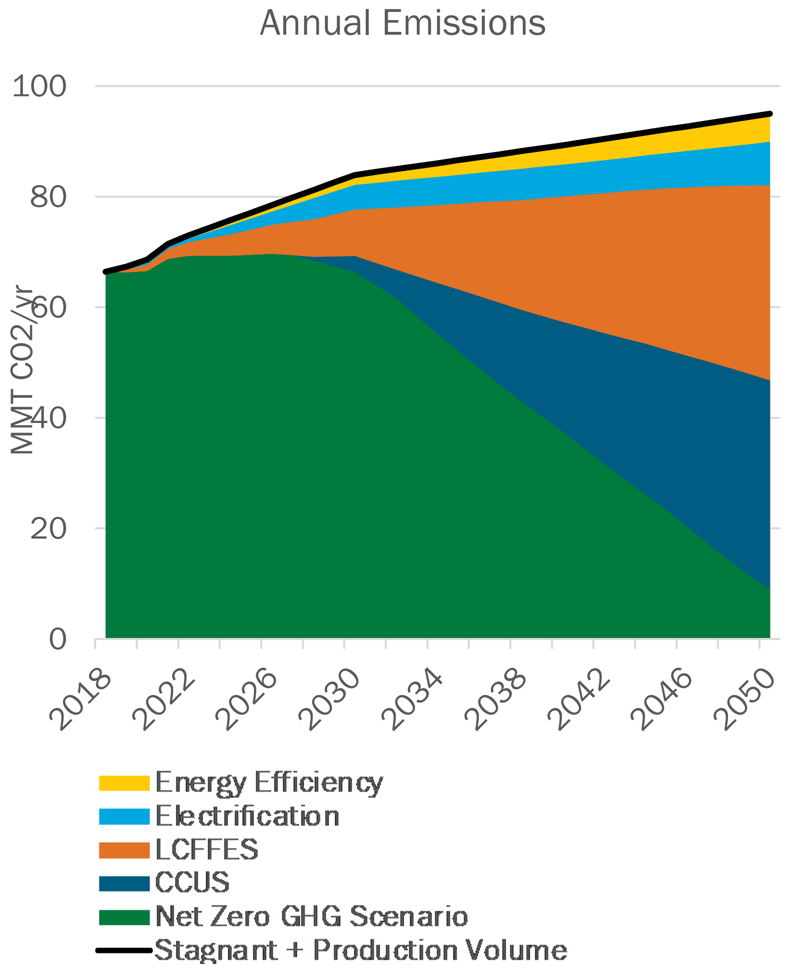
Figure: Share of energy consumption by fuel type for the U.S. cement industry in 2018 (source: USGS 2022)

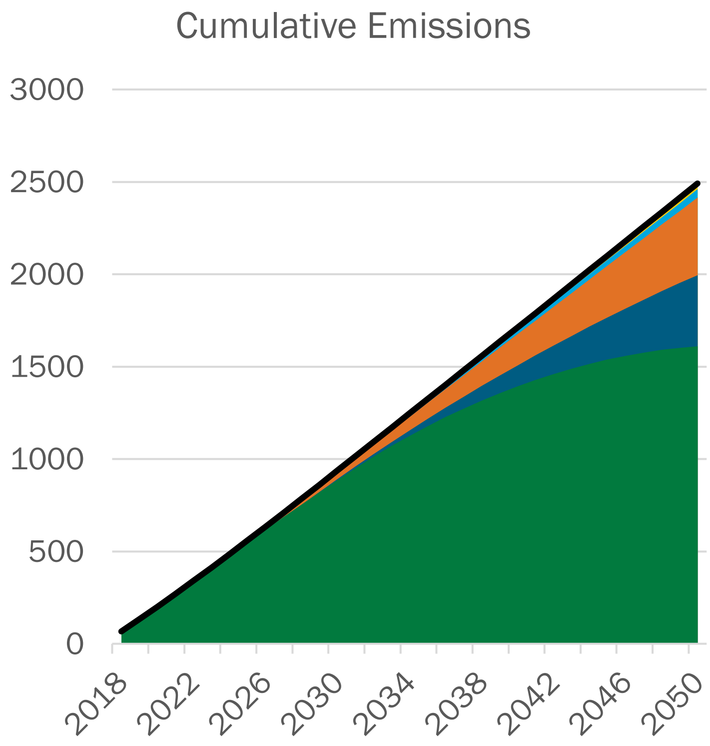
Decision tree for U.S. cement decarbonization

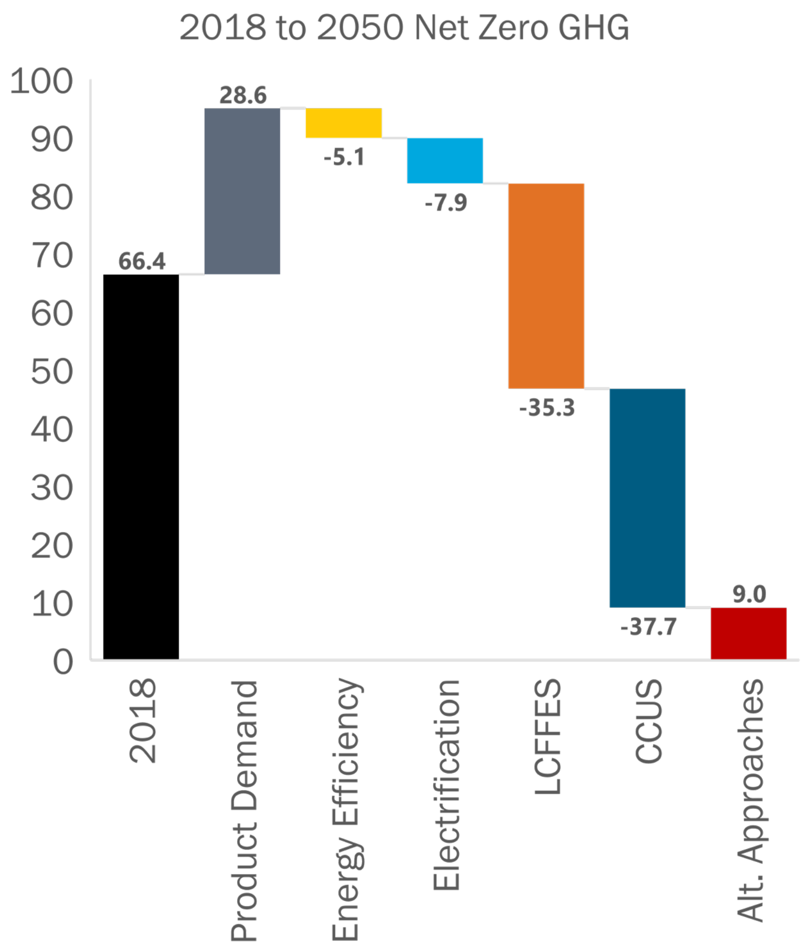


Emissions reductions by decarbonization pillar

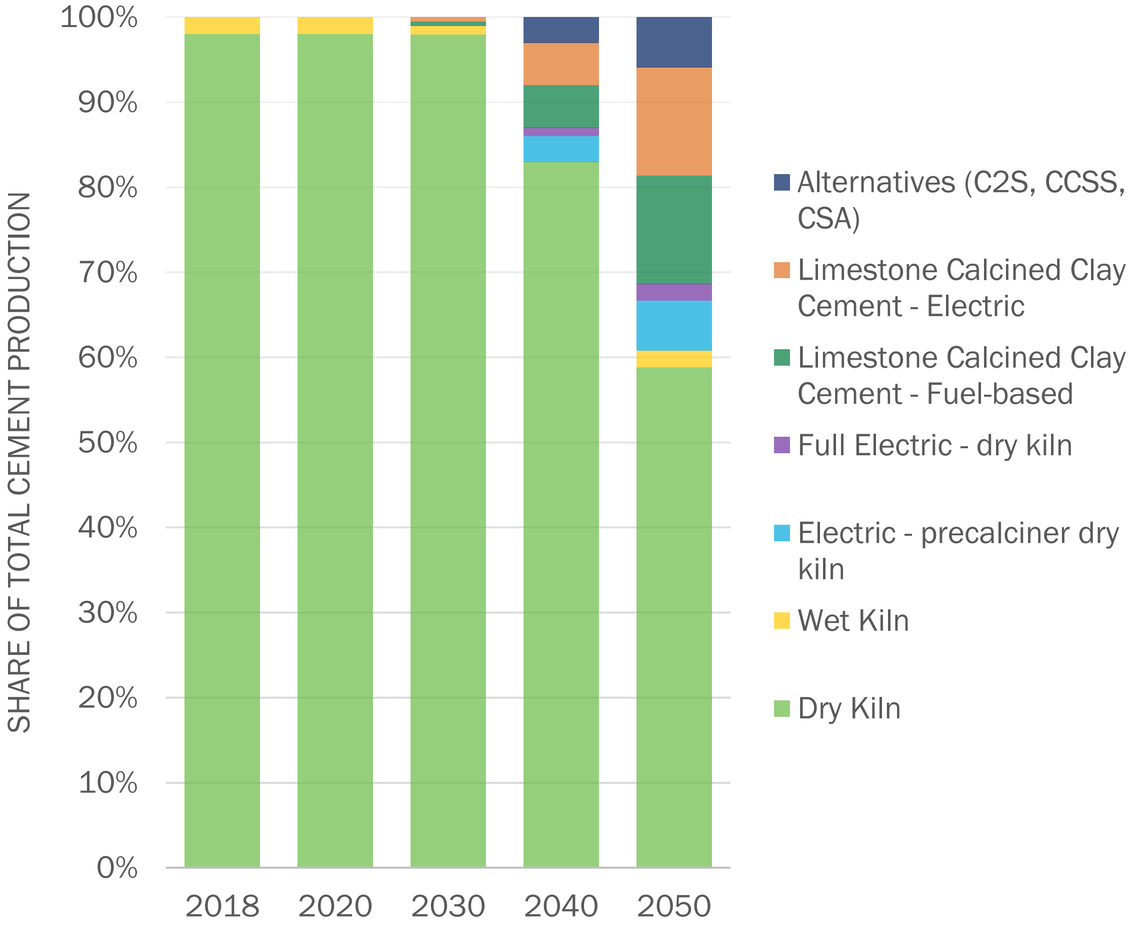
Energy efficiency, electrification, LCFFES, and CCUS respectively contribute to about 6%, 9%, 41%, and 44% of emissions reduction between 2018 and 2050.

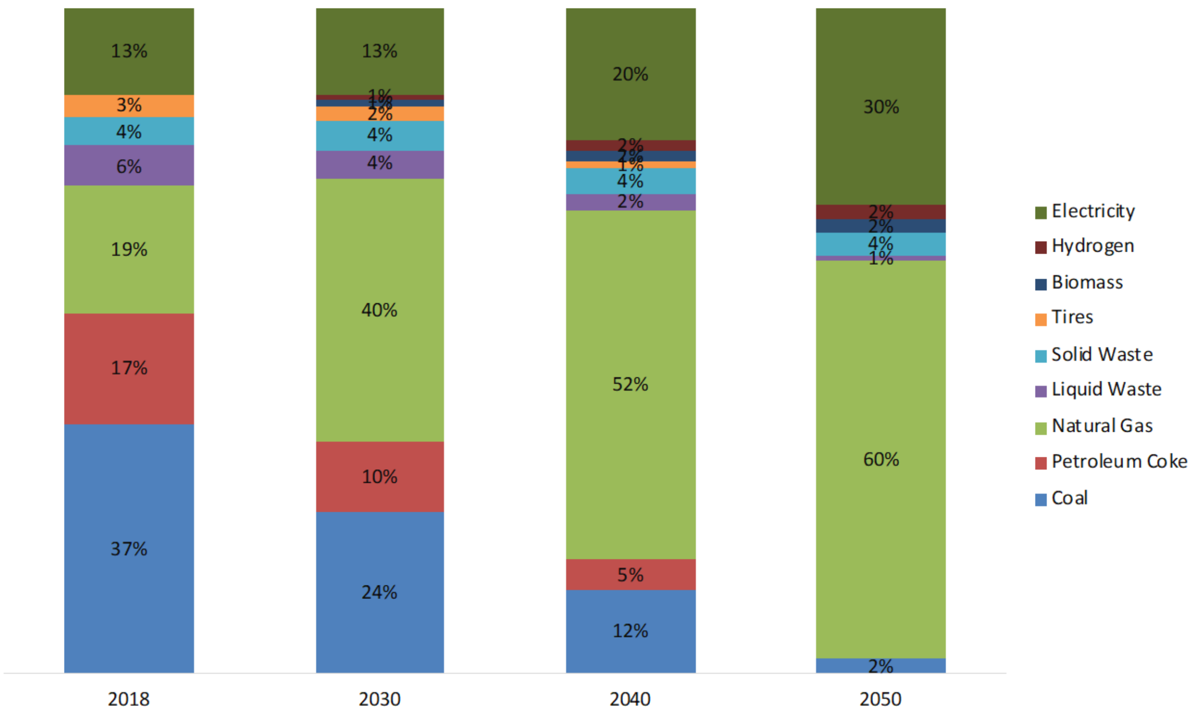






Production routes & fuel mix





Energy efficiency pillar contributes to about 6% of emissions reduction from 2018 to 2050

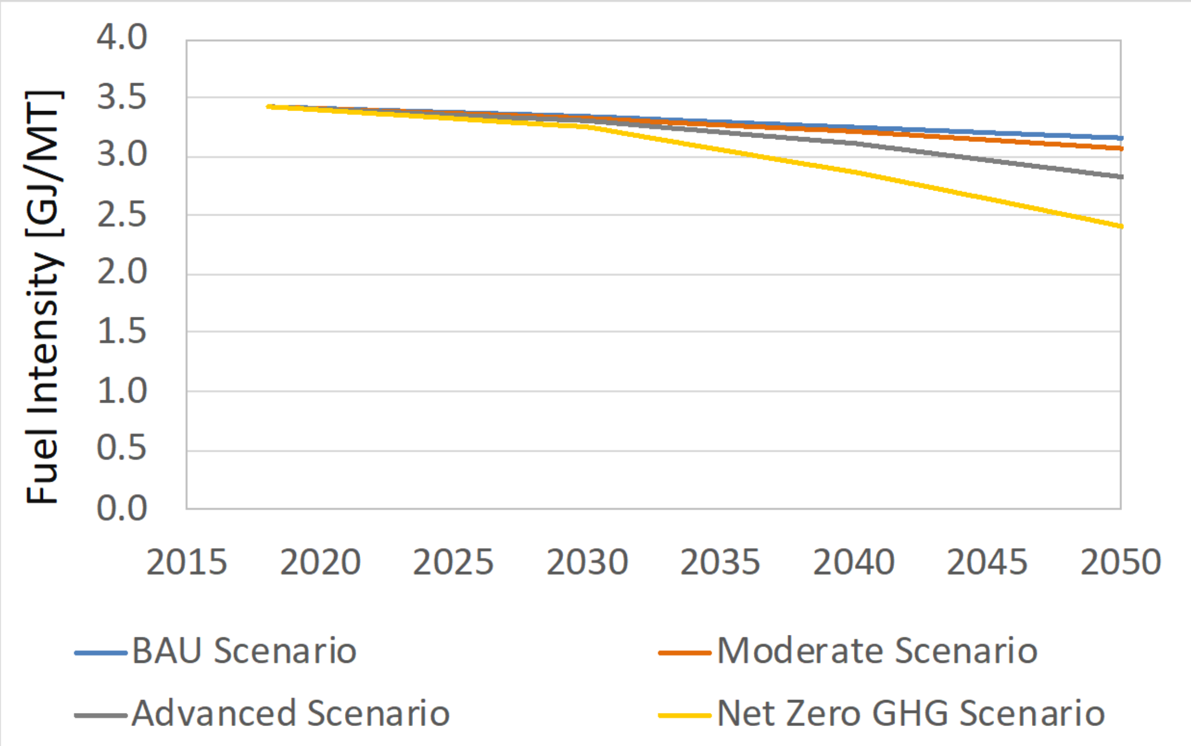


Figure A. Forecasted **fuel** intensity of the U.S. cement industry up to 2050 under different scenarios

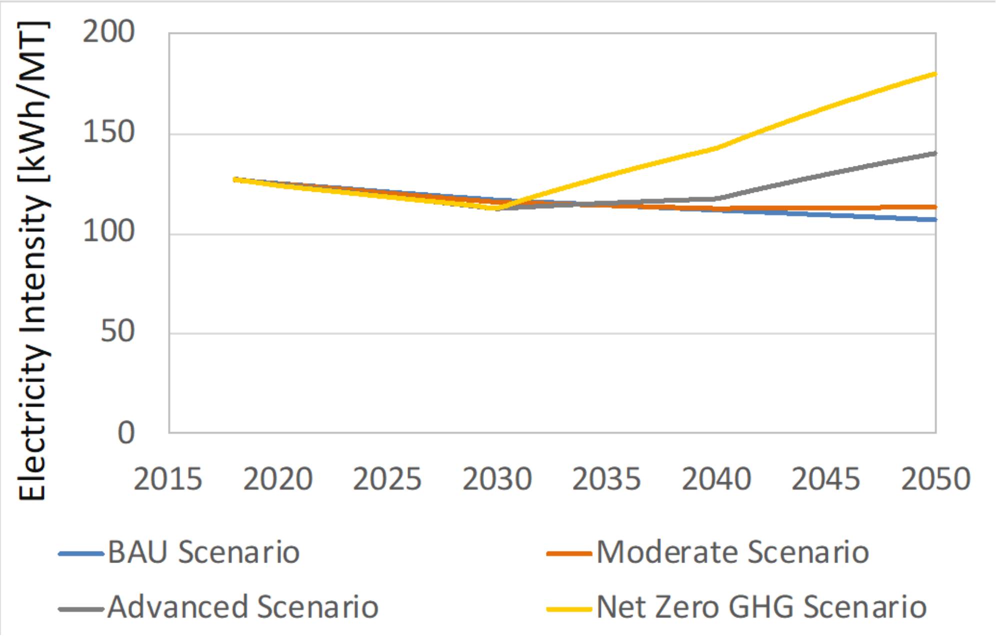


Figure B. Forecasted **electricity** intensity of the U.S. cement industry up to 2050 under different scenarios

Electrification pillar contributes to about 9% of emissions reduction from 2018 to 2050

- **Electric** Limestone Calcined Clay Cement is modeled under electrification pillar,
- **Fuel-Based** Limestone Calcined Clay Cement is modeled under LCFFES pillar.

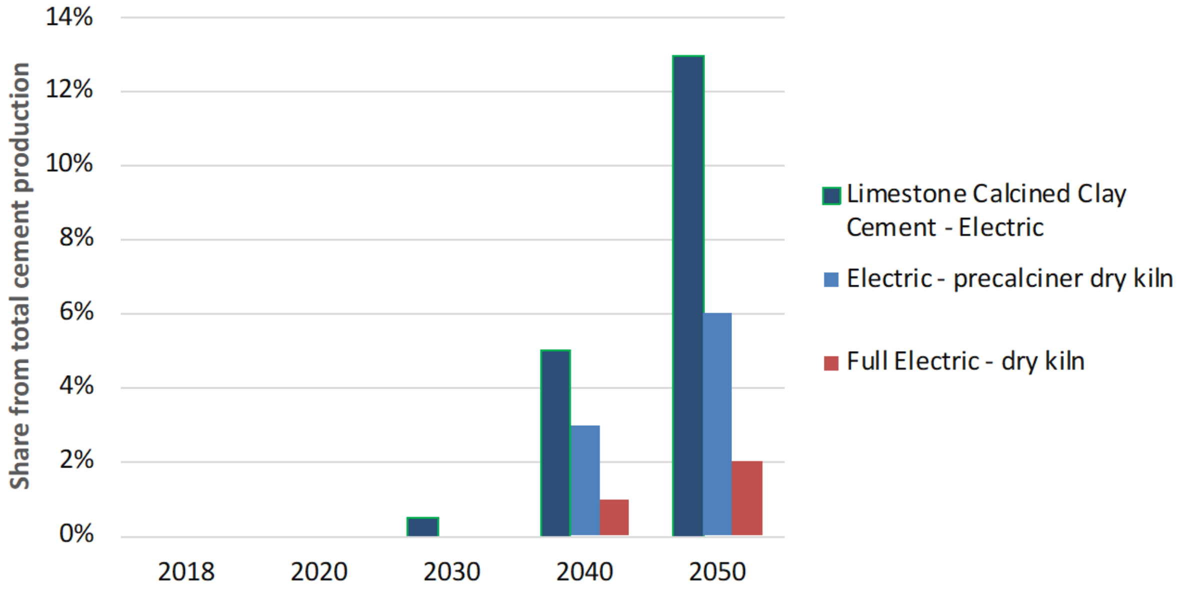


Figure A: Share of electrified production routes from total cement production in the U.S. under **Net Zero GHG scenario**.

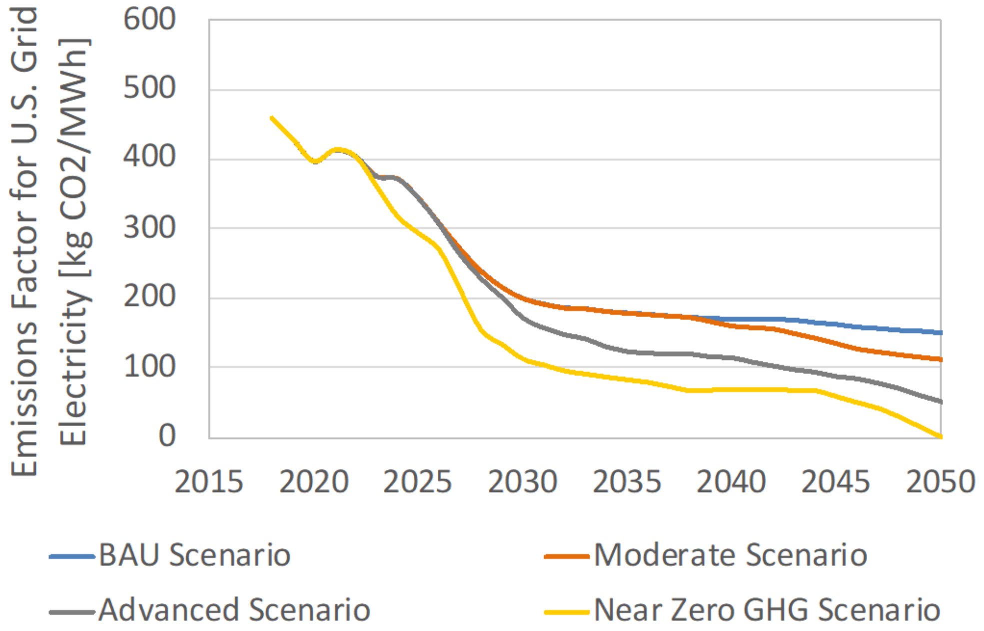


Figure B: Electricity grid CO_2 emissions factor forecast in the U.S. under the different scenarios

LCFFES pillar contributes to about 41% of emissions reduction from 2018 to 2050

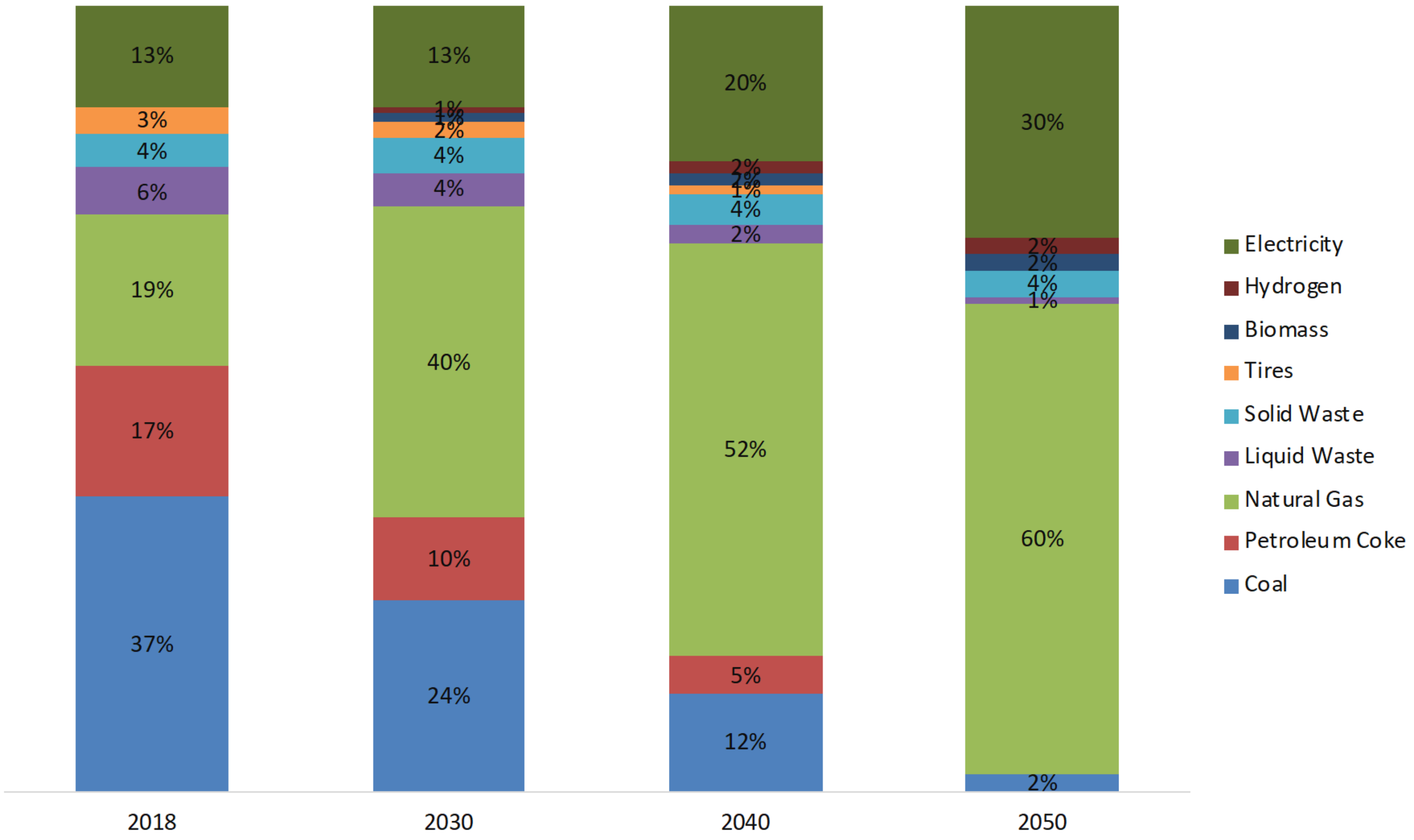
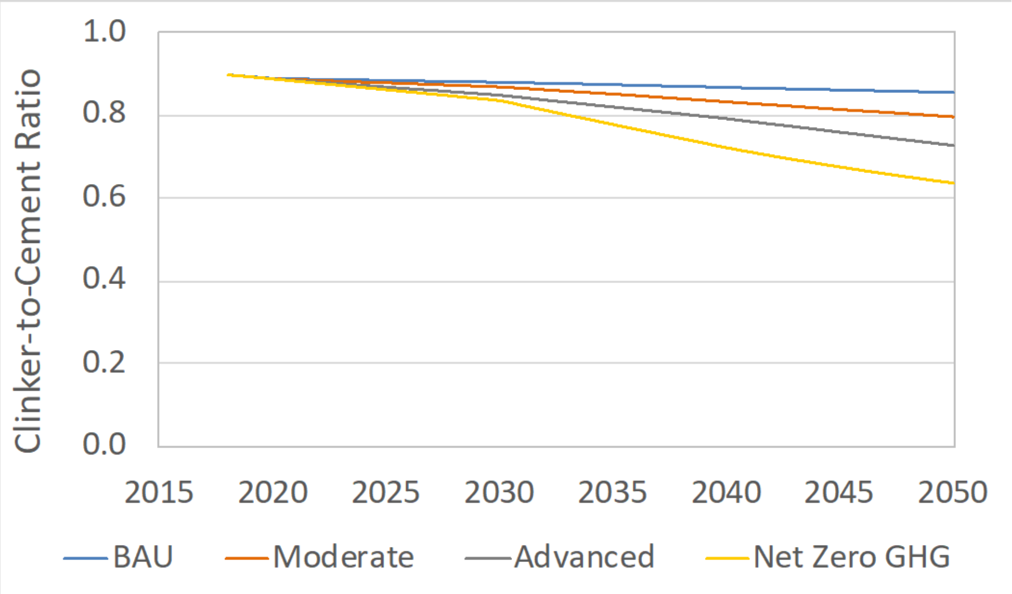


Figure : **Energy mix** projections for the U.S. cement industry under the **Net Zero GHG scenario**, 2018-2050

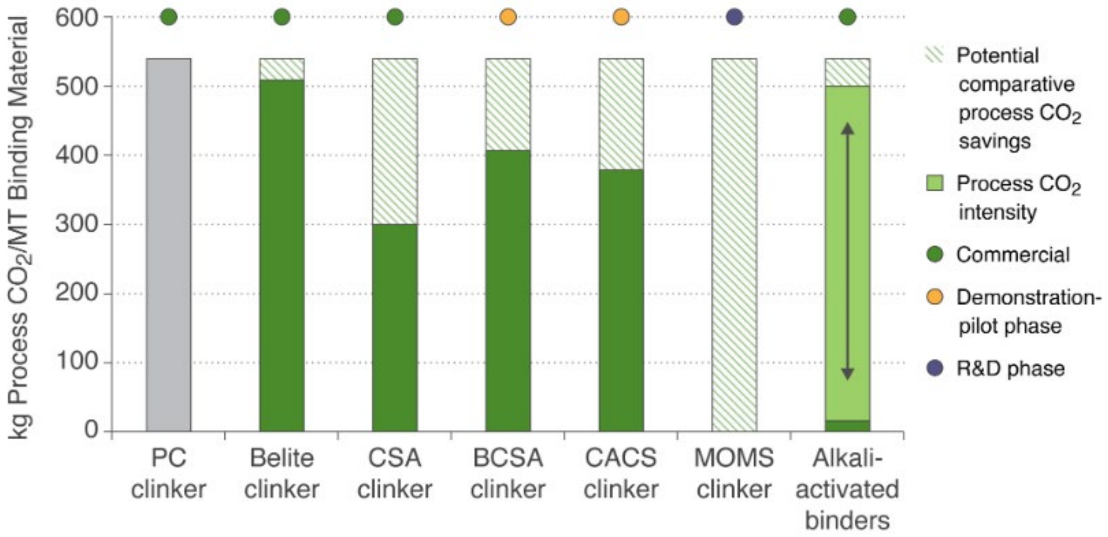
LCFFES: Clinker to cement ratio and supplementary cementitious materials (SCMs)



Overall clinker to cement ratio of the U.S. cement industry up to 2050 under different scenarios

- Utilizing SCMs like fly ash, blast furnace slag, ground limestone, calcined clay, etc. in cement reduces energy use and CO_2 emissions per ton of cement produced.
- The LCFFES pillar contributes to 41% of CO2 emissions reduction during 2018-2050 under the Net Zero GHG scenario and clinker-to-cement ratio reduction is a key part of that.
- Limestone Calcined Clay Cement is an emerging commercialized blended cement where up to 50% of clinker is substituted with calcined clay and limestone, maintaining performance while reducing emissions.
- Limestone Calcined Clay Cement is gaining momentum in the U.S. and globally.
- Clay calciner can use either fuel or electricity for heating.

LCFFES: Alternative binding materials/Alternative cement



Process-related CO_2 emissions intensity for cement binding materials

- Included only 3 alternative cements
  - Belite based cement
  - Carbonatable Calcium Silicate cement
  - Calcium Sulfoaluminate cement
- About 1% adoption in 2040 and 2% in 2050 in the Net Zero scenario.
- Alternative binding materials are not expected to have a substantial contribution to overal CO_2 emisisons reduction by 2050.

CCUS pillar contributes to about 44% of emissions reduction from 2018 to 2050

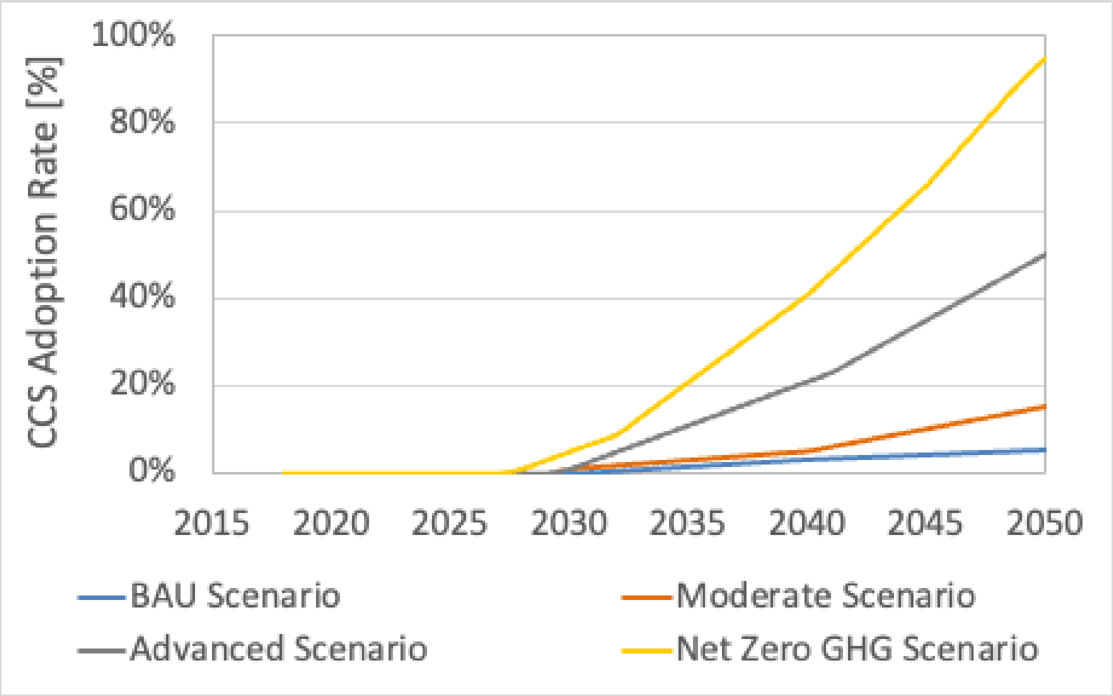


Figure A: CCS adoption rate in the US cement industry in each scenario

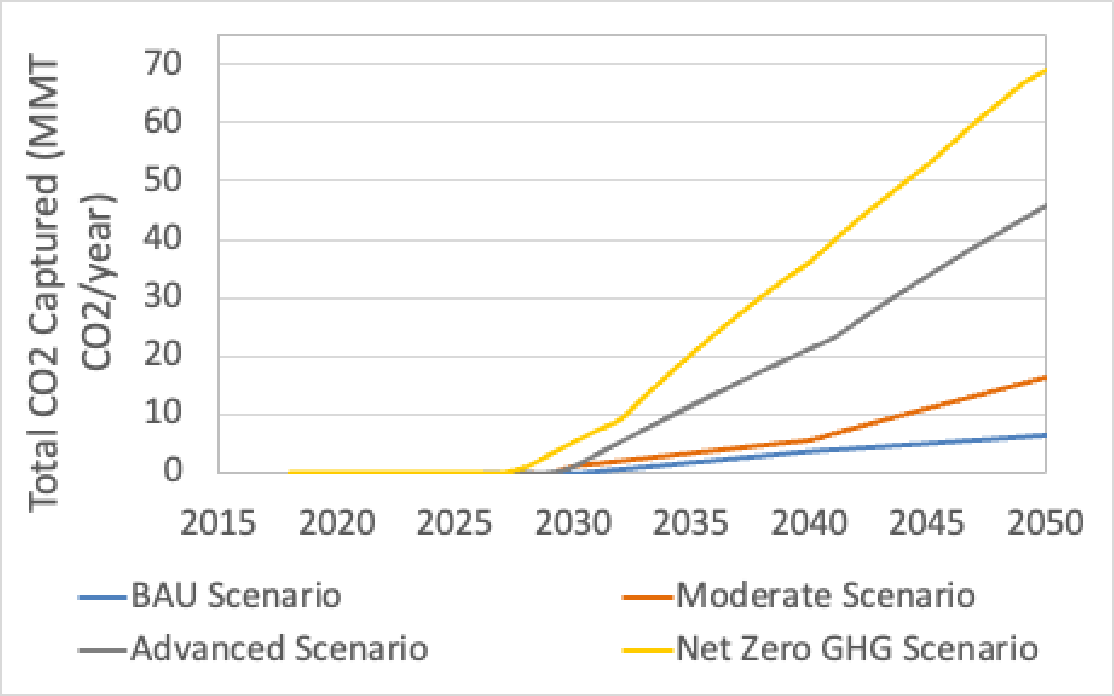


Figure B. Annual CO_2 captured in the U.S. cement industry in each scenario

Challenges

Energy Efficiency

- Tradeoffs in efficiency improvements. Changes to a single unit process may affect upstream or downstream efficiency or energy consumption.

Electrification

- Technological Challenges.
  - High heat demand of cement processes. Electrified alternatives to incumbent technology must meet process temperature demands (850ºC – 1500ºC), have comparable product throughput, and retain product performance characteristics.
  - Retrofitting existing facilities with electrified alternatives.
- Need for Additional Electric Infrastructure.
- Availability of a Large Amount of Clean Electricity.

Challenges

LCFFES

- Availability of SCMs and clinker alternatives, including regionality and supply chain.
- Unproven performance and safety (durability) characteristics of SCMs and alternative binders
- Limited access to low carbon fuels
- Regulatory/standards
    - Regulations – prescriptive building codes and standards.
    - Regionality of performance requirements of SCM-blended cement
    - Regulations around criteria air pollutants and solid waste
- Retrofitting existing equipment to accommodate low carbon fuels
- Cost – limited large scale production of SCMs and alternative binders = higher cost.

Challenges

CCUS

- No one size fits all solution – Unique geographical features and regionality of each facility may require a different set of approaches.
- Scale-up and cost reduction for cement/concrete products that leverage carbon utilization and mineralization.
- Uncertainty around the impact of carbon capture technologies on the product quality
- Energy and physical footprint needs.

Challenges

Sector-wide, pillar/technology agnostic

- Corporate inertia
- Risk adverse to implement new technologies
- Unpredictability of future regulatory landscapes and the complexities of permitting processes may increase cost and delays.
- Cost
  - CAPEX – upfront cost of installing new technologies, including energy efficiency, electrification, low carbon fuels and feedstocks (SCMs), CCUS.
  - OPEX, especially for electrified technologies compared with natural gas, CCUS.
  - limited large scale production of SCMs and alternative binders = higher cost

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Chemicals
Strategies and Analysis Summary

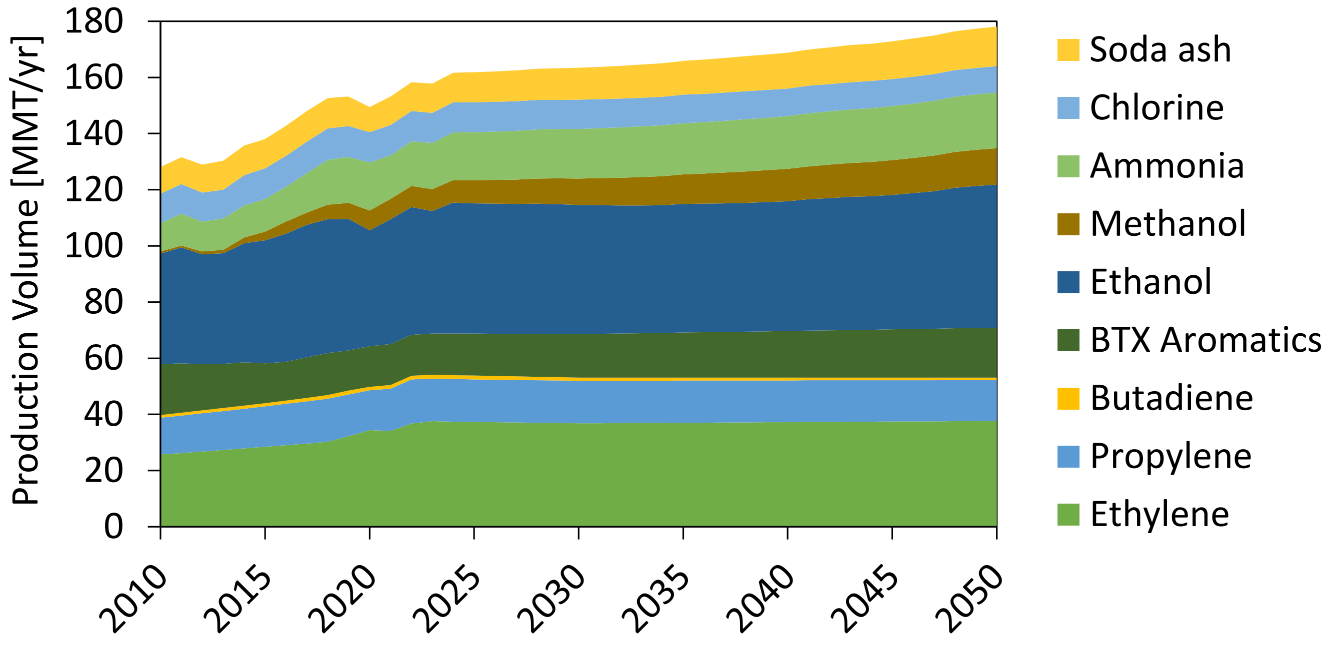
Industrial Efficiency and Decarbonization Office

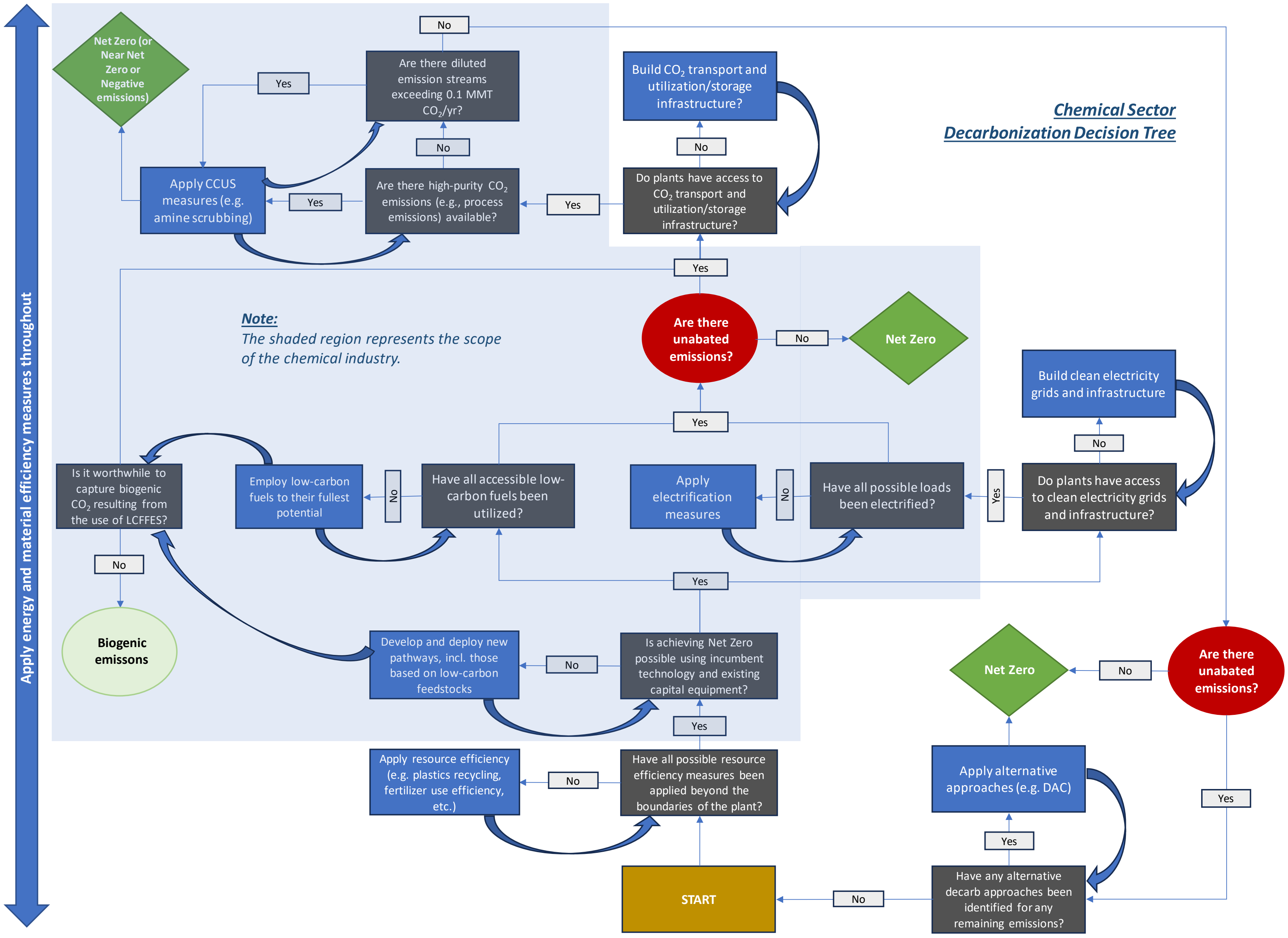
May 15, 2024

Context and framing for the Chemicals Sector

High level description of the industry

- The U.S. chemical industry contributed over 25% to the total GDP in 2022, valued at $486 billion.
- It manufactures 70,000+ distinct products across 11,000+ facilities.
- In 2022, the U.S. ranked as the world's second-largest chemical producer, meeting nearly 13% of global demand.
- The sector employs approx. 4.1 million individuals, directly or indirectly.
- It consumes 25% of total primary and 26% of final energy within U.S. manufacturing.
- Responsible for 28% of overall and 31% of onsite GHG emissions in U.S. manufacturing.
- Historical data shows a 16% growth in chemical production from 2010 to 2020.
- Projections suggest a further 20% growth in basic chemical production between 2020 and 2050.




Chemical Sector
Decarbonization Decision Tree
Apply energy and material efficiency measures throughout
Note:
The shaded region represents the scope of the chemical industry.
START
Have all possible resource efficiency measures been applied beyond the boundaries of the plant?
No
Apply resource efficiency (e.g. plastics recycling, fertilizer use efficiency, etc.)
Yes
Is achieving Net Zero possible using incumbent technology and existing capital equipment?
No
Develop and deploy new pathways, incl. those based on low-carbon feedstocks
Yes
Have all accessible low-carbon fuels been utilized?
No
Employ low-carbon fuels to their fullest potential
Is it worthwhile to capture biogenic CO_2 resulting from the use of LCFFES?
No
Biogenic emissons
Do plants have access to clean electricity grids and infrastructure?
No
Build clean electricity grids and infrastructure
Yes
Have all possible loads been electrified?
No
Apply electrification measures
Yes
Are there unabated emissions?
No
Net Zero
Yes
Do plants have access to CO_2 transport and utilization/storage infrastructure?
No
Build CO_2 transport and utilization/storage infrastructure?
Yes
Are there high-purity CO_2 emissions (e.g., process emissions) available?
Yes
Apply CCUS measures (e.g. amine scrubbing)
No
Are there diluted emission streams exceeding 0.1 MMT CO_2/yr?
Yes
No
Net Zero (or Near Net Zero or Negative emissions)
Are there unabated emissions?
No
Net Zero
Yes
Have any alternative decarb approaches been identified for any remaining emissions?
Yes
Apply alternative approaches (e.g. DAC)
No

Chemicals Waterfall Chart

Petrochemicals (325110)

Ethylene	Propylene	Butadiene	Benzene, Toulene, Xylenes (BTX aromatics)
Steam cracking (NGL)	Steam cracking	Steam cracking	Pygas from naphtha steam cracking
Steam cracking (napththa)	Fluidized catalytic cracking	Electrified steam cracking	Reformate from catalytic reformers
Steam cracking (gas oil)	Propane catalytic dehydrogenation	Direct glucose to butadiene	Toluene disproportionation
Electrified steam cracking	Metathesis	Ethanol to butadiene	Toluene hydrodealkylation
Methanol-to-olefins (MTO) (ethylene)	Electrified steam cracking		Methanol-to-aromatics (MTA)
Ethanol dehydration	Methanol-to-olefins (MTO) (propylene)		

Basic Organic Chemicals (325193, 325199)

Ethanol	Methanol
Dry milling	Steam-methane reforming (SMR)
Wet milling	Autothermal reforming (ATR)
Electrified dry milling process	Biomass gasification
Syngas fermentation	Water electrolysis / CO_2 to methanol

Basic Inorganic chemicals (325180)

Chlorine-Sodium Hydroxide (Chlor-Alkali)	Sodium Carbonate (soda ash)
Mercury cell technique	Monohydrate process
Diaphragm cell technique	Carbonation process (Searles lake)
Membrane cell technique	Electrified process
Oxygen depolarized cathode (ODC)	

Nitrogenous Fertilizers (325311)

Ammonia
Steam-methane reforming (SMR)
Coal gasification
Ammonia synthesis only
Autothermal reforming (ATR)
Water electrolysis
Methane Pyrolysis
Biomass gasification

Key:

Conventional production pathway

Emerging production pathway

> Covers ~1/3rd of the sectoral GHG emissions

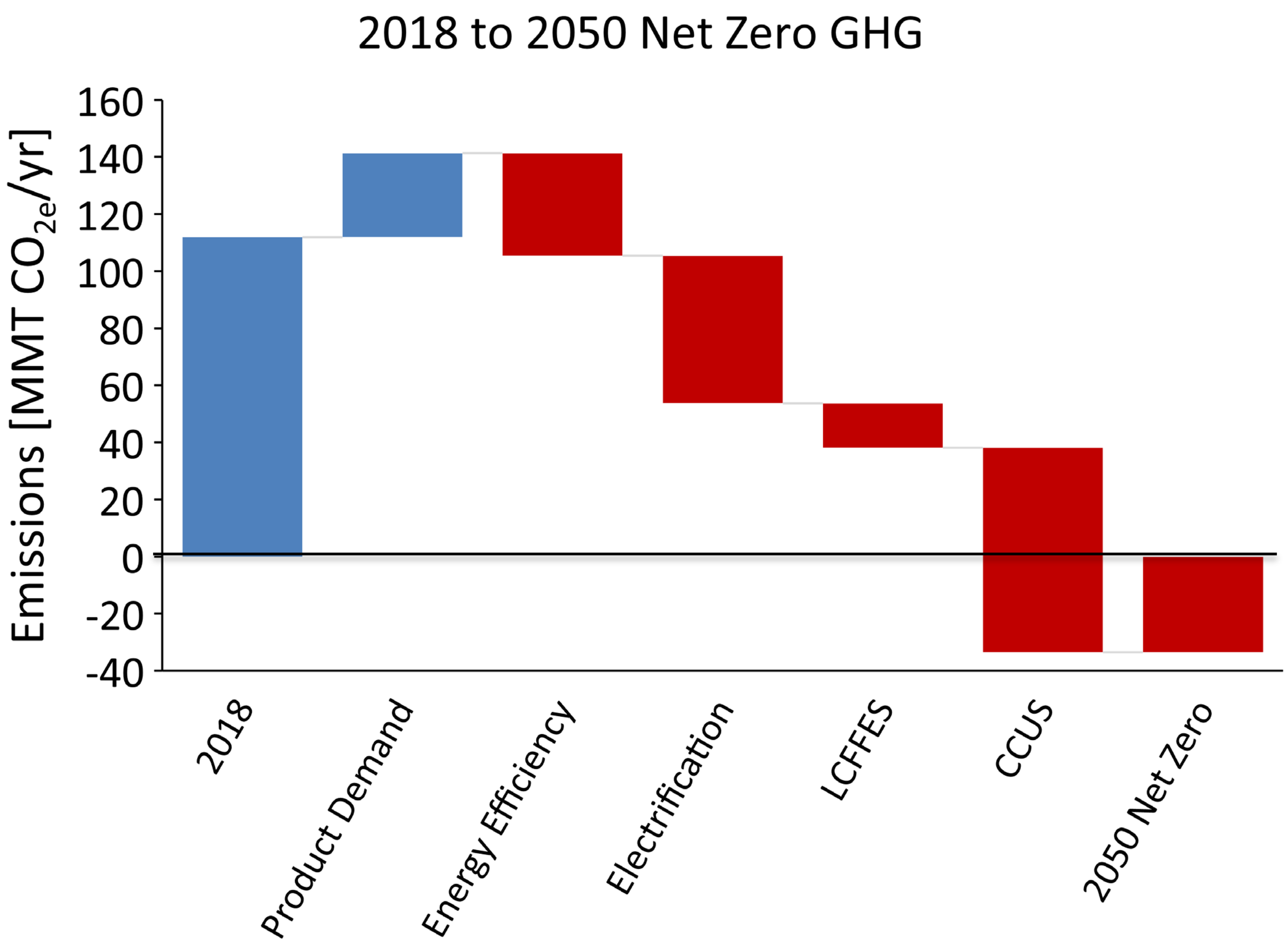
> For *most* studied pathways:

Fuel and electricity intensities disaggregated by:

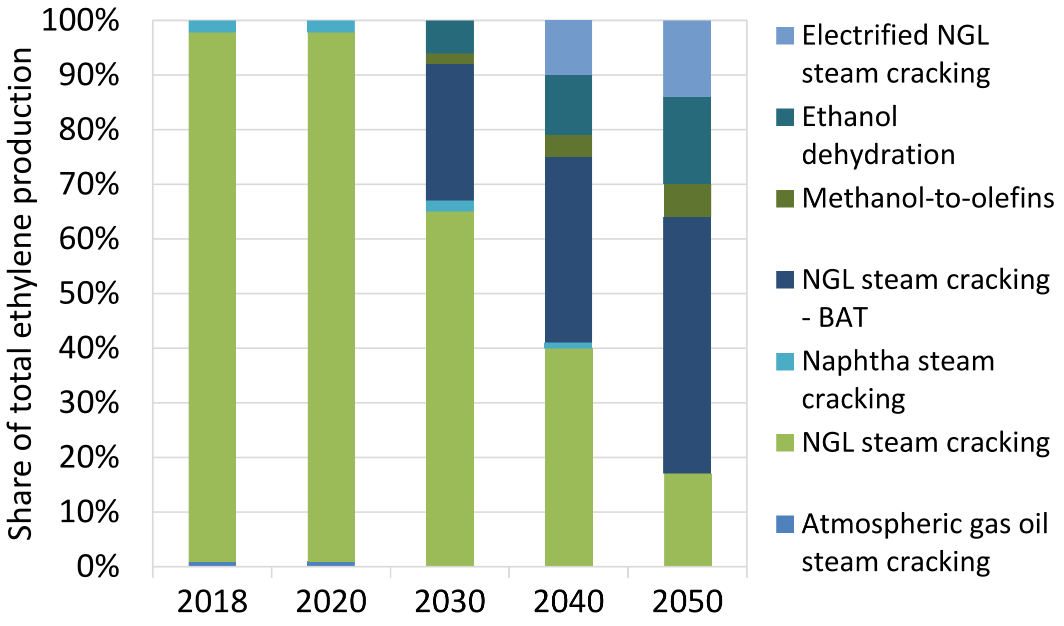
- *unit operation*
- *energy carrier*
- *end use applications*

Chemicals Waterfall Chart

Preliminary results for nine large-scale energy-intensive chemicals manufacturing



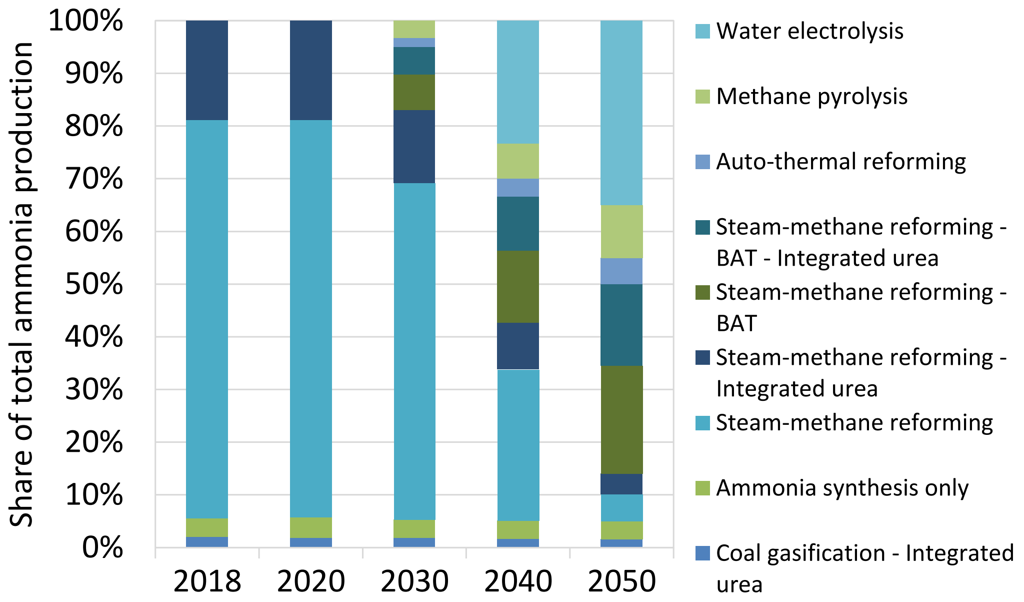
Ethylene Production Routes



- Future will be a mix of both thermochemical cracking and alternative processes (e.g., electrified cracking, ethanol dehydration, and methanol-to-olefins).

Material efficiency	Energy efficiency - EE	Electrification	Low carbon fuels, feedstocks, and energy sources - LCFFES	Carbon capture, utilization, and storage - CCUS
Major assumptions and impact: Assuming a 50% plastics recycling rate by 2050 could ultimately impact the future demand for ethylene in relevant plastics manufacturing.	**Major assumptions:** *Up to 75% of NGL steam cracking to adopt BAT by 2050. *Phase out AGO and naphtha steam cracking by 2050. *0.8% p.a. autonomous improvement. **Impact:** A 24% reduction in projected CO_2 emissions in 2050.	**Major assumptions:** *Impact from electricity grid decarbonization. *Transition 14% to electrified steam cracking by 2050, starting from 2030. **Impact:** A 15% reduction in projected CO_2 emissions in 2050.	**Major assumptions:** *Transition 16% to ethanol dehydration and 6% to MTO in 2050. *Use of byproduct fuels. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 7% reduction in projected CO_2 emissions in 2050.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** A 33% reduction in projected CO_2 emissions in 2050.

Ammonia Production Routes



- Hydrogen feedstock production remains primary decarbonization lever for ammonia in 2050
- Future will be a mix of thermal reforming and alternatives (e.g., water electrolysis (35%), methane pyrolysis (10%), and some direct ammonia synthesis.

Material efficiency	Energy efficiency - EE	Electrification	Low carbon fuels, feedstocks, and energy sources - LCFFES	Carbon capture, utilization, and storage - CCUS
Major assumptions and impact: A 10% reduction in demand by 2050 is assumed due to ammonia use efficiency measures, with fertilizer use efficiency contributing significantly at 75%.	**Major assumptions:** *Up to 80% of conventional SMR-HB to adopt BAT by 2050. *Transition 5% to ATR in 2050. *0.8% p.a. autonomous improvement. **Impact:** A 15% reduction in projected CO_2 emissions for 2050 due to EE measures.	**Major assumptions:** *Impact from electricity grid decarbonization. *Transition 10% to methane pyrolysis and 35% to water electrolysis in 2050. **Impact:** A 53% reduction in projected CO_2 emissions in 2050.	**Major assumptions:** *Switch entirely to NG where renewable alternatives are not applicable. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 2% reduction in projected CO_2 emissions in 2050.	**Major assumptions:** Capture 90% of all direct CO_2 emissions by 2050. **Impact:** A 25% reduction in projected CO_2 emissions in 2050.

Chemicals-Specific Challenges and Drivers

Manufacturing Transition Challenges:

- Complexity of shifting to low-carbon processes.
- Concerns over co-product yields and pathway maturity.

Feedstock Dynamics:

- Market shifts affecting availability and pricing.
- Impact of declining fuels demand on petrochemical feedstock market.

Integrated Process Adaptation:

- Retrofitting challenges for complex plants.
- Costliness of adapting highly integrated processes.

Electricity Demand and Infrastructure:

- Increased demand and need for infrastructure upgrades.
- Reliance on renewables for sustainability.

Economic Constraints and RD&D:

- Challenges in justifying low-carbon alternatives economically.
- Importance of research for cost-competitive alternative pathways.

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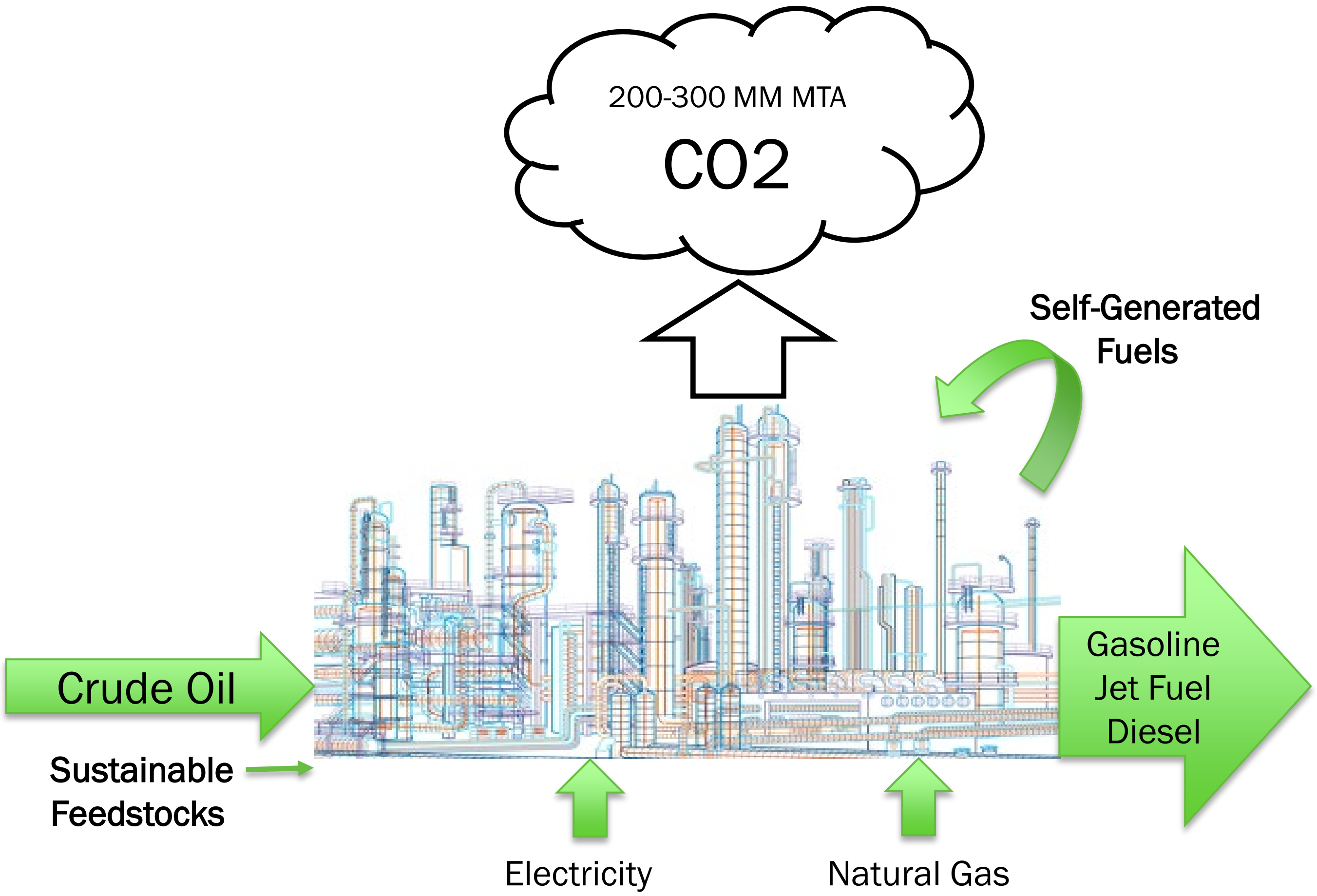
Petroleum Refining Strategies and Analysis Summary

Industrial Efficiency and Decarbonization Office

May 15, 2024

Context and framing for the Petroleum Refining Sector

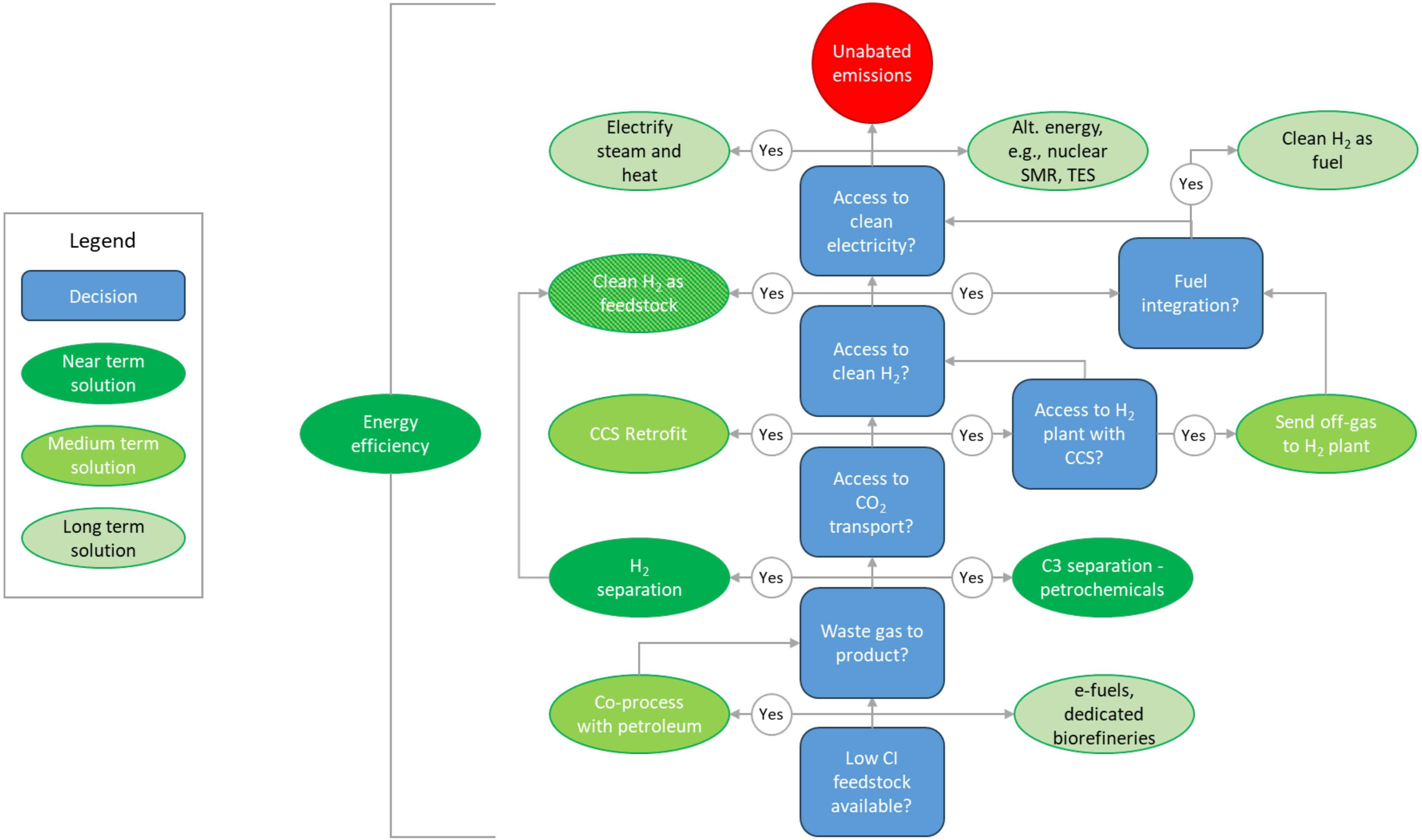


- ~ 125 operating refineries in the U.S.
- Process ~16 million barrels of crude oil per day. 18.7% of global refining capacity.
- Over 85% of product slate is gasoline, diesel, and jet fuels
- Over 50% of sector fuel self-generated
- Generate nearly 300 billion gallons of refinery products per year
- ~20-30 Process units per refinery
- Over 20 % of the manufacturing industry CO_2 emissions
- Over 3 % of US total CO_2 emissions

Minor products include LPG, butane, petrochemical feedstocks, coke, asphalt, and fuel oil.

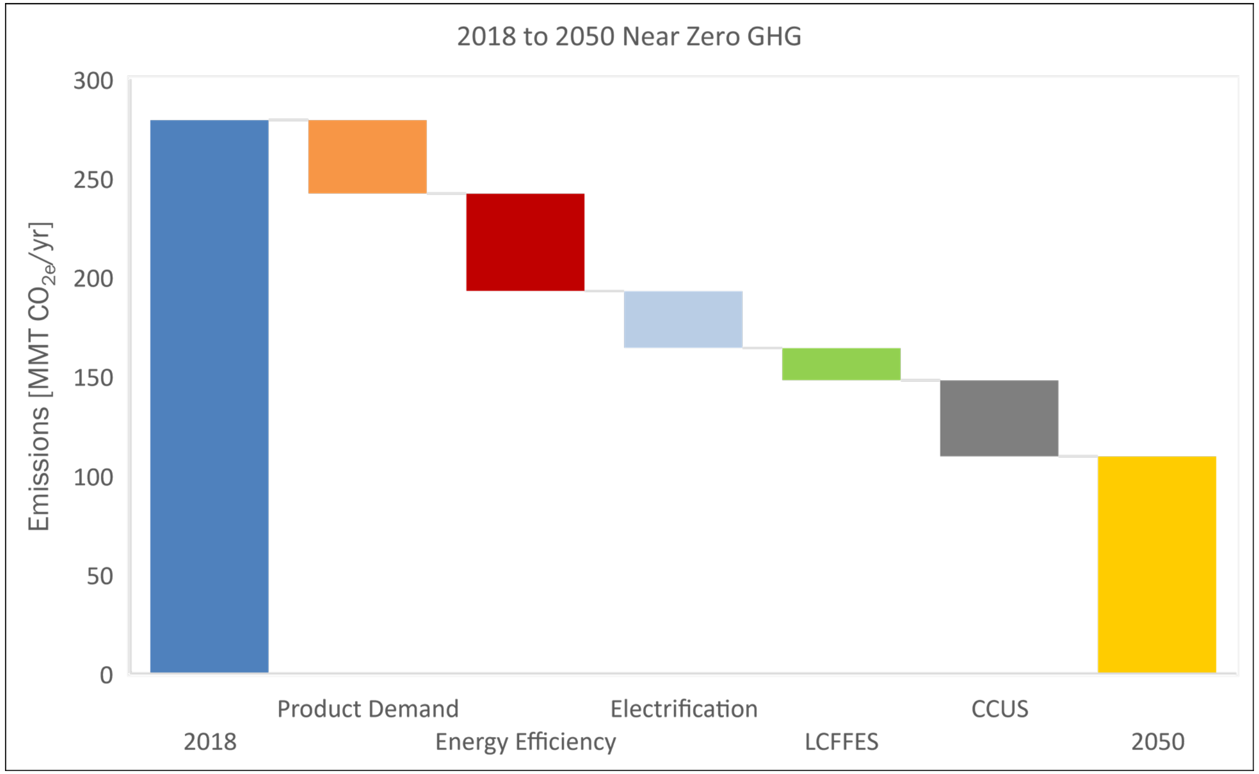
Source: HPI Market Data 2023, U.S. Energy Information Administration

Refining Decarbonization Technology Decision Tree



Refining Waterfall Chart and Assumptions

Scope 1 and 2

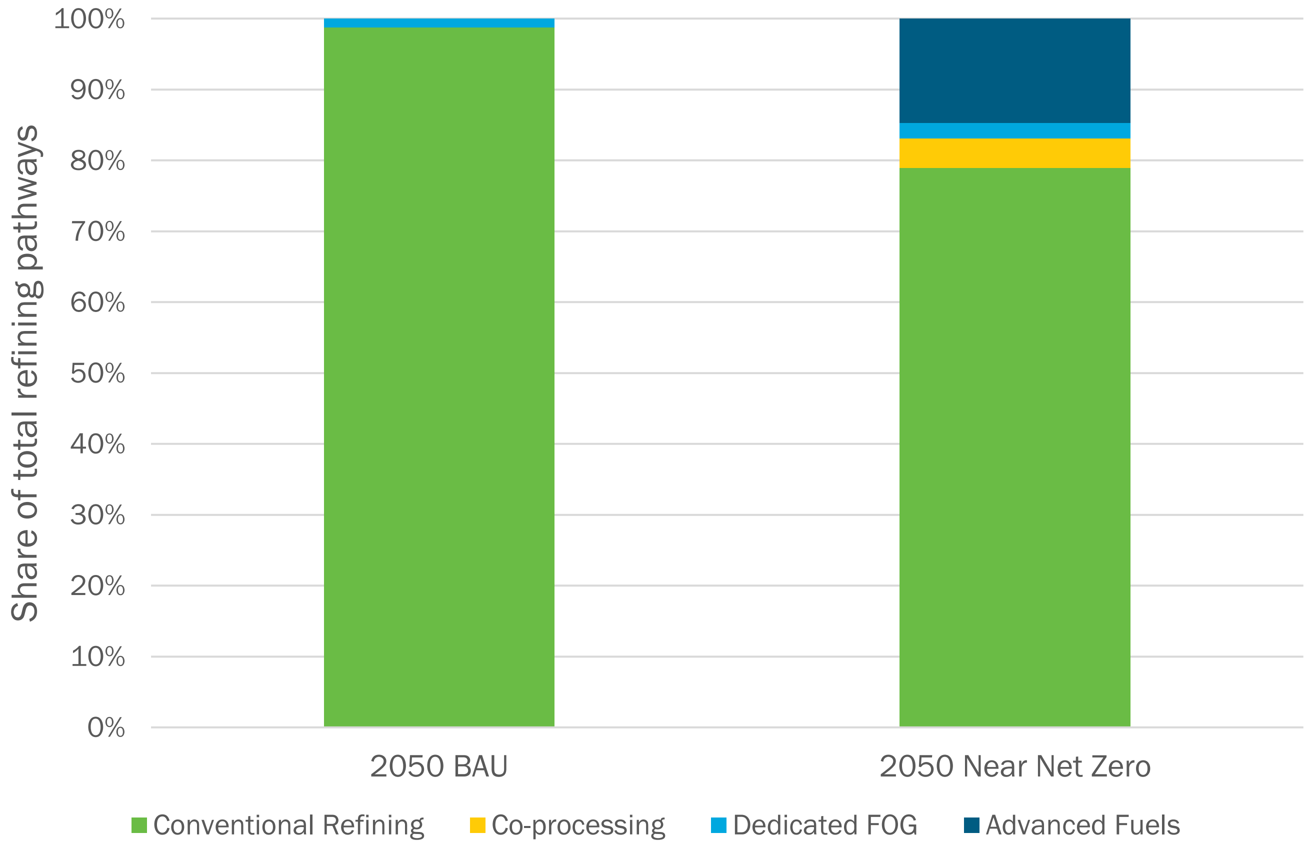


Scenario	Product Demand	Energy Efficiency	Electrification	LCFFES	CCUS
Near Net-Zero	~20% reduction in crude feedstock throughput	1.0%/year	~30% electrolysis H2 feedstock, 10-15% electrified boiler duty	AEO Reference case planned capacity RD and biodiesel	~30% capture from H2 plants, ~50% from cogeneration, and ~10% FCC

Scenario	Grid electricity	Hydrogen supply	Alternative feedstocks	Crude Reduction	CO_2 infrastructure
Near Net-Zero	Decarbonized grid by 2050	Larger buildout within OCED Regional Hydrogen Hub regions	AEO Reference case planned capacity renewable diesel and biodiesel, plus slight additions based on IEA and NREL sources	Reduction in petroleum crude consistent with the potential availability of feedstocks in the DOE Billion Ton Study and goals set in the Sustainable Aviation Fuel Grand Challenge.	National CO_2 pipeline expansion, leveraging pipeline networks proposed by the Carbon Capture Coalition (2021)

PRELIMINARY DATA. DO NOT CITE.

Petroleum Refining Production Routes



PRELIMINARY DATA. DO NOT CITE.

- Near net-zero 2050 conventional refining and dedicated FOG pathways improve carbon intensity by over 50% and 70%, respectively, relative to 2050 BAU.
- Significant growth in advanced pathways (~15%), such as biomass-derived pyrolysis oils and CO_2 utilization, will require development of cost-competitive processing and conversion technologies.
- Modest decarbonization of refinery products results in significant downstream decarbonization of transportation sector.

Petroleum Refining-Specific Challenges and Drivers

Conventional Refining Challenges:

- Extensive, multi-scale efficiency improvements CapEx constrained.
- Gradual improvements tied to end-of-life equipment replacement.

Dedicated FOG based SAF/RD Plants Challenges:

- FOG feedstock availability constraints.
- Dependence on financial incentives for competitiveness.
- Requirement for new feedstocks, low-cost pre-treatment technologies, and advanced catalysts/process designs.

Co-Processing of Bio-based Crude Substitute Challenges:

- Limited availability and logistics of biobased feedstocks.
- Requirement for spare capacity in existing assets.

Advanced Fuel Pathways Challenges:

- Developmental stage with limited cost competitiveness.
- Focus on advanced process designs, new catalysts, and pre-treatment technologies.
- Potential long-term support for circular economy initiatives.

Access to low cost, low CI H_2

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Food and Beverage Strategies and Analysis Summary

Industrial Efficiency and Decarbonization Office

May 15, 2024

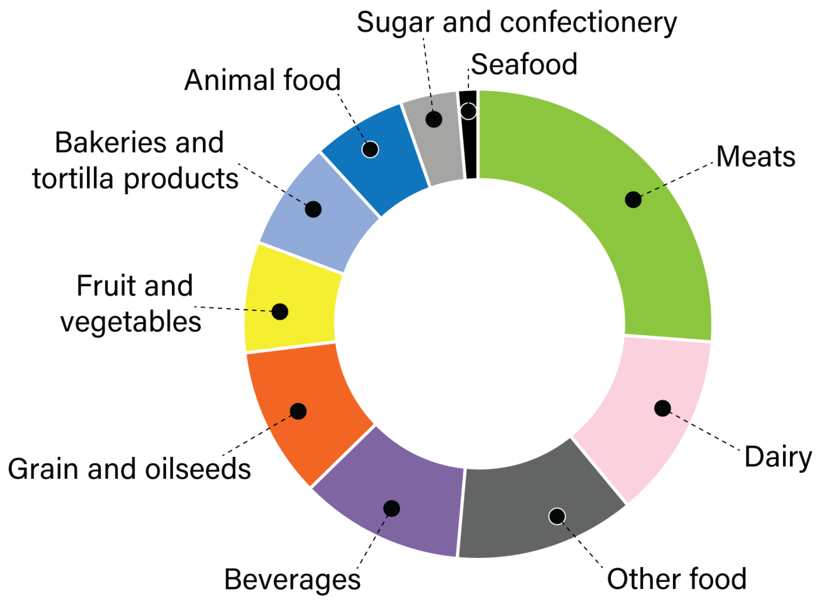
U.S. Food & Beverage Manufacturing

U.S. Food & Beverage Manufacturing in 2021:

- $1 trillion sales/value of shipments/revenue[1]
    - 16.8% of manufacturing sector's sales[1]
- $463 billion value added[1]
- 1.7 million workers[1]
    - 15.4% of all manufacturing plant employees
    - 1.1% of all U.S. nonfarm employment
- 41,080 plants[2]
    - California (6,301)
    - Texas (2,782)
    - New York (2,662)

Components of food and beverage manufacturing: Sales, value of shipments, or revenue by industry, 2021

Meat processing (26 percent) and dairy product manufacturing (13 percent) are the largest components of the food sector's sales

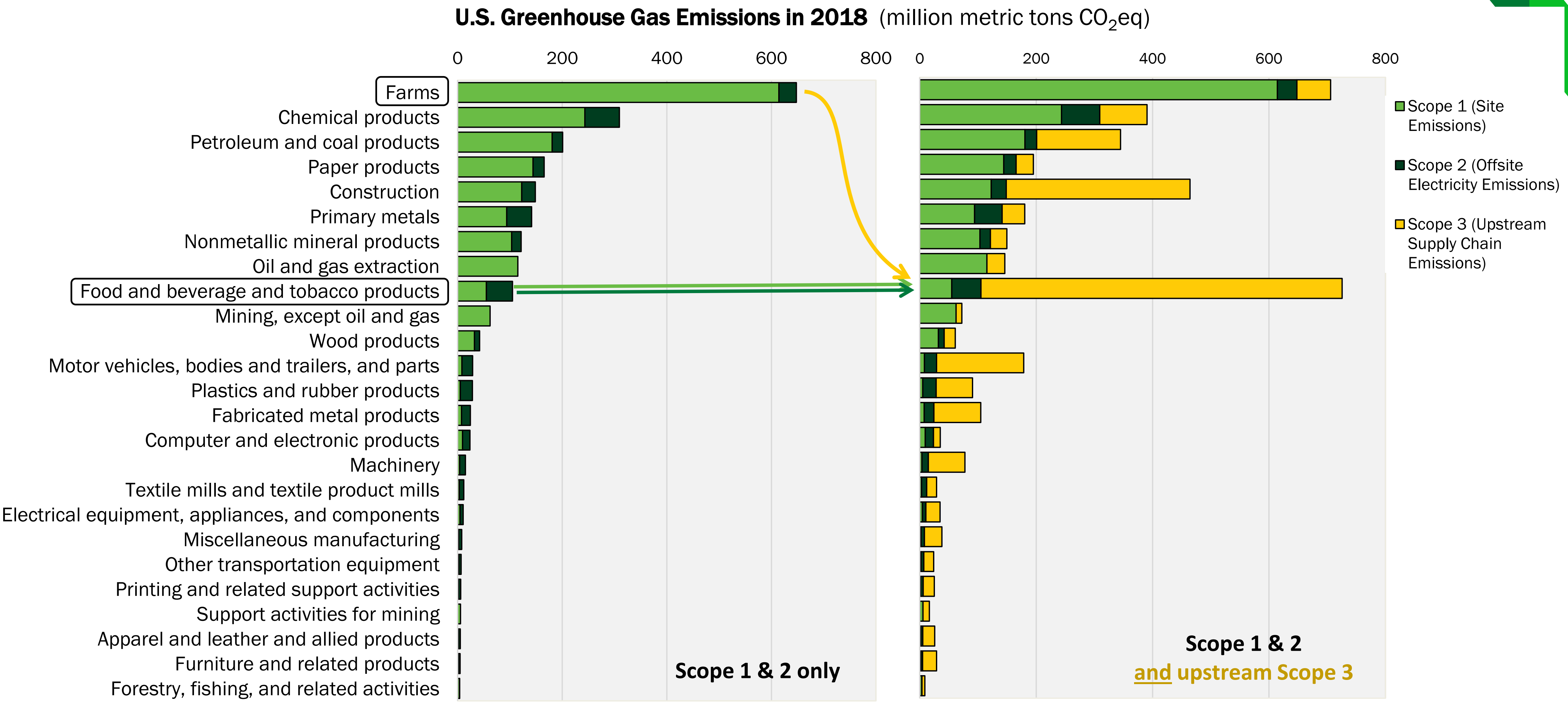


Source: USDA, Economic Research Service using data from U.S. Department of Commerce, Bureau of the Census, 2021 Annual Survey of Manufactures; data as of December 2022.

Sources: 1. U.S. Census Bureau. "Annual Survey of Manufactures." 2022. https://www.census.gov/programs-surveys/asm.html. 2. U.S. Census Bureau. "County Business Patterns." 2022. https://www.census.gov/programs-surveys/cbp.html
Data summarized on USDA. "Food and Beverage Manufacturing." 2023. https://www.ers.usda.gov/topics/food-markets-prices/processing-marketing/food-and-beverage-manufacturing/

Figure source: USDA 2023. https://www.ers.usda.gov/topics/food-markets-prices/processing-marketing/food-and-beverage-manufacturing/; **Data source:** U.S. Census Bureau. 2022. https://www.census.gov/programs-surveys/asm.html

GHG Emission in Context: Significance of Supply Chain Emissions



Data Source: DOE EEIO-IDA tool

For more information, see Strategic Analysis poster on the EEIO-IDA tool

Food and beverage and tobacco products

EEIO-IDA United States Base Case Results

Total Emissions (2018)

Scope 1 & 2	Scope 1, 2 & 3
105	726

million metric tons CO_2eq

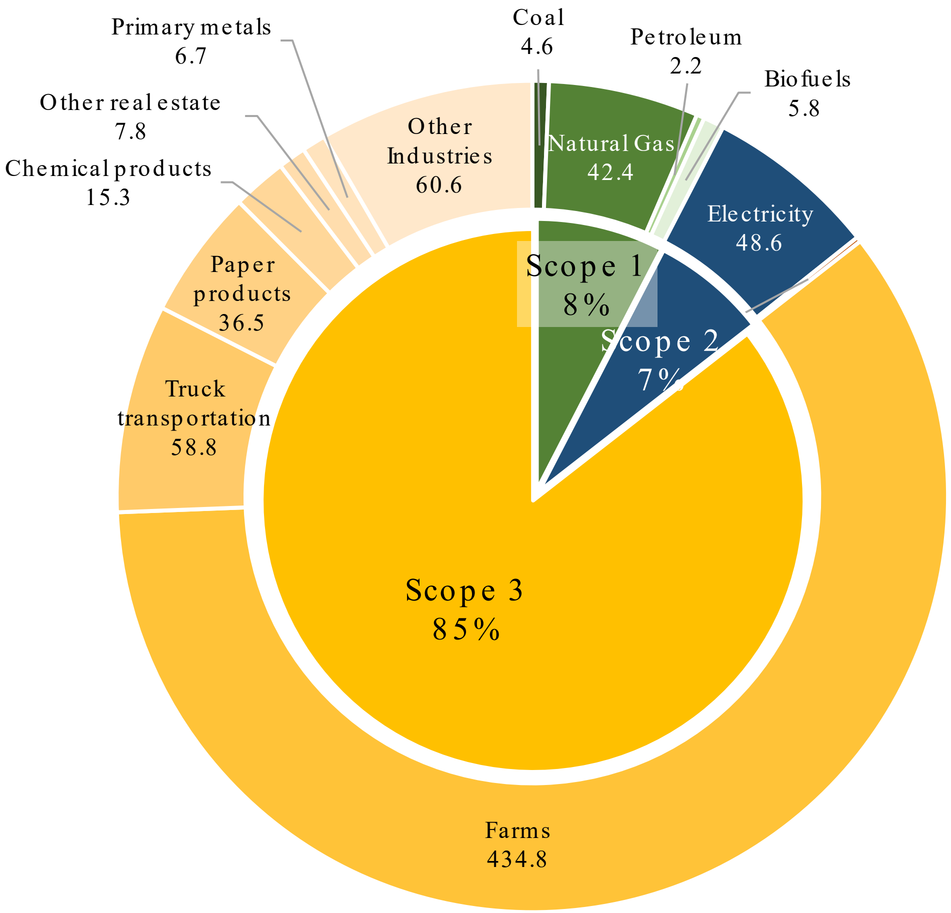
Top 5 upstream (source) sectors for inherited embodied emissions:

- Farms
- Truck transportation
- Paper products
- Chemical products
- Other real estate

Top 5 downstream (destination) sectors for this sector's products:

- Food and beverage and tobacco products*
- State and local general government
- Food services and drinking places
- Social assistance
- Hospitals

* Destination is end-users of this sector's products



Food and beverage and tobacco products

(NAICS 311, 312)

Scope 1, Scope 2, and Upstream Scope 3 Emissions of the Food and Beverage and Tobacco Products Sector

2018 Base Case
(million metrics tons CO_2eq)

Scope 1 (onsite combustion) emissions represent 8% of the embodied emissions of this sector's products

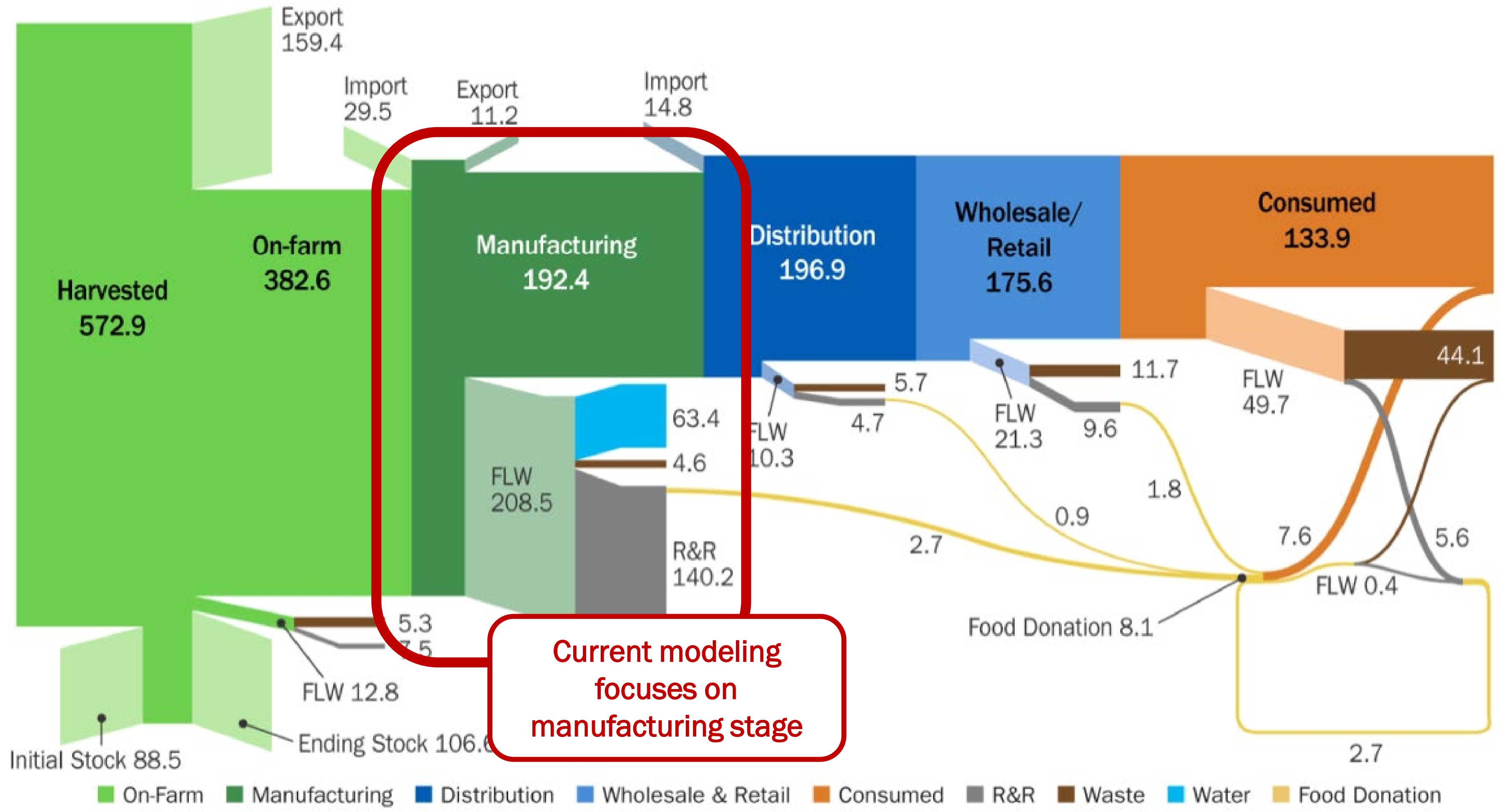
Scope 2 (offsite electricity generation) emissions represent 7% of the embodied emissions of this sector's products

The remaining 85% of embodied emissions are **Scope 3** (upstream supply chain)

All emissions shown are cradle-to-gate and do not include downstream impacts of product distribution or use

For more information, see Strategic Analysis poster on the EEIO-IDA tool

U.S. Food Supply Chain Mass Flow

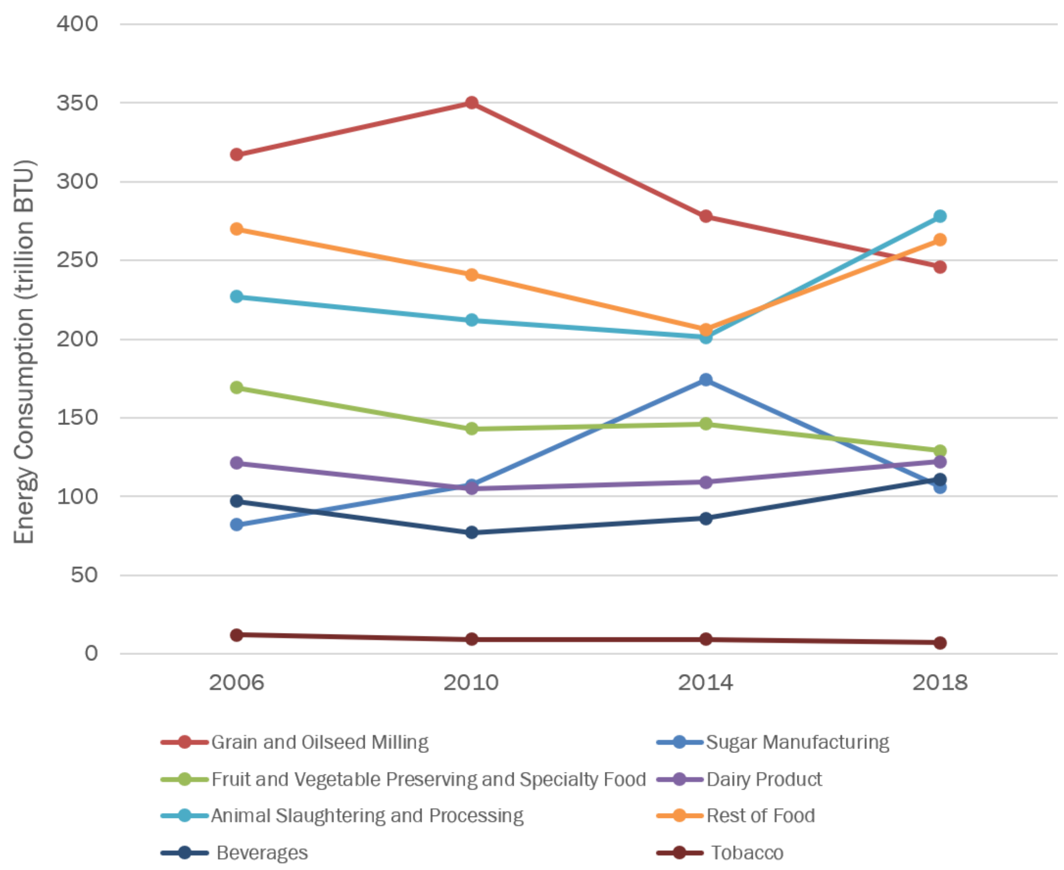


FLW = food loss and waste
R&R = recycled and recovered

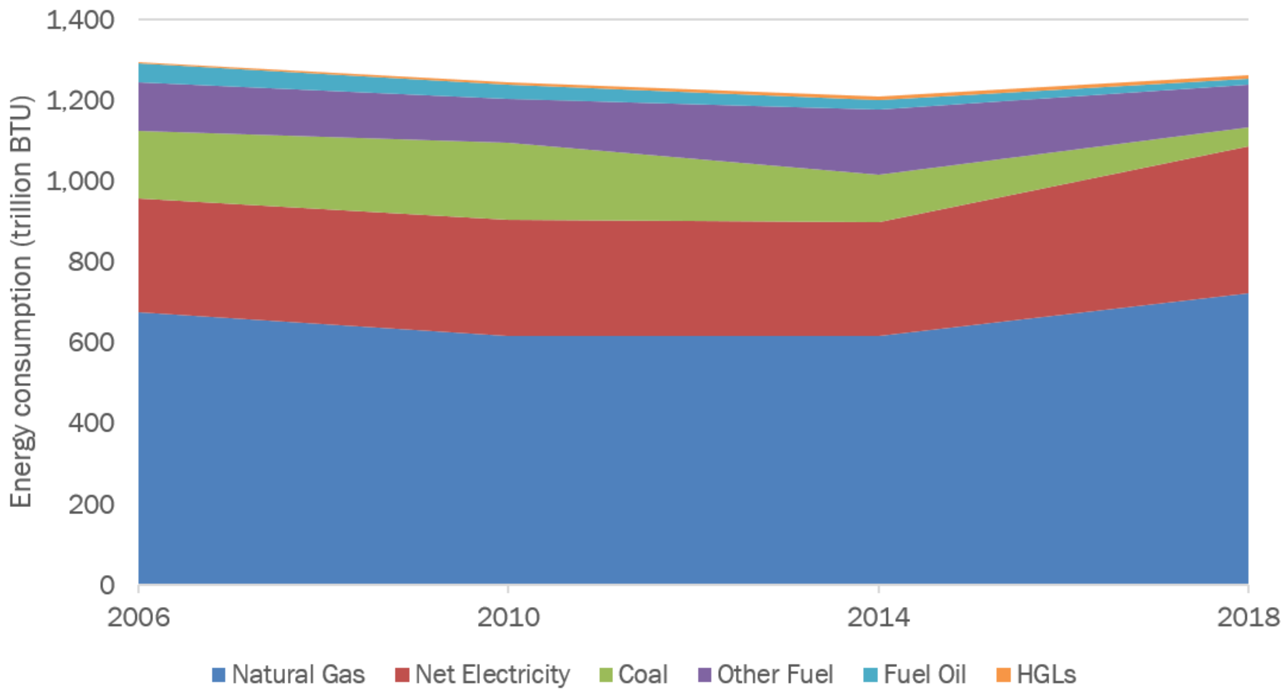
Values in MMT (million metric tons)
Figure 16 from DOE *Sustainable Manufacturing and the Circular Economy* Report, 2023

Manufacturing Energy Consumption Survey (MECS) historical data

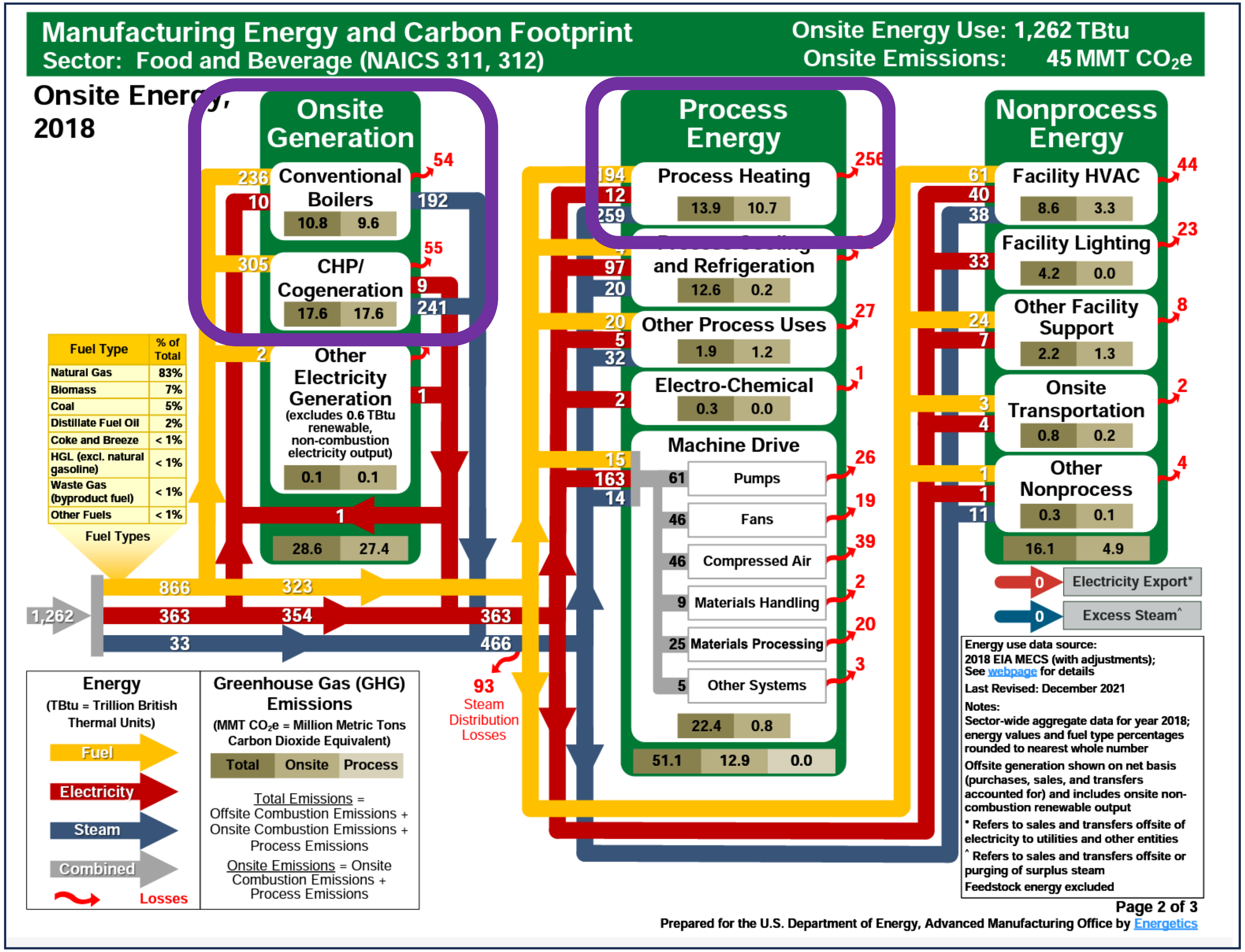
Food & beverage manufacturing energy consumption by subsector (trillion BTU) 2006-2018



Food & beverage manufacturing total energy consumption (trillion BTU) 2006-2018

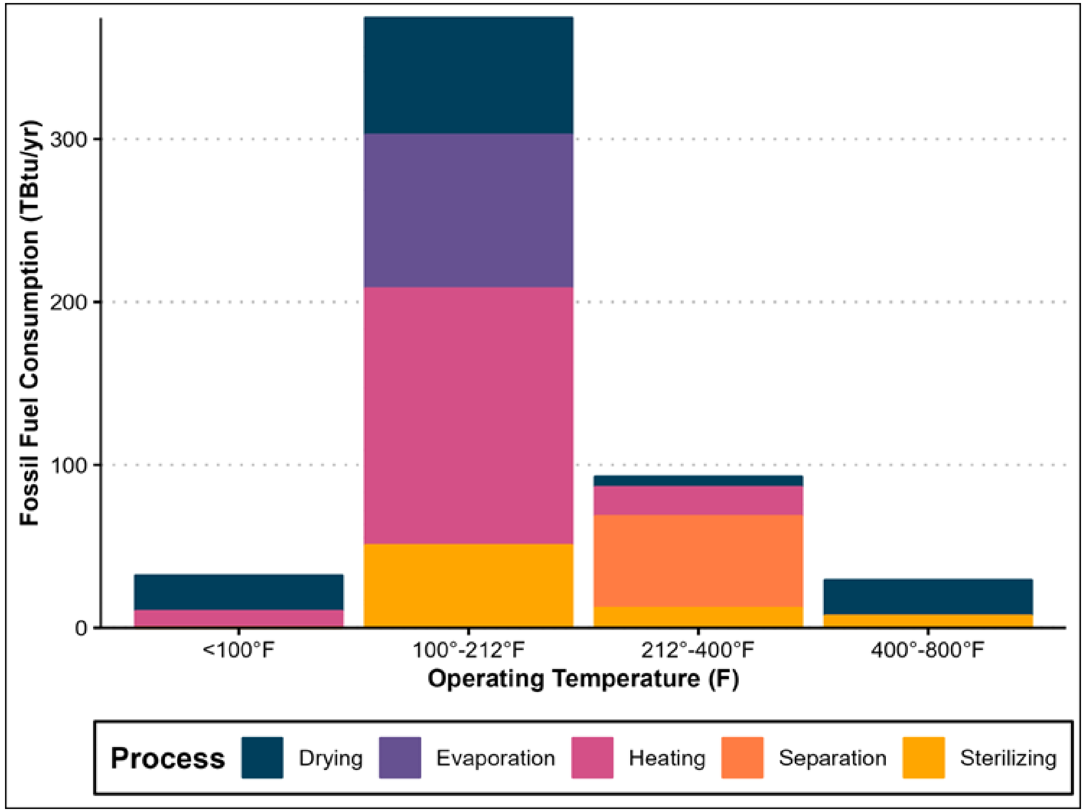


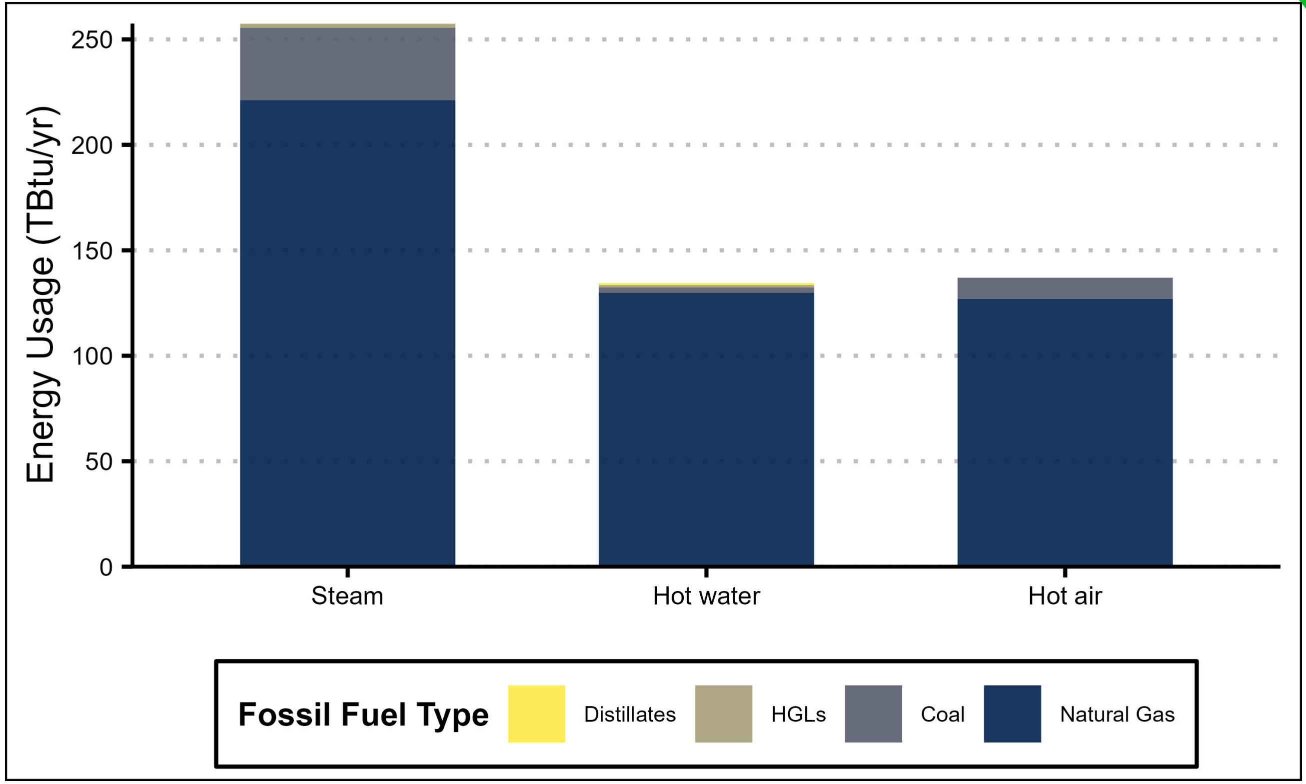
Food & Beverage Manufacturing Energy & Carbon Footprint (2018)



https://www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf

Better understanding of processes to better define decarbonization opportunities



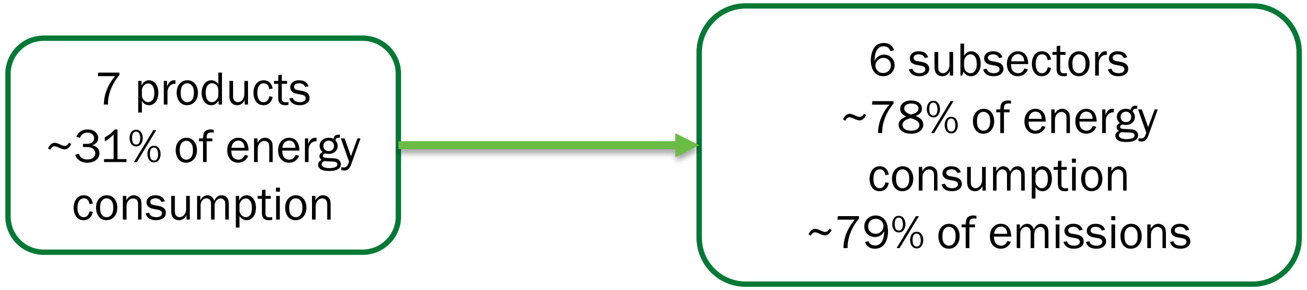


Food and beverage thermal process fossil fuel consumption by temperature range/heating medium demand for six modeled subsectors, 2018

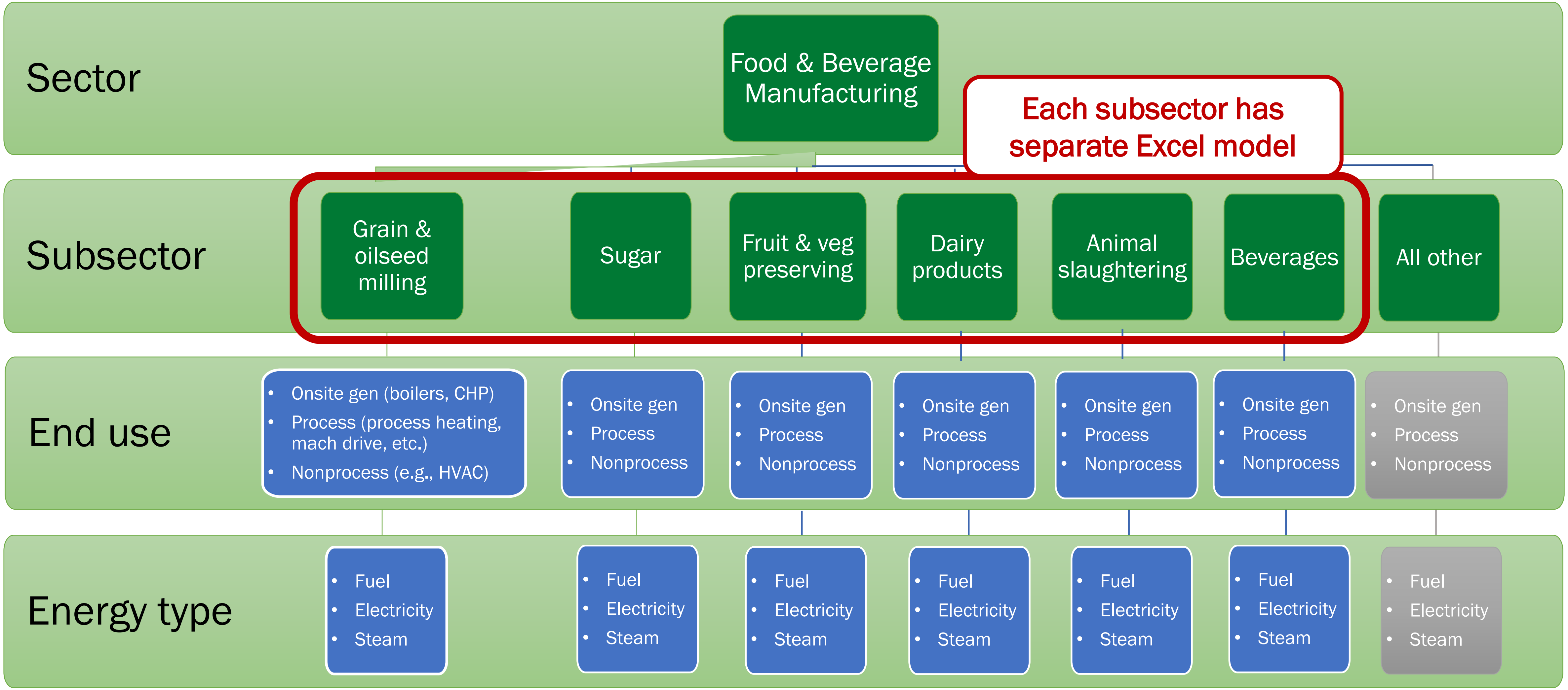
Developed from EIA MECS data and multiple sources:*Abed, Kurji, and Abdul-Majeed 2015; Bär and Voigt 2019; Beer Judge Certification Program 2008; Bostick 2018; Brush, Masanet, and Worrell 2011; Clottey 1985; Craft Beer and Brewing n.d.; Cresko, Thekdi, et al. 2022; Ensinas et al. 2007; EPA 1995; Sheehan et al. 1998; Masanet et al. 2008; Ramírez, Patel, and Blok 2006; Kalogirou 2003; Hurburgh, Misra, and Wilcke 2008; Dunford 2019; Mosenthin et al. 2016; Kemper 1998; Sugarprocesstech 2017; Sugarprocesstech 2021; Hugot 2014; Practical Action 2009; Safefood 360° 2014; Wiese and Jackson 1993; Siddiq and Uebersax 2018; Amit et al. 2017; Rotronic n.d.; Santonja et al 2019; Verheijen 1996; Sheridan and FAO 1991; Maribo et al. 1998; Dharmadhikari 2016; Stika 2009; Stier 2020; Ziegler 1979. "Sugar Boiling the Syrups in the Vacuum Pans." The Sugar Journal 42: 27.*

Food & Beverage Sector Modeling Additions

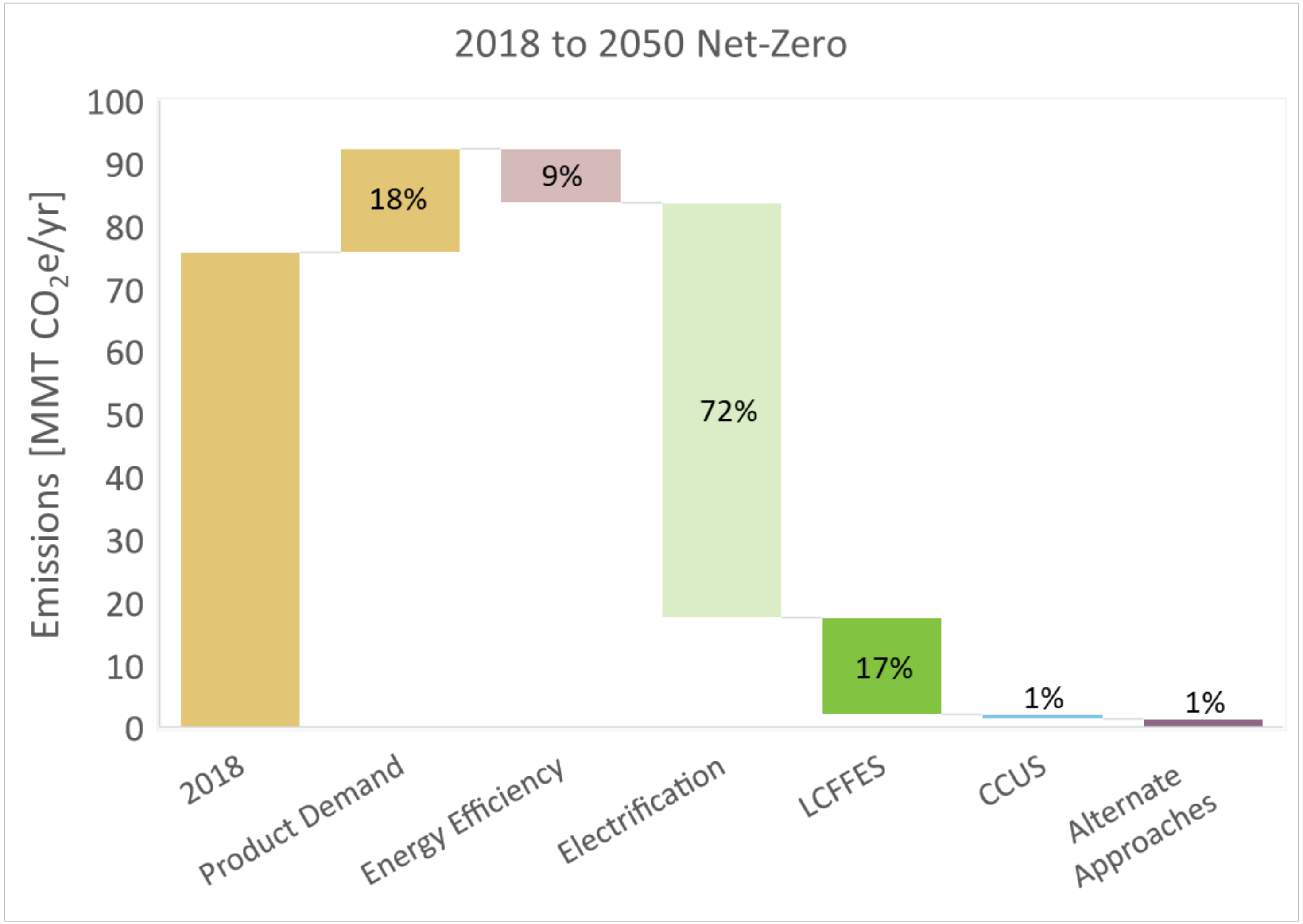
- Expanded **range of food/beverage products** & total sector coverage
- Updated **energy intensity, energy mix, and emissions**
- Better understand the **major processes** and decarbonization options
  - Detailed breakdown of process heating and other end uses
- Improve **electrification** assumptions/estimates
- Find better information on **reducing food waste** and how that will **influence the future demand**



Basic Breakdown of the Models



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)

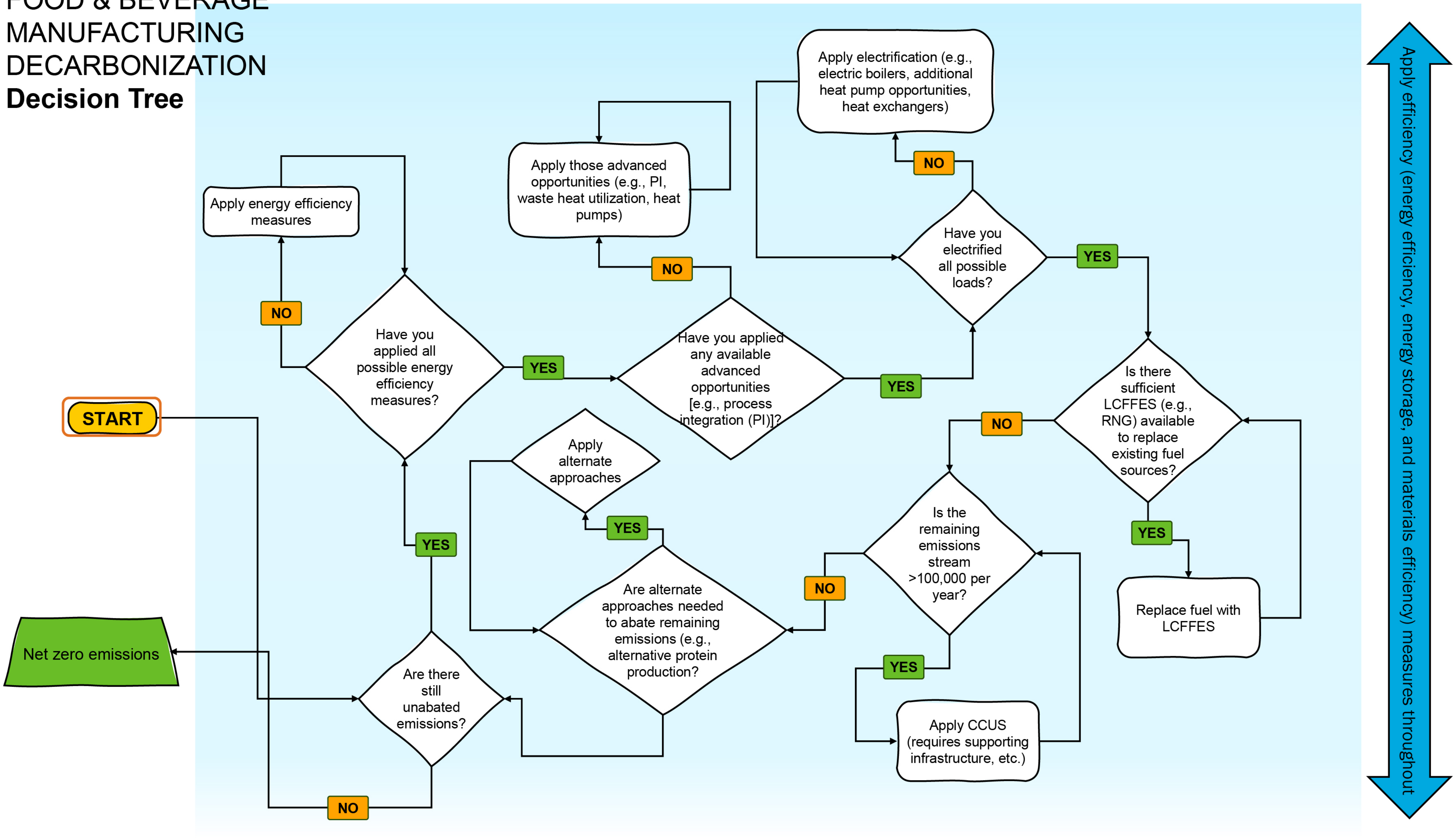
Subsectors modeled:

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

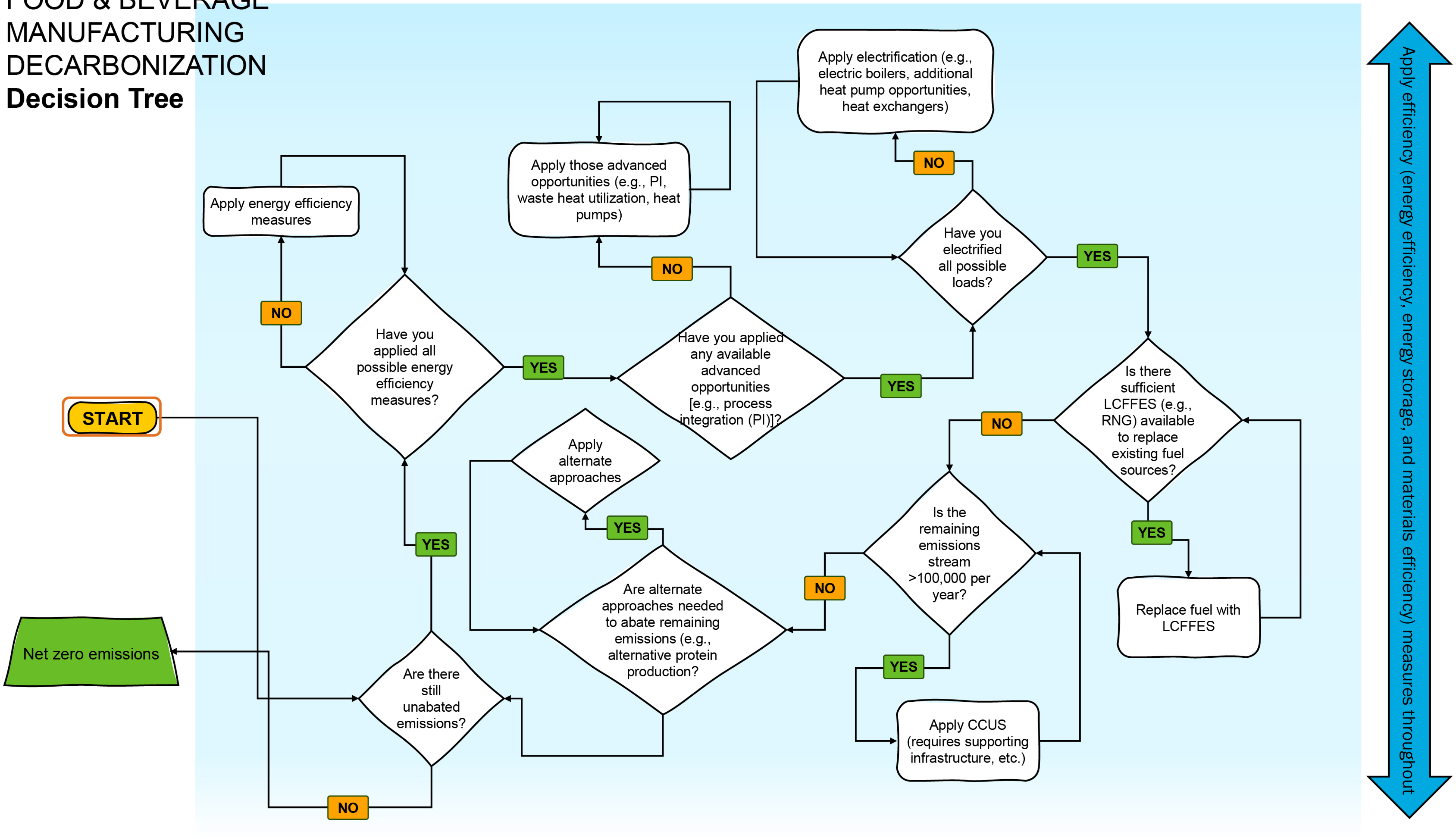
Account for 78% of energy and 79% of emissions total for food & bev subsector

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

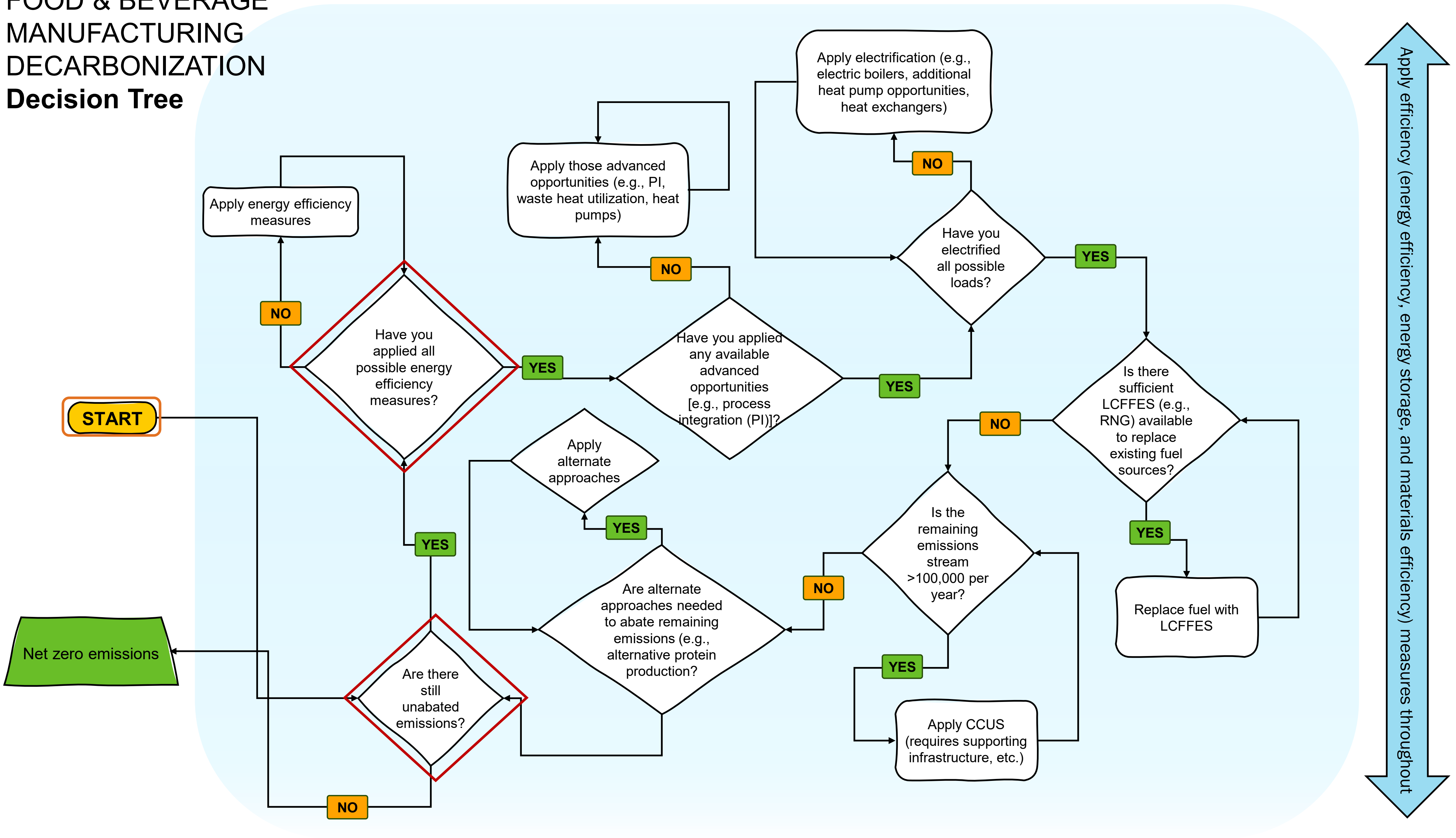
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



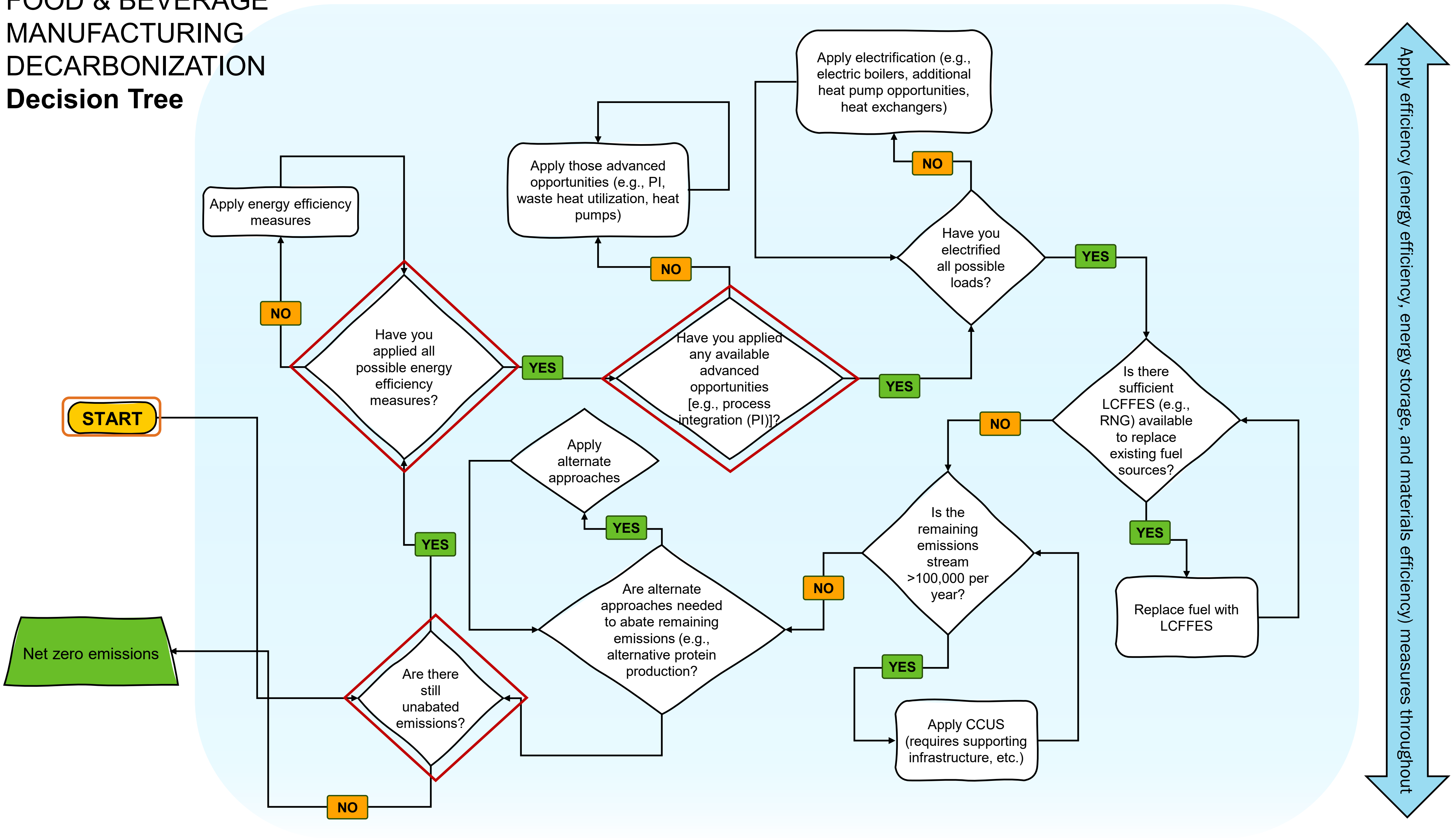
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



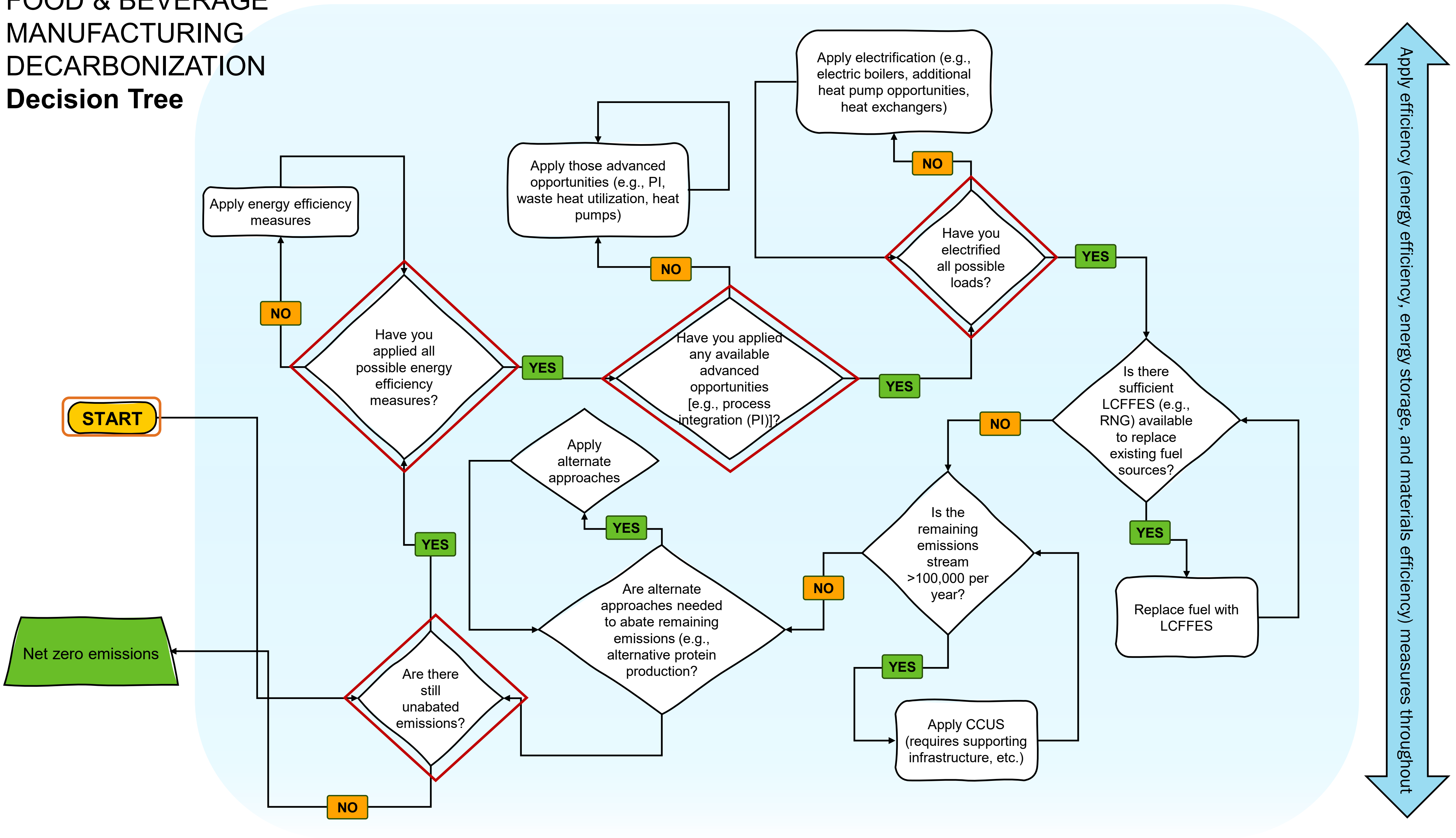
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



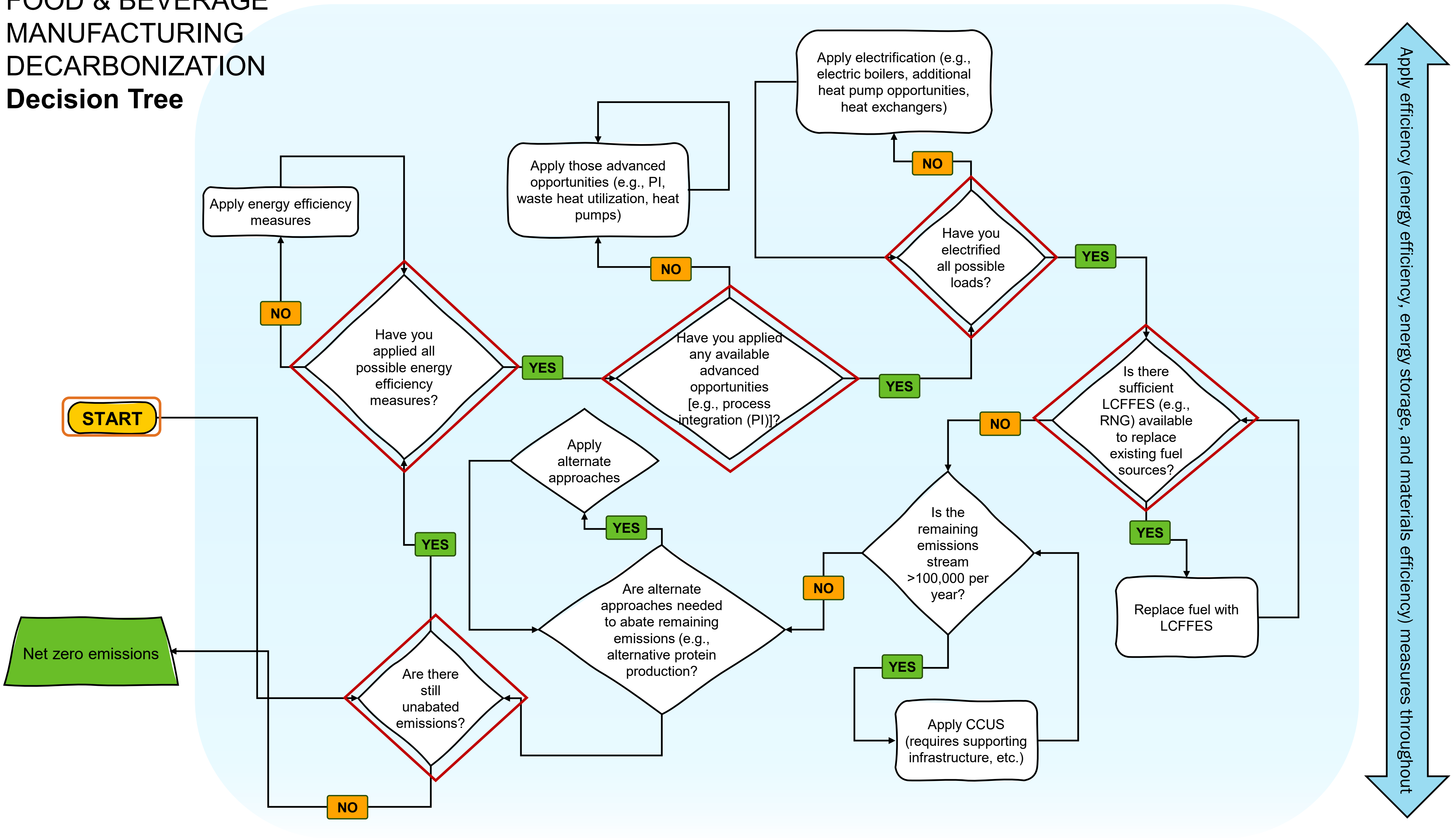
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



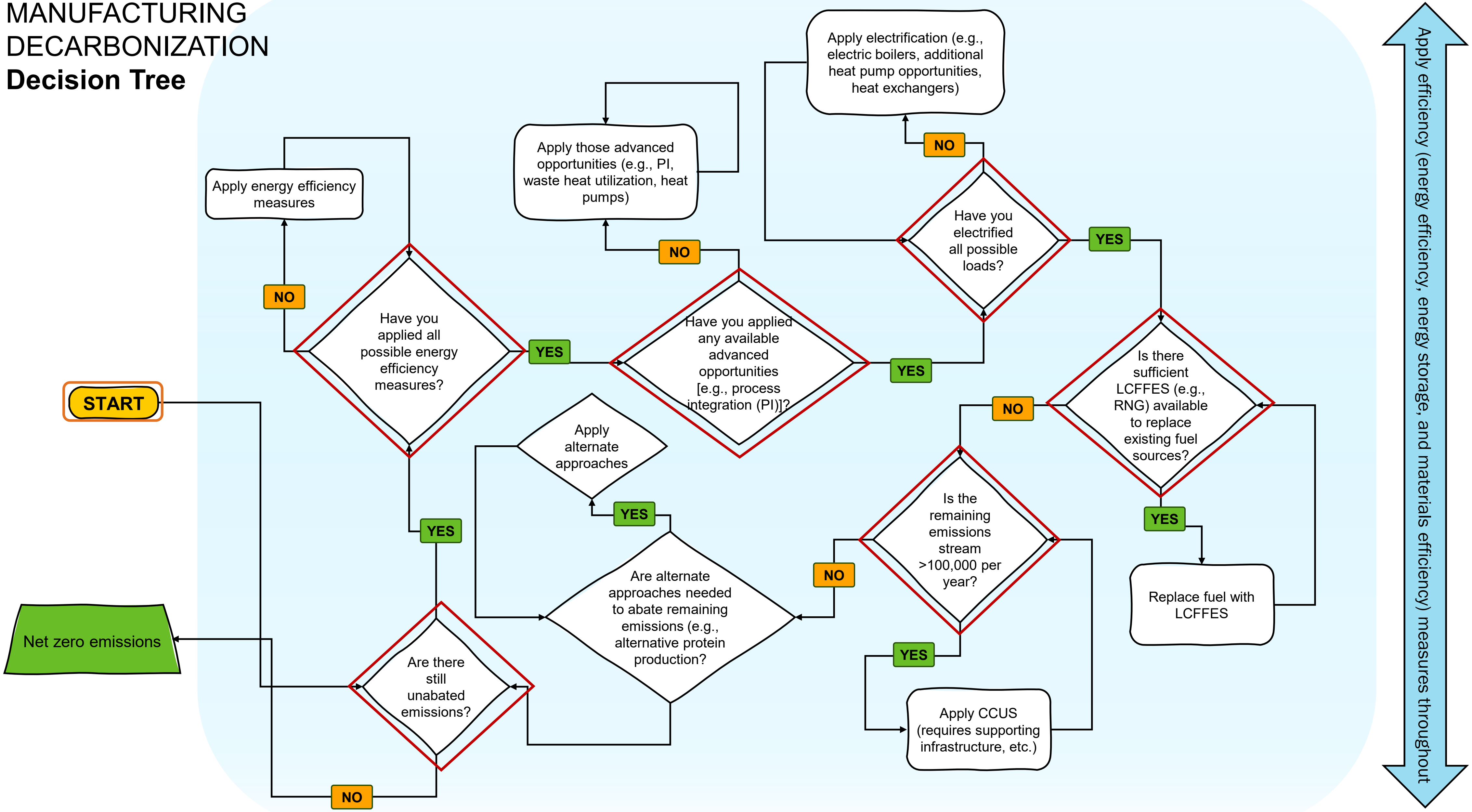
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



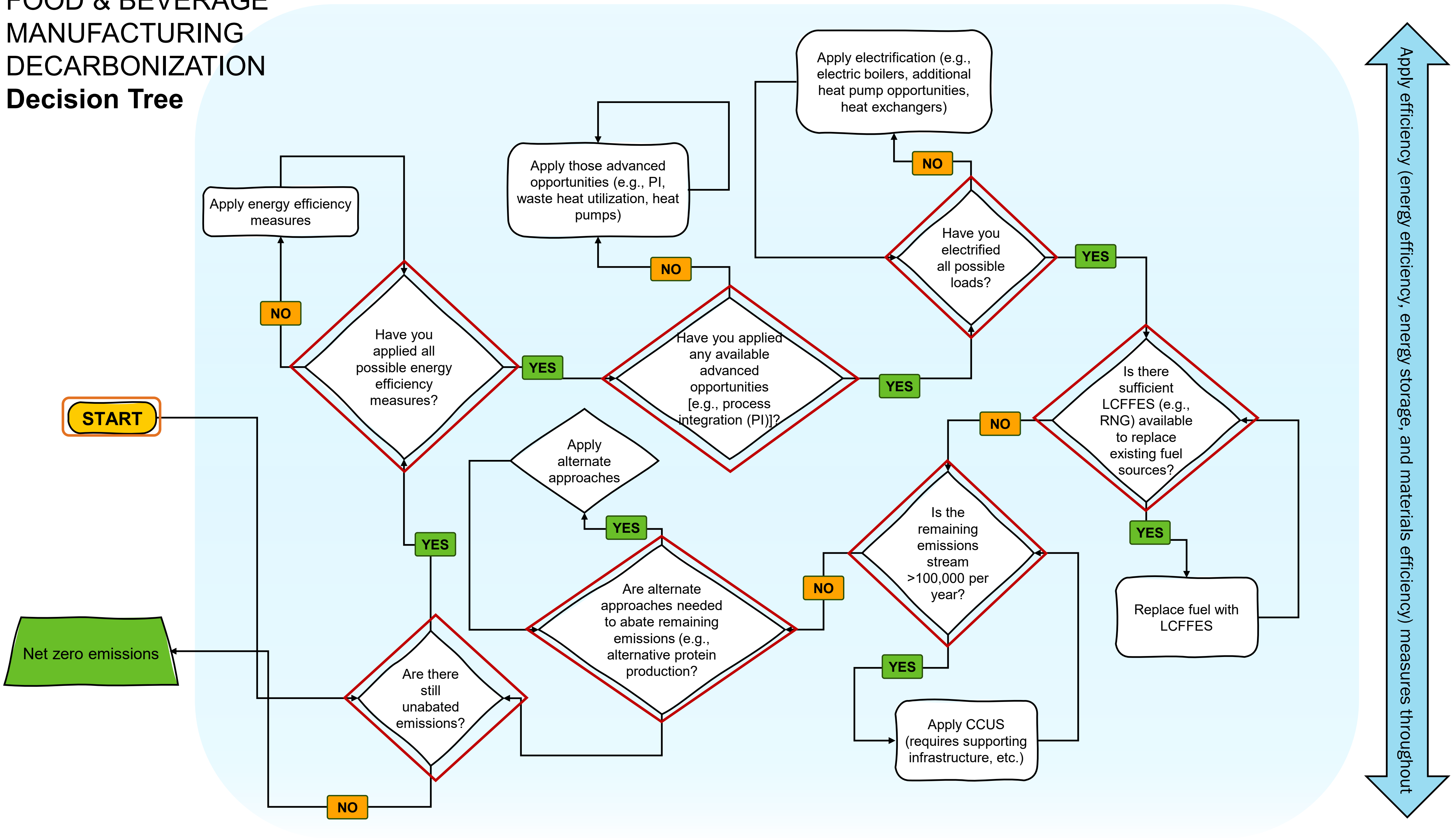
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



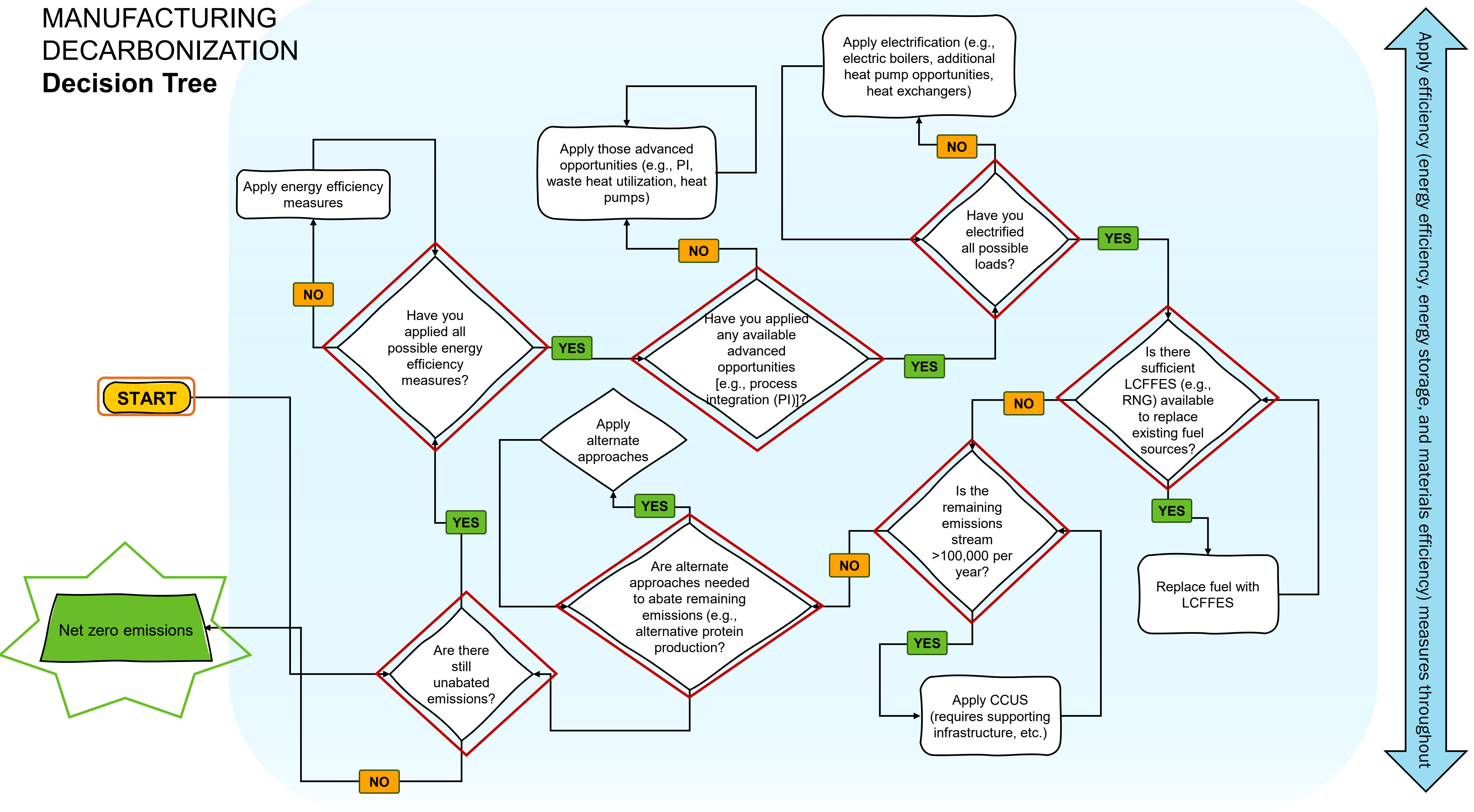
FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



FOOD & BEVERAGE MANUFACTURING DECARBONIZATION **Decision Tree**



Food & beverage subsector barriers and challenges

Institutional	• Smaller companies-low profit margins and less capital access • Meet food safety requirements (sometimes regulatory)
End Products	• Consumer sensitivity to product changes • Lower associated quality (color, taste, etc.) with certain techs
Infrastructure	• Supply chain constraints
Economic	• Low cost of natural gas/elec. compared to limited and expensive low-carbon fuels or clean elec.
Process	• Safety and performance issues associated with hydrogen and/or hydrogen/natural gas blends in existing equipment
Material Efficiency	• Impacts outside industry bounds - difficult to alter/impact consumer behavior
Carbon Capture	• Infeasibility of carbon capture technologies for small, distributed facilities with limited carbon emissions

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

INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Pulp and Paper Strategies and Analysis Summary

Industrial Efficiency and Decarbonization Office

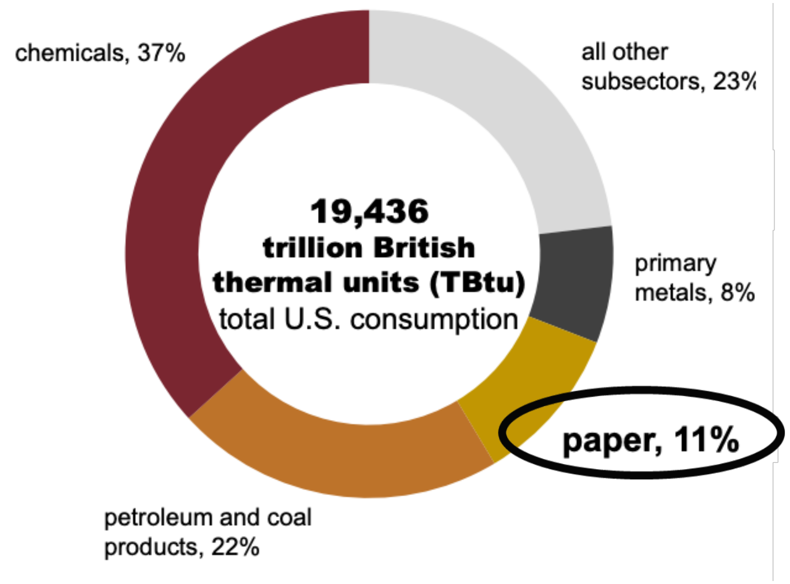
May 15, 2024

U.S. Pulp and Paper Sector

- Pulp and Paper sub-sector produces multiple product types
  - Graphic paper, hygiene products, packaging products, pulp, etc.
- Represents 4% of manufacturing GDP
- Employs ~400,000 workers in high-paying jobs

- Energy, emissions, other relevant details:
  - Accounts for 11% of total energy consumption in the manufacturing sector
  - Accounts for ~7% of energy related emissions from manufacturing sector
  - Utilizes ~50% of harvested timber in the U.S.

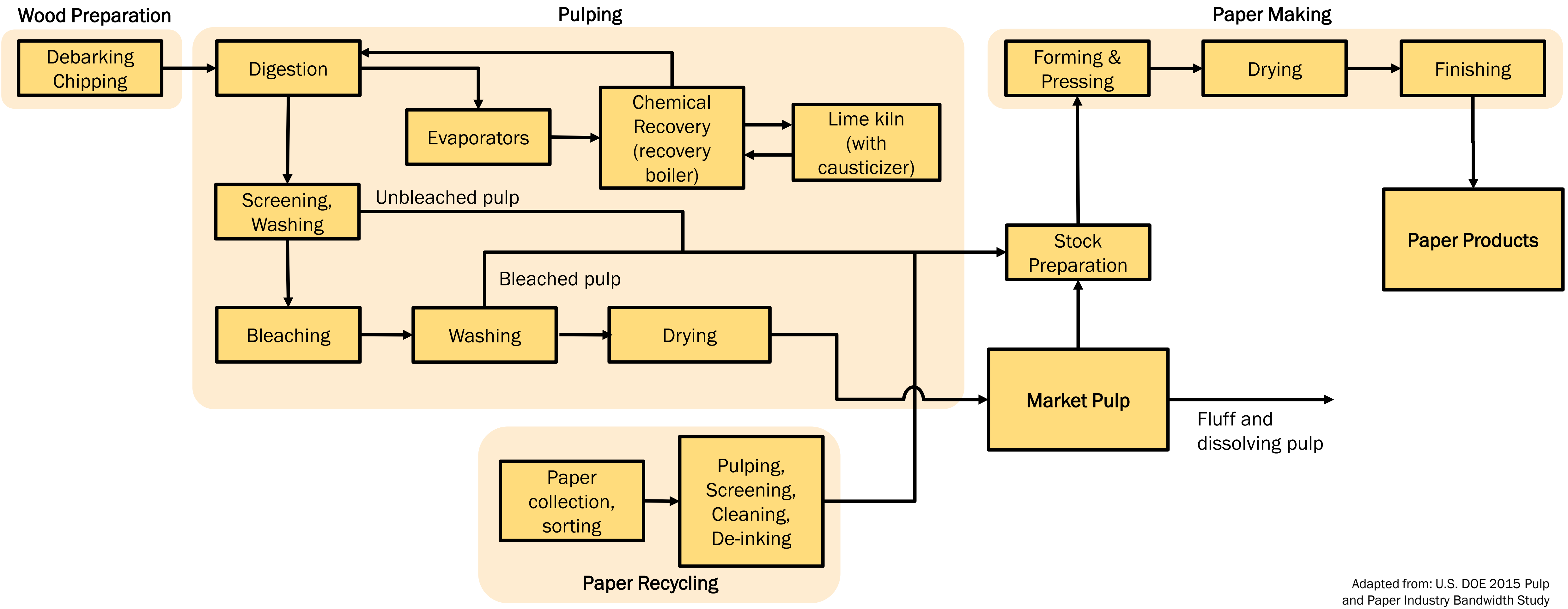
Proportion of total energy consumption by subsector (%) -MECS 2018



-MECS 2018, NCASI 2023, Fischer International 2020

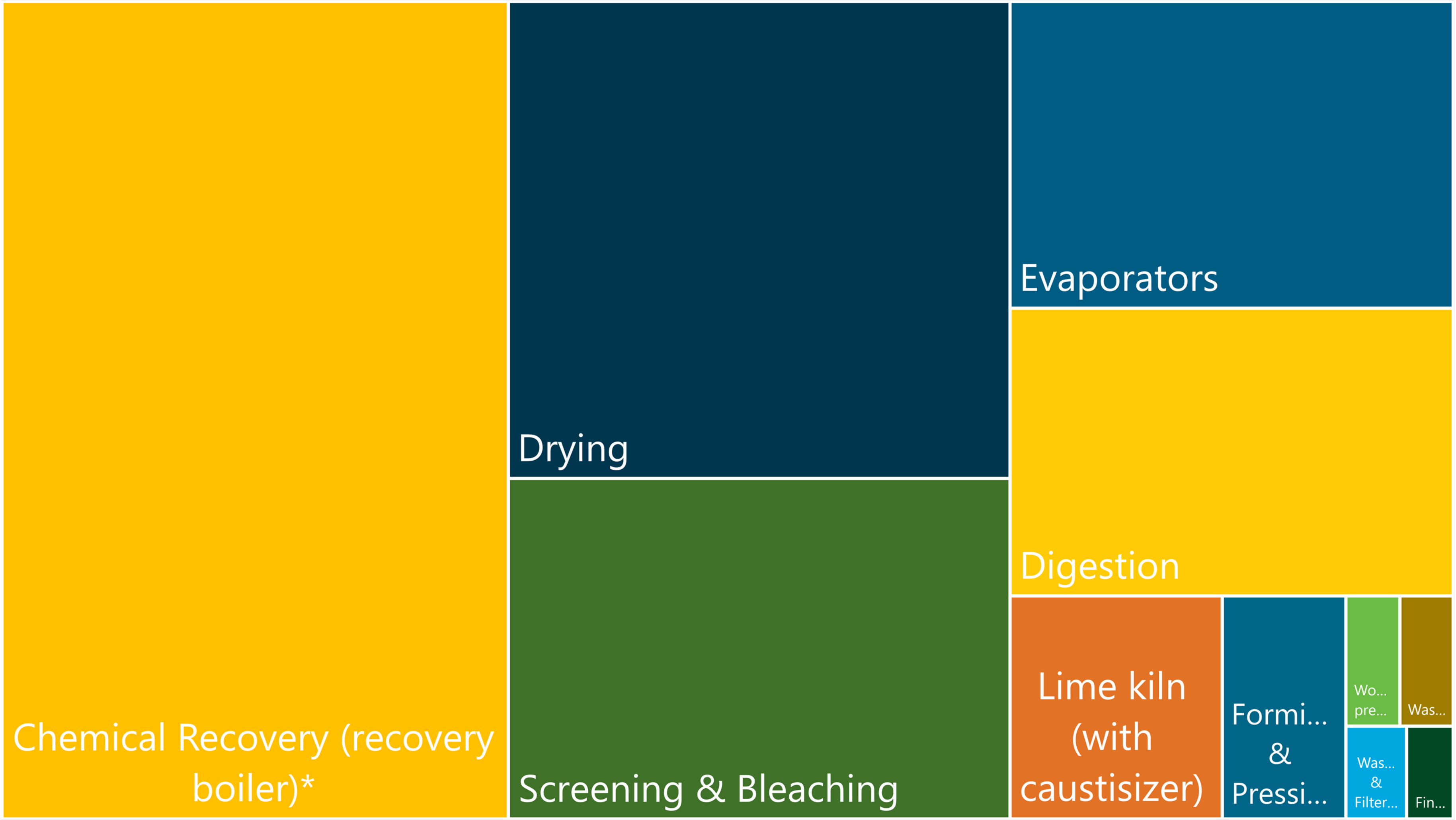
U.S. Pulp and Paper Sub-sector

Unit processes assumed for different product types



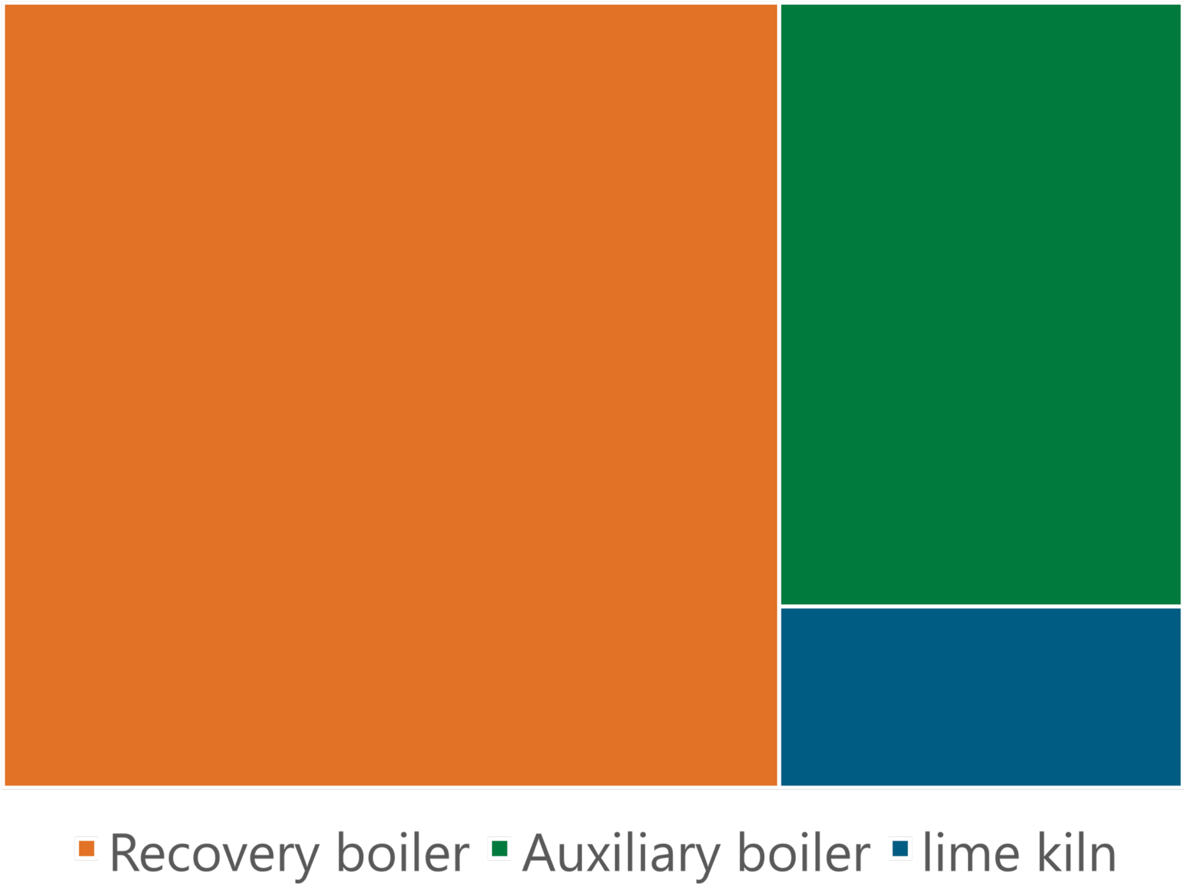
Adapted from: U.S. DOE 2015 Pulp and Paper Industry Bandwidth Study

Typical energy (fuel and electricity) Consumption for the Pulp and Paper sector *Recovery boiler uses black liquor as fuel



Energy use of different processes	GJ/t
Wood preparation	0.33
Digestion	5.91
Washing & Filtering	0.26
Evaporators	6.30
Chemical Recovery (recovery boiler)	-19.18
Lime kiln (with caustisizer)	2.20
Screening & Bleaching	7.92
Washing	0.32
Forming & Pressing	1.28
Drying	11.09
Finishing	0.20

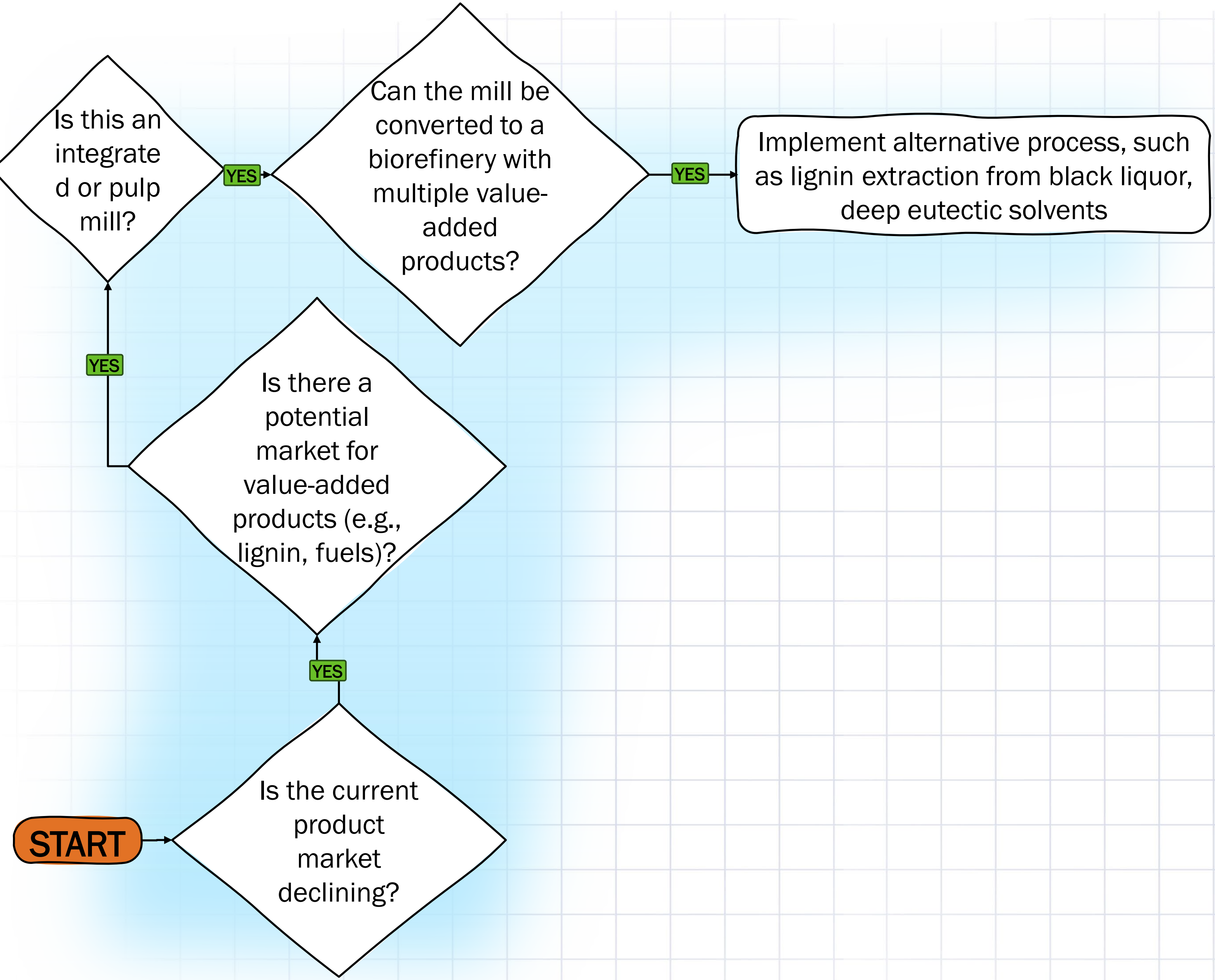
Typical Scope 1 CO_2 emission from Pulping



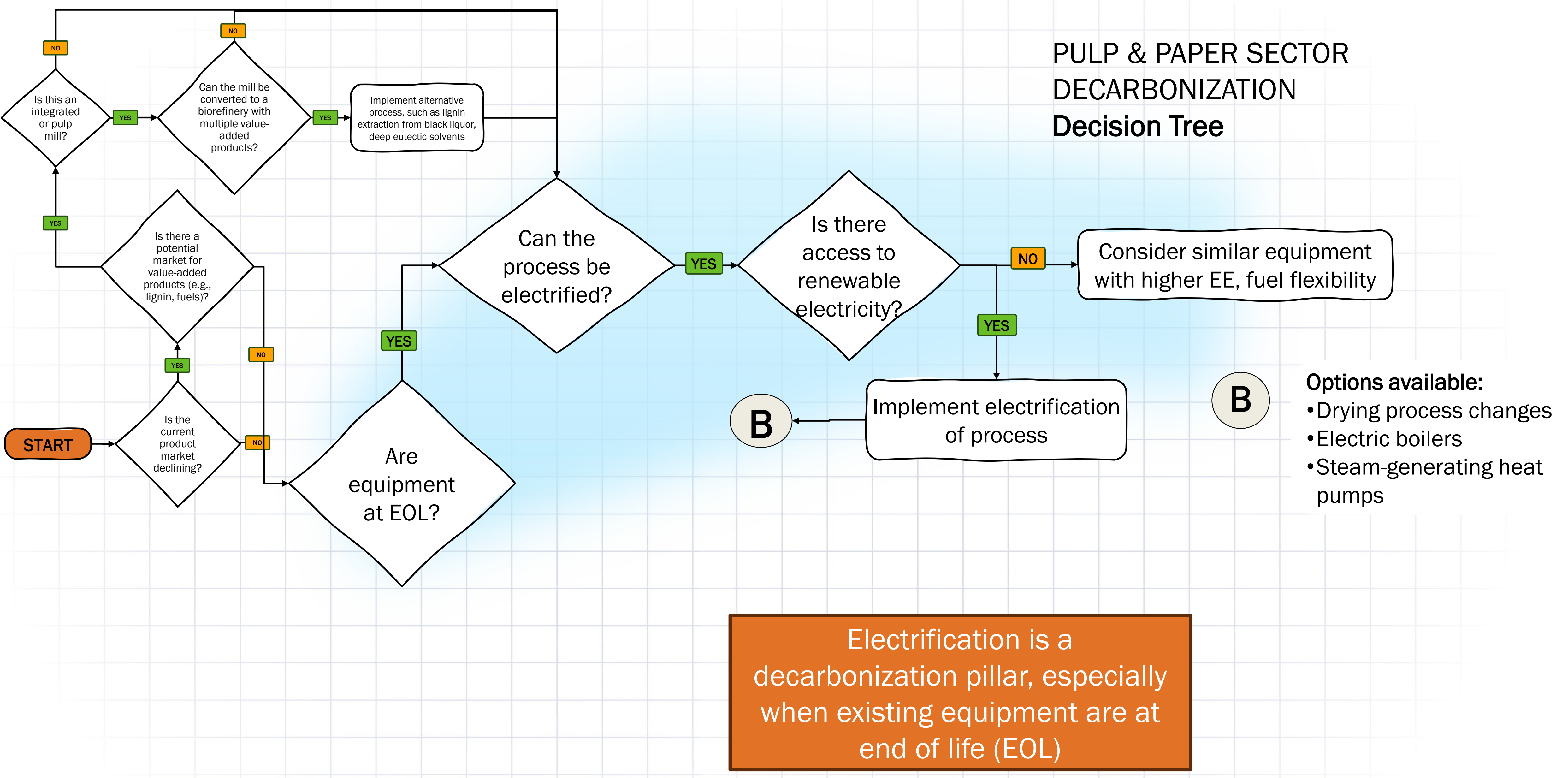
Emitting process/ equipment	total emissions
Recovery boiler	65.80%
Auxiliary boiler	26.30%
Lime kiln	7.90%

PULP & PAPER SECTOR DECARBONIZATION

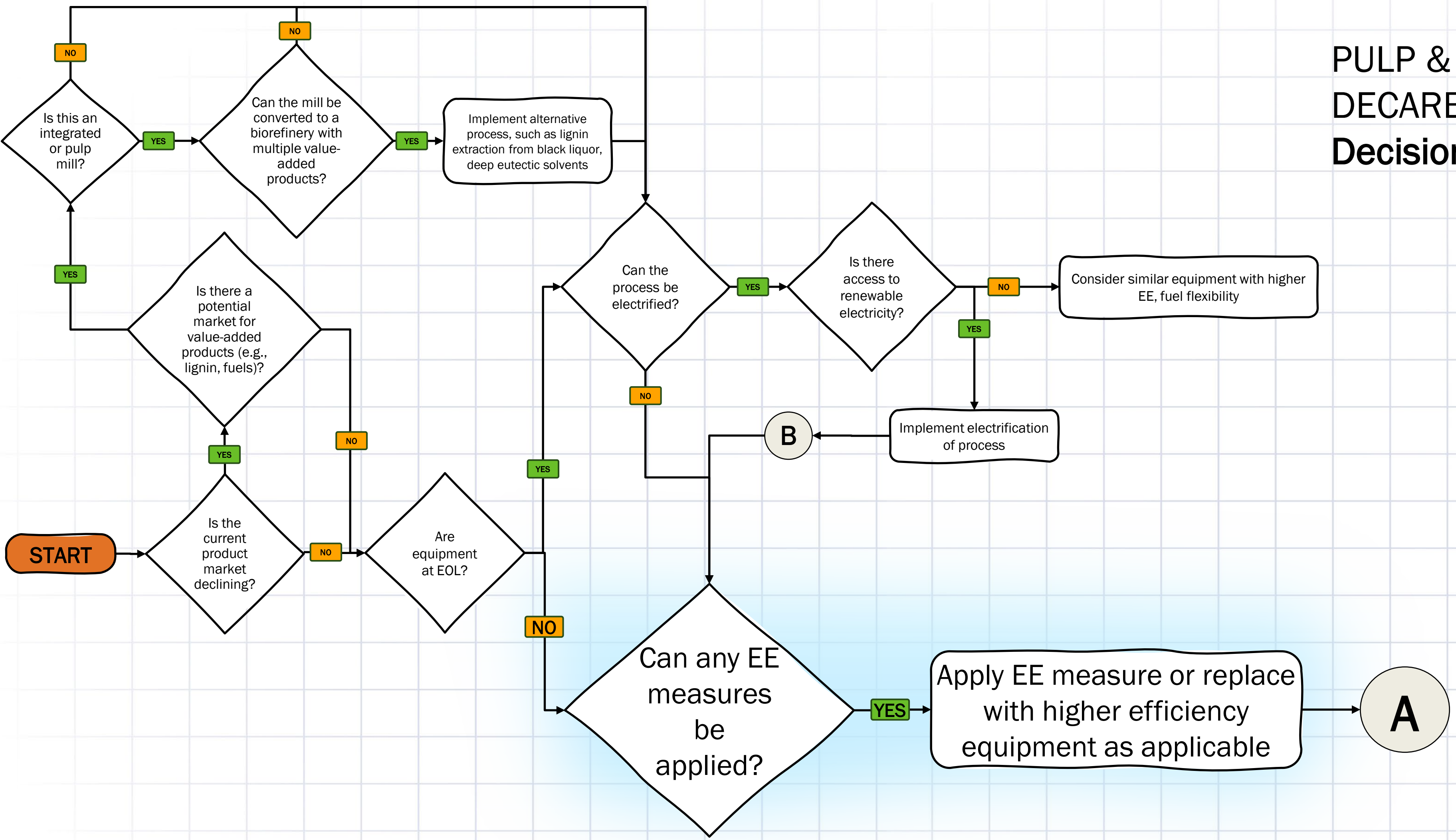
Decision Tree



Alternative process implementation can depend on market trends


PULP & PAPER SECTOR
DECARBONIZATION
Decision Tree
START
Is the current product market declining?
YES
NO
Is there a potential market for value-added products (e.g., lignin, fuels)?
YES
NO
Is this an integrated or pulp mill?
NO
YES
Can the mill be converted to a biorefinery with multiple value-added products?
NO
YES
Implement alternative process, such as lignin extraction from black liquor, deep eutectic solvents
Are equipment at EOL?
YES
Can the process be electrified?
YES
Is there access to renewable electricity?
NO
Consider similar equipment with higher EE, fuel flexibility
YES
Implement electrification of process
B
B
Options available:
•Drying process changes
•Electric boilers
•Steam-generating heat pumps
Electrification is a decarbonization pillar, especially when existing equipment are at end of life (EOL)

PULP & PAPER SECTOR 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

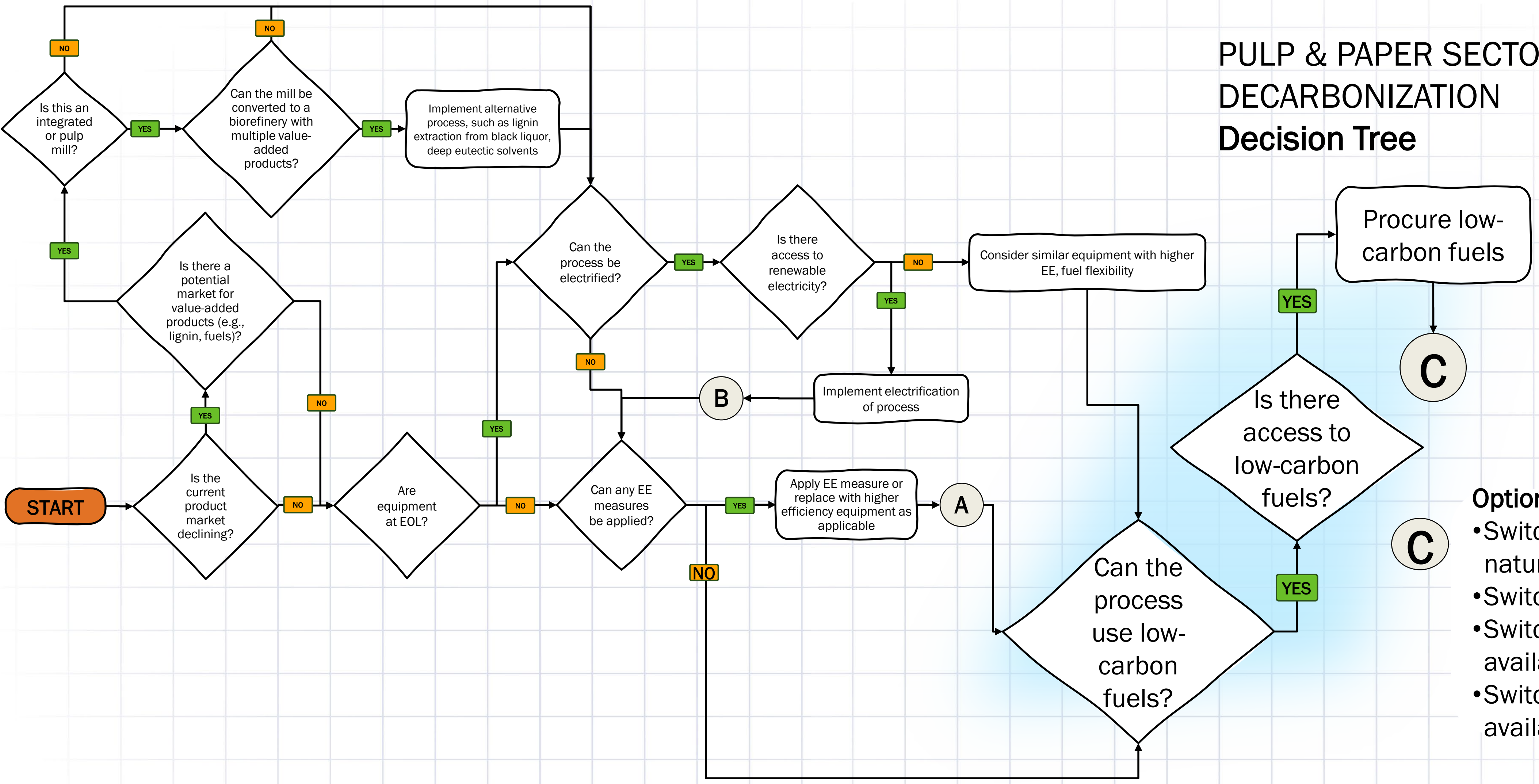
B

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

Energy efficiency (EE), the foundational pillar for decarbonization, will reduce the energy consumption and decarbonization pathways necessary

PULP & PAPER SECTOR 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

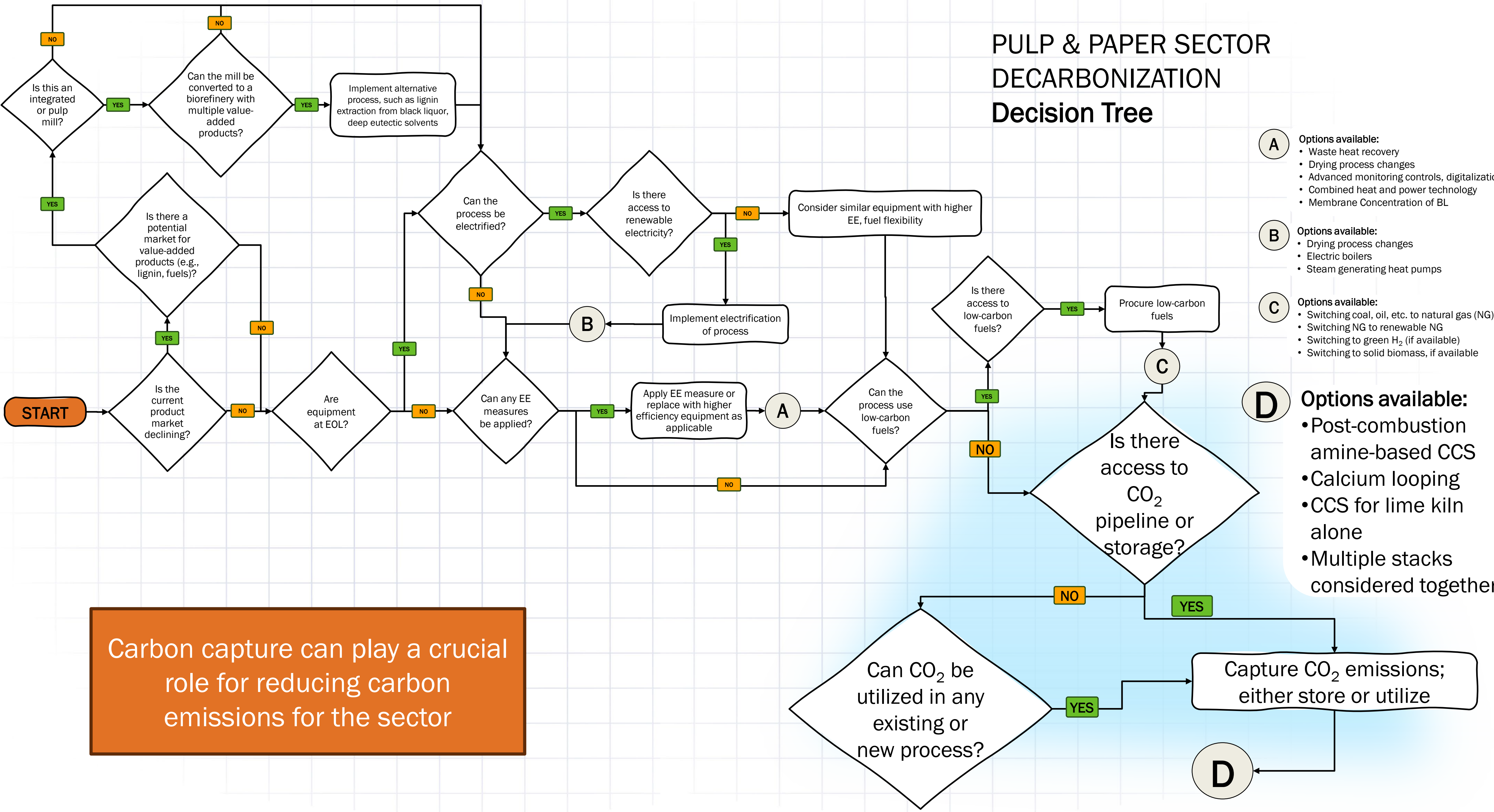
C

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

Low-carbon fuels can be considered when electrification is not an option or due to ease of access

PULP & PAPER SECTOR DECARBONIZATION
Decision Tree



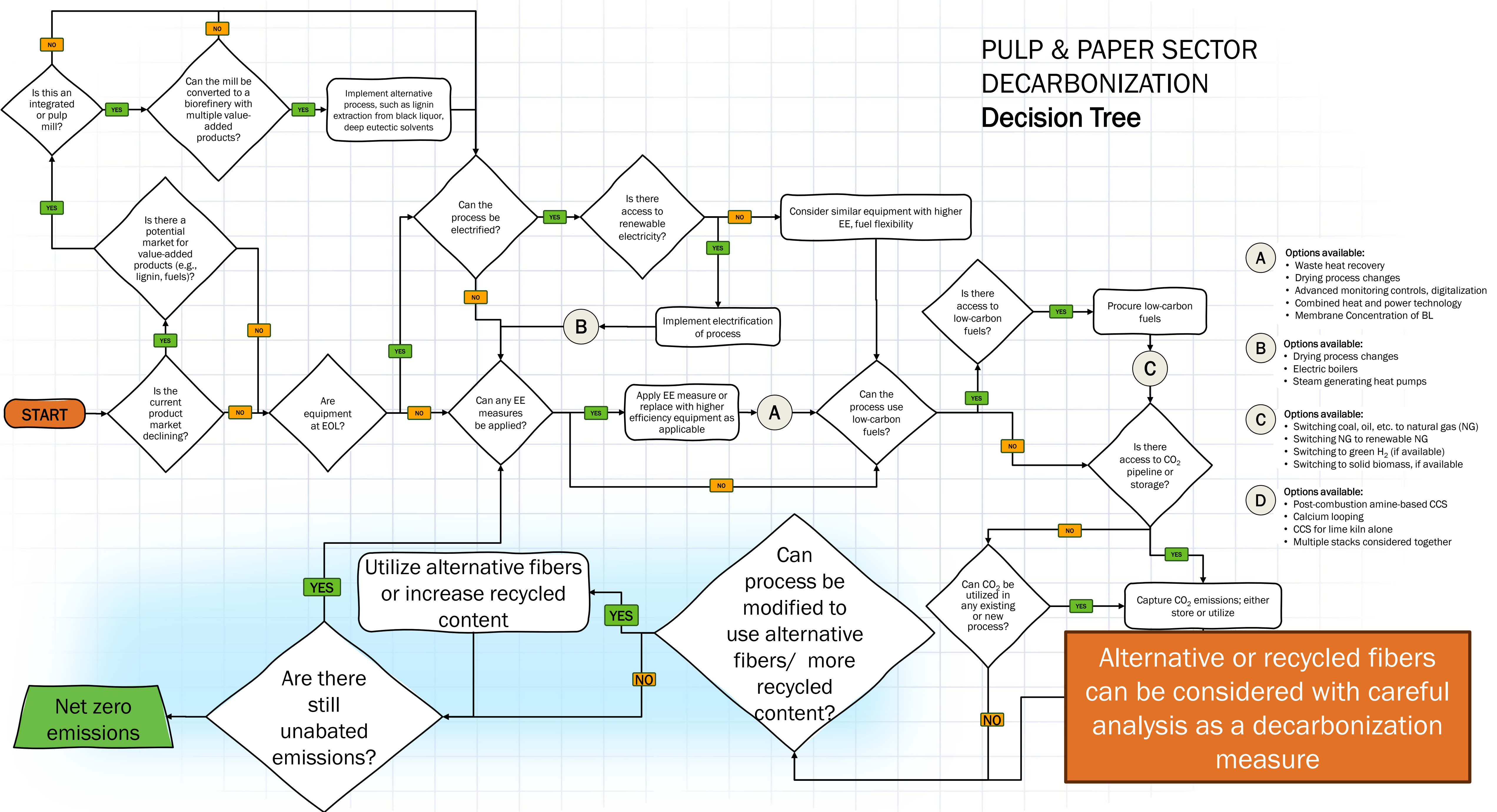
A Options available:
- Waste heat recovery
- Drying process changes
- Advanced monitoring controls, digitalization
- Combined heat and power technology
- Membrane Concentration of BL

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

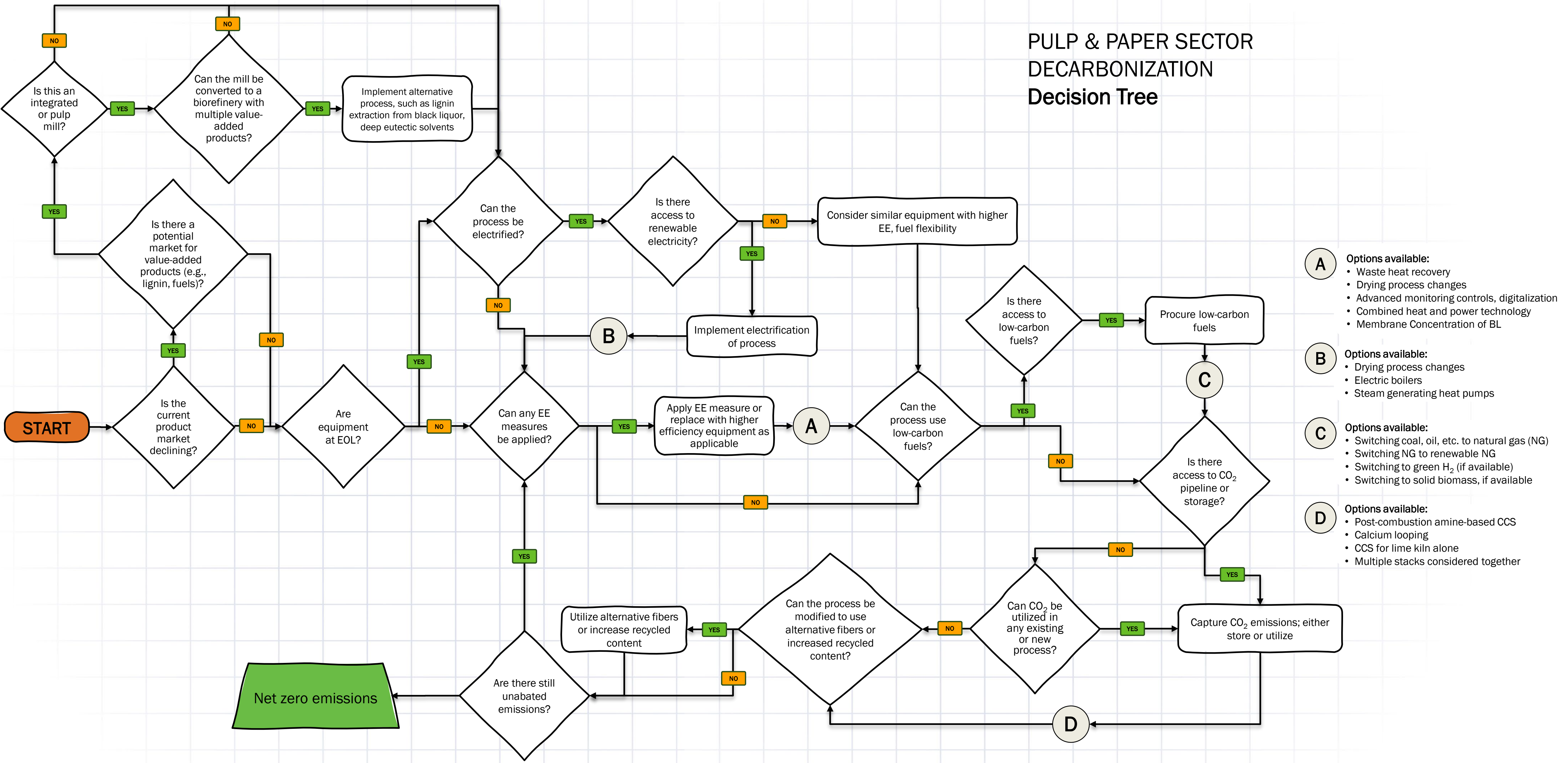
D **Options available:**
- Post-combustion amine-based CCS
- Calcium looping
- CCS for lime kiln alone
- Multiple stacks considered together

Carbon capture can play a crucial role for reducing carbon emissions for the sector



PULP & PAPER SECTOR DECARBONIZATION
Decision Tree
START
Is the current product market declining?
YES
NO
Is there a potential market for value-added products (e.g., lignin, fuels)?
YES
NO
Is this an integrated or pulp mill?
YES
NO
Can the mill be converted to a biorefinery with multiple value-added products?
YES
NO
Implement alternative process, such as lignin extraction from black liquor, deep eutectic solvents
Are equipment at EOL?
YES
NO
Can the process be electrified?
YES
NO
Is there access to renewable electricity?
YES
NO
Consider similar equipment with higher EE, fuel flexibility
Implement electrification of process
B
Can any EE measures be applied?
YES
NO
Apply EE measure or replace with higher efficiency equipment as applicable
A
Can the process use low-carbon fuels?
YES
NO
Is there access to low-carbon fuels?
YES
Procure low-carbon fuels
C
Is there access to CO_2 pipeline or storage?
YES
NO
Can CO_2 be utilized in any existing or new process?
YES
NO
Capture CO_2 emissions; either store or utilize
Alternative or recycled fibers can be considered with careful analysis as a decarbonization measure
Can process be modified to use alternative fibers/ more recycled content?
YES
NO
Utilize alternative fibers or increase recycled content
Are there still unabated emissions?
YES
Net zero emissions
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

PULP & PAPER SECTOR DECARBONIZATION
Decision Tree



Assumptions in the Sector Modeling

#	Production route	Products
1	Market Pulp Mill (non-integrated)	Fluff pulp
2	Tissue Mill (non-integrated)	tissue, hygiene products
3	Specialty Mill (non-integrated)	Specialty paper and others
4	Recycled Mill (non-integrated)	Recycled paper and paperboard
5	Bleached Mill (integrated)	Paper and paperboard
6	Unbleached Mill (integrated)	Paper and paperboard

Assumptions considered play an extensive role in the results obtained.

Assumptions in the Sector Modeling

#	Production route	Products	Energy efficiency	Material Efficiency
1	Market Pulp Mill (non-integrated)	Fluff pulp	Energy efficiency applied to specific technologies, including: debarking upgrades, chip screening &conditioning, advanced digestion additives, waste heat recovery, high efficiency refiners, lime kiln modification, high consistency forming, press section upgrades, improved drying technologies	Increased recycled content, plan to add deep eutectic solvents and membrane separation once adoption is estimated
2	Tissue Mill (non-integrated)	tissue, hygiene products		No imported pulp, but can include this and other alternative pulps
3	Specialty Mill (non-integrated)	Specialty paper and others		No imported pulp, but can include this and other alternative pulps
4	Recycled Mill (non-integrated)	Recycled paper and paperboard		None
5	Bleached Mill (integrated)	Paper and paperboard		Considered imported pulp, potential for alternative pulp
6	Unbleached Mill (integrated)	Paper and paperboard		Considered imported pulp, potential for alternative pulp

Assumptions considered play an extensive role in the results obtained.

Assumptions in the Sector Modeling

#	Production route	Products	Energy efficiency	Material Efficiency	Electrification	LCFFES
1	Market Pulp Mill (non-integrated)	Fluff pulp	Energy efficiency applied to specific technologies, including: debarking upgrades, chip screening &conditioning, advanced digestion additives, waste heat recovery, high efficiency refiners, lime kiln modification, high consistency forming, press section upgrades, improved drying technologies	Increased recycled content, plan to add deep eutectic solvents and membrane separation once adoption is estimated	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 100% biomass in lime kiln, and 80% in auxiliary boiler
2	Tissue Mill (non-integrated)	tissue, hygiene products		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass for through-air drying, 70% in auxiliary boiler, 12% hydrogen
3	Specialty Mill (non-integrated)	Specialty paper and others		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass in auxiliary boiler
4	Recycled Mill (non-integrated)	Recycled paper and paperboard		None		Switch to 80% biomass in auxiliary boiler
5	Bleached Mill (integrated)	Paper and paperboard		Considered imported pulp, potential for alternative pulp		Switch to 100% biomass in repulping and lime kiln, and 80% in auxiliary boiler
6	Unbleached Mill (integrated)	Paper and paperboard		Considered imported pulp, potential for alternative pulp		Switch to 80% biomass in auxiliary boiler

Assumptions considered play an extensive role in the results obtained.

Assumptions in the Sector Modeling

#	Production route	Products	Energy efficiency	Material Efficiency	Electrification	LCFFES
1	Market Pulp Mill (non-integrated)	Fluff pulp	Energy efficiency applied to specific technologies, including: debarking upgrades, chip screening & conditioning, advanced digestion additives, waste heat recovery, high efficiency refiners, lime kiln modification, high consistency forming, press section upgrades, improved drying technologies	Increased recycled content, plan to add deep eutectic solvents and membrane separation once adoption is estimated	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 100% biomass in lime kiln, and 80% in auxiliary boiler
2	Tissue Mill (non-integrated)	tissue, hygiene products		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass for through-air drying, 70% in auxiliary boiler, 12% hydrogen
3	Specialty Mill (non-integrated)	Specialty paper and others		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass in auxiliary boiler
4	Recycled Mill (non-integrated)	Recycled paper and paperboard		None		Switch to 80% biomass in auxiliary boiler
5	Bleached Mill (integrated)	Paper and paperboard		Considered imported pulp, potential for alternative pulp		Switch to 100% biomass in repulping and lime kiln, and 80% in auxiliary boiler
6	Unbleached Mill (integrated)	Paper and paperboard		Considered imported pulp, potential for alternative pulp		Switch to 80% biomass in auxiliary boiler

Assumptions considered play an extensive role in the results obtained.

Assumptions in the Sector Modeling

#	Production route	Products	Energy efficiency	Material Efficiency	Electrification	LCFFES	CCUS
1	Market Pulp Mill (non-integrated)	Fluff pulp	Energy efficiency applied to specific technologies, including: debarking upgrades, chip screening & conditioning, advanced digestion additives, waste heat recovery, high efficiency refiners, lime kiln modification, high consistency forming, press section upgrades, improved drying technologies	Increased recycled content, plan to add deep eutectic solvents and membrane separation once adoption is estimated	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 100% biomass in lime kiln, and 80% in auxiliary boiler	33% post combustion carbon capture in boilers and lime kiln, as applicable
2	Tissue Mill (non-integrated)	tissue, hygiene products		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass for through-air drying, 70% in auxiliary boiler, 12% hydrogen	
3	Specialty Mill (non-integrated)	Specialty paper and others		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass in auxiliary boiler	
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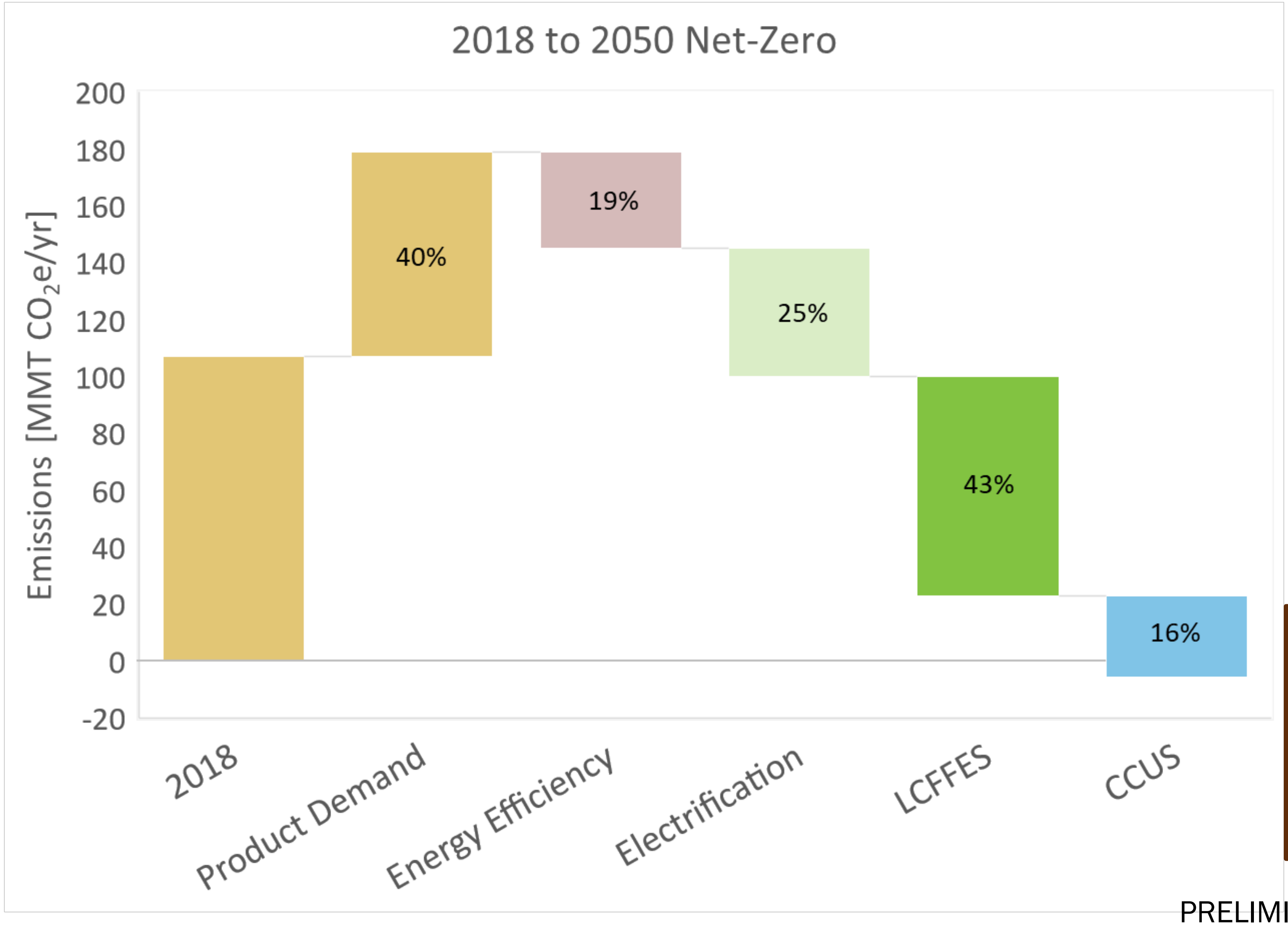
Assumptions considered play an extensive role in the results obtained.

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

LCFFES and Electrification (electricity grid decarbonization) play key role in for reaching Net Zero emissions in 2050

PRELIMINARY DATA. DO NOT CITE.

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

Sector-specific Challenges

By Decarbonization Pillar

Energy Efficiency	Alternative Processes	Alternative Fibers/ Increased Recycled Content
Low cost of purchased energy	High capital cost and technology cost	Availability of alternative fibers
Cost of technology and availability of capital funds	Low selling price for fuels, poor return on investment	Impact of declining market on recycled fiber availability
Market trends	Market trends	End-product quality impacts
Technical knowledge	Lack of expertise in processes, products, markets	Storage and transport constraints
		Uncertainty around carbon accounting and biogenic emissions
		Potential increase in energy use

Sector-specific Challenges

By Decarbonization Pillar

Energy Efficiency	Alternative Processes	Alternative Fibers/ Increased Recycled Content	Electrification	LCFFES	CCUS
Low cost of purchased energy	High capital cost and technology cost	Availability of alternative fibers	Availability of renewable electricity	Low-carbon fuel availability	Cost and technology choice
Cost of technology and availability of capital funds	Low selling price for fuels, poor return on investment	Impact of declining market on recycled fiber availability	Need for additional electric infrastructure	Technical barriers => process efficiency impact	Scale and multiple sources of emissions
Market trends	Market trends	End-product quality impacts	Limited applicability	Uncertainty of costs	Efficacy of storage
Technical knowledge	Lack of expertise in processes, products, markets	Storage and transport constraints	Cost of technology and renewable energy	Storage and transport constraints	Infrastructure for transport, storage, utilization
		Uncertainty around carbon accounting and biogenic emissions		Uncertainty around carbon accounting and biogenic emissions	
		Potential increase in energy use			

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INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Iron & Steel Strategies and Analysis Summary

Industrial Efficiency and Decarbonization Office

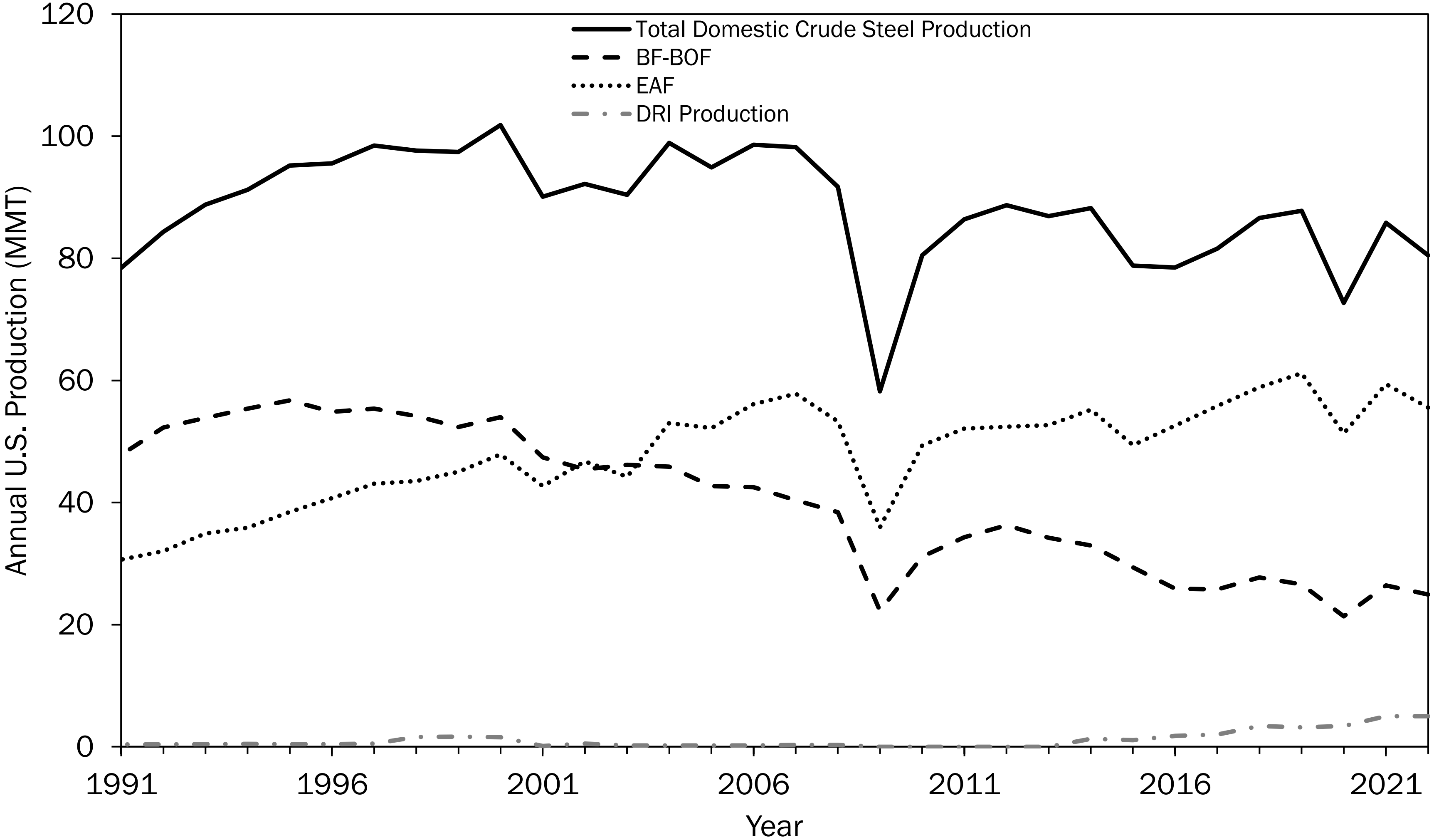
May 15, 2024

Iron & steel at a Glance

- Iron and steel manufacturing is one of the most energy- and emissions-intensive industries worldwide
  - The iron and steel industry accounts for around a quarter of greenhouse gas (GHG) emissions from the global manufacturing sector
- The U.S. steel subsector produced 82 MMT of crude steel in 2022
  - 4% of global production and the fourth-largest producer of steel in the world
  - U.S. steel production methods:
    - 29% made using BF-BOF (blast furnace-basic oxygen furnace)
    - 71% made using EAF (electric arc furnace)
- Energy and emissions profile:
  - In 2018, U.S. iron and steel manufacturing emitted a total of 100 MMT CO_2e
  - In 2018, U.S. iron and steel manufacturing consumed 1,076 TBtu of energy
    - 37% Natural Gas
    - 28% Coke and Breeze
    - 17% Electricity
    - 16% Blast Furnace & Coke Oven Gases

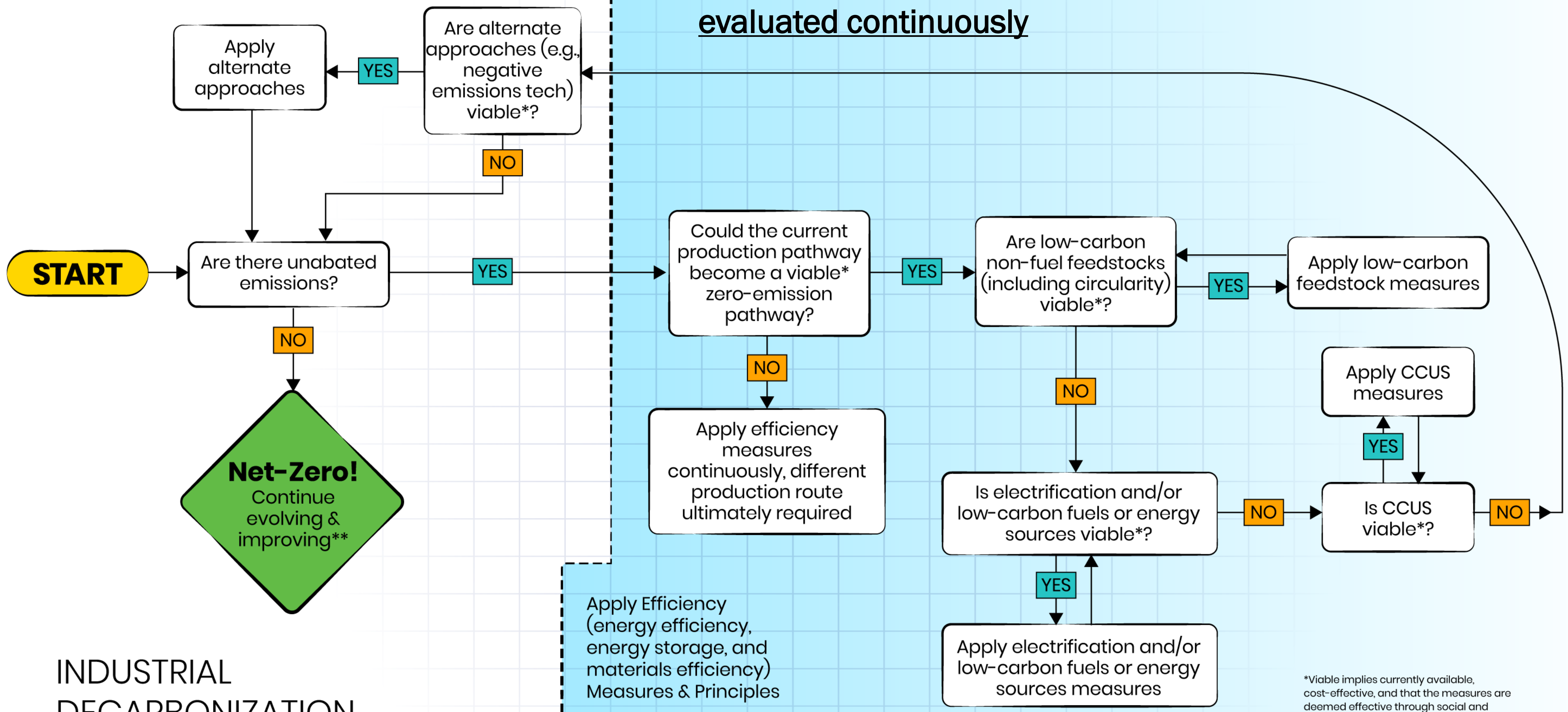
U.S. Steel Production by Route

- American production has been predominantly via the electric arc furnace since the early 2000s
- DRI production has been expanding rapidly in the last 10 years with major installations coming online in LA, OH, and TX.
- Alongside growing domestic production, the U.S. is a major importer of DRI/HBI and imported an estimated 1.6 MMT in 2019 for consumption primarily in EAFs (MIDREX, IIMA 2020)
- It seems that further penetration of EAFs into the U.S. production mix is contingent on increasing supply of ore-based metallics.



World Steel Association Production Statistics 2022-1991

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

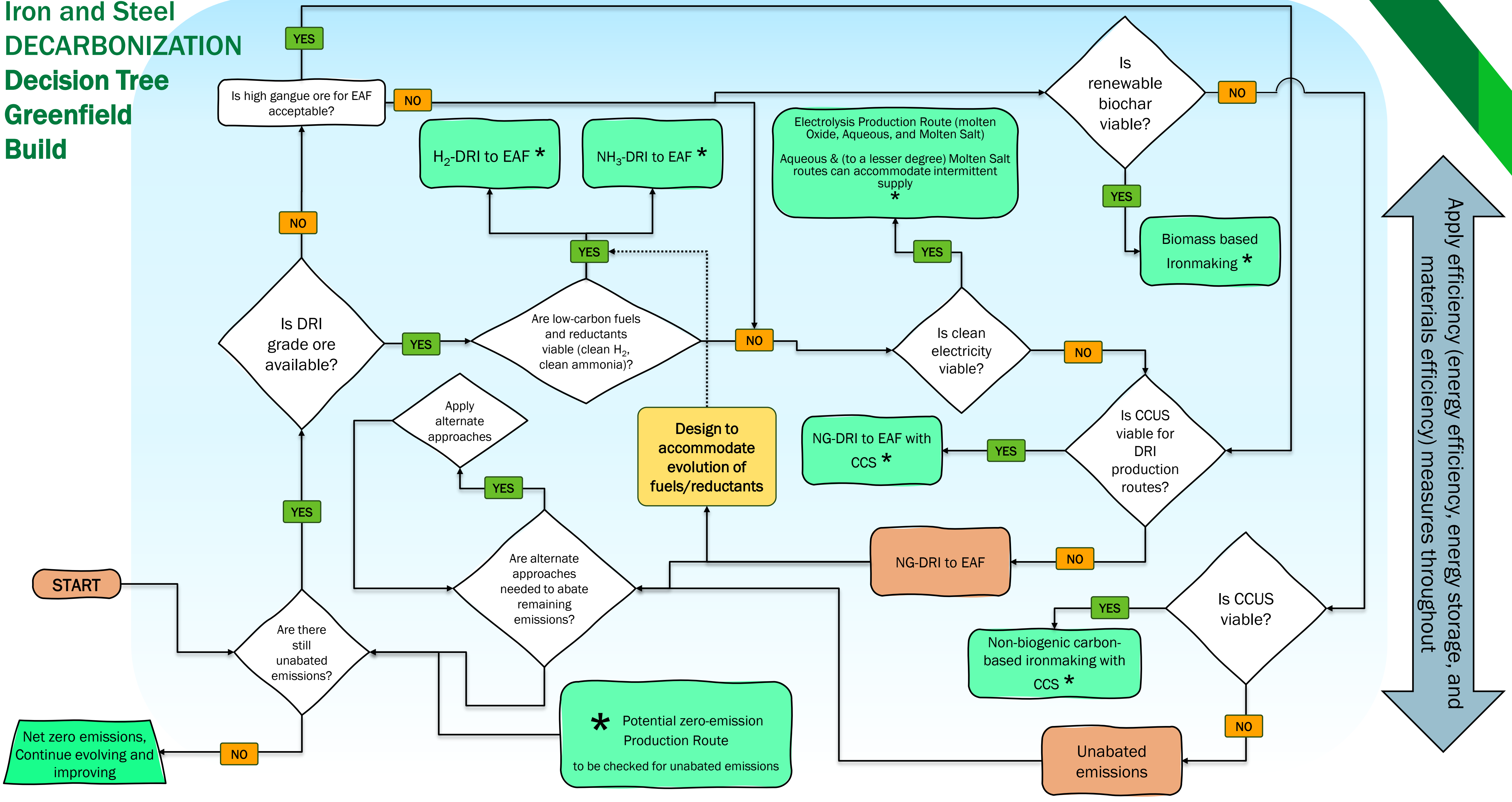


INDUSTRIAL DECARBONIZATION **Decision Tree**

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

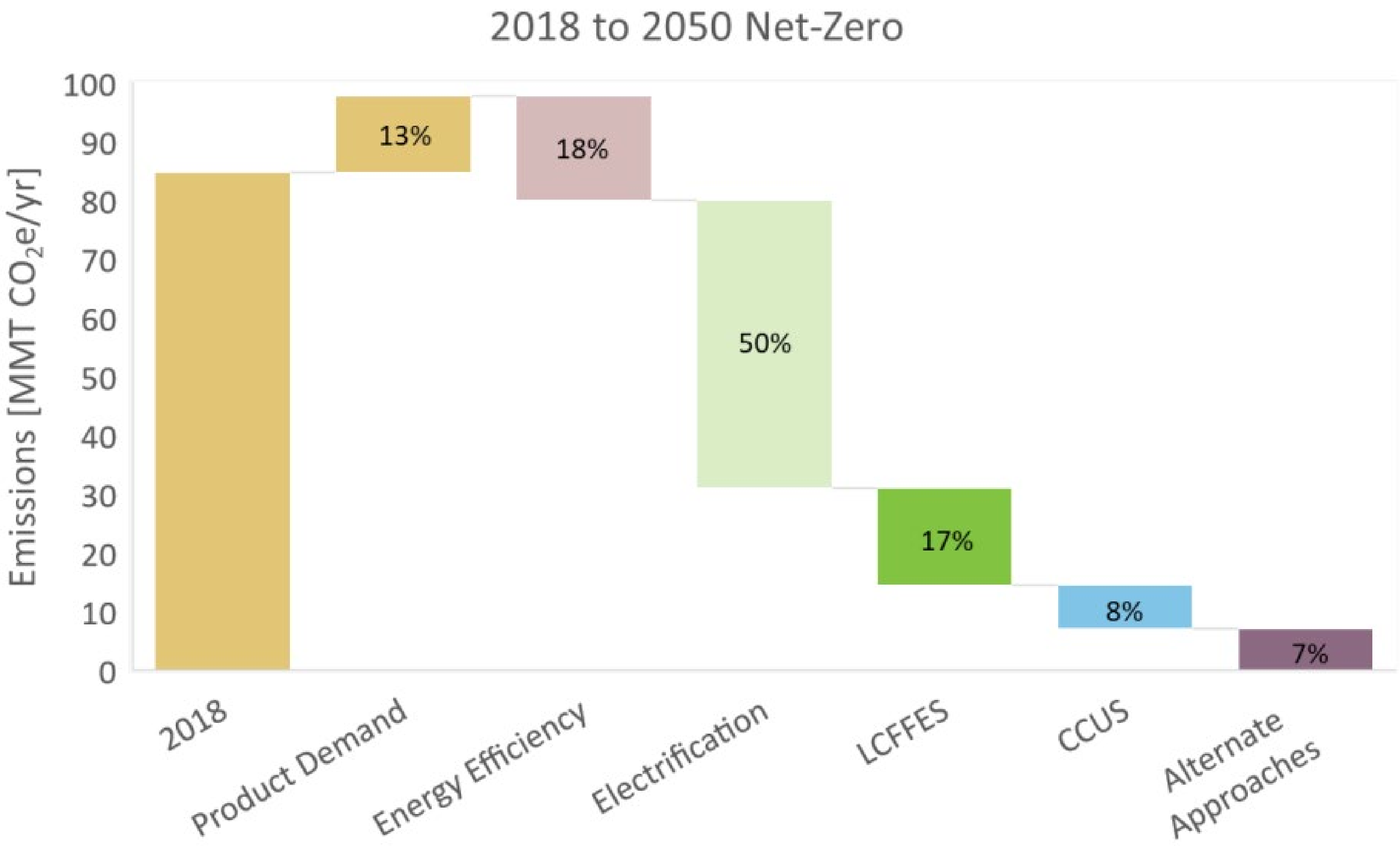
** Morrow, William III et al. 2017. "U.S. Industrial Sector Energy Productivity Improvement Pathways." U.S. Industrial Sector Energy Productivity Improvement Pathways (aceee.org)

Iron and Steel DECARBONIZATION Decision Tree Greenfield Build



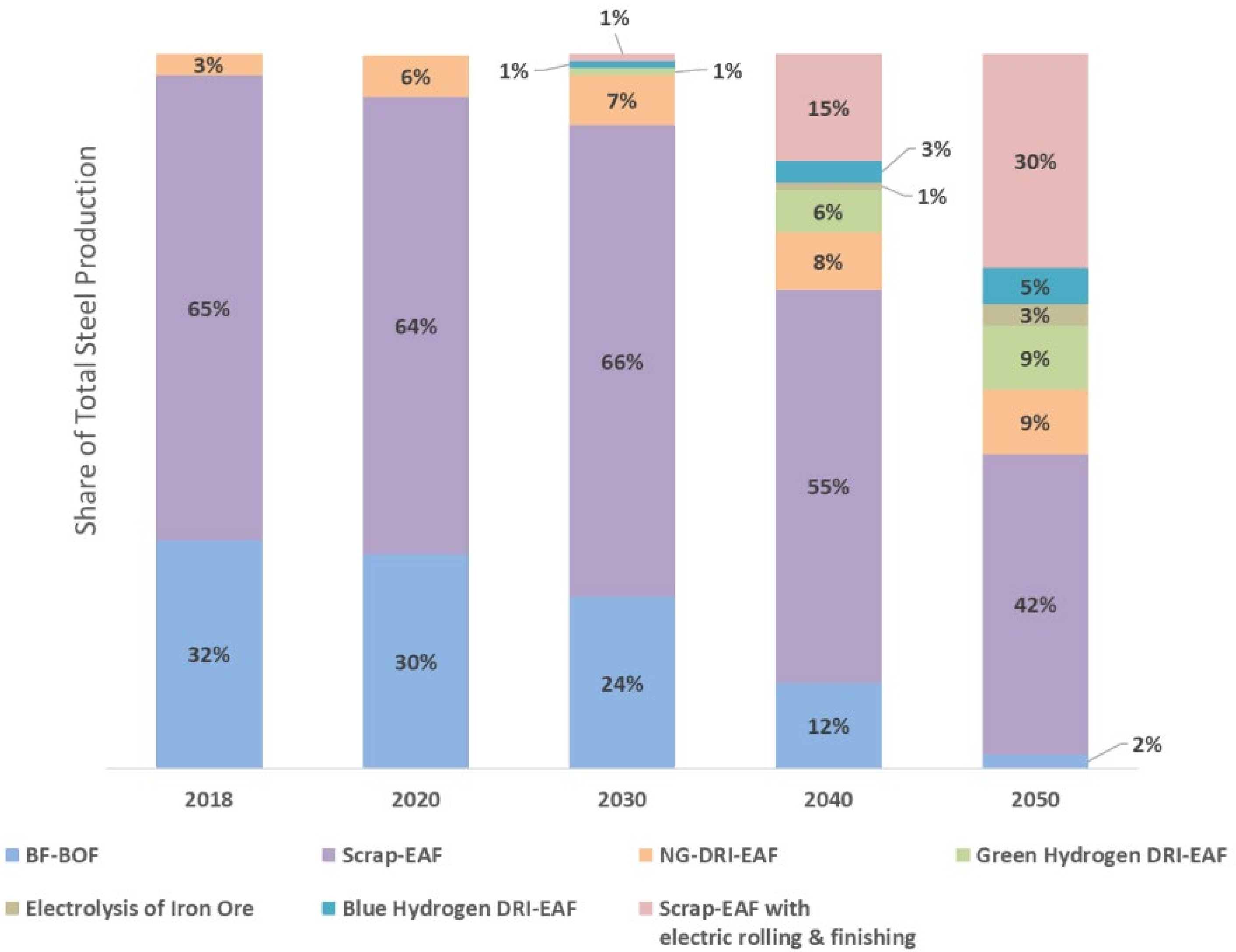
Net-Zero by 2050 Scenario

Example of a 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



Production Routes in a Net-Zero Scenario

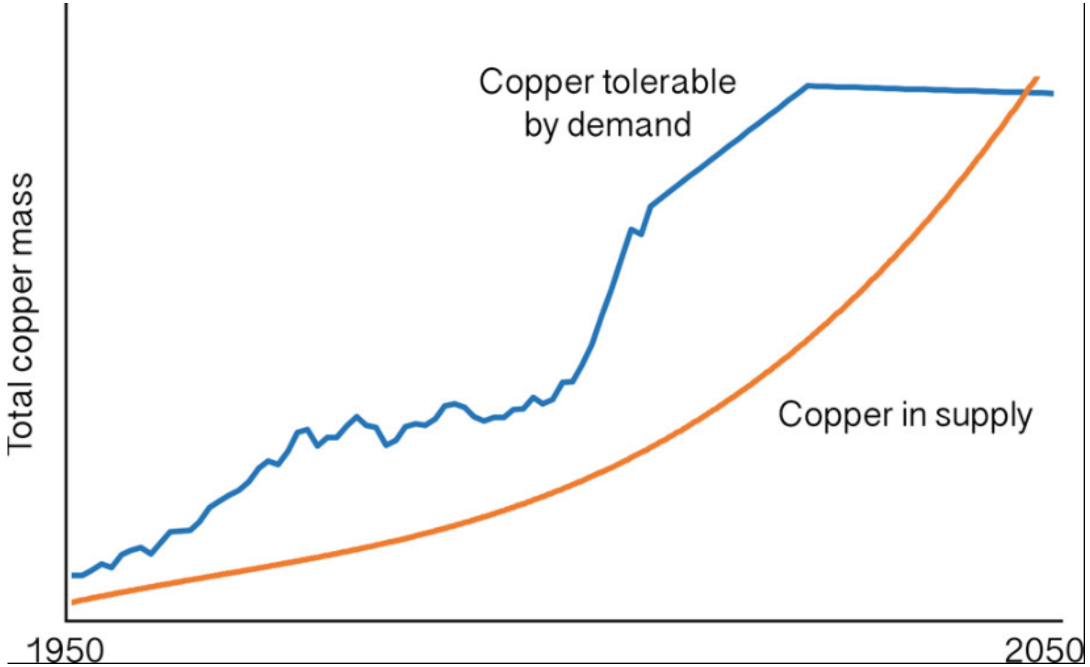
- Modeling assumptions
  - US electric grid CO2 emissions reduction to zero in 2050
  - Slight increase in natural gas usage and doubling of electricity usage
- Net Zero Scenario:
  - BF-BOF substantial phase out by 2050
  - Scrap-based EAF bulk of production route
  - Small portion with clean hydrogen based DRI-EAF processes and iron ore electrolysis

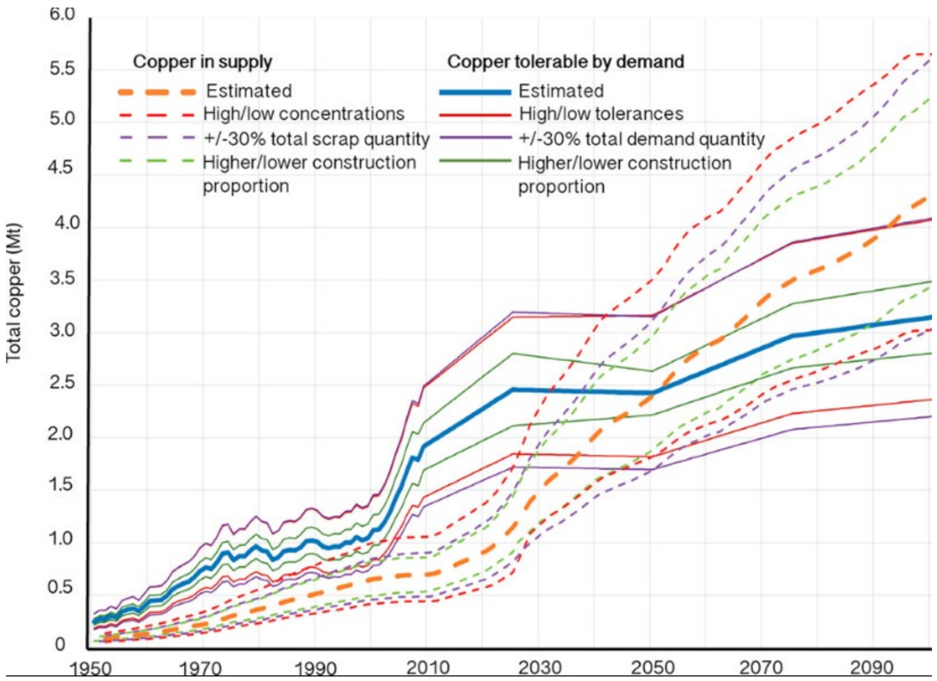


Sector-specific challenges

- Energy Efficiency:
  - Initial investment cost
  - Harsh environment prohibitive to waste heat recovery technologies, smart manufacturing, and next gen information technology solutions
- Industrial Electrification:
  - Harsh environment not immediately conducive to electrical heating equipment longevity
  - Electric heating may not have the bandwidth to support high processing temperatures (reheating, large scale batch/continuous furnaces)
- Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES):
  - Better understanding of available quantities, cost, and life cycle assessments of alternative fuels (biomass, H2, green electricity)
- Material Efficiency:
  - Recycling manufacturing byproducts requires added focus on product quality, availability of scrap, and complex steel alloy preparation

Copper Accumulation in Scrap Supply





Katrin E. Daehn, André Cabrera Serrenho, and Julian M. Allwood
Environmental Science & Technology **2017** 51 (11), 6599-6606 DOI: 10.1021/acs.est.7b00997

- Copper cannot be refined oxidatively from steel during typical production and is commonly intimately mixed with scrap steel due to its inclusion in many steel products.
- Excessive copper can compromise the quality of steel, typically the surface quality in deep drawing applications (food packaging, automotive etc.)
- Typical management of copper levels is done by dilution and scrap mixing, as such virgin iron units must continue to enter the system to manage the increasing copper level.
- This has the potential to become a major barrier for increasing recycling levels, as markets for less copper tolerant (flate, plate) products appear to be growing far faster than copper tolerant market segments (bars etc.)

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Other Industries Summary

Industrial Efficiency and Decarbonization Office

May 15, 2024

Sectors in Other Industries

<u>Manufacturing</u>
- Aluminum
- Glass
- Fabricated metals
- Transportation manufacturing
- Plastics
- Foundries
- Electronics
- Textiles
- Machinery

<u>Non-manufacturing</u>
- Agricultural
- Construction
- Mining
- Data centers
- Water
- Wastewater

<u>The bigger picture</u>:
Other manufacturing industries are:
- 85% of manufacturing establishments
- 63% of manufacturing revenue/value of shipments
- 79% of manufacturing employees
- 50% of manufacturing energy costs

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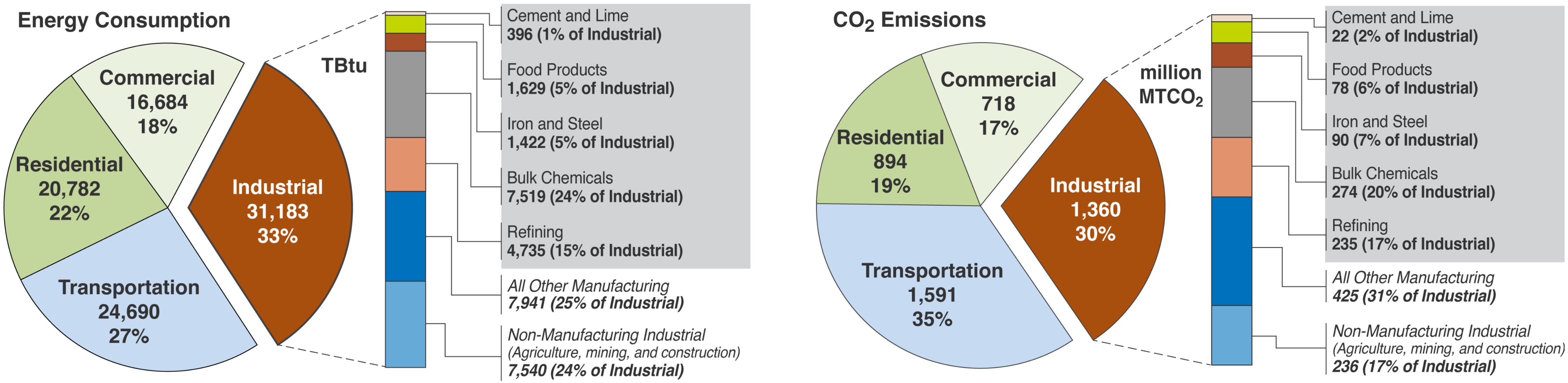
The emissions implication

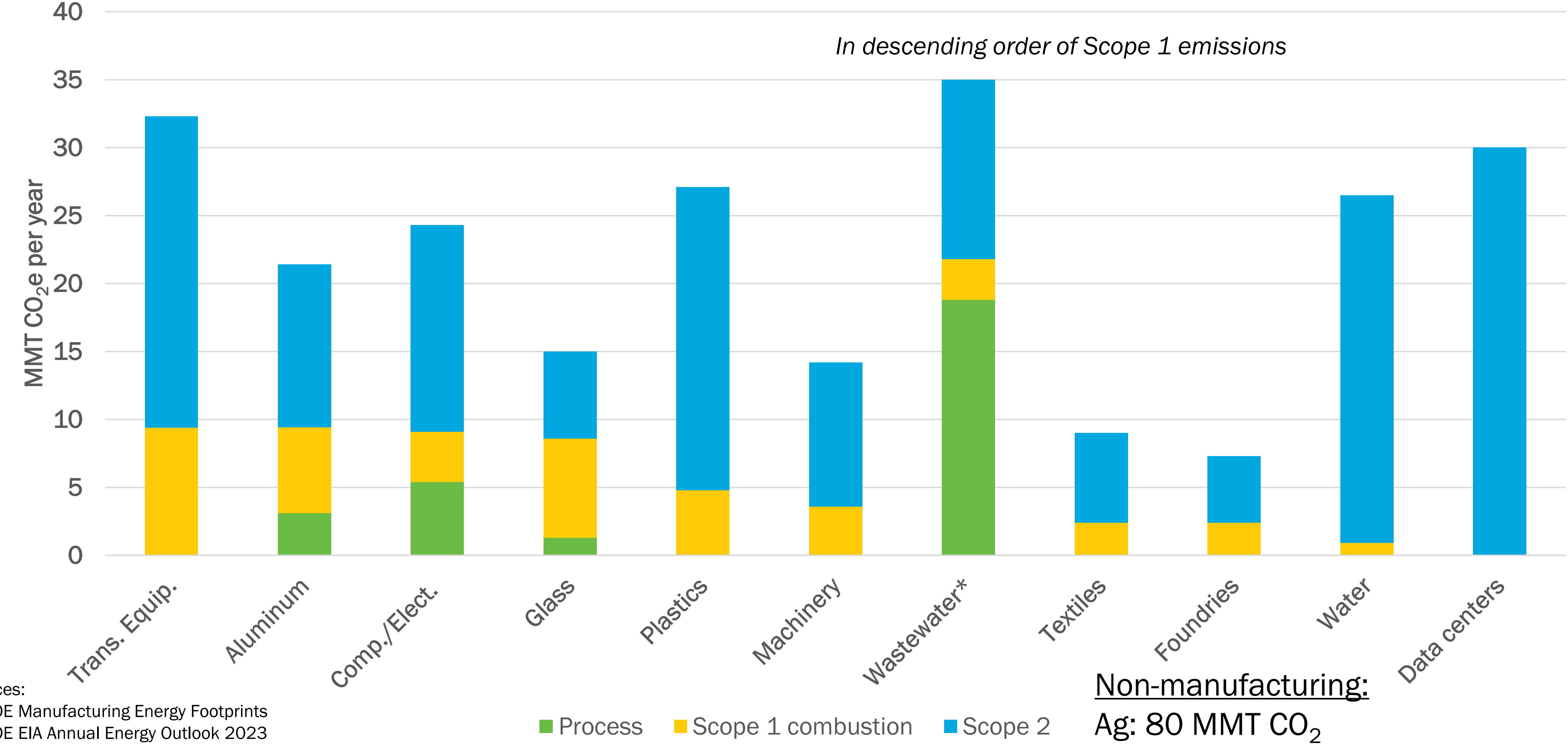


Other industries encompasses 44% of industrial emissions

**Pulp and paper: 6% of industrial energy use and 4% of industrial energy-related CO_2 emissions*

US DOE. Industrial Decarbonization Roadmap. September 2022.

Emissions from Other Industries



*estimated emissions using multiple sources

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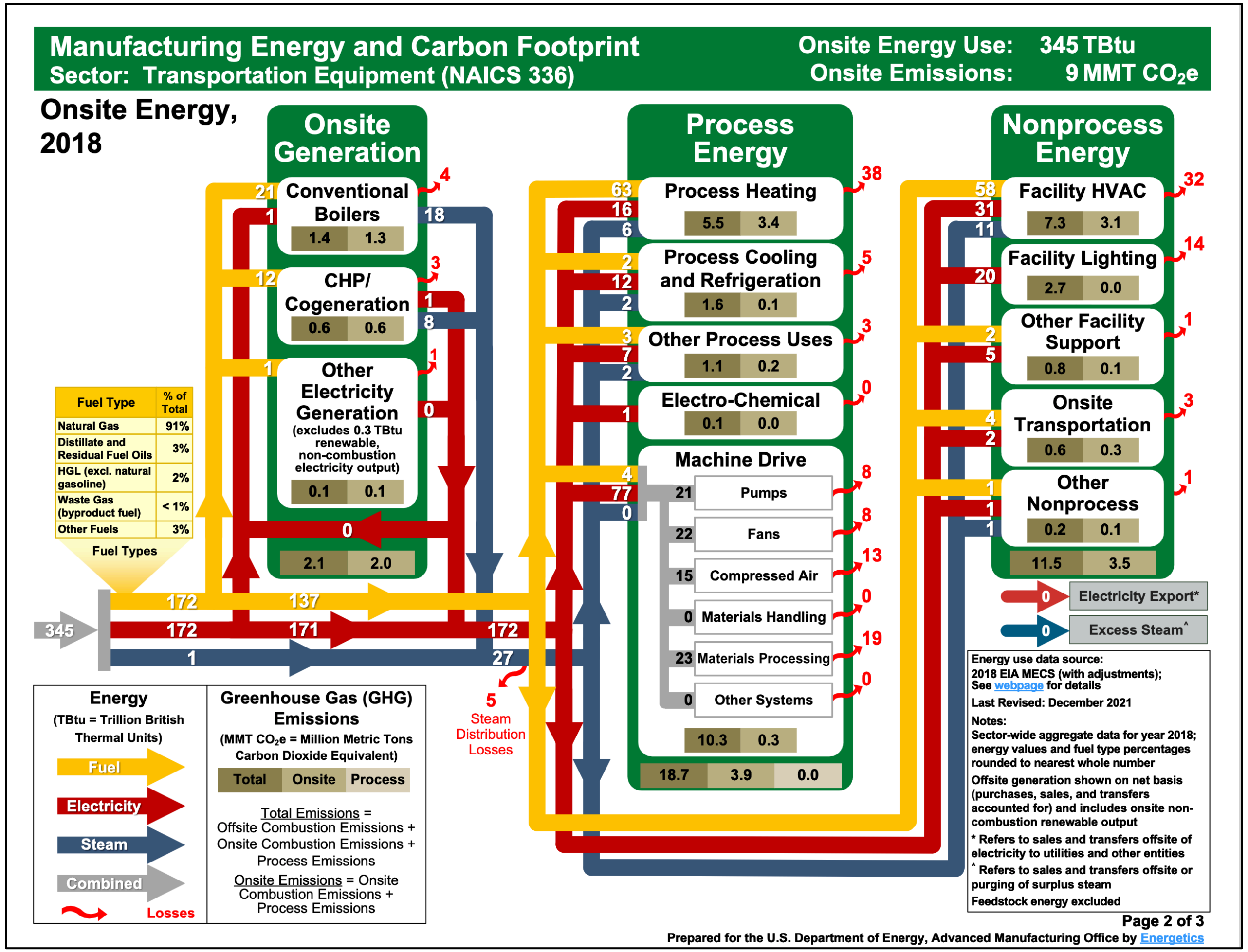
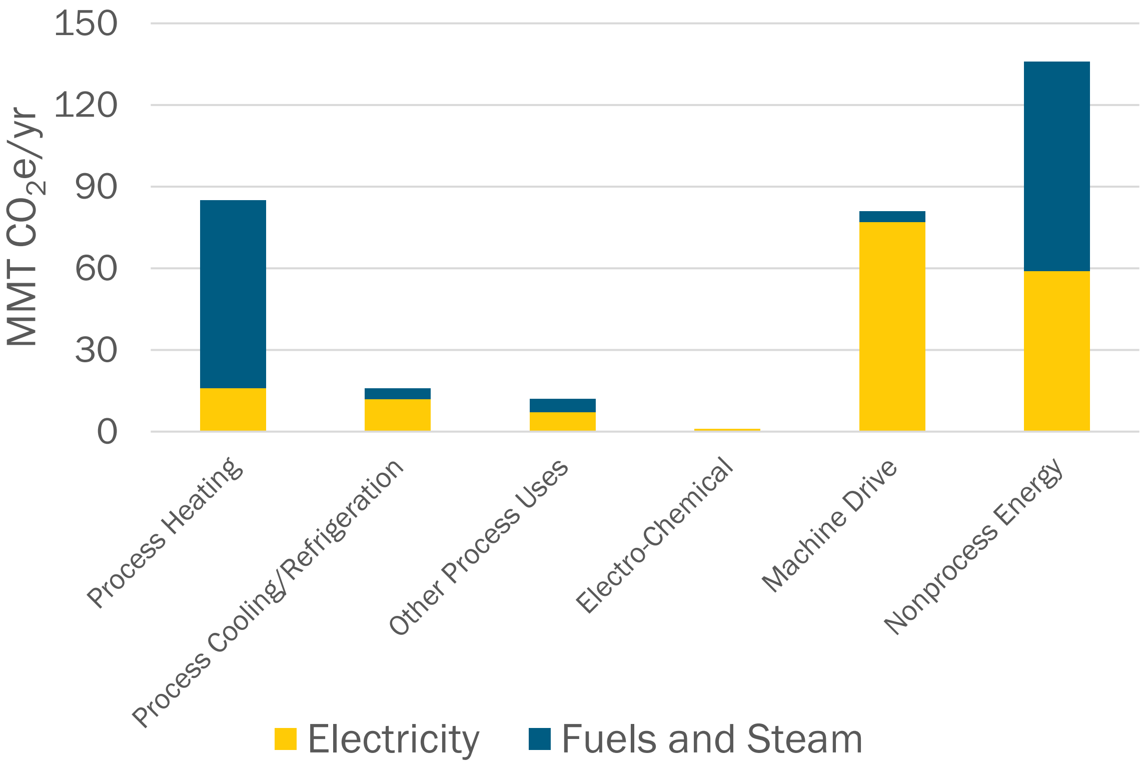
Sources:
USDOE Manufacturing Energy Footprints
USDOE EIA Annual Energy Outlook 2023
USEPA GHG Reporting Inventory
Zib III et al. 2021. Journal of Cleaner Production.
Siddik et al. 2021. Environmental Research Letters.

<u>Non-manufacturing:</u>
Ag: 80 MMT CO_2
Construction: 82 MMT CO_2
Mining: 81 MMT CO_2

Transportation Equipment deeper dive

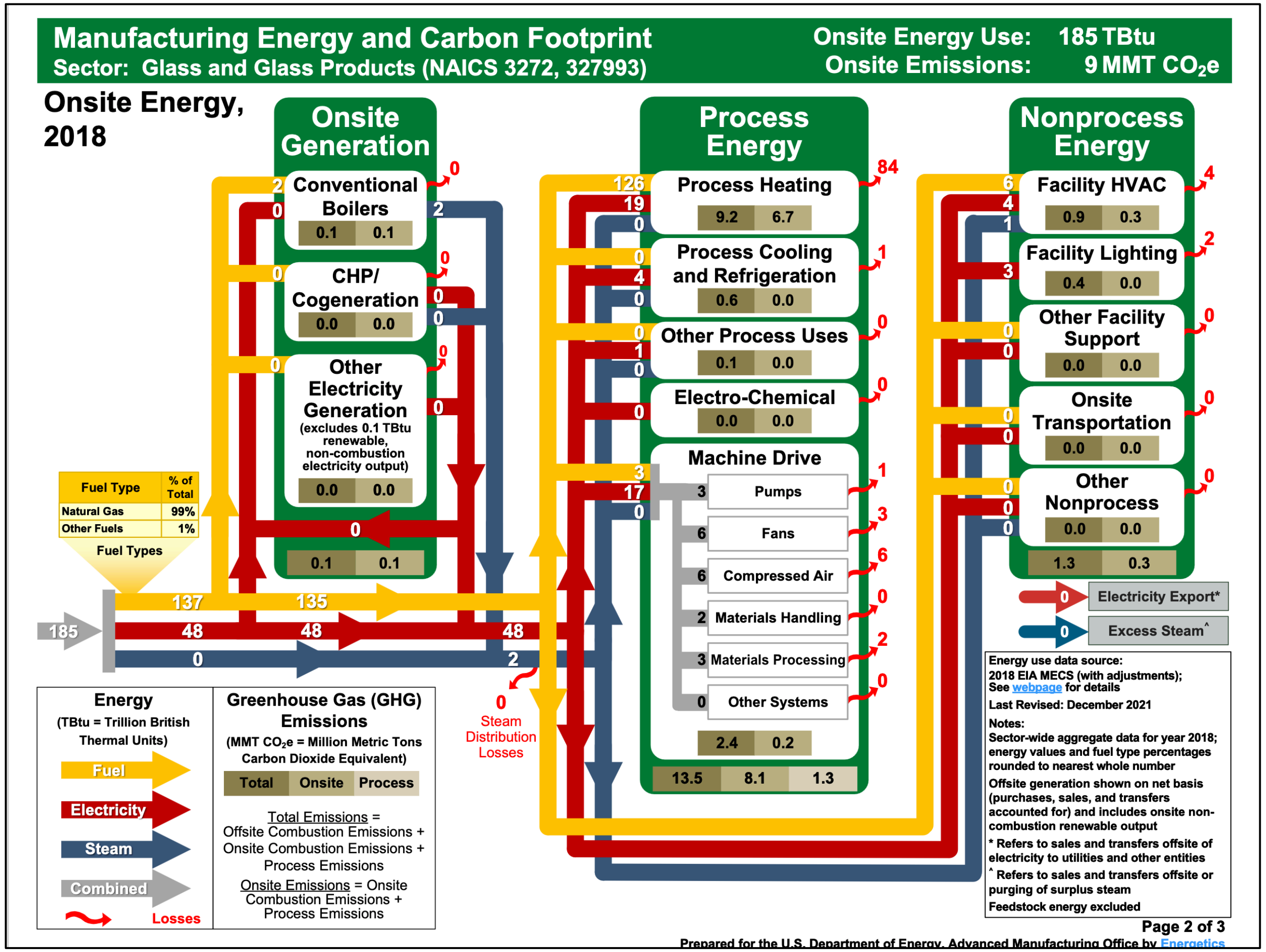


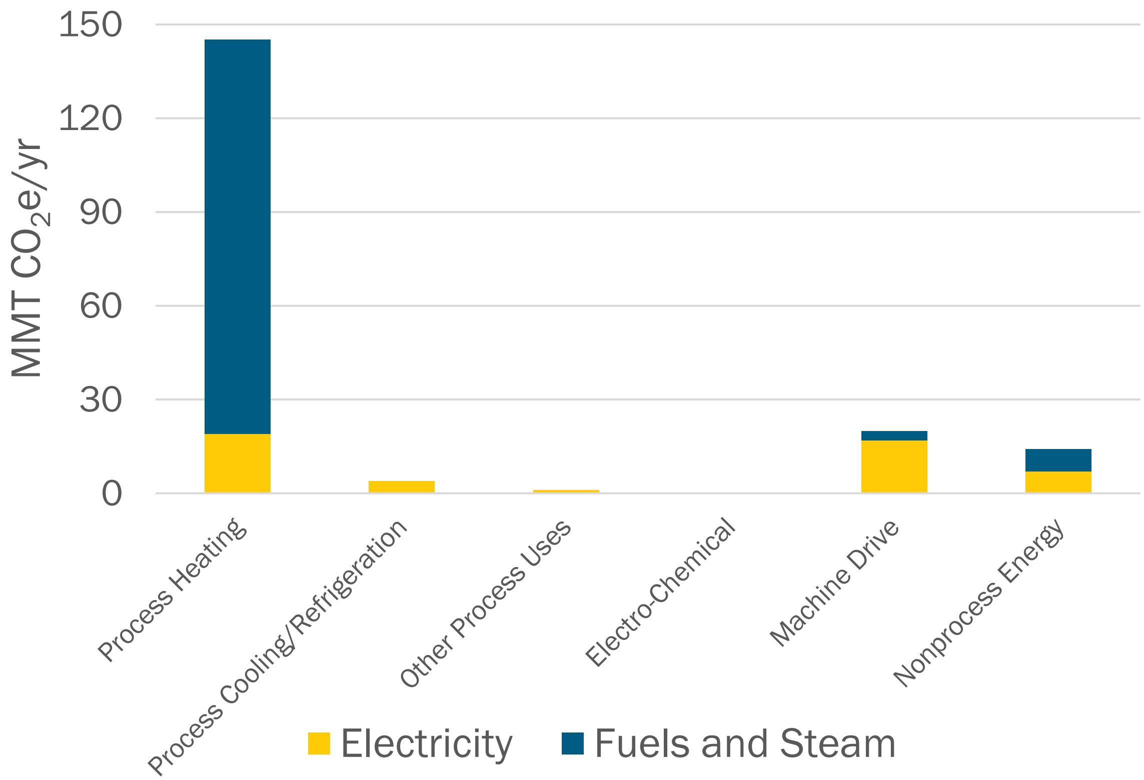


Of the total 345 TBtu supplied to the sector, 158 TBtu are lost (46%; largely as heat).

Source: USDOE Manufacturing Energy Footprints

Glass deep dive

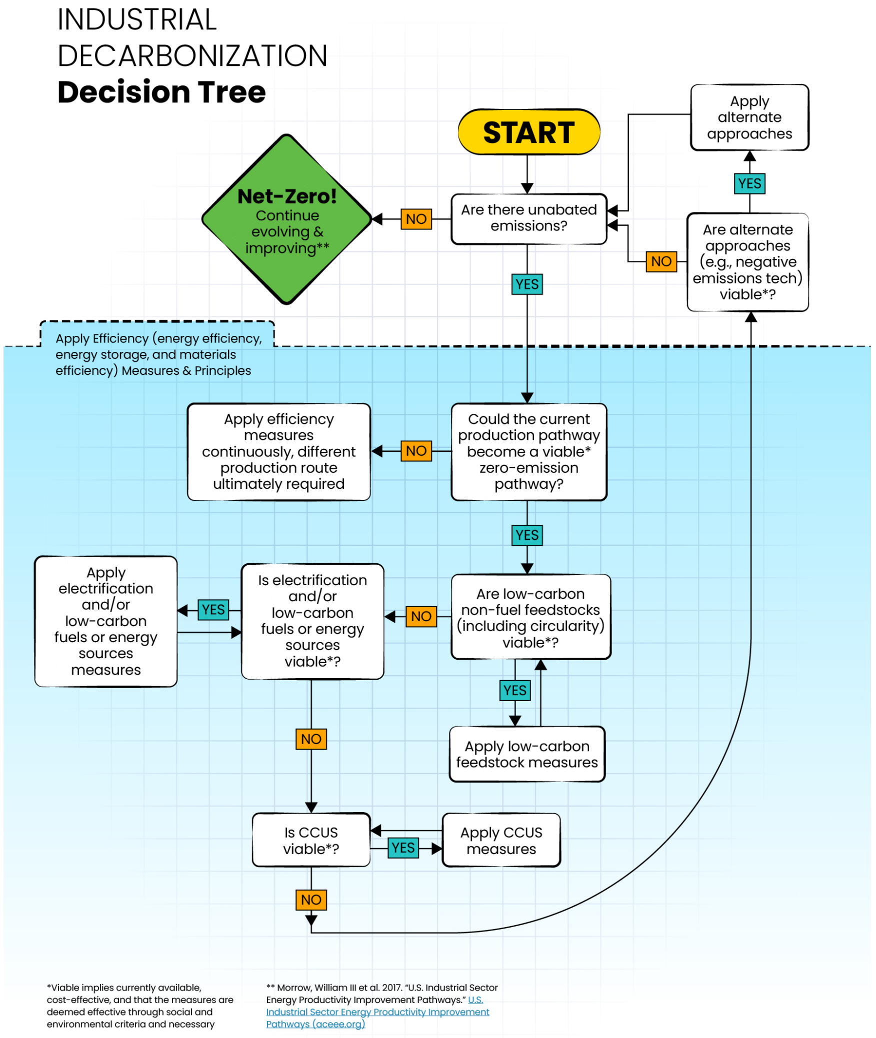




Of the total 185 TBtu supplied to the sector, 103 TBtu are lost (56%; largely as heat).

Source: USDOE Manufacturing Energy Footprints

Opportunities for Other Industries



Pillar	Transportation Equip.	Glass
Energy Efficiency	Process efficiency; motor system efficiency; HVAC efficiency	Furnace and burner control & design; Oxygen-lancing; Use of post consumer cullet;
Electrification	Electroheating technologies; Load control; Energy storage	Electroheating technologies
LCFFES	Onsite renewables	Onsite renewables; Biofuels; H_2
CCUS	Likely not viable	Difficult due to other contaminants in stack

Challenges for Other Industries

Energy Efficiency
- Materials constraints, specifically for harsh environments
- Capital investments
  - Timing
  - Magnitude

Electrification
- “Spark Gap”
- Electroheating technologies
  - have smaller thermal output than fossil fuel fired
  - heat materials differently with different capabilities
- Risk (to production, safety)
- Supply chain delays
- Lack of clean electricity supply

- LCFFES
  - Costs
  - Regulatory uncertainty
  - Storage
  - Availability and lack of infrastructure

- Non-manufacturing emissions
  - Fugitive emissions (starting with tracking)
  - Electrification of mobile sources, including partial electrification
  - Feed additives for livestock

- Non-technical challenges
  - Small-to-medium manufacturers
  - Broader workforce issues
  - Diverse and distributed