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Pathways Analysis Summary: Decarbonization Potential for Industrial Subsectors - Preliminary Modeling Results

Authors

Cresko, Joe
Dollinger, Caroline
Armstrong, Kristina
et al.

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Pathways Analysis Summary: Decarbonization Potential for Industrial Subsectors

Preliminary Modeling Results

June 20, 2024

DRAFT

Disclaimer

Authors and Contributors

The Pathways Analysis and Modeling is executed by a core team listed below, responsible for all aspects of production including developing the models, drafting this report, and generating the results presented within. The work is led by the U.S. Department of Energy (DOE) Industrial Efficiency and Decarbonization Office and involved team members from Argonne National Laboratory (ANL), Energetics, Global Efficiency Intelligence (GEI), Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), Nexight, and Oak Ridge National Laboratory (ORNL).

Kristina Armstrong
ORNL
Swaroop Atnoorkar
NREL
Greg Avery
NREL
Aline Banboukian
ORNL
Bob Brasier
Energetics
Larrie Brown
Energetics
Alberta Carpenter
NREL
Joe Cresko
IEDO
Hernan Delgado
ANL
Caroline Dollinger
Energetics
David Forrest
Nexight
Sam Gage
Energetics
Logan Guy
Energetics[i]
Ali Hasanbeigi
GEI
Chukwunwike Iloeje
ANL
Dipti Kamath
ORNL
Unique Karki
LBNL
Heather Liddell
Energetics[ii]
Tae Lim
LBNL
Seungwook Ma
Energetics
Prashant Nagapurkar
ORNL
Sachin Nimbalkar
ORNL
Ikenna Okeke
ORNL
Peng Peng
LBNL
Kristin Powell
Energetics
Thomas Price
Energetics
Prakash Rao
LBNL
Brian Ray
Energetics
Samantha Reese
NREL
Isabelle Sgro Rojas
Energetics
Arman Shehabi
LBNL
Kenta Shimizu
Energetics
Michael Sortwell
Energetics[iii]
Cecilia Springer
GEI
Shravan Sreekumar
Nexight
Darlene Steward
NREL
Daniel Stewart
Energetics
Sarang Supekar
ANL
David Thaller
Energetics
Kiran Thirumaran
ORNL
David Turpin
Nexight
Taylor Uekert
NREL
Shubhankar Upasani
NREL
Julien Walzberg
NREL
Hope Wikoff
NREL
Li Yu
ANL
Jibran Zuberi
LBNL

[i] Now Deloitte
[ii] Now Purdue University
[iii] Now Office of Clean Energy Demonstrations

Joe Cresko (IEDO) led this analysis and modeling effort and co-led development of this report with Caroline Dollinger (Energetics). Working group leads are provided below:

CCUS
Sarang Supekar, ANL

Cement
Ali Hasanbeigi, GEI

Chemicals
Jibran Zuberi, LBNL

Electric grid
Brian Ray, Energetics

Electrification
Ali Hasanbeigi, GEI (co-lead)
Jibran Zuberi, LBNL (co-lead)

Food and beverage
Caroline Dollinger, Energetics

Hydrogen
Peng Peng, LBNL

Iron and steel
Ali Hasanbeigi, GEI

Material efficiency
Alberta Carpenter, NREL

Model development
Kristin Powell, Energetics

Petroleum refining
Sam Gage, Energetics

Pulp and paper
Dipti Kamath, ORNL

Rest of industry
Seungwook Ma, Energetics (co-lead)
Sachin Nimbalkar, ORNL (co-lead)

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Yaroslav Chudnovsky, IEDO

Keith Jamison, IEDO

Felicia Lucci, IEDO

Paul Majsztrik, IEDO

Zachary Pritchard, IEDO

Barclay Satterfield, IEDO

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List of Acronyms and Abbreviations

AD	anaerobic digestion
AEO23	Annual Energy Outlook 2023
AGO	atmospheric gas oil
ANL	Argonne National Laboratory
ATR	autothermal reforming
BAU	business as usual
BECCS	bioenergy with carbon capture and storage
BF-BOF	blast furnace-basic oxygen furnace
Btu	British thermal unit
BTX	benzene, toluene, and xylenes
C	Celsius
CAPEX	capital expenditure
CDQ	coke dry quenching
CE	circular economy
CEA	controlled-environment agriculture
CCS	carbon capture and storage
CCSC	carbonatable calcium silicate clinker
CCUS	carbon capture, utilization, and storage
CH_4	methane
CHP	combined heat and power
CI	carbon intensity
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	coefficient of performance
CSA	calcium sulfo aluminate
DOE	U.S. Department of Energy
DRI-EAF	direct reduced iron- electric arc furnace
EAF	electric arc furnace
EE	energy efficiency

EEIO-IDA	Environmentally Extended Input-Output for Industrial Decarbonization Analysis Tool
EERE	Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPC	engineering, procurement, and construction
F	Fahrenheit
FCC	fluid catalytic cracking
FLW	food loss and waste
FOG	fats, oils, and greases
FSC	food supply chain
GDP	gross domestic product
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
H_2-DRI	hydrogen-direct reduced iron
HFCs	hydrofluorocarbons
HGL	hydrocarbon gas liquid
HTHP	high-temperature heat pumps
HWHP	hot water heat pump
IAC	Industrial Assessment Center
IAI	International Aluminum Institute
IEDO	Industrial Efficiency and Decarbonization Office
IoT	Internet of Things
ITC	Investment Tax Credit
LAFA	loss-adjusted food availability
LBNL	Lawrence Berkeley National Laboratory
LC3	limestone calcined clay cement
LCDs	liquid crystal displays
LCFFES	low carbon fuels, feedstocks, and energy sources

LED	light-emitting diode
m^3	cubic meter
ME	material efficiency
MECS	Manufacturing Energy Consumption Survey
MEMS	microelectromechanical systems
MMT	million metric ton
MSW	municipal solid waste
MTA	methanol-to-aromatics
MTO	methanol-to-olefins
MW	megawatt
N_2O	nitrous oxide
NAICS	North American Industry Classification System
NET	negative emissions technology
NF_3	nitrogen trifluoride
NGL	natural gas liquids
NPV	net present value
NREL	National Renewable Energy Laboratory
ODC	oxygen depolarized cathode
ORC	organic Rankine cycle
ORNL	Oak Ridge National Laboratory
PEM	proton exchange membrane
PET	polyethylene terephthalate
PF	plant factory
PFCs	perfluorocarbons
PPAs	power purchase agreements
PSIG	pounds per square inch gauge
PTC	Product Tax Credit
PV	photovoltaic
R&D	research and development
RD&D	research, development, and demonstration

ReEDS	Regional Energy Deployment System
RFI	request for information
RNG	renewable natural gas
SAF	sustainable aviation fuel
SCMs	supplementary cementitious materials
SF_6	sulfur hexafluoride
SGHP	steam-generating heat pump
SIDERWIN	development of new methodologieS for InDustrial CO2-freE steel pRoduction by electroWINning
SMEs	small and medium enterprises
SMR	steam methane reforming
SOEC	solid oxide electrolyzer cells
SPK	synthetic paraffinic kerosene
syngas	synthetic gas
TBtu	trillion British thermal units
TFEC	total final energy consumption
TPC	technology possibility curve
TRL	technology readiness level
TRT	top-pressure recovery turbine plants
U.S.	United States
USDA	U.S. Department of Agriculture
VFD	variable frequency drive
W&R	wholesale and retail
WHR	waste heat recovery

Executive Summary

This provides a summary of draft modeling efforts undertaken by the U.S. Department of Energy (DOE) Industrial Efficiency and Decarbonization Office (IEDO) as an extension and expansion of the 2022 *Industrial Decarbonization Roadmap*.[iv] IEDO is providing these draft modeling results to support stakeholder engagement and inform office- and department-wide strategy and decision making. Section 1 provides an overview of the context for this analysis and modeling as well as information on the decarbonization pillars characterized and the models themselves. Section 2 presents modeling results of one net-zero emissions pathway each for six industrial subsectors: cement, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper. It is important to note that these pathways are just one example and there is no single pathway for any single industrial subsector. Competition across different possible pathways will be essential to industrial decarbonization success. Section 3 provides an overview of the "rest of industry" subsectors and a high-level overview of net-zero barriers, challenges, pathways, and technologies. IEDO will continue to consider net-zero pathways and modeling for these rest of industry subsectors. Additional details will be made available in the future on the IEDO website.[v]

[iv] Often abbreviated as the "*Roadmap*" throughout this document. Industrial Decarbonization Roadmap | Department of Energy

[v] See: https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

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1 Introduction

This document outlines a framework that can meet the modeling and analysis needs of industrial decarbonization pathways, and provides a summary of draft modeling efforts undertaken by the U.S. Department of Energy (DOE) Industrial Efficiency and Decarbonization Office (IEDO) as an extension and expansion of the 2022 *Industrial Decarbonization Roadmap*.[1] To support the *Transforming Industry* Request for Information (RFI) and May 2024 workshop, IEDO is providing these draft modeling results to inform office- and department-wide strategy and decision making. This section includes information on scope, decarbonization pathways, pillars, scenarios, and net-zero pathway models. Section 2 provides examples of a net-zero emissions pathway for six industrial subsectors: cement, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper. While a pathway is provided per subsector, it is important to note that these are just one example and there is no single pathway for any single industrial subsector. Competition across different possible pathways will be essential to industrial decarbonization success. Section 3 provides an overview of the "rest of industry" subsectors and a high-level overview of net-zero barriers, challenges, pathways, and technologies. IEDO will continue to consider net-zero pathways and modeling for these rest of industry subsectors.

Additional details will be made available in the future on the IEDO website.[2] This effort is intended to help evaluate the impact of decarbonization technologies with the goal of complete decarbonization (net-zero) of the American industrial sector by 2050. Such an effort will allow us to understand the drivers of decarbonization and evaluate incumbent and next generation technologies in a structured and transparent manner.

1.1 What is a Decarbonization Pathway?

Within the context of this industrial modeling framework, we define a decarbonization pathway as a sequence of technology deployments and retirements over time that allow the industry to arrive at an established level of carbon emissions in an established timeframe. In the context of an industry-wide modeling framework, each pathway can be formalized as a set of time-dependent array of assets comprised of numerous and variegated energy and production technologies that get deployed to produce a set of manufactured goods to meet a certain demand for those goods, while pursuing some sort of

Net-Zero Pathway

As defined in the *Industrial Decarbonization Roadmap*, a ***pathway*** is a set of specific actions needed to achieve progress in and across the decarbonization pillars, while remaining informed and supplemented by research, development, and demonstration (RD&D) to advance viable solutions (i.e., technologies, practices, approaches, behaviors) that will need to be adopted at scale in the marketplace.

[1] Often abbreviated as the "*Roadmap*" throughout this document. Industrial Decarbonization Roadmap | Department of Energy
[2] See: https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

objective(s) and acting under a certain set of constraints or rules. These objectives and constraints can emerge from economic, environmental, social, technical, or operational factors. A decarbonization pathway, by definition, would therefore include an explicit emissions reduction goal or constraint.

A highly detailed pathway would be associated with time-dependent estimates of aggregated quantities such as emissions, energy use, materials use, labor, costs, etc., which can be linked to broader economic, environmental, and social impacts emerging from the pathway. A challenge in modeling of the industrial sector are limitations in data and information related to specific production assets across the industrial subsectors. In general, there are varying levels of representation for different manufacturing industries industrial decarbonization models. For example, the iron and steel subsector has considerably less heterogeneity and greater data availability than the food and beverage or chemicals subsectors. As a result, any analysis that seeks to understand effects of one or more of the above decarbonization pillars on multiple industries should be able to simultaneously represent industries with varying levels of data resolution.

Given these challenges, our current approach has been to develop detailed spreadsheet models for each subsector studied, in which decarbonization pathways are generated by a trying to achieve a certain objective (e.g., net-zero emissions) subject to certain restrictions or considerations. More detail on the models is provided in Section 1.5. Generating multiple such pathways under various scenarios or parameters of interest can generate a useful "set of possible futures" that can elucidate a wide range of technology and policy decisions.

For example, direct reduction of iron ore using clean hydrogen would be considered a decarbonization technology option under this definition. Should clean hydrogen-based direct reduction technology be deployed to displace conventional steel production facilities over time, the collective technology turnover and associated changes in energy use, emissions, costs, and other attributes would collectively constitute a pathway.

There is no unique pathway to deep decarbonization and it requires efforts on all fronts. Some strategies are common to all pathways while others involve tradeoffs whose risks and benefits will need to be weighed carefully. Additionally, research and development (R&D) to develop new technologies and improve cost effectiveness is needed to help achieve these pathways and reach net-zero emissions for individual subsectors and the industry as a whole. As such, this effort seeks to:

- Assess a broad array of low to high maturity technology options to lower manufacturing GHG emissions
- Develop manufacturing subsector decarbonization scenarios based on assessments of technology risks, barriers, and incentives

- Examine potential impacts of technology deployment across the decarbonization pillars of energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS)
- Compare technology pathways that focus on facility-level decarbonization with those that target broader supply chain decarbonization.

1.2 Context and Scope

Table 1 provides an overview of the different type of industrial emissions.

Table 1. Industrial Sector Emissions (as defined in the *Industrial Decarbonization Roadmap*)

Emission type	Description
Fuel-related emissions	Emissions associated with the combustion and use of fuels (from fossil or non-fossil sources) at industrial facilities for needs other than electricity (e.g., for process heat). Included in Scope 1 emissions.
Electricity generation emissions	Emissions attributed to the generation of electricity used at industrial facilities, whether that electricity is generated onsite or offsite. Also called Scope 2 emissions.
Industrial process emissions	Non-energy-related process emissions from industrial activities (e.g., direct CO_2 emissions from chemical transformations in materials being processed). Included in Scope 1 emissions.
Manufactured product life cycle emissions	Emissions generated from cradle-to-grave (or cradle-to-cradle) that include emissions generated both upstream of the manufacturing processes (supply chain) and downstream (during product use and end of life). The upstream and downstream emissions are also called Scope 3 emissions.

This modeling work includes Scope 1 and 2 emissions in the reported values for the industrial sector and excludes Scope 3 upstream and downstream emissions. Scope 1 emissions refer to direct GHG emissions that occur gate-to-gate during steel production while Scope 2 emissions refer to indirect GHG emissions associated with the production of purchased utilities such as electricity and steam.[3] For the purposes of this model, emissions associated with the production of hydrogen have been included in Scope 2 emissions.

The work presented in this report is an extension of the modeling done for DOE's 2022 *Industrial Decarbonization Roadmap*.[4] The *Roadmap* including modeling of the decarbonization impacts and pathways for five manufacturing subsectors: cement; chemicals; food and beverage; iron and steel; and petroleum refining. This modeling work includes those five subsectors and adds pulp and paper. Table 2 specifies the scope of emissions for each subsector included in this modeling.

[3] See Scope 1 and Scope 2 Inventory Guidance | U.S. EPA
[4] Industrial Decarbonization Roadmap | Department of Energy

Table 2. Scope of Emissions Included in the Pathways Modeling Effort

Industry Subsector	Electricity Generation CO_2 Emissions	Fuel-Related CO_2 Emissions	Process-Related CO_2 Emissions	CH_4, N_2O, and Other Non-CO_2 GHG Emissions	Subsector Coverage in Analysis
Cement	Included	Included	Included	Included	Full subsector coverage
Chemicals	Included	Included	Included	Included	Partial coverage[a]
Food and beverage	Included	Included	N/A[c]	Included	Partial coverage[b]
Iron and steel	Included	Included	Included[d]	Included	Full subsector coverage
Petroleum refining	Included	Included	N/A[c]	Included	Full subsector coverage
Pulp and paper	Included	Included	N/A[c]	Included	Full subsector coverage

Acronyms: carbon dioxide (CO_2), greenhouse gas (GHG), methane (CH_4), nitrous oxide (N_2O)

[a] For the chemicals subsector, a subset of high-volume, high-emitting chemicals accounting for 40% of total chemicals manufacturing GHG emissions[5] were included in this analysis: ethylene; propylene; butadiene; benzene, toluene, and xylenes (BTX) aromatics; chlorine; sodium hydroxide (caustic soda); sodium carbonate (soda ash); ethanol; methanol; and ammonia. See Section 2.2 for more details.

[b] For the food and beverage manufacturing subsector, a representative set of subsectors accounting for 78% of total food and beverage manufacturing GHG emissions[6] were included in this analysis: grain and oilseed milling; sugar product manufacturing; fruit and vegetable preserving and specialty food manufacturing; dairy product manufacturing; animal slaughtering and processing; and beverage manufacturing. See Section 2.3 for more details.

[c] No process-related emissions associated with food and beverage manufacturing, petroleum refining, or pulp and paper manufacturing are reported by the U.S. Environmental Protection Agency in the Inventory of U.S. Greenhouse Gas Emissions and Sinks.[7] Fugitive emissions from the petroleum refining subsector are not included.

[d] In the iron and steel industry, most process-related CO_2 emissions are related to coke consumption. Some studies categorize coke use under energy-related emissions, while others categorize coke use under process-related emissions. Regardless, emissions associated with coke consumption are included in this analysis.

This modeling work focuses on industrial energy and emissions and does not directly model cost estimates. However, economics are a key evaluation criterion for industrial decarbonization technologies, can change as a technology matures, and vary according to use case. Examples of economic criteria include cost to abate carbon, cost to produce a carbon-abated product, levelized cost of heat (or clean energy), broader levelized cost of material transformation, and others. Many types of cost and factors influence the development and deployment of any technology, including initial design and analysis, permitting, regulatory compliance, training, downtime, capital, operating costs; demand incentives; potential future regulatory or market drivers; competitiveness; and resilience (e.g., from supply chain disruptions, natural disasters).

DOE estimates that more than 60% of heavy industry emissions reductions needed to achieve net-zero by 2050 will come from technologies that are still in the innovation pipeline

[5] Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data | Energy Information Administration; Inventory of U.S. Greenhouse Gas Emissions and Sinks | U.S. Environmental Protection Agency; and Chemicals Manufacturing Energy and Carbon Footprint | Department of Energy.

[6] Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data | Energy Information Administration; Inventory of U.S. Greenhouse Gas Emissions and Sinks | U.S. Environmental Protection Agency; and Food and Beverage Manufacturing Energy and Carbon Footprint | Department of Energy.

[7] U.S. Environmental Protection Agency - Inventory of U.S. Greenhouse Gas Emissions and Sinks

and are not currently market ready.[8] DOE invests in early-stage technologies with the goal of accelerating their technology readiness through deployment. Technoeconomic analysis is a key tool to estimating the impact of individual technologies. More information on shorter term (by 2030) cost estimates for commercially available technologies is provided in the *Pathways to Commercial Liftoff: Industrial Decarbonization* reports (including deep dives on chemicals, refining, and cement.[9]

1.3 Decarbonization Pillars: Crosscutting Carbon-Reducing Technologies, Processes, and Practices

The *Industrial Decarbonization Roadmap* and this modeling effort consider four crosscutting decarbonization pillars: energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy systems (LCFFES); and carbon capture, utilization, and storage (CCUS).[10] Full definitions for the pillars can be found in the *Roadmap* Section 1 and are summarized in Table 3 below with manufacturing-specific examples.

Table 3. Decarbonization Pillars

Pillar	Energy Efficiency	Industrial Electrification	Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)	Carbon Capture, Utilization, and Storage (CCUS)
Definition	Advancements that minimize industrial energy demand, directly reducing the GHG emissions associated with fossil fuel combustion.	Technologies that utilize electricity for energy, rather than combusting fossil fuels directly, enable the subsector to leverage advancements in low-carbon electricity from both grid and onsite generation sources.	Substitutions for fossil-based fuels, feedstocks, and energy sources to further reduce combustion- and process-associated industrial emissions.	Multi-component strategy for mitigating difficult-to-abate emissions involves capturing generated CO_2 before it can enter the atmosphere; utilizing captured CO_2 whenever possible; and storing captured CO_2 long-term to avoid atmospheric release.
Technology examples	• Variable frequency drives • Process integration • Strategic energy management	• Steam-generating heat pumps • Hot water heat pumps • Electric boilers	• Biomass • Biofuels • Biogas • Clean hydrogen	• Post-combustion carbon capture and storage for large point source emissions

As noted in the *Roadmap,* boundaries between pillars can be indistinct as crosscutting actions, approaches, and infrastructure investments may accelerate progress and improvements across multiple pillars.

[8] Pathways to Commercial Liftoff: Industrial Decarbonization - Department of Energy
[9] Ibid.
[10] Industrial Decarbonization Roadmap | Department of Energy

Beyond the four main pillars, material efficiency (including material substitution, resource conservation, and circular economy strategies) is an important crosscutting decarbonization lever that can have impacts across the four main pillars and is detailed in Section 1.3.5. For example, end-of-life materials could be used as low-carbon feedstocks within the LCFFES pillar, but would need to be used in an energy-efficient manner. Because these strategies can be difficult to quantify and may have impact outside the bounds of an industrial facility, material efficiency is not fully covered in these modeling results. Material efficiency strategies need further exploration and analysis, including defensible life cycle and technoeconomic assessments.

1.3.1 Energy Efficiency

Energy efficiency measures and system design are fundamentally important at all industrial decarbonization stages since they apply to incumbent and future technologies. Energy efficiency could potentially reduce as much as 467 million metric tons (MMT) of industrial CO_2 emissions by 2050 by some estimates.[11] Energy efficiency measures also indirectly reduce the onus and cost of decarbonization for other more direct approaches such as industrial electrification, LCFFES, and CCUS as well as the cost of decarbonizing the electricity sector.

Energy efficiency measures include (among others): production-side energy efficiency such as process intensification, process integration, on-site combined heat and power generation, waste heat recovery, smart manufacturing controls integration, and strategic co-location of facilities along a value chain for industrial symbiosis.

Energy efficiency barriers include inadequate awareness of efficiency measures and incentives; unfavorable return on investment due to low fossil energy cost and/or high additional equipment cost (particularly applicable to smart manufacturing); operations disruptions during retrofits; waste heat integration engineering constraints; lack of strategic energy management to ensure improvements persist; and rebound effects. Additionally, water conservation and management are often overlooked due to perceived sufficient availability at low cost to manufacturers. A circular economy would narrow, slow, regenerate, and close material flows, keep materials' value within the economy, minimize waste, and generate potential economic and environmental benefits over the linear "take-make-waste" economy.

1.3.2 Industrial Electrification

Electrification of fossil fuel-using industrial mechanical, thermal, and chemical processes can significantly reduce energy consumption and associated GHG emissions. This includes switching to heat pumps, electric boilers, electric furnaces, advanced electro-heating technologies (that rely on microwaves, infrared waves, electromagnetic induction, or plasma

[11] Nadel and Ungar. 2019. *Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050 | ACEEE*.

for instance), electro-chemical and electrically assisted biological processes, membrane separation, and electrification of rotary equipment.

As the grid decarbonizes, purchased electricity-related emissions will reduce as well. Industrial processes requiring low-to-medium grade temperature heat are comparatively simpler to electrify as opposed to high-temperature processes and should thus be prioritized. Additionally, electrical process heating equipment has better temperature and process control, which may result in a higher production rates and fewer maintenance requirements.

Barriers to industrial electrification include clean electricity availability, reliability, and cost; inefficiencies and inadequacies in transmission and distribution infrastructure; scale-up risks and performance or quality trade-offs with electrified processes; high capital cost of electricity-driven equipment; disruption and/or drastic reconfiguration of existing processes during retrofits; material limitations under harsh environments; and constraints on type, grade, and availability of feedstocks that could be processed (e.g., steel scrap in electric arc furnaces).

1.3.3 LCFFES

Manufacturing industry's almost ubiquitous demand for thermal energy for process heat, as well as demand for certain feedstocks, has the potential to at least partially be met with low- and zero-carbon alternatives.[12] These alternatives are collectively termed low-carbon fuels, feedstocks, and energy sources (LCFFES). Examples of LCFFES include replacing fossil fuels and fossil fuel-derived non-fuel feedstocks with low-carbon energy carriers and non-fuel feedstocks (such as hydrogen; ammonia; synthetic fuels including e-fuels; sustainably sourced biomass, biogas,[13] and bioproducts; and chemical precursors from CO_2) and utilizing clean thermal energy sources (such as solar, geothermal, or small modular nuclear reactors). Beyond meeting industry's current demands, some strategies incorporating LCFFES can provide the opportunity for a more robust system than is currently employed, with the integration of energy storage (such as thermal energy storage[14]). Each LCFFES will have a unique set of approaches, barriers, and opportunities; this section provides some broad examples on biomass, hydrogen, and thermal energy sources.

Biomass could be used as a low-carbon fuel either directly or through gasification for process heat in industrial processes. Conventional and alternative bio-feedstocks could substitute petroleum-based non-fuel feedstocks. Both approaches present a significant potential to reduce GHGs when sustainably sourced and transported in a way that does not cause net positive emissions from land use and land use change or create significant impulses of carbon flux in the short run, both of which could lead to significant warming

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[12] *To decarbonize industry, we must decarbonize heat | Joule*.
[13] Biogas-Renewable natural gas - U.S. Energy Information Administration (EIA)
[14] Energy StorM – DOE Office of Electricity Energy Storage Program (sandia.gov)

within the 2050 timeframe. Barriers to biomass use in industry include varying regional availability, competition from other end uses such as electricity generation, timber, and land use for food crops cultivation, and inconsistent carbon accounting practices that don't always accurately account for land use-related life cycle emissions.

Hydrogen is another potential LCFFES when obtained from water electrolysis using a clean energy source such as wind, solar, or nuclear or from conventional steam methane reforming of natural gas with carbon capture and storage. By some estimates, hydrogen is expected to make up between 10%–35% of total industrial final energy consumption in a decarbonized industry.[15] Barriers to use of hydrogen in industry include high production cost, safety and transport and storage cost concerns, detrimental distribution infrastructure impacts when blended with natural gas, and significant changes needed in burners and heat exchangers design due to dramatically different flame characteristics and heat transfer mechanisms compared to other gaseous or liquid hydrocarbon fuels.

Thermal energy sources supplied directly via clean energy (e.g., solar, geothermal, small modular nuclear reactors) could provide low- or zero-carbon process heat and/or drive thermodynamic power cycles. Barriers to solar thermal energy sources include intermittency, low areal density, achievable temperature, and challenges associated with high-temperature heat transfer media.[16] For geothermal energy sources, challenges and opportunities differ between the near surface hydrothermal and nonhydrothermal applications and deep geothermal opportunities. Non-hydrothermal is significantly limited by its low reservoir temperature, often coupled with a heat pump, but has abundant geographic distribution. Hydrothermal sources offer modestly higher temperatures but have limited geographic distribution. Deep geothermal opportunities take advantage of the thermal gradient in the earth's crust, but come with significant challenges, especially as they approach the depths necessary for higher temperature industrial process heat demands. Nuclear energy (from fission and/or future fusion reactors) can also offer an LCFFES opportunity for industrial electricity and heat.[17] Recent advances in reactor designs provide the potential for addressing higher temperature industrial process heat demand. [18]

1.3.4 CCUS

CCUS technology opportunities include capture and reuse (utilization for e-fuels, chemical precursors, etc.) or sequestration (long-term storage in geological formations, saline aquifers, minerals, etc.) of high-purity process CO_2 streams and low-purity combustion CO_2 streams.

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[15] U.S. National Clean Hydrogen Strategy and Roadmap | Department of Energy
[16] *To decarbonize industry, we must decarbonize heat | Joule*.
[17] Richard D. Boardman et al. 2021. "Process Heat for Chemical Industries." *Encyclopedia of Nuclear Energy* 3: 49-60. https://doi.org/10.1016/B978-0-12-819725-7.00198-7.
[18] *To decarbonize industry, we must decarbonize heat | Joule*.

In cases where CO_2 is produced as a byproduct of non-combustion chemical reactions such as calcining, fermentation, and gasification (and combustion of fuels with oxygen), the relatively high purity of CO_2 streams can allow economically viable carbon capture with minimal additional treatment, cost, and energy expenditure. Such high purity sources already supply the merchant CO_2 market (currently at 14 MMT/year capacity)[19] and are expected to be sources for CO_2 utilization applications such as synthesis of chemical precursors and e-fuels.[20] CO_2 generated from fuel combustion, which constitutes over 72% of all industrial CO_2 emissions,[21] would require additional processes to separate CO_2 from waste streams, including those that use amine-based solvents, solid sorbents, calcium looping, membrane separation, cryogenic separation, and reactive capture. Carbon capture shows promise in significantly reducing emissions, particularly for industrial processes generating low-CO_2 concentration streams. Yet it remains prohibitively expensive due to high capture facilities capital costs and the parasitic energy loads they add.

Other CCUS barriers include the uncertainty of merchant and captive CO_2 markets in a low-carbon future; concerns around feasibility, safety, and monitoring of a nationwide CO_2 pipeline transport and long-term CO_2 storage infrastructure; facilities' lack of proximity to a viable CO_2 storage location; and inadequate guidelines on captured, reused, and stored carbon accounting. Some industrial subsectors such as cement and concrete may need to rely on CO_2 capture in addition to electrification, low-carbon fuels, or other approaches since these approaches do not avoid the release of CO_2 from limestone pyroprocessing, which can comprise up to 60% of cement production emissions.

1.3.5 Material Efficiency

Raw materials extraction and processing contribute to about 50% of global GHG emissions.[22] Materials and resources entering, used or produced within, and leaving industrial facilities have embodied environmental impacts and can significantly affect the environment and worker and community health and safety. Efficient use of materials and resources (including circularity and alternative processes, feedstocks, and innovative products) can reduce U.S. industry's environmental impacts and the upstream and downstream emissions that reach the broader economy. More efficient use of materials and resources and proper siting of industrial facilities can mitigate negative impacts and provide environmental and social benefits to impacted communities.

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[19] Supekar and Skerlos. 2014. "Market-Driven Emissions from Recovery of Carbon Dioxide Gas." *Environ. Sci. Technol.* 48 (24): 14615–14623. https://doi.org/10.1021/es503485z.

[20] Zang et al. 2021. "Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO2 from Industrial and Power Plants in the United States." *Environ. Sci. Technol.* 55(11): 7595-7604. https://doi.org/10.1021/acs.est.0c08674.

[21] Inventory of U.S. Greenhouse Gas Emissions and Sinks | U.S. Environmental Protection Agency

[22] Ellen MacArthur Foundation. 2021. *Completing the Picture: How the Circular Economy Tackles Climate Change*. https://www.ellenmacarthurfoundation.org/publications/completing-the-picture-climate-change; International Resources Panel. 2019. *Global Resources Outlook 2019: Natural Resources for the Future We Want*. https://www.resourcepanel.org/reports/global-resources-outlook.

Material efficiency measures include (among others):

- Redesign, reuse, repurposing, and recycling of all, especially energy and carbon-intensive industrial products and commodities, as well as their substitution with functionally identical (or better) alternatives with lower embodied carbon.
- Various measures to reduce water use and water quality impacts of manufacturing operations include reuse (e.g., cascading rinse waters, returning boiler condensate), servicing and retrofitting cooling systems, leak repair, and exploring alternative water sources (e.g., gray water) particularly for end uses that do not require potable water.
- Waste reductions lower the energy, material, and other resource demands of a manufacturing facility. Less resources are used to produce the same amount of goods. Further, waste reduction can reduce costs (waste disposal and overall energy, material, and resource costs since more of these go into the product), dependence on outside entities to accept the waste, and risk of environmental hazard associated with toxic waste transportation and processing.

Water conservation and management are often overlooked due to perceived sufficient availability at low cost to manufacturers. A circular economy would narrow, slow, regenerate, and close material flows, keep materials' value within the economy, minimize waste, and generate potential economic and environmental benefits over the linear "take-make-waste" economy. Other material circularity and material efficiency barriers include absent or inadequate reverse supply chain infrastructure, scale-up risks and performance or quality trade-offs with alternative substitutes, higher costs relative to linear supply chains, concerns around labor costs, possible job losses, regulatory standards, and rebound effects.

1.4 Decarbonization Scenarios

This modeling effort aligns with DOE's 2022 *Industrial Decarbonization Roadmap* to classify relevant decarbonization technologies into four pillars: energy efficiency; industrial electrification; LCFFES; and CCUS. For this summary, DOE has also defined four composite technical scenarios in alignment with the *Industrial Decarbonization Roadmap*: business as usual (BAU), moderate technology adoption, advanced technology adoption, and net-zero GHG.[23] These technical composite scenarios consider technologies in all four decarbonization pillars and vary by degree rather than approach and are used to evaluate the CO_2e emissions reduction potential for manufacturing subsectors studied. A brief description of each scenario is provided below; the example pathways shown in this summary are for the net-zero scenarios only. Specific assumptions vary by subsector and the net-zero scenario assumptions are discussed in Section 2.

Business as Usual (BAU): Assumes a slow improvement in energy efficiency and adoption of commercially available electrification technologies.

[23] Industrial Decarbonization Roadmap | Department of Energy

Moderate Technology Adoption: Assumes a higher rate of energy efficiency improvements, more switching to LCFFES, and a higher rate of electrification than the BAU scenario. It also assumes low adoption of CCUS.

Advanced Technology Adoption: Assumes even higher energy efficiency improvement, more-aggressive switching to LCFFES, a higher rate of electrification, and CCUS adoption.

Net-Zero GHG: Assumes subsector-wide achievement of net-zero CO_2e emissions, with the most accelerated levels of energy efficiency improvements, switching to LCFFES, electrification, and CCUS adoption.

After the BAU, each scenario reflects a range of progressively more aggressive pathways to net-zero subsector emissions by 2050. The scenarios do not evaluate or include full life cycle GHG emissions associated with manufactured products, upstream and downstream (Scope 3) emissions, or emissions embodied in imported materials. As noted in Table 2, the chemicals and food and beverage subsectors modeling results only include representative sample for scenario analysis given the wide range of product outputs.

1.5 Industrial Decarbonization Pathways Models: Structures, Assumptions, Inputs, and Data Sources

The pathways analysis presented in this document is based on models developed for each subsector. These are Excel-based models that estimate energy- and process-related emissions for select industrial processes based on assumed feedstocks, manufacturing technologies, energy intensities, and energy sources. The model fundamentally calculates the aggregate energy & emission impact for the subsector based on adoption rate, energy source, in context with other technologies included in the models. Each model starts with a forecast of production volume from 2018 to 2050 in annual increments. Today's facilities and technologies are defined as a baseline and key upcoming technologies are identified. In practice, the model assigns an energy intensity impact to each identified technology (Note: the energy intensity assigned in the model is based on data gathered exogenously and can be adjusted/updated by the model user as technologies change and more detailed information becomes available). As the overall production of products shifts from traditional technologies to next-generation technologies, the model calculates the potential impact on energy intensity. This required energy is then used to predict associated emissions by adding assumptions for the energy sources used each year (specifically: onsite-generated electricity, grid electricity, and specific fuel types–each with an associated level of emissions per energy unit). In this way, energy-related emissions are predicted over time. At the same time, process emissions are calculated for each assumed technology and feedstock. Specifically, 'process emissions' refers to onsite GHG emissions that are typically produced in a chemical reaction from the feedstock during manufacturing. Energy-related and process-related emissions are added together for each year. Finally, the impact of assumed carbon capture technologies is applied based on process-specific details to give the final magnitude of unabated emissions.

These models are limited to technology-based solutions. They are also dependent on significant literature review and calculations from the user to accurately input the appropriate adoption rates and simultaneous energy-related impacts of key technologies. The benefit of this effort is significantly increased resolution and nuance for technology impact in each considered subsector. Calculations are bottom-up where possible and specifically customized for subsector details such as paper mill recovery boilers, the cement sectors clinker-to-cement ratio, and the petroleum refining subsector's process integration.

The models leverage and expand upon what was included in the *Roadmap*, including through added time resolution (annual basis for 2018 through 2050); expanded bottom-up analysis to capture specific technologies or process units; increased resolution for input variables such as fuel sources, non-energy process emissions, multiple carbon capture technologies, and electricity-related emissions; added nuance to calculations for carbon capture, electrification, onsite electricity generation, and hydrogen; standardized carbon accounting; and disaggregated emission results for onsite vs. offsite, biogenic vs. non-biogenic, and carbon sequestration vs. utilization. Additionally, pillar breakdown calculations were refined to more accurately capture adoption of technologies and to separate industrial electrification from LCFFES. Including a wider range of products helps better characterize the decarbonization pathways and impacts within each subsector as a whole. This section provides information on the models and additional detail can be found in Appendix A.

1.5.1 Model Structure

The general goal was customization to capture subsector nuance but harmonization across all sectors for key inputs, outputs, and carbon accounting. Specifically, there are two overarching model structures: one which fully replaces incumbent facilities with alternative production routes (Figure 1: chemicals, cement, and iron and steel models) and a second which is limited to the incumbent process but focuses with greater resolution on specific modifications to process sub-units (Figure 2: petroleum refining, pulp and paper, and food and beverage models).

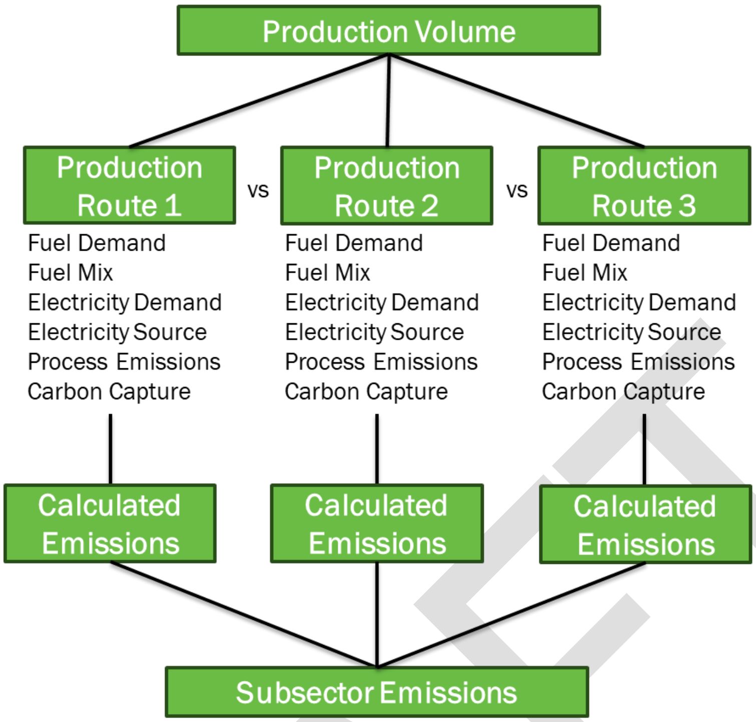

Figure 1. Model structure and flow for alternative production routes

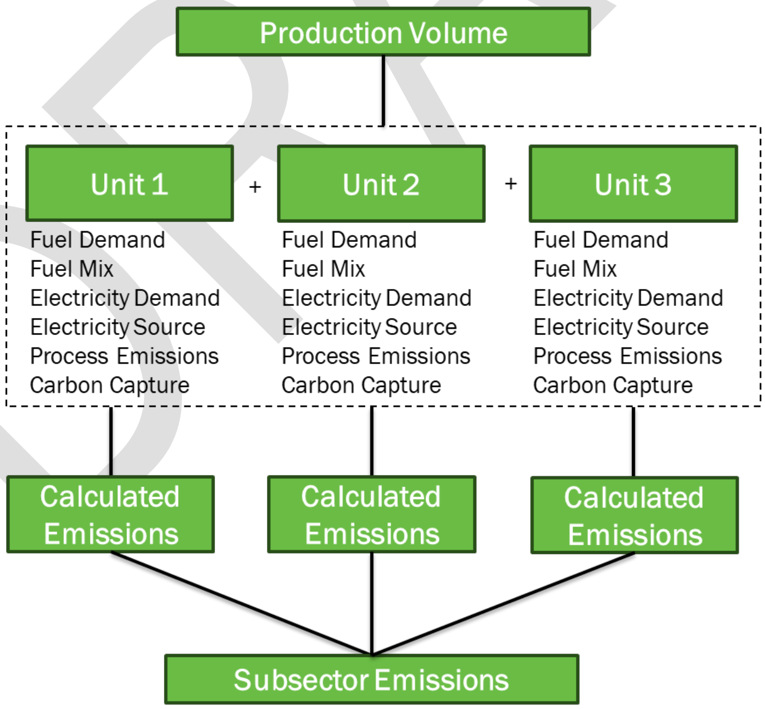

Figure 2. Model structure and flow for higher resolution of a production route

1.5.2 Key Modeling Variables

Table 4 provides an overview of key variables within the models. The same key modeling variables (fuel demand, fuel mix, etc.) are applied for each subsector regardless of overarching model structure. However, in Figure 1 models, inputs are defined for each production method while in Figure 2 models, inputs are defined for each sub-unit (ex. specific unit operations or equipment categories).

Table 4. Key Variables for Pathways Analysis

Variable	Description
Production	Annual production for 2018 through 2050
Technology adoption rate	Percent industry adoption, by production weight
Energy intensity	Disaggregated by fuel- & electricity- based energy Included gate-to-gate energy intensity (gigajoules/metric ton of product)
Steam	Attributed to fuel or electricity based on production method (e.g., electrification technology for steam generation shifts this energy demand from fuel to electricity)
Fuel mix	Disaggregated into specific fuel type (e.g., natural gas, biomass, diesel)
Fuel emission intensity	Emission factor (kg CO_2e/gigajoule) for each fuel type Biogenic factor for each fuel type
Hydrogen as fuel	Disaggregated into grey, green, blue
Electricity mix	Specified onsite vs. grid electricity generation
Electricity emission intensity	Emission factor based on assumed technology source (kg CO_2e/MWh)
Energy efficiency	Assumed rates of energy efficiency improvements based on operational improvements and technology adoption
Process emissions	Included non-energy process emissions (metric tons of CO_2e/metric ton of product)
Carbon capture	Included carbon capture technology and adoption rate details

Additional detail on carbon accounting, industrial electrification with grid decarbonization, and material efficiency/demand reduction is provided below.

Carbon accounting: Non-biogenic emissions are reported but credit is given to the capture of both biogenic and non-biogenic emissions. Thus, significant capture of biogenic emissions has the potential to produce net negative emission values. The utilization vs. storage of all captured carbon has been disaggregated as a variable within this model. However, credit for both is included in the CCUS pillar in the output figures.

Industrial electrification with grid decarbonization: The impact of electric grid decarbonization is attributed to the electrification pillar. If a process is electrified without adjusting for grid decarbonization, emissions will often increase. Thus, the two variables must be considered within the same pillar's calculations to accurately capture electrification benefits.

Material efficiency/demand reduction: For the four key scenarios (including the net-zero scenarios described in this document), the production values are the same across each scenario. Additional sensitivity analysis can be conducted in varying production across each scenario. Material efficiency/demand reduction is difficult to quantify, and work will continue to explore this crosscutting impact.

1.5.3 Data Sources

This Excel-based modeling work leverages multiple different sources of publicly available data. Inputs and impacts are calculated on an annual basis for 2018 through 2050. Model inputs include production projections through 2050, baseline energy and emissions intensity, technology-specific energy and fuel reduction potentials, fuel mixes, grid emissions,

A main data source for the modeling work presented here is the U.S. Energy Information Administration's (EIA's) Manufacturing Energy Consumption Survey (MECS),[24] released every four years with extensive energy consumption data for individual manufacturing subsectors (from three- to six-digit North American Industry Classification System (NAICS) codes). The energy consumption data is broken down by individual end use within manufacturing facilities. The latest data year available for MECS is 2018, released in 2021. The next data year of 2022 is expected to be released around 2025. An extensive analysis of the MECS data and presentation of manufacturing subsector energy consumption and emissions is available from the IEDO "Manufacturing Energy and Carbon Footprints".[25]

The U.S. Environmental Protection Agency's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*[26] is another key data source and provides economy-wide GHG emissions, energy-related industrial emissions, and detailed non-energy-related (or process) emissions for individual industrial subsectors or products. Other EIA references utilized for this modeling include the Annual Energy Outlook (which includes projections out to 2050), Monthly Energy Review[27] (also provides historical energy consumption), Petroleum & Other Liquids,[28] among others.

[24] Manufacturing Energy Consumption Survey - U.S. Energy Information Administration
[25] Manufacturing Energy and Carbon Footprints (2018 MECS) | Department of Energy
[26] U.S. Environmental Protection Agency - Inventory of U.S. Greenhouse Gas Emissions and Sinks
[27] U.S. Energy Information Administration - Monthly Energy Review, Tables 11.1 through 11.5.
[28] Petroleum & Other Liquids Data - U.S. Energy Information Administration

Figure 3 provides the economy-wide and industrial subsector breakdown of total emissions (both Scope 1 and 2) for the modeling baseline year of 2018 using these key data sources. The industrial sector accounted for about 28% of total U.S. emissions.

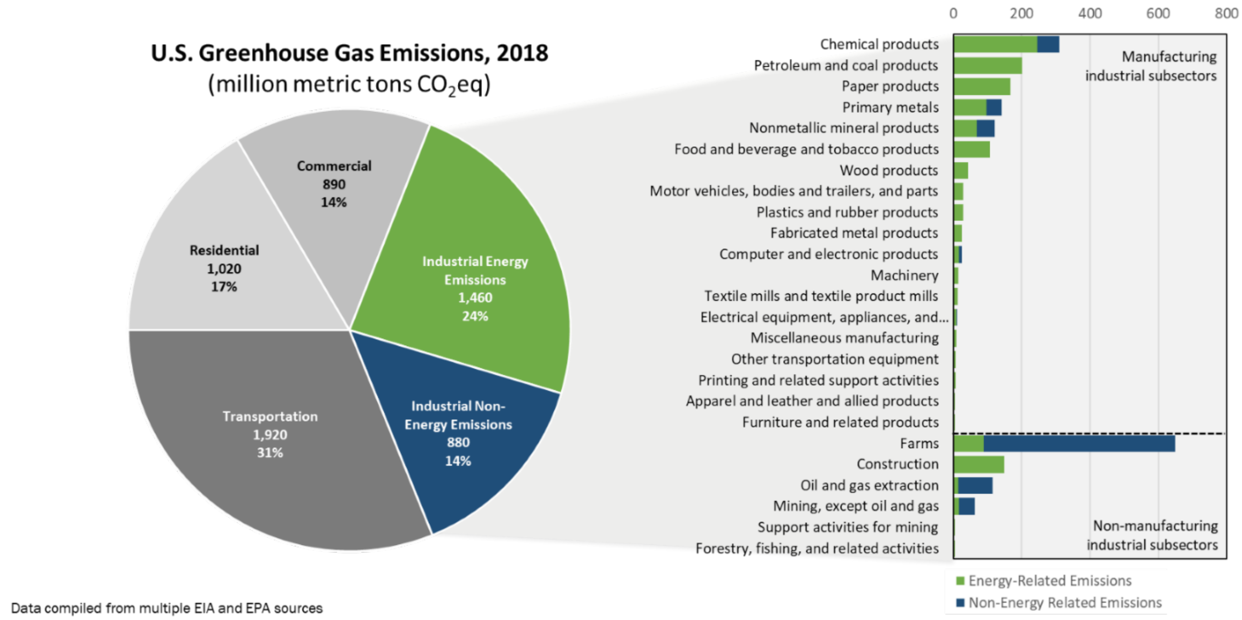

Figure 3. U.S. GHG emissions in 2018 by economic sector (left pie chart) and a breakout by industrial subsector (right bar chart)

The carbon dioxide (CO_2)-equivalent emissions in million metric tons (MMT CO_2e) are shown, as well as the percent contribution of that sector of the whole economy. Both Scope 1 (from onsite combustion and process-generated non-energy) and Scope 2 (from consumption of offsite-generated electricity) emissions are included. Note the large amount of non-energy emissions in the Farms subsector is due to multiple factors, including from the application of fertilizers, livestock, manure, and other factors.[29] Data compiled from multiple EIA and EPA sources: EIA Monthly Energy Review,[30] EIA Manufacturing Energy Consumption Survey,[31] EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks,[32] DOE IEDO EEIO-IDA Tool.[33] Note the large amount of non-energy emissions in the Farms subsector is due to multiple factors, including from the application of fertilizers, livestock, manure, and other factors.[34]

2 Subsector-specific Decarbonization Pathways

This section provides a high-level snapshot of each of the six modeled subsectors, major barriers and challenges to reaching net-zero emissions, modeled results of an example net-zero pathway along with applicable technologies by pillar, an illustration of key decarbonization decision points, and details on the net-zero scenario assumptions.

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29 Sources of Greenhouse Gas Emissions | U.S. EPA
30 U.S. Energy Information Administration - Monthly Energy Review, Tables 11.1 through 11.5.
31 U.S. Energy Information Administration - Manufacturing Energy Consumption Survey
32 U.S. Environmental Protection Agency - Inventory of U.S. Greenhouse Gas Emissions and Sinks
33 Department of Energy - Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool
34 Sources of Greenhouse Gas Emissions | U.S. EPA

2.1 Cement Manufacturing

2.1.1 Subsector Snapshot

The U.S. cement industry is integral to the nation's infrastructure development. Cement production is expected to grow through 2050, driven by population growth and urbanization. Globally, the cement industry accounts for around 7% of CO_2 emissions.[35] In 2022, 95 million metric tons of cement were produced across 96 facilities in the U.S. and two in Puerto Rico,[36] primarily using modernized dry kilns,[37] and with an average annual capacity of 1.3 MMT.[38]

Relative to cement production, the production of clinker, the intermediate product for cement, has remained relatively stable in the United States. Therefore, the U.S. clinker-to-cement ratio has slightly decreased over the past five years, and this ratio is an important indicator affecting the energy use and CO_2 emissions per ton of cement produced.

Cement manufacturing consumed 367 trillion British thermal units (TBtu) primary energy and 296 TBtu onsite energy and accounted for 66 MMT CO_2e total emissions in 2018.[39] Coal was the largest source of onsite energy (43%), followed by natural gas (22%) and petcoke (19%), with other fuels making up the balance.[40] The production of clinker, the intermediate product for cement, consumes the majority of energy in the overall cement production process–almost all fuels and around 60% of cement facility electricity–and accounts for around 95% of total cement CO_2 emissions. The cement industry also incurs a significant amount of process emissions (from the chemical conversion process used in the production of clinker, a component of cement), accounting for 58% of cement subsector total emissions.[41]

Process-related CO_2 emissions account for about 58% of total CO_2 emissions and energy-related CO_2 emissions accounted for 42%. In addition, electricity represents about 8% of total CO_2 emissions from the U.S. cement industry.[42].

2.1.2 Net-Zero Emissions Barriers and Challenges

With the anticipated growth of U.S. cement production, there is an urgent need to implement comprehensive decarbonization measures. The diverse energy sources and dependencies within the U.S. cement subsector necessitate a multifaceted approach to decarbonization. The transition to a decarbonized cement industry is fraught with both technical and non-technical challenges that could affect the pace and extent to which the pathways are

[35] Global Cement Industry's GHG Emissions — Global Efficiency Intelligence
[36] Cement (usgs.gov)
[37] Low Carbon Cement - Pathways to Commercial Liftoff (energy.gov)
[38] Global database of cement production assets and upstream suppliers | Dryad
[39] Manufacturing Energy and Carbon Footprint: Sector: Cement (NAICS 327310)
[40] Ibid.
[41] Ibid.
[42] Industrial Decarbonization Roadmap | Department of Energy

adopted. This section provides an overview of the major barriers faced by the subsector and is not meant to be comprehensive.

Major Energy Efficiency Barriers and Challenges

- **Tradeoffs in efficiency improvements**. Tradeoffs must be carefully considered when attempting to improve efficiency, and how changes to a single unit process may affect upstream or downstream efficiency or energy consumption. For example, multistage preheaters/precalciners improve the overall efficiency of the calcination process by delivering the raw materials to the kiln at higher temperature but require larger electricity consumption compared to the conventional process. In addition, increases in preheater efficiency may be neutralized by decreases in clinker cooler heat recovery.
- **Cost**. Costs for installing new energy efficiency technologies have proved to be a barrier for existing commercially available technologies. While cost savings can be ultimately achieved in the long run, upfront capital expenditures may deter organizations to broadly implement these technologies at their facilities. In addition, factors such as the unpredictability of future regulatory landscapes and the complexities of permitting processes further escalate costs and introduce delays.

Major Industrial Electrification Barriers and Challenges

- **Technological Challenges**. Electrified alternatives to incumbent technology must meet process temperature demands (850^{o}C – 1500^{o}C), have comparable product throughput, and retain product performance characteristics. New technologies should be compatible with existing facilities and auxiliary equipment for ease of implementation. Many electrified heating techniques exist but face unique challenges within the context of cement manufacturing and may require additional process equipment changes that hinder adoption. For example, resistance heating requires very large heat transfer areas at higher temperatures and microwave heating requires a high number of adjacent units to meet the thermal requirements when flow volume is high.
- **Need for Additional Electric Infrastructure.** Electrification of the calciner alone is expected to add 90-100 megawatts of electric load to the facility. In addition to the energy that needs to be procured by the facility either from the grid or via offsite/onsite clean power generation, the infrastructure required to accommodate additional demand can be expensive and, in some cases, difficult to implement. If procuring energy from a utility, it adds to the facility's reliance on the grid and decarbonizing the subsector will be highly dependent on the cleanliness of the supplied electricity.
- **Availability of a Large Amount of Clean Electricity.** The decarbonization benefits of electrification are only realized when the electricity is from clean sources. The projected increase in electricity demand means that providing clean electricity may be an even bigger constraint.

- **Cost of Operation**. The energy cost associated with operating an electric system has been one of the biggest barriers to electrification in the last decade given the availability of cheap fossil fuels (coal and natural gas) in the United States. It is important to look at the holistic cost of operation (taking into account maintenance, and product loss) when comparing operations in order to mitigate this barrier. As the prices of clean electricity and electric equipment continue to drop, electrification of the cement industry can be an important option to achieve a high reduction of CO_2 emissions. Adoption of any price on carbon in the future, can make electrification more cost competitive.

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

- **Availability**. The availability and ease of access to LCFFES may determine the degree to which they are adopted. Cement facilities are typically co-located with quarries and are not proximal to natural gas pipelines, making the establishment of connections to these facilities difficult. For supplementary cementitious materials (SCMs) and clinker alternatives, the availability of raw materials is constrained, and alternatives are needed. Common SCMs, such as blast furnace slag and fly ash, are byproducts from other industries where decarbonization is occurring, resulting in limited generation of these materials. Moreover, in some cases, materials used for SCM and alternative binders are in direct competition with other subsectors, such as aluminum.

- **Regulatory**. Regulatory challenges persist in implementing new technologies. At present, prescriptive building codes and standards, which requires specific compositions or materials, do not allow the broad use of new SCMs and alternative binders, preventing adoption and implementation. Acceptance and deployment of new manufacturing processes are also limited due to the prescriptive nature of common standards. Performance requirements for SCM-blended cements also vary by region, further adding to these challenges. Additional regulatory barriers include permitting for natural SCM mining and storage requirements for materials that can be used as SCM, such as fly ash. For low-carbon fuels, regulations around NOx emissions and solid waste are key barriers.

- **Technical**. Performance of SCM and alternative binders must meet or exceed that of portland cement or other incumbent technology, with particular concern about durability under diverse conditions and long-term safety. For low-carbon fuels, retrofitting existing equipment to accommodate different combustion attributes may be needed.

- **Cost**. Given the recent shift towards emissions reduction, coupled with the regulatory environment and corporate inertia, alternative materials are in their infancy, resulting in limited large-scale production and higher costs.

Major Carbon Capture, Utilization, and Storage (CCUS) Barriers and Challenges

- **Technical**. There is no one-size-fits-all solution; the unique geographical features and regionality of each facility may require a different set of approaches. Relative to other subsectors, carbon utilization and mineralization in cement products are a unique opportunity for cement producers. However, further work is needed to scale-up and reduce cost. The U.S. cement subsector does not have enough carbon storage options that could accommodate large volumes of CO_2 and ensure its permanent storage or utilization. In parallel, there is still some uncertainty around the impact of carbon capture technologies on the product quality.
- **Infrastructure**. The energy and physical footprint needed to support CCUS systems are substantial. Depending on size, these systems may require tens to hundreds of megawatts, and the existing, onsite electrical infrastructure may not be able to support this added demand. The local grid may also not have enough capacity in some cases. In addition, the physical footprint can be quite large (sometimes as large as the cement facility itself), resulting in significant challenges with retrofitting existing facilities.
- **Cost**. Capital and operating expenditures associated with CCS are substantial, even before considering the energy penalties inherent to the process. As noted above, cement/concrete products that utilize CO_2 must continue to reduce cost to be a viable alternative.

2.1.3 Net-Zero Emissions Pathways and Technologies

A net-zero emissions cement subsector will require comprehensive decarbonization technology adoption across all pillars. An example output for a modeled net-zero decarbonization pathway by 2050 is shown in Figure 4. U.S. cement production is assumed to increase by 43% during the same period to meet the needs of a growing population and expanding economy. CCUS is anticipated to make the largest contribution to CO_2e emissions reduction, followed closely by the LCFFES pillar, which includes the adoption of supplementary cementitious materials (SCMs), including calcined clay, and a low amount of alternative binding materials adoption. Note that the electrification pillar impact includes the reduction in electric grid CO_2e emissions as well as a low amount of adoption of electrified heating processes.

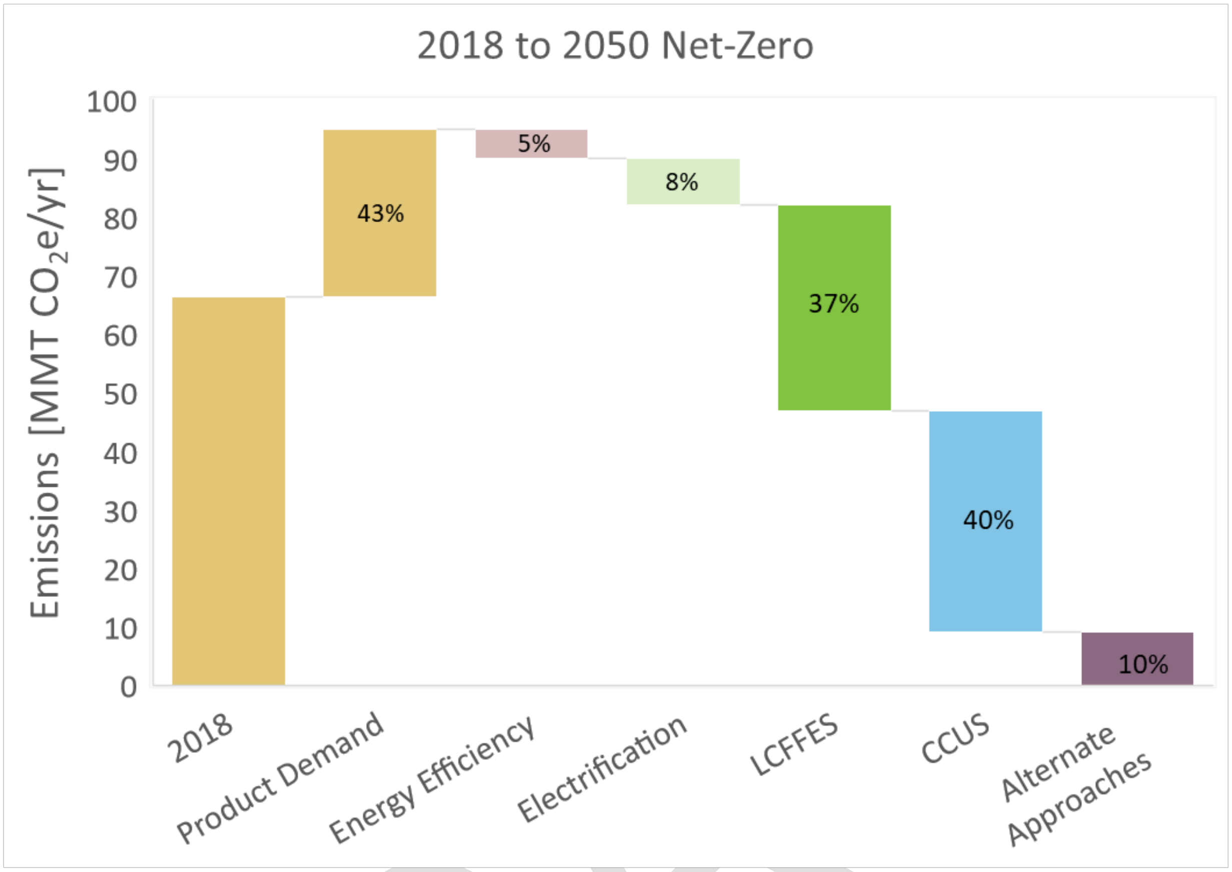

Figure 4. Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions (million metric tons (MMT)/year) for U.S. cement manufacturing, 2018–2050

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.

Figure 5 shows a more granular production routes representation in this net-zero emissions cement industry scenario. Note, the plot below is only representative output from preliminary modeling runs and is not based on actual facility data. The incumbent technology, dry kiln, is assumed to continue to be the primary route for cement production, with an increasing role for alternative technologies in the out years. The wet kiln, a less energy efficient process compared with the dry kiln, is assumed to be phased out by 2040. By 2050, limestone calcined clay cement roughly accounts for 25% of cement production, combining both fuel and electric processing routes.

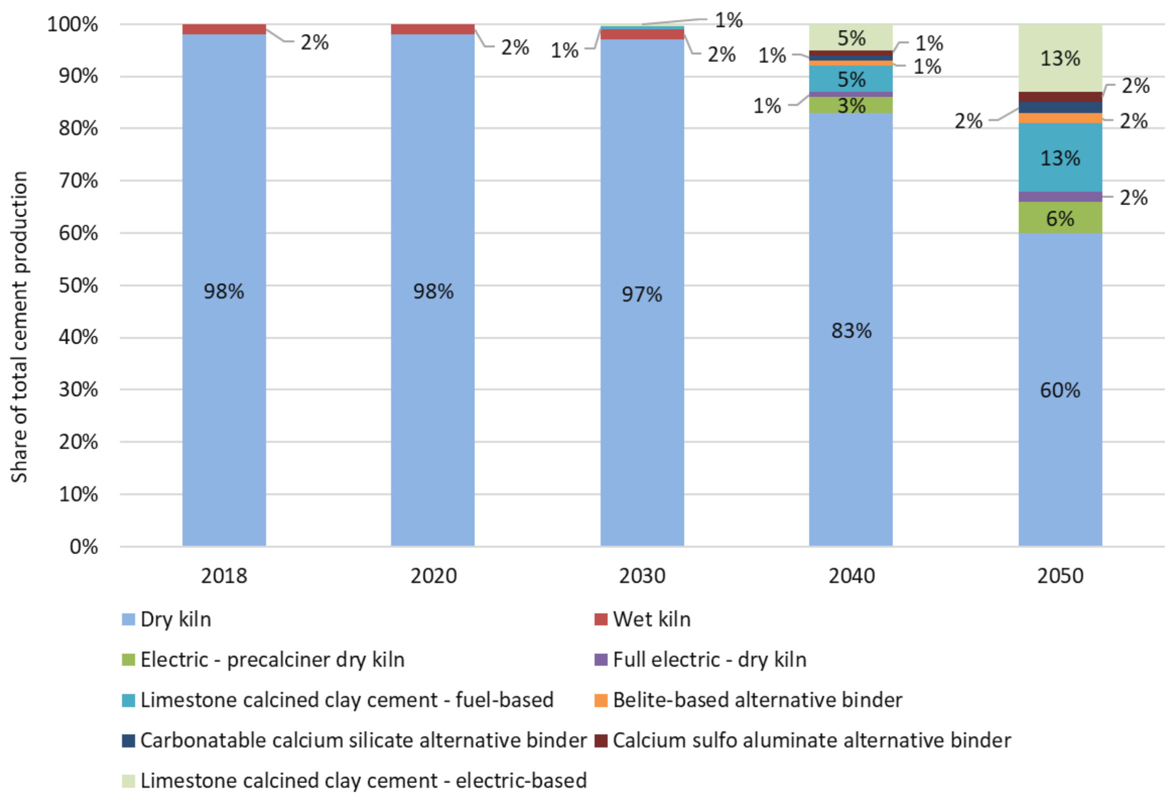

Figure 5. Example U.S. cement manufacturing production route share by decade under a net-zero emissions scenario, 2018–2050

This representation is based on preliminary modeling runs and does not rely on actual facility data. This figure may differ to the associated Roadmap figure due to additional modeling considerations included here. Acronyms: CSA (calcium sulfo aluminate), CCSC (carbonatable calcium silicate clinker), C2S (Belite). Source: This work.

Detailed below are the key technologies within each pillar to achieve a decarbonized cement subsector under this example scenario.

Energy Efficiency Impact

Companies will have to carefully consideration technology choices phasing, for energy efficiency and the other pillars, and at a facility-level or an industry-wide scale, to avoid emission “lock-ins” or creating potential stranded assets or “dead-ends” in the future. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

There are many commercially available energy efficiency technologies for the cement industry. However, most have not been adopted primarily due to economics. The use of high efficiency multistage pre-heat/precalciner kilns has already been widely adopted across the

U.S.[43] While other technologies, such as high efficiency clinker cooling and more efficient grinding, which are available now, could have an impact in the near term if adopted.

In particular, waste heat recovery (WHR) power generation technology is a promising opportunity. This technology uses a portion of the medium temperature (between 200 and 400 degrees Celsius (°C)) waste heat of kiln flue gases to generate electricity. Although it does not reduce the amount of electricity used at a cement facility, it uses excess heat to generate electricity for on-site use or export to the grid.

A number of emerging technologies are being explored, including those for grinding and raw material processing. For example, high activation grinding can assist with the incorporation of alternative raw materials in cement production to decrease overall emissions. Other emerging grinding technologies include ultrasonic and plasma comminution.[44]

Given the large share (58%) of process emissions in overall emissions from cement production, energy efficiency may play a relatively minor role in cement decarbonization. In the net-zero GHG scenario, energy efficiency technologies only contribute to 6% of annual CO_2 emissions reduction in 2050 compared to 2018 level.

However, implementation of commercialized energy efficiency measures, despite varying capital requirements, can lead to cost savings, improved productivity, enhanced product quality, and improved environmental compliance, less risk exposure to fluctuating energy costs, and reduction of air pollution.

Industrial Electrification Impact

Around 85%-90% of the energy in cement manufacturing is consumed in thermal processing, predominantly fueled by carbon-intensive sources such as coal and petcoke.[45] While challenges exist, electrification of the precalciner and kiln have gained significant interest in the industry. Given the primary pathway of reducing clinker content in cement, electrification has a relatively modest (9%) impact on decarbonizing the U.S. cement industry. Nonetheless, the electrification of heating and calcining will result in reduction in overall CO_2 emissions, especially since the U. S. electricity grid is rapidly decarbonizing.

Electrification of the precalciner: Most modern cement calciners share common design elements, such as multiple cyclone preheaters and the use of direct suspension to maximize heat transfer. Electric calciners offer a cleaner and more precise, controllable process compared to traditional fossil fuel-based methods, which is especially important for limestone calcined clay cement as strict temperature control is needed to maintain its performance characteristics.

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43 Industrial Decarbonization Roadmap | Department of Energy
44 A Review of Emerging Energy-efficiency and CO2 Emission-reduction Technologies for Cement and Concrete Production | LBNL
45 Manufacturing Energy Consumption Survey - U.S. Energy Information Administration

Many electrified designs to replace or retrofit the existing precalciner design are possible and have been proposed and studied, including rotary, fluidized bed, and entrainment precalciners, as well as different mechanisms for heating, such as resistance, microwave, induction, and hybrid. However, many are still lower in technical maturity, and sustained R&D is needed to reach a demonstration level.

Electrification of the kiln: Attempts to produce portland cement clinker in stationary electric vessels have often failed in the past because of the adhesive nature of the clinker as well as the high temperature requirements (~1500°C). While there are no commercially available technologies today, a few electric furnace technologies are being piloted. This includes the RotoDynamic heater, developed by Coolbrook, which is an electric rotary kiln technology based on resistive heating. In 2023, a pilot installation successfully demonstrated the capabilities of the system for industrial use achieving temperatures as high as 1000°C and validated its technical pathway to 1600°C.

Pathways for complete electrification in a single non-distinguished step, while further away from commercialization, could play a role in the future. Studies have shown that calcination and sintering of cement can be done at lower temperatures when using microwaves. Bench scale systems that have combined electric resistance heating with microwave have shown significantly lower energy consumption compared to traditional methods[46].

Given the wide variety of electric options available for both the precalciner and the rotary kiln, the energy required is expected to vary significantly with each technology and design consideration. Further, the energy performance of these systems is expected to change as the technologies are scaled and become more mature. Understanding these potential variabilities will be necessary to choose the best technology options to have the highest decarbonization impact.

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

Clinker production accounts for around 95% of total CO_2 emissions in the U.S. cement industry. Therefore, reducing the clinker-to-cement ratio with supplementary cementitious materials (SCMs) that have lower embodied carbon and using alternative binders to replace portland cement are primary pathways cement decarbonization. In addition, phasing out carbon-intensive fuels, coal and petcoke, for natural gas also provide emissions reductions. LCFFES contributes to 42% of CO_2 emissions reductions between 2018 and 2050 under the net-zero scenario.

Supplementary cementitious materials (SCMs): Common SCMs include fly ash, blast furnace slag, natural pozzolans, ground limestone and calcined clay, all of which have lower embodied carbon than clinker. Alternative SCMs, such as those from recycled waste (e.g., concrete demolition waste, glass powder), biomaterials (e.g., rice husk ash, biochar), and engineered SCMs (e.g., from silicate-based rocks), are also being explored. Finally, limestone

[46] Kaewwichit et.al, "Development of Microwave-Assisted Sintering of Portland Cement Raw Meal." Journal of Cleaner Production P3 (142): 1252–58. https://doi.org/10.1016/j.jclepro.2016.07.009.

calcined clay cement (LC3), using kaolinite, has gained significant interest. Studies have shown that up to 50% of clinker can be substituted with LC3 without performance degradation.

Alternative binders: Alternative binder materials are those that use different raw materials than portland cement or in different proportions. They are mostly attractive in niche, lower-risk applications and are at different stages of maturity. Three were considered for this study: belite-based, calcium sulfo aluminate, and carbonatable calcium silicate clinker, each with pros and cons. For example, belite based binders, which can be produced at lower temperatures thereby reducing CO_2 emissions, are much harder than traditional clinker and require more electric power for grinding. The most suitable alternative binder will primarily be based on application and cost.

Fuel switching: Fuel switching from coal and petroleum coke to less carbon-intensive fuels and energy sources, such as natural gas and sustainable biomass, can reduce emissions from the cement industry. Ultimately, the amount of emissions reduction will be dependent on the pathways adopted. The Net-Zero scenario completely phases out petcoke and reduces coal consumption to 2% of the total fuel mix. Natural gas consumption triples from 2018 levels as the primary replacement of these fuels.

It should be noted that hydrogen as an alternative fuel is not considered as an effective strategy for the cement subsector. Clean hydrogen is a valuable commodity, better suited as a low-carbon feedstock in the chemical and refinery industries or as a reductant in hydrogen-based direct reduction ironmaking.

Carbon Capture, Utilization, and Storage (CCUS) Impact

The implementation of CCUS technologies in the cement industry has a large potential to mitigate Scope 1 emissions. CCUS contributes to a 43% reduction in CO_2 emissions from 2018 to 2050 under the net-zero GHG scenario.

Because the majority of CO_2 emissions from cement production originate from limestone calcination (and not fuel combustion), post-combustion technologies are of primary interest. These technologies do not require changes to the clinker-burning process and are appropriate for new kilns as well as retrofits.

Innovative CCUS approaches, such as calcium looping and oxy-combustion capture, are emerging as potentially more cost-effective alternatives to post-combustion capture. These methods seem to be more efficient as they avoid mixing the large fraction of high purity process CO_2 with the smaller fraction of CO_2 resulting from fuel combustion. It is important to note that these methods demand additional energy. However, the abundance of low and medium temperature waste heat may help offset this increase.

Carbon utilization and mineralization is of high interest to the industry and technologies vary in their commercialization status. Technologies such as CarbonCure and Solidia are already available for commercial use in ready-mix facilities and precast concrete facilities, respectively. Carbon mineralization technologies, such as Blue Planet and Carbon8, are also being piloted. More than 20 organizations are working on commercialization of technologies to convert CO_2 to carbonate products for the U.S. construction subsector.[47]

2.1.4 Key Decarbonization Decisions

A transformation of the cement subsector will require a holistic view of the anticipated decarbonization pillars and technologies that will become (or may become, depending on technoeconomic factors) viable and available over varying timeframes out to mid-century and beyond. One way to assess these pathways is by starting with a decision-tree framework, as depicted in Figure 6 below. The decision tree is depicted as a circular process until net-zero emissions is achieved to account for solutions that may not yet be commercially available. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission "lock-ins" and potential stranded assets in the future.

[47] Industrial Decarbonization Roadmap | Department of Energy

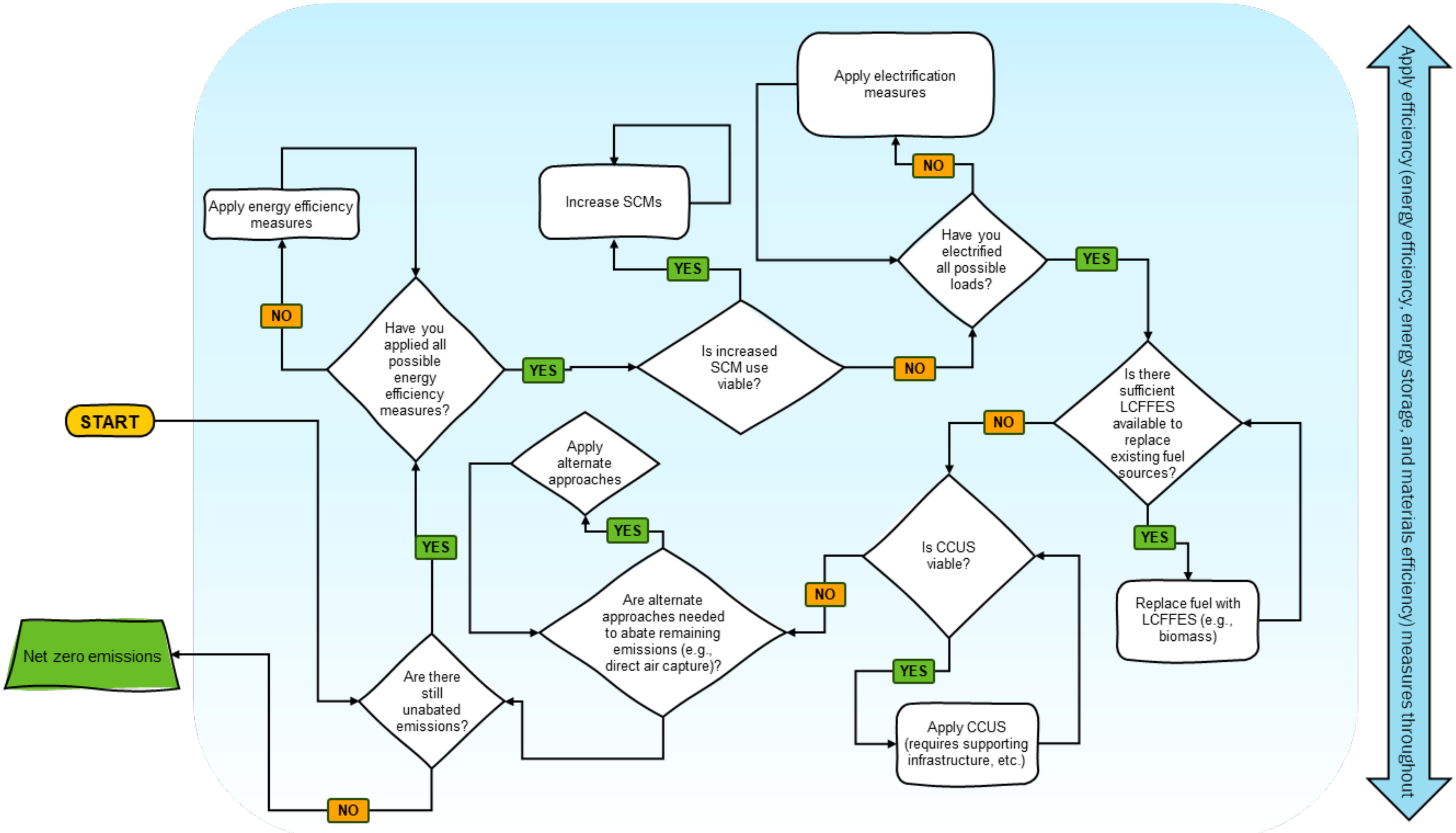

Figure 6. Cement manufacturing decarbonization decision tree

An example of a cement manufacturing decarbonization decision tree. Efficiency measures should be applied through all steps as indicated by the blue arrow (including energy and materials efficiency, energy storage, etc.). Note, sequencing and specific decarbonization strategies may vary. This figure is provided for discussion purposes and as a way to identify the barriers and opportunities in pathways to decarbonization and better understand decision making.

2.1.5 Modeling Assumptions

In the net-zero scenario, the most ambitious assumptions were made across all the decarbonization pillars to reach a net-zero cement subsector. In this scenario emissions decrease by 86% between 2018 and 2050 through application of technologies across the four pillars. This decrease occurs while U.S. cement production increases by 43% during the same period to meet the needs of a growing population and expanding economy.

The electrification pillar includes electric limestone calcined clay cement. LCFFES includes fuel-based limestone calcined clay cement. Most of the LCFFES emissions reduction comes from clinker substitution while some comes from switching to lower carbon fuels. Only 1% adoption of alternative cement is assumed in 2040 and 2% adoption by 2050 under the net-zero scenario as it not expected that these alternative binding materials will have a substantial contribution to overall emissions reduction by 2050. Under this scenario, the clinker to cement ratio drops from 0.9 in 2018 to 0.64 in 2050. This substantial decrease has a large contribution to the total subsector emissions reduction.

The clinker to cement ratio is implemented at the ‘production pathway’ level to address process differences. For this model, electricity energy intensity is specified per mass of cement production, while fuel energy intensity and non-energy process emissions are specified per mass of clinker production to reflect that the majority of fuel and non-energy process emissions are tied to clinker production processes and therefore change as the clinker-to-cement ratio changes. For alternative processes that do not include clinker (such as carbonatable calcium silicate), all three variables are specified per mass of cement production.

Table 5 provides the baseline fuel intensities (gigajoules per metric ton clinker) and electric intensities (kilowatt-hour per metric ton cement) for each production route.

Table 5. Cement Model Baseline Energy Intensities by Production Route

Production Route	Fuel Intensity (GJ/MT clinker)	Electric Intensity (kWh/MT cement)
Dry kiln	3.4	127
Wet kiln	5	127
Electric precalciner – dry kiln	1.22	731
Full electric – dry kiln	0	883
Fuel-based limestone calcined clay cement	3	127
Electricity-based limestone calcined clay cement	0	794
Belite-based (C2S) alternative binder	2.71	127
Carbonatable calcium silicate (CCSS) alternative binder	2.41	127
Calcium sulfo aluminate (CSA) alternative binder	2.87	127

Figure 7 shows the assumed fuel mix in the U.S. cement subsector up to 2050 under the net-zero scenario. The share of coal and petroleum coke substantially drops between 2018 and 2050 and the share of natural gas substantially increases. The share of electricity also increases more than two times because of precalciner electrification and the use of electric calciner for limestone calcined clay cement production.

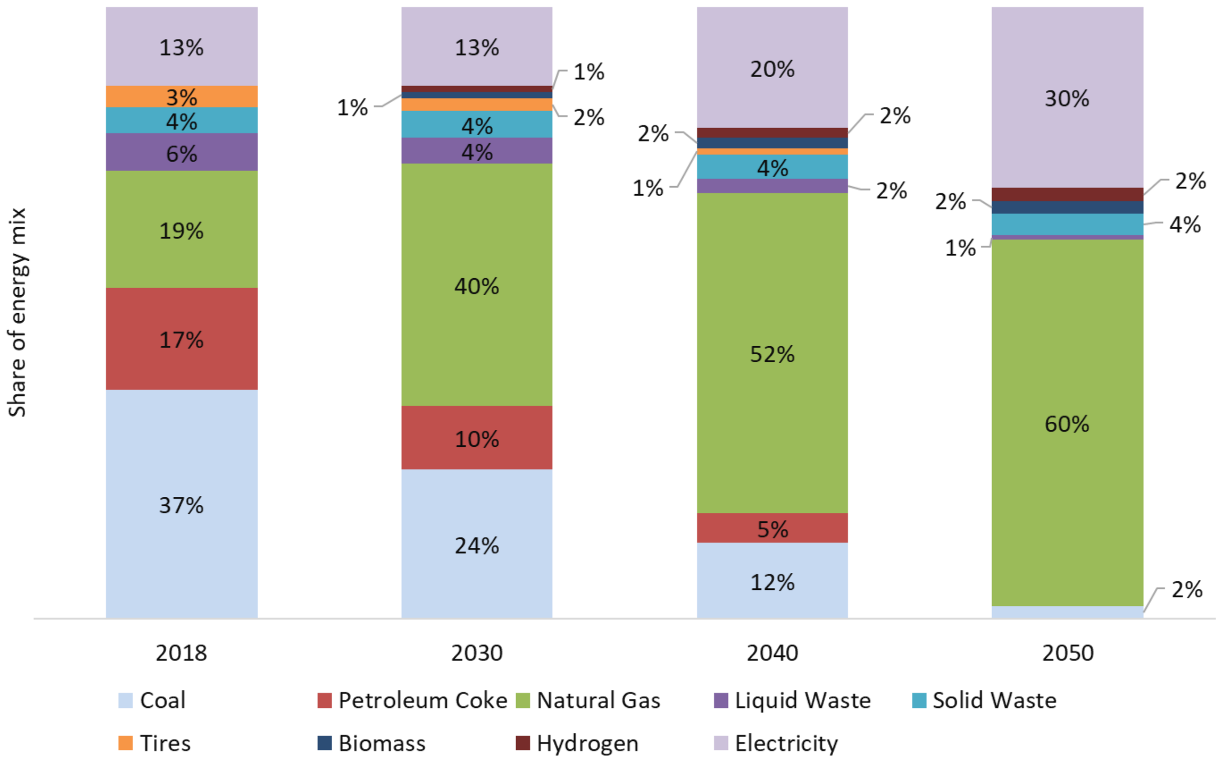

Figure 7. U.S cement subsector fuel mix by decade under the example net-zero scenario

The net-zero scenario additionally assumes and annual 1.2% reduction in fuel intensity and a 1% reduction in electricity intensity to account for BAU improvements. For CCUS, it is assumed that by 2050, 95% of remaining emissions are captured and sequestered using amine absorption.

2.2 Chemicals Manufacturing

2.2.1 Subsector Snapshot

The U.S. chemical industry plays an important role in the nation's economy, contributing significantly across various economic sectors. Valued at $486 billion, it accounted for over 25% of the nation's GDP in 2022.[53] Operating through more than 11,000 facilities, the chemical industry manufactures over 70,000 products, with nearly two-thirds of its facilities owned and operated by small and medium enterprises (SMEs).[54] In 2022, the U.S. was the

[53] Chemical Sector Profile (cisa.gov)
[54] Ibid.

world's second-largest chemical producer, satisfying nearly 13% of global demand.[55] Employment within this subsector is extensive, engaging nearly 4.1 million individuals across research, manufacturing, and transportation.[56]

As the most energy-intensive subsector within U.S. manufacturing, the chemicals subsector significantly contributes to primary energy use and GHG emissions. In 2018, the subsector consumed 4,842 TBtu of primary energy, constituting 25% of the total primary energy consumption within U.S. manufacturing.[57] Additionally, the subsector accounted for 332 MMT CO_2e of Scope 1 and 2 GHG emissions in 2018, about 28% of total U.S. manufacturing emissions.[58] Given the increasing focus on sustainability and competitive pressures, reducing GHG emissions from the U.S. chemical industry is imperative.

Chemicals manufacturing is comprised of multiple subsectors[59] covering numerous chemicals and categorized into four segments: agricultural chemicals, basic chemicals, specialty chemicals, and consumer products. Figure 8 shows the total GHG emissions (both process and combustion) for the top 12 emitting subsectors plus the remainder of the chemicals subsector, with the top three (other basic organic chemicals, petrochemicals, and plastics materials and resins) accounting for 50%. Within the subsector, numerous processes yield multiple co-products, resulting in some chemical production being contingent on specific chemical processes. This subsector's intricate interdependencies and heterogeneity pose challenges for energy analysis and the development of decarbonization strategies within the chemical industry. This complexity sets it apart from more homogenous subsectors, making the task of devising effective decarbonization approaches more difficult.

55 Ibid.
56 Ibid.
57 https://www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs
58 https://www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs
59 Divided into 29 six-digit coded North American Industry Classification System subsectors.

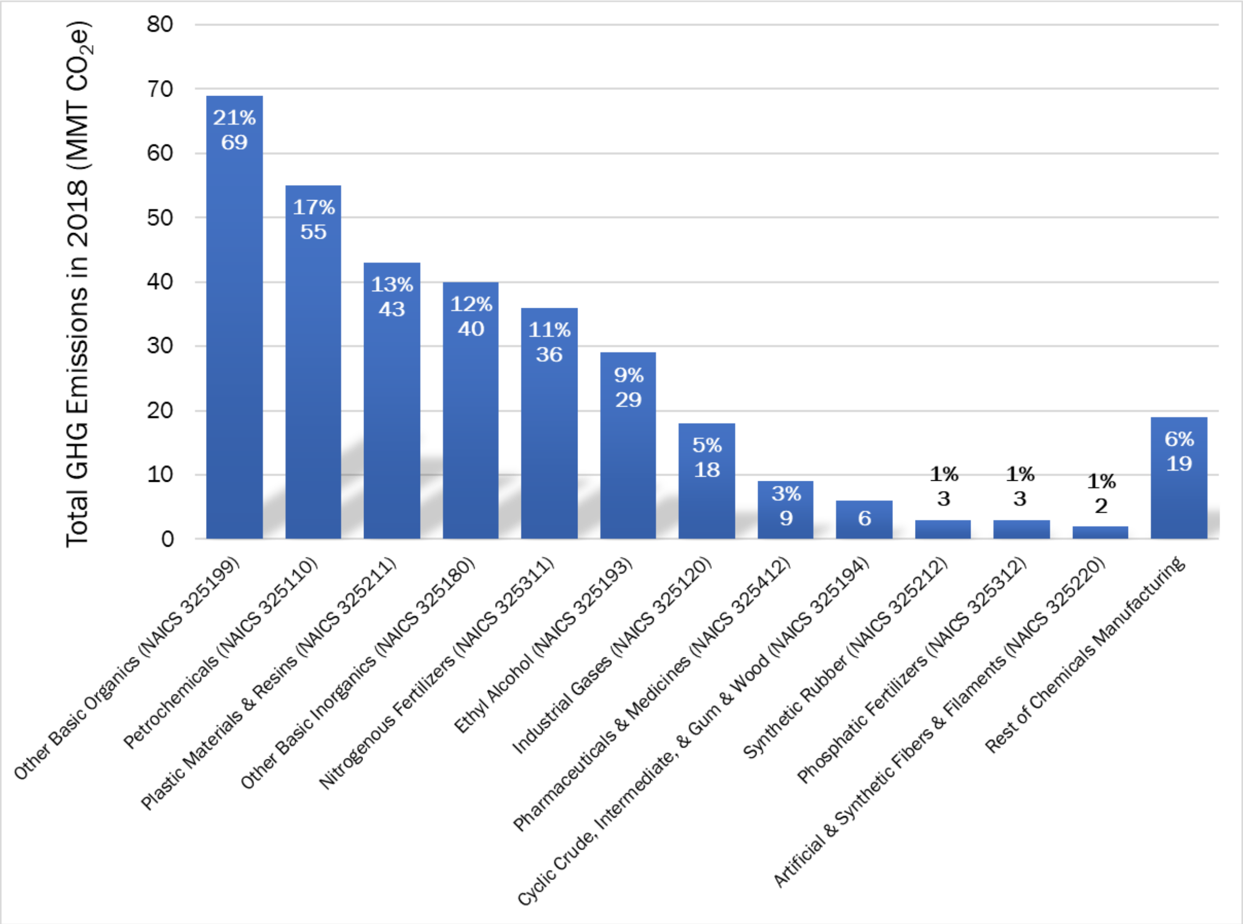

Figure 8. Breakdown of top emitting U.S. chemical manufacturing subsectors in 2018 (percent of chemicals manufacturing total and in million metric tons CO_2e) by North American Industry Classification System (NAICS) categories

Includes Scope 1 (onsite process and combustion) and Scope 2 (offsite combustion) emissions. Data sources: From analysis of EIA Manufacturing Energy Consumption Survey[60] and EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks.[61]

2.2.2 Net-Zero Emissions Barriers and Challenges

This work focuses on Scope 1 and 2 emissions within the U.S. chemical subsector while also acknowledging the potential impact of decarbonization technologies and pathways on broader Scope 3 supply chain emissions. It assesses how advancements and best practices can effectively curtail energy demand and emissions while sustaining economic growth, aligning with the goal of achieving net-zero GHG emissions. However, the chemical industry faces notable barriers that impede decarbonization efforts. This section provides an overview of the major barriers faced by the subsector and is not meant to be comprehensive.

[60] U.S. Energy Information Administration - Manufacturing Energy Consumption Survey
[61] U.S. Environmental Protection Agency - Inventory of U.S. Greenhouse Gas Emissions and Sinks

- Transitioning to low-carbon manufacturing involves overcoming challenges such as shifting from energy-intensive processes while ensuring that alternative cleaner pathways for all co-products develop at a similar pace.
- Water stress affects emerging industrial processes, necessitating careful planning for water usage and resource availability in, for example, large-scale electrolysis and bio-feedstock production.
- Plastics' diversity, combined with single-stream recycling in the U.S., leads to contamination and reduced plastic quality, while high costs and complexities impede effective waste management, hindering high recycling rates.
- Retrofitting chemical facilities faces challenges due to a high degree of integration of unit processes, leading to significant downtime and costs, alongside compatibility issues with original feedstock designs.
- Energy efficiency improvements face hurdles due to limited internal capital, competing projects, retrofitting risks, and logistical challenges such as space limitations and large distances.
- Transitioning chemical industries to electrified processes increases clean electricity demand, requiring clean grid capacity and infrastructure upgrades.
- Competition with low-cost fossil fuels hinders the adoption of electrified technologies and alternative fuels like clean hydrogen and RNG, despite their potential for significant market share by 2050.
- Disruptions in the supply chain, such as potential decrease in gasoline and natural gas demand, can significantly impact the availability and cost of chemical feedstocks, but offer low-carbon pathway opportunities. Developing resilient supply chains that can adapt to such disruptions is essential for the stability of the chemical industry.
- Widespread adoption of CCUS faces challenges due to high application costs, regulatory uncertainties, lack of financial incentives, and the need for extensive infrastructure and CO_2 transport systems.

2.2.3 Net-Zero Emissions Pathways and Technologies

This modeling work is particularly focused on major high-volume and high-emission chemicals like lower olefins, BTX aromatics, chlor-alkali, soda ash, ethanol, methanol, and ammonia, which collectively contribute nearly 40% of the total subsector emissions. Though they represent a portion of the emissions from the chemicals subsector, they are only a few example chemicals and do not address a pathway to full subsector decarbonization. Each class of chemicals must be individually assessed to provide a comprehensive pathway for decarbonizing the chemicals subsector.

An example output for a modeled net-zero emissions pathway for these chemicals by 2050 is shown in Figure 9. This scenario assumes U.S. production for the chemicals modeled would increase by 17% between 2018 and 2050 to account for demand. The production amounts are also impacted by the assumption the United States reaches the Environmental Protection Agency's goal of a 50% recycling rate for plastics.[62] The figure illustrates a decrease in emissions, with the specific goal of achieving net-zero (or potentially negative emissions) by 2050, relative to 2018 levels. This goal hinges on the adoption of transformative technologies and the incorporation of low-carbon manufacturing pathways.

The modeling projections for the studied chemicals indicate a decline in emissions, with a specific aim of reaching 33.5 MMT CO_2e negative emissions by 2050 (see Figure 9), compared to 2018 levels in the net-zero scenario. This goal hinges on the adoption of transformative technologies and the integration of low-carbon approaches into manufacturing processes.

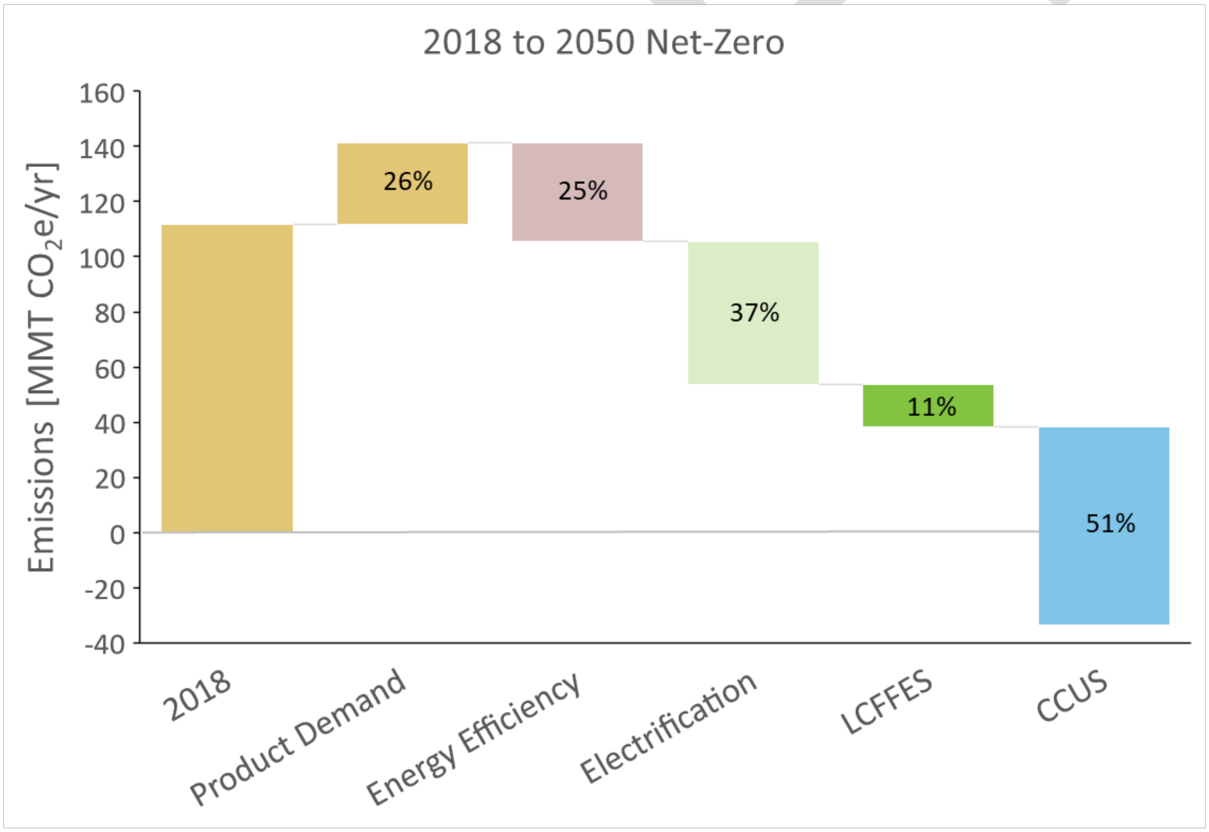

Figure 9. Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions (million metric tons (MMT)/year) for modeled U.S. chemicals, 2018–2050

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

[62] Environmental Protection Agency. 2024. "U.S. National Recycling Goal." https://www.epa.gov/circulareconomy/us-national-recycling-goal.

subsector's total emissions in 2018. This figure may differ to the associated Roadmap figure due to additional modeling considerations and total chemicals modeled. Source: This work.

Several factors contribute to CO_2 emission reductions in Figure 9, with annual reductions attributed to different decarbonization pillars from 2018 to 2050 in the net-zero scenario. Achieving net-zero within the chemical subsector necessitates subsector-wide efforts for all chemicals. Ethanol production for fuels contributes significantly to the subsector's potential emissions reduction in 2050. It is distinguished by its predominantly bio-based nature, primarily produced from corn. A substantial portion of CO_2 emissions in ethanol manufacturing does not arise from fuel combustion but rather are process CO_2 emissions released during fermentation. Within the study's system boundary, bioenergy with carbon capture and storage (BECCS) is credited towards non-biogenic CO_2 emissions. Enhancing the deployment of BECCS in ethanol manufacturing emerges as an important measure contributing to the overall decarbonization of the U.S. chemical industry. However, the broader implications of ethanol production, including bio-feedstock production, land use, and fertilizer use, also contribute to Scope 3 GHG emissions. Hence, although BECCS from ethanol manufacturing are highlighted as avenues for achieving negative emissions, caution is warranted regarding lifecycle emissions. Nevertheless, even without BECCS, emissions reductions are deemed feasible by 2050. More specifically, omitting the impact of BECCS, the studied portion of the U.S. chemical industry still has the potential to reduce emissions to only 16 MMT CO_2e emissions in 2050 in a near net-zero scenario.

Moreover, broader measures are being considered for decarbonizing the entire U.S. chemical subsector. These measures include grid decarbonization, adoption of biofuels and hydrogen, electrified steam generation, plastics recycling, and the application of other crosscutting technologies. Such comprehensive strategies are essential for meeting the ambitious net-zero emissions target by 2050.

Energy Efficiency Impact

The chemical industry operates through integrated facilities with multiple unit operations, aiming to produce a wide array of products. Improving energy efficiency involves implementing technical and operational measures, transitioning to more efficient manufacturing pathways, and adopting the best available technologies.

Companies will have to carefully consideration technology choices phasing, for energy efficiency and the other pillars, and at a facility-level or an industry-wide scale, to avoid emission "lock-ins" or creating potential stranded assets or "dead-ends" in the future. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

Two categories of improvements are identified:

- Current operational improvements, requiring minimal investment costs, involve enhanced process monitoring, improved solvents, regular maintenance, fixing steam leaks, better heat exchanger designs, and efficient motors. Despite their scale, these measures play a crucial role in reducing energy losses and optimizing operations.

- Large efficiency improvements, needing substantial investments, include replacing equipment with cutting-edge technologies such as low-pressure catalysts for ammonia synthesis, membrane separation in steam cracking, and alternative configurations for chlor-alkali production. Despite longer payback times, these technologies significantly enhance efficiency and reduce CO_2 emissions.

This work projects potential CO_2 savings of 36 MMT, equivalent to 25% of projected total CO_2 emissions from the U.S. chemical industry by 2050. Heat integration and optimizing heat utilization are key drivers for energy efficiency improvements. As the technoeconomics of potential advanced technologies become clear, future assessments may expand energy efficiency scope by exploring solutions like process intensification, advanced separation techniques, thermal energy storage, and modular nuclear CHP systems.

Material Efficiency Impact

The U.S. chemicals industry has seen growth in production, particularly in exports. However, the overall production of certain chemicals is projected to increase moderately by 2050, reflecting a shift towards a circular economy and heightened material efficiency. Initiatives targeting plastic littering, single-use plastic restrictions, polymer recycling enhancement, and agricultural practice improvement are key drivers in this transition.

Plastics, with a current recycling rate of only 9% as reported by EPA,[63] pose a significant challenge due to high demand for single-use plastics leading to substantial waste. To tackle this, there is a pressing need to increase plastic collection, recycling yield rates, and the use of recycled plastics to replace virgin materials. Europe's current recycling rate of approximately 30% sets a precedent, with the U.S. aiming for a 50% recycling rate by 2030, aligning with its national goals. Plastics are predominantly derived from petrochemicals, making the shift towards increased recycling pivotal for reducing CO_2 emissions from the petrochemical subsector and maintaining production levels. Achieving these goals requires transforming waste management practices, expanding waste collection, and investing in advanced recycling methods like chemical recycling.

Industrial Electrification Impact

The transition to electrification in chemical industries holds promise for reducing CO_2 emissions through clean energy utilization. Electrified heating technologies, such as high-temperature heat pumps (HTHP) and electric resistance heating, exhibit lower energy intensity and offer substantial emissions reductions, especially when integrated with clean energy sources. HTHPs can supply low-to-medium temperature process heat suitable for various chemical processes, potentially electrifying a considerable portion of the heat demand in industries like ethanol and chlor-alkali production. Electric resistance heating

[63] Plastics: Material-Specific Data | U.S. EPA

offers simplicity, efficiency, and potential for widespread adoption in the U.S. chemical industry, particularly in high-temperature steam generation. Electrified steam cracking furnaces are gaining attention from major manufacturers to significantly reduce emissions. Electromagnetic heating technologies show promise in speeding up chemical reactions, with potential applications in various industries, albeit requiring further research and development support.

In addition, processes like ammonia and methanol production may shift towards hydrogen generated from clean electricity. It should be noted that hydrogen stands out and significantly impacts the electrification pillar because it is the largest need for ammonia and methanol, two major but small subsets of the chemicals analyzed. When considering the full U.S. chemical subsector, the impacts of clean hydrogen could be much smaller. Furthermore, several new innovative electrochemical processes are currently in development, including key pathways such as the electrochemical oxidative coupling of methane for ethylene manufacturing, electrochemical ammonia synthesis, and electrochemical ethanol production. The current landscape concerning these electrochemical processes and several other next-generation technologies in nascent stages, characterized by low technology readiness levels (TRLs), is somewhat ambiguous. Hence, it is important to emphasize the necessity of researching and advancing these technologies to higher TRLs for eventual commercial deployment.

Overall, technological advancements and government support are crucial for realizing the full potential of electrification in reducing CO_2 emissions in the chemical industry. Electrified technologies demonstrate lower energy intensity compared to conventional options, with their attractiveness increasing as electricity grids decarbonize. The primary advantage of electrification is the potential to decarbonize the electricity grid. Aggressive decarbonization scenarios, coupled with the lower energy intensity of electrified technologies, promise substantial reductions in CO_2 emissions. Commercially available technologies for electrifying heat and specific processes, such as electric boilers and compressors, can be integrated with clean energy sources or clean power contracts. However, challenges include limited access to cost-competitive power purchase agreements (PPAs) and on-site constraints. Electrification has the potential to reduce up to 37% of projected CO_2 emissions by 2050 in the example net-zero scenario (Figure 9), but regional challenges and clean grid variability may necessitate long-duration energy storage solutions, crucial to align zero-carbon power purchases with the chemical industry's operational needs.

The growing demand for clean electricity presents an opportunity to enhance grid-process interactions' flexibility. For instance, electrolyzers can adjust output to contribute to load shedding or provide additional supply as required, further bolstered by short-term storage solutions. The transition to clean hydrogen necessitates ample access to clean electricity, with estimates suggesting significant electricity requirements and corresponding grid capacity for electrolytic production of major chemical products. However, challenges persist, notably the CO_2 emissions associated with grid-electricity-generated hydrogen until complete decarbonization of the electric grid is achieved. Alternative approaches such as integrating non-carbon energy sources like wind or solar with electrolysis could bolster capacities for chemical manufacturing while reducing emissions.

Electrolytic pathways, although superior environmentally compared to traditional methods like steam methane reforming (SMR), are poised to advance further, with ongoing research focusing on enhancing efficiency and reducing costs. Water electrolysis for hydrogen, a relatively mature technology, boasts various electrolyzer types, each with its strengths and considerations. Alkaline electrolyzers, more developed, offer modular units with substantial capacities and long lifetimes. Proton exchange membrane (PEM) electrolyzers, although in early market stages, provide advantages such as high hydrogen output pressure, potentially lowering downstream compression costs. Solid oxide electrolyzer cells (SOEC) hold promise for higher efficiencies at elevated temperatures.

Research efforts worldwide aim to drive down the costs of electrolytic hydrogen production, with projections suggesting a substantial reduction in capital costs by 2050. This anticipated cost decline aligns with expectations of increased clean hydrogen deployment, potentially offering a more economical investment compared to traditional methods like SMR with carbon capture and storage (blue hydrogen). However, the widespread adoption of cleaner hydrogen pathways hinges on factors like electricity prices, which currently present a significant economic challenge compared to natural gas.

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

The LCFFES pillar primarily focuses on transitioning to bio-feedstocks, clean methanol, and low-carbon fuels, showcasing diverse strategies aimed at substantial CO_2 emissions reductions within the U.S. chemical industry. Chemical feedstock for organics cannot be decarbonized, as carbon is essential for their structure and properties. However, alternative sources like biomass, CO_2, industrial waste, and recycled materials can replace fossil fuels. Bio-feedstocks like bioethanol are successfully used in bulk chemical production. Studies suggest they could contribute 5-20% of petrochemical feedstocks by 2050; however, their life cycle impacts and feedstock heterogeneity must be considered.

In this work, a maximum contribution of 15% emission reduction from LCFFES is estimated (Figure 9), driven in part by bio-feedstocks. Clean hydrogen presents a viable option for zero-carbon process heat and electricity in the chemical subsector. A literature study has examined the potential and barriers of integrating clean hydrogen into U.S. industrial processes, projecting that it could constitute up to 25% of the fuel mix for the U.S. chemical industry by 2050. Primarily intended for medium-temperature process heat like steam generation and drying processes, clean hydrogen faces challenges such as competition with low-cost natural gas and uncertainties in carbon pricing policies. While clean hydrogen is considered as a feedstock in this work, only byproduct hydrogen from processes like steam cracking and chlor-alkali is evaluated as a fuel for process heat and fuel cell CHP.

Renewable natural gas (RNG), generated from waste biomass feedstock, is also considered a viable option for integration into existing natural gas infrastructure. Other clean energy sources like deep geothermal and direct solar energy usage have potential but are contingent on specific processes and geographical locations.

Carbon Capture, Utilization, and Storage (CCUS) Impact

The significance of CCUS in reducing CO_2 emissions within chemical manufacturing processes is highlighted in Figure 9. CCUS stands out primarily due to its assumed capacity to capture high-purity biogenic process CO_2 from ethanol manufacturing, which accounts for over 50% of the potential CO_2 emissions reduction attributed to CCUS. Excluding ethanol-specific bioenergy with carbon capture and storage (BECCS), electrification emerges as the primary method for decarbonizing the chemicals subsector, followed closely by energy efficiency. However, given that many high-impact CO_2 utilization pathways are still in their infancy and concerns exist regarding large-scale geological storage, CCUS is viewed as a supplementary option after exhausting other decarbonization avenues.

CCUS presents a promising avenue for reducing emissions within the U.S. chemical subsector, particularly for addressing hard-to-abate CO_2 emissions stemming from energy-intensive processes. While it is recommended as a last resort following the exploration of other decarbonization strategies, CCUS offers cost-effective capture opportunities for high-purity CO_2 sources such as ammonia, methanol, and ethanol manufacturing. Nonetheless, integrating CCUS into various processes would necessitate significant adaptations, particularly in large furnaces like steam crackers.

In the net-zero scenario, CCUS could potentially reduce CO_2 emissions by 72 MMT by 2050 (Figure 9), with approximately half of this reduction originating from capturing biogenic CO_2 from ethanol facilities. However, capturing the remaining emissions, primarily from diluted CO_2 streams, is expensive despite available tax credits. The captured CO_2 is earmarked for long-term storage, with potential utilization pathways including geological storage, mineralization, enhanced oil recovery (EOR), or conversion into products such as plastics (non-single use). Nonetheless, the long-term efficacy of these utilization pathways and their impact on emissions necessitate comprehensive carbon accounting and lifecycle analysis, which currently exceed the scope of this work.

2.2.4 Key Decarbonization Decisions

A transformation of the chemicals subsector will require a holistic view of the anticipated decarbonization pillars and technologies that will become (or may become, depending on technoeconomic factors) viable and available over varying timeframes out to mid-century and beyond. One way to assess these pathways is by starting with a decision-tree framework, as depicted in Figure 10 below.

The decision tree is depicted as a circular process until net-zero emissions is achieved to account for solutions that may not yet be commercially available. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission "lock-ins" and potential stranded assets in the future.

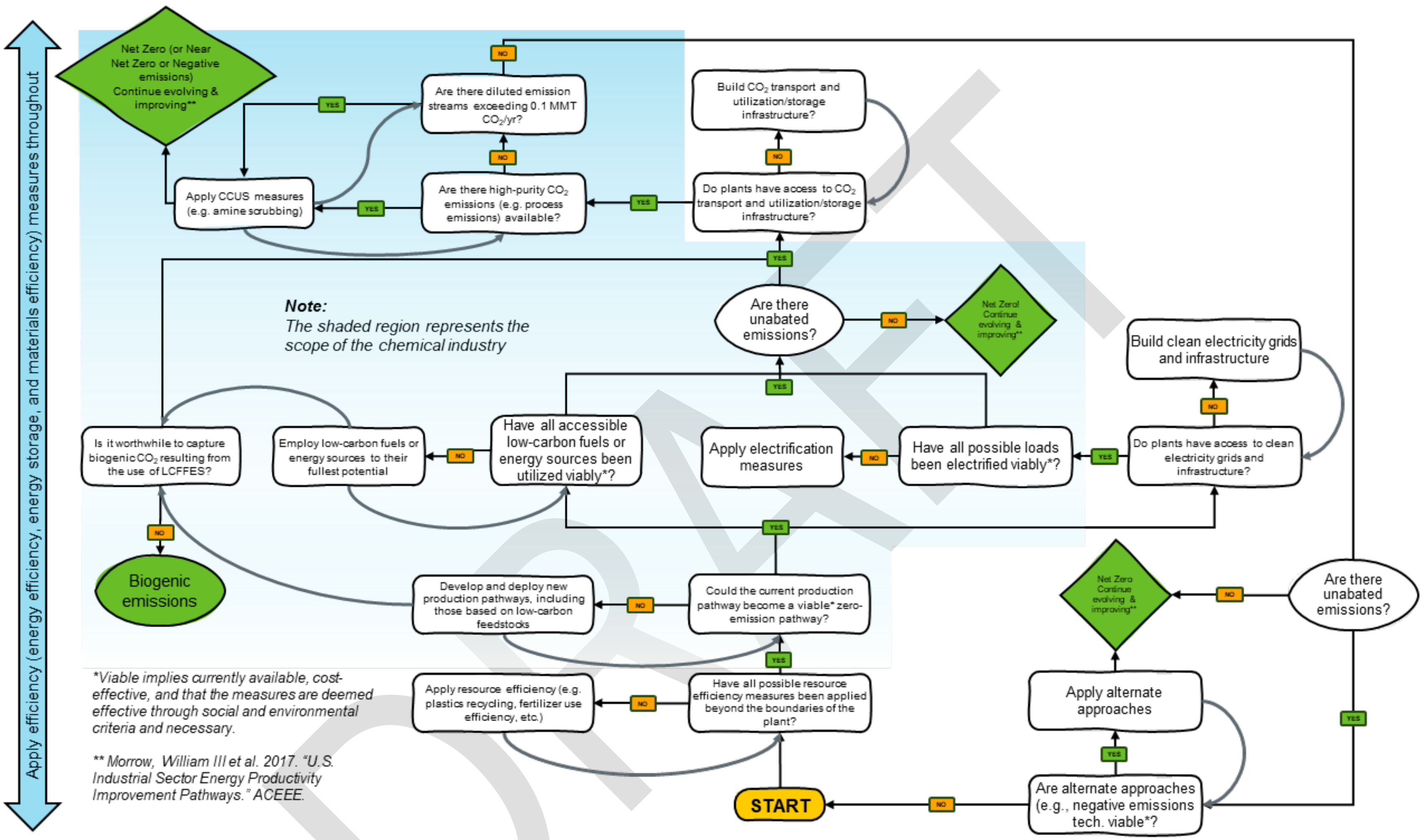

Figure 10. Chemicals manufacturing decarbonization decision tree

An example of a chemicals manufacturing decarbonization decision tree. Efficiency measures should be applied through all steps as indicated by the blue arrow (including energy and materials efficiency, energy storage, etc.). Note, sequencing and specific decarbonization strategies may vary. This figure is provided for discussion purposes and as a way to identify the barriers and opportunities in pathways to decarbonization and better understand decision making.

2.2.5 Modeling Assumptions

Table 16 through Table 19 in Appendix B provide the major assumptions in the net-zero scenario for each chemical modeled.

2.3 Food and Beverage Manufacturing

2.3.1 Subsector Snapshot

The U.S. food supply chain is composed of multiple stages–agriculture, manufacturing (where products are packaged and prepared for eventual consumption), wholesale and retail, and consumption (both at homes and food services).[64] Additional areas of the supply chain with non-negligible energy consumption and emissions include post-harvest processing between manufacturing and agriculture and warehousing between manufacturing, wholesale, and retail. Because the food supply chain is so interconnected, it can be difficult to account for decarbonization impacts within only one specific stage and there are significant data gaps within food and beverage manufacturing and across the entire supply chain. To achieve net-zero emissions by 2050, decarbonization efforts will need to be considered within each stage. This section provides a summary of modeling results for an example pathway for U.S food and beverage manufacturing to reach net-zero emissions by 2050.

Because food and beverage manufacturing is heterogenous (composed of the thousands of facilities across the U.S. of all sizes, producing vastly different products from milk to salad dressing to chocolate bars and everything in between), it can be a challenge to estimate the energy intensity or consumption of one particular product. However, the U.S. Energy Information Administration's (EIA's) Manufacturing Energy Consumption Survey (MECS)[65] is released every four years with a treasure trove of energy use data for six food and beverage manufacturing subsectors which account for 79% of energy and 78% of emissions for food and beverage manufacturing overall.[66] This data includes energy use by type (offsite purchased vs. onsite generated steam and electricity and specific fuels) and end use, allowing for more detailed analysis of decarbonization opportunities by technology type. The MECS data, extensive food supply chain mass flow analysis work conducted by Oak Ridge National Laboratory (ORNL), and additional research on existing process heating mediums (hot air, steam, and hot water) and temperature needs serve as the backbone of this modeling.

Food and beverage manufacturing is a key piece of the industrial sector and the U.S. overall, adding $463 billion to the economy in 2021.[67] Also in 2021, the subsector employed more than 1.7 million workers, accounting for 15.4% of all manufacturing employees and 1.1% of

[64] Both agriculture and manufacturing are considered to fall under the industrial sector. IEDO's predecessor (AMO) only focused on the manufacturing stage, while the office is working to also consider impacts beyond manufacturing. Agriculture is additionally discussed in the "rest of industry" section below.
[65] Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data | Energy Information Administration
[66] See All Manufacturing and Food & Beverage Manufacturing Energy and Carbon Footprints | Department of Energy
[67] 2018-2021 Annual Survey of Manufactures: Tables (census.gov)

all U.S. nonfarm employment.[68,69] Food and beverage manufacturing 2021 sales of $1 trillion accounted for 16.8% of the manufacturing subsector's sales.[70] Food and beverage manufacturing facilities are located across the United States, amounting to over 41,000 facilities in 2021, with California containing the highest number (6,301), followed by Texas (2,782) and New York (2,662).[71,72]

Food and beverage manufacturing is composed of eleven key four-digit North American Industry Classification System (NAICS) subsectors. U.S. food and beverage manufacturing accounted for 8% of total manufacturing subsector emissions, 6% of onsite emissions, 10% of primary energy, and 9% of onsite energy.[73] A detailed breakdown of energy end use, energy loss, and emissions can be found on the *Manufacturing Energy and Carbon Footprint: Food and Beverage*.[74] Table 6 provides the energy consumption and emissions for the six modeled food and beverage subsectors in 2018, as well as the remainder accounted for in the rest of food and beverage manufacturing.

Table 6. Food and Beverage Manufacturing Subsectors Energy Consumption and Emissions 2018

NAICS Code	Subsector	Fuel consumption (TBtu)	Electricity consumption (TBtu)	Onsite emissions (MMT CO_2e)	Total emissions (MMT CO_2e)
3112	Grain and Oilseed Milling*	196	50	10	17
31131	Sugar Product Manufacturing*	102	4	5	5
3114	Fruit and Vegetable Preserving and Specialty Food Manufacturing*	95	34	5	10
3115	Dairy Product Manufacturing*	83	39	5	10
3116	Animal Slaughtering and Processing*	170	108	9	24
3121	Beverage Manufacturing*	65	46	3	9
	Rest of food and beverage manufacturing**	188	82	9	22
311, 312	Food and Beverage Manufacturing Total	899	363	45	96

** Subsectors included in this modeling effort.*

*** The "rest of food and beverage manufacturing" subsectors that were not modeled (and associated NAICS codes) are confectionary products (NAICS 31134 and 31135); seafood products (3117); bakeries & tortillas (3118); other food (3119); and tobacco manufacturing (3122).*

68 Ibid.
69 USDA ERS - Food and Beverage Manufacturing
70 2018-2021 Annual Survey of Manufactures: Tables (census.gov)
71 USDA ERS - Food and Beverage Manufacturing
72 County Business Patterns (CBP) (census.gov)
73 See All Manufacturing and Food & Beverage Manufacturing Energy and Carbon Footprints | Department of Energy
74 Food and Beverage Manufacturing Energy and Carbon Footprint | Department of Energy.

Data sources: Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data | Energy Information Administration; Inventory of U.S. Greenhouse Gas Emissions and Sinks | U.S. Environmental Protection Agency; and Food and Beverage Manufacturing Energy and Carbon Footprint | Department of Energy.

The U.S. manufactured a total of 209 million metric tons (MMT) of food in 2018. The largest subsector in terms of mass throughput was oil and grain[75] with 70.1 MMT manufactured. Next was dairy products with 42.2 MMT (by milk-fat basis), vegetables with 33.9 MMT, and animal products with 32.6 MMT (including any inedible portions that are sold at retail). The remaining five commodity groups (fruit, sugar, nuts, peanuts, and seafood) together contributed less mass than animal products. From 2020 to 2030, most food commodity groups are expected to increase production by a few percent per year, though fruit products manufactured in the United States seem to decline slightly, despite rising consumer demand, due to increased imported fruit. By 2050, the U.S. is estimated to manufacture 251 MMT of food up from 209 MMT in 2018 (about 20% increase).

Most subsectors within food and beverage manufacturing primarily rely on natural gas (34% –73% of the total onsite energy), with electricity as a close second (12%–60%). Two subsectors (grain and oilseed milling and sugar and confectionary manufacturing) still rely on coal for substantial portion of their site energy (7%–17%) for boilers, combined heat and power (CHP), and process heating. The animal product processing subsector is the highest energy consumer with a majority (39%) provided by electricity. While grain and oilseed milling have a similar site energy use, its primary energy demand is only 21% of the site-level energy use coming from electricity. The sugar and confectionary manufacturing subsector also has a substantial energy contribution from biomass (23%)–namely the combustion of waste bagasse, which can lower GHG emissions if excluding biogenic carbon.

The vast majority of food and beverage manufacturing processes fall in the low and medium temperature range as shown in Figure 11 and the subsector relies on fuel use for process heating mediums as shown in Figure 12. Natural gas accounted for the largest share of fossil fuel utilization in process heating, boiler, and CHP operations followed by coal in 2018. The largest share of fossil fuel (about 50%) was used to generate steam through boiler and CHP systems. The steam generated provides process heating demands for various processes with a required temperature between 90 degrees Fahrenheit (°F) and 365°F. This temperature range shows that food and beverage manufacturing utilizes low- to medium-grade steam for its processes (see Figure 11). Four of the six subsectors studied utilized mostly steam as a heating medium, the remaining two (animal slaughtering and processing and beverage manufacturing) used hot water as the majority heating medium.

[75] Includes products sold as raw ingredients (e.g., flour and oil) and finished products (e.g., pasta, bread)

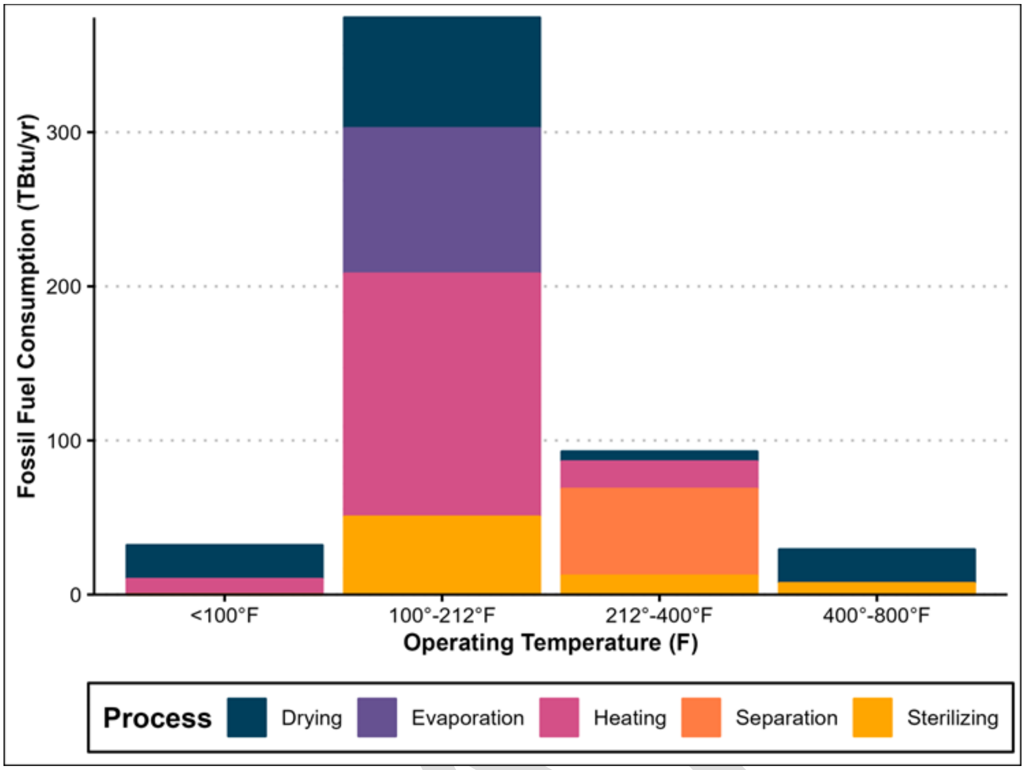

Figure 11. Food and beverage thermal process fossil fuel consumption for defined temperature ranges, 2018

Literature review was conducted to identify the applicable thermal unit processes, estimated temperature ranges, required heating mediums (hot water, steam, and hot air), and fuel breakdown by subsector to better define the EIA MECS process heating, boilers, and CHP categories. References include: 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.

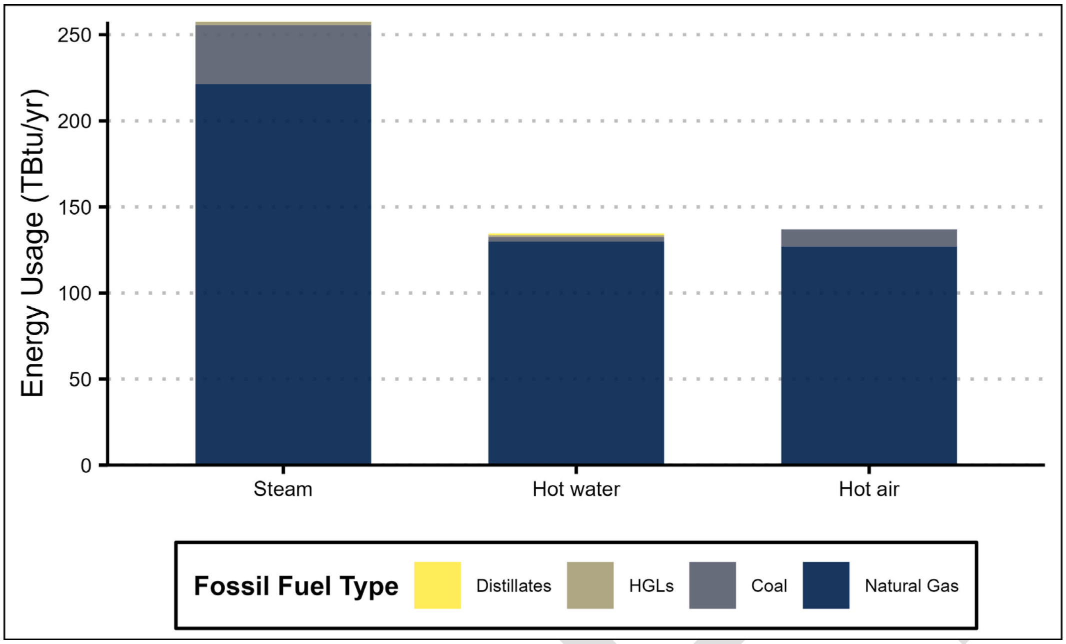

Figure 12. Breakdown of fossil fuel usage type for process heating mediums, such as steam, hot water, and hot air in food and beverage manufacturing, 2018

Literature review was conducted to identify the applicable thermal unit processes, estimated temperature ranges, required heating mediums (hot water, steam, and hot air), and fuel breakdown by subsector to better define the EIA MECS process heating, boilers, and CHP categories. References include: 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.

2.3.2 Net-Zero Emissions Barriers and Challenges

Major barriers for food and beverage manufacturing decarbonization are outlined below by decarbonization pillar and are not meant to be comprehensive.

Major Energy Efficiency Barriers and Challenges

- Because profit margins in the food and beverage manufacturing subsector tend to be slim, access to capital would greatly aid energy efficiency measures adoption. Additionally, other barriers such as lack of information/awareness, corporate/facility priorities, and equipment retirement rates/sunk capital, exist that will limit the uptake of energy efficiency, if not addressed.
- Investment in energy efficiency measures for fossil fuel-based systems could lock in higher CO_2e emissions. Large capital costs to improve fossil fuel system energy efficiency is not practical if that system will need to be replaced in order to meet decarbonization goals. Companies will need to balance these investments in fossil fuel systems, such as maintenance or operational energy efficiency measures, as needed for the duration of the system's useful life or until it is replaced by a decarbonized

system. Decision support tools are needed to support sensible investment in improving the fossil fuel systems' energy efficiency.

Major Industrial Electrification Barriers and Challenges

- Three major current challenges with electrification are 1) the cost disparity between electricity costs (both usage and demand charges) and natural gas costs, 2) the current emissions associated with grid-generated electricity, and 3) supply chain issues creating long wait periods for necessary equipment.
- The first challenge could change with time, when these cost disparities may or may not be narrowed. Generation of onsite clean electricity (e.g., onsite solar) is a means to lower electric charges (both usage and demand) though mostly after the onsite energy generation system has been paid off.
- Between now and when targets of a cleaner grid targets are achieved, emissions savings from electrification will likely be modest, particularly for systems that are replacing highly efficient fossil fuel systems. While this makes the short-term financial metrics (e.g., simple payback or return on investment) less attractive, use of more sophisticated financial metrics (e.g., levelized cost of CO_2e abated) that project costs and emissions reductions over the lifetime of the project can help address this barrier.
- The final barrier has created delays for facilities that are ready to electrify their fossil-fuel systems. Electrification will lead to a considerable increase in facilities' electric demand, which in turn may require electrical infrastructure upgrades. The necessary equipment, such as transformers, have long lead times (over one year as of the writing of this report) and increasingly rising costs. Delays associated with acquiring the necessary equipment is presently a barrier towards electrification.

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

- Barriers of fuel switching and mixing in general (e.g., hydrogen mixed with natural gas) include possible negative performance or safety impacts on existing combustion equipment. Performance impacts contribute to potential product quality concerns that may lead to industry hesitation in adopting technologies capable of utilizing hydrogen as a fuel source.
- Hydrogen: Though hydrogen as a low-carbon fuel is not expected to play a large role in decarbonization of food and beverage manufacturing, there may be specific subsector or facility applications to help meet net-zero goals. Similar to other subsectors, barriers to hydrogen consumption include the need for significant supply chain infrastructure and hydrogen-targeted policy instruments to stimulate both supply and demand side use.
- Biomass: Availability and sourcing is a main concern and barrier for biomass; there is limited access to low-cost resources and transportation, while specific onsite storage

requirements for make it difficult to incorporate biomass as a fuel source within industrial facilities.

- Biofuels: Biofuels are mainly used as transport fuels with few applications in manufacturing. They also have very high production and storage costs, which is attributed as the reason there has been limited adoption by the industrial sector thus far.

Major Carbon Capture, Utilization, and Storage (CCUS) Barriers and Challenges

- The main barrier to CCUS in food and beverage manufacturing is applicability overall: within this subsector, facilities range in size but are mainly small and medium so generally they do not have a sufficient "capturable" level of point source emissions (e.g., greater than 100,000 MT CO_2 per year).

2.3.3 Net-Zero Emissions Pathways and Technologies

This work modeled the impacts of the four decarbonization pillars (energy efficiency, industrial electrification, LCFFES, and CCUS)[76] across six modeled food and beverage manufacturing subsectors: 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 are the highest energy consumers and emitters in the subsector (as shown in Table 6), accounting for 79% of the total food and beverage manufacturing onsite energy consumption and 78% of emissions for 2018.[77]

A net-zero emissions food and beverage manufacturing subsector will require comprehensive decarbonization technology adoption across all pillars. An example output for a modeled net-zero decarbonization pathway by 2050 for the six subsectors is shown in Figure 13. During the same period, total production for these subsectors increases about 19% due to expected growing population demand. Electrification makes the largest contribution to CO_2e emissions reductions followed by energy efficiency. The LCFFES pillar has the next highest potential, providing a target that the subsector will need to meet after energy efficiency and electrification measures are taken into consideration. CCUS has limited potential in food and beverage manufacturing because the subsector is comprised of mostly small-scale, dispersed facilities and lower concentration of point-source CO_2e emissions where CCUS would not be economical and was only implemented for two subsectors (grain and oilseed milling and beverage manufacturing) in the net-zero scenario.

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[76] See the Industrial Decarbonization Roadmap for more detail on the decarbonization pillars.
[77] See All Manufacturing and Food & Beverage Manufacturing Energy and Carbon Footprints | Department of Energy

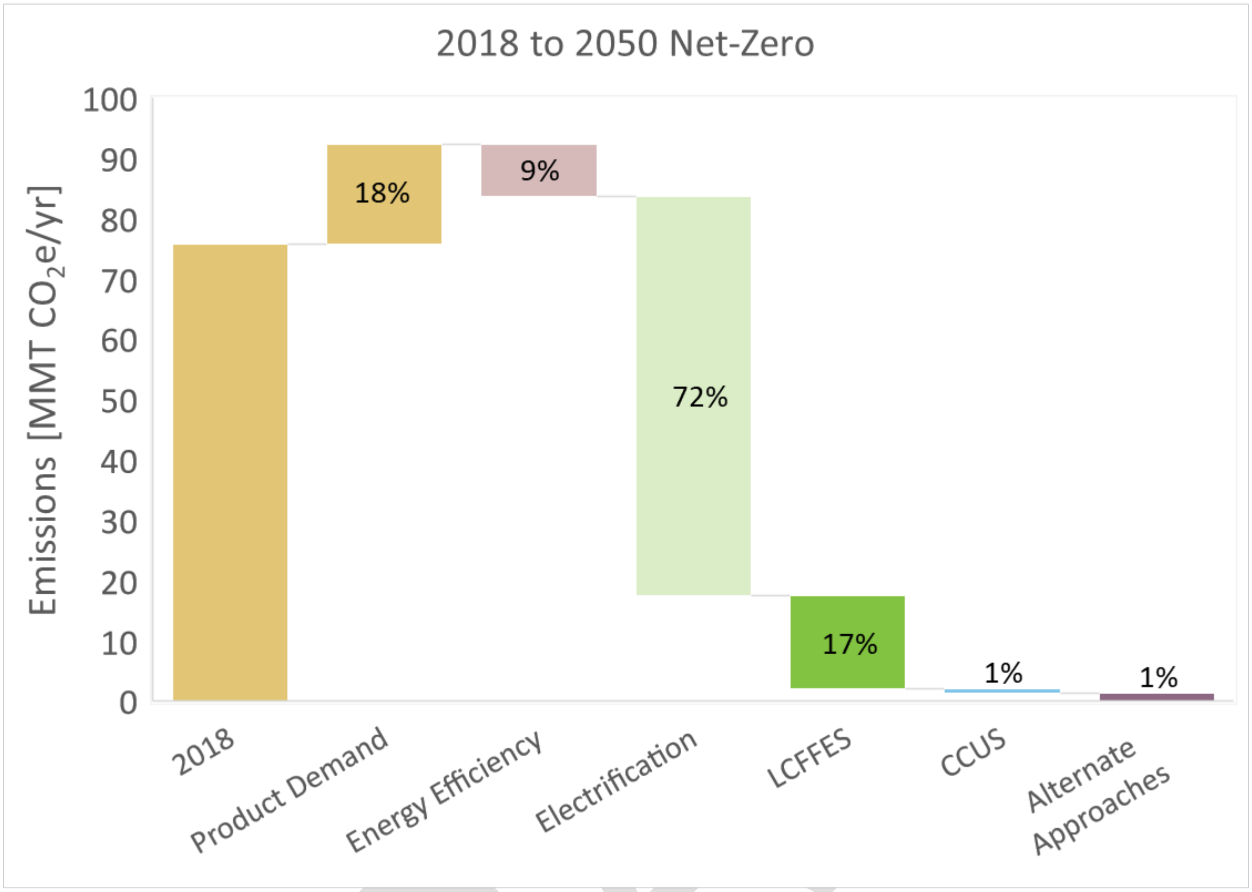

Figure 13. Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions (million MT/year) for select U.S. food and beverage manufacturing subsectors, 2018-2050

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. Details on assumptions, parameters, and timing of transformative technology application can be found below and in Section 2.3.5. This figure may differ to the associated Roadmap figure due to additional modeling considerations and additional food and beverage manufacturing coverage modeled. Source: This work.

After energy efficiency and electrification, LCFFES can help the subsector reach near-zero for the processes that cannot be electrified, with the small remaining amount of emissions coming from the emissions factors for the specific types of LCFFES utilized. CCUS has limited potential and would generally only be applicable for larger capturable emitters in the grains and oilseed milling and beverage manufacturing subsector. Alternate approaches other than those modeled in this work (e.g., negative emissions technologies, alternative proteins), powered by clean energy sources, would be needed to reach the last 1% to net-zero. More analysis is needed to determine what the most applicable balance of LCFFES would be for food and beverage manufacturing, but it is likely to be a small amount of hydrogen with future analysis work planned on the potential of onsite biogas generation.

The impacts of each decarbonization pillar on reducing the six modeled U.S. food and beverage manufacturing subsectors emissions, including specific technologies, are discussed in more detail below.

Energy Efficiency Impact

While electrification will have the largest impact for the food and beverage manufacturing subsector, opportunity still exists for energy efficiency measures adoption. Energy efficiency provides an avenue for reducing current fossil fuel consumption of equipment on stock, while also reducing the potential electricity demand when the fossil fuel equipment stock is electrified. Food and beverage manufacturing employs a substantial amount of stationary combustion equipment, which comprises distribution systems such as steam and hot water piping. The subsector also utilizes motor systems, specifically in raw materials and products cooling and refrigeration. Efficient energy usage could potentially reduce energy consumption, and mitigate GHG emissions within the facilities where they combust fossil fuels, and outside the facilities where electricity is generated through fossil fuels.

Companies will have to carefully consideration technology choices phasing, for energy efficiency and the other pillars, and at a facility-level or an industry-wide scale, to avoid emission "lock-ins" or creating potential stranded assets or "dead-ends" in the future. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

Three main areas of energy efficiency were included in this modeling effort for food and beverage manufacturing: boilers, ovens, and dryers; machine drive applications (pumps, fans and blowers, air compressors, refrigeration compressors); and process integration. For boilers, ovens, and dryers, some energy efficiency options could include tuning air/fuel ratios, minimizing excess boiler blowdown, increasing boiler condensate return, using steam traps, insulating any bare pipes and equipment, determining areas where steam pressure and temperature can be reduced. Options for increasing motor efficiency can include replacing old motors with premium efficiency or advanced motors, establishing predictive and preventive maintenance programs, or applying energy efficiency belts. Upgrading controls on air compressors and sequencing multiple air compressors could yield energy savings and ensure that the equipment is operating at the actual required pressure. Additionally, the use of variable frequency drives for motors, pumps, fans and blowers, and refrigeration compressors can yield higher energy savings potential. Refrigeration compressors may realize energy usage reductions of up to 17% through the application of the aforementioned energy efficiency measures. Similarly, energy reduction in the applications of pumps, fans and blowers, and air compressors are estimated as 15%, 23%, and 36%, respectively.

Process integration (through pinch analysis) can identify thermodynamically optimal arrangement of heat exchangers/heat pumps to minimize the need for conventionally supplied heating and cooling (e.g., from boilers and chillers), working best in facilities that operate their processes continuously as opposed to batch operations. Pinch analysis involves quantifying temperatures and thermal energy demands for processes requiring cooling and heating, determining where process integration can occur through heat exchangers or heat pumps. By strategically aligning temperature profiles and maximizing heat recovery opportunities, it is possible to reduce energy consumption while maintaining process efficiency, resulting in costs and GHG emission reductions. It is estimated that effective process integration can reduce the fossil fuel energy consumption of process heating equipment between 23% and 75% while reducing the electrical energy requirements of chillers and coolers between 19% and 80%.

Industrial Electrification Impact

Electrification of fossil fuel-using equipment in food and beverage manufacturing is estimated to play a significant role in reducing energy consumption and associated GHG emissions, largely due to the low- and medium-temperature process demands (see Figure 11 and Figure 12). Electric equipment typically is more efficient than their fossil-fuel-using counterparts. As the grid proceeds towards decarbonizing its mix of fuels employed to produce electricity, purchased electricity-related emissions will also be reduced. Food and beverage manufacturing requires low to medium-grade heat for their processes; comparatively, low-to-medium grade heating equipment is comparatively simpler to electrify as opposed to high-temperature processes. Electrical process heating equipment has better temperature and process control, which may result in a higher production rate and fewer maintenance requirements. The subsector can implement the use of hot water heat pumps (HWHPs), steam-generating heat pumps (SGHPs), electric boilers and water heaters, advanced electro-heating technologies (such as microwave, inductive, infrared, and ohmic heating), and electric pre-concentrators (membranes) to avoid using existing fossil fuel equipment.

Approximately 25% of fossil fuel consumption for process heating purposes in the food and beverage manufacturing subsector is to produce hot water for processes such as heating, cooking, cleaning, pasteurization, fermentation, and scalding, among others. Instead of operating fossil fuel boilers and water heaters, the subsector could employ hot water heat pumps that can generate identical thermal energy in hot water at comparatively lower energy consumption. Adoption of HWHP systems can reduce the fossil fuel intensity of processes and products and associated Scope 1 emissions. Not only do they eliminate the application of fossil fuels, but they are also highly efficient. Additionally, higher energy savings potential can be achieved if the HWHP systems utilize waste heat generated from other equipment and processes.

Similar to HWHPs, efficient SGHP operations require a low-grade heat source. In SGHP systems, since higher temperature lifts are required to produce steam, a low-grade heat source is imperative. SGHP systems, therefore, are an excellent choice to generate low-temperature steam and process heat, though industrial heat pumps are limited to around

175°C (349°F).[78] Since SGHP systems are more sophisticated than HWHP systems, the technology is not as mature as compared to HWHPs. Adoption of SGHP systems can reduce the fossil fuel intensity and Scope 1 emissions of steam-generating and drying processes, specifically boilers and dryers. They are more efficient than boilers and likely incur lesser losses as compared to combustion and thermal losses in boilers. Similar to HWHPs, higher energy savings can be achieved in SGHPs is waste heat from other equipment and processes is utilized.

Electric boilers, also analogous to electric resistance heating or electrode boilers, generate thermal energy by heating the electrode which consequently heats water into steam, or by sending electric current directly to the water resulting in hot water or steam. Electric boilers are comparatively a more mature and simpler technology than the HWHPs and SGHPs. Electric boilers are more efficient than fossil fuel boilers with an efficiency ceiling of up to 99 percent (as opposed to the 60-80 percent combustion efficiency of fossil fuel-fired boilers). Since they are more mature, their operating pressures and temperatures are higher than the SGHPs; they can generate saturated and superheated steam with pressures and temperatures reaching up to 1,000 pounds per square inch gauge (PSIG) and 660°F.[79] They are well suited for any applications where heat pumps may not be technically or logistically viable. Apart from higher efficiencies, electric boilers also provides better control, faster ramp-up times, and require less maintenance than fossil fuel-fired boilers.

Applicable advanced electro-heating technologies may include processes such as microwave, inductive, infrared, and ohmic heating, among others. These technologies operate differently from conventional process heating through the combustion of fossil fuels and can reduce the baseline energy consumption between 10% and 90%, depending on the technology. Microwave and ohmic heating are primarily employed in batch processes in food production facilities for processes such as post-packaged pasteurization and sterilization. The impact of microwaving varied across different food products, with some maintaining identical quality while others exhibited lower quality, accelerated degradation, color changes, or alterations in taste, so these technologies should be studied on a case-by-case basis.

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

In order to mitigate emissions from fossil fuel usage, sourcing energy from LCFFES, such as hydrogen or biogas, especially to meet requirements of those high temperature manufacturing processes where electrification technologies cannot currently address, is a critical decarbonization pathway for manufacturing. Certain food and beverage manufacturing subsectors already consume a portion of LCFFES, namely sugar manufacturing which uses bagasse as a fuel and grain and oilseed milling, animal slaughtering and processing, and beverage manufacturing subsectors which utilize some

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[78] Annex 58 High-Temperature Heat Pumps Task 1 Report - IEA Technology Collaboration Programme
[79] Electrification of industrial boilers in the USA: potentials, challenges, and policy implications | Energy Efficiency

wood chips and bark as fuel. As shown in Figure 13, LCFFES will play a smaller role in food and beverage manufacturing decarbonization but will be needed to help reach net-zero.

Hydrogen will likely see a limited application as a fuel for this subsector, but there may be certain locations or processes where it could be utilized. Biogas could be produced via anaerobic digestion and consumed as a fuel in place of natural gas for higher temperature processes and/or for steam generation purposes. Biomass (namely woody biomass which is already used to an extent) could be sourced externally and used for steam generation though it has lower efficiencies (roughly 75-90%) compared to natural-gas fired processes, which have efficiencies between 85-90%. Although food waste can in theory be a biomass resource, most of this waste within the manufacturing subsector is already re-utilized in some way, where primary un-utilized losses occur in the supply chain and on the consumer side.[80] Because natural gas makes up the majority of fuel consumed for food and beverage manufacturing, potential for biofuels utilization is considered very low within this space as it is instead considered as a potential replacement to distillate fuel oils and hydrocarbons.

Carbon Capture, Utilization, and Storage (CCUS) Impact

As noted above, CCUS has limited potential in food and beverage manufacturing. The subsector is comprised of mostly small-scale, dispersed facilities and lower concentration of point-source CO_2e emissions where CCUS would not economically make sense. Based on U.S. Environmental Protection Agency data,[81] it is estimated that carbon capture (specifically amine absorption) would only be applicable in the grains and oilseed milling and beverage manufacturing subsectors for facilities that have CO_2 streams large enough to be "capturable" (point sources emitting greater than 100,000 MT CO_2/year at time of capture). Any amount of LCFFES application after energy efficiency and electrification in either subsector would result in less capturable emissions. In the future, facilities in these subsectors would need to determine the optimal level of CCUS vs. LCFFES, which may be dependent upon the economics of each as a decarbonization strategy.

Material Efficiency Impact

U.S. food manufacturing (e.g., packaging, preparation, slaughtering) is driven by what consumers choose to eat and what is available. New food options, such as meat alternatives, could change the expected demands and impacts of the food supply chain. Overall changes in consumer habits or behaviors, such as trying to eat healthier, would also have an impact on the demand for manufactured food. But one key potential driver of demand change is a reduction in consumer-level generated waste. While food waste occurs in the initial food supply chain stages (agriculture and manufacturing), most of it is repurposed in some way (e.g., animal feed, industrial uses, land application, anaerobic digestion). Conversely, over 30% of food purchased for consumption ends up wasted, usually in a landfill, an incinerator, or sewer. The EPA and the USDA have set a national goal

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[80] From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste | U.S. EPA

[81] U.S. Facility Level Information on GreenHouse gases Tool (FLIGHT). https://ghgdata.epa.gov/ghgp/main.do.

to reduce end user related food waste by 50% by 2030 from 2015 levels, which includes the distribution system, wholesale and retail (W&R), food services, and residential stages of the food supply chain (FSC).[82]

Studies have shown that simple policy and behavior changes can have a dramatic impact on waste reduction efforts, such as improving expiration date labels. Other simpler behavioral changes could involve municipally assisted waste diversion practices (e.g., community composting, wastewater treatment or other centralized co-digestion) or consumer education campaigns.[83,84] Additionally, behavioral changes such as smaller portion sizes, reducing the amount of food plated, meal kits, and others that have a potentially high payoff but are substantially more difficult to implement. Another option that could be implemented by the manufacturing stage, with the goal of substantially reducing the consumer stages' waste: shelf-life extension via improved packaging materials or design, new processing techniques, or new manufacturing schemas.

There are many technologies and strategies that can be employed by food manufacturers to reduce consumer food waste. Preliminary work has been conducted identifying the types of technologies being developed that can be used to prolong perishable food's shelf life. So far, three main categories have shown to be the most promising: edible coatings, active atmosphere, and processing changes. Edible coating is primarily employed for preserving the freshness of vegetables and fruits, effectively extending their shelf lives by 5-20 days. Active atmosphere finds its key applications in the preservation of animal products, contributing to a shelf-life extension of 7-14 days. Finally, process changes can range from specialized treatments during food processing, such as thermosonication, postharvest UV-C treatment, and bactofugation. These technologies are commonly applied in the dairy, vegetable, and animal products, resulting in shelf-life increases.

In addition to changes the existing food supply chain can make, upending the supply chain altogether with controlled-environment agriculture (CEA) or distributed agriculture infrastructures can effectively extend shelf-life (by reducing the length of the distribution stage and getting food to consumers more quickly), in addition to other substantial benefits. Integration of co-optimized crop production with CEA solutions, including a range of structures from photovoltaic incorporated greenhouses to fully artificially lighted plant factories (PFs), could address food security, sustainability, and energy justice barriers while shielding food production from losses due to pests and increasingly erratic weather.

2.3.4 Key Decarbonization Decisions

A transformation of the food and beverage manufacturing subsector will require a holistic view of the anticipated decarbonization pillars and technologies that will become (or may

[82] EPA. 2023. "United States 2030 Food Loss and Waste Reduction Goal." https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal.
[83] Estimating Quantities and Types of Food Waste at the City Level - NRDC
[84] ReFED - Solution database

become, depending on technoeconomic factors) viable and available over varying timeframes out to mid-century and beyond. One way to assess these pathways is by starting with a decision-tree framework, as depicted in Figure 14 below.

The decision tree is depicted as a circular process until net-zero emissions is achieved to account for solutions that may not yet be commercially available. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission "lock-ins" and potential stranded assets in the future.

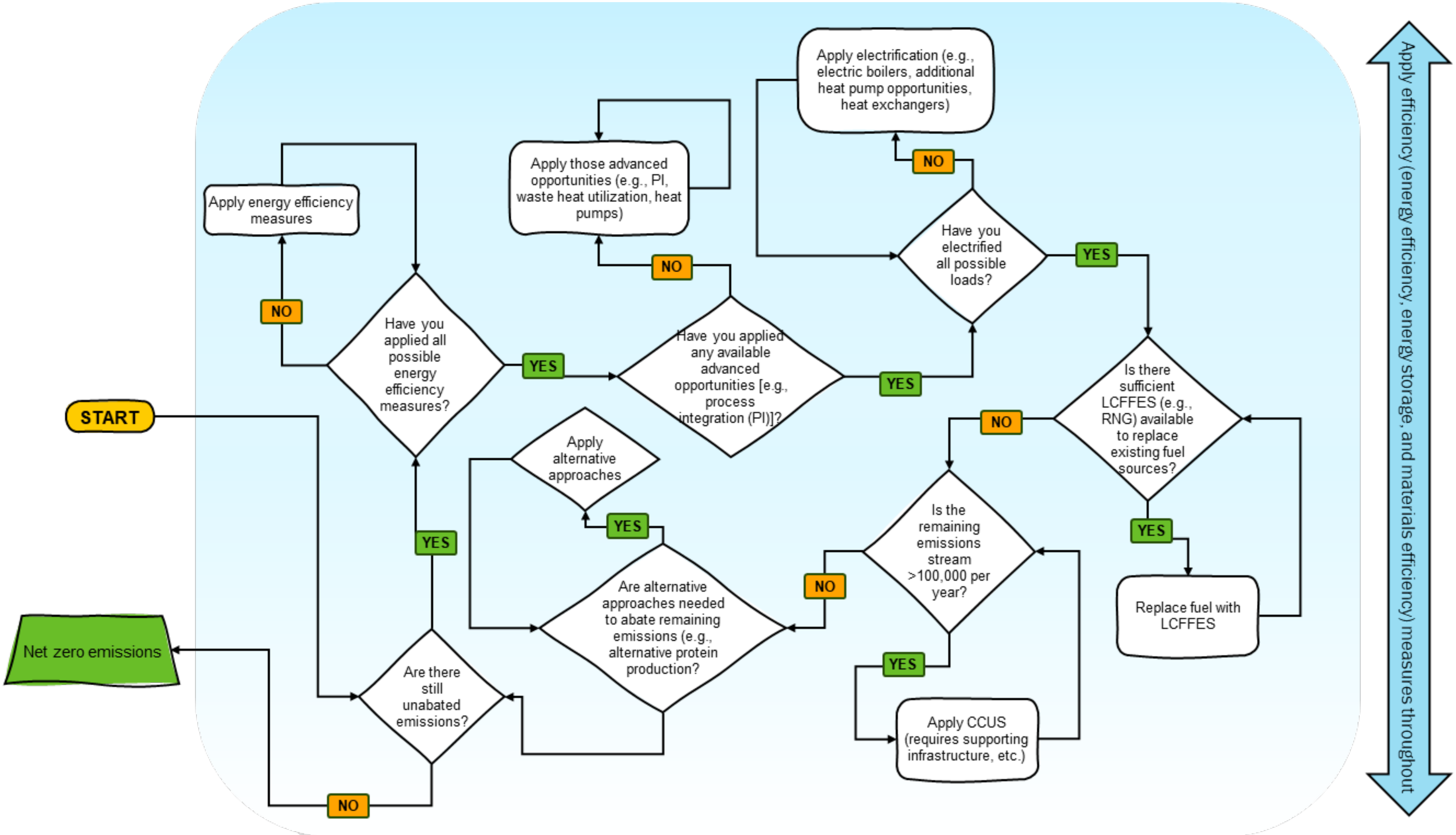

Figure 14. Food and beverage manufacturing decarbonization decision tree

An example of a food and beverage manufacturing decarbonization decision tree. Efficiency measures should be applied through all steps as indicated by the blue arrow (including energy and materials efficiency, energy storage, etc.). Note, sequencing and specific decarbonization strategies may vary. This figure is provided for discussion purposes and as a way to identify the barriers and opportunities in pathways to decarbonization and better understand decision making.

2.3.5 Modeling Assumptions

This example net-zero scenario includes ambitious technology adoption assumptions, especially for the energy efficiency and industrial electrification pillars. The net-zero scenario for food and beverage manufacturing assumes full adoption of relevant energy efficiency measures, 95% realization of electrification potential based on relevant end use temperature ranges, and elimination of fossil fuel consumption (replacing any remaining fuel needs after energy efficiency and electrification with low-carbon fuels). Two subsectors (beverage manufacturing and grain and oilseed milling) include adoption of amine absorption carbon capture and storage for a portion of the subsectors' remaining emissions, as described in Section 2.3.3.

The scenario experiences an increase in electricity consumption to account for the elimination of fossil fuels. In this scenario, the shift towards electrification is approximately 72%. The electricity consumption in 2050 is estimated to increase by 208% as compared to the baseline electricity consumption in 2022. The share of adoption rates for the decarbonization measures and technologies is similar to the other scenarios. Overall adoption rates are two to three times higher than that of the BAU scenario. In total, the net-zero scenario estimates that the 95% of the subsector will be electrified by 2050, while achieving 100% of the potential for energy efficiency, and the remaining decarbonization is achieved through LCFFES, CCS, and alternate approaches.

NREL's Regional Energy Deployment System (ReEDS) model was employed to estimate the adoption rates of identified pillars and their constituent technologies.[85] This modeling utilized the ReEDS High Demand Growth scenario, nascent technologies, and 95% decarbonization by 2050.

Table 7. Key Net-Zero Scenario Assumptions by Category with Values for 2050

Pillar	2050 Values (Percentage of maximum potential)
Energy Efficiency	5%-100% depending on technology (see Table 8 for adoption rates)
LCFFES	3.8%-12.9%
Industrial Electrification	2.8%-100% depending on technology (see Table 8 for adoption rates)
CCUS	Grain & oilseed milling: Capture 4.1% of remaining direct CO_2e emissions Beverages: Capture 0.9% of remaining direct CO_2e emissions

[85] 2022 Standard Scenarios Report: A U.S. Electricity Sector Outlook (Technical Report) | OSTI.GOV

Adoption Rates

Technology adoption rate: The adoption rates of individual decarbonization technologies are assumed to follow an S-curve and are modeled as:

$$\text{Adoption Rate} = N_u/(1+\exp(-k*(\text{year}-x_0))$$

where N_u = maximum long-term implementation [% of industry]; k=speed of implementation variable; x_0=year when 50% of long-term implementation is reached.

The final adoption rate assumptions by scenario for decarbonization technology equipment are displayed in Table 8.

Table 8. Decarbonization Equipment Net-Zero Scenario Adoption Rates

Equipment	Net-Zero Scenario Adoption Rate(s)
Membrane pre-concentrator (electrification)	4%
Steam-generating heat pump (electrification)	81-92%
Advanced electroheating technologies (electrification)	17%
Electric boiler (electrification)	8%
Hot water heat pump	92-95%
Process heating energy efficiency	100%
Machine drives energy efficiency	100%
Refrigeration compressors energy efficiency	100%

2.4 Iron and Steel Manufacturing

2.4.1 Subsector Snapshot

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 global manufacturing GHG emissions.[86] The U.S. steel subsector produced 82 MMT of crude steel in 2022, about 4% of global production and the fourth-largest producer of steel in the world behind China, India, and Japan.[87] There were 11 integrated steel mills and 101 mini-mills in the U.S. in 2022,[88] with an average annual capacity of 1.62 MMT.[89] Around 29% of steel in the U.S. was produced by primary steelmaking facilities using the BF-BOF production route

[86] Iron and Steel Technology Roadmap – International Energy Agency
[87] Iron and Steel - USGS
[88] Ibid.
[89] Global Steel Plant Tracker - Global Energy Monitor

(depicted in Figure 15) and 72% was produced by the electric arc furnace (EAF) route[90] (typically called secondary steelmaking, process shown in Figure 16), which has about a third of the carbon footprint of BF-BOF produced steel.[91]

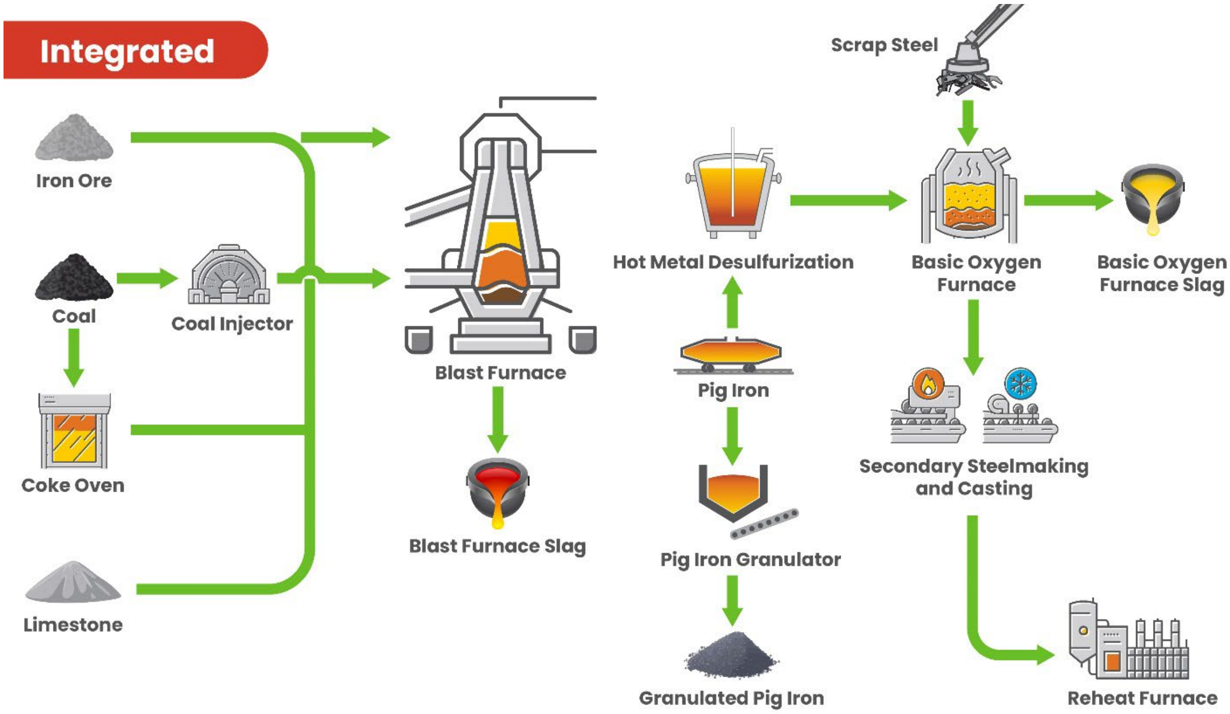

Figure 15. Integrated steel mill process flow diagram

[90] Iron and Steel - USGS
[91] How Clean is the U.S. Steel Industry? — Global Efficiency Intelligence

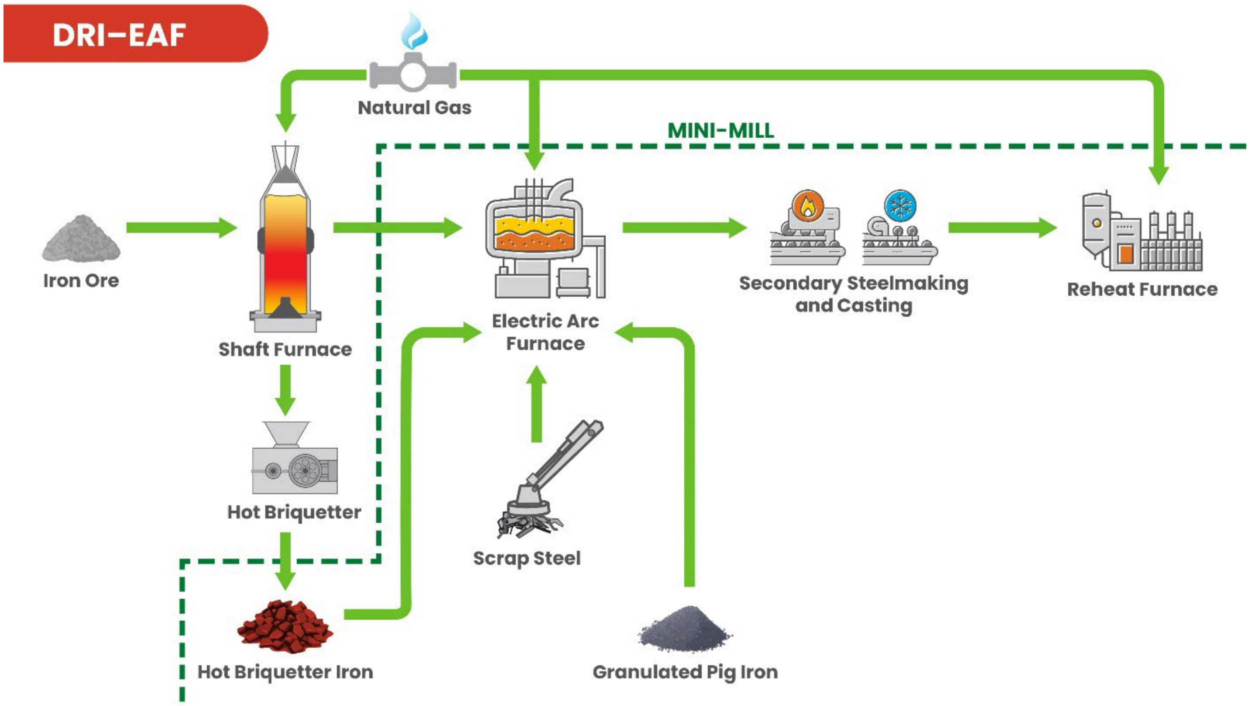

Figure 16. Steel mini-mill process flow diagram

In 2018, U.S. iron and steel manufacturing emitted a total of 100 MMT CO_2e, 9% of total manufacturing emissions.[92] For the same year, iron and steel mills accounted for 1,469 trillion British thermal units (TBtu) of primary energy consumption, about 7% of the total U.S. manufacturing energy consumption.[93] At 37% of the total, natural gas represented the largest share of energy consumption, followed by coke and breeze (28%), electricity (17%), blast furnace and coke oven gases (16%), coal (2%), and a small amount (<1%) of petroleum coke, distillate fuel oil, and waste gas.[94]

This section provides an example net-zero emissions pathway for U.S iron and steel manufacturing to reach net-zero CO_2 emissions by 2050. The diverse energy sources and dependencies within the U.S. iron and steel subsector necessitate a multifaceted approach to decarbonization.

2.4.2 Net-Zero Emissions Barriers and Challenges

This section provides an overview of the major barriers faced by the subsector and is not meant to be comprehensive.

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92 See All Manufacturing and Iron & Steel Manufacturing Energy and Carbon Footprints | Department of Energy
93 Ibid.
94 Manufacturing Energy Consumption Survey - U.S. Energy Information Administration. See Table 3.2. Energy Consumption as a Fuel By Manufacturing Industry and Region and Table 5.2 Energy Consumed as a Fuel by End Use By Manufacturing Industry with Net Electricity and Manufacturing Energy and Carbon Footprint: Iron and Steel (NAICS 331110, 3312)

Major Energy Efficiency Barriers and Challenges

- While many energy efficiency technologies are already commercialized and often yield energy and cost savings with favorable payback periods (e.g., under three years), some major energy efficiency technologies will require large investments. For example, the cost of retrofitting existing equipment with new technologies may be prohibitive due to needed infrastructure or footprint changes, among other factors.
- Each facility has specific needs that will drive the most favorable selection of energy efficiency opportunities.
- Deployment of waste heat recovery technologies is limited due to the low cost of natural gas and harsh environment (dust, high temperatures, and corrosive gases).
- Similarly, deploying artificial intelligence, smart manufacturing, and internet of things (IoT) solutions is challenging due to the harsh environment as well as the moment of inertia against the drastic change.

Major Industrial Electrification Barriers and Challenges

- The subsector's production environment has many corrosive gases that could result in frequent failure of electrical heating equipment. For example, there can be significant maintenance challenges for ceramic high temperature heating elements in a high impact environment.
- For reheating equipment, switching from fuel-fired burners to an induction heater might only work for thin slabs or billets with current technologies, and facilities might need some significant redesign to electrify this process, which requires very high temperatures.
- More RD&D is needed to improve furnace design so that resistance heating can be scaled up in batch and continuous furnaces.
- Emerging technologies for steel galvanizing and heat treatment (e.g., annealing) need RD&D to assess the mitigation potential of these technologies and assist with their increased uptake.
- Yield and scalability of electrolysis of iron ore are not yet at a commercial scale, and the technology is still in the RD&D stage.
- Fundamental questions about the energy footprint of electrolysis remain, including whether the iron ore would need energy-intensive preprocessing before undergoing electrolysis.
- RD&D is needed to investigate the comprehensive costs and benefits of electrolysis at scale (material and energy costs, value of byproducts, etc.).

- Scale-up of technology to meet demand and the high capital cost involved are the biggest barriers to implementing electrification technologies in the iron and steel industry.
- Laboratory testing is ongoing, indicating a prolonged and costly development phase, and limited flexibility compared to alternative methods.
- Profitability of new processes is contingent on the availability and affordability of clean electricity, posing a hurdle in the absence of widespread cheap and accessible clean energy sources.
- Large-scale testing and process optimization are needed to improve operational efficiency and bring down costs before such technologies could be adopted.
- Resources are needed to help plan for and optimize the additional load from electrification technologies on the electricity grid. RD&D could investigate the best ways to meet the capacity needs of industrial zones or clusters where high-voltage electricity transmission infrastructure can deliver electricity for steel production. Investing in the electricity grid and increasing the share of clean energy in the power sector energy mix will help accelerate the use and benefits of steel electrification technologies.

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

- More detail is needed to map timelines for switching to lower-carbon footprint fuel. Costs and availability for fuel switching need to be mapped out at a granular level to inform facility-level decision-making.
- Potential benefits of biomass need to be better characterized to ensure biomass use does not actually increase overall emissions. Biomass may only be feasible for certain facilities in specific locations, and more research is needed on local biomass resources availability and life cycle impacts.
- The most important obstacle faced by hydrogen (H_2)-DRI production is the production of low-carbon hydrogen at large quantities at an economical price. H_2-DRI method face challenges related to the steady supply of H_2, reliance on clean electricity, and potential uncertainties in operating costs, especially high electricity costs. A H_2-DRI steel facility would require access to cheap, emissions-free electricity, high-quality iron ore, skilled manpower, and a stable market. In addition, improving electrolyzer performance is a key measure to reduce energy consumption and emissions associated with H_2-DRI-EAF steel production.
- There is a need for increased effort in designing solutions for low-cost clean hydrogen as well as safe hydrogen transport and storage. Most current hydrogen production is fossil-fuel reliant. While the use of clean hydrogen decreases CO_2 emissions, electricity

demand increases. In addition to investment in clean power generation and distribution, substantial capital investment is needed to significantly increase U.S. clean hydrogen production capacity.[95]

Major Carbon Capture, Utilization, and Storage (CCUS) Barriers and Challenges

- CCUS adoption in the U.S. steel industry faces technical, financial, and logistical challenges. CCUS technologies require operational efficiency and cost-effectiveness enhancements. Specific challenges include the diverse emission sources in steel facilities, potential leakages during capture, and the increased energy required to operate CO_2 capture systems. The latter can be both a technical challenge, as integration of the CCS system might be complex, and a financial one, given the cost implications of sourcing or producing clean energy. Moreover, processes that convert CO_2 emissions into valuable products often require clean hydrogen, which might be challenging to secure for some steel facilities.
- Financial barriers to CCUS projects are high, making them less attractive to steel companies without clear mitigation incentives. Also steel facilities in certain regions could face extended CO_2 transport needs to access suitable geological storage sites.
- Substantial investment and policy support for CCUS in the steel industry are needed ranging from promoting innovation and testing to validation, piloting, and scale-up. Clear market incentives and innovative business models are crucial to mitigate associated CCUS projects costs and risks. Moreover, site selection for CO_2 storage should be stringent to minimize environmental risks such as potential leakages. RD&D could focus on design innovations to increase the purity and concentration of the CO_2 stream, making capture more efficient and cost-effective. There are also RD&D opportunities for to explore low-cost CCUS technologies like calcium-looping lime production.
- While promising, carbon utilization technologies have not been demonstrated at scale. RD&D could help overcome technical barriers such as the need for technologies that operate at lower temperatures, thereby reducing costs. More work is needed to understand the potential use of CO_2 for chemical production.

Major Material Efficiency Barriers and Challenges

- Recycling steel and byproducts from iron and steel production requires close attention to the quality of recycled products, an ongoing focus of recycling technology development.
- Economically, scrap availability over time is a key issue for EAF producers using scrap as a feedstock mainly due to scrap contamination (especially copper). Prime scrap EAF production is the current lowest emissions production route for U.S. steel producers,

[95] See Hydrogen Shot | Department of Energy

but there will be prime scrap supply constraints over time, meaning that the industry will need to supplement scrap with alternative iron units, which will need to come from low-carbon sources. Copper contamination is widespread in steel scrap with no economic removal method yet available.

- There are a number of potential barriers to scaling up material efficiency in the steel industry. There may be tradeoffs between individual material efficiency strategies and energy efficiency in specific end-use sectors. For example, measures to improve building operational energy efficiency or decarbonize building energy use, such as additional insulation and heat exchange ventilation systems, would likely increase the material consumption of buildings. Using wood materials also requires consideration of the sustainability and availability of the materials, which may limit the applications of using mass timber as a steel substitute in the U.S. Thus, it is important that tradeoffs from material efficiency strategies are comprehensively analyzed.
- In addition, current recycling processes may not be optimized to handle the complexities of different steel alloys or the removal of all contaminants efficiently. Efficient collection, sorting, and processing of scrap steel are essential for material efficiency. However, gaps in the supply chain can hamper these efforts. Initial investments in new technologies or processes centered around material efficiency can be substantial, potentially discouraging smaller steel producers. Finally, inconsistent regulations across states and regions, such as regions from which the U.S. imports scrap, can impede the adoption of new recycling and material efficiency methods.
- However, there are a number of inherent incentives to material efficiency. Improved recycling and recovery of waste products can lead to cost savings and environmental benefits. Realizing the full potential of a circular economy demands a multi-faceted approach, including benchmarking, data collection, and the promotion of circular strategies. Additionally, understanding the intricate supply chain dynamics and the embodied carbon in products necessitates comprehensive research. To truly harness material efficiency as a decarbonization pillar, robust RD&D is imperative to delineate the supply chain contributions and pinpoint GHG reduction opportunities across the steel supply chain.

2.4.3 Net-Zero Emissions Pathways and Technologies

A net-zero emissions iron and steel subsector will require comprehensive adoption of decarbonization technologies across all pillars. An example output for a modeled net-zero decarbonization pathway by 2050 is shown in Figure 17. This scenario assumes U.S. steel production would increases by 15% between 2018 and 2050 to meet the needs of a growing population and expanding economy.

Electrification is anticipated to make the largest contribution to CO_2e emissions reduction, followed the energy efficiency and LCFFES pillars. All four decarbonization pillars (energy efficiency, electrification, LCFFES, and CCUS) will help reduce emissions to near-zero, but alternate approaches other than those included in the pillars (e.g., negative emissions technologies), powered by clean energy sources, will need to be adopted to reach net-zero. The electrification pillar includes reductions in electric grid CO_2 emissions and the adoption of green H_2-DRI[96] and blue H_2-DRI[97] is captured under LCFFES pillar. Because these processes are electricity-intensive, the U.S. electric grid CO_2 emissions factor significantly influences the electrification pillar emissions reductions.

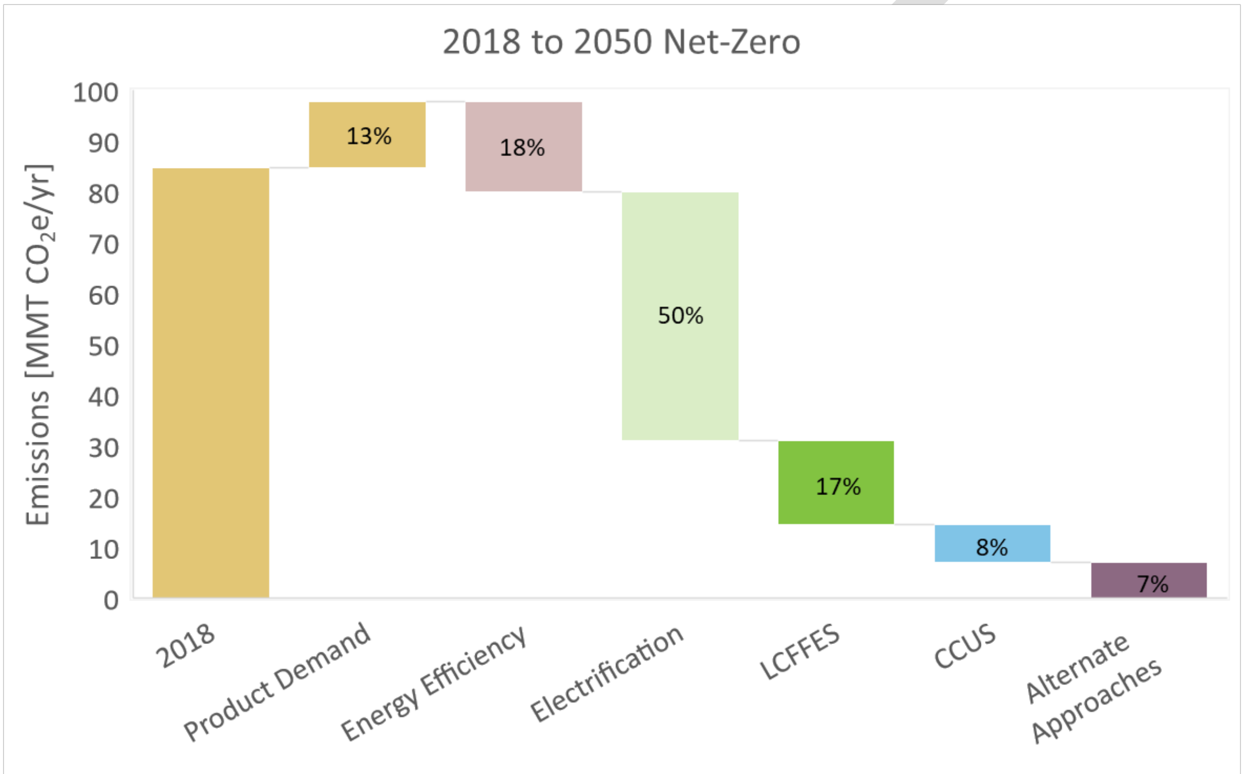

Figure 17. Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions (million metric tons (MMT)/year) for U.S. iron and steel manufacturing, 2018–2050

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.

The electrification and energy efficiency pillars make the largest cumulative contribution to the CO_2 emissions reduction in the industry up to 2050. The main four decarbonization pillars will help reduce emissions to near zero, but alternate approaches other than those modeled in this work (e.g., negative emissions technologies), powered by clean energy sources, would be needed to reach net-zero.

[96] Green H_2-DRI is defined as steel from direct reduced iron that has been produced using H_2 via electrolysis powered by clean electricity such as wind and solar.
[97] Blue H_2-DRI is defined as steel from direct reduced iron that has been produced using H_2 via steam methane reforming (SMR) with the addition of carbon capture and storage (CCS).

The impact of electrification in Figure 17 includes the reduction in electric grid CO_2 emissions and the adoption of green H_2-DRI.[98] DOE assumed the BF-BOF process would be substantially phased out by 2050 under the net-zero scenario; by this time, most steel will be produced by scrap-based EAF and a small portion with clean hydrogen-based DRI-EAF processes and iron ore electrolysis. While the impact of green H_2-DRI is captured under the electrification pillar, blue H_2-DRI[99] is captured under LCFFES pillar. Because all these processes are electricity-intensive, the U.S. electric grid CO_2 emissions factor and its projection to 2050 significantly influence the CO_2 emissions projection results under the electrification pillar. A small amount of hydrogen would be consumed as a fuel for the BF-BOF process also under the LCFFES pillar. By 2050, it is assumed that 80% of remaining emissions would be captured via amine absorption under the CCUS pillar.

Figure 18 shows a more granular representation of a possible net-zero pathway for the iron and steel industry. Note, this figure is only representative output from preliminary modeling runs, it is not based on actual data. The figure shows the BF-BOF process would be substantially phased out by 2050 under a net-zero scenario; by this time, most steel would be produced by scrap-based EAF (with and without electric rolling and finishing) and a small portion with clean hydrogen-based DRI-EAF processes and iron ore electrolysis. The increase in scrap-based EAF could be limited by the availability of higher-quality scrap. Manufacturers face scrap challenges mainly due to contamination (especially from copper) and there is not yet an economic contaminant removal process. Green H_2-DRI-EAF and blue H_2-DRI-EAF account for 9% and 5% of total production in 2050, respectively.

[98] Green H_2-DRI is defined as steel from direct reduced iron that has been produced using H_2 via electrolysis powered by clean electricity such as wind and solar.
[99] Blue H_2-DRI is defined as steel from direct reduced iron that has been produced using H_2 via steam methane reforming (SMR) with the addition of carbon capture and storage (CCS).

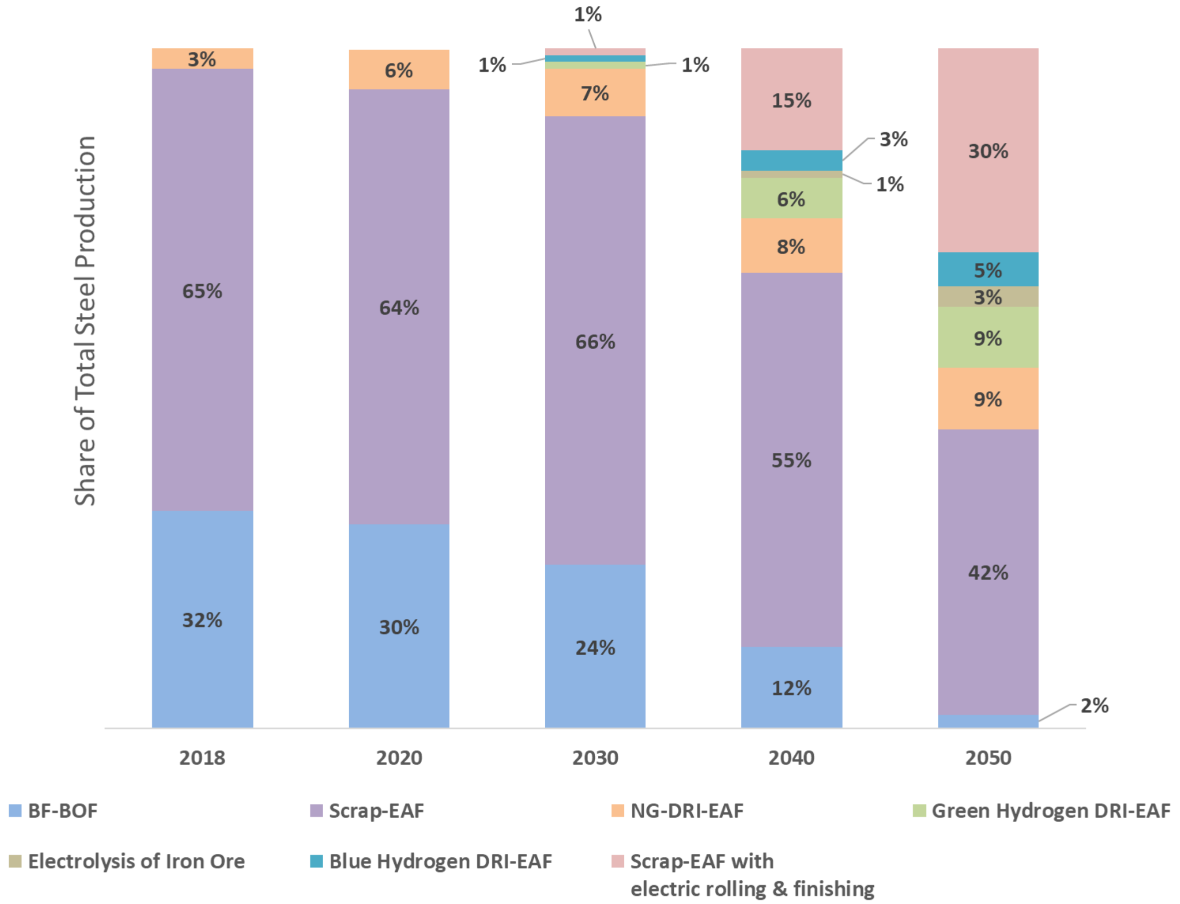

Figure 18. Example U.S. iron and steel manufacturing production route share by decade under a net-zero emissions scenario, 2018–2050

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). Source: This work.

Energy Efficiency Impact

Companies will have to carefully consideration technology choices phasing, for energy efficiency and the other pillars, and at a facility-level or an industry-wide scale, to avoid emission "lock-ins" or creating potential stranded assets or "dead-ends" in the future. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

Energy efficiency improvements can be a first step towards decarbonization of the steel industry, with specific applications in coke-making, BF ironmaking, BOF and EAF improvements, and more efficient casting and rolling processes. A prior guidebook of energy efficiency measures for the U.S. iron and steel industry divides energy efficiency technologies into cross-cutting measures and process-specific measures.[100] A variety of

[100] Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry | ENERGY STAR

energy efficiency technologies (e.g., coke dry quenching (CDQ), top-pressure recovery turbine plants (TRT)) are already available to be deployed on a commercial scale in the steel industry.[101] Emerging technologies associated with smart manufacturing or the Internet of Things like predictive maintenance and machine learning or digital twins to improve process control can assist with energy management systems.

Cross-cutting measures include technologies that can improve efficiency across energy management programs and systems, energy and process control systems, steam systems (boilers, combined heat and power, and steam distribution), motor systems, pump systems, fan systems, and compressed air systems. These are general improvements that can be made with commercialized technologies that are applicable to most industrial facilities.

Process-specific measures include specific improvement technologies for iron ore sintering, coke making, ironmaking in a blast furnace, BOF and EAF steelmaking, casting and refining, and shaping (hot rolling and cold rolling). In EAF operations, which primarily use recycled steel and electricity, energy efficiency measures (such as advanced furnace technologies, improved scrap preheating processes, and optimized operational practices) can significantly reduce electricity consumption, thereby directly impacting Scope 2 emissions. For the BF-BOF route, which relies heavily on coal and coke, energy efficiency measures like waste heat recovery, improved insulation, and process optimization can reduce the need for fossil fuels, thus cutting direct emissions from the steelmaking process.

Industrial Electrification Impact

Use of EAF steel production over other routes is a form of electrification, and the United States already produces the majority of its steel via the EAF route. In the United States, use of scrap-based EAF steel production to meet any new scale-up in domestic production is likely to be more economical and environmentally beneficial than adopting other steelmaking technologies, at least in the near- to medium-term but could be limited by scrap availability and quality requirements. The transition to electric-based heating and processing in the steel industry is poised to significantly lower overall CO_2 emissions, particularly as the U.S. electricity grid continues its rapid shift towards decarbonization.

In terms of emerging technologies, there are two primary direct electrification processes for steel production, electrolysis and electrowinning. They offer distinct approaches to transforming iron ore into liquid steel. Green H_2-DRI which produces iron using green H_2 produced from electrolysis process that uses clean electricity is an indirect electrification process for the steel industry (see “Impact of LCFFES” below for more details on H_2-DRI). Other electrification technologies for the steel industry include electrifying reheating furnaces and scaling up electric induction furnaces. Ladle and tundish heating can be switched to resistance, infrared, or plasma heating. Also, other emerging technologies could

[101] Net-Zero Roadmap for China’s Steel Industry - LBNL and Global Efficiency Intelligence

save energy and materials for steel galvanizing and heat treatment, such as the Flash Bainite heat treatment process to replace the annealing of steel.

Electrolysis of iron ore (e.g., the molten oxide electrolysis process) involves subjecting iron ore to high temperatures (approximately 1550°C) and utilizing electricity as a reductant. The technical viability of iron electrolysis has been demonstrated in laboratory and small pilot settings and could be a transformative technology in the long term. Electrowinning (e.g., SIDERWIN[102]) grinds iron ore into an ultrafine concentrate, leaches it, and then reduces it in an electrolyzer at around 110°C. The resulting iron plates are processed in an EAF to yield steel. These electrolytic processes boast potential energy efficiency and reduced capital expenditure (CAPEX) by bypassing upstream stages required in traditional steel production routes. As shown previously in Figure 18, this modeling for this example net-zero pathway assumed that by 2050, scrap-based EAF would remain the predominant steel production pathway (72%), followed by 9% each of DRI-EAF and green H_2-DRI-EAF, 5% blue H_2-DRI-EAF, 3% iron ore electrolysis, and the remaining 2% by BF-BOF.

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

In terms of fuel switching, several alternative fuels (e.g., natural gas, sustainable biomass, biogas, and clean hydrogen), can replace coal or coke as a fuel or reducing agent in the iron and steelmaking processes and significantly reduce CO_2 emissions. For this work, the energy mix for steel production was estimated through 2050. Over time, coal, coke, and breeze are eliminated from the energy mix under the net-zero GHG scenario, while the share of electricity increases from 22% in 2018 to 45% in 2050.[103] Natural gas increases slightly, from 46% in 2018 to 52% in 2050.

A key technology in the LCFFES pillar is the use of H_2-DRI-EAF to decarbonize steel production. Hydrogen-based DRI-EAF steelmaking refers to using hydrogen as an alternative reductant to produce iron that is then often processed into steel in an EAF. There are two DRI production methods: 1) The shaft furnace method using H_2 to reduce iron ore pellets in a furnace and 2) the fluidized bed method operating in a reactor chamber with finely processed iron ore powders. The shaft furnace method allows for easier integration with existing steel facilities, while the fluidized bed method avoids the need for pelletization. Additionally, H_2-DRI possesses one of the highest technology readiness levels and lowest development costs when compared with other emerging decarbonization technologies for the steel industry. Thus, its commercial implementation could take place within a relatively short period of time.

DRI-EAF results in lower CO_2 emissions compared to the BF-BOF steel production route, and further reduction of CO_2 emissions can be achieved by utilization of clean hydrogen produced from clean energy (clean hydrogen) as the energy source and reducing agent for

[102] SIDERWIN is the abbreviation for "development of new methodologieS for InDustrial CO_2-freE steel pRoduction by electroWINning". See https://www.siderwin-spire.eu/

[103] Including the electricity demand to produce hydrogen that is used as a reducing agent in H_2-DRI.

the production of DRI, thus releasing water instead of CO_2. In the modeled results for the iron and steel sector, a majority of the total H_2 (over 90% for the Net-Zero Scenario) is assumed to be used as a reductant in the H_2-DRI process and small share of H_2 is consumed as a fuel. Both green H_2-DRI (using hydrogen produced via electrolysis powered by clean electricity) and blue H_2-DRI (using hydrogen produced via steam methane reforming with CCS) are assumed as applicable in the modeled results (see Figure 18).

Carbon Capture, Utilization, and Storage (CCUS) Impact

Carbon capture, utilization, and storage (CCUS) can be used to decarbonize BF-BOF steel facilities in the U.S. Various processes located throughout the facility account for a large amount of CO_2 emissions (power plant stack, coke oven gas (COG), blast furnace stack, sinter stack, BOF stack, hot strip mill stack, plate mill stack, and lime kiln); however, carbon capture from these is difficult without a common flue stack.[104] Natural gas-based DRI production can also be retrofitted with post-combustion carbon capture.[105] There are CCUS applications for smelting reduction as well as reheating.

Post-combustion capture is one of the most relevant CCUS technologies for iron and steel manufacturing, where CO_2 is captured from flue gases after combustion of fossil fuels. This technology is particularly suitable for integration into existing steel facilities, allowing for retrofitting with minimal disruption to ongoing operations. Another promising approach is pre-combustion capture, where fuels are converted into a synthesis gas (syngas), and CO_2 is captured before combustion. This method is more efficient but requires more significant modifications to existing infrastructure. Additionally, oxy-fuel combustion, which involves burning fossil fuels in pure oxygen instead of air, resulting in a flue gas that is primarily water vapor and CO_2, is also gaining traction. This method simplifies CO_2 capture but requires substantial changes to the combustion process.[106,107]

Material Efficiency Impact

Although not modeled as part of this effort due to lack of data and overall complexity, material efficiency and demand management can be a significant decarbonization lever to reach a net-zero economy. Multiple strategies exist in each of the product life-cycle stages, ranging from steel product design (e.g., improving design to have lighter products, optimizing to minimize material use, design for longer life, reusability and ease of high-quality recycling), steel product manufacturing (e.g., improving material efficiency in the production and fabrication processes, increasing material waste recycling), steel product use (e.g., extending the building and product lifetime, intensifying product use, and switching to other low-carbon alternative materials, such as mass timber for certain kinds of buildings), and steel product end-of-life (e.g., increasing building component direct reuse, increasing the

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104 Cost of Capturing CO_2 from Industrial Sources - NETL
105 Toward green steel: Modeling and environmental economic analysis of iron direct reduction with different reducing gases - ScienceDirect
106 Carbon Dioxide Capture Approaches | NETL
107 CO_2 capture in integrated steelworks by commercial-ready technologies and SEWGS process - ScienceDirect

recycling rate of steel products, and remanufacturing of steel products). The current practice of using recycled scrap to make steel via EAFs saves virgin raw materials as well as the energy required for converting them and reduces the CO_2 intensity of steel production and could possibly increase in the future, based on the end result steel product.

2.4.4 Key Decarbonization Decisions

A transformation of the iron and steel subsector will require a holistic view of the anticipated decarbonization pillars and technologies that will become (or may become, depending on technoeconomic factors) viable and available over varying timeframes out to mid-century and beyond. One way to assess these pathways is by starting with a decision-tree framework, as depicted in Figure 19 below.

The decision tree is depicted as a circular process until net-zero emissions is achieved to account for solutions that may not yet be commercially available. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission “lock-ins” and potential stranded assets in the future.

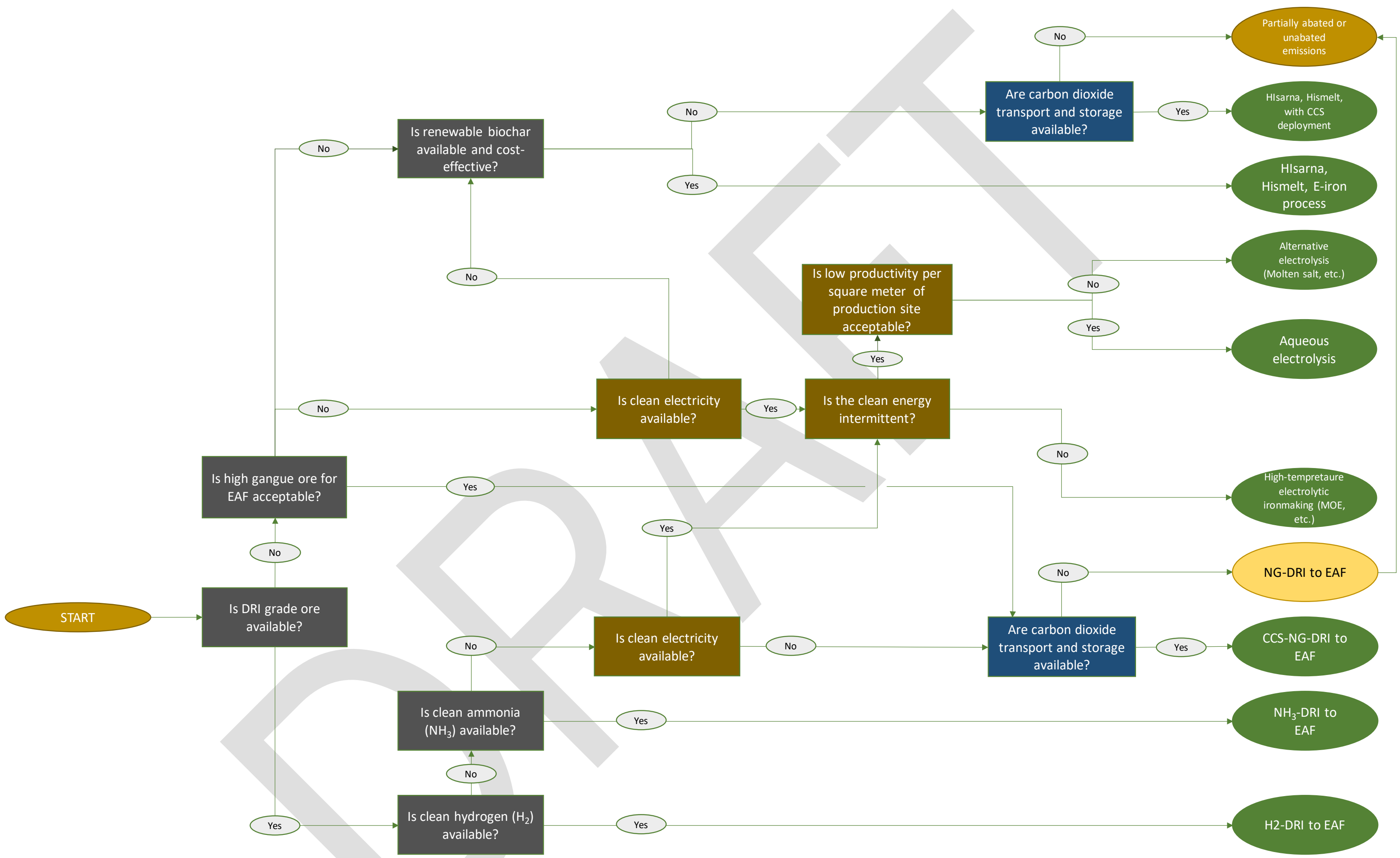

Figure 19. Iron and steel manufacturing decarbonization decision tree

2.4.5 Modeling Assumptions

In the net-zero scenario, the most ambitious assumptions were made across all the decarbonization pillars to reach a net-zero iron and steel subsector. In this scenario, emissions decrease by 83% between 2018 and 2050 through application of technologies across the four pillars. This decrease occurs while U.S. steel production increases by 15% during the same period to meet the needs of a growing population and expanding economy. The overall fuel energy intensity of the subsector decreases by 58% between 2018 and 2050. Under this example scenario, hydrogen demand for the subsector is projected to be 0.89 MMT per year by 2050, with over 91% being used as a non-fuel feedstock and 9% as a fuel.

Electrification and energy efficiency pillar measures make the largest cumulative contribution to the emissions reductions in the net-zero scenario. As shown in Figure 18, the production route share of BF-BOF from total domestic steel production would drop from 32% in 2018 to 2% in 2050 while the share of scrap-based EAF increases from 65% to 72% (total for scrap EAF with and without electric rolling and finishing) in the same period. As noted previously, increases in scrap-based EAF could be limited by the availability of prime scrap, while copper contamination remains a significant concern today. Green H_2-DRI-EAF and blue H_2-DRI-EAF account for 9% and 5% of total production in 2050, respectively. The assumed fuel, electric, and total baseline energy intensities for each production route are provided in Table 9.

Table 9. Iron and Steel Model Baseline Energy Intensities by Production Route

Production Route	Fuel Intensity (GJ/MT)	Electric Intensity (GJ/MT)	Total Energy Intensity (GJ/MT)
BF-BOF	20.6	2.4	23
Scrap-based EAF	3.2	2.6	5.8
Scrap-based EAF with electric rolling and finishing	0.8	5.0	5.8
Natural gas-based DRI-EAF	15	2.7	17.7
Green hydrogen-based DRI-EAF	2.4	14.7	17.1
Blue hydrogen-based DRI-EAF	15	2.7	17.7
Iron ore electrolysis	2.4	17	19.4

Figure 20 shows the assumed energy mix in the U.S. iron and steel subsector up to 2050 under the example net-zero scenario. Over time, coal, coke, and breeze are nearly eliminated from the subsector's energy mix, while the share of electricity increases to more than half due to the increase in electrified production pathways.

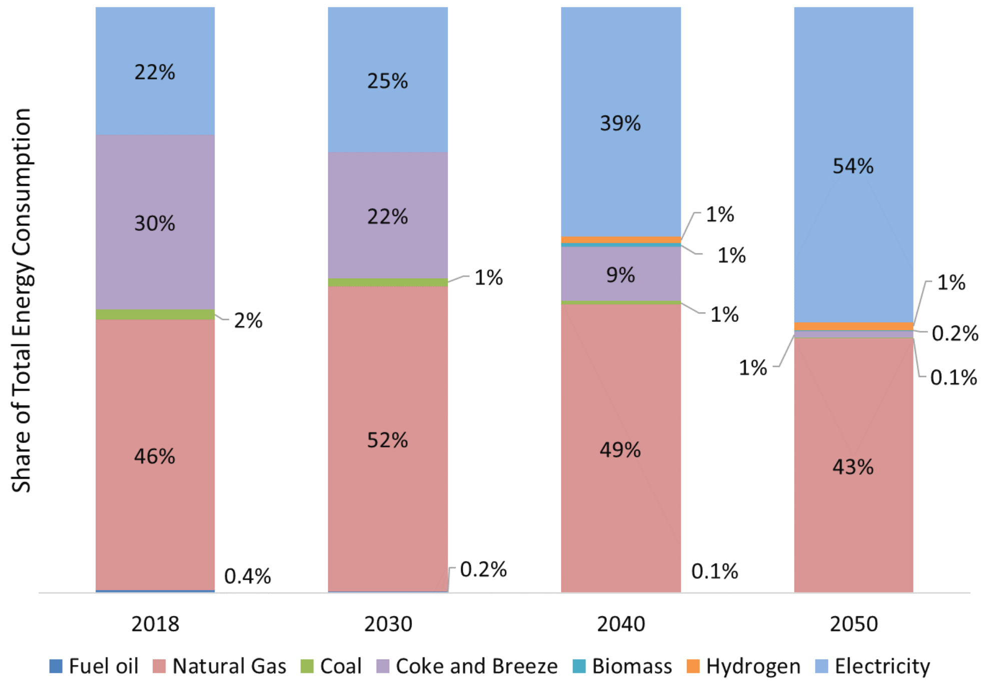

Figure 20. U.S iron and steel subsector energy mix by decade under the example net-zero scenario

The net-zero scenario additionally assumes and annual 1.2% reduction in fuel intensity and a 1% reduction in electricity intensity to account for BAU improvements. For CCUS, it is assumed that by 2050, 80% of remaining emissions from the BF-BOF, natural gas-based DRI-EAF, and blue hydrogen DRI-EAF production routes are captured and sequestered using amine absorption.

2.5 Petroleum Refining

2.5.1 Subsector Snapshot

Petroleum refining plays a key role in the energy supply chain by delivering fuels for transportation and industrial applications, feedstocks to the petrochemical industry, and other value-added products. As of 2022, there were approximately 125 petroleum refineries in the U.S. with a total operating capacity of nearly 18 million barrels (bbl) of crude oil per day.[108] Overall, including blending fractions, the U.S. produces about 298 billion gallons of refined petroleum products, more than four-fifths is used for transportation fuels including 147 billion gallons of motor gasoline, 77 billion gallons of distillate fuel oil (diesel, renewable diesel, biodiesel, and renewable heating oil), and 25 billion gallons of jet fuel.[109] Most of the 36 billion gallon remainder is used for other products, including asphalt and road oil, lubricants, waxes, petrochemical feedstocks, and other miscellaneous products. The American Petroleum Institute (2023) estimates that the oil and gas industry supported 10.8 million direct and indirect jobs and contributed nearly $1.8 trillion to the economy in 2021

[108] Refinery Capacity Report - U.S. Energy Information Administration
[109] U.S. Refinery Net Production - U.S. Energy Information Administration

with 105,000 jobs and $350 billion attributed to petroleum refining and products specifically (NAICS 324).[110]

The U.S. petroleum refining industry is one of the highest GHG-emitting manufacturing subsectors, with Scope 1 and 2 emissions accounting for an estimated 244 MMT CO_2 in 2018.[111] Note that, this estimate only includes the direct and indirect emissions associated with the conversion of crude oil to refined products and not the extraction of crude oil nor the eventual combustion of refinery products.

2.5.2 Net-Zero Emissions Barriers and Challenges

Numerous barriers must be overcome to achieve deep decarbonization of the refinery subsector and the use of refined products. Below barriers are categorized by decarbonization pillar as one of three types, financial, technical, and infrastructure. Financial barriers are related to fundamental economics, investment factors, and internal competition for capital that impede the implementation of decarbonization measures. Technical barriers relate to physical and chemical processes that require technological solutions. Infrastructure barriers relate to limitations imposed by insufficient transportation networks, underdeveloped supply chains, lack of suppliers or service providers, and limited internal resources, such as staffing. This section provides an overview of the major barriers faced by the subsector and is not meant to be comprehensive.

Major Energy Efficiency Barriers and Challenges

- **Financial:** Making significant improvements in energy efficiency will require many small projects with relatively low returns that will compete for internal capital. Achieving deeper levels of efficiency will require revamps and shutdowns of equipment with financial penalties and may have significant potential impact on overall reliability as new technologies are implemented. Self-generated fuels in the refining industry will need to be addressed as fuel demand decreases due to higher efficiency processes. Also, with the projected cost of natural gas remaining low and lack of industry-specific energy efficiency incentives, the economics of these projects will be challenging.
- **Technical:** There is a strong need for low-cost waste heat recovery technologies. Refiners produce large amounts of heat below 350°F that is released to the environment. Current technologies incorporating organic Rankine cycle (ORC) principles have high costs and relatively low thermodynamic efficiencies. Advancing technologies that convert low-grade heat to power or high-grade heat will accelerate adoption rates for these technologies. New heat pump technologies will likely play a significant role as well.

[110] Impacts of the Oil and Natural Gas Industry on the US Economy in 2021 - American Petroleum Institute and PwC

[111] Manufacturing Energy and Carbon Footprint: Petroleum Refining (NAICS 324110)

- **Infrastructure:** Limited staffing to undertake the multiple small projects across multiple process units typical of energy efficiency activities will be a barrier to their implementation.

Major Industrial Electrification Barriers and Challenges

- **Financial**: The low cost of natural gas projected into the future relative to the delivered cost of electricity reduces economic incentives for electrifications projects. Electrification projects will need to include significant thermodynamic efficiency or productivity improvements to see significant movement towards electrification of the industry.
- **Technical**: Refining requires large continuous and high temperature heating demands for its processing requirements. There is limited commercial availability of electrically driven process heaters capable of achieving the scales necessary in refineries. Technologies that generate H_2 from electrolysis or methane pyrolysis are options; however, use of H_2 as a fuel is challenged on overall efficiency and cost relative to using natural gas or self-generated fuels.
- **Infrastructure**: Increased electrification would require significant electrical service upgrades across facility infrastructure for importing additional electricity. Additionally, there is limited availability of clean electricity, without which electrification may not have net CO_2 savings.

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

- **Financial:** For low carbon feedstocks, the California Low Carbon Fuel Standard market, Federal Renewable Fuel Standard, Biodiesel Production and Blending Tax Credit, and the Sustainable Aviation Fuel (SAF) Credit in the Inflation Reduction Act have incentivized first generation renewable fuels from fats, oils, and greases (FOG) but may not be sufficient for next generation renewable fuels. For low carbon fuels and electricity, there currently are no incentives for consuming them (i.e., 45V credit is for producers not consumers of H_2 and similarly the Product Tax Credit (PTC) and Investment Tax Credit (ITC) for clean generation), and these fuels will compete with grey fuels at parity. For low carbon fuels, using clean hydrogen has significant potential to replace both grey hydrogen and fuel gas used in a refinery, however technologies that can generate this hydrogen at lower costs and with less capital are needed.
- **Technical:** Refineries are specifically designed to process petroleum crude and intermediates. Currently limited alternative non-fossil based intermediate feedstocks are being processed, but these pose risks to equipment, piping, and catalysts. Pre-treatment and processing technologies that allow a larger slate of feedstocks to be refined in existing facilities are needed. Longer term, alternative energy source technologies, such as nuclear and renewable natural gas, are needed to replace fossil-based fuel technologies that rely on clean energy or carbon capture.

- **Infrastructure:** There is currently limited availability of alternative feedstocks for refining as well as a lack of developed supply chains for processing advanced bio-oils and biogas in a refinery. Additionally, hydrogen transportation by pipeline requires significant investment and is limited to shorter distances.

Major Carbon Capture, Utilization, and Storage (CCUS) Barriers and Challenges

- **Financial:** Magnitude of upfront capital investments necessary to achieve significant step changes in emissions could far exceed historical capital expenditures of many refineries. This will specifically be a challenge for smaller facilities. Additionally, energy requirements for current carbon capture technology are high and will increase cost and likely require additional infrastructure.
- **Technical:** There is a need for lower cost technologies that can efficiently capture lower purity CO_2 streams and those with contaminants (e.g., fines in fluid catalytic cracking (FCC) units).
- **Infrastructure:** The is very limited CO_2 pipeline infrastructure in the U.S., as well as the uncertainty in availability of long-term sequestration sites. For the high levels of carbon capture needed in the near net-zero cases, there will be challenges on the capacities of engineering, procurement, and construction (EPC) firms to build both the facilities and pipelines. Space constraints for large CO_2 absorber technology within existing facilities make significant CO_2 capture difficult. Additionally, permitting of CO_2 pipelines and associated regulatory requirements will be challenging and could delay implementations.

2.5.3 Net-Zero Emissions Pathways and Technologies

A near net-zero emissions refining subsector will require comprehensive decarbonization technology adoption across all pillars. An example output for a modeled near net-zero decarbonization pathway by 2050 is shown in Using process-level foundational data including process level throughput, average fuel and electricity consumption, and utility carbon indices, a CO_2 emissions baseline for the entire industry was developed. Projections of the GHG reduction potential were generated by applying various decarbonization technologies across the four pillars at the individual process unit level. The resulting projections were created based on historical performance trends and a comprehensive literature review of current decarbonization technologies, barriers to adoption, and current financial incentives. As shown in Figure 21. This scenario projects emissions reductions of about 61% for the U.S. petroleum refining subsector when the four pillars are applied. Alternate approaches (powered by clean energy sources) would be needed to reach net-zero. By 2050, subsector production is projected to decrease by 13% compared to 2018. Energy efficiency is anticipated to make the largest contribution to CO_2e emissions reduction, followed by CCUS. Electrification (including electric grid emission reductions) and LCFFES are projected to have a lower contribution to the total emissions reductions.

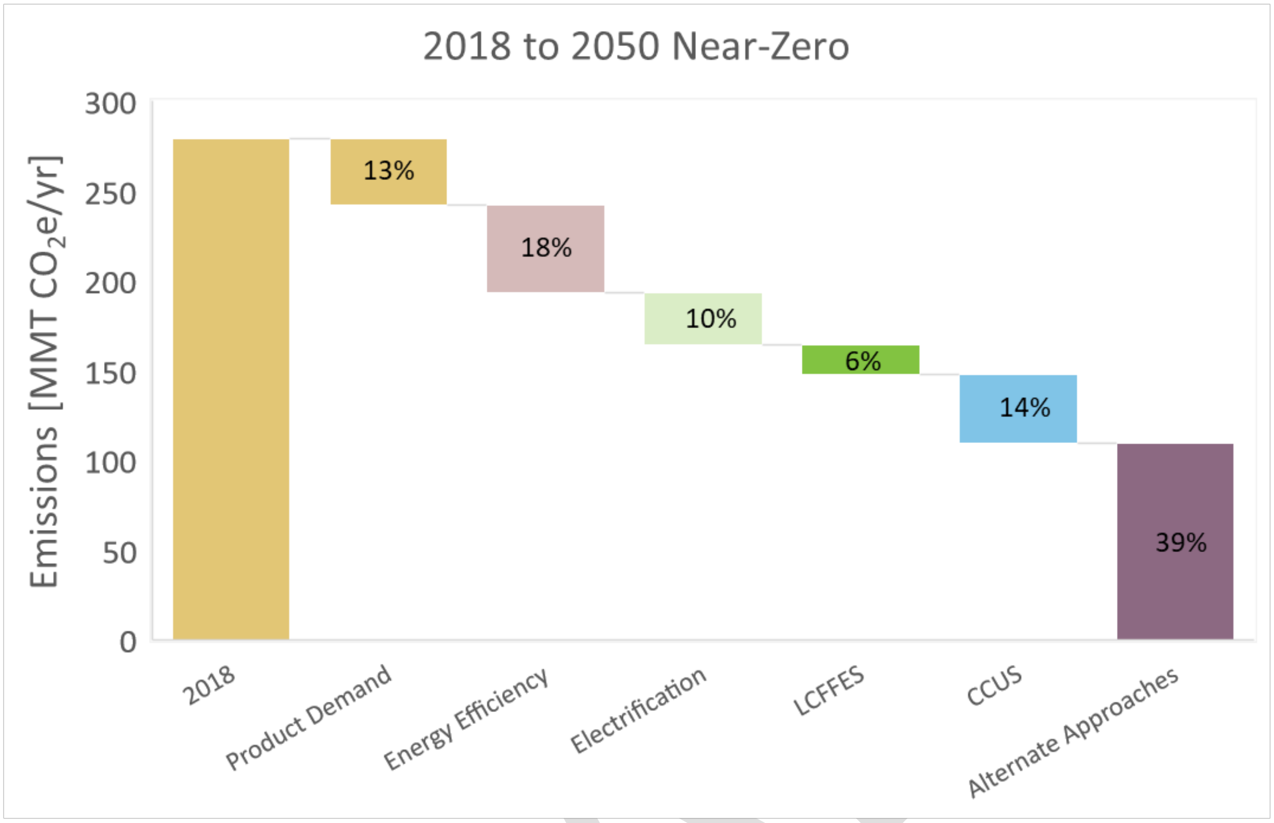

Figure 21. Example near net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions (million metric tons (MMT)/year) for U.S. petroleum refining, 2018–2050

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.

This section describes some of the technical short-, mid-, and long-term strategic pathways the offer high potential for decarbonizing the refining subsector. Short-, mid-, and long-term are defined as 0–5 years, 5–15 years, and 15–30 years, respectively.

Energy Efficiency Impact

Companies will have to carefully consideration technology choices phasing, for energy efficiency and the other pillars, and at a facility-level or an industry-wide scale, to avoid emission "lock-ins" or creating potential stranded assets or "dead-ends" in the future. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

- **Short-term:** Technologies and pathways include cogeneration, integrated combined heat and power; high efficiency variable speed drives and motors; and advanced controls.
- **Mid-term:** Technologies and pathways include next-generation waste heat recovery technologies to convert waste heat into usable power or heat energy, (e.g., heat pumps

and organic Rankine cycle); advanced furnace designs; advanced heat exchanger designs.

- **Long-term:** Technology replacement, such as divided wall, membranes, and low-pressure and temperature catalytic systems. Digital refining and artificial intelligence.

Industrial Electrification Impact

- **Short-term:** Electrification of rotating equipment, such as condensing turbines and other low efficiency steam driven rotating equipment. Technologies include heat pumps and mechanical vapor compression.
- **Mid-term:** Electrification of heat, such as steam boilers and low-thermal demand fired process heaters.
- **Long-term:** Process technology replacement, such as conversion of conventional thermal-catalytic process technologies with electrochemical-based conversion technology.

Low Carbon Fuels, Feedstocks, and Energy Sources Impact

- **Short-term:** Optimization of crude feedstock selection, prioritizing feedstocks with lower hydrogen demand and embodied carbon from extraction; purchase of low carbon fuels (H_2 and RNG), further development of current alternative feedstocks (e.g., fats, oils, and greases).
- **Mid-term:** Lower cost technologies for production of low-carbon clean hydrogen, promote refinery integration with low carbon energy sources (e.g., onsite thermal energy storge and integrated cogeneration with low carbon hydrogen); conversion and co-processing of next-generation alternative feedstocks as bio-oils (e.g., woody biomass, agricultural residues, and municipal solid waste).
- **Long-term:** Integration of onsite small modular nuclear energy for heat and power; promote development of nascent alternative feedstocks (algae and CO_2).

Carbon Capture, Utilization, and Storage Impact

- **Short-term:** Carbon capture of hydrogen plants (steam methane reforming units).
- **Mid-term:** Carbon capture of onsite cogeneration plants.
- **Long-term:** Carbon capture of fluid catalytic cracking and general combustion units, such as fired heaters and boilers; utilization of CO_2 as refinery feedstock.

Remaining Emissions Gap

The remaining gap between *near* net-zero and net-zero will require alternative approaches that exceed what is likely possible with high-TRL technologies and existing incentive mechanisms. However, when considering longer time scales, consideration will also need to include external factors, such as a change in the global economic environment that could impact U.S. refining capacities, as well as, shifting commodity markets that significantly change fuels costs. For example, an increase in natural gas cost relative to electricity, could result in an aggressive adoption of electrified heating, or the development of new and abundant non-fossil feedstocks could significantly shift basic refining technologies.

For the direct and indirect emissions from the refining subsector specifically, closing the gap between *near* net-zero and net-zero remains a significant challenge. Market factors, economic incentives, and even world events could significantly influence both the direction and rate of subsector decarbonization by shifting overall refining product demands or yield profiles.

2.5.4 Key Decarbonization Decisions

A transformation of the petroleum refining subsector will require a holistic view of the anticipated decarbonization pillars and technologies that will become (or may become, depending on technoeconomic factors) viable and available over varying timeframes out to mid-century and beyond. One way to assess these pathways is by starting with a decision-tree framework, as depicted in Figure 22. This figure represents the barriers and near-, medium-, and long-term opportunities for refinery decarbonization that may be applicable to a specific refinery. These types of decision trees can be used to develop a broad strategy for specific facilities.

Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission “lock-ins” and potential stranded assets in the future.

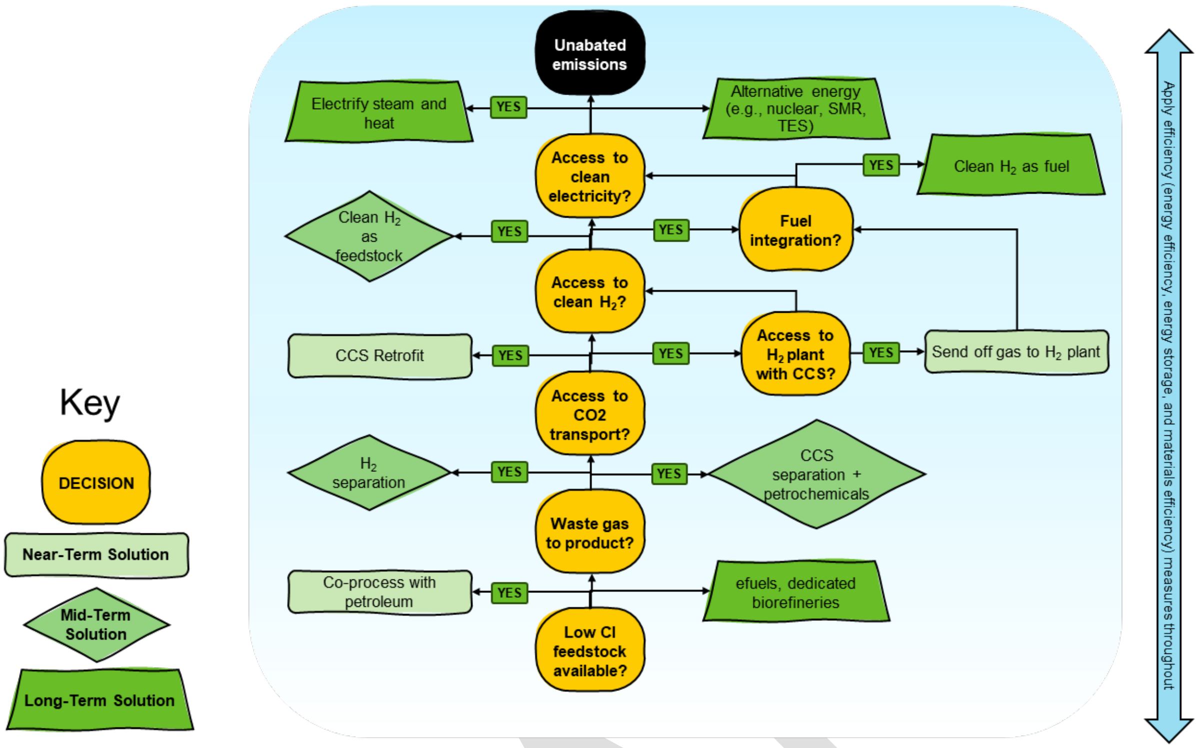

Figure 22. Petroleum refining decision trees: barriers and short-, mid-, and long-term solutions

An example of a petroleum refining decarbonization decision tree. Efficiency measures should be applied through all steps as indicated by the blue arrow (including energy and materials efficiency, energy storage, etc.). Note, sequencing and specific decarbonization strategies may vary. This figure is provided for discussion purposes and as a way to identify the barriers and opportunities in pathways to decarbonization and better understand decision making.

2.5.5 Modeling Assumptions

This section provides information on the assumptions used in the refining model. More detail can be found in Table 21 in Appendix B.

General Assumptions

- Emissions reductions shown on the abatement curve include only direct emissions and indirect emissions associated with imported power.
- Emissions associated with hydrogen production were included for all hydrogen consumed or burned within the refinery.
- Emissions associated with processing of non-fossil-based feedstocks were excluded from the total emissions from the facility.
- No credit was taken for direct emissions from burning any self-generated fuels that were a result of processing non-fossil-based feedstocks.

Petroleum Feedstocks

There are many diverging projections for petroleum refining throughput. However, U.S. refineries have a competitive advantage over most global regions, because of lower feedstock and energy costs along with higher technology complexity. Therefore, a significant decrease in U.S. refining throughput would require a reduction in demand for liquid transportation fuels not just domestically, but in all parts of the world. For this reason, the EIA's AEO 2023 Reference Case[112] was chosen, projecting a modest increase in U.S. refinery utilization, but slightly less production relative to our 2018 baseline. This equates to about a 1% decline to 2050. A further 16% drop in petroleum crude was assumed due to a combination of biogenic feedstocks, discussed below, and replacement of refinery products with next generation alternatives. This reduction is consistent with the potential availability of feedstocks in the 2016 *Billion-Ton Report*,[113] a forthcoming multi-national laboratory assessment, and goals set in the Sustainable Aviation Fuel Grand Challenge.

Non-petroleum Feedstocks

Due to existing regulations like the Low Carbon Fuels Standard in California and policies like the Biodiesel and Renewable Diesel Income Tax Credit, U.S. refiners are incentivized to produce transportation fuels with lower lifecycle emissions. The most cost-effective way to do this is to produce them from biogenic feedstocks rather than crude oil. Consequently, products like renewable diesel, biodiesel, and synthetic paraffinic kerosene (SPK, a component of SAF) represented the largest growth area for the refining industry. However, the only commercialized method of production requires FOG-based feedstocks which have limited availability. Therefore, the AEO Reference Case projects only a modest increase in renewable diesel and biodiesel production from now to 2050; this was the basis for our model's biofeedstocks throughput projection. Bio-based feedstocks throughput was about 40,000 bbl/cd in 2018 and more than 250,000 bbl/cd in 2050. However, the supply of FOG was increased to produce 380,000 bbl/cd based on the IEA projection and assume co-processing of biogenic feedstocks with petroleum crude at 5% on a volumetric basis in accordance with R&D conducted at NREL.

Emissions Cost Assumptions

The refinery subsector is unique in that there are a relatively small number of large facilities with diverse sets of process units, many of which have hydrogen production and cogeneration plants onsite. As such, access to hydrogen and CO_2 infrastructure and facility configuration will play an integral role in the selection of decarbonization pathways by determining which opportunities are available for deployment. While facility-specific technoeconomic analysis is necessary, a more general assessment points to a typical loading order based on estimated CO_2 abatement costs. Figure 23 provides a range of costs using common electricity price ($19.7/MMBtu) and natural gas price ($4.6/MMBtu) assumptions taken from the 2050 industrial sector of the EIA AEO reference case.

[112] Annual Energy Outlook 2023 - U.S. Energy Information Administration (EIA)
[113] 2016 Billion-Ton Report | Department of Energy. Plans are included to update data using the newly-released 2023 Billion-Ton Report.

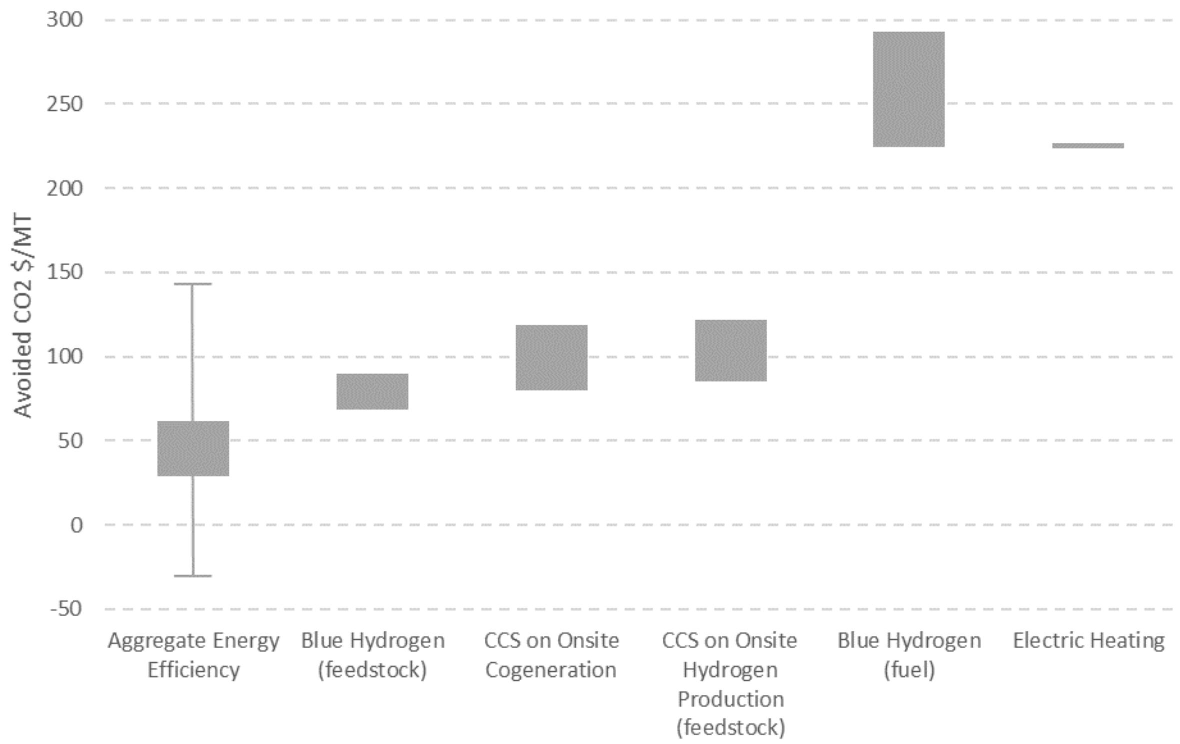

Figure 23. Typical ranges for the incremental cost of different decarbonization pathways including energy efficiency, hydrogen feedstock, carbon capture on cogeneration, hydrogen fuel, and electrification of process heat and steam.

Notes and references: Energy efficiency (Morrow et al. 2015),[114] hydrogen feedstock (Huges and Zolle 2022),[115] carbon capture on cogeneration (Schmitt et al. 2023).[116] Hydrogen fuel is the same reference for purchased feedstock compared with natural gas combustion and electrification of process heat and steam assumes moderate and near net-zero 2050 grid emissions intensities compared with natural gas combustion.

Common assumptions used in generating CO_2 cost methodology shown in Figure 23 are bulletized below.

- EIA AEO 2023 range of 2050 industrial electricity prices ($18.74-$22.67) and natural gas prices ($3.75-$7.24/MMBtu)
- Carbon intensity of purchased electricity is 0 kg CO_2/MMBtu
- Dollar year adjusted from 2010 and 2018 to 2022 using EIA real to nominal price factors.
- Capture costs adjusted to avoided costs (including emissions from the carbon capture process and CO_2 transmission & storage).

114 Efficiency improvement and CO_2 emission reduction potentials in the United States petroleum refining industry (escholarship.org)
115 Cost of Capturing CO_2 from Industrial Sources - NETL
116 Cost and Performance of Retrofitting NGCC Units for Carbon Capture - NETL

- Except of cogeneration/general combustion, assume unabated emissions from carbon capture process.

Table 10 provides an overview of the key crosscutting external factions that can drive these scenario assumptions while Table 21 in the appendix provides additional assumptions detail.

Table 10. Key Crosscutting External Factors Driving Near Net-zero Refining Scenario Assumptions

Scenario	Grid Electricity	Hydrogen Supply	Alternative feedstocks	Crude Reduction	CO_2 infrastructure
Near Net-Zero	Decarbonized grid by 2050	Larger buildout within Office of Clean Energy Demonstrations Regional Clean Hydrogen Hub[117] 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 *2016 Billion-Ton Report*,[118] a forthcoming multi-national laboratory assessment, 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)

[117] Regional Clean Hydrogen Hubs | Department of Energy
[118] 2016 Billion-Ton Report | Department of Energy. Plans are included to update data using the newly-released 2023 Billion-Ton Report.

2.6 Pulp and Paper Manufacturing

2.6.1 Subsector Snapshot

The United States produced approximately 65.3 million metric tons of paper and paperboard in 2022, which constituted 23.6 percent of global production.[119] As of 2023, the U.S. pulp and paper subsector accounted for more than 4% of the country's GDP.[120] The subsector also accounted for about 15% of the manufacturing primary energy consumption in 2018, becoming the third largest consumer in the manufacturing subsector after chemicals and petroleum and coal products.[121] In terms of greenhouse gas (GHG) emissions, the subsector emits ~7% of the total GHG emissions from the U.S. manufacturing subsector.[122] As per the EPA, the pulp and paper subsector emitted 31.2 million metric tons of CO_2e across the 188 facilities that reported to the GHG Reporting Program.[123]

The emissions of this subsector might seem low compared to other subsectors (7% of manufacturing), but this is mainly due to the substantial use of biomass-based fuels, such as pulping liquor and waste wood, that emit biogenic emissions.[124] Biogenic emissions have been broadly considered to be net-zero emissions due to the CO_2 uptake during the biomass growth period.[125] However, biogenic emissions in the subsector can be more than 50% of the total emissions;[126] it might be imperative to broaden our decarbonization goal to include biogenic carbon emissions to the oft-considered fossil fuel and process emissions, especially for this subsector.[127]

This subsector is diverse with multiple product types, including graphic papers, containerboard, linerboard, tissue, and specialty paper, used for a myriad of uses. Specific mills included in the subsector are market pulp mills, tissue mills, specialty mills, recycled mills, bleached integrated mills, and unbleached integrated mills. Figure 24 provides a basic flow diagram of the processes involved in pulp and paper manufacturing. At the mill-level, major emissions sources include recovery boilers, wood waste boilers, power boilers, natural gas turbines and lime kilns which provide energy for steam generation, electricity generation, process heating, and chemical recovery.

119 U.S. pulp and paper industry - statistics & facts | Statista
120 Pulp & Paper Manufacturing | NCASI
121 Manufacturing Energy Consumption Survey - U.S. Energy Information Administration
122 Ibid.
123 GHGRP Pulp and Paper | U.S. EPA
124 Life cycle carbon footprint analysis of pulp and paper grades in the United States using production-line-based data and integration :: BioResources
125 Impact of Biogenic Carbon Neutrality Assumption for Achieving a Net-Zero Emission Target: Insights from a Techno-Economic Analysis | Environmental Science & Technology
126 Life cycle carbon footprint analysis of pulp and paper grades in the United States using production-line-based data and integration :: BioResources (ncsu.edu)
127 Impact of Biogenic Carbon Neutrality Assumption for Achieving a Net-Zero Emission Target: Insights from a Techno-Economic Analysis | Environmental Science & Technology

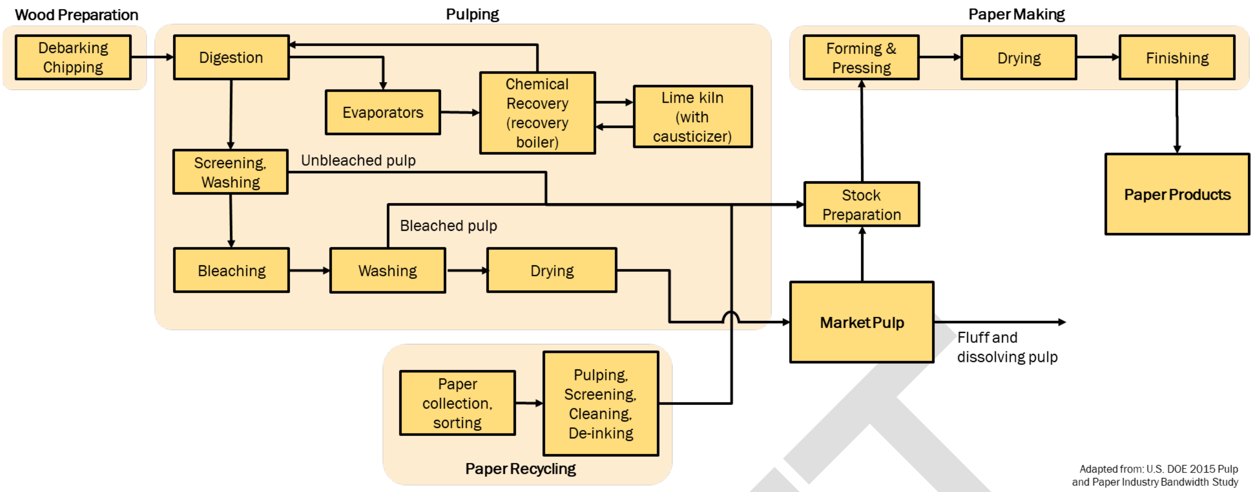

Figure 24. Pulp and paper process flow diagram

2.6.2 Net-Zero Emissions Barriers and Challenges

This section provides an overview of the major barriers faced by the subsector and is not meant to be comprehensive.

Major Energy Efficiency Barriers and Challenges

- **Current low cost of purchased energy:** Typically, purchased energy costs tend to be low, leading to lower economic benefits of installing energy-efficient technologies.
- **Cost of technology and the availability of capital funds:** The high upfront capital cost of multiple new energy-efficient technologies can be a barrier to implementing them. The limited availability of capital funds hinders the implementation of high-cost technologies.
- **Technical knowledge:** Technologies such as membrane-based black liquor concentration will require additional technical know-how to develop and produce them. Such technologies can also change the energy mix needed at the facility, for instance, membrane-based concentration increases electricity use while reducing steam consumption.
- **Market trends:** The current pulp and paper subsector has certain products that are declining, such as newsprint and writing paper. There can be a difficulty to invest in new and high-capital technologies when participating in such declining markets.

Major Industrial Electrification Barriers and Challenges

- **Limited Applicability:** A large portion of the steam used in integrated mills is obtained from the combustion of black liquor in the recovery boiler and the combustion of wood wastes. Electric processes may be applicable either for auxiliary fossil-fuel-based steam production or for downstream paper production processes, especially for non-integrated paper mills.

- **Need for Additional Electric Infrastructure:** Switching to electric boilers for producing steam can increase the facility's electric load demand. This may require facility upgrades to handle the additional electricity demand, which will have to be met by either the grid or through onsite clean power generation. If electricity is procured from the grid , the facility's grid reliance increases, and the reduction in emissions will depend on the grid decarbonization.
- **Availability of Clean Electricity**: The decarbonization benefits of electrification are only realized with low-carbon electricity. The projected increase in electricity demand means that providing low-carbon electricity may be an even bigger constraint.
- **Cost of technology:** The high upfront capital cost of electrification technologies can be a barrier to implementing them. Similarly, the low fuel cost in the U.S. can add to this barrier.

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

- **Availability:** While it is expected that there will be an annual availability of ~one billion tons of biomass, there will also be competition between different applications. The competition can be from end-uses such as sustainable aviation fuel for the hard-to-abate transportation sector, which may justify higher biomass prices compared to using biomass as a fuel to be combusted. Existing integrated and pulping mills can have continued access to biomass due to proximity and existing supply mechanisms; however, non-integrated paper mills may face difficulties in procuring biomass. There can be seasonal variations in the production and, therefore, availability. Additionally, clean hydrogen may not be as readily available, making it more difficult to use.
- **Technical barriers:** Biomass use in boilers can lower boiler efficiencies. This can be due to impurities or moisture content in the biomass. Additionally, biomass can be heterogeneous and inconsistent in its contents, even when pelletized, making operations more challenging. The existing equipment might need upgrades to utilize this fuel source effectively. In terms of hydrogen use as a fuel, the concentration of hydrogen in the fuel blend plays a critical role; when the concentration of the hydrogen in the fuel blends is below 20%, little impact on operations and equipment is expected. Increasing the hydrogen concentration beyond 20% can lead to equipment issues and will require additional research and development.
- **Uncertainty of costs:** The cost of LCFFES, such as clean hydrogen, can be high and whether projections for lower cost will be realized is unknown. Similarly, it is expected that as demand increases, biomass cost-at-gate can increase, due to multiple reasons, such as longer transportation distances. Increasing the fuel density through processing steps, such as pelletization to decrease transportation costs, can increase production costs further contributing to the uncertainty in predicting fuel costs.

Major Carbon Capture, Utilization, and Storage (CCUS) Barriers and Challenges

- **Cost:** One of the key challenges associated with CCUS deployment is the initial high capital investment associated with most types of carbon capture technologies applicable to the industry sector, such as pulp and paper. The typical costs of carbon capture are similar to those in other industries, such as waste-to-energy, cement production, and other power production processes.[128]
- **Scale:** A portion of annual U.S. pulp and paper mills emissions could be addressed by the deployment of CCUS. In the case a solvent-based capture system is deployed, the parasitic energy penalty required for solvent regeneration is non-trivial. Specifically, the average parasitic energy intensity of a solvent-based capture is about 3.5 GJ/metric tons CO_2, which would need a larger, more efficient boiler in many cases and increases the overall cost of technology. In addition, a large volume of amine handling has its inherent challenges. Other technologies, such as calcium looping, might be more effective for the pulp and paper sector, but will require demonstrated success before wide-scale deployment.
- **Safety:** Safe handling of captured CO_2 from the capture location to the sequestration or utilization site remains unclear.
- **Infrastructure:** While the location of industrial facilities considers the proximity of feedstock and energy sources a priori, the location of CO_2 pipeline network and sequestration infrastructure for CCUS was not a factor for currently existing U.S. pulp and paper facilities. Depending on the location of the pulp and paper facility, especially at U.S. regions without CO_2 pipeline or storage, the adoption of CCUS will require this infrastructure in-place.

2.6.3 Net-Zero Emissions Pathways and Technologies

A net-zero emissions pulp and paper subsector will require a comprehensive adoption of decarbonization technologies across all pillars. An example output for a modeled net-zero decarbonization pathway for the six mill types modeled by 2050 is shown in Figure 25. This example scenario projects CO_2e emissions reductions of 108% by 2050. LCFFES makes the largest contribution, followed closely by the CCUS pillar. It should be noted that the impact of electrification includes the reduction in electric grid CO_2 emissions as well as the small adoption of electrified steam production processes. An alternative net-zero approach considered involved increased electrification (with more aggressive deployment of electric boilers) and reduced biomass use. This analysis was carried out based on the assumption that non-integrated mills will not have as much access to biomass as fuel and will have to resort to electric boilers instead. This alternative scenario will have an increase in electrification instead of increased use of biomass, which will change the order of the contribution from each pillar.

[128] Post combustion CO_2 capture in pulp and paper production – Aker Carbon Capture

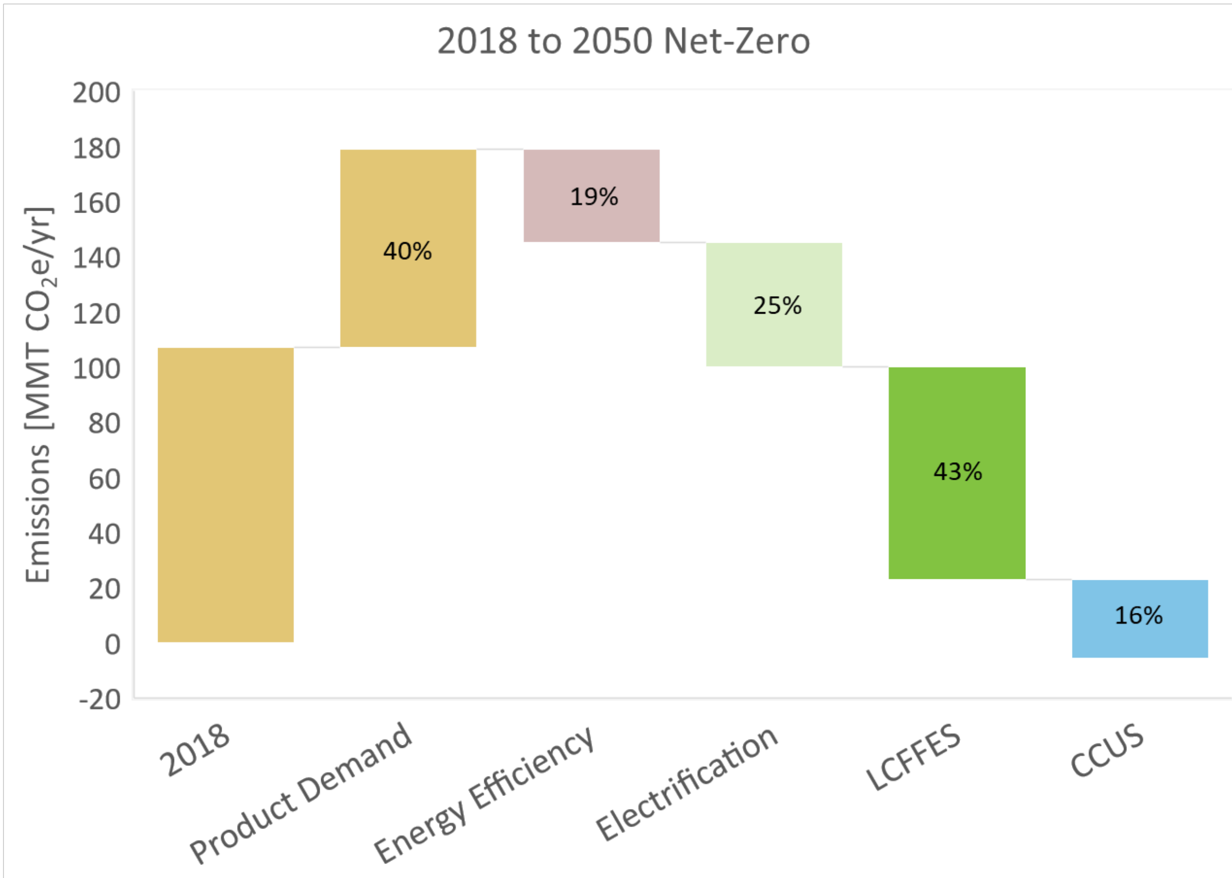

Figure 25. Example net-zero decarbonization pathway showing the impact of decarbonization pillars on CO_2e emissions (million metric tons (MMT)/year) for U.S. pulp and paper manufacturing, 2018–2050

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

Figure 26 represents the different mill and product types in the U.S. pulp and paper subsector and their inter-flows. Similarly, the mill types considered in the model are market pulp mill, tissue mill, specialty mill, recycled mill, bleached integrated mill, and unbleached integrated mill. Different products were assumed to be produced in these mills, including graphic paper, virgin packaging paper, recycled packaging paper, virgin paperboard, recycled paperboard, market pulps, specialty pulps, tissue/towel, specialty paper, and other types of paper. The subsector was modeled starting with the flow of the lumber through the wood preparation step to the pulping process, followed by the paper-making step. With an increase in recycled content, the paper recycling step was assumed to gain more importance over time.

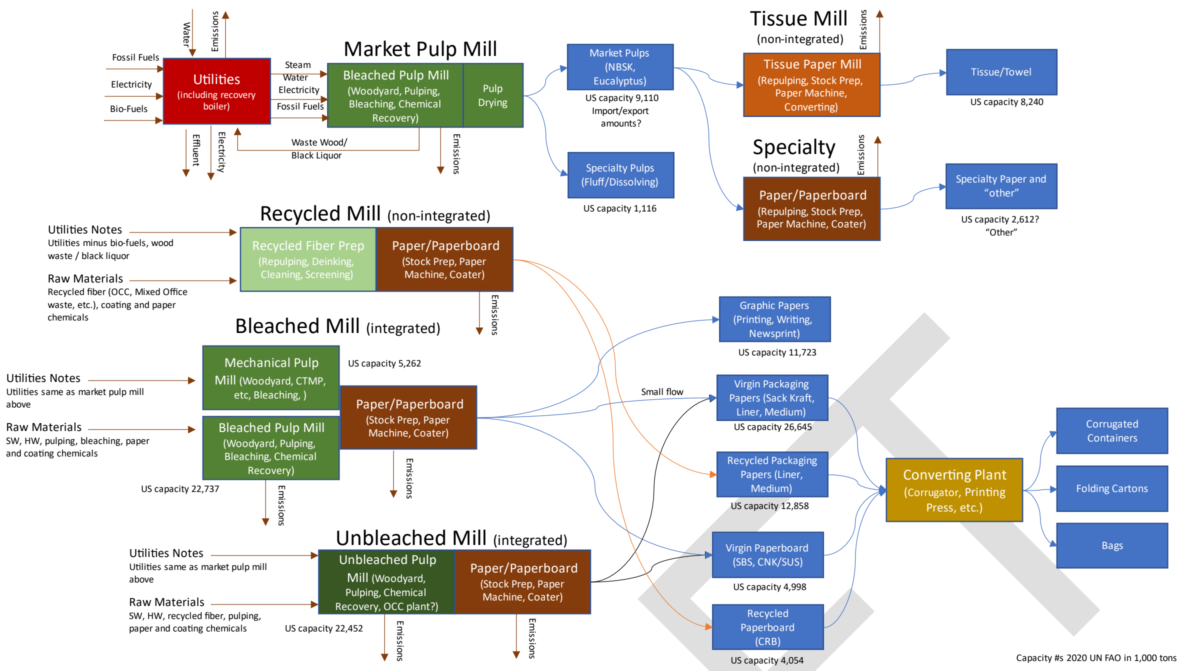

Figure 26. Different mill and product types in the U.S. pulp and paper subsector and their inter-flows

Energy Efficiency Impact

Energy efficiency is the foundational pillar among the four decarbonization pillars considered in this study and is a key component of reducing emissions for the subsector. To make significant improvements in energy efficiency, the pulp and paper mills will need to adopt multiple EE technologies. Various factors can influence the choice and adoption rate, such as age of existing equipment, type of products produces, and facility complexity. Companies will have to carefully consideration technology choices phasing, for energy efficiency and the other pillars, and at a facility-level or an industry-wide scale, to avoid emission "lock-ins" or creating potential stranded assets or "dead-ends" in the future. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

Some of the different technologies that can be relevant to the pulp and paper subsector include:

- **Waste heat recovery:** Recovery of heat can greatly increase the energy efficiency for this subsector. Multiple processes can have a waste heat recovery technology introduced; debarkers, pulp machines, bleach plants, and boilers to name a few. Once implemented, optimization would be key in continuously improving the performance of the waste heat recovery systems.

- **Advanced monitoring controls and digitalization:** Digitalization can be an important method of improving the energy performance in mills by optimizing their performance. Production processes can be monitored through smart manufacturing technologies, such as supervisory control and data acquisition and manufacturing execution systems. Enterprise resource planning can lead to lower energy consumption by helping facilitate operations and maintenance (Sundaramoorthy et al. 2023).

- Membrane Concentration of black liquor: The black liquor from the pulping processes is concentrated from ~15% solids to ~85% solids with the evaporators. Membrane concentration of black liquor up to 30% solids, can reduce steam consumption by ~30%.

Industrial Electrification Impact

The electrification technologies for the pulp and paper subsector are electrification of the auxiliary boilers for production of steam used in the pulp mills and paper production processes, especially for non-integrated paper mills. Electrification of the steam generation with the decarbonization of the grid can lead to a significant lowering of GHG emissions over time. Additionally, clean electricity can also be purchased to accelerate the reduction in Scope 2 emissions. Steam-generating heat pumps can also be utilized instead of electric boilers. Heat pumps work by transferring heat from a low-temperature source to a high-temperature sink, using a small amount of energy. In the pulp and paper mills, steam-generating heat pumps can be used to supplement the steam from the recovery boiler. However, heat pumps need to be further evaluated for this subsector.[129]

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

The pulp and paper subsector might be one of the few sectors that uses a significant proportion of LCFFES, as of 2018. This is mainly due to the use of pulping liquors and wood waste to produce steam and electricity while recovering the pulping chemicals in the recovery boiler. The modeling effort considered increasing the current use of LCFFES to include utilizing a greater portion of forest residues and other wood wastes not currently used. The U.S. is expected to produce one billion tons of biomass annually that would be available for various purposes, including as fuel[130]. The pulp and paper subsector has experience with the use of biomass-based fuels, making the use of additional LCFFES more natural and easier to implement.

Due to the additional use of LCFFES, the biogenic emissions are expected to increase, while the fossil emissions will be lowered. The most probable source for LCFFES for this subsector would be forest residues, sawmill chips or pellets. Low-carbon hydrogen is considered as a fuel only for the tissue mill types, where there have been cases of H_2 in the Yankee dryer. The H_2 use has been limited to a maximum of 4% of the subsector's total natural gas consumption, whereas the wood chips/ pellets have been maximized to up to 80% in the

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[129] Zuberi, M Jibran S, Ali Hasanbeigi, and William R Morrow. 2022. "Electrification of U.S. Manufacturing With Industrial Heat Pumps." https://www.globalefficiencyintel.com/electrification-of-us-manufacturing-with-heat-pumps.

[130] Langholtz, M. H., B. J. Stokes, and L. M. Eaton. 2016. "2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy." Oak Ridge, TN. https://doi.org/10.2172/1271651.

net-zero scenario. While not considered in this modeling effort, renewable natural gas or biogas, solar thermal energy, and geothermal energy are other viable LCFFES alternatives that can be useful on a case-by-case basis, depending on location and other factors.

Carbon Capture, Utilization, and Storage (CCUS) Impact

Carbon capture, utilization and storage in the pulp and paper subsector is uniquely suited as a decarbonization strategy that can help attain net-zero Scope 1 CO_2 emissions. Typically, about 87% of onsite CO_2 emissions in the pulp and paper subsector emanates from the combustion of biomass (black liquor and hog fuel) in the recovery boiler and multi-fuel boiler respectively.[131] If the biomass is considered to have been sustainably grown, the CO_2 emissions from biomass combustion are considered "biogenic". To this effect, capture of more than 25% CO_2 in this subsector represents an indirect removal of atmospheric CO_2 – a term known as negative emissions technology (NET). The specific NET for carbon capture in the pulp and paper subsector is referred to as BioEnergy with carbon capture and storage (BECCS). In terms of implementation, the amine-based post-combustion technology seems to be well suited for the pulp and paper subsector given that it is mature and well-established in the power sector. Regardless of the capture technology adopted, there are various technical issues associated with carbon capture use in the pulp and paper subsector. The percentage of all fuel emissions that are captured in the pulp and paper subsector in each of the four composite scenarios was assumed to be 33% by 2050 in the net-zero scenario, based on a recent study.[132]

2.6.4 Key Decarbonization Decisions

A transformation of the pulp and paper subsector will require a holistic view of the anticipated decarbonization pillars and technologies that will become (or may become, depending on technoeconomic factors) viable and available over varying timeframes out to mid-century and beyond. One way to assess these pathways is by starting with a decision-tree framework, as depicted in Figure 27 below.

The decision tree is depicted as a circular process until net-zero emissions is achieved to account for solutions that may not yet be commercially available. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of

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[131] Sagues, W. J., H. Jameel, D. L. Sanchez, and S. Park. 2020. "Prospects for Bioenergy with Carbon Capture & Storage (BECCS) in the United States Pulp and Paper Industry." Energy & Environmental Science 13 (8): 2243–61. https://doi.org/10.1039/D0EE01107J.
Onarheim, K., P. Kangas, S. Kaijaluoto, V. Hankalin, and S. Santos. 2016. "Techno-Economic Evaluation of Retrofitting CCS in a Market Pulp Mill and an Integrated Pulp and Board Mill." http://ieaghg.org/exco_docs/2016-10.pdf.
[132] Malmberg, Barry. 2023. "Opportunities for Carbon Capture in Pulp and Paper Energy Systems." DOE Workshop on Decarbonization Challenges and Priorities in the Forest Products Industry. https://www.energy.gov/sites/default/files/2023-11/Low Carbon Energy Sources-Barry Malmberg-NCASI 1.pdf.

energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission "lock-ins" and potential stranded assets in the future.

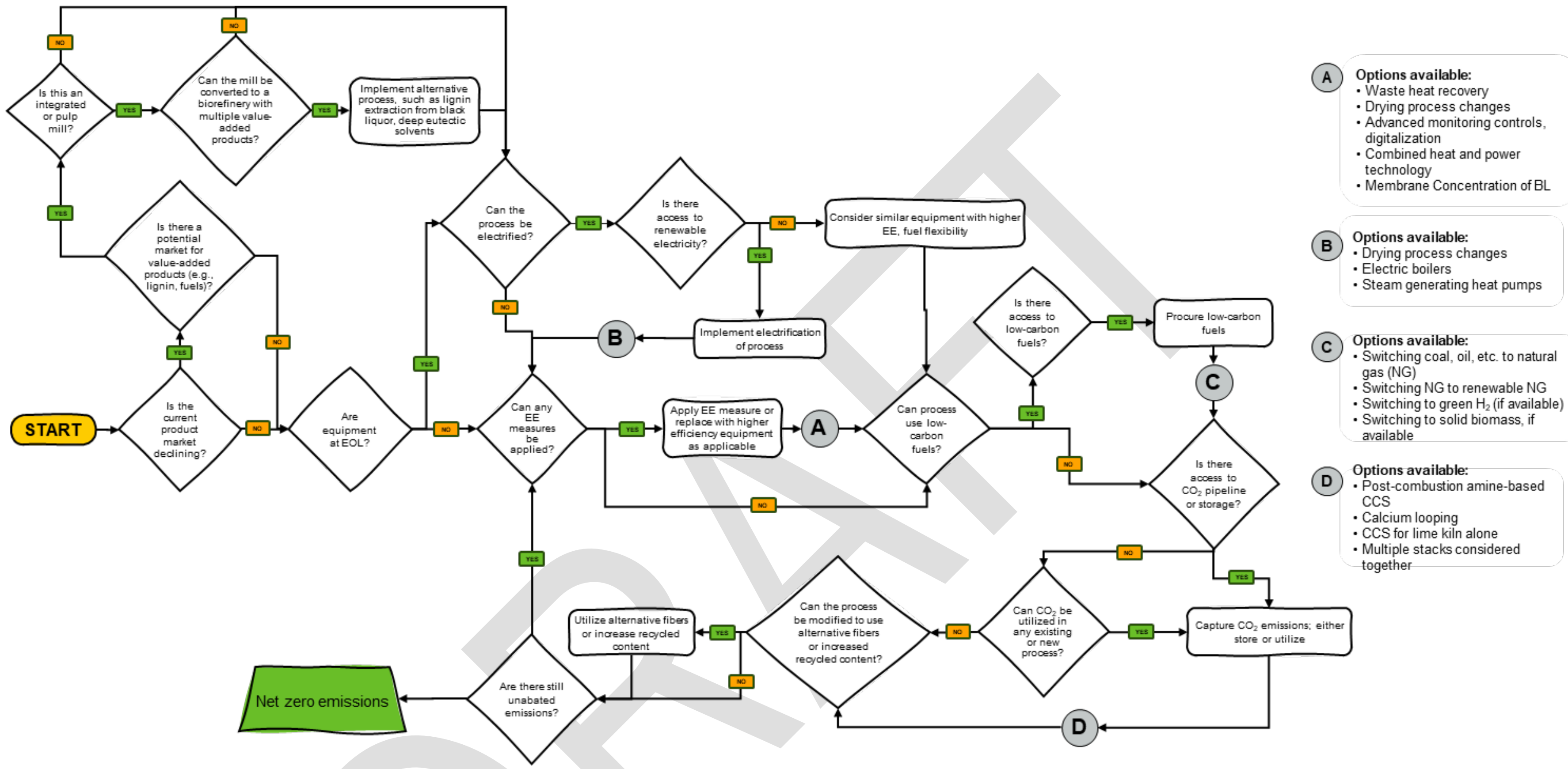

Figure 27. Pulp and paper manufacturing decarbonization decision tree

2.6.5 Modeling Assumptions

Table 22 through Table 28 in Appendix B provide an overview of the major assumptions in the net-zero scenario for each pulp and paper mill modeled.

3 Decarbonizing Rest of Industry

Beyond the six manufacturing subsectors covered above, the "rest of industry" is large and diverse, representing a footprint of over just under half of the industrial sector's energy-related emissions in 2018 as shown in Figure 3. "Rest of industry" is defined as other manufacturing (the rest of the manufacturing subsector excluding cement, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining), the nonmanufacturing subsector (agriculture and forestry; mining, oil, and gas; and construction), data centers, and water and wastewater treatment. Each subsector is briefly described below, followed by a summary of decarbonization pathways and opportunities. Specific net-zero emissions pathways and models have not yet been identified and modeled in detail for the rest of industry, so the pathways and opportunities are described in general.

Other manufacturing covers the production of products and intermediaries ranging from alumina and aluminum to computers, electronics, and electrical equipment. Agriculture and forestry involve the raising and harvesting of crops, animals, and timber. Mining, oil, and gas relate to the extraction of energy, metallic and non-metallic minerals, and other resources from the Earth's surface and underground. Construction includes establishments engaged in the construction and engineering of residential and non-residential buildings, as well as infrastructure such as highways and utility system. Data centers revolve around information technology infrastructure including servers, storage, networking equipment, and supporting auxiliary equipment. Finally, water and wastewater treatment are associated with delivery of water to building and facilities and the management of wastewater to remove contaminants and hazardous material before disposal or return to the water supply. Each of these subsectors has a unique energy profile regarding major energy consuming processes and equipment, types of non-energy related emissions, and decarbonization opportunities.

3.1 Rest of Industry Snapshot

3.1.1 Other Manufacturing

"Other manufacturing" includes the manufacturing subsectors other than the six covered in detail above. The GHG emissions in other manufacturing accounted for 21% of total manufacturing emissions in 2018 and includes transportation equipment (including car and truck manufacturing) (2.8% of total manufacturing emissions), plastics (2.3%), electronics (2.1%), fabricated metals (2.1%), aluminum (primary and secondary) (1.8%), glass (1.3%), machinery (1.2%), textiles (0.8%), and foundries (0.6%) manufacturing subsectors.[133]

[133] Manufacturing Energy and Carbon Footprints | Department of Energy

Process heating systems and thermal loads are vital in these subsectors for different operations (e.g., melting, heat treatment, molding, soldering, and drying). These processes require significant energy inputs, typically achieved through the combustion of fossil fuels or use of steam, and lead to substantial GHG emissions. The high temperatures needed for melting metals like recycled aluminum, shaping plastics, or curing paints in automotive production not only contribute to direct emissions from furnaces and heaters but also to indirect emissions associated with steam consumption. The challenge for these subsectors is to balance the essential need for precise temperature control and thermal processing with the urgent need to reduce their carbon footprint while also maintaining production quality and efficiency.

In these other manufacturing industry sectors, the process heating systems and thermal loads are vital for different operations, including melting, heat treatment, molding, soldering, and drying. These processes require significant energy inputs, typically achieved through the combustion of fossil fuels or steam usage, leading to substantial GHG emissions. The high temperatures needed for melting metals like recycled aluminum, shaping plastics, or curing paints in automotive production not only contribute to direct emissions from furnaces and heaters but also to indirect emissions associated with steam consumption. The challenge for these industries is to balance the essential need for precise temperature control and thermal processing with the urgent need to reduce their carbon footprint and reduce their impact on climate change. Innovations in energy efficiency, electrification, LCFFES, and CCUS are critical paths forward in reducing these emissions while maintaining production quality and efficiency.

Alumina and Aluminum

In 2018, the U.S. alumina and aluminum subsector accounted for 372 TBtu of energy consumption and 21 MMT CO_2e emissions.[134] The primary aluminum industry relies on electrolytic reduction processes in addition to melting, demanding substantial thermal energy. The GHG emissions come largely from the CO_2 released during the electrolysis process (using carbon anodes) and the combustion of fossil fuels for electricity generation. In secondary aluminum production, process heating systems are used for melting scrap aluminum. This process contributes to GHG emissions, primarily from the combustion of natural gas in furnaces. However, recycling aluminum requires only 5% of the energy used in primary production, significantly reducing its carbon footprint.[135]

The primary aluminum subsector was responsible for approximately 90% of global emissions in 2019 while the secondary aluminum manufacturing was observed to be responsible for remaining 10%.[136] A majority of the aluminum sector's emissions (77%) are generated in the smelting process where aluminum is extracted from bauxite. Within the aluminum

[134] Manufacturing Energy and Carbon Footprint: Sector: Alumina and Aluminum (NAICS 3313)
[135] Sustainability – Recycling | Aluminum Association
[136] https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf

sector's emissions roughly 62% of the emissions were due to electricity use, followed by thermal energy, process emissions and others at 16%, 12% and 10% respectively.[137]

Glass

In 2018, the U.S. glass manufacturing subsector accounted for 272 TBtu of energy consumption and 15 MMT CO_2e emissions.[138] The glass industry uses process heating for melting, forming, and annealing glass products, demanding continuous operation of high-temperature furnaces. These furnaces are typically fueled by natural gas or electricity, leading to significant GHG emissions through direct combustion and indirect energy consumption. The production of glass involves heating raw materials to temperatures above 3000°F, which not only requires large amount of energy but also results in considerable GHG emissions, this also includes process-related emissions.

Fabricated Metals

In 2018, the U.S. fabricated metals subsector accounted for 479 TBtu of energy consumption and 24 MMT CO_2e emissions.[139] Fabricated metals manufacturing includes processes like welding, forging, and heat treating. These processes often use direct-fired furnaces and electric induction heaters, leading to GHG emissions from both direct combustion of fuels and indirect emissions from electricity use. The subsector is focused on improving energy efficiency and integrating clean energy sources.

Transportation Equipment

In 2018, the U.S. transportation equipment manufacturing subsector accounted for 659 TBtu of energy consumption and 32 MMT CO_2e emissions.[140] Cars and truck manufacturing industry uses process heating in painting, drying, metalworking, and part curing. The GHG emissions are attributed to the combustion of fuels for direct heating and the significant electricity consumption for operations like paint curing and drying. Efforts to reduce emissions include optimizing process efficiency and adopting low-emission technologies such as electrotechnologies, low-carbon fuels, etc.

Plastics

In 2018, the U.S. plastics and rubber products manufacturing subsector accounted for 562 TBtu of energy consumption and 27 MMT CO_2e emissions.[141] The production of plastics is largely fossil fuel based as nearly 90% of plastic products generated today are from petroleum feedstocks. The demand for plastics will likely grow rapidly in the future reaching 4.2 Gt CO_2e by 2050 with nearly half share attributed to production processes while the remaining half of the share attributed to end-of-life emissions of plastic.[142] Process heating

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[137] https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf
[138] Manufacturing Energy and Carbon Footprint: Glass and Glass Products (NAICS 3272, 327993)
[139] Manufacturing Energy and Carbon Footprint: Sector: Fabricated Metals (NAICS 332)
[140] Manufacturing Energy and Carbon Footprint: Transportation Equipment (NAICS 336)
[141] Manufacturing Energy and Carbon Footprint: Plastics and Rubber Products (NAICS 326)
[142] https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC-sectoral-focus-Plastics_final.pdf

in the plastics industry is essential for extrusion, molding, and thermoforming. While less energy and carbon intensive per unit of production compared to metals, the industry's larger production volumes mean its GHG emissions are significant, primarily from electricity use.

Foundries

In 2018, the U.S. foundries subsector accounted for 160 TBtu of energy consumption and 7 MMT CO_2e emissions.[143] The U.S. foundry industry is very heterogenous. The subsector is a $50 billion industry that directly employs more than 160,000 individuals.[144] Additionally, it indirectly supports over 300,000 jobs across various related sectors, including equipment manufacturers, service providers, material suppliers, and companies that use castings in their products.[145] Foundries are heavy users of process heating for melting and casting metals, generating considerable GHG emissions from the combustion of coke, coal, and natural gas.

Computers, Electronics, and Electrical Equipment

In 2018, the U.S. computers, electronics, and electrical equipment manufacturing subsector accounted for 393 TBtu of energy consumption and 24 MMT CO_2e emissions.[146] The electronics industry uses process heating in soldering and printed circuit board manufacturing, with GHG emissions mainly from electricity use. The precision required in these processes limits immediate shifts to lower-emission technologies, placing emphasis on sourcing clean energy and enhancing energy efficiency. The electronics industry contributes to towards 4% of global greenhouse gas emissions.[147] The U.S. electronics subsector includes facilities that produced semiconductors, light emitting diodes (LEDs), microelectromechanical systems (MEMS), liquid crystal displays (LCDs), and photovoltaic (PV) cells and together emitted nearly 6.1 MMT CO_2e greenhouse gas emissions in 2017.[148] For the United States, nearly 74% of these direct or on-site emissions were emitted by the semiconductor etching and chamber cleaning process followed by fuel combustion process (12%), fluorinated heat transfer fluids (10%) and nitrous oxide (N_2O)-using processes (4%).[149] The etching and chamber cleaning processes possessed a large footprint due to their use of fluorinated gases, such as perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and hydrofluorocarbons (HFCs) that possessed high global warming potential. In addition to direct emissions, the indirect emissions related to electricity use (for equipment, heating, cooling, lighting, etc.), supply chain (raw materials,

143 Manufacturing Energy and Carbon Footprint: Sector: Foundries (NAICS 3315)
144 American Foundry Society - https://www.afsinc.org/industry-statistics
145 Ibid.
146 Manufacturing Energy and Carbon Footprint: Sector: Computers, Electronics and Electrical Equipment (NAICS 334, 335)
147 https://www.idtechex.com/en/research-article/decarbonizing-the-electronics-industry-with-sustainable-manufacturing/28329.
148 https://www.epa.gov/sites/default/files/2018-10/documents/electronics_manufacturing_2017_industrial_profile.pdf.
149 Ibid.

product use, transportation, end of life, etc.) are also a major contributor to subsector's GHG emissions.

Textiles

In 2018, the U.S. textiles manufacturing subsector accounted for 183 TBtu of energy consumption and 9 MMT CO_2e emissions.[150] In textiles, process heating is used for drying, curing, and chemical processing. The sector's GHG emissions come from both direct fuel combustion and indirect electricity consumption. The highest emitting processes include dyeing and finishing, yarn preparation, fiber production, and fabric production, among others.

Machinery

In 2018, the U.S. machinery manufacturing subsector accounted for 299 TBtu of energy consumption and 14 MMT CO_2e emissions.[151] This subsector utilizes process heating for metalworking processes such as welding and heat treating. GHG emissions are primarily from direct combustion of fuels in furnaces and indirect emissions from electricity usage.

3.1.2 Agriculture and Forestry

Agriculture and forestry involve the raising and harvesting of crops, animals, and timber. As noted in Section 2.3, the U.S. food supply chain is composed of multiple stages beginning with agriculture and followed by manufacturing (where products are packaged and prepared for eventual consumption), wholesale and retail, and consumption (both at homes and food services). Additional areas of the supply chain with non-negligible energy consumption and emissions (and for which data generally is not available) include post-harvest processing (between manufacturing and agriculture) and warehousing (between manufacturing, wholesale, and retail). Because the food supply chain is so interconnected, it can be difficult to account for decarbonization impacts within only one specific stage. Additionally, there are significant data gaps within food and beverage manufacturing and across the entire food supply chain.

Agriculture and forestry non-energy related emissions were significantly larger than energy-related emission in this subsector by almost a factor of seven in 2018.[152] Beef cattle was responsible for the largest share of both energy-related and non-energy related emissions at over a third of the subsector total. Large contributors were methane emissions associated with enteric fermentation from feed digestion and nitrous oxide emissions from soil in pasturelands. Poultry and eggs were the next largest at 15% of subsector emissions and corn at 10%. Those three in combination were about half of all agricultural emissions. Indirect emissions from generation of purchased electricity were the largest energy-related source followed closely by diesel fuel combustion.

[150] Manufacturing Energy and Carbon Footprint: Textiles (NAICS 313-316)
[151] Manufacturing Energy and Carbon Footprint: Machinery (NAICS 333)
[152] Inventory of U.S. Greenhouse Gas Emissions and Sinks - U.S. Environmental Protection Agency

Outdoor operations, such as those for grains, livestock, and forestry, typically favor diesel fuel for energy consumption, mostly used for mobile equipment. Indoor operations, like nurseries and greenhouses, predominantly consume natural gas for space heating. Others, such as dairy, poultry, and eggs rely significantly on electricity for space cooling, lighting, and refrigeration. Subsector-wide, irrigation constitutes about one-seventh of agriculture and forestry energy consumption, over half of which is electricity and nearly a third is natural gas. Notably, agriculture and forestry products contribute about 5% of domestic energy production including ethanol, biodiesel and renewable diesel, biogas, and fuel wood. The industrial sector consumes almost half of this energy, primarily through combustion of wood and wood waste in wood products and paper industries, and the transportation sector consumed the next most at about one-third, primarily through biofuels.[153] Expansion of the bioenergy economy is an important decarbonization opportunity for this subsector. Additionally, some decarbonization technology opportunity areas that may overlap with the manufacturing subsector might include distributed or controlled environment agriculture, agrivoltaics, and others.

3.1.3 Mining, Oil, and Gas

Mining, oil, and gas involve the extraction of energy, metallic and non-metallic minerals, and other resources from the Earth's surface and underground. Emissions come from a combination of onsite fuel combustion, offsite grid electricity,[154] and fugitive releases and non-energy combustion such as flaring.[155] Natural gas extraction was by far the largest source of GHG emissions at over half of the subsector total. Oil extraction was one-quarter of emissions, coal mining about one-sixth, and the rest of mining at one-twelfth. Within oil and gas, non-energy related emissions were larger than energy related emission by almost two-to-one. Most of those emissions were due to the leakage of methane. Energy use comes mostly from the combustion of self-produced lease and plant fuels.[156]

For coal mining, non-energy related emissions, also mostly related to methane leakage, was higher than energy related emissions by over eight-to-one. Within oil and gas, most energy use was for motor drives to run drilling equipment, pumps, and compressors. Across the subsector, fuel use for off-grid generators was also a significant consumer of energy. Within mining, energy use varies significantly from site to site; though on average about half of energy use is for drilling, blasting, digging, and extracting ore including various equipment for materials handling and ancillary demands (e.g., ventilation and dewatering), and the other half of energy use is for concentration. This latter stage separates barren waste rock

153 Biomass explained | U.S. Energy Information Administration
154 U.S. Census Bureau, Economic Census: Mining; detailed Statistics using state energy price data from EIA https://www.eia.gov/naturalgas/data.php#consumption and emissions factors from EPA.
155 Inventory of U.S. Greenhouse Gas Emissions and Sinks - U.S. Environmental Protection Agency
156 See Natural Gas Data - U.S. Energy Information Administration (EIA); as defined by EIA, lease and plant fuels are "natural gas used in well, field, and lease operations (such as gas used in drilling operations, heaters, dehydrators, and field compressors) and as fuel in natural gas processing plants." https://www.eia.gov/tools/glossary/index.php?id=Lease.

from valuable minerals through crushing and grinding followed by physical (e.g., gravity, floatation, magnetic) and chemical (e.g., froth floatation, leaching) separation.

3.1.4 Construction

Construction includes establishments engaged in the construction and engineering of residential and non-residential buildings, as well as infrastructure such as highways and utility system. Most emissions[157] come from fuel combustion in mobile equipment for excavation, grading, materials handling, transportation, and so forth. In 2018, an estimated three-quarters were from gasoline and diesel fuel, which also include other smaller uses such as onsite electricity generation. The next largest source was indirect emissions associated with purchased electricity at about 15%, which is typically used for tools and other equipment as well as worksite lighting. The remaining were from natural gas, lubricants, and other fuels. Natural gas and other manufactured gases are often used to provide temporary space heating for worksites and the proper curing of concrete during the colder times of the year.

In addition to energy, the construction subsector consumes significant amounts of materials such as sand, stone, and gravel used in site work and concrete mix, precast concrete and cement, steel for structural members, rebar, and framing, and many others. These materials have large energy and environmental footprints, and the construction industry could play an important role in motivating low GHG emissions intensive manufacturing. Finally, construction and demolition waste are substantial, more than twice that of municipal solid waste by weight,[158] and resource circularity could be an important way to decarbonization economy wide.

3.1.5 Data Centers

Data centers revolve around information technology infrastructure including servers, storage, networking equipment, and supporting auxiliary equipment. These buildings consume 10 to 50 times more energy per floor space compared to a typical commercial building and account for about 2% of total U.S. electricity consumption.[159] Emissions estimates focus on electricity consumption for operation of electronic equipment (e.g., servers, data storage, and networking) and infrastructure such as for equipment cooling, space conditioning, and power conversion. About half of energy use is for servers, a third for infrastructure, and most of the remaining sixth is for data storage.

Shipments of data center equipment have grown rapidly over the past years, though energy consumption has not grown proportionally. Equipment has become more efficient, for

[157] U.S. Census Bureau, Economic Census: Construction using national energy price data from EIA and emissions factors from EPA and breakdown of non-highway fuel use from DOT, FHWA, Highways Statistics Series https://www.fhwa.dot.gov/policyinformation/statistics.cfm (Table MF-24) and EIA Distillate Fuel Oil and Kerosene Sales by End Use https://www.eia.gov/dnav/pet/PET_CONS_821USE_A_EPD2D_VCN_MGAL_A.htm.
[158] Construction and Demolition Debris: Material-Specific Data | Environmental Protection Agency
[159] Data Centers and Servers | Department of Energy

example through smaller transistor sizes in microchips and solid-state storage mediums, and more advanced power conversion devices. Data centers have also grown larger with higher utilization levels, leading to economies of scale and more efficient cooling.[160] While data centers constitute a significant driver of electricity demand growth, their impact is complex and related to the broader role information technology plays across the energy economy. Furthermore, as individual data centers grow, their local impacts on power system infrastructure may inhibit subsector growth or incentivize demand-side management to reduce peak loads and provide load flexibility.

3.1.6 Water and Wastewater Treatment

The water and wastewater treatment subsector is associated with the delivery of water to building and facilities and the management of wastewater to remove contaminants and hazardous material before disposal or return to the water supply. Commercial and industrial wastewater treatment accounted for a total of 100 MMT CO_2e emissions in 2018 (less than 1% of total U.S. emissions).[161] The energy-related emissions are mainly from electricity consumed for pumping water. Pumps also consume fuels, particularly for industrial applications. In the western United States, water is also transported long distances to connect supply and demand.[162] Within treatment plants, removal of unwanted materials to meet water quality standards involves a series of stages from settling tanks and screening to remove large solids and aeration to accelerate microbial activity and the breakdown of organic matter. Subsequent stages could include filtration and ultraviolet disinfection. The remaining sludge is either burned, buried, sold as product (e.g., fertilizer), or sent to an anaerobic digestor for biogas production.[163]

The treatment of wastewater commonly leads to methane emissions as biogenic material breaks down under anaerobic conditions. Industrial wastewater treatment may have specialized methods to remove materials related to the source industry. From a facility perspective, these methane emissions can be far larger than the indirect emissions from electricity use.[164] Beyond subsector energy consumption and emissions, there are broader issues around water security, calls for greater circularity in water use, and needs for water by other sources, such as desalination of brackish water.

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[160] Shehabi, Arman et al. 2016. *United States Data Center Energy Usage Report.* https://www.osti.gov/biblio/1372902.

[161] 2018 electricity consumption estimated at 120 TWh/year from Water & Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply not including irrigation and livestock which is included in Agriculture and Forestry. Fugitive emissions of 42.5 MMT CO_2 Eq. in 2018 from domestic and industrial wastewater treatment from
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 – Main Report (epa.gov)

[162] Geographic Footprint of Electricity Use for Water Services in the Western U.S. (Journal Article) | OSTI.GOV

[163] Opportunities for Recovering Resources from Municipal Wastewater (Technical Report) | OSTI.GOV

[164] Song, Cuihong et al. 2023. "Methane Emissions from Municipal Wastewater Collection and Treatment Systems." https://pubs.acs.org/doi/10.1021/acs.est.2c04388 https://doi.org/10.1021/acs.est.2c04388.

3.2 Net-Zero Emissions Barriers and Challenges

Though the rest of industry subsectors have not yet been modeled as part of this work, this section provides an overview of barriers and challenges to decarbonization and is not meant to be comprehensive.

3.2.1 Energy Efficiency Barriers and Challenges

Financial

- Oil and gas industries use self-produced fuels that are readily available and low-cost relative to purchased electricity. Along with the low cost of natural gas, it is hard to make financial sense for the energy efficiency projects.
- In certain industries (e.g., iron foundries), the existing infrastructure (e.g., cupola furnaces) is very old and expensive. Retrofitting energy efficiency technologies on them is like a bandage on the problem. It's not a long-term solution.
- For some projects, initial investment would be significant.

Technical

- Harsh environment for waste heat recovery technologies.[165]
- Need for aggressive technology deployment and training efforts.
- Need for RD&D efforts in the field of smart manufacturing and internet of things.[166]

Infrastructure

- Older and industrial scale facilities can be harder and time consuming to replace before end of life due to high cost of replacement.

3.2.2 Industrial Electrification Barriers and Challenges

Financial

- Equipment and energy costs are typically higher compared to gas-fired furnaces of equal capacity. However, these costs may be offset by savings in other areas of production, such as increased production speeds or reduction in inventory.

Technical

- Limited range from current battery technologies given duty cycles needed, significant reductions in cold weather, reduced utilization factors for mobile equipment left idle during charging.
- The design capacity and size of fuel-fired systems are extremely large. For example – electrifying large fuel-fired dryers would be very challenging and would require tremendous amount of electricity.

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165 Technologies and Materials for Recovering Waste Heat in Harsh Environments (Technical Report) | OSTI.GOV.

166 Smart Manufacturing Pathways for Industrial Decarbonization and Thermal Process Intensification.

- Achieving the same product quality and characteristics would be challenging in certain cases.
- Electric systems provide different heat transfer mechanisms and maximum temperature conditions.
- While some electric heating technologies are well-established, others are still being developed or are not yet widely adopted in industrial applications. Technology deployment efforts should address the risk portion of the technologies.
- Safety considerations are also important for microwave and other electric heating, and there is often a concern about the dangers of microwave leakage and the need for protection against electromagnetic radiation.

Infrastructure

- Limited availability of clean electricity.
- Many sites do not have access to grid electricity (e.g., construction prior to electrical service, remote sites for mining, oil, and gas, large land plots with equipment far from hookups).
- Service upgrades needed, particularly for vehicle chargers given the scale of mobile equipment.
- Switching to electric heating significantly increases the demand for electricity. Many industrial facilities may not have access to the electrical infrastructure needed to support such high loads, necessitating costly upgrades.

3.2.3 Low Carbon Fuels, Feedstocks, and Energy Sources (LCFFES) Barriers and Challenges

Financial

- High capital cost for on-site implementation (e.g. solar photovoltaics, wind turbines, biogas plant, etc.)
- High cost of low-carbon alternatives when compared with traditional fossil fuel sources for instance the higher cost of renewable natural gas to fossil natural gas,
- Uncertainty in policy and regulations on LCFFES may increase financial risks and make it difficult for manufacturers to secure funding to implement low carbon solutions.
- Biomass transportation costs, industry needs to correlate with supply locations to minimize costs; can constrain the applicability to certain locations.

Technical

- Hydrogen
  - Safety: Greater leak potential than methane; Low density allows hydrogen to disperse and rise rapidly, raising risk for explosions indoors

- Storage constraints: About ~3 times the volume is needed to get the same amount of energy as methane.[167]
- Challenges to accommodate varied blends, which can cause early embrittlement of piping, requiring special coatings on the inside of the piping and vessels.

- Biomass
  - Pre-processing needed for heterogeneity of sources; Increases costs and complexity, for low-quality biomass, validation with process needed.
  - Biomass combustion related GHG emissions may not yield net carbon emission reduction. GHG emissions may not be recaptured for decades; Sustainability of biomass source.
  - Non-GHG emissions; Volatile organic compounds, NOx, particulate matter
- Solar Thermal
  - Transportation of heat to process equipment is going to be challenging.
  - Meeting demand continuity: risk of process disruption.
  - Integration into large-scale industrial plants and temperature limitation.
  - Large footprint: Competition of land for expanding processing facilities, electricity production, agricultural uses.

Infrastructure

- Limited total supply of alternatives like renewable natural gas due to feedstock constraints, and natural gas infrastructure may require reconfiguration to account for RNG supply locations.
- Lack of existing infrastructure for distribution and transportation and therefore these transportation networks need to be built which could be expensive and time consuming.
- Lack of infrastructure for safe storage (for hydrogen, renewable natural gas, biodiesel)

3.2.4 Carbon Capture, Utilization, and Storage (CCUS) Barriers and Challenges

Financial

- Outside of natural gas processing, relatively small point sources without low CO_2 concentrations.
- High capital and operating costs (due to energy and raw materials) required for carbon capture as well as for storage and transportation (Wide variation of costs). CCS investments are net present value (NPV) negative.

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167 Hydrogen Storage | Department of Energy

- Due to cost uncertainties and risks, it can be challenging to secure funding for financing industrial scale plants.

Technical

- Non-manufacturing involves significant mobile sources that suitable for carbon capture.
- Majority of CCS projects have not yet reached a level of widespread implementation.
- Can increase energy consumption significantly.
- Concerns related to safety and transport of CO_2.

Infrastructure

- Lack of CO_2 transport and storage infrastructure. (lack of specialized pipelines to carry condensed and high-pressure CO_2).
- Leakage of high-pressure CO_2 can cause safety issues.
- Lack of regulatory framework for storage thereby posing a challenge for its compliance.
- CCS may increase water footprint and therefore can be a concern for water scarce areas

3.3 Net-Zero Emissions Pathways and Technologies

Each subsector has a unique energy profile regarding major energy consuming processes and equipment, types of non-energy related emissions, and decarbonization opportunities, some of which overlap with those already discussed in the manufacturing subsectors above. This section provides a high-level view of short-, mid-, and long-term decarbonization opportunities for the rest of industry subsectors.

3.3.1 Short-term Pathways

In the short term, decarbonization pathways for rest of industry subsectors might include:

- **Deployment of energy efficiency** such as improving furnace efficiency and recovering waste heat in the glass industry,[168] utilizing oxyfuel combustion to improve energy efficiency in high-temperature processes like forging and heat treating in fabricated metals, and improvement of plastic production processes, namely in existing processes of steam cracking and naphtha catalytic cracking units.
- **Addressing fugitive methane emissions** is a critical need given methane's high global warming potential. There is substantial leakage of methane throughout all stages of oil and gas extraction as well as from underground coal mining. There is additional

[168] Deep decarbonization of glassmaking, Christopher W. Sinton, American Ceramic Society Bulletin, Volume 102, No. 4, Available at https://ceramics.org/wp-content/uploads/2023/05/May-2023_Feature.pdf

methane leakage from wastewater treatment plants as well as dairy, poultry, and swine farms. Captured methane could be utilized for energy and offset natural gas production demand.

- **Onsite clean energy generation** could be deployed to reduce purchased grid electricity or reduce fuel consumption for electric generators. Agrivoltaics could provide clean electricity and improve agricultural productivity and provide other ancillary benefits.
- **Electrification of drilling equipment, pumps, and compressors** in oil and gas could improve energy efficiency and reduce emissions as the electric grid decarbonizes or in combination with onsite clean energy generation. Current equipment typically runs on diesel fuel or self-generated gases.
- **Heat pumps and geothermal energy** could be deployed for various functions including space conditioning for indoor agriculture (e.g., greenhouses and vertical farming) and livestock (e.g., poultry, swine, and dairy). In the construction industry, air source heat pumps could be used for temporary space conditioning and water heating.
- **Switching to sustainable biogenic fuel and feedstock sources** such as use of biomass for process heat and bio-based plastics.

3.3.2 Mid-term Pathways

In the mid-term, decarbonization pathways for rest of industry subsectors might include:

- **Reductions in process related emissions** such as use of inert anodes (made up of ceramics, metal alloys, cermet, etc.) in addition to carbothermic reduction or multipolar electrolytic cells in aluminum smelting.
- **Increased material circularity** such as maximizing scrap metal use in the fabricated metals industry and increasing recycling rates for aluminum and plastics. Options for plastics include chemical and mechanical recycling as well as demand side management (decreased use of single use plastics such as polyethylene terephthalate bottles, food containers, stirrers, cutlery, bags, wet wipes, etc.).
- **Supply chain decarbonization** such as sustainable agriculture processes to grow cotton used in the textile industry.
- **Hybridization and electrification of mobile equipment**, the majority of construction, about half of agriculture and forestry, and a quarter of mining energy use is for mobile equipment such as tractors, combines, loaders, and haulers. These typically use diesel fuel but could be paired with electric motors for improved efficiency or replaced with fully electric drive.
- **Improved agricultural practices** such as improved soil management and optimized application of fertilizers could reduce nitrous oxide emissions as well as avoid upstream emissions associated with production of agricultural chemicals. This could

be accomplished within the context of precision agriculture and use of sensors and controls to measure and offer GHG mitigation emissions strategies and support productivity and sustainability.

- **Broader mining supply chain electrification** could be supported by changes to extraction and concentration processes. Some types of mineral processing have shifted toward leaching and solvent extraction (e.g., copper) due to degrading ore quality and lack of suitable ore types for conventional approaches. Rather than refined through elevated temperatures, electrowinning is used to achieved high purity levels. In the case of iron ore, electricity-based refining like direct reduced iron to electric arc furnace require higher iron content feeds than convention blast furnaces. Processing at mines could be modified to meet the necessary standards.
- **Feed additives for livestock** could reduce methane emissions from enteric fermentation that occurs during digestion. A variety of supplements to animal feed have been suggested to inhibit the production of methane. Methane constitutes a loss of feed energy, and its reduction could be beneficial beyond reducing GHG emissions. However, any changes to animal diets must be proven against adverse effects to health and production.
- **Increased production of bioenergy and bioproducts** can be accomplished through a variety of pathways that to transform biomass to useful products and intermediaries. Agricultural and forestry waste residues, municipal wastewater sludge, animal manure, among others can be used to produce biofuels, biochemicals, and bio-feedstocks for traditional refining and chemicals industries, as well as biogas that could be used directly or upgraded to pipeline quality renewable natural gas.
- **Carbon capture and sequestration** could be deployed at natural gas processing plants and current oil fields that employ enhanced oil recovery (EOR) could be transformed to long term CO_2 storage. Natural gas processing plants strip CO_2 from raw gas and generate relatively high purity streams, reducing capture costs. Some plants already capture those emissions for EOR and have the associated pipeline infrastructure in place. Current EOR mostly uses terrestrial sources of CO_2, but anthropogenic sources could be used instead.

3.3.3 Long-Term Pathways

Longer term decarbonization pathways will depend on what is adopted in the short and medium terms. Additional information and input are needed to better understand and estimate the net-zero pathways for the rest of industry to help the industrial sector as a whole reach net-zero emissions by 2050 and what unique challenges and barriers those pathways may face.

Appendix A–Additional Modeling Details

The models presented here forecast energy use and GHG emissions for individual subsectors under several different technical scenarios. Reported emissions include Scope 1 and 2 emissions for the subsector (both energy-related emissions and non-energy process emissions). DOE has used 2018 as the base year for all scenarios with predictions modeled 2018-2050 in one-year increments. Baseline modeling parameters for U.S. facilities include production volume, incumbent production methods, gate-to-gate fuel and electricity intensity per mass of produced product, the mix of fuel types (natural gas, coal, biomass, etc.), the national value for U.S. electric grid GHG emissions, non-energy process emissions, and installed capacity for CCUS. This modeling then applies technical solutions for decarbonization which are either currently available or in the research and development stage.

This modeling effort aligns with DOE's 2022 *Industrial Decarbonization Roadmap* to classify these decarbonization technologies into four pillars: energy efficiency; industrial electrification; LCFFES; and CCUS.[169] See Section 1.3 for additional information on pillar definitions. DOE has also defined four composite technical scenarios in alignment with the 2022 *Industrial Decarbonization Roadmap*:

Technical Composite Scenarios

Business as Usual (BAU): Assumes a slow improvement in energy efficiency and adoption of commercially available electrification technologies.

Moderate Technology Adoption: Assumes a higher rate of energy efficiency improvements, more switching to LCFFES, and a higher rate of electrification than the BAU scenario. It also assumes low adoption of CCUS.

Advanced Technology Adoption: Assumes even higher energy efficiency improvement, more-aggressive switching to LCFFES, a higher rate of electrification, and CCUS adoption.

Net-Zero GHG: Assumes subsector-wide achievement of net-zero CO_2e emissions, with the most accelerated levels of energy efficiency improvements, switching to LCFFES, electrification, and CCUS adoption.

These technical composite scenarios take into account technologies in all four decarbonization pillars and vary by degree rather than approach. Additionally, this modeling simulates four pillar-based scenarios which are unrealistic, but which illustrate the maximum possible impact of each pillar for the subsector.

Production volume is projected based on population and other factors and assumed to be the same for all technical composite scenarios. Other modeling details include:

169 Industrial Decarbonization Roadmap | Department of Energy

- **Biogenic vs. non-biogenic carbon accounting**: A 'biogenic factor' has been applied to all energy and non-energy emissions. This factor ranges from 0 to 1, with 0 being biogenic and 1 being non-biogenic. All calculated emissions are multiplied by this biogenic factor so that only non-biogenic emissions are reported but credit is given to the capture of both biogenic and non-biogenic emissions. Thus, significant capture of biogenic emissions has the potential to produce net negative emission values.
- **Energy efficiency:** While data collection has been completed at the individual technology or production route level, there are many options for process and energy efficiency modifications over the next three decades. These may include energy efficiency improvements to boilers, dryers/ovens, chillers, pumps, fans, or air compressors or process integration. There is also significant heterogeneity in which optimization options will be selected at each facility as the industry transitions to best available technologies. Thus, in addition to explicitly modeling the adoption of key energy efficiency technologies, scenarios also apply a top-down annual improvement in energy efficiency based on historical energy efficiency gains and an aggregated assessment of reviewed energy efficiency technologies. This simulates the overall march towards progress as older facilities are replaced by newer and more efficient equipment.
- **Hydrogen as fuel:** This modeling considers the potential for hydrogen use as an alternative fuel for high-temperature industrial heating in the U.S. The models disaggregate hydrogen fuel sources into grey, green, and blue hydrogen with the rate of hydrogen use, mix of hydrogen production technologies, and impact on emissions predicted from 2018-2050. The implementation of hydrogen use as a fuel varies across subsectors.
- **Carbon capture:** A detailed carbon capture model has been integrated into these calculations. Assessed capture technologies include direct capture of high concentration CO_2, amine absorption, calcium looping, and oxycombustion. The analysis includes details of carbon capture technology, cost and energy penalty for CO_2 capture and transportation, as well as the potential requirement for an auxiliary plant to power the assumed rate of carbon capture.
- **Captured carbon utilization vs. storage:** The utilization vs storage of all captured carbon has been disaggregated as a secondary variable within this model. Both sequestered and captured carbon are reported under the CCUS pillar.
- **Scope 1 vs. Scope 2 emissions:** As noted above, this modeling includes Scope 1 and 2 emissions in the reported values for the industrial sector, excluding Scope 3 upstream and downstream emissions. Scope 1 emissions refer to direct GHG emissions that occur gate-to-gate during production while Scope 2 emissions refer to indirect GHG emissions associated with the production of purchased utilities such as electricity and

steam. For the purposes of this model, emissions associated with the production of hydrogen have been included in Scope 2 emissions. Specifically,

- ‘Scope 1 emissions’ = 'onsite, non-biogenic fuel emissions' + 'non-biogenic process emissions (non-energy)' + 'onsite electricity emissions' + ‘onsite emissions from energy generation required for carbon capture’ - 'total carbon captured'
- ‘Scope 2 emissions' = 'offsite, non-biogenic fuel emissions' + 'grid electricity emissions' + ‘grid emissions for energy required for carbon capture’

Appendix B–Supporting Subsector Information

Chemicals

Table 11 through Table 19 provides the major assumptions in the net-zero scenario for each chemical modeled.

Ammonia

Table 11. Ammonia Net-Zero Decarbonization Scenario Assumptions

Production pathway (projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
Coal gasification - Integrated urea (2%) Ammonia synthesis only (3%) Steam-methane reforming - SMR (45%) Autothermal reforming - ATR (5%) Methane pyrolysis (10%) Water electrolysis (35%)	**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 drivers:** Sustainable agricultural production.	**Major assumptions:** *Up to 80% of conventional SMR-HB to adopt BAT (improved heat integration, pre-reforming, etc.) 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 drivers:** Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	**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 drivers:** Clean energy grid integration, reduced or no dependency on fossil fuels and feedstocks, emissions reduction, etc.	**Major assumptions:** *Switch entirely to NG where clean 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 drivers:** Cost competitiveness, emissions reduction, etc.	**Major assumptions:** Capture 90% of all direct CO_2 emissions by 2050. **Impact:** A 25% reduction in projected CO_2 emissions in 2050. **Major drivers:** Carbon pricing and regulations, availability of high-purity CO_2 streams, integrated urea manufacturing, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

BTX Aromatics

Table 12. BTX Aromatics Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
*Extraction from reformate (60%) *Extraction from pygas (6%) *Toluene disproportionation (9%) *Toluene hydroalkylation (<1%) *Methanol-to-aromatics - MTA (24%)	**Major assumptions and impact:** Assuming a 50% plastics recycling rate by 2050 could ultimately impact the future demand for BTX in relevant plastics manufacturing. **Major drivers:** Incentive to reduce plastic pollution and its negative impacts on ecosystems, public awareness of recycling, environmental regulations.	**Major assumptions:** *Up to 55% of conventional pathways to adopt BAT (heat integration, process intensification, advanced process control, and optimization, etc.) by 2050. *0.8% per annum autonomous improvement. **Impact:** A 20% reduction in projected CO_2 emissions for 2050 due to EE measures. **Major drivers:** Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. **Impact:** A 10% reduction in projected CO_2 emissions in 2050. **Major drivers:** Clean energy integration in power grids.	**Major assumptions:** *Transition 25% to MTA in 2050. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 15% reduction in projected CO_2 emissions in 2050. **Major drivers:** Cost competitiveness, emissions reduction, availability of low-cost clean methanol, and its sustainable supply chain, etc.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** A 38% reduction in projected CO_2 emissions in 2050. **Major drivers:** Carbon pricing and regulations, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Butadiene

Table 13. Butadiene Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
Steam cracking (66%) Electrified steam cracking (16%) Direct glucose to butadiene (7%) Bioethanol to butadiene (11%)	**Major assumptions and impact:** Assuming a 50% recycling rate for rubber and plastics by 2050 could significantly affect the future demand for butadiene in polymer manufacturing. **Major drivers:** Incentives to reduce rubber and plastics pollution and its negative impacts on ecosystems, public awareness of recycling, environmental regulations, etc.	**Major assumptions:** *Up to 50% of conventional steam cracking to adopt BAT (including NMP extraction) by 2050. *0.8% per annum autonomous improvement. **Impact:** A 25% reduction in projected CO_2 emissions for 2050 due to EE measures. **Major drivers:** Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. *Transition 16% to electrified steam cracking by 2050, starting from 2030. **Impact:** A 16% reduction in projected CO_2 emissions in 2050. **Major drivers:** Clean energy integration in power grids, reduced or no dependency on fossil fuels and feedstocks, emissions reduction, etc.	**Major assumptions:** *Transition 7% to direct glucose and 11% to bioethanol to butadiene in 2050. *Use of byproduct fuels. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 17% reduction in projected CO_2 emissions in 2050. **Major drivers:** Cost competitiveness, emissions reduction, availability of bio-feedstock, low-cost clean methanol, and its sustainable supply chain, etc.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** A 24% reduction in projected CO_2 emissions in 2050. **Major drivers:** Carbon pricing and regulations, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Chlor-Alkali

Table 14. Chlor-Alkali Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
Mercury cell technique (0%) Diaphragm cell technique (0%) Membrane cell technique (84%) Oxygen depolarized cathode - ODC (16%)	**Major assumptions and impact:** Assuming a 50% plastics recycling rate by 2050 could ultimately impact the future demand for chlorine in relevant plastics manufacturing. **Major drivers:** Incentive to reduce plastic pollution and its negative impacts on ecosystems, public awareness of recycling, environmental regulations.	**Major assumptions:** *Phase out mercury and diaphragm cells at a constant rate, aiming for a 0% contribution from both by 2050. *Transition 64% to membrane cell (BAT) and 16% to ODC by 2050. *0.8% per annum autonomous improvement. **Impact:** A 35% reduction in projected CO_2 emissions for 2050 due to EE measures. **Major drivers:** Cost reduction, resource conservation, market demand for sustainable products, mercury and asbestos emissions reduction, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. *By 2050, 50% of the steam generation for membrane cell technologies is projected to be electrified through the use of HTHP. **Impact:** A 46% reduction in projected CO_2 emissions in 2050. **Major drivers:** Clean energy integration in power grids, reduced or no dependency on fossil fuels, energy efficiency, emissions reduction, etc.	**Major assumptions:** *Increased use of byproduct H_2 in H_2 fuel cell CHP within the context of the BAT assumptions. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 17% reduction in projected CO_2 emissions in 2050. **Major drivers:** Cost competitiveness, emissions reduction, suitable technology for byproduct H_2 utilization, etc.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** Negligible. **Major drivers:** Carbon pricing and regulations, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Ethanol

Table 15. Ethanol Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
Dry milling (100%) Wet milling (0%) Syngas fermentation (inconclusive for now)	No major material efficiency measures are considered.	**Major assumptions:** *Transition 60% to BAT (membrane separation, new enzymes, etc.) by 2050. *Phase out wet milling at a constant rate (0% by 2050). *0.8% per annum autonomous improvement. **Impact:** A reduction of 6.2 MMT of CO_2 p.a. in 2050 due to EE measures compared to 2050 BAU. **Major drivers:** Cost reduction, resource conservation, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. *Assume 30% of mills implement HTHPs. **Impact:** A reduction of 4.6 MMT of CO_2 p.a. in 2050 compared to 2050 BAU. **Major drivers:** Clean energy grid integration, reduced dependency on fossil fuels, energy efficiency, emissions reduction, etc.	**Major assumptions:** *Phase out coal. *30% biogas by 2050. *5% biomass (corn stover) by 2050. **Impact:** A reduction of 6.1 MMT of CO_2 p.a. in 2050 compared to 2050 BAU. **Major drivers:** Cost competitiveness, emissions reduction, availability of waste biomass, etc.	**Major assumptions:** *All fermentation emissions captured by 2050. *No capture of fuel emissions. **Impact:** A reduction of 29.9 MMT of CO_2 p.a. in 2050 due to BECCS (counted as negative emissions within the system boundaries). **Major drivers:** Availability of high-purity biogenic CO_2 streams, access to CO_2 transport infrastructure, potential negative emissions (BECCS), etc.

Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Ethylene

Table 16. Ethylene Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
*Atmospheric gas oil steam cracking - AGO (0%) *Natural gas liquids steam cracking - NGL (64%) *Naphtha steam cracking (0%) *Electrified steam cracking (14%) *Methanol-to-olefins - MTO (6%) *Ethanol dehydration (16%)	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 drivers: Incentive to reduce plastic pollution and its negative impacts on ecosystems, public awareness of recycling, environmental regulations, etc.	Major assumptions: *Up to 75% of NGL steam cracking to adopt BAT (optimal furnace heat balance, improved furnace coils, membrane separation, new column designs, etc.) 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 for 2050 due to EE measures. Major drivers: Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	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 drivers: Clean energy integration in power grids, reduced or no dependency on fossil fuels and feedstocks, energy efficiency, emissions reduction, etc.	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 drivers: Cost competitiveness, emissions reduction, availability of bio-feedstock, low-cost clean methanol, and its sustainable supply chain, etc.	Major assumptions: Capture 70% of all direct CO_2 emissions by 2050. Impact: A 33% reduction in projected CO_2 emissions in 2050. Major drivers: Carbon pricing and regulations, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Methanol

Table 17. Methanol Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
Steam-methane reforming - SMR (45%) Autothermal reforming - ATR (5%) Water electrolysis (35%) Biomass gasification (15%)	No major material efficiency measures are considered.	**Major assumptions:** *All conventional SMR-MS to adopt BAT (improved heat integration, pre-reforming, etc.) by 2050. *Transition 5% to ATR in 2050. *0.8% per annum autonomous improvement. **Impact:** An 8% reduction in projected CO_2 emissions for 2050 due to EE measures. **Major drivers:** Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. *Transition 35% to water electrolysis (e-methanol) in 2050. **Impact:** A 39% reduction in projected CO_2 emissions in 2050. **Major drivers:** Clean energy grid integration, reduced or no dependency on fossil fuels and feedstocks, feedstock CO_2 utilization, emissions reduction, etc.	**Major assumptions:** *Transition 15% to bio-methanol in 2050. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 10% reduction in projected CO_2 emissions in 2050. **Major drivers:** Cost competitiveness, emissions reduction, bio-feedstock availability and sustainable supply chain, etc.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** A 37% reduction in projected CO_2 emissions in 2050. **Major drivers:** Carbon pricing and regulations, availability of high-purity CO_2 streams, access to CO_2 transport infrastructure, negative emissions (BECCS), etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Propylene

Table 18. Propylene Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
*Steam cracking (21%) *Electrified steam cracking (6%) *Fluid catalytic cracking - FCC (41%) *Propane dehydrogenation (11%) *Metathesis (4%) *Methanol-to-olefins - MTO (17%)	**Major assumptions and impact:** Assuming a 50% plastics recycling rate by 2050 could ultimately impact the future demand for propylene in relevant plastics manufacturing. **Major drivers:** Incentive to reduce plastic pollution and its negative impacts on ecosystems, public awareness of recycling, environmental regulations, etc.	**Major assumptions:** *Up to 55% of conventional pathways to adopt BAT (optimal furnace heat balance, structured packing, improved process control and optimization, etc.) by 2050. *Transition 11% to propane dehydrogenation, and 4% to metathesis in 2050. *0.8% p.a. autonomous improvement. **Impact:** A 21% reduction in projected CO_2 emissions for 2050 due to EE measures. **Major drivers:** Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. *Transition 6% to electrified steam cracking by 2050, starting from 2030. **Impact:** A 16% reduction in projected CO_2 emissions in 2050. **Major drivers:** Clean energy integration in power grids, reduced or no dependency on fossil fuels and feedstocks, emissions reduction, etc.	**Major assumptions:** *Transition 17% to MTO in 2050. *Use of byproduct fuels. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 20% reduction in projected CO_2 emissions in 2050. **Major drivers:** Cost competitiveness, emissions reduction, availability of low-cost clean methanol, and its sustainable supply chain, etc.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** A 31% reduction in projected CO_2 emissions in 2050. **Major drivers:** Carbon pricing and regulations, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Soda Ash

Table 19. Soda Ash Net-Zero Decarbonization Scenario Assumptions

Production pathway (Projected market share by 2050)	Material efficiency	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
Monohydrate process (93%) Direct carbonation (7%; assumed as carbon neutral already in the base year)	**Major assumptions and impact:** Assuming a 50% container glass recycling rate by 2050 could ultimately impact the future demand for soda ash in glass manufacturing. **Major drivers:** Glass recycling initiatives, public awareness of recycling, environmental regulations.	**Major assumptions:** *Transition 95% to BAT (rotary steam dryers, heat integration, etc.) by 2050. *0.8% per annum autonomous improvement. **Impact:** A 10% reduction in projected CO_2 emissions for 2050 due to EE measures. **Major drivers:** Cost reduction, resource conservation, market demand for sustainable products, environmental regulations, etc.	**Major assumptions:** *Impact from electricity grid decarbonization. *By 2050, 50% of the steam generation electrified through the use of HTHP and electric boilers. *5% electrified calcination by 2050 (market entry in 2040). **Impact:** A 28% reduction in projected CO_2 emissions in 2050. **Major drivers:** Clean energy grid integration, reduced dependency on fossil fuels, energy efficiency, emissions reduction, etc.	**Major assumptions:** *Switch entirely from coal to NG by 2050. *Up to 10% RNG in the fuel mix by 2050. **Impact:** A 3% reduction in projected CO_2 emissions in 2050. **Major drivers:** Cost competitiveness, emissions reduction, etc.	**Major assumptions:** Capture 70% of all direct CO_2 emissions by 2050. **Impact:** A 37% reduction in projected CO_2 emissions in 2050. **Major drivers:** Carbon pricing and regulations, high CO_2 concentration in flue gases, access to CO_2 transport infrastructure, etc.

Impact is estimated as the percentage of CO_2 savings compared to the CO_2 emissions projected in the 2050 BAU scenario. Acronyms: BTX = Benzene, Toluene and Xylenes, BAT = Best Available Technologies, BAU = Business-As-Usual, BECCS = Bioenergy with Carbon Capture and Storage, CHP = Combined Heat and Power, EE = energy efficiency, HB = Haber Bosch, HTHP = High Temperature Heat Pump, MMT = Million Metric Tons, MS = Methanol Synthesis, RNG = Renewable Natural Gas, p.a. = per annum.

Food and Beverage

Table 20 provides an overview of the decarbonization technologies applied in the modeling, along with the associated processes, subsectors, and pillars.

Table 20. Overview of Food and Beverage Net-Zero Scenario Technologies and Emissions Reductions

Technology	Applicable Process(es)	Subsectors	Pillar	Emission Reduction from 2018 to 2050 NZ
2018 Emissions	All processes	All six subsectors	N/A	75.7
Emissions from increased product demand	All processes	All six subsectors	B/A	16.5
Boiler energy efficiency measures*	Low/High temp Direct/Indirect hot water/Steam	All six subsectors	Energy Efficiency	-8.5
	Facility HVAC	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing		
Air Compressors energy efficiency measures**	Machine Drive	All six subsectors		
Chillers energy efficiency measures (Motors/VFD)**	Process Cooling and Refrigeration	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing		
Dryers/ovens energy efficiency measures*	Low/High temp Convective hot air dryers	All six subsectors		
Fans and Blowers energy efficiency measures**	Machine Drive	All six subsectors		
Process Integration	Low/High temp Convective hot air dryers	All six subsectors		
	Low/High temp Direct/Indirect hot water	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing		
	Process Cooling and Refrigeration	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing		
Pumps energy efficiency measures**	Machine Drive	All six subsectors		

Advanced electroheating technologies	Low/High temp Convective hot air dryers	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing	Electrification	-66.2
Electric boiler	Low/High temp Direct/Indirect hot water/Steam	All six subsectors		
Hot water heat pump	Facility HVAC	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing		
	Low/High temp Direct/Indirect hot water	Beverages, Dairy, Fruit & Veg, Grain & Oilseed, Meat Processing		
Membrane Pre-concentrators	Low/High temp convective hot air dryers	All six subsectors		
Steam Generating Heat Pump	Low/High temp convective hot air dryers	All six subsectors		
	Low/High temp Direct/Indirect steam	All six subsectors		
Low-carbon fuels switching	Processes with remaining fuel demand	All six subsectors	LCFFES	-15.5
Post-combustion carbon capture and storage (amine absorption)	Remaining combustion emissions	Beverages, Grain & Oilseed	CCUS	-0.8

** Boilers, ovens, and dryers energy efficiency measures: tuning air/fuel ratios, minimizing excess boiler blowdown, increasing boiler condensate return, using steam traps, insulating any bare pipes and equipment, determining areas where steam pressure and temperature can be reduced.*

***Machine drive applications (pumps, fans and blowers, air compressors, refrigeration compressors) energy efficiency measures: replacing old motors with premium efficiency or advanced motors, establishing predictive and preventive maintenance programs, or applying energy efficiency belts; air compressors - upgrading controls and sequencing multiple compressors; use of variable frequency drives (VFDs). Refrigeration compressors may realize energy usage reductions of up to 17% through the application of the aforementioned energy efficiency measures. Similarly, energy reduction in the applications of pumps, fans and blowers, and air compressors are estimated as 15%, 23%, and 36%, respectively.*

Petroleum Refining

Table 21. Petroleum Refining Net-Zero Scenario Pathways Assumptions and Emissions Reductions

Production Pathway	Efficiency	Electrification	LCFFES	CCUS	Production % in 2050 for Near Net-Zero	Emissions reduction % from 2050 BAU*
Conventional refining	• Artificial intelligence /digitalization • Heat Pumps • Integrated Cogen • Advanced furnace/ heat exchanger designs • Waste Heat Recovery	• Replace steam turbine • Clean H_2	• Low carbon intensity H2 as a feedstock • RNG • Biofeed to SMR Note: alternate feedstocks are shown in co-Processing	• CC Amine replacement (cryo, adsorbents, etc.) • Blue H_2	**2050 BAU:** 99% **2050 Near Net-Zero:** 80%	**2050 BAU:** 42 kg CO_2/bbl of refined product **2050 Near Net-Zero:** 21kg CO_2/bbl of refined product *(51%)*
Co-processing of biobased crude substitute in conventional refining	• Novel Catalyst • Advanced process designs • Advanced heat exchangers & metallurgy	• Clean H_2	• Novel catalyst • Advanced process designs • New Improved feedstock prep technology	• CC Amine replacement (cryo, adsorbents, etc.)	**2050 BAU:** ~0% **2050 Near Net-Zero:** 4%	**2050 BAU:** N/A **2050 Near Net-Zero:** 2 kg CO_2/bbl of refined product**
Dedicated FOG based SAF/RD plants	• Catalyst • Advanced process tech • Advanced heat exchangers • Controls	• Clean H_2 • New Electro-chem technolo-gies	• Novel Catalyst • Adv Process Designs • Low carbon intensity H_2 as a feedstock • New feed sources	• Process designs with carbon capture	**2050 BAU:** ~1% **2050 Near Net-Zero:** 2%	**2050 BAU:** 66 kg CO_2/bbl of refined product **2050 Near Net-Zero:** 17 kg CO_2/bbl of refined product *(73%)*
Advanced Biofuel Pathways (pyrolysis, Fischer-Tropsch, etc.)	• Catalysts • Advanced separation • Novel process designs	• Clean H_2 • New Electro-chem technolo-gies	• Novel technologies • Improved process design • Nuclear	• Process designs that incorporate carbon capture • CO2 as a feedstock	**2050 BAU:** ~0% **2050 Near Net-Zero:** 14%***	Not calculated, *seeking input from RFI respondents*

** Percent reduction in pathway carbon intensity*

***Emissions reduction of co-processing is negative, since combustion of catalyst coke and off-gases release biogenic CO2 that is not counted and there is a slight reduction in overall hydrogen demand relative to no co-processing (even though there may be significant hydrogen consumption upstream of the refinery). Assumes some carbon capture on FCC units, since majority of co-processed sustainable feedstock is assumed to be processed in FCC.*

****Based on DOE Billion Ton Study*

Drivers/Barriers of Production Routes (excluding economics)

Conventional Refining: Large GHG reduction impacts will require access to low CI H_2, CO_2 pipelines, and availability of low CI feedstocks that can be processed in existing assets. Electrification of the grid will be significant but done by others. Efficiency has significant potential but will be difficult to implement if not incentivized assuming energy costs stay low. Additionally, improvements will be small gradual improvements that align with end-of-life equipment replacement.

Co-Processing of Biobased Crude Substitute in Conventional Refineries: This pathway is restricted mainly by the availability (and logistics) of biobased feedstocks. It also requires spare capacity in existing assets, and availability of low CI hydrogen for processing if maximizing GHG reductions are to be achieved.

Dedicated FOG based SAF/RD Plants: Standalone RD and SAF plants are currently feedstock availability limited and also require financial incentives (based on present technology) to be competitive. This pathway needs new feedstocks, new low-cost pre-treatment technologies, and advanced catalysts and process designs that can tolerate a wider selection of feedstocks without excessive capex. Low cost, low CI H2 is also a strong benefit.

Advanced Biofuel Pathways (pyrolysis, FT, etc.): Alternate pathways that replace conventional refining are still in development. Some technologies are known but are not cost competitive. The main driver for these wide range of options will initially be focused on advanced process designs, new catalysts, and new pre-treatment technologies that will likely incorporate several conventional refining technologies. The long-term advantage of this route is that it will likely also support circular economy initiatives.

Pulp and Paper

Table 22 provides an overview of the net-zero scenario technologies applied, to which processes and mill types, as well as the relative pillar impact on emissions reductions. Table 23 through Table 28 provide the major assumptions in the net-zero scenario for each mill modeled.

Table 22. Overview of Pulp and Paper Net-Zero Scenario Technologies and Emissions Reductions

Technology	Process	Mill type	Pillar	Emission Reduction from 2018 to 2050 net-zero (MMT CO_2e/year)	% contribution in 2050 with 2018 emissions as baseline	% contribution in 2050 with product increase as baseline
2018 Emissions	All processes	All	N/A	107.05	100%	60%
Emissions from increased Product demand	All processes	All	N/A	+71.01	66%	40%
Autonomous energy efficiency improvement	All processes	Market pulp mill, Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency	-33.97	-32%	-19%
Equipment upgrades	Wood prep (debarking)	Market pulp mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency			
	Refining/ screening (refiner)	Market pulp mill, Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill				
	Forming/ pressing (high consistency forming)	Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill				
	Forming/ pressing (press section upgrades)	Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill				

Technology	Process	Mill type	Pillar	Emission Reduction from 2018 to 2050 net-zero (MMT CO_2e/year)	% contribution in 2050 with 2018 emissions as baseline	% contribution in 2050 with product increase as baseline
	Drying (improved drying technologies)	Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill				
	Chemical prep (lime kiln modifications)	Market pulp mill, Bleached integrated mill, Unbleached integrated mill				
	Evaporation (additional evaporation effects)	Market pulp mill, Bleached integrated mill, Unbleached integrated mill				
Waste heat recovery	Wood prep	Market pulp mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency			
	Pulping/ Cooking	Market pulp mill, Bleached integrated mill, Unbleached integrated mill				
	Boilers	Market pulp mill, Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill				
	Bleaching	Bleached integrated mill				
Chip screening and conditioning	Wood prep	Market pulp mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency			
Advanced digestion additives	Pulping/ Cooking	Market pulp mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency			
Optimization	Stock prep (batch stock)	Tissue mill, Specialty mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency			
	Forming/ pressing (air supply, paper machine vacuum)	Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill				

Technology	Process	Mill type	Pillar	Emission Reduction from 2018 to 2050 net-zero (MMT CO_2e/year)	% contribution in 2050 with 2018 emissions as baseline	% contribution in 2050 with product increase as baseline
Through air drying	Drying (improved drying technologies)	Tissue mill	Energy Efficiency/ Material Efficiency			
Recovery boiler temperature monitoring	Chemical prep	Market pulp mill, Bleached integrated mill, Unbleached integrated mill	Energy Efficiency			
Electric Boiler	Auxiliary boilers	Market pulp mill, Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill	Electrification	-45.23	-42%	-25%
Fuel switching to biomass	Auxiliary boilers, chemical prep (lime kilns)	Market pulp mill, Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill	LCFFES	-76.96	-72%	-43%
Fuel switching to hydrogen	Drying (Yankee dryers)	Tissue mill	LCFFES			
Post-combustion carbon capture	Recovery and auxiliary boilers, lime kilns	Market pulp mill, Tissue mill, Specialty mill, Recycled mill, Bleached integrated mill, Unbleached integrated mill	CCS	-28.75	-27%	-16%

Market Pulp Mill (Non-Integrated)

Table 23. Market Pulp Mill (Non-Integrated) Net-Zero Decarbonization Scenario Assumptions

Product(s)	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)	Material efficiency
Fluff pulp	Debarking upgrades, chip screening & conditioning, advanced digestion additives, waste heat recovery (debarking, pulp machine, digestor, bleach plant, recovery boiler, auxiliary boiler), high efficiency refiners, additional evaporation effects, lime kiln modification, recovery boiler temperature monitoring	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 100% biomass in repulping and lime kiln, and 80% in auxiliary boiler	33% post combustion carbon capture in boilers and lime kiln	Increased recycled content, plan to add deep eutectic solvents and membrane separation once adoption is estimated

Tissue Mill (Non-Integrated)

Table 24. Tissue Mill (Non-Integrated) Net-Zero Decarbonization Scenario Assumptions

Product(s)	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)	Material efficiency
Tissue, hygiene products	Batch stock optimization, refining upgrades, high consistency forming, paper machine vacuum system optimization, turbulent bars, air supply optimization, improved drying techniques, boiler heat recovery, through-air drying	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 80% biomass for through-air drying, 70% in auxiliary boiler, 12% hydrogen	33% post combustion carbon capture in boiler	No imported pulp, but can include this and other alternative pulps

Specialty Mill (Non-Integrated)

Table 25. Specialty Mill (Non-Integrated) Net-Zero Decarbonization Scenario Assumptions

Product(s)	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)	Material efficiency
Specialty paper and others	Batch stock optimization, refining upgrades, high consistency forming, paper machine vacuum optimization, air supply optimization, turbulent bars, shoe press and other press upgrades, coating nozzle upgrades, boiler heat recovery	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 80% biomass in auxiliary boiler	33% post combustion carbon capture in boiler	No imported pulp, but can include this and other alternative pulps

Recycled Mill (Non-Integrated)

Table 26. Recycled Mill (Non-Integrated) Net-Zero Decarbonization Scenario Assumptions

Product(s)	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)	Material efficiency
Recycled paper and paperboard	Continuous repulping, high consistency recovered fiber pulping, repulping rotor upgrades, batch stock optimization, deinking flotating optimization, refining upgrades, high consistency forming, press section upgrades, turbulent bars, air supply optimization, improved drying technologies, paper machine vacuum system optimization, boiler heat recovery	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 80% biomass in auxiliary boiler	33% post combustion carbon capture in boiler	None

Bleached Mill (Integrated)

Table 27. Bleached Mill (Integrated) Net-Zero Decarbonization Scenario Assumptions

Product(s)	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)	Material efficiency
Paper and paperboard	Debarking upgrades, chip screening & conditioning, advanced digestion additives, waste heat recovery (debarking, pulp machine, digestor, bleach plant, recovery boiler, auxiliary boiler), high efficiency refiners, additional evaporation effects, lime kiln modification, recovery boiler temperature monitoring, batch stock optimization, high consistency forming, press section upgrades, turbulent bars, air supply optimization, improved drying technologies, paper machine vacuum system optimization	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 100% biomass in repulping and lime kiln, and 80% in auxiliary boiler	33% post combustion carbon capture in boilers and lime kiln	Considered imported pulp, potential for alternative pulp

Unbleached Mill (Integrated)

Table 28. Unbleached Mill (Integrated) Net-Zero Decarbonization Scenario Assumptions

Product(s)	Energy efficiency	Electrification	Low carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)	Material efficiency
Paper and paperboard	Debarking upgrades, chip screening & conditioning, advanced digestion additives, waste heat recovery (debarking, pulp machine, digestor, recovery boiler, auxiliary boiler), high efficiency refiners, additional evaporation effects, lime kiln modification, recovery boiler temperature monitoring, batch stock optimization, high consistency forming, press section upgrades, turbulent bars, air supply optimization, improved drying technologies, paper machine vacuum system optimization	Electric boiler modification for auxiliary boiler, can include steam-generating heat pumps	Switch to 80% biomass in auxiliary boiler	33% post combustion carbon capture in boilers and lime kiln	Considered imported pulp, potential for alternative pulp

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