Washington State Industrial Emissions Analysis

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Introduction

Industry, especially "heavy" industry responsible for producing basic materials like metals, chemicals, and cement, tends to be highly carbon-intensive, generating high emissions per unit of economic value added. Emissions are typically associated with fossil fuel combustion, often for thermal energy needed to process raw materials, but also with chemical processes, such as the calcination of limestone for cement, that are an inherent part of production. Industry also tends to be capital-intensive, and many industries rely on fixed industrial "ecosystems" for energy and materials that lock in carbon-intensive methods of production. Moreover, basic material producers frequently compete in global markets, making costly transition efforts economically challenging.

Altogether, these characteristics make heavy industries "hard to abate." Decarbonizing these industries is not simply a matter of using cleaner fuels and improving efficiency, although these may be important strategies. The challenges are also technical and transformational: changing production systems, developing new infrastructure, and deploying new technologies to avoid or capture emissions in ways that are economically sustainable.

One implication is that, for many industries, decarbonizing is not a simple matter of choosing from a menu or cost curve of greenhouse gas emission abatement options. Instead, most studies look at industrial decarbonization "routes" or "pathways" that lay out a sequence of transformational steps needed to cost-effectively decarbonize over time, considering systemic interdependencies and scenarios for broader economic transformation, an example of which might be the development of a green hydrogen fuel economy.

The correct pathway for a particular industry will vary by its starting circumstances and geography. A basic prerequisite, therefore, is to understand in detail what these circumstances are. Key variables include energy intensities, types of fuel consumption, technical processes used, and structural interdependencies with other industries and value-chain partners.

In Washington State, current understanding of these variables for key industries is incomplete. Facility-level greenhouse gas reporting that provides information on total direct emissions by facility may not provide insight into quantities of fuels consumed; use of purchased electricity, heat, or steam; or the proportion of emissions attributable to fuel combustion, process emissions, and non-fuel energy consumption. A basic first step as identified in the 2021 State Energy Strategy is to improve data collection to develop robust, Washington-specific decarbonization roadmaps for industry emissions.

The Washington State Department of Commerce contracted with the Clean Energy Transition Institute (CETI) from January 1 to June 30, 2021 under contract #S19-52212-003, Task 5. Policy and Strategies Development to provide the following deliverables:

1. Suggest ideas for how Washington could achieve more detailed analysis of greenhouse gas emissions in the state's industrial facilities than is currently performed by the Department of Ecology.[1]

[1] Washington State Department of Ecology, "Facility Greenhouse Gas Reports," Facility greenhouse gas reports, 2021, https://ecology.wa.gov/Air-Climate/Climate-change/Greenhouse-gases/Greenhouse-gas-reporting/Facility-greenhouse-gas-reports.

2. Identify available data sources, data collection methods, and data-sharing mechanisms for greenhouse gas emissions from the state's industrial facilities.
3. Prepare a targeted analysis and case study on the potential for the manufacturing and use of green cement in Washington.

The CETI, in collaboration with the Stockholm Environment Institute-US (SEI-US), developed this report and its companion Excel document, *Washington State Industrial Emission Characterization Tables,* to provide these deliverables. In consultation with the Department of Commerce, the following industries were researched and analyzed, listed in order of emissions from most to least in Washington State:

- Pulp and Paper
- Petroleum Refineries
- Wood Products
- Food Processing
- Chemicals
- Cement
- Aerospace Manufacturing
- Glass
- Steel

The first section of this report, General Observations on Data Gaps, offers a short narrative about data gaps with a table of Common Industrial Data Gaps and Potential Sources or Estimation Methods.

The second section of this report, Industry Overviews, provides short descriptions of each industry, with descriptions of decarbonization strategies specific to each industry, and is meant to be read in conjunction with the Characterization Tables. These tables are organized in nine tabs in Excel, with a tab for each of the listed industries, as well as one for cement, for which we have written a roadmap case study that could be replicated in subsequent work for the other eight industries.

The Characterization Tables look at the upstream, production phase, and downstream emissions for each industry, describing the production processes for each industry and the dominant emission sources. There is a section labeled "Emissions Data Needed," which is divided into four color-coded columns labeled F (Fuel-yellow); E (Electricity-red); S (Steam-blue); and P (Process-gray). Columns are marked with an "X" where emissions data need to be collected.

In the column labeled "Key Supporting Information," the Characterization Tables provide facts about the industrial process for each sector that are relevant to understanding how the emissions are produced. This column is followed by one labeled "Data Reported under US SPA/Ecology GHGRP, in which known collected emissions information is noted.

The final two columns in the Characterization Tables are "Priorities for Additional Information" and "Potential Sources of Additional Information and Proposed Approach" in which are placed observations specific to each industry about what additional emissions information gathering should be prioritized and suggestions about how to go about obtaining the additional emissions data.

At the bottom of each tab is an energy flow diagram, reproduced from the U.S. Energy Information Administration's *Manufacturing Energy Consumption Survey* (MECS),[2] which indicates typical energy needs and fuel consumption specific to each industry considered. Combined with the Characterization Tables, these diagrams can provide helpful insights into current industrial energy and fuel intensities, including proportional amounts of electricity consumption (which typically are not reported under the GHGRP).

Each industry tab also lists the respective facilities that are currently reporting emissions to the Washington State Department of Ecology.

The Case Study on Green Cement is provided as a separate standalone document.

[2] U.S. Energy Information Administration, "2018 Manufacturing Energy Consumption Survey (MECS)," 2021, https://www.eia.gov/consumption/manufacturing/data/2018/.

1. General Observations on Data Gaps

For most industries, *direct* production-phase greenhouse gas emissions are well understood. For larger industrial facilities (>10,000 tonnes CO_2e emitted per year), these data are reported to Washington State under the Department of Ecology's greenhouse gas Reporting Program (GHGRP). In many cases, the GHGRP also captures specific types of fuels used and whether emissions arise from fuel combustion (fossil or biogenic) or direct (non-combustion) chemical processes.

Data already collected by Ecology therefore constitute a significant portion of the data needed to inform industry-wide decarbonization strategies, and much (if not all) of the data that might be needed for benchmarking GHG emissions at industrial facilities for allocation purposes under a cap-and-trade program.[3]

For reference, the Energy Futures Initiative report examining decarbonization strategies in California[4] relies almost exclusively on data reported to the California Air Resources Board (CARB) under its Mandatory Reporting Rule, which is analogous to Ecology's GHGRP, in summarizing data on industrial greenhouse emissions and fuel consumption. Similarly, CARB used this same dataset to establish industry-specific greenhouse gas emissions benchmarks for its cap-and-trade program.[5]

Nevertheless, for the purpose of developing comprehensive decarbonization strategies for Washington industries, there are some important categories of "missing" data. A comprehensive strategy, for example, might look at both direct and *indirect* greenhouse emissions associated with industrial production of goods and materials.

Indirect emissions include those associated with the offsite production of energy used by industrial facilities (e.g., purchased electricity, heat, and steam), as well as emissions generated throughout an industry's value chain, both upstream of production (e.g., mining, extraction, and transportation of raw materials used in production) and downstream (e.g., transportation, use, and disposal or recycling of finished industrial products). A comprehensive strategy would also address emissions at *smaller* production facilities that are not required to report to the GHGRP because they fall below the 10,000 tCO_2e/year threshold.

Table 1 provides an overview of common data gaps for Washington industries, along with general strategies that could be used to fill these gaps (i.e., how data could be obtained, or how emissions could be estimated where specific data are unavailable). Where relevant, more detailed indications of how to obtain or estimate data are provided in the accompanying document, *Washington State Industrial Emission Characterization Tables*.

[3] P Erickson and Michael Lazarus, "Issues and Options for Benchmarking Industrial GHG Emissions" (Stockholm Environment Institute (SEI), 2010), https://www.sei.org/publications/issues-options-benchmarking-industrial-ghg-emissions/.

[4] Melanie Kenderdine et al., "Optionality, Flexibility, & Innovation: Pathways for Deep Decarbonization in California" (Energy Futures Initiative, 2019), https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5cadebd04cd61c00017a563b/1554901977873/EFI+California+Summary+DE+PM.pdf.

[5] CARB, "Development of Product Benchmarks for Allowance Allocation (2010 Regulation, Appendix B to the First 15-Day Notice)" (California Air Resources Board, July 2011), https://ww2.arb.ca.gov/sites/default/files/classic/regact/2010/capandtrade10/candtappb.pdf.

Table 1. Common Industrial Emission Data Gaps and Potential Sources

	Data Gaps	Priority	Possible Sources and/or Estimation Methods
Production phase	GHG emissions from purchased electricity, heat, and steam. Quantities of electricity, heat, or steam produced offsite and used by large industrial facilities are *not* currently reported under the GHGRP. For most industries, these energy sources can constitute a significant – sometimes predominant – portion of the industry's total carbon footprint, especially those whose production is electricity intensive, such as electric arc furnace steel production.	High	Ecology is anticipating new requirements for industrial facilities to report data on purchased energy. Other options may include: ▪ For electricity, obtaining data from utilities on electricity sales to industrial customers ▪ For all energy, examining tax records for relevant energy generation facilities

	Facility-specific data on fuel consumption and combustion vs. non-combustion (process) GHG emissions. Under the GHGRP, reporters typically have the option to measure GHG emissions directly using continuous emissions monitoring systems (CEMS) rather than calculate emission on a "mass balance" basis using data on the types and quantities of fuels consumed and/or other data related to chemical processes that result in non-combustion GHG emissions. If CEMS are used, then in some cases Ecology may only have data on total GHG emissions, without insight into specific types of fuel consumption or what percentage emissions arises from fuel combustion vs. industrial processes. (This is true for Ash Grove cement, for example.)	Medium	Options here may include:
			▪ For large, single industrial facilities, directly interviewing the facility owners may be the simplest way to obtain this data
			▪ Where multiple facilities are involved, data could be estimated based on typical fuel consumption patterns and production processes used. Data could be obtained from (for example):
			  o U.S. EIA Manufacturers Energy Consumption Survey (MECS) data
			  o Interviews with industry associations
			  o Conducting state-specific audits of specific industries (similar to MECS)[6]

	Facility output data. To understand how facilities compare in terms of energy efficiency and/or emissions intensity, data on physical quantities and	Medium	Relevant output data is often reported under the GHGRP, so may be readily accessible, even if it is not publicly reported in all cases. (For example,

[6] California, for example, conducted an industry-wide audit of refineries as a benchmark for understanding energy consumption in this industry (ca. 10 years ago).

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	economic value of productive output is needed. This could be important for benchmarking exercises, for example, but could also be useful for understanding the "starting point" for Washington industries in the context of a decarbonization strategy. For some industries, multiple options may exist for measuring output. One question for cement, for example, is whether to benchmark against clinker production or final cement produced.[7]		hydrogen producers may report quantities of hydrogen produced.) Where output data are not readily available, options could include: ▪ For large, single industrial facilities, directly interviewing the facility owners ▪ Conducting state-specific audits of specific industries (similar to MECS) ▪ Incorporating output data in GHGRP requirements
	Data on equipment types and ages. Detailed information on industrial facility processes and equipment, including the age and depreciation of relevant equipment, could be useful in developing more detailed plans for industrial decarbonization	Low	GHGRP data often include information on the number and type of specific kinds of industrial production units (varies by industry). More detailed data *may* be available from: ▪ Property tax records ▪ Siting permits or other records filed with local air agencies
	GHG emissions, fuel consumption, and other data at smaller production facilities. For some industries, a significant data gap is understanding GHG emissions from smaller production facilities that fall below the GHGRP reporting threshold of 10,000 tCO_2e/year. Industries we reviewed for which smaller-scale production may be prevalent include: ▪ Cement and concrete[8] ▪ Chemicals ▪ Food processing ▪ Glass	High	Depending on the strategies being pursued, it may be sufficient to estimate energy use and emissions from smaller facilities. As a rule of thumb, for example, most direct fuel combustion at smaller facilities is likely to involve natural gas. Options for obtaining data may include: ▪ Working with electric and natural gas utilities to obtain information on sales to commercial/industrial customers ▪ Consulting local air agencies to identify facilities based on permit data

[7] Erickson and Lazarus, "Issues and Options for Benchmarking Industrial GHG Emissions."

[8] Washington has one cement plant (Ash Grove in Seattle). However, there are likely multiple concrete batch plants (producing ready-mix concrete) throughout the state, all of which fall below the GHGRP reporting threshold (this is true nationwide – there are no ready-mix concrete producers reporting to U.S. EPA's GHGRP). Identifying and obtaining data on concrete batch plants is particularly important because this is where (in the United States) most blending of cement with other materials occurs – a key strategy for reducing the overall emissions intensity of cement/concrete.

	▪ Wood products		▪ Interviewing relevant industry associations to obtain data on the number of in-state facilities and typical energy use ▪ Combining data from the above sources with typical industry-wide energy consumption data from the EIA MECS ▪ Possibly consulting data on energy use and demand-side management programs[9]
Upstream and downstream	Sources and types of raw materials used in production. All manufacturing and heavy industries rely on raw materials as inputs. For some kinds of materials, mining, extraction, or production emissions can be significant, e.g., mining of minerals used in cement and steel production, extraction of crude oil used in refineries and in the production of petrochemicals, agricultural production of unprocessed food, etc. Addressing these emissions could be an important part of a comprehensive industrial decarbonization strategy.	Low/ Medium	Although potentially important from a strategic standpoint, it may not be necessary to have detailed data on the precise sources of raw materials and the producers of these materials. One approach could be: ▪ Consult with large producers and/or industry associations about the typical origins of key raw materials ▪ Estimate associated emissions based on independent assessments of the emissions intensity of mining, extraction, or production. ▪ Use general estimates of transportation emissions based on known major sources of, and transportation modes for, industrial inputs
	Use and disposal phase activity data and emissions. For some industries, “downstream” use and/or disposal of products can be a significant source of total emissions (e.g., transportation fuels). For any industry, consideration of use and disposal practices could be an important part of a comprehensive decarbonization strategy, especially, for example, if there are opportunities to improve product design to promote	Low/Medium	As with upstream emissions, it may not be necessary to have detailed data on sources and quantities of downstream emissions. In many cases – at least for initial planning purposes – it could be sufficient to estimate emissions, as well as understand in broad terms what current relevant use and disposal practices are. Strategies could include: ▪ Consult with relevant industry associations

[9] The California Public Utilities Commission, for example, maintains a database on energy use and performance of utility demand-side management programs (https://cedars.sound-data.com/). The UTC may have similar data that could be accessed to identify energy use and savings for specific types of customers.

	durability and reuse, or there is untapped recycling potential.		▪ Consult waste reduction advocacy groups ▪ Review relevant "circular economy" literature ▪ Consult with waste management companies ▪ Review waste composition studies for Washington State[10]

[10] For example: https://apps.ecology.wa.gov/publications/documents/1607032.pdf

2. Industry Overviews

Pulp and Paper

Paper and paperboard manufacturing involves the processing of wood, recycled paper products, and other sources of cellulose fibers into pulp and ultimately into end-use paper products. Many pulp and paper facilities integrate the pulping and papermaking processes, but some are standalone pulp mills or paper production facilities.

According to 2019 state industrial emissions reporting data, there were 13 pulp and paper facilities in Washington with annual emissions over 10,000 metric tons of carbon pollution. Together, these pulp and paper facilities accounted for approximately 6.7 MMT CO_2e (34% of reported industrial greenhouse gas emissions), making pulp and paper the highest emitting industrial sector in Washington.

Six of the seven largest pulp and paper mills in Washington (accounting for over 80% of the industry's reported emissions) use the Kraft chemical pulping process, which involves cooking wood chips in sodium sulfide and sodium hydroxide chemicals at high temperature and pressure to dissolve the lignin in wood and extract cellulose fibers. The other large mill in Washington uses the less common sulfite chemical pulping process, while other smaller mills in Washington use thermomechanical pulping.

Onsite steam and electricity production used in the pulp and paper manufacturing process is the dominant source of the industry's greenhouse gas emissions. Black liquor, a by-product of the pulping process containing spent chemicals and biomass residues that is subsequently combusted in onsite boilers, represents the largest source of fuel for the pulp and paper industry.

There are also upstream and downstream emissions associated with the pulp and paper industry. Harvesting of trees for virgin wood results in a large amount of forest biomass residue that is typically disposed of via open burning at logging sites. On the downstream side, decomposition of unused organic residue from the pulp and paper manufacturing process (pulp and paper mill sludge), and post-consumer/post-industrial paper products disposed of in landfills, may contribute to greenhouse gas emissions.

Decarbonization Strategies

Pathways to fully decarbonizing the pulp and paper industry will likely involve a mix of energy efficiency strategies, more efficient fuel use, new pulping technologies, carbon capture, and circular economy strategies. Electrification potential is relatively low for the pulp and paper industry due to its use of high temperature process heat.[11]

- **Energy Use Efficiency.** Over 80% of the energy consumed by the pulp and paper industry comes from boiler fuel,[12] largely to produce process steam. Energy efficiency improvements to steam systems,

[11] Kenderdine et al., "Optionality, Flexibility, & Innovation: Pathways for Deep Decarbonization in California."

[12] U.S. Environmental Protection Agency, "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Manufacturing Industry" (U.S. Environmental Protection Agency, 2010), https://www.epa.gov/sites/production/files/2015-12/documents/pulpandpaper.pdf.

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therefore, represent the most significant opportunities for energy savings and emissions reductions in pulp and paper mills.[13]

- **Fuel Use Efficiency.** One promising decarbonization strategy is called black liquor gasification, which involves creating a clean syngas from black liquor, a byproduct of the pulping process. The syngas can then be used to produce electricity and process steam at higher efficiency than direct black liquor combustion in traditional recovery boilers. Syngas from black liquor gasification could also be used in biorefineries to produce biofuels and hydrogen, replacing the use of fossil fuels in other industries.

- **Low-Carbon Pulping Technology.** A new class of solvents, known as deep eutetic solvents, may be able to dissolve wood into pulp—extracting lignin, hemicellulose, and cellulose—with significantly less energy required compared to traditional chemical pulping processes. Research and development for deep eutetic solvents is currently underway in Europe with a plan for commercial implementation by 2030.[14]

- **Carbon Capture.** CO2 emissions from boilers that burn biomass residue leftover after pulping, and from lime kilns used in the Kraft chemical recovery process, may not be easily avoided. Carbon capture could be used to prevent these emissions from reaching the atmosphere, although the cost of carbon capture at pulp and paper mills has not been widely studied and remains relatively uncertain.[15] Furthermore, developing the carbon transportation and storage infrastructure needed to support carbon capture may be more challenging near pulp and paper mills, which tend to be in more remote locations near forest resources.

- **Material Efficiency.** Circular economy strategies, such as increased paper product recycling and utilization of biomass waste streams throughout the pulp and paper value chain (e.g., forest residues and pulp and paper mill sludge), could reduce energy use by the industry and replace fossil fuel use in other industries.

Petroleum Refineries

Petroleum refineries convert crude oil into petroleum products, such as transportation fuels. In the United States refining a 42-gallon barrel of crude oil produces, on average, about 19 to 20 gallons of gasoline, 11 to 13 gallons of diesel fuel, 3 to 4 gallons of jet fuel, and numerous other petroleum products used to make a variety of chemicals and plastics.[16] Washington State has five refineries that produce approximately 6,607,202 tons CO2e of greenhouse gases each year.[17] Although production methods at refineries can be complicated

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[13] Klaas Jan Kramer et al., "Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry" (Ernest Orlando Lawrence Berkeley National Laboratory, 2009), https://www.energystar.gov/sites/default/files/buildings/tools/Pulp_and_Paper_Energy_Guide.pdf.

[14] "PROVIDES," Institute for Sustainable Process Technology, accessed June 11, 2021, https://ispt.eu/projects/provides/.

[15] D. Leeson et al., "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources," *International Journal of Greenhouse Gas Control* 61 (June 1, 2017): 71–84, https://doi.org/10.1016/j.ijggc.2017.03.020.

[16] "Refining Crude Oil," U.S. Energy Information Administration (EIA), accessed July 5, 2021, https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil.php.

[17] Washington State Department of Ecology, "Facility Greenhouse Gas Reports."

(involving a range of different chemical processes and production pathways), all refinery production involves three basic steps:

- **Separation,** which involves piping crude oil through hot furnaces, based on differences in volatility, to separate these crude oil constituents into common boiling-point fractions.
- **Conversion,** where distillates are converted into lighter, higher-value products. Catalytic cracking is the most common process for conversion. Other types of conversion (e.g., alkylation and reforming) use chemical processes to rearrange molecules rather than splitting (or "cracking") them.
- **Treatment,** where petroleum products are stabilized and upgraded by separating them from less desirable products.

Decarbonization Strategies

With Washington State's emissions limits, liquid fuels used in the transportation sector are expected to be largely displaced by electricity by mid-century.[18] However, liquid fuels will continue to be part of the state's energy mix for transportation, buildings, industry, and electricity generation for decades to come. In addition to liquid fuels, refineries produce gaseous fuels and numerous other petroleum products that are used in thousands of consumer products and industrial processes. Demand for these other refinery products (or sustainable alternatives) is likely only to grow.

Therefore, decarbonization of the petroleum refining industry will involve a mix of reduced production, process emissions reductions, or capture at refineries, and a shift to clean fuels production. Meeting future demand for the clean fuels needed to achieve economy-wide decarbonization—especially biofuels, hydrogen and other electrofuels, and bioproducts—will be a significant opportunity to leverage the resources, knowhow, and workforce of the oil and gas industry. Expertise in the oil and gas industry may be applicable to broader industrial deployment of CCUS and the development of an offshore wind industry.[19]

- **Reduced Refinery Production**. The most affordable pathway to achieving Washington State's emissions limits involves widespread electrification of the transportation sector, displacing the use of liquid fossil fuels.[20] Following that pathway, demand for liquid fuels in Washington is expected to peak in 2025 and decline by over 60% by 2050. Liquid fossil fuels are expected to be phased out entirely by 2050, replaced by a mix of synthetic liquid fuels, liquid biofuels, and gaseous hydrogen. As demand for liquid fossil fuels declines, some existing refineries may be able to modify production processes to favor petrochemical production over liquid fuels.[21]
- **Refinery Energy Efficiency**. While the vast majority of emissions from the refining industry come from the use of the fuels produced, some emissions reductions can be achieved at refineries through

[18] Washington State Department of Commerce, "Washington 2021 State Energy Strategy" (Washington State Department of Commerce, 2020), https://www.commerce.wa.gov/growing-the-economy/energy/2021-state-energy-strategy/.

[19] International Energy Agency, "Net Zero by 2050 - A Roadmap for the Global Energy Sector" (International Energy Agency, 2021), https://www.iea.org/reports/net-zero-by-2050.

[20] Washington State Department of Commerce, "Washington 2021 State Energy Strategy."

[21] "Reduce, Repurpose, Reinvent: Long-Term Refinery Outlook Defined by Diverging Regional Imperatives," IHS Markit, 2020, https://ihsmarkit.com/research-analysis/reduce-repurpose-reinvent-longterm-refinery-outlook.html.

energy efficiency measures (e.g., improved operation and control, improved heat recovery, advanced process technology, utilities optimization, and hydrogen and fuel gas management).[22]

- **Carbon Capture, Utilization, and Storage.** The oil industry is also equipped with the technological and engineering capabilities to handle volumes of CO_2 and to support the scale up of CCUS, therefore, as a starting point it is an excellent option for partially decarbonizing the industry. It may be possible to implement carbon capture technology for numerous point sources at refineries, including furnaces and boilers, steam methane reformers (to produce blue hydrogen), and catalytic cracking units. However, numerous distinct sources of emissions and relatively dilute concentrations of CO_2 in flue gases from boilers, furnaces, and catalytic crackers at refineries suggest that carbon capture may be more expensive in comparison to other industries.[23]

- **Green Hydrogen (as a refining input).** As an alternative to implementing carbon capture at steam methane reformers, hydrogen used at refineries could be produced from carbon-free electricity by electrolyzers.

- **Clean Fuels.** The petroleum industry in Washington could directly contribute to production and deployment of synthetic liquid fuels, liquid biofuels, and hydrogen, leveraging its available equipment, technical knowledge, and fuels transportation experience. Petroleum refineries may be well positioned to shift toward green hydrogen production and support the decarbonization of hard-to-decarbonize industries given refineries' existing systems to handle and produce hydrogen. Additionally, numerous refineries in the U.S. have already pursued retrofits to enable production of renewable diesel or sustainable aviation fuels.[24] In the future, integrated biorefineries, like conventional refineries today, may be able to produce a range of products including biofuels, biopower, and bioproducts.[25] Bioproduct replacements for petrochemicals (e.g., bio-based propane, butane, ethane, naphtha, lubricants, waxes, and paints) are relatively nascent and have varying degrees of technical viability.[26]

Wood Products

Wood product manufacturing involves the production of intermediate and finished wood products such as lumber, plywood, veneers, wood containers, wood flooring, wood trusses, and prefabricated wood buildings. Harvested logs are made into wood products through processes including de-barking, sawing, drying, planing, shaping, smoothing, laminating, and assembling.

Onsite steam and electricity production used in the wood product manufacturing process is the dominant source of the industry's greenhouse gas emissions. Hogfuel (i.e., wood and bark sawmill residue) is typically

[22] Karen Law, Michael Chan, and Simon Mui, "Carbon Reduction Opportunities in the California Petroleum Industry" (NRDC, 2013), https://www.nrdc.org/sites/default/files/california-petroleum-carbon-reduction-IB.pdf.

[23] Leeson et al., "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources."

[24] "Reduce, Repurpose, Reinvent: Long-Term Refinery Outlook Defined by Diverging Regional Imperatives."

[25] "Integrated Biorefineries," Department of Energy, accessed June 24, 2021, https://www.energy.gov/eere/bioenergy/integrated-biorefineries.

[26] Deborah Gordon and Madhav Acharya, "Oil Shake-up: Refining Transitions in a Low-Carbon Economy" (Carnegie Endowment for International Peace, 2018), https://carnegieendowment.org/files/Gordon_DrivingChange_Article_April2018_final.pdf.

the largest source of fuel used onsite by the wood products industry. Fossil fuels are also used to power vehicles onsite.

There are also upstream and downstream emissions associated with the wood products industry. Harvesting of trees for virgin wood results in a large amount of forest biomass residue that is typically disposed of via open burning at logging sites. On the downstream side, decomposition of unused organic residue from the wood products manufacturing process (lumber mill residue), and post-consumer/post-industrial wood products disposed of in landfills, may contribute to greenhouse gas emissions.

According to 2019 state industrial emissions reporting data, there were 17 wood products facilities in Washington with annual emissions over 10,000 metric tons of carbon pollution. Together, these facilities accounted for approximately 1.3 MMT CO_2e (7% of reported industrial greenhouse gas emissions). Approximately 45% of the industry's emissions came from two lumber mills located in Aberdeen and Burlington/Mount Vernon.

Decarbonization Strategies

Pathways to decarbonizing the wood products industry will likely involve a mix of energy efficiency improvements, electrification, and circular economy strategies.

- **Energy Efficiency.** Emissions from electricity generation and onsite heat production could be reduced by installing energy efficient equipment at facilities and deploying systems for waste heat capture and reuse and combined heat and power.
- **Electrification**. Lower heat requirements than many other industrial subsectors enable electrification in wood products manufacturing, including solutions such as ultraviolet wood curing, industrial heat pumps, and electric machine drives.[27]
- **Material Efficiency**. Circular economy strategies, such as increased wood product recycling and use of biomass waste streams throughout the product value chain (e.g., forest residues and lumbermill/sawmill biomass residue), could reduce energy use by the industry and replace fossil fuel use in other industries.

Food Processing

Food processing facilities in Washington manufacture diverse products such as frozen French fries, juice, and dairy products. Together, large food processing facilities in Washington produced over 570,000 metric tons of CO_2e emissions in 2019.[28]

Major sources of greenhouse gas emissions from food processing facilities include fossil fuel combustion for heating, cooking, drying, and other processes; non-combustion processes, such as methane emissions from onsite wastewater treatment plants and hydrofluorocarbon emissions from refrigeration; and purchased electricity.[29] Steps involved in food processing typically include:

[27] Kenderdine et al., "Optionality, Flexibility, & Innovation: Pathways for Deep Decarbonization in California."

[28] Washington State Department of Ecology, "Facility Greenhouse Gas Reports."

[29] Erickson and Lazarus, "Issues and Options for Benchmarking Industrial GHG Emissions."

- **Inspection, Grading, and Washing**, involving a variety of electrical equipment including motors, conveyors, and pumps;
- **Processing**, including any of a wide variety of activities that can involve peeling, blanching, juice extraction, filtering, pasteurization, and others, depending on the particular product being made;
- **Freezing or Canning**, in which the products are frozen (using large quantities of electricity) or canned (often using large quantities of heat); and
- **Packaging**, in which the products are placed in their final packaging for shipment.

Decarbonization Strategies

Compared to industries with large thermal energy requirements and/or those that produce significant non-combustion related process emissions, decarbonization of food processing may be relatively straightforward. Food processing is still energy intensive, however, with significant heat and steam usage for some applications, like canning. Within the food processing industry itself, therefore in the production phase, prominent strategies will involve a combination of process optimization, waste reduction, energy efficiency, and electrification (Figure 1).

Electrification potential in the food industry (e.g., meeting thermal energy demand with electricity) is relatively high compared to other industries, given generally lower temperature heat requirements.[30] Large potential also exists for using biomass energy and biogas, as well as solar thermal and geothermal.[31] One option is to utilize biogenic methane generated from wastewater treatment plants that are often co-located with food processing facilities, which otherwise are the industry's largest source of process (non-combustion) greenhouse gas emissions. Over 15% of greenhouse gas emissions from Washington's largest food processors consists of methane from industrial wastewater treatment.[32]

As with other industries, however, a full decarbonization strategy is likely to involve interventions both upstream and downstream from food production (Figure 1). This could include efforts to reduce emissions from food production – including in the chemicals sector where synthetic fertilizers are produced – as well as efforts to shift food consumption patterns, e.g., away from energy-intensive processed foods towards less carbon-intensive food products, and to reduce food waste. Another area to target, both within the food processing industry and downstream, would be improving the energy efficiency of, and reducing refrigerant emissions (e.g., HFCs) from, refrigeration equipment.

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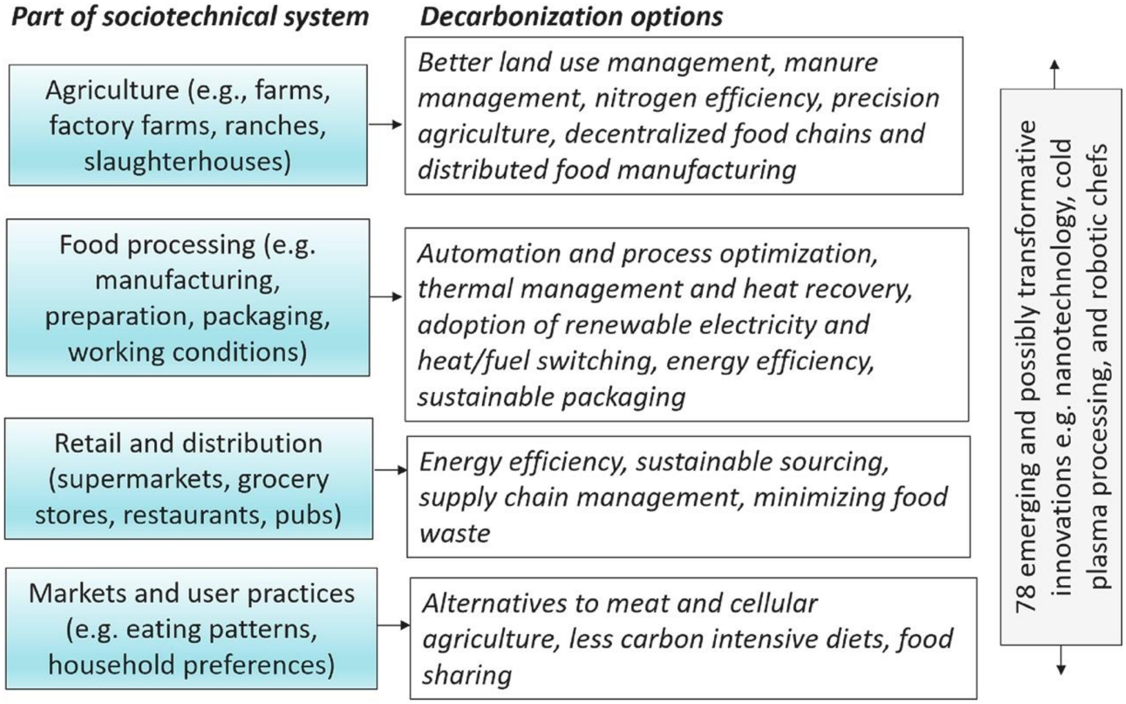
[30] Benjamin K. Sovacool et al., "Decarbonizing the Food and Beverages Industry: A Critical and Systematic Review of Developments, Sociotechnical Systems and Policy Options," *Renewable and Sustainable Energy Reviews* 143 (June 1, 2021): 110856, https://doi.org/10.1016/j.rser.2021.110856.

[31] Sovacool et al.

[32] Washington State Department of Ecology, "Facility Greenhouse Gas Reports."

Figure 1. Sociotechnical Options for Decarbonizing the Food and Beverage System[33]



Chemicals

Nationwide, the U.S. chemical industry is large and diverse, producing a wide array of both intermediate and final products used in goods and services throughout the economy. Supply chains, which extend domestically and internationally, are complex and intertwined. Although the industry is hardly monolithic, most chemical products (including fertilizers and plastics) are derived from fossil fuel feedstocks, especially petroleum, with petrochemicals at the base of a wide range of chemical supply chains.[34]

The industry is also energy intensive. Major sources of greenhouse gas emissions from chemical manufacturers include direct combustion of fossil fuels to produce heat, and non-combustion process emissions that occur from using fossil fuels and other raw materials as feedstocks.

In Washington State, the chemical industry includes numerous small companies that manufacture a variety of chemicals.[35] Most larger facilities are involved in producing chemicals related to fertilizer production. Agrium Kennewick Fertilizer Operations, for example, is the largest chemical-sector emitter in the state and produces nitrogenous fertilizer (which results in significant non-combustion N_2O emissions).

Solvay Chemicals and Air Liquide produce hydrogen and/or hydrogen derivates (e.g., hydrogen peroxide), which are used primarily to produce ammonia for fertilizer production. The process of reforming methane

[33] Sovacool et al., "Decarbonizing the Food and Beverages Industry."

[34] Peter G. Levi and Jonathan M. Cullen, "Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products," *Environmental Science & Technology* 52, no. 4 (February 20, 2018): 1725–34, https://doi.org/10.1021/acs.est.7b04573.

[35] Erickson and Lazarus, "Issues and Options for Benchmarking Industrial GHG Emissions."

(CH_4) to hydrogen (H_2) releases CO_2 as both a combustion emission and a process emission. Another large emitter, Emerald Kalama Chemicals, makes petrochemical additives for the food industry; the firm's primary source of emissions would likely be fuels used to heat multiple boilers and heaters.[36]

Decarbonization Strategies

As a whole, the chemical industry is particularly "hard to abate" because of its complexity (involving many intermediate products), and because interdependent industry segments have developed over time around fossil fuel-dependent production pathways.[37] Full decarbonization will require different strategies tailored to different industry segments. Petrochemicals incorporated in various products can be released during product use and disposal, so efforts to decarbonize the industry must look at full lifecycle emissions.[38]

Within the fertilizer and food production supply chains, key strategies will likely involve energy use efficiency and – where possible – electrification of energy. However, full decarbonization will likely require:

- **Use of Green (or Blue) Hydrogen** to produce ammonia. This could avoid process emissions associated with steam reformation of methane to produce hydrogen. Green hydrogen could also be used to supply thermal energy. One challenge, however, is that ammonia is typically converted to other compounds – primarily urea – to be used as fertilizer. Urea production requires a source of carbon, which today is typically the methane used in hydrogen/ammonia production.[39] Making urea "net zero" may require alternate sources of carbon, e.g., either derived from biomass or direct air capture.

- **Abatement of N_2O Emissions.** Nitric acid production generates substantial N_2O emissions if these emissions are not controlled. However, emissions can be cost-effectively reduced (typically by 95-98%, but up to 99%) using control technologies installed at oxidation reactors.[40] (The Agrium Kennewick plant does not currently use any control technology.)

Finally, given that use of green hydrogen and non-fossil sources of carbon are likely to be cost prohibitive for some time, another key strategy is likely to be **downstream efficiency improvements in fertilizer application, including use of nitrification inhibitors**.[41]

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[36] Erickson and Lazarus.

[37] Max Åhman, "Perspective: Unlocking the 'Hard to Abate' Sectors" (World Resources Institute, March 2020), https://files.wri.org/expert-perspective-ahman.pdf.

[38] Energy Transitions Commission, "Mission Possible Sectoral Focus: Plastics" (Energy Transitions Commission, January 2019), https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-plastics/.

[39] Andrea Valentini, "Decarbonising the Fertilizer Industry: Is Green Ammonia the Answer or Should We Focus Elsewhere?," *Argus Media* (blog), May 19, 2021, https://www.argusmedia.com/en/blog/2021/may/19/decarbonizing-the-fertilizer-industry-is-green-ammonia-the-answer-or-should-we-focus-elsewhere.

[40] Michael C. E. Groves and Alexander Sasonow, "Uhde EnviNOx® Technology for NOX and N2O Abatement: A Contribution to Reducing Emissions from Nitric Acid Plants," *Journal of Integrative Environmental Sciences* 7, no. sup1 (August 1, 2010): 211–22, https://doi.org/10.1080/19438151003621334; "Nitrous oxide emissions from nitric acid production," The Nitric Acid Climate Action Group, accessed June 16, 2021, http://www.nitricacidaction.org/about/nitrous-oxide-emissions-from-nitric-acid-production/.

[41] Justin Ahmed et al., "Reducing Agriculture Emissions through Improved Farming Practices" (McKinsey & Company, 2020), https://www.mckinsey.com/industries/agriculture/our-insights/reducing-agriculture-emissions-through-improved-farming-practices.

Aerospace Manufacturing

Aerospace manufacturing involves the production of aircraft parts from metal, carbon fiber, and other materials as well as aircraft assembly, testing, and delivery. Aircraft parts may be manufactured and assembled onsite or procured from outside contractors/suppliers.

The dominant sources of emissions from aerospace manufacturing are electricity use and onsite use of fossil fuels (typically natural gas) to generate electricity and heat for facility operations. A large portion of energy use in aerospace manufacturing is associated with aircraft surface finishing operations, including anodizing, plating, coatings, painting and stripping processes, and testing operations.[42]

According to 2019 Washington State industrial emissions reporting data, there were five aerospace manufacturing facilities in the state with annual emissions over 10,000 metric tons of carbon pollution. Together, these facilities accounted for approximately 0.15 MMT CO_2e (0.8% of reported industrial greenhouse gas emissions). All five facilities are owned by The Boeing Company.

Decarbonization Strategies

Pathways to eliminating greenhouse gas emissions from aerospace manufacturing will likely involve a mix of energy efficiency improvements, smart manufacturing processes, electrification, clean fuels, and circular economy strategies.

- **Energy Efficiency:** Emissions from electricity generation and onsite heat production could be reduced by installing energy efficient equipment at facilities and systems for waste heat capture reuse and combined heat and power.

- **Smart Manufacturing**. The use of modern information and communication technologies and process automation can reduce energy intensity of manufacturing (some estimates suggest that smart manufacturing can reduce industrial energy intensity by 20%).[43] Additive manufacturing, also known as 3-D printing, can use energy-intensive raw materials more efficiently by precisely forming and assembling parts and products.

- **Electrification**. Lower heat requirements than many other industrial subsectors enable electrification in aerospace manufacturing, including solutions such as industrial heat pumps and electric machine drives.[44]

- **Clean Fuels**. Where cheaper direct electrification is not possible, residual need for liquid and gaseous fuels can be met with low-carbon substitutes for fossil fuels, including renewable natural gas and electrofuels.

[42] "ENERGY STAR Focus on Energy Efficiency in Aerospace & Defense," Energy Star, accessed May 10, 2021, https://www.energystar.gov/industrial_plants/improve/energy_star_focus_energy_efficiency_aerospace.

[43] Ethan A Rogers, "The Energy Savings Potential of Smart Manufacturing" (American Council for an Energy-Efficient Economy (ACEEE), 2014), https://www.aceee.org/sites/default/files/publications/researchreports/ie1403.pdf.

[44] Kenderdine et al., "Optionality, Flexibility, & Innovation: Pathways for Deep Decarbonization in California."

- **Increased Carbon Fiber and Metal Recycling:** As much as 90% of airplanes by weight may be recyclable for parts reuse and scrap.[45] Some recycled aerospace-grade carbon fiber may be able to be reused in aircraft, while excess can used to make other products such as electronics accessories, car parts, and railcar undercarriages. Product designs that enable easy disassembly of parts and materials recovery may increase recycling potential.

Glass

Four main types of glass are manufactured in the United States: flat glass (e.g., windows); container (hollow) glass; fiberglass; and specialty glass. Glass is made primarily from silica sand with lime, soda, cullet (recycled glass), and other ingredients added. The mixture is then melted together at a high temperature.

Washington State is home to three major glass manufacturing facilities, including Cardinal Glass, a flat glass manufacturer in Winlock (near Chehalis); Ardagh Glass, a glass bottle manufacturer (and major glass recycler and supplier of wine bottles) in Seattle; and Owens-Illinois, a glass container manufacturer in Kalama. Together these facilities emit approximately 180,000 metric tons of greenhouse gases annually (Washington Dept. of Ecology 2019).

Glass manufacturing also is a major source of local air pollution and water pollution in Washington. According to the Washington State Department of Ecology air emissions inventory,[46] the Ardagh Group's glass recycling plant in South Seattle is the largest stationary source of particulate matter and sulfur dioxide in King County and has recently been cited for numerous violations by the Department of Ecology.[47]

Specific production methods can vary for different types of glass, but basic production steps include:

- **Batch Preparation and Mixing**, where silica (sand), soda, potash, and (in some cases) cullet are combined with stabilizers, including lime, magnesium oxide, and aluminum oxide. Materials are ground and mixed until a uniform mixture is obtained (the "batch" or "frit"), which is then melted in a furnace. Additives and refining agents may also be included.

- **Melting and Refining,** in which a raw material batch is fired in a furnace heated either by combustion or electricity or a combination of both, and sometimes using oxygen instead of regular combustion air to increase efficiency and reduce nitrous oxide emissions. Refining, which involves removal of bubbles, and homogenization, also occur in the furnace. In the U.S., most glass furnaces are fired by natural gas and some (especially container-glass furnaces) use electric boosters, as glass is a conductor at high temperatures. In such cases, electricity can represent up to 20% of the energy input to the furnace. Use of electric boost is less common in furnaces that produce flat glass.

- **Conditioning and Forming**, in which glass is transferred out of the furnace into a forehearth, where it is conditioned to have the desired temperature distribution, and then delivered to the forming

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[45] The Boeing Company, "Global Environment Report 2020" (The Boeing Company, 2020), https://www.boeing.com/resources/boeingdotcom/principles/environment/pdf/2020_environment_report.pdf.

[46] "Air Emissions Inventory," Washington State Department of Ecology, accessed June 30, 2021, https://ecology.wa.gov/Air-Climate/Air-quality/Air-quality-targets/Air-emissions-inventory.

[47] "King County Responsibility Lease Detail & Attestation Form," DocumentCloud, 2019, https://www.documentcloud.org/documents/6434979-King-County-Responsibility-Form-Ardagh.html.

equipment, where it is either shaped continuously (e.g., the float or rolled glass processes used to make flat glass) or separated into individual portions ("gobs") for blowing or pressing into containers.

- **Finishing,** in which various processes and treatments may be applied to affect glass characteristics. These steps may include annealing (reheating and cooling of the glass to remove stresses), toughening (also accomplished by a reheating, followed by rapid cooling with air jets), and coatings (e.g., mirrors).

Decarbonization Strategies

The high temperatures required to melt raw materials cause glass manufacturing to be highly energy intensive and have a high share of energy-related CO_2 emissions.[48] Glass manufacturing also has significant process emissions resulting from the melting of carbonate raw materials (limestone, dolomite, soda ash).

Therefore, decarbonization pathways for the glass industry will involve a combination of measures to reduce *energy-related emissions*, including fuel switching, electrification, waste heat recovery, and process intensification; and material efficiency strategies to avoid *process emissions*. Carbon capture, utilization and storage could also be used to mitigate process emissions, but its potential use in the glass industry has not been widely investigated and could face numerous challenges, including the tendency for glass manufacturing facilities to be relatively small and distributed, the presence of acidic compounds, and relatively low CO_2 concentrations in flue gas.[49]

- **Fuel Switching**. Carbon-free fuels, including biogas, synthetic methane, biomass, and green hydrogen, can be substituted for fossil fuels to provide high temperature process heat needed to melt raw materials and cullet. Numerous projects are currently underway in Europe and the United Kingdom to test the use of hydrogen for decarbonization of the glass industry.[50]

- **Electrification**. Alternatively, some process heating can potentially be electrified using electric melting furnaces technologies such as sub-merged electrodes, microwaves, and plasma. However, electric melting furnaces may not be suitable for all glass types.[51]

- **Waste Heat Recovery**. After waste heat is minimized as much as possible through equipment energy efficiency improvements and electrification, remaining waste heat can be recovered and reused to reduce overall energy demand and energy-related emissions. Waste heat can be reused for preheating of combustion gases, raw materials, and cullet; onsite building heating/cooling; electricity generation; or offsite heating needs through district heating systems.[52]

- **Process Intensification**. Incremental energy efficiency gains can be made by implementing various manufacturing process intensification measures, including use of advanced process controls,

[48] Michael Zier et al., "A Review of Decarbonization Options for the Glass Industry," *Energy Conversion and Management: X* 10 (June 1, 2021): 100083, https://doi.org/10.1016/j.ecmx.2021.100083.

[49] Glass Alliance Europe, "The European Glass Sector Contribution to a Climate Neutral Economy" (Glass Alliance Europe, 2019), https://www.glassallianceeurope.eu/images/para/gae-position-paper-on-decarbonisation-june-2019_file.pdf.

[50] "HyGlass," IN4climate.NRW, accessed July 6, 2021, https://www.in4climate.nrw/en/best-practice/projects/2020/hyglass/; "HyNet North West," HyNet North West, accessed July 6, 2021, https://hynet.co.uk/; "Kopernikus-Projekte," Kopernikus-Project: P2X, accessed July 6, 2021, https://www.kopernikus-projekte.de/en/projects/p2x.

[51] Zier et al., "A Review of Decarbonization Options for the Glass Industry."

[52] Zier et al.

adjustments to raw material preparation, and modifications to furnace and burner design and operation.[53]

- **Material Efficiency**. Increasing recycling of glass, which is limited to container glass and glass fibers, can significantly reduce CO_2 emissions from glass-making. However, the current rate of glass recycling is already high in the United States. Mixing recycled glass (cullet) with raw materials, or using cullet entirely, avoids both energy-related and process CO2 emissions. Cullet has a lower melting temperature than the raw materials used in glass-making, requiring less process heat. Carbonate raw materials (limestone, dolomite, soda ash) also directly release CO2 when heated for glass-making.[54]

Steel

Steel is produced from both virgin materials (primary iron extracted from iron ore) and secondary materials (scrap). The steel industry globally uses three dominant production pathways:

- The **Blast Furnace-Basic Oxygen Furnace (BF-BOF)** pathway involves the conversion of iron ore pellets into pig iron in a coke-fired blast furnace (BF) followed by the conversion of pig iron into steel in a basic oxygen furnace. Coke, used as a fuel in the BF, is a purified fossil fuel made by heating coal or oil in the absence of air. The BF-BOF process is typically integrated at a single plant along with the coke production, sintering, and pelletization processes. CO_2 is emitted at many points in the BF-BOF process, but the BF is the largest source of emissions.

- The **Scrap-Electric Arc Furnace (scrap-EAF)** pathway involves production of recycled steel from scrap materials. The scrap steel is melted for reuse in a furnace that heats charged material by means of an electric arc. Steel production from scrap using an electric arc furnace (EAF) is a lower emissions pathway, but there are still emissions from electricity generation and direct (process) emissions from consumption of carbon-containing electrodes and from scrap oxidizing.

- The **Direct Reduced Iron-Electric Arc Furnace (DRI-EAF)** pathway involves feeding direct reduced iron (DRI) into an electric arc furnace to produce steel. DRI, also referred to as sponge iron, is made by converting solid iron oxide into solid iron in the presence of high heat and a reducing syngas containing hydrogen and carbon monoxide, derived from natural gas or coal. Producing DRI from iron ore avoids the need for coking and sintering, but still produces carbon emissions from fossil fuel combustion and the use of syngas.

Globally, about two-thirds of steel is produced via the BF-BOF process, which uses mostly iron ore as its feedstock (with small amounts of scrap). In the United States, the majority of steel is produced using EAF, which is significantly less greenhouse gas-intensive, especially since the primary input is scrap metal. Only around 5% of current U.S. steel production currently uses DRI.

In Washington State, the only producer of crude steel is Nucor Steel in Seattle, which uses an EAF and relies exclusively on scrap to make steel rebar, flat bar, channel, and other similar products. After crude steel is cast, additional processes convert the steel to finished products at forges. One forge, Jorgenson Forge, is based in

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53 Zier et al.

54 Ecofys, "Methodology for the Free Allocation of Emission Allowances in the EU ETS Post 2012: Sector Report for the Glass Industry" (European Commission, 2009), https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm_study-glass_en.pdf.

Tukwila, WA. Together, Nucor Steel and Jorgensen Forge release an estimated 180,000 tons CO_2e of greenhouse gases each year (Washington Dept. of Ecology 2019).

Decarbonization Strategies

Decarbonization pathways for the steel industry will initially involve incremental emissions reduction strategies, such as material efficiency, technology performance improvements, and fuel shifting away from coal to less-carbon intensive alternatives, such as natural gas and bioenergy. Full decarbonization of the steel industry will rely on a mix of carbon capture and maturation of innovative steelmaking approaches, including many that use hydrogen.

- **Material Efficiency**. Nearly a third of the metallic raw material inputs to steelmaking globally come from recycled scrap steel, with steel recycling rates around 80-90%.[55] While recycled steel can be produced using scrap and EAFs with little or no CO_2 emissions, already high recycling rates and growing steel demand mean that increased recycling has a limited role in decarbonization. Material efficiency measures that reduce overall steel demand while delivering the same services (e.g., extended building lifetime, improved yields through additive manufacturing, building design improvements, vehicle lightweighting, etc.) have greater potential to reduce steel industry emissions.

- **Technology Performance Improvements**. The energy intensity of steelmaking processes can be reduced through modifications to existing processes, including installation of waste-heat recovery systems, process optimization through digitization, addition of top-pressure recovery turbines to blast furnaces, use of higher quality coke, use of higher iron content in ores.[56] However, technology performance improvements only reduce carbon emissions and must be used in combination with other strategies for deeper decarbonization of steel manufacturing.

- **Fuel Shifting (excluding hydrogen)**. Replacing coal use in steelmaking with alternatives, such as natural gas and bioenergy, can significantly reduce emissions. Natural gas and some forms of biomass can be injected into blast furnaces to reduce coal use. Gas can also be used in the DRI-EAF process, producing about 20% fewer direct emissions than the BF-BOF process using coal.[57]

- **Carbon Capture, Utilization, and Storage**. Carbon capture technology can be implemented at steel mills to reduce emissions. Captured CO_2 could then be either permanently stored underground or utilized by other industries. Implementing carbon capture may be operationally challenging at steel mills due to the number of different point sources of emissions (e.g., blast furnace, coke plant, sinter plant, etc.).[58] One solution could be combining flue gas streams to enable carbon capture at a single point.

- **Hydrogen-Based DRI-EAF Steelmaking**. The DRI-EAF process typically relies on natural gas, so entirely replacing gas with emissions-free hydrogen produced from renewable energy (or from natural gas with carbon capture) could enable a nearly emissions-free steel production process. This

[55] International Energy Agency, "Iron and Steel Technology Roadmap" (International Energy Agency, 2020), https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[56] International Energy Agency.

[57] International Energy Agency.

[58] Leeson et al., "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources."

decarbonization pathway would need to rely on a plentiful and cheap renewable electricity to produce large amounts of low-cost, emissions-free hydrogen.

- **Other Novel Steelmaking Processes**. In addition to the hydrogen-based DRI process, other new methods[59] for reducing iron oxides into iron are being developed that may reduce or eliminate process-related carbon emissions, including approaches that also use hydrogen as a reductant and others like Boston Metal's steelmaking process that uses electricity rather than hydrogen to directly reduce iron ore. It remains unclear which decarbonized steelmaking processes will most rapidly achieve cost competitive pricing and commercial scale.

[59] Mark Peplow, "Can Industry Decarbonize Steelmaking?," Chemical & Engineering News, 2021, https://cen.acs.org/environment/green-chemistry/steel-hydrogen-low-co2-startups/99/i22.

3. Conclusion

The goal of the research and analysis presented in this paper and the accompanying Excel document, *Washington State Industrial Emission Characterization Tables,* was to identify where and how to improve understanding of greenhouse gas emissions from Washington's major industries, for the purpose of identifying options for decarbonization.

Accordingly, the combined deliverables for this assignment describe the production processes and dominant emission sources for the upstream, production phase, and downstream emissions for nine Washington State industries; provide short overviews of possible decarbonization strategies for each industry; and identify where data gaps may exist for informing these strategies.

> Through leveraging existing data (especially data reported under Ecology's greenhouse gas reporting program) and closing identified data gaps, deep decarbonization pathways for Washington industries will be better understood and can be implemented in a way the meets the state's emission reduction goals while taking into account economic, workforce, and community considerations.

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