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Revision 0

Industrial Requirements Status Report and Down-Select of Candidate Technologies

May 2023

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ABSTRACT

The report discusses the potential for implementing Integrated Energy Systems (IES) using advanced nuclear reactors to provide thermal and electrical energy to carbon-emitting industries while reducing their carbon footprint. Nine different industries were reviewed to determine their decarbonization potential, opportunities for nuclear thermal integration, and the carbon footprint of each. The report also identifies specific integration points and streams for most processes, including temperature and pressure requirements of integrating nuclear power with industrial processes. The report also provides insights on advanced nuclear reactors and their potential for us in IES for decarbonization. The target audience for the report is broad, but mainly addressed to the industry leads and nuclear reactor developers. The report recommends that in the short term, a few processes should be identified to continue research and investigation so that front end engineering design work can provide technical analysis for integrating nuclear heat and replacing existing carbon-emitting thermal sources. The work emphasized the significant decarbonization opportunity across each of the technologies looked at as well as how novel and useful nuclear integration is to reduce the environmental impact of these significant industries.

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ACRONYMS

ABWR	advanced boiling water reactor
ACR	advanced CANDU reactor
AHWR	advanced heavy-water reactor
ALWR	advanced light-water reactor
APWR	advanced pressurized water reactor
BF-BOF	blast furnace followed by basic oxygen furnace
BOF	basic oxygen furnace
CWM	corn wet milling
DRI-EAF	direct reduction followed by electric arc furnace
FAS	free alongside ship
FT	Fischer-Tropsch
GCFR	gas-cooled fast reactor
GCR	gas-cooled reactor
GHG	greenhouse gas
GIF	Generation IV International Forum
HERON	holistic energy resource optimization network
HP	high pressure
HTGR	high-temperature gas-cooled reactor
HTSE	high-temperature steam electrolysis
IES	integrated energy system
LFR	lead-cooled faster reactor
LP	low pressure
LMFR	liquid metal fast reactor
MMSA	Methanol Market Services Asia
MMT	million metric tons
MP	medium pressure
MSR	molten salt reactor
NGNP	next generation nuclear plant
NSSC	neutral sulfite semichemical
PBMR	pebble bed modular reactor
PFD	process flow diagram
SFR	sodium-cooled fast reactor
SMNR	small modular (nuclear) reactor (nominally SMR, ‘N’ added to avoid conflict with steam methane reforming)

SMR	steam methane reforming (may be small modular reactor in context of specific nuclear small modular reactor design names)
TES	thermal energy storage
TRI	toxic release inventory
TRL	technology readiness level
UAN	urea ammonium nitrate
VHTR	very high-temperature reactor
WGS	water gas shift reaction
WSA	World Steel Association

1. INTRODUCTION

The United States has incentivized and formally declared various climate change mitigation policies which will require significant energy consumption changes across the United States energy profile. Non-renewable carbon sources account for around three-quarters of all domestic energy consumption, as noted in Figure 1. The two primary decarbonization targets of the United States include a 50% reduction in carbon emissions by 2030 (relative to 2005 levels) and full decarbonization by 2050 (United States Department of State and United States Executive Office of the President 2021). Replacing the energy source or offsetting the emissions of nearly 77 Quads (81.2 Exajoules, or an average load of about 2.6 TW) is a significant challenge that will require multiple simultaneous solution approaches including non-emitting power generation, electrification, and innovative process development. Less than 40% of the domestic energy consumption was used in electricity generation in 2021. Decarbonizing heat use is needed to achieve the aggressive goals put forward by the United States.

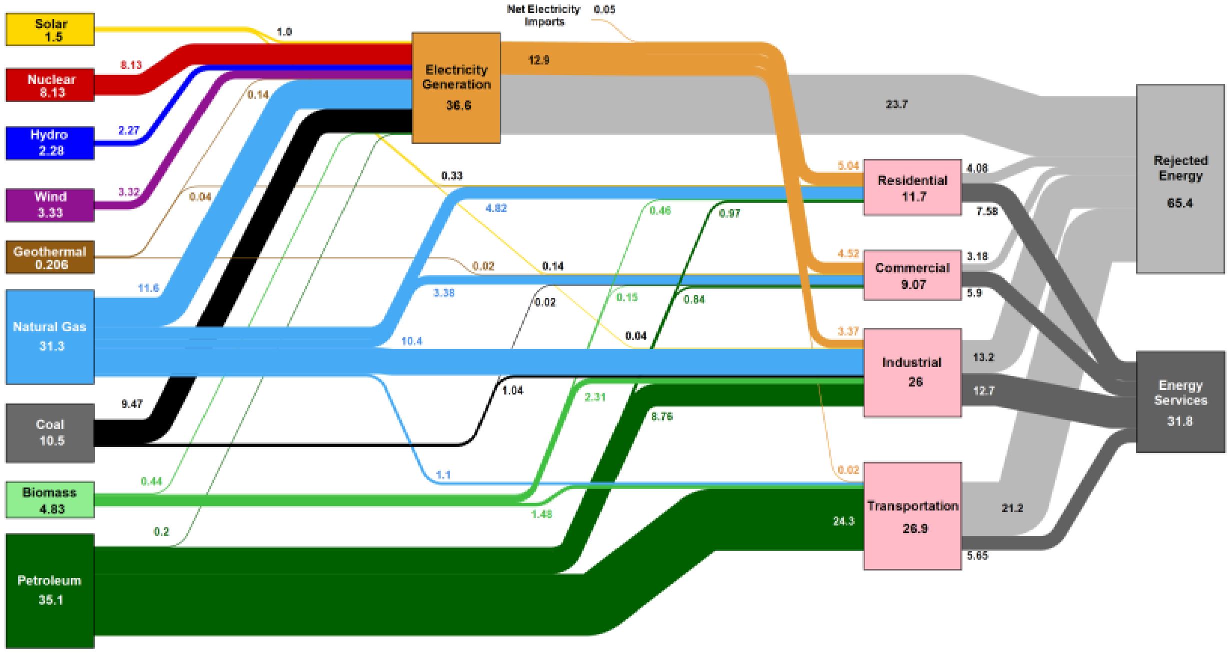

Figure 1. U.S. total energy Sankey Diagram (Lawrence Livermore National Laboratory and United States Department of Energy 2022).

The Integrated Energy Systems (IES) program of the Department of Energy (DOE) is evaluating the opportunity for nuclear-generated energy to replace energy sourced from petroleum, coal, and natural gas in various areas of the economy. Nuclear reactors are heat generators that have traditionally almost exclusively made domestic electricity at relatively low rates of thermal-to-electric conversion efficiency. As seen above in Figure 1, the majority of energy is consumed as heat either directly at end use or in the production of goods. Direct thermal energy use from nuclear is so far an untapped market.

Thermally integrating nuclear reactors with industrial users is complex for a variety of reasons including engineering, social, legal, and regulatory. The IES program is generating decision frameworks, databases, models, and technoeconomic analyses that can provide structure and insight into the operation and deployment of systems with integrated nuclear energy. Full technoeconomic analyses are termed “use cases” and they utilize the complete toolset of technical and economic analysis tools including engineering modeling leveraging the HYBRID analysis framework and economic uncertainty modeling leveraging the Holistic Energy Resource Optimization Network (HERON) software (Idaho National Laboratory n.d.-a, b; Frick et al. 2022).

Detailed process information is required to understand the opportunity for nuclear integration with particular industries. Compiling an understanding of the magnitude and conditions of energy flows within industrial processes is needed to engineer nuclear generated heat integration. This understanding needs to include internal material flows, specific thermal requirements of independently operated stages of industrial processes, and electrical requirements. To be specific, the differences must be characterized between internal and external loads, and process flow documentation must be developed that differentiates how heat is transported and consumed through a prototypical industrial plant. Figure 2 shows how various energy flows may interact within an integrated energy park.

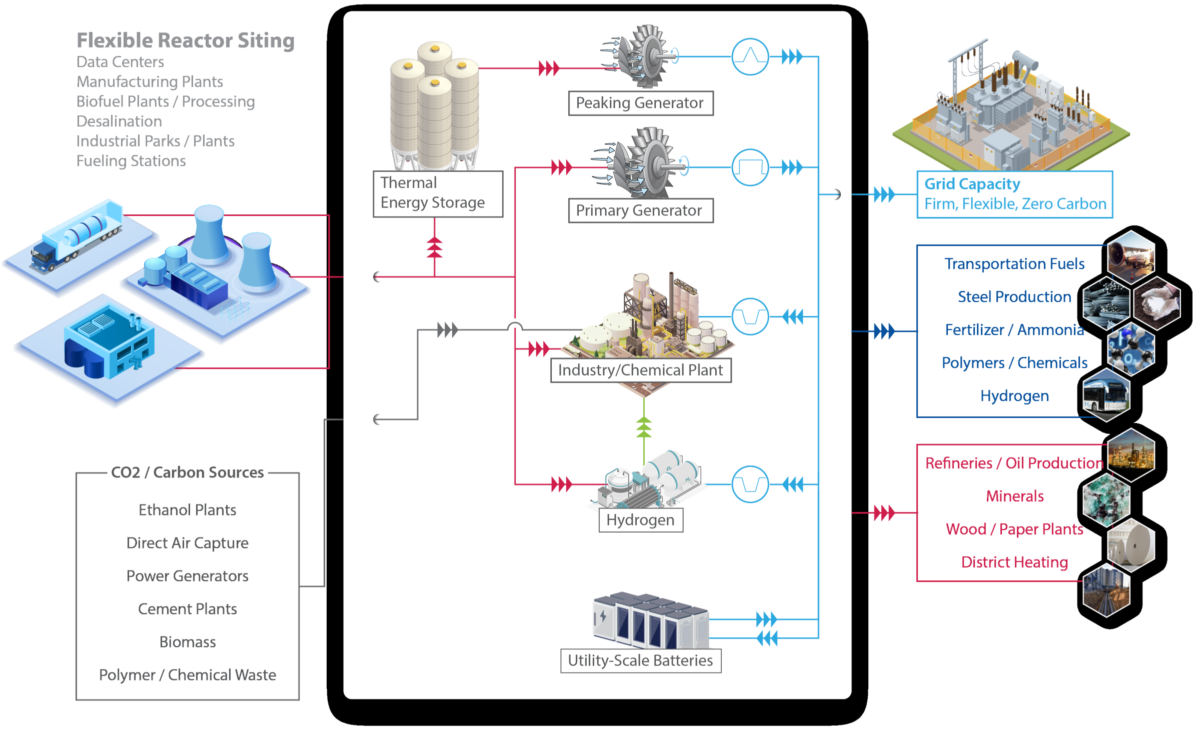

Figure 2. Energy flow diagram showing how nuclear power can be flexibly used across multiple industries.

To develop future use cases that will help address domestic decarbonization goals, the IES program has been reviewing industries that are use large quantities of thermal and electrical energy. This process has so far been done primarily through open literature studies and through the distribution of an industrial survey sent to existing contacts of IES leadership. This is to narrow down to a set of five candidate industries that will be studied through the rest of the fiscal year by IES program researchers: completing the documentation necessary to give the program a head start on future use cases with the candidate industries.

This work is also intended to leverage open-source information and publication where possible. The FORCE toolset, which includes HYBRID and HERON, is open-source. By generating open-source materials, national laboratory resources can maximize the impact to the taxpayer. Future work can focus generalized results to specific industrial parks.

In this report, the industrial survey is reported. In addition, an overview of advanced reactors is included. Various industries are detailed, and a few are selected as priorities in the conclusions.

2. INDUSTRIAL SURVEY

To develop an effective decarbonization plan using nuclear reactors integration with industrial processes, we conducted a survey that was shared with partners in various industrial companies. The survey was carefully crafted and shared with relevant industrial points of contact. The goal of the survey was to gather information on current process flow streams and energy consumption patterns, and to identify opportunities for integrating nuclear reactors into industrial processes.

2.1 Industrial Survey Questions

The survey questions aimed to gather information about a wide range of industrial processes, including manufacturing, chemical, energy production and distribution, agriculture, transportation, and other related industries. Although the IES team has received some responses, we are still actively collecting data to improve the comprehensiveness of our analysis. The survey link is currently active, at least until the publication date of this report. The survey can be accessed using the following URL: [https://inlhrfedramp.gov1.qualtrics.com/jfe/form/SV_02sXEonBQBJVYma].

2.1.1 Question 1

Select the industrial process(es) that are of interest to your company.

☐ Hydrogen Production
☐ Concrete Production
☐ Synthetic Fuels Production
☐ BioFuel Production
☐ Carbon Sequestration
☐ Glass Production
☐ Paper Production
☐ Steel
☐ Polymers
☐ Ammonia
☐ Minerals
☐ Desalination
☐ Oil Refining
☐ Mining
☐ Drilling
☐ Petrochemicals
☐ Chemicals
☐ Oil production.

2.1.2 Question 2

Describe current carbon-reduction goals and strategies proposed by your company, if applicable.

2.1.3 Question 3

Is integration of integrated energy systems with an advanced nuclear reactor of interest to your industrial process?

☐ Yes ☐ No ☐ Possibly

2.1.4 Question 4

Within what timeframe do you envision integrating your system with IES-TES (assuming the commercial system was immediately available)?

☐ Immediately ☐ 1–5 Years ☐ 6-10 Years ☐ >10 Years ☐ I don’t know ☐ N/A

2.1.5 Question 5

Rank your company’s primary research needs that would help accelerate the implementation of IES at your company. Drag and drop the options below in order of priority.

Drag and drop the options below in order of priority.
1 = Highest priority / 5 = Lowest priority

Priority No.		Priority No.	
________	Economic Viability	________	Black Start Capability
________	System Safety	________	Decarbonization
________	Integration Points	________	Product diversification
________	System Control (i.e., operation modes, transient smoothing)	________	Capital investment

2.1.6 Question 6

Please provide the following.

	Temperatures, pressures, mass flow rates, and process information, if applicable	1 = Highest priority 3 = Lowest priority 1	2	3
Steam pressures and temperatures		☐	☐	☐
Temperatures and pressures for processes which consume conventional heating fuel (e.g., natural gas)		☐	☐	☐
Processes in your facilities that use external heat and/or electricity		☐	☐	☐

2.1.7 Question 7

What are the external steam, heat, and electricity loads (i.e., kWe or kWth loads) required by your plants (either typically, or any specifically those that would be best fits for IES)?

	Typical (kWe) Load	Typical (kWth) Load	IES Interest (kWe) Load	IES Interest (kWth) Load
External steam				
Heat				
Electricity				

2.1.8 Question 8

What is the priority for the following forms of energy output from an IES or TES-assisted system would best fit your operation or process requirements and goals for incremental decarbonization?

	High Priority	Medium Priority	Low Priority	N/A
Electricity	☐	☐	☐	☐
Heat augmentation via heat exchangers (i.e., not sensitive to heat transfer fluid)	☐	☐	☐	☐
Heat transfer fluid	☐	☐	☐	☐
Hot oil	☐	☐	☐	☐
Hot water	☐	☐	☐	☐
Steam	☐	☐	☐	☐
Other, please describe:	☐	☐	☐	☐

2.1.9 Question 9

Describe a generalized energy demand schedule for your plant and the energy form (electricity, steam pressure and temperature, etc.) under normal operating conditions (e.g., 24/7/365, batch-style periodic in short duration).

Optional: You may upload a demand schedule.

2.1.10 Question 10

Is your company interested in learning more about how advanced reactor demonstration capabilities and reactor coupling with industrial processes (i.e., integrated energy systems) can decarbonize your facility, company, and processes? Optional: Please include any information in support of your selection in the box provided below.

☐ Yes ☐ No ☐ Possibly

Comments:

2.1.11 Question 11

If there are factors we neglected to consider that are extremely important, please include them below.

2.1.12 Question 12

Is your facility currently set up to sell excess electricity generation to the grid?

☐ Yes ☐ No

3. OVERVIEW OF ADVANCED REACTORS

While demand for industrial heat is significant and currently largely met by fossil fuel sources, this has resulted in a considerable environmental impact due to greenhouse gas emissions. To address this issue, the use of advanced nuclear reactors for industrial heat production is gaining attention as a promising alternative. Coupling advanced nuclear reactors with industrial heat users offers a range of benefits, including a source of reliable, clean, and cost-effective energy for industries that require high-temperature heat, such as hydrogen, ammonia, mining, steel, district heating, and several energy products discussed in this study.

Unlike traditional nuclear reactors, advanced reactors are designed to use non-traditional types of fuel and coolant fluids that allow them to operate at higher temperatures, making them particularly well-suited for coupling with industrial heat users. To continue and expand the environmental benefits of existing nuclear power plants operating globally, new advanced reactors need to be designed and developed to replace older plants as they retire. The Generation IV International Forum (GIF) is an international forum forming a technology roadmap for examining and developing these new nuclear systems with a focus on the nuclear reactor and its energy conversion systems, as well as the facilities related to the fuel cycle, extraction, and waste disposal, which are crucial for overall performance and capability (Abram 2002).

Private industries are currently developing numerous advanced nuclear reactors, often with the help of federal research laboratories. These advanced reactors are primarily categorized based on the type of coolant they use as follows:

- Liquid metal fast reactors (LMFR)
  - Sodium-cooled fast reactors (SFR)
  - Lead-cooled fast reactors (LFR)
- Water-cooled reactors
  - Advanced light-water reactors (ALWRs), including pressurized water reactors (APWR) and boiling water reactors (ABWR)
  - Advanced heavy water reactors (AHWR)
- Gas-cooled reactors (GCR)
  - Gas-cooled fast reactors (GCFR)
  - High-temperature gas-cooled reactors (HTGR) or very high-temperature reactors (VHTR)
- Molten-salt reactors (MSR)
  - Molten salt cooled reactors
  - Molten salt fueled reactors

For the purpose of coupling nuclear systems with industrial applications, the four main types of nuclear reactors selected and identified as potential options for industrial decarbonization are: HTGRs, LMFRs, MSRs, and (ALWRs). One reasonable option is to categorize advanced reactor systems based on their thermal output and operating temperature range. Table 1 shows three operating temperature ranges identified: low (<350°C) for ALWR and heavy-water reactors, medium (350–650°C) for MSRs, SFRs, and LFRs, and high (>650°C) for GCRs and HTGRs or VHTRs. Each of these categories was further divided into three subcategories: micro/small (<25 MWth) for microreactors, small to medium (25–750 MWth) for small modular reactors (SMRs), and large NPPs (>750 MWth).

Table 1. Classification of advanced NPPs, based on their operating temperature ranges and thermal outputs.

Low Temperature ~(<350°C)			Medium Temperature ~(350–650°C)			High Temperature ~(>650°C)		
<25 MWth	20–700 MWth	>700 MWth	<25 MWth	20–700 MWth	>700 MWth	<25 MWth	20–700 MWth	>700 MWth

Microreactors	SMRs/medium	Larger NPPs	Microreactors	SMRs/medium	Larger NPPs	Microreactors	SMRs/medium	Larger NPPs
—	APWR	AHWR	Heatpipes	MSR	GCFR	Heatpipes	HTGR	HTGR
—	IPWR	ABWR	HTGR*	LFR	SFR	HTGR	GCFR	—
—	—	APWR	—	SFR	MSR	—	MSR*	—

The temperature requirements for heat applications can vary widely depending on the specific use. Barnert et al. (Barnert, Krett, and Kupitz 1991) presented a visual representation of this variation and how it corresponds to several nuclear reactor types, as shown in Figure 3, including the temperature requirements range from just above room temperature for applications such as hot water and steam for agriculture (agro) industry, district heating, and sea water desalination, to as high as 1000° Celsius for applications such as process steam and heat for the chemical industry, high-pressure injection steam for enhanced oil recovery, oil shale and oil sand processing, oil refinery processes, olefine production, and coal and lignite refinement. Water splitting for hydrogen production requires even higher temperatures. The use of nuclear energy for supplying process heat is limited to an upper temperature limit of 1000°C based on the current design of advanced nuclear systems. Some industrial processes, such as steel production, require temperatures above 1000°C, and in such cases, nuclear energy may still be utilized through secondary energy carriers such as electricity, hydrogen, and synthesis gas as described further in the relevant subsequent sections in this report.

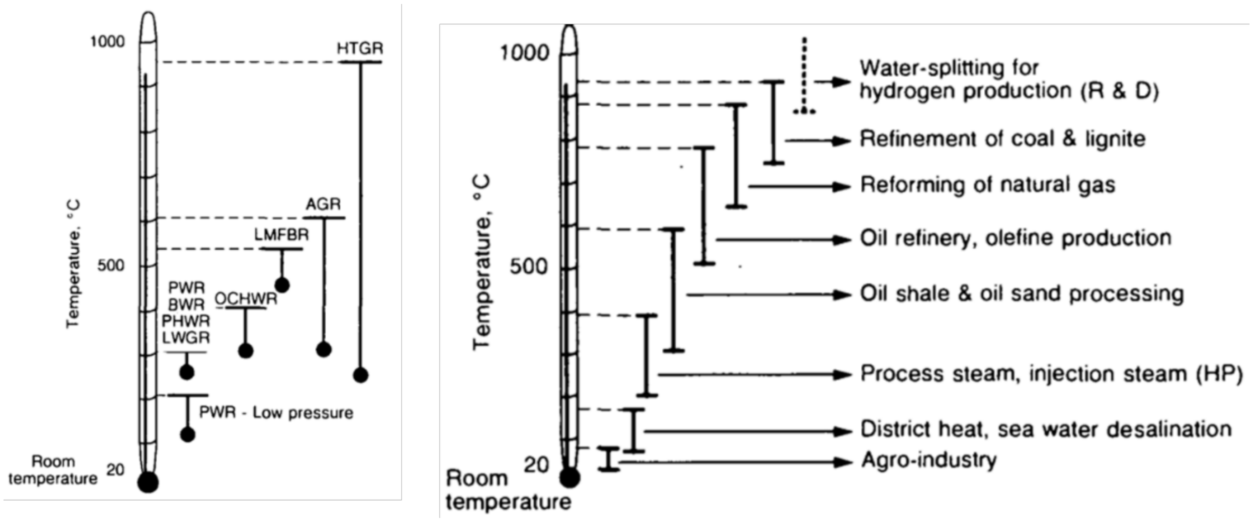

Figure 3. Visual representation of a few industrial applications and how they correspond to several nuclear reactor types (Barnert, Krett, and Kupitz 1991).

3.1 High-Temperature Gas Reactors

High-temperature gas-cooled reactors are a promising technology for decarbonizing industrial applications due to their ability to provide relatively higher temperature heat for a range of industrial processes. HTGRs utilize helium gas as a coolant and graphite as a moderator, enabling them to operate at higher temperatures than conventional nuclear reactors, up to 1000°C for the VHTRs. This high-temperature operation makes them well-suited for supplying heat to industrial processes that require temperatures of up to 900°C, such as chemical manufacturing, hydrogen, steel production, and cement production.

One key advantage of HTGRs for industrial applications is their high efficiency. Because they operate at high temperatures, they can achieve higher conversion efficiencies than conventional fossil fuel-based heat sources, resulting in lower emissions and reduced fuel consumption. HTGRs can also be designed for cogeneration, in which both electricity and heat are produced, further improving their efficiency, and reducing the overall cost of energy production.

Another advantage of HTGRs for industrial decarbonization is their inherent safety features. The use of helium gas as a coolant eliminates the possibility of a coolant leak, and the graphite moderator has a high melting point and low coefficient of thermal expansion, reducing the risk of structural failure (Reitsma, Silady, and Kunitomi 2014).

Figure 4 shows a schematic of a graphite-moderated and helium-cooled VHTR system that can be utilized for both electricity and hydrogen cogeneration. The reactor core typically is either a prismatic block or a pebble bed design, with an initial target temperature of 1000°C for hydrogen production. The first VHTR, the Pebble bed modular reactor (PBMR), was planned for construction in South Africa, with temperatures of 950°C, but it lost government funding in 2010 (Buckthorpe 2017). In 2012, China began constructing a 200-MW high-temperature pebble bed reactor, with design outlet temperatures of 750°C. Many national programs are considering the deployment of HTR within Generation IV, and some are planning to construct a prototype that uses gas outlet temperatures ranging from 750°C to 850°C.

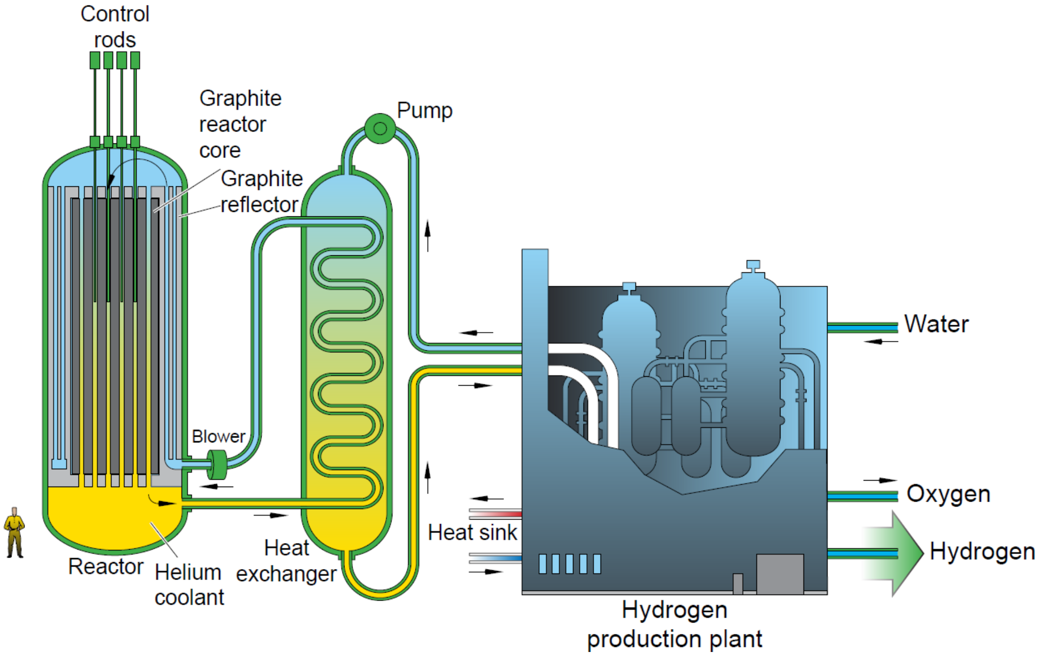

Figure 4. Schematic diagram of a very-high-temperature reactor (Buckthorpe 2017).

3.2 Liquid Metal Fast Reactors

Liquid metal fast reactors are a type of nuclear reactor that utilizes liquid metal (usually sodium or lead) as both the coolant and the neutron moderator. LMFRs are capable of high-temperature operation and can achieve very high conversion efficiencies due to their fast-neutron spectrum, making them a promising technology for decarbonizing industrial applications.

The medium- to high--temperature operation of LMFRs allows them to co-supply heat to industrial processes that require temperatures up to 570°C, such as hydrogen production, metal smelting, and glass manufacturing (Peakman and Merk 2019). LMFRs can also be designed for cogeneration, in which both electricity and heat are produced, further improving their efficiency and reducing the overall cost of energy production.

LMFRs also have the potential to improve the sustainability of the nuclear fuel cycle. Because they operate on a fast-neutron spectrum, they can utilize fertile materials (i.e., depleted uranium and thorium) as fuel, in addition to traditional enriched uranium and plutonium fuels. This has the potential to reduce the amount of high-level nuclear waste generated by the nuclear fuel cycle, while also improving the sustainability and security of the fuel supply.

Figure 5 shows a diagram for a possible design of an SFR. While the significant past experience accumulated with LMFR designs (specifically in Europe for SFRs) means that this system can be deployed earlier than other advanced reactor prototypes, there are challenges to be addressed in the deployment of LMFRs for industrial decarbonization, including the relatively high capital costs associated with building and deploying the reactor relative to other reactor types (Cochran 2015).

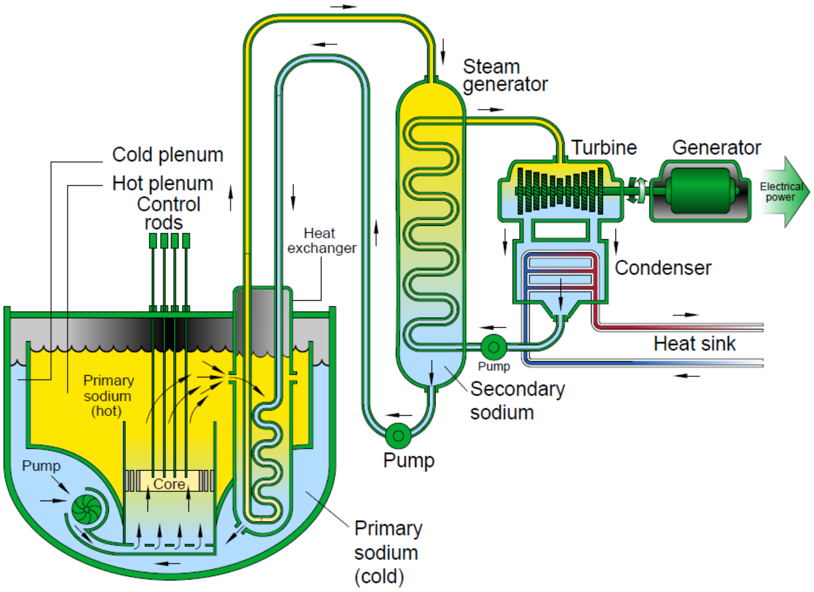

Figure 5. Schematic diagram of sodium-cooled fast reactor (Buckthorpe 2017).

3.3 Molten Salt Reactors

Molten Salt Reactors (MSRs) are a type of nuclear reactor that uses a liquid mixture of salts as both the coolant and the fuel carrier. MSRs have several unique features that make them a promising technology for decarbonizing industrial applications. One key advantage of MSRs is their ability to operate at high temperatures, up to 750°C or higher, which makes them well-suited for supplying high-temperature process heat for a range of industrial processes (Serp et al. 2014).

MSRs can also utilize a variety of fuels, including thorium, uranium, and plutonium, as well as spent nuclear fuel, which could help reduce the amount of nuclear waste generated by the nuclear fuel cycle (Humphrey and Khandaker 2018). A typical MSR has a sodium fluoride salt coolant, which contains dissolved uranium fuel. The coolant flows through channels in the graphite core for moderation. The fission products are continually removed and the actinides have to be fully recycled, while plutonium and other actinides can be introduced into the reactor, along with U238, without requiring fuel fabrication. This means that MSRs have the potential to operate on a continuous basis rather than requiring shutdowns for refueling. In addition, MSRs have a built-in safety feature, in which the fuel mixture expands as it heats up, which reduces the reactor's reactivity and prevents the possibility of a runaway chain reaction.

Figure 6 shows a diagram for a possible design of an MSR. Despite its potential, there are still technical and regulatory challenges to be addressed in the deployment of MSRs for industrial decarbonization. These include the need for advanced materials that can withstand the highly corrosive salt mixture, specifically for cogeneration and heat extraction via heat exchangers from the molten salt loop, and the need for regulatory frameworks that can accommodate the unique features of MSRs. Overall, MSRs have the potential to play an important role in decarbonizing industrial processes and reducing greenhouse gas emissions, and ongoing research and development efforts are focused on overcoming the challenges and realizing this potential.

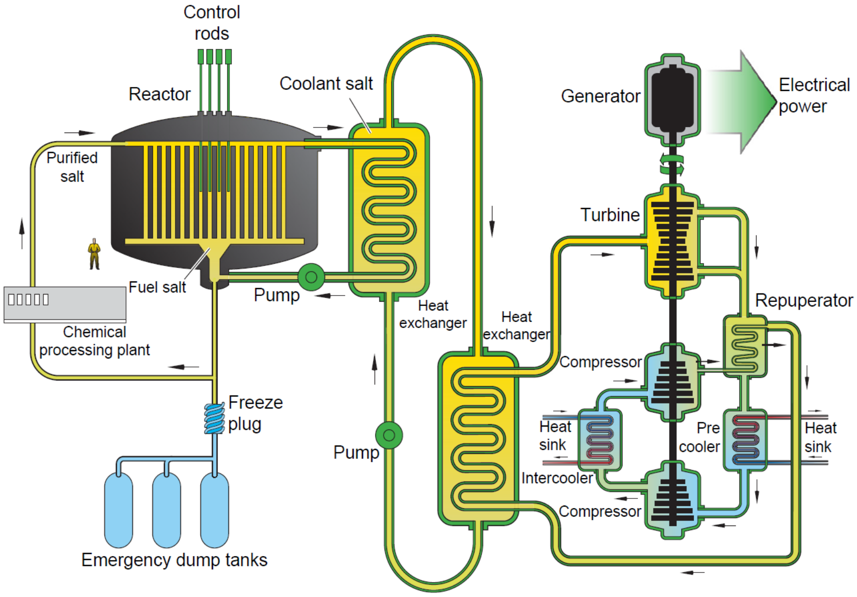

Figure 6. Schematic diagram of sodium-cooled fast reactor (Buckthorpe 2017).

3.4 Advanced Light-Water Reactors

Advanced light-water reactors are a type of nuclear reactor that builds on the design of existing LWRs with advanced features and improvements. ALWRs are designed to have fewer active safety systems and are more efficient and more flexible than previous generations of LWRs. These features make them well-suited for decarbonizing industrial applications. ALWRs use light-water as both the coolant and the neutron moderator, and they typically operate at higher temperatures and pressures than earlier LWR designs.

One promising ALWR design for industrial decarbonization is the Small Modular Reactor (SMNR[1]). SMNRs are smaller and more compact than traditional nuclear reactors, which allows them to be manufactured and transported more easily. SMNRs can also be deployed in remote or off-grid locations, where they can provide reliable and low-carbon electricity and heat for industrial processes. As it relates to their potential for industrial decarbonization, ALWRs build upon a proven track record of safety and reliability, with decades of operational experience in nuclear power plants around the world. ALWRs are also designed with advanced safety features, such as passive cooling systems, which make them more resilient to accidents or other events.

The typical fluid temperatures for ALWRs are generally higher than those of traditional LWRs. ALWRs typically operate at fluid temperatures up to 350°C and pressures between 10–15 MPa.

Supercritical water-cooled reactors are also promising for industrial decarbonization, though they are still under development with conceptual designs. Figure 7 shows a diagram of a supercritical ALWR represented within the GIF forum, also known as supercritical water-cooled reactor (SCWR). The design employs water above the thermodynamic critical point (374°C, 22 MPa), which results in higher thermal efficiency compared to current light-water reactors. The supercritical water drives the turbine directly, without the need for a secondary steam system. Such design allows the plant to operate at higher pressure and temperatures, offering a significant increase in thermal efficiency (~44% or more, offering up to 33% efficient improvement over current LWR designs) (Schulenberg and Leung 2023, Rahman et al. 2020). The SCWR employs uranium oxide fuel, which is dissolved in the supercritical water, and is enriched in the case of the open fuel cycle option. The reactor operates in a direct, once-through cycle, similar to the

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[1] Note that SMR is the traditional acronym both for small modular reactor within the nuclear industry and steam methane reforming in processes producing hydrogen. For this report, SMNR will address small modular [nuclear] reactors

PWR, and employs a thermal-neutron or fast-neutron spectrum with light- or heavy-water moderation.

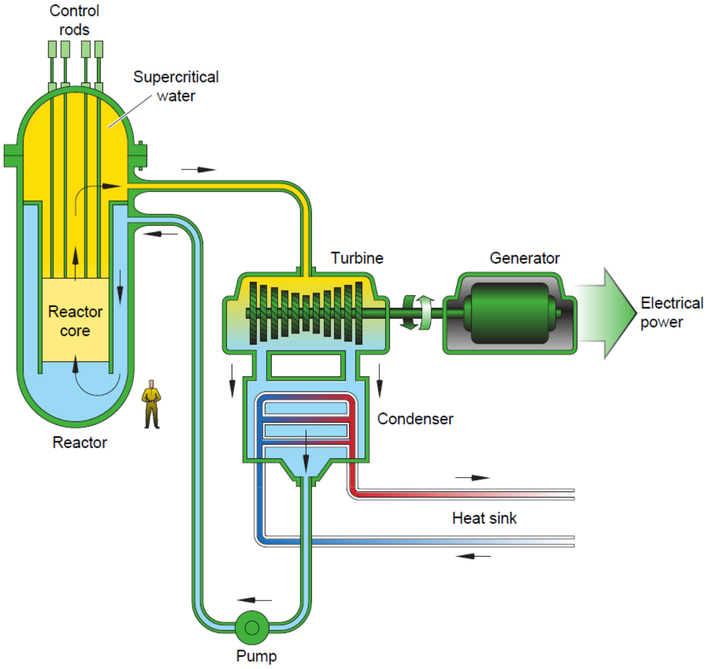


Figure 7. Schematic diagram of supercritical ALWR (Buckthorpe 2017).

However, because supercritical water has different chemical properties from liquid water, and because it requires a higher operating temperature, materials used in traditional reactors may not be suitable for an SCWR (Prchal et al. 2009). Materials used in fuel cladding and pressure tube designs will require much longer expected lifetimes, and there is ongoing work to characterize the mechanical properties of candidate alloys. Additionally, the SCWR presents challenges in high-temperature creep and strength, irradiation, stress corrosion cracking, corrosion, and water chemistry stability, all of which impact safety. No reactors have so far been built using supercritical water as the coolant. Typical ALWRs and SMRs remain a more realistic target for A-LWR integration with industrial process, at least in the short term.

4. INDUSTRIAL TECHNOLOGIES REVIEWED

Various industrial technologies known for their significant carbon emissions were evaluated. The objective of this review was to assess their potential integration with nuclear technologies. In this section, the findings and insights gathered from the evaluation process are discussed.

4.1 Ammonia

Ammonia, comprised of hydrogen and nitrogen atoms (NH_3), is the second-largest chemical product produced in the world. Ammonia is a primary feedstock of fertilizer supporting half of the global population but requires significant energy consumption, about 1.8% of global energy use and more than half of hydrogen use, and results in significant CO_2 emissions. Five hundred million tonnes of carbon dioxide are produced as a byproduct during the process (The Royal Society 2020).

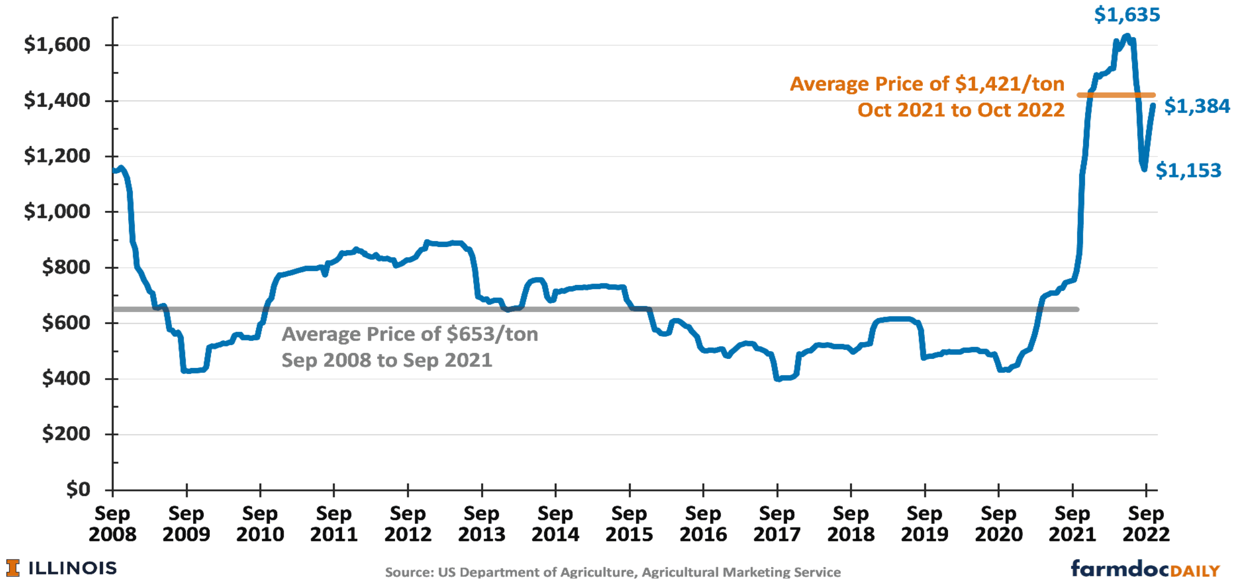
4.1.1 Statistics: Production, Usage, Price, Location

Ammonia production was estimated at 130 and 183 Mt worldwide in 2000 and 2020, respectively, and it is expected to increase to 223 Mt by 2030 and 333 Mt by 2050 (International Renewable Energy Agency and Ammonia Energy Association 2022). Eighty-five percent of ammonia is used as a raw material of fertilizer while the remaining are used other products including textiles, refrigeration, and explosives. Demand for ammonia as fertilizer accounted for 156 Mt in 2020 and is expected to increase to 267 Mt by 2050 (International Renewable Energy Agency and Ammonia Energy Association 2022). In addition to existing ammonia demand, there is emerging new demand for ammonia. Liquid ammonia is one of the emerging candidates for alternative maritime fuel of large ship as part of net-zero carbon economy (Fahnestock and Bingham 2021, Sveistrup Jacobsen et al. 2022). Another emerging demand for ammonia is an energy carrier as the means of transporting hydrogen (Aziz, Wijayanta, and Nandiyanto 2020). All considered, global ammonia demand can reach up to 688 Mt (International Renewable Energy Agency and Ammonia Energy Association 2022).

According to Mineral Commodity Summaries by the United States Geological survey (United States Geological Survey 2022, 2020, USGS 2022), Ammonia of 17 Mt is produced in 2020 by 17 companies at 32 plants in 16 states of the United States (U.S.). The U.S. ranks third in ammonia production, behind China (47.5 Mt) and Russia (19.7 Mt). Figure 8 represents the location of ammonia production facilities in the U.S. and their capacity per year in the unit of thousand tonnes. Production capacities in Louisiana, Oklahoma, and Texas account for 60% of the total production capacity in the U.S. CF Industries Inc. has the largest production capacity in the U.S., accounting for approximately 40% of total capacity. U.S. producers operated at about 84% of rated capacity. Ammonia produced is distributed through the ammonia pipeline, barges on the Mississippi river, and by railroad train. The amount of ammonia consumed in the U.S. is about 19.1 Mt, approximately 2 Mt higher than U.S. production. The difference is mainly made up for through imports from Trinidad and Tobago (63%) and Canada (34%).

Figure 8. Ammonia production facilities in the U.S. and their capacity in kilo metric tons per year (United States Geological Survey 2020).

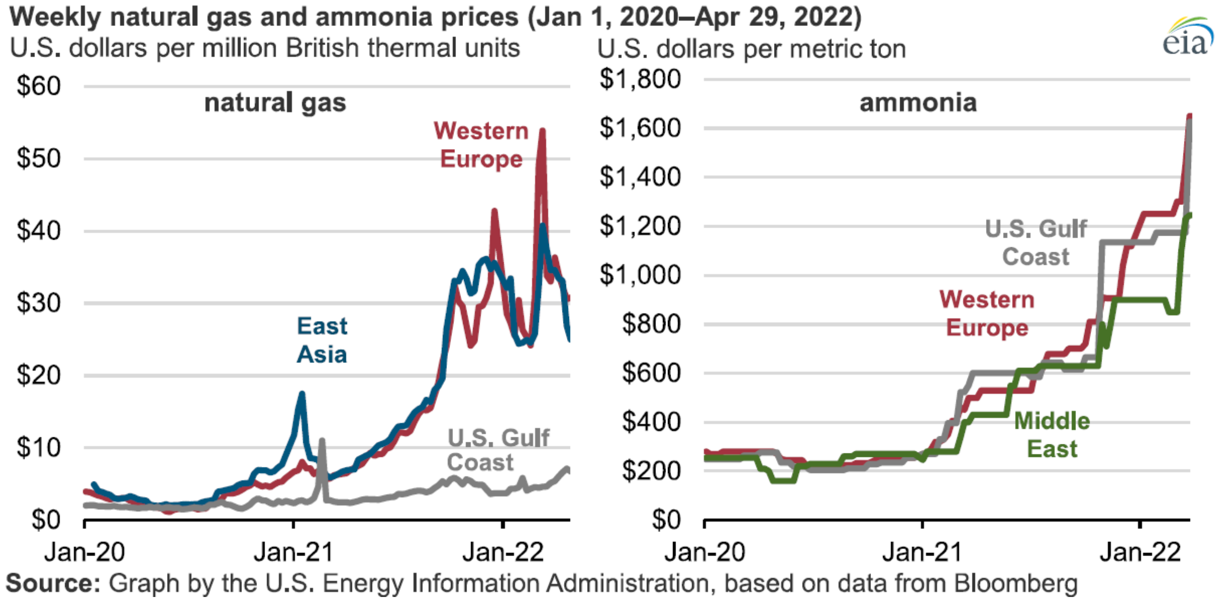
Figure 9 shows the anhydrous ammonia price in Illinois, U.S., showing that the average price from 2008 to 2021 was $653 per short ton while the average price between October 2021 and October 2022 is $1,421 per short ton. The price increase is attributed to the Ukrainian-Russia war and the accompanying high natural gas price (Schnitkey et al. 2022, Schnitkey et al. 2023).



Source: US Department of Agriculture, Agricultural Marketing Service

Figure 9. Anhydrous ammonia price in Illinois (Schnitkey et al. 2022).

Figure 10 represents the price of natural gas and anhydrous ammonia in three different regions for the last two years. Note that the price of ammonia has sharply risen, with the price of ammonia having a close relationship to the price of natural gas. Prices for ammonia in the U.S. have risen consistent with international natural gas prices (($6/MMBtu to $35/MMBtu), rather than rising similarly to domestic ($2.6/MMBtu to $5.00/MMBtu) natural gas prices. (Tejasvi Raghuveer et al. 2022, Raghuveer and Wilczewski 2022).


Weekly natural gas and ammonia prices (Jan 1, 2020–Apr 29, 2022)

Source: Graph by the U.S. Energy Information Administration, based on data from Bloomberg

Figure 10. National gas and ammonia prices in last 2 years (Raghuveer and Wilczewski 2022).

4.1.2 Ammonia Synthesis

The ammonia synthesis process can be divided into two stages: (1) how hydrogen is produced and what raw material is employed, and (2) how ammonia is synthesized and purified.

4.1.2.1 Hydrogen Preparation

In hydrogen manufacturing, a variety of raw materials and corresponding methods have been suggested. Currently, steam methane reforming (SMR) using natural gas is the most popular and economical method for commercial hydrogen production, adopted for most hydrogen produced in ammonia synthesis in the U.S. In SMR, methane from natural gas reacts with steam and is converted into hydrogen and carbon monoxide with the aid of a catalyst. Water-gas shift reaction (WGSR) accompanies SMR to produce additional hydrogen. SMR is an endothermic reaction, and some of the natural gas is burned as a fuel to obtain the energy required drive the reactions. Total energy consumption in an ammonia plant based on SMR is estimated as 28 GJ/tonne NH_3.

Steam methane reforming $CH_4 + H_2O \rightleftarrows CO + 3H_2$

Water-Gas shift reaction $CO + H_2O \rightleftarrows CO_2 + H_2$

Partial oxidation is the process to produce CO and H_2 by supplying a limited amount of oxygen. This exothermic process does not require additional energy. This process is usually employed when either heavy oil or biomass is selected as raw material. It is also employed as an ancillary hydrogen conversion method used for the Haber-Bosch process. Partial oxidation is divided into two methods based on catalyst use. Thermal partial oxidation (TPOX) requires a high temperature of 1200°C without catalyst, whereas catalytic partial oxidation (CPOX) requires relatively low temperature of 800–900°C with the aid of a catalyst. However, the catalysts used in this method can be easily poisoned by sulfur contents. Thus, the CPOX method cannot be used for materials containing high amounts of sulfur.

Ideal reaction for oil $C_{12}H_{24} + 6\ O_2 \rightarrow 12\ CO + 12\ H_2$

Ideal reaction for coal $C_{24}H_{12} + 12\ O2 \rightarrow 24\ CO + 6\ H_2$

Coal autothermal gasification is the second popular method to produce hydrogen in the world, mostly done in China. Raw material (usually coal) reacts with both water and oxygen introduced in high temperature and the operating temperature can reach up to 1500 °C. This process is an integration of steam reforming and partial oxidation. Instead of burning extra fuel, energy required for an endothermic steam reforming reaction is replenished by the exothermic partial oxidation reaction, which is the reason that the process is called autothermal.

$$C_nH_m + H_2O + O_2 \rightarrow n\ CO + H_2$$

Hydrothermal gasification is the process in which raw materials react with a high temperature and pressurized water solution. Water participates not only as solvent but also as reactant. As supercritical water is usually employed for gasification purposes, it is also referred to as supercritical water gasification (SCWG). Supercritical water has high diffusivity and low polarity, in which most organic compounds can become soluble. In addition, organic salts that were soluble in the ambient water are no longer soluble and deposited in supercritical water. Alkali salt (NaOH, KOH, Na_2CO_3, K_2CO_3 etc.) can be employed as a homogenous catalyst. This process targets sewage sludge and wet biomass as raw material.

The sulfur-iodine cycle is one the best-known thermochemical cycle to produce hydrogen, also referred to as ISPRA Mark 16 cycle or general atomic cycle.

Bunsen Reaction $2H_2O + SO_2 + I_2 \rightarrow H_2SO_4 + 2HI$

$$2HI \rightarrow I_2(g) + H_2(g)$$

$$H_2SO_4 \rightarrow H_2O(g) + SO_3(g)$$

$$SO_3(g) \rightarrow SO_2(g) + \tfrac{1}{2}O_2(g)$$

Electrolysis is defined as a chemical decomposition using electrical current. Direct water electrolysis that decomposes water into hydrogen and oxygen is a traditional method to produce hydrogen, but it is an energy intensive process. Many alternate electrolysis processes have been suggested. The Cu-Cl cycle is a four-step thermochemical cycle for hydrogen production, avoiding direct water electrolysis. The benefit of this process is that the maximum temperature required is about 530°C.

Drying

Hydrolysis

Oxygen Production

Hydrogen Production

4.1.2.2 Nitrogen Preparation

There are three technically mature commercial processes (Technology Readiness Level of 8–9) to produce purified nitrogen from air: air cryogenic distillation, pressure swing adsorption (PSA), and membrane permeation. (1) The cryogenic distillation method can separate the nitrogen from the air using the different boiling point of each of the gaseous components in the air, requiring extremely low temperatures. This process is adequate for large-scale capacity facilities (250–25,000 Nm^3h^{-1}). Direct current (DC) electrical energy required is 0.396 GJ per tonne of N_2 produced. (2) Pressure swing adsorption method is a process to employ selective adsorbent materials. Zeolite, a selectively adsorbent material, attracts and adsorbs nitrogen more strongly than oxygen, allowing for only nitrogen to be captured within the separation vessel after air flow. The vessel is pressurized to enhance adsorption performance and adsorbed nitrogen is eventually released by decreasing the pressure. This process fits for small scale capacity facility (25–800 Nm^3h^{-1}). Nitrogen purity up to 99.8 wt% can be obtained and DC energy requires 0.792–1.116 GJ/tonne N_2. (3) Membrane permeation method employs selective permeability of a membrane to nitrogen. Nitrogen cannot permeate a membrane while other component of air such as oxygen, carbon dioxide and vapor can permeate the membrane. Thus, only nitrogen remains and concentrates. Drawback of this process is its relatively low purity of N_2 product (95 wt%). Capacity of facilities using membrane are ranged from 3 to 3000 Nm^3h^{-1}. DC energy is consumed 0.792–2.268 GJ per tonne of N_2 produced.

4.1.2.3 Ammonia Synthesis: Haber-Bosch Process

The Haber-Bosch process can refer to two processes: either only the reactor unit needed to synthesize ammonia under high-pressure conditions with an iron catalyst in narrow scope or the entire process to manufacture ammonia including hydrogen generation and purification. This process can be categorized in two ways: (1) hydrogen production method (ranging from desulfurization to methanation) and (2) the ammonia synthesis including pressurization, ammonia synthesis, and ammonia separation and storage.

The conventional Haber-Bosch process uses natural gas and is the most common manufacturing method in the U.S. Figure 11 shows conventional ammonia production process using Haber-Bosch process (Asiri, Inamuddin, and Boddula 2020, Rouwenhorst et al. 2019).

The desulfurization process removes inherent sulfur in the natural gas that might harm the catalyst of downstream processes. Hydrogen in the process is produced by SMR. Most of the methane converts into syngas at this stage. Since this reaction is endothermic, some natural gas is burned to supply the energy. The secondary reformer performs partial oxidation reactions. The main purpose of this step is to introduce the nitrogen without using an air separation unit. As air is introduced, oxygen reacts with methane and burns off, and only nitrogen remains which can be used for ammonia synthesis. Methane conversion to hydrogen comes incidentally. The secondary reformer is usually designed to operate as an adiabatic reactor. Typical operating conditions in the primary reformer are 750–820°C while the secondary reformer temperatures are raised to 950–1025°C. Nickel catalysts are widely employed in this process, resulting in methane of 8–12 vol.% and 0.3–1.0 vol.% remaining after the primary and secondary reformer. The operating pressure is typically 25–30 bar. Note that although a low operating pressure is preferred if only the thermodynamic yields are considered, a high-pressure ammonia unit is more practical when considering all used materials (Zhang, Sun, and Hu 2021).

A reaction (WGS) is performed to increase the hydrogen yields and remove CO. Carbon dioxide is produced as a byproduct. The industrial practice uses two-stage treatment. The first stage operates at 350°C with a Fe-Cr oxide catalyst while the second-stage operates at 200–250°C with a Cu-based catalyst. High-temperature WGS reactions can take advantage of rapid kinetics with a cheap catalyst while low-temperature WGS reactions have a thermodynamic improvement on CO conversion.

After the WGS reaction, the synthetic gas (syngas) might contain up to 20 vol.% CO_2. Carbon dioxide capture is required before the ammonia synthesis not only because it is considered to be a greenhouse gas but also because it can react with ammonia to form carbamates which can clog pipelines. Organic sulfur material is also removed in this step. Options include chemical absorption using alkanolamine or potassium carbonate while physical absorption may occur using the Sulfinol process (sulfolane + diisopropanol), Rectisol, (methanol), or Selexol (polyethylene glycol). Captured CO_2 can be employed to synthesize other chemical materials including urea (as a product of ammonia and CO_2). Methanization is the process to remove trace of CO and CO_2 entirely after the CO_2 capture before ammonia synthesis. A Ru-based and Rh-based catalyst is preferred at operating conditions of 300–400°C.

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$CO2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The key to the Haber-Bosch process is its very high-pressure operating conditions to make ammonia reaction favorable. Most of the energy required is consumed to pressurize the hydrogen and nitrogen. Operating conditions for the Haber-Bosch process are 100–200 bar and 350–525°C. It is known that iron catalyst is one of best fits for this process as BASF found.

Final ammonia separation from the reaction mixture is most maturely done through condensation. As temperature decreases to -20~30°C based on pressure, only ammonia is condensed and separated as liquid. Ammonia separation via absorption with metal halide and adsorption with zeolite are other candidate processes. The more ammonia is separated before reflux, the better ammonia yields can be obtained. Separated ammonia is cooled down and stored in liquid form. Figure 11 represents the flow diagram of Haber-Bosch process and operating temperatures of each stage. Figure 12 shows the industrial plant designed suggested by KBR (left) and Haldor Topsøe (right). Table 2 tabulated the energy consumed at each stage in the Haber-Bosch process. The total energy consumed is 28 GJ/tonne NH_3 and most of the energy consumed is at the turbine compression. About 60% of energy loss also occurs at the turbine compression.

There are some studies to replace the Haber-Bosch process. Direct electrolysis to synthesis ammonia is one candidate, and estimated energy consumed in current technology is 31–37 GJ/tonne NH_3. (Rouwenhorst et al. 2019).

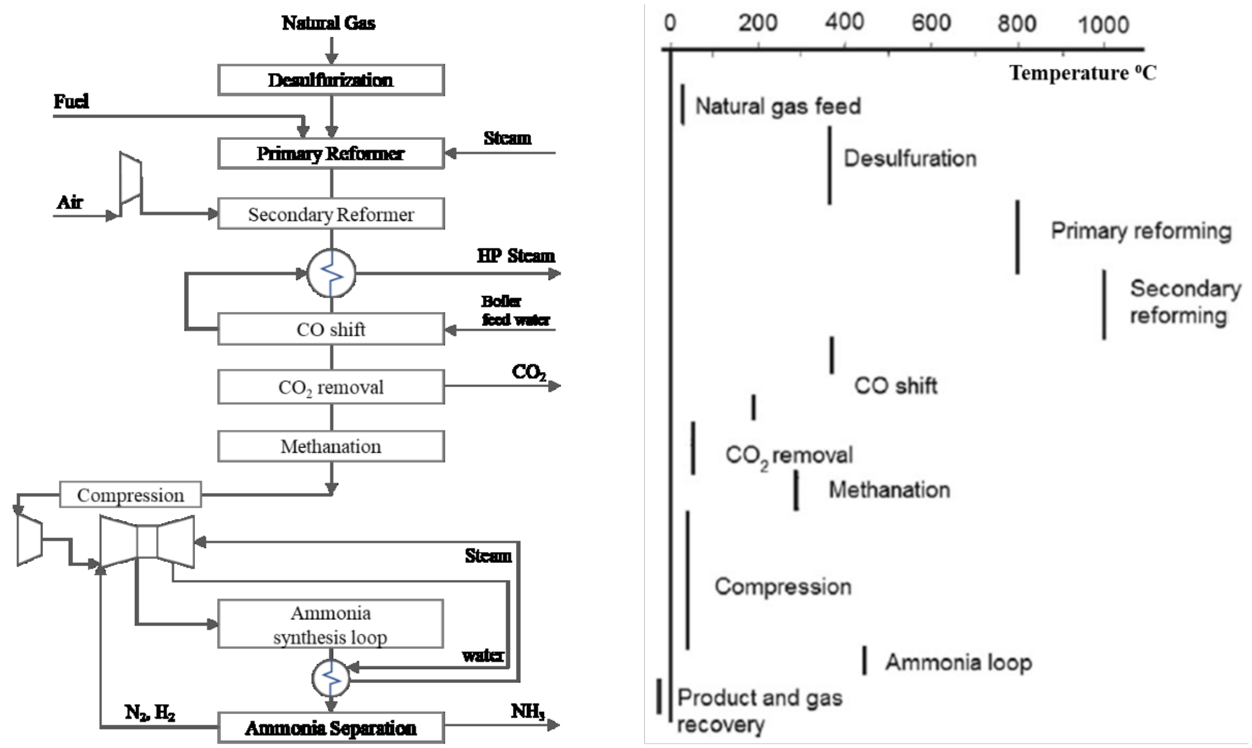


Figure 11. Conventional ammonia production process and operating conditions (Asiri, Inamuddin, and Boddula 2020).

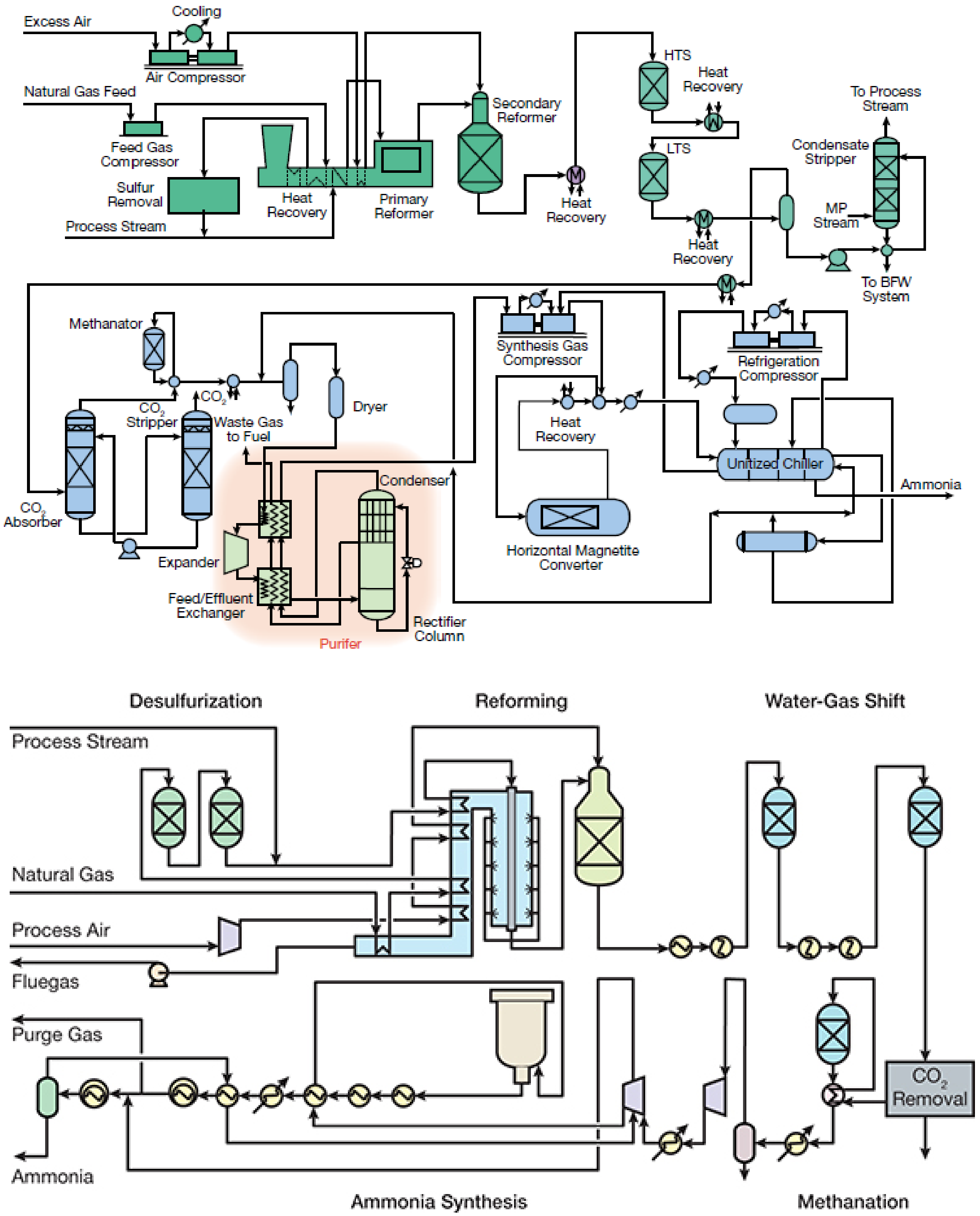


Figure 12. Modern commercial ammonia plant design: (up) KBR and (down) Haldor Topsøe (Venkat Pattabathula 2016).

Table 2. Energy consumed in Haber-Bosch process (Asiri, Inamuddin, and Boddula 2020).

	HHV	LHV	Exergy
Reformer feed	24.64	22.26	23.26
Fuel	7.87	7.07	7.45
Total energy to HP steam Production	11.59	11.59	5.52
Losses			
Reforming	0.38	0.38	4.94
Steam generation	0.33	0.33	2.38
Gas purification	1.30	1.30	0.67
Synthesis	1.72	1.72	1.55
Turbines + compressor	6.53	6.53	0.54
Total losses	11.55	10.92	10.54
Energy in NH_3	20.96	17.11	20.13

Values reported in GJ/t NH_3

4.1.2.4 Downstream Product and Process

The flow diagram of major downstream nitrogen compounds synthesized from natural gas is shown in Figure 13. The number in each component shows the amount of production by the U.S. in 2020 in the unit of thousand metric tons of gross weight and of contained nitrogen weight (within parentheses), respectively.

Ammonia is usually stored in a form of pressurized liquid, which is referred to as anhydrous ammonia, as opposed to ammonia solution (International Energy Agency 2021). In the U.S., some anhydrous ammonia is directly used as a fertilizer. Urea, urea ammonium nitrate (UAN) solution, ammonium nitrate, ammonium sulfate, ammonium phosphate, nitric acid (manufactured by the Ostwald process) are other major nitrogen compounds that originate from ammonia. They are usually employed as either fertilizer itself or raw materials of fertilizer. 88% ammonia produced in the U.S. 2020 is utilized as fertilizer.

Urea containing high amount of nitrogen, in 46% by weight, is widely used as fertilizer. Urea is made through combining ammonia and CO_2, and is therefore usually manufactured at an ammonia plant because CO_2 is produced as a byproduct in an ammonia plant can be directly used for the urea synthesis. Two chemical reactions are involved to synthesis the ammonia. First, ammonia and carbon dioxide can react to form ammonium carbamate in the condition of 14 MPa and 170–190°C. In the second reactor, ammonium carbonate is dehydrated, forming urea. Impurities are removed by a distillation tower and an evaporator. Under high temperature and low pressure in the distillation tower, the ammonium carbamate is decomposed back to ammonia and carbon dioxide, and light gases are flown off. Urea solution from the distillation tower is concentrated in the evaporation step. Concentrated urea solution is sprayed out in the prilling tower, resulting in crystallized solid form of urea (Chemical Engineering World; 2020).

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4$$

$$NH_2COONH_4 \rightarrow NH_2CONH_2 + H_2O$$

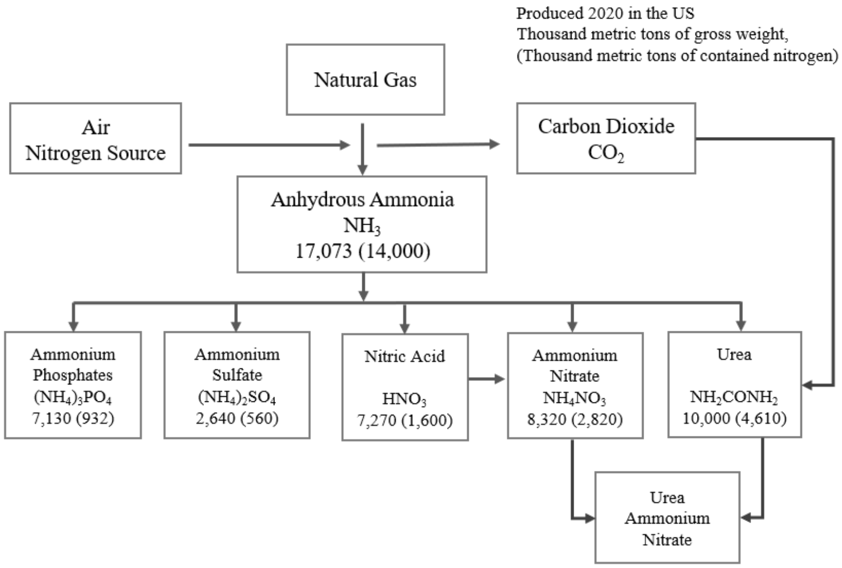


Figure 13. Major downstream nitrogen compounds from natural gas in the U.S. (United States Geological Survey 2020).

4.2 Chlor-Alkali

Chlorine ranks among the top ten chemicals produced in the U.S. by weight (Mansfield, Depro, and Perry 2000; Pellegrino 2000), with 2021 production at approximately 12 million tons (United States Environmental Protection Agency 2022), and as one of most energy-intensive mass-produced chemicals (Brueske, Kramer, and Fisher 2015). Notably, process temperatures are low (~100°C) and electricity use is high, potentially making chlorine production well-suited for pairing with a nuclear reactor.

4.2.1 Market

Chlorine is used directly for disinfection of water supplies, in the paper industry, and in the production of vinyl chloride (precursor to the polymer polyvinyl chloride), used in the disinfectant sodium hypochlorite, in other chemicals and pharmaceuticals, and as a reactant in various industries (Mansfield, Depro, and Perry 2000, Pellegrino 2000). In the dominant method of production – electrolysis of brine – sodium hydroxide is co-produced at a rate of about 1.1 times by mass, and so the markets for chlorine and sodium hydroxide both significantly impact plant economics (sodium hydroxide is also known as caustic soda or lye). Consequently, plants are known as chlor-alkali plants. U.S. plants are primarily located along the Gulf Coast. Updated information about the chlorine market will be included in future milestones.

4.2.2 Production Process

Electrolytic production of chlorine requires significant electric power as well as heat. Chlorine is produced by the electrolysis of sodium chloride (table salt) dissolved in water (brine), The brine may be supplied directly, or solid sodium chloride may be dissolved to produce brine. Electrolysis produces chlorine anions and sodium cations along with hydroxides anions and hydrogen gas (H_2). Chlorine ions are attracted to the anode and form chlorine gas (Cl_2), while the sodium ions are attracted to the cathode and form sodium hydroxide with the hydroxide ions. A mechanism is necessary to keep the chlorine ions separated from the other species, in order to prevent production of undesired compounds and to reduce the amount of hydrogen mixed with the chlorine gas (Pellegrino 2000). Hydrogen is produced at a rate of

0.03 kg per kg of chlorine (McMillan et al. 2016).

There are three types of electrolysis cells: diaphragm, membrane, and mercury. All three accomplish the necessary separation of the products of electrolysis. Diaphragm cells utilize a barrier constructed from a mixture of asbestos and polytetrafluoroethylene, through which sodium ions pass and which may be integrated with the cathode, and produce a sodium hydroxide solution of 10% – 15% with significant salt content. Membrane cells utilize an ion-exchange membrane constructed of fluorinated polymers through which sodium ions pass, and produce a sodium hydroxide solution of 30% – 33%. Mercury cells do not use a rigid barrier, and instead pass a layer of mercury through the bottom of the cell, which collects sodium ions and thus becomes Hg-Na alloy (amalgam). The amalgam must be processed in a decomposer to produce sodium hydroxide. While the mercury cell and decomposer produce a highly concentrated sodium hydroxide solution, the cell operates at a higher voltage and thus consumes more electric energy. By comparison, the diaphragm cell requires less electric energy but more thermal energy in post-cell evaporation of the sodium hydroxide solution to reach the standard commercial concentration of 50% (weight by weight or weight by volume). Membrane cells and diaphragm cells have similar electric consumption per unit product. Additionally, the mercury cell comes with serious environmental mitigation needs due to the toxicity of mercury, while the diaphragm cell creates the presence of asbestos fibers in the cell and necessitates disposal of used diaphragms as hazardous waste (Pellegrino 2000). Mercury cells have not been built in the U.S. since 1970. As of 1997, diaphragm cells were the most common in the U.S. while membrane cells were the least common (Mansfield, Depro, and Perry 2000).

The overall process is represented in Figure 14, showing the process flow for a plant using the diaphragm cell. Some differences between mercury and membrane cells exist.

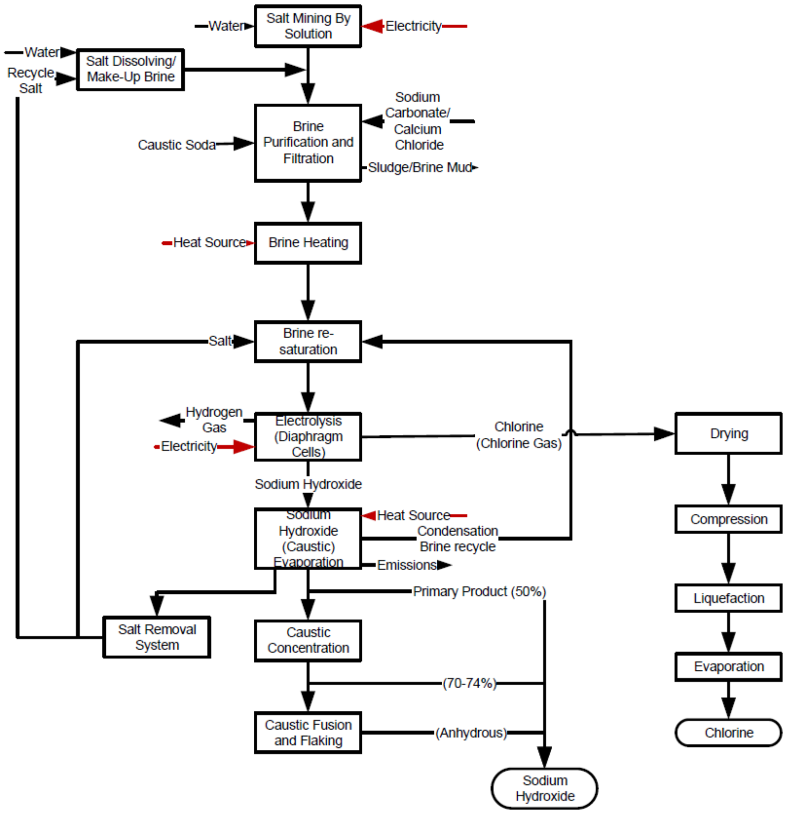


Figure 14. Process flow diagram for a chlor-alkali plant based on the diaphragm cell. From (McMillan et al. 2016), based on (Pellegrino 2000; Tilak V. Bommaraju 2002).

4.2.3 Energy Requirements and Opportunity for Nuclear Reactor Integration

In electrolytic chlor-alkali plants in general, heat is used to bring the brine to the process temperature of 95 – 100°C (Tilak V. Bommaraju 2002), to evaporate sodium hydroxide for concentration, and optionally in some plants, to evaporate the brine in order to remove sulfates (before rehydrating for input to the cell). Chlorine plants do not export energy (Pellegrino 2000).

An ‘average’ membrane or diaphragm cell plant (determined from sum totals for the U.S. chlor-alkali industry (Colin McMillan 2016)) producing 828 metric tonnes of chlorine per day has a daily heat demand of 2.7 TJ. In existing plants, some portion of this heat is delivered by steam at 177°C (Colin McMillan 2016) to bring process operating temperatures near 100°C. The plant also demands an average of 141 MW of electric power (Colin McMillan 2016) continuously. Under the assumption that the heat demand is only the heat necessary for the process, 3.26 MJ of thermal energy and 4 kWh of electric energy would be required to produce 1 kg of chlorine. When accounting for sodium hydroxide production, plants utilizing diaphragm cells will require a higher rate of heat in order to evaporate the sodium hydroxide solution to the standard commercial concentration than plants utilizing the other two types of cells (Pellegrino 2000). Consequently, the energy requirement given earlier (3.26 MJ based on an ‘average’ plant using diaphragm or membrane cells) is expected to be an underestimate for diaphragm cell plants and an overestimate for membrane and mercury cell plants. By comparison, the electric energy consumed (4 kWh based on an ‘average’ plant) is relevant to diaphragm and membrane cells, but is considerably lower than the value for mercury cell plants. Electricity consumption values found in (Pellegrino 2000) are for the cell only, at about 2.8 kWh/kg of chlorine, and so do not reflect all the electric needs of the plant (for example, motorized compression of chlorine gas is not included). For mercury cells, (Pellegrino 2000), gives approximately 3.6 kWh/kg.

4.2.3.1 Decarbonization Potential

Due to use of fossil fuels for heat, the ‘average’ membrane/diaphragm cell plant emits 2,014 metric tonnes of CO_2 per day, or 2.43 kg of CO_2 per kg of chlorine (McMillan et al. 2016). These figures do not include emissions from electric generation; thus, as average grid generation emits considerable carbon at present, and any existing on-site electric generation is likely to be fossil fuel-fired, the decarbonization potential from supplying all heat and electricity from a co-located nuclear reactor is greater.

4.3 Methanol

4.3.1 A Brief Overview

Methanol or methyl alcohol, also known as wood alcohol, primarily serves as a feedstock in chemical industries (Perez Sanchez et al. 2022), as a stand-alone fuel, or as a fuel blend in gasoline to boost its octane number (Verhelst et al. 2019). It is a colorless liquid with a density of 792 kilograms per cubic meter and a calorific value of 22.7 megajoules per kilogram. As illustrated in Figure 15, a significant growth in methanol production in the United States of America (USA) can be witnessed since the year 2010. The remainder of this section is organized as follows: in section 4.3.2, diverse applications, or usages of methanol as a product are summarized. Next, section 4.3.3 enumerates crucial target sectors wherein methanol has a large demand as a feedstock. Then, in section 4.3.4, commercial feedstocks and pathways for production or generation of methanol are enlisted. In section 4.3.5 contains list of major North American methanol producers and port storage capacities. Finally, section 4.3.6 summarizes potential for nuclear-sourced heat to produce methanol, and the key takeaways essential for analyzing the use of nuclear-generated decarbonized heat for methanol production.

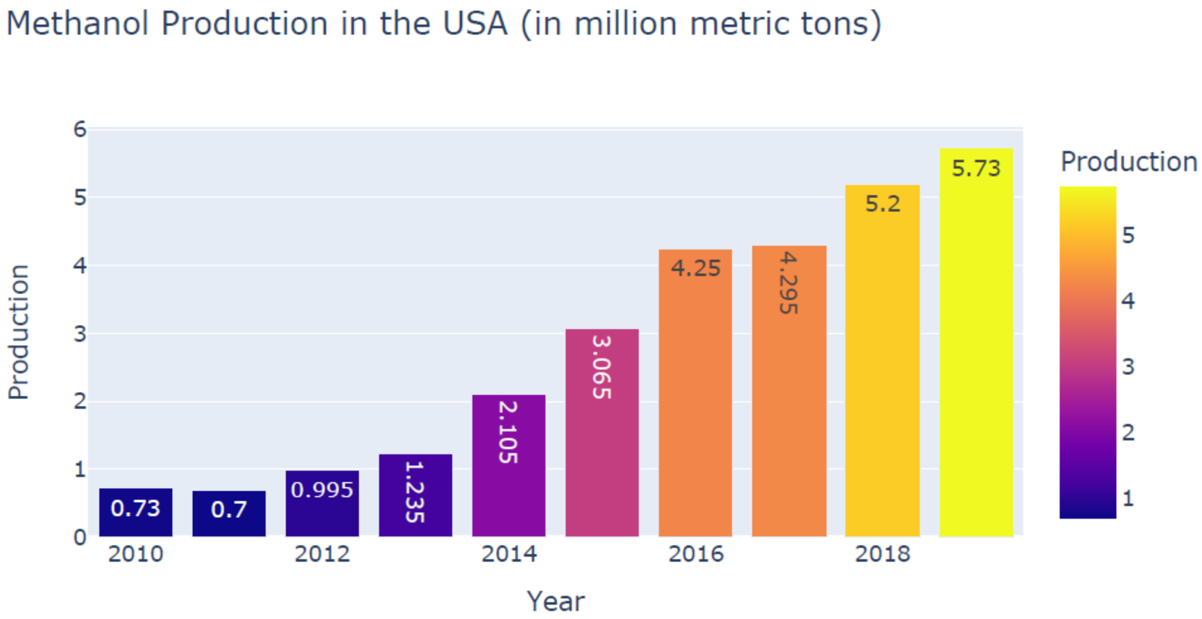


Figure 15. Methanol production in units of million metric tons in U.S. during 2010-2019 (American Chemistry Council, 2020).

4.3.2 Methanol: Applications

Methanol has several critical end uses. In chemical and petrochemical processes, methanol serves as a feedstock for production of formaldehyde (Brown and Parkyns 1991; Malik, Abatzoglou, and Achouri 2021), olefins – especially ethylene and propylene – used as intermediates for other chemical products (Tian et al. 2015; Idaho National Laboratory 2012), and for generation of synthetic gasoline (Idaho National Laboratory 2010). Methanol's role as a fuel blend or additive, or for direct combustion, generates high-volume demand in the transportation sector. As a fuel additive, methanol's higher-octane rating than gasoline enhances efficiency of internal combustion engines (Verhelst et al. 2019). Additionally, methanol-powered portable appliances are quite popular in China and in Africa, and methanol as a substitute to fuel oil for heating in chemical processes is also gaining significant traction (see Applications in (Methanol Institute n.d.)).

For the year 2021, a net global production of 107 million metric tons (MMT) of methanol was estimated by Methanol Market Services Asia (MMSA) of Methanol Institute (Methanol Institute n.d.). Figure 16 illustrates breakdown of global methanol demand by application. The applications corresponding to methanol-to-olefins (34 MMT) processes, formaldehyde production (25 MMT), and combustion and gasoline blending (12 MMT) lead the chart.

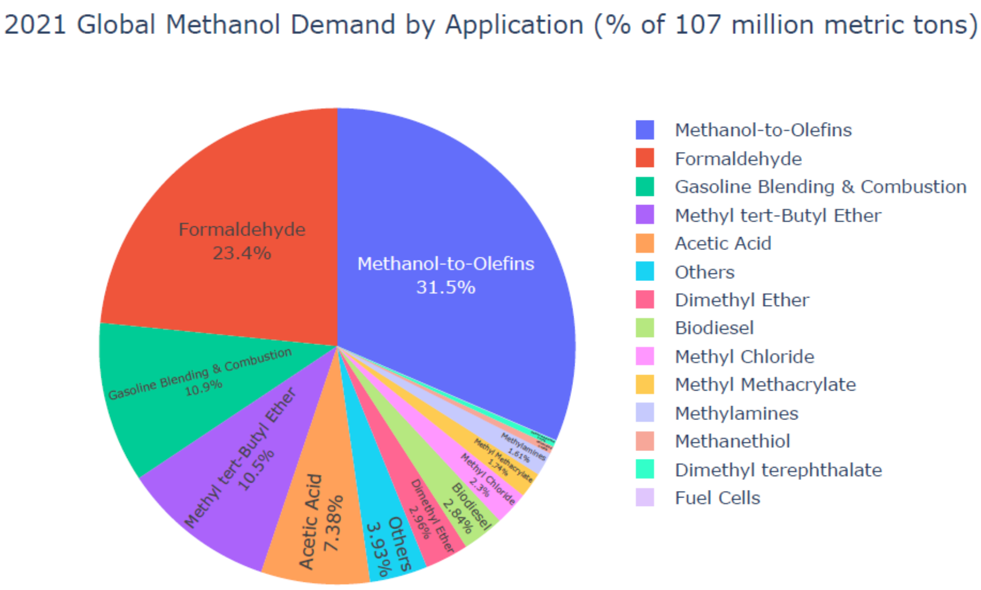


Figure 16. Global methanol demand by application for the year 2021 (Methanol Institute n.d.).

In summary, various end uses of methanol can be categorized under three broad headings: chemicals, fuels, miscellaneous or other applications. The global methanol end-use categorization in MMT is shown in Figure 17.

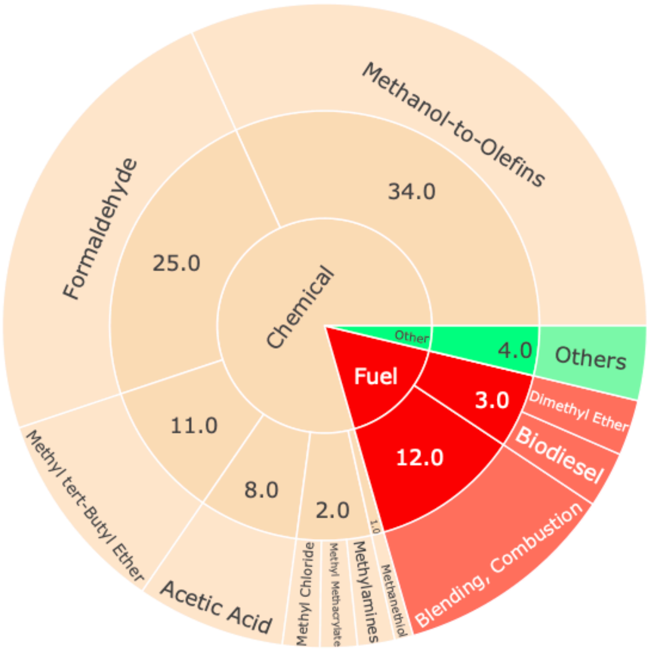


Figure 17. Global methanol end-use categorization (in MMT, Methanol Institute n.d.).

4.3.3 Top Five Target Markets for Methanol

This section highlights the target sectors with a potential for bulk or high-volume methanol demand as a feedstock. The data was collected over the years from 2017 to 2021. Figure 18 illustrates the top five sectors with highest demands for methanol as an input or a chemical precursor. There are two core observations.

1. A significant global growth of methanol-to-olefins (MTO) production is noted, which has increased by around 62% since 2017.
2. High-volume methanol demands from the rest of the four sectors are near constant yet numerically significant.

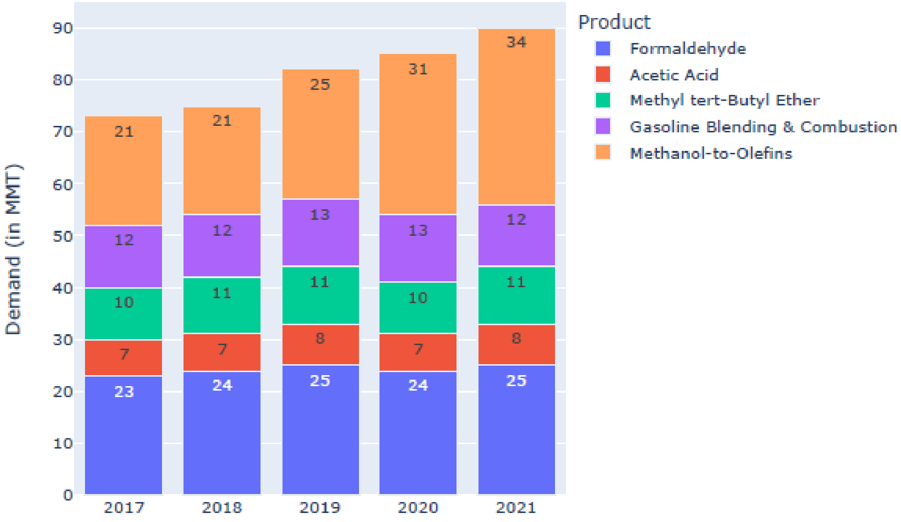


Figure 18. Target markets for methanol based on end use (in MMT, Methanol Institute n.d.).

Most importantly, as shown in Figure 19, light olefins are projected to be fastest-growing segment within the USA. The light olefins, or, ethylene and propylene, are unique due to their ubiquitous end use in various industries including manufacturing of plastics, detergents, antifreeze, synthetic fibers, coatings or paints, and their usages in the textile industry. Furthermore, the USA's annual market size of methanol is projected to increase to 8.4 MMT by the year 2027, as highlighted in Figure 20. This is expected as global prices for methanol have shown a significant growth in the post-pandemic years (Figure 21), with an uptick in manufacturing activity. China, as the largest methanol consumer, accounts for roughly 20% of the total global volume. This is about twice the methanol consumption within the USA (Methanol Institute and Methanol Market Services Asia 2023).

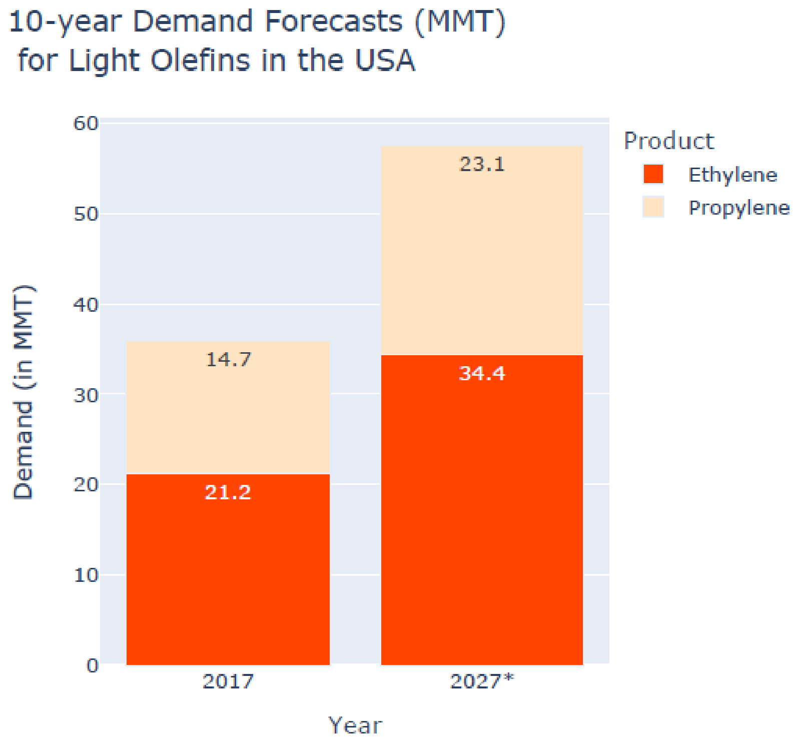


Figure 19. Demand forecasts for light olefins in the USA (in MMT, Statista 2020b)

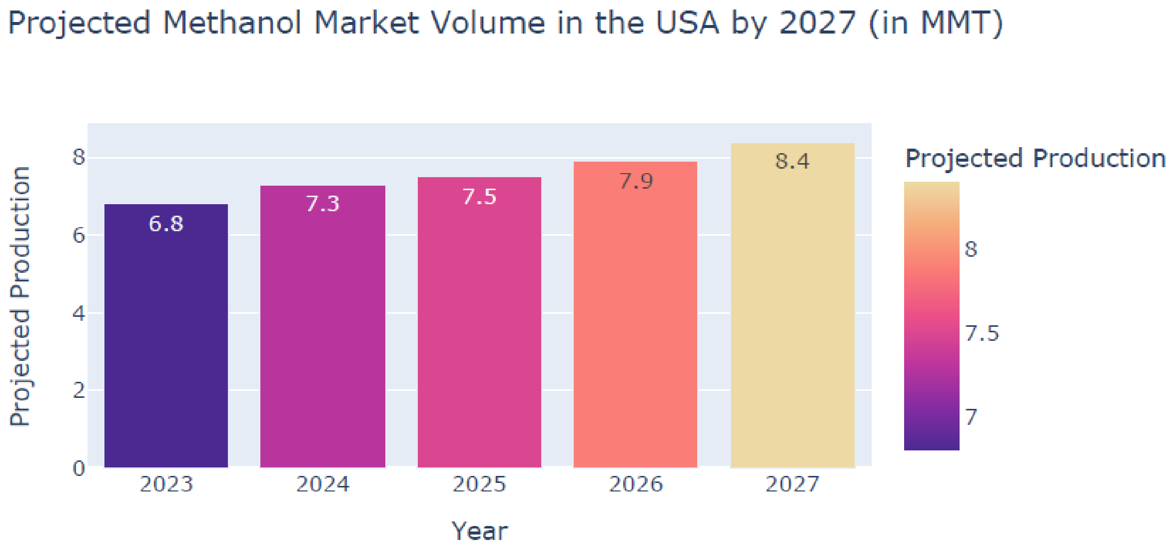


Figure 20. Projected methanol market volume (MMT) in the U.S. by the year 2027 (Statista 2020a)

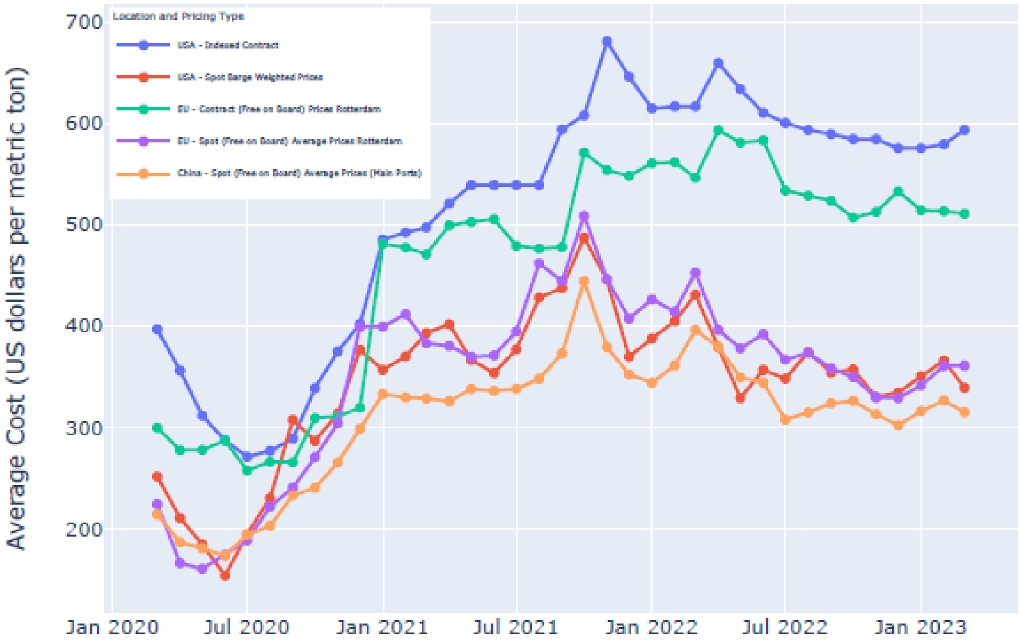


Figure 21. Global monthly methanol prices (U.S. dollar per metric ton) by location and type (Methanol Institute, 2023).

4.3.4 Methanol Production

Synthetic gas, or syngas, which is composed of hydrogen, carbon monoxide, and carbon dioxide, serves as the primary precursor for methanol production. Consequently, there are multiple feedstocks and pathways commercially available for methanol production.

4.3.4.1 Feedstocks and Pathways

Around 55-65 % of global methanol producers use natural gas as a feedstock for syngas generation. Next, lignite or brown coal provides syngas for 30-35% of global methanol generation. The rest of the methanol production is enabled by biomass, coking gas. In summary, there are three main feedstocks: natural gas, coal, and biomass (IndexBox 2023; Harris et al. 2021).

Another feedstock is methane, which is directly converted into methanol using a catalyst, but its industrial-scale adoption is yet to be realized (Ravi, Ranocchiari, and van Bokhoven 2017). Besides, carbon dioxide reduction using hydrogen is also an alternative being explored. For instance, sourcing of high-purity carbon dioxide as an industrial byproduct from ammonia or ethanol production (Zang et al. 2021). Such pathways create a potential for integrated industrial processes with chemical co-productions.

The above-mentioned feedstock breakdown, however, corresponds to global methanol production. In effect, these average numbers are heavily skewed by coal-driven methanol production in mainland China, with a record methanol production of 69 MMT observed in the year 2019 (Methanol Institute n.d.). Referring back to Figure 15, there is a meteoric eight-fold growth in methanol production within the USA from 2010 to 2019. This growth is concomitant with availability of competitively priced natural gas, which, since the year 2010, had average (yearly) closing price under $7 per million British thermal units. Therefore, the percentage of methanol produced using natural gas in the USA can be safely assumed to be at least 80%. To construct an accurate Sankey diagram of the feedstock breakdown in the USA and their corresponding pathways, future work involves a deeper dive into finer details. These details can be harvested from sophisticated databases hosted by Bloomberg and S&P.

4.3.4.2 Process Flow

The process flow for methanol synthesis can be broadly described under three macros, as illustrated in Figure 22. A brief overview of each macro process is listed next.

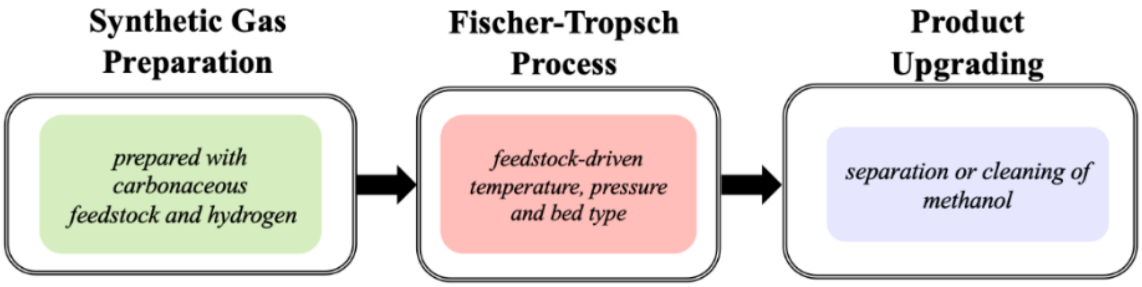


Figure 22. A high-level architecture of process flow for methanol synthesis.

1. *Syngas Preparation*: First, the feedstock is cleaned, dried and/or pulverized. Subsequently, it is treated with steam and oxygen at high temperatures. Next, the syngas is cleaned to preclude corrosion of downstream Fischer-Tropsch reactor. The syngas fed downstream is conditioned to a typical 2:1 molar ratio of hydrogen and carbon monoxide and is brought to appropriate temperature and pressure requirements for downstream Fischer-Tropsch reactor. It must be noted that syngas preparation is a highly endothermic process. The process conditions vary with feedstock: coal (gasification, Idaho National Laboratory 2012), natural gas (steam methane reforming, auto thermal reforming, or mix of both (Idaho National Laboratory 2010)), and biomass (gasification) (IndexBox 2023). Consequently, the temperature and pressure conditions for syngas processor (reformer or gasifier) are also contingent on feedstock. For instance, based on moisture content, and on bed type, a gasifier's exit temperature ranges between 350°C-1700°C (Idaho National Laboratory 2012; Steynberg 2004; Shao et al. 2023) with a steam input pressure ranging over 50–80 bar. In contrast, natural gas reforming occurs at conditions 700°C-1000°C and 3-25 bar, particularly for hydrogen generation within the USA (Basu 2018). The pressure ranges can, however, move up and beyond. For example, a pressure requirement of 40 bars for converting natural gas to methanol and then to gasoline with Exxon-patented process (Idaho National Laboratory 2010). To conclude, regardless of syngas's exit temperature and pressure, it must be conditioned and cooled prior to its synthesis to methanol in downstream Fischer-Tropsch reactors. Therefore, it is imperative to source or recuperate heat from syngas cooling and divert it to the downstream Fischer-Tropsch reactor. The information for this macro process is summarized in Figure 23.

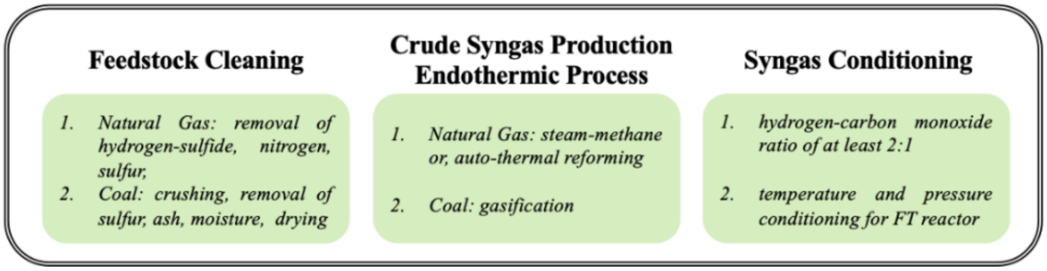


Figure 23. A zoomed-in architecture of the process corresponding to syngas preparation.

2. *Fischer-Tropsch (FT) Process*: In the next macro process, a FT reactor converts the mixture of carbon monoxide and hydrogen, or syngas, into liquid hydrocarbons. Effectively, it is catalytic hydrogenation of carbon monoxide. The inlet temperature conditions within FT reactor vary between 200°C-350°C and the inlet pressure requirement may go up to 75 bar (Idaho National Laboratory 2010). It must be noted that the temperature requirements in FT reactor are achieved by recuperating heat by syngas cooling (Zang et al. 2021; United States Department of Energy n.d.). Consequently, FT reactors vary in characteristics as shown in Figure 24, as downstream synthesis is dependent on end product(s).

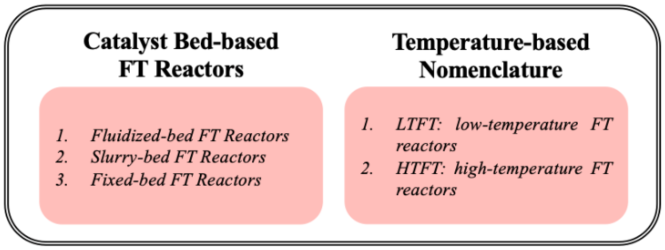


Figure 24. Fischer-Tropsch reactor characterization based on catalyst bed type and temperature.

3. *Product Upgrading*: Any additional downstream processing involves product upgrading. The first step mainly involves methanol de-watering (separation from water). Then, based on the desired end-product(s), the number of subprocesses and their corresponding temperature and pressure conditions vary, as illustrated in Figure 25.

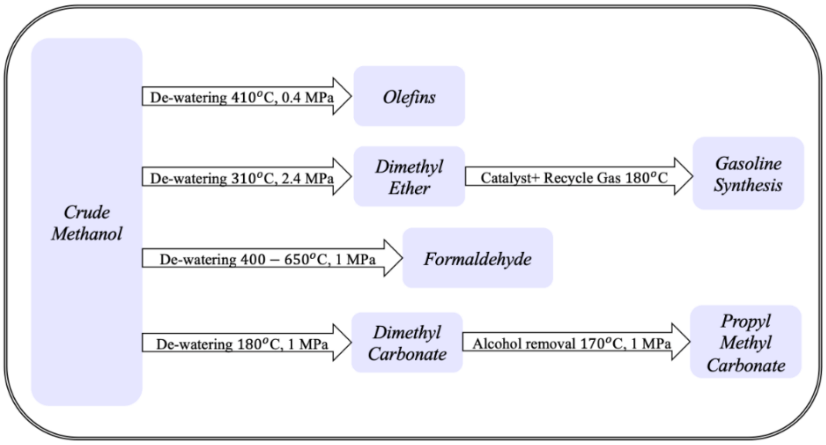


Figure 25. Upgrading conditions contingent on end-product (Idaho National Laboratory 2012, 2010; Zang et al. 2022; Matsukata et al. 2011; Maldonado et al. 2010)

4.3.5 Major North American Methanol Producers and Port Storage Capacities

In North America, major methanol producers are ExxonMobil Chemical Company (USA), Methanex Corporation (Canada), Celanese Corporation (USA). Based on publicly available data from Methanol Institute, a storage capacity of 1.9 million metric tons can be confirmed at 10 of the 17 ports in the USA (Methanol Institute and Methanol Market Services Asia 2023). Californian ports in Long Beach and Los Angeles have a combined bulk liquid methanol storage capacity of 344,565 metric tons. The largest domestic capacity of 600,000 metric tons is in southern coast at St. Rose, Louisiana. The nested pie-chart in Figure 26 summarizes data for methanol storage capacities at North American ports.

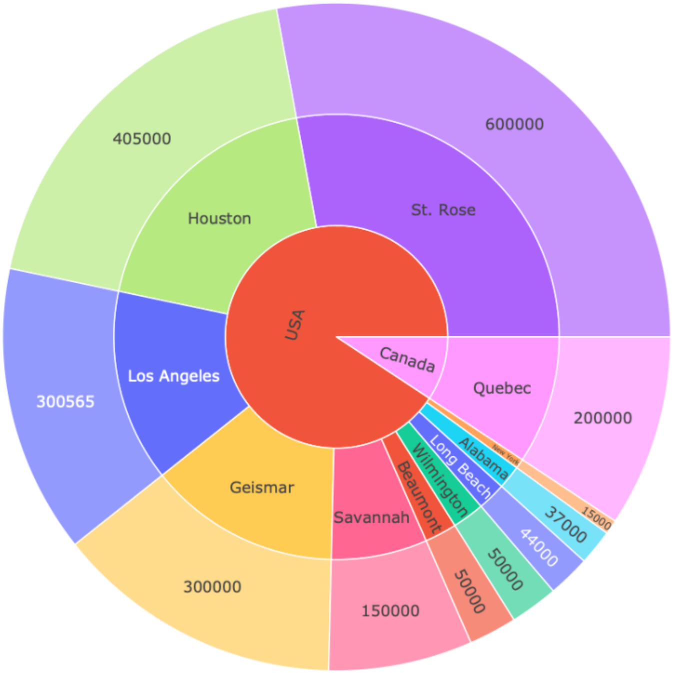


Figure 26. North American ports with confirmed methanol storage capacities (in metric tons).

4.3.6 Nuclear-Integrated Methanol Production

In the case of nuclear-driven methanol synthesis, sourcing of nuclear-generated heat is most relevant during syngas production. Syngas generation is a highly endothermic process and requires additional heat sourcing by burning feedstock such as natural gas or coal. The process heat for syngas production is also sourced by combusting the tail gas (as a refinement of the sour gas obtained as a byproduct from gasifier) or by burning light fuel gas (Idaho National Laboratory 2012, 2010).

Moreover, the efficiency of syngas generation is driven by hydrogen content in the feedstock. In the case of coal as a feedstock, hydrogen and oxygen can be sourced from high-temperature steam electrolysis (HTSE) operation driven by nuclear heat. Technical evaluations, with detailed Aspen models, were performed for integration of HTGR-HTSE hybrid with coal-based MTO conversion (Idaho National Laboratory 2012) and with coal-based methanol-to-gasoline conversion (Idaho National Laboratory 2010). For natural gas as a feedstock, nuclear-generated steam can be directly fed into the steam methane reformer (Idaho National Laboratory 2010).

The FT reactor must be designed to recuperate heat from the syngas's exit temperature. Resultantly, the first two macro processes in Figure 22 involve significant thermal exchanges. Additional technical evaluation studies on nuclear-integrated methanol production must also be initiated for other end products with high-volume demands. The remaining four sectors include formaldehyde, acetic acid, methyl tert-butyl ether, and fuel-based utilizations (revisit Figure 18).

Last, a deeper dive is needed to assess economic viability, specifically in terms of variable or fluctuating natural gas prices. The nuclear-sourced direct or indirect heat for methanol production can potentially reduce methanol-price susceptibility to natural gas cost. Other factors include, but are not limited to, carbon pricing, methanol storage and transportation costs, local environmental protection laws, and most importantly, finding leverages with recently introduced inflation reduction act. Nonetheless, the cost of natural gas as a feedstock is of paramount importance. As a case in point, BASF, one of the world's largest chemical companies, announced closure of its toluene di-isocyanate plant in Ludwigshafen, Germany. This is ascribed to higher gas prices in Europe post Russia-Ukraine conflict.

The section on nuclear-driven methanol production concludes with the following key takeaways.

- A large-scale syngas generation process requires heat sourcing above 800°C.
- Syngas generator and FT reactor must be co-designed to maximize overall process efficiency via heat recuperation from syngas conditioning.
- Nuclear-HTSE hybrid is most appropriate for augmenting hydrogen and oxygen content in gasifiers.
- Use of natural gas, with methane as its core component, is most conducive toward efficient catalysis, but increases susceptibility of methanol prices to gas markets.
- Use of biomass as a feedstock requires heat sourcing at diverse temperature and pressure ranges, based on biomass composition and moisture content.

4.4 Mining

Mining is the process extracting precious materials from the ground either directly from the surface or through underground extraction methods. Mining industries can be broadly divided into three categories: coal, metal, and industrial minerals.

4.4.1 Coal Mining

The amount of coal produced within the U.S. for last 50 years with different rank (a form of coal classification) is presented in Figure 27. Bituminous and subbituminous are produced equally within the U.S., and they combine to represent a majority of U.S.-produced coal. The amount of annual coal production within the U.S. has decreased for the last 15 years due to environmental issues and the narrow range of coal use. However, coal industries within the U.S. are still projected to have produced 0.577 billion short tons (earning 18.7 billion dollars) in 2021. It is estimated that 471 billion short tons of coal are reserved at the Demonstrated Reserve Base in the U.S. Wyodak, the largest coalbed located in Wyoming. This coalbed produced approximately 205 million short tons in 2021, accounting for 35% of annual coal production. Pittsburgh and Illinois No. 6 coalbed complete the top three domestic coal producing sites (United States Energy Information Administration 2022a).

According to EIA's annual coal report, the prices of lignite, subbituminous, bituminous, and anthracite in 2021 are $20.10, $14.18, $61.68 and $107.08 per short tons, respectively. Coal of 501.366 MMst, 91.89% of total annual usage within the U.S. in 2021, is used as fuel for electric power plants. Other coal use including coke, commercial, and institutional usage are 25.845, 17.589, and 0.811 MMst respectively. Coal for coke production has higher prices than coal burned at power plants. Metallurgical coal, which is used as raw material of coke is $159.28 per short tons and coke is $252.35 per short tons based on based on the free alongside ship (f.a.s.) value. Averages sales price of U.S. coal in 2021 is $31.76 per short ton while average price of coal delivered to power plant are $37.32 per short ton, meaning that delivery cost accounts for 15% of coal price delivered to electric power plant (United States Energy Information Administration 2022a).

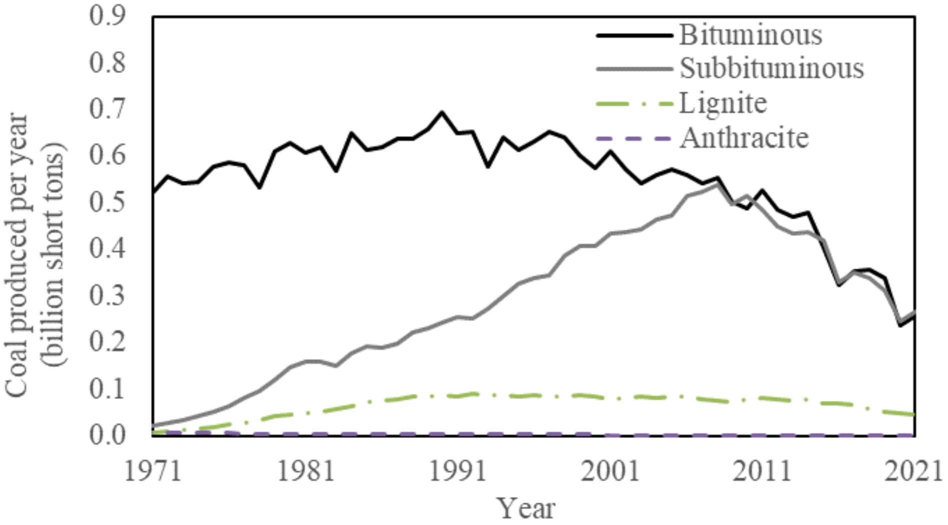


Figure 27. Coal annual production for last 50 years with different rank (United States Energy Information Administration 2022a).

Coal mining can be divided into two categories based on the location of coal deposits, and the accompanying mining method. Coal mining at less than 200 feet underground is called surface mining while more than 200 feet underground is called underground mining. In the U.S., surface mining accounts for two-thirds of the entire coal production, which is easier than underground mining. Figure 28 shows the annual coal production by underground and surface depths.

Coal immediately below the surface is mined by strip mining. Strip mining removes soil and rock (referred to as overburden) above the coal seam and then digs to the exposed coal. Mining performed along vertical contours of terrain is called contour strip mining while mining in flat areas is called area strip mining. Open-pit mining is another form of coal mining wherein miners dig down the surface of the pit like a step. The incline section of the step is called “batter” while flat part of the step is called as “bench”. Mountaintop mining is for the coal at the peak of the mountain. Area reclamation is necessary around mines, as soil and vegetation are necessarily destroyed. Reclamation typically occurs concurrently with mining or immediately following the end of mining activities. Production performance for open pit, contour strip, area strip, mountaintop is 16.54. 13.42, 6.07 and 3.52 short tons per person per hour, respectively. Those surface mining method are illustrated in Figure 29.

In underground mining, tunneling is the key to mining. Continuous method mining is designed to break up the coal bed from the faces and move forward through the bed. Longwall mining slices the coal bed along the face, making 0.6~6 m thick coal slice. Traditional mining using explosives is seldom employed within the U.S. Performance of continuous, longwall, and conventional underground mining methods are 5.99, 3.23 and 0.7 short tons per person per hour. Figure 30 shows the mining machine used at underground.

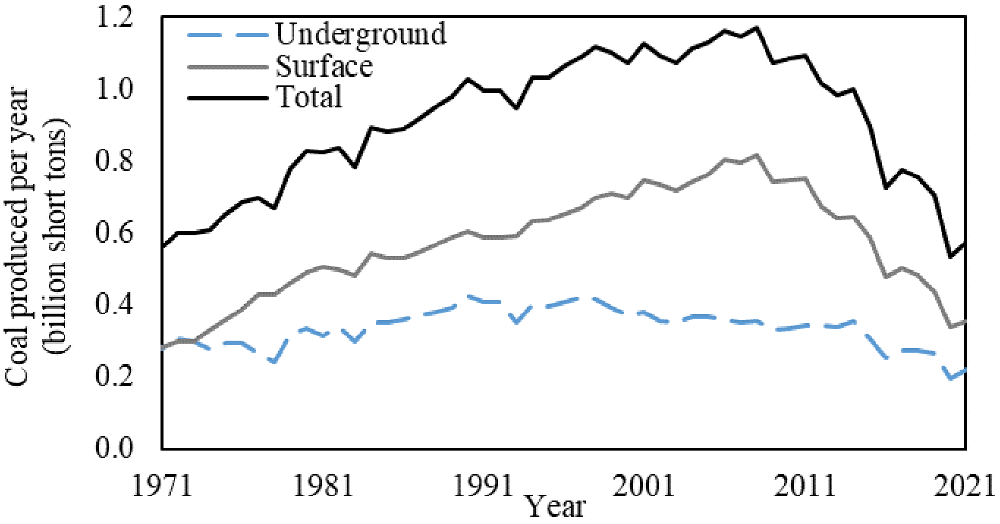


Figure 28. Annual coal production based on the depth for last 50 years (United States Energy Information Administration 2022a).

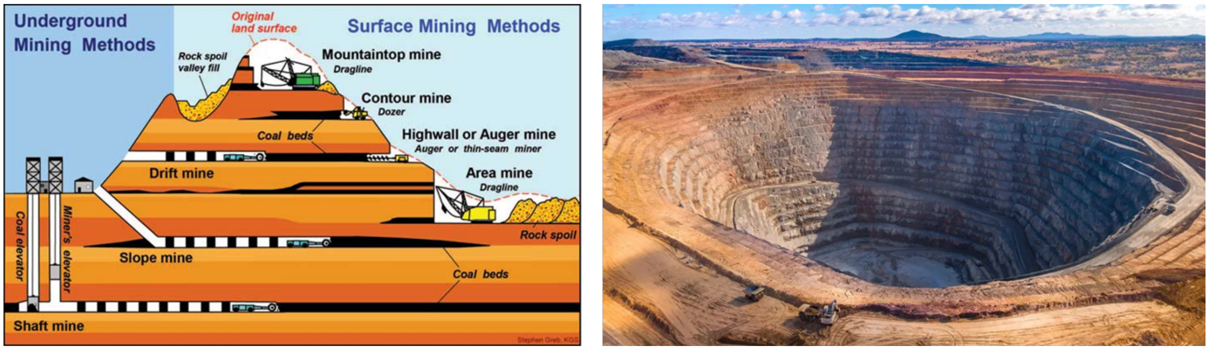


Figure 29. Surface mining method (left), mountaintop (Mac 2016), contour and area mining (right) and open pit (Evolution Mining 2019).

Figure 30. Underground mining methods: continuous(left) (Sandvik n.d.) and longwall (right) (Seismological Society of America 2022).

4.4.2 Metal Mining

Metal and metallic mineral mining facilities combine to be about twice as large as the coal mining industry in U.S. in economic value. Metal mining revenues produce around $33.8 billion. Figure 31 shows the location and kinds of metal and metallic mineral mine within the U.S. According to records reported to Toxics Release Inventory (TRI) program, 87 metal mining facilities exist in the U.S. (United States Environmental Protection Agency 2023). Mines in western states usually produce copper, silver, and gold while eastern mines produce zinc and other rare earth elements. Copper, gold, iron ore, and zinc account for total value of metal mine of 35%, 31%, 13% and 7%, respectively (United States Geological Survey 2022).

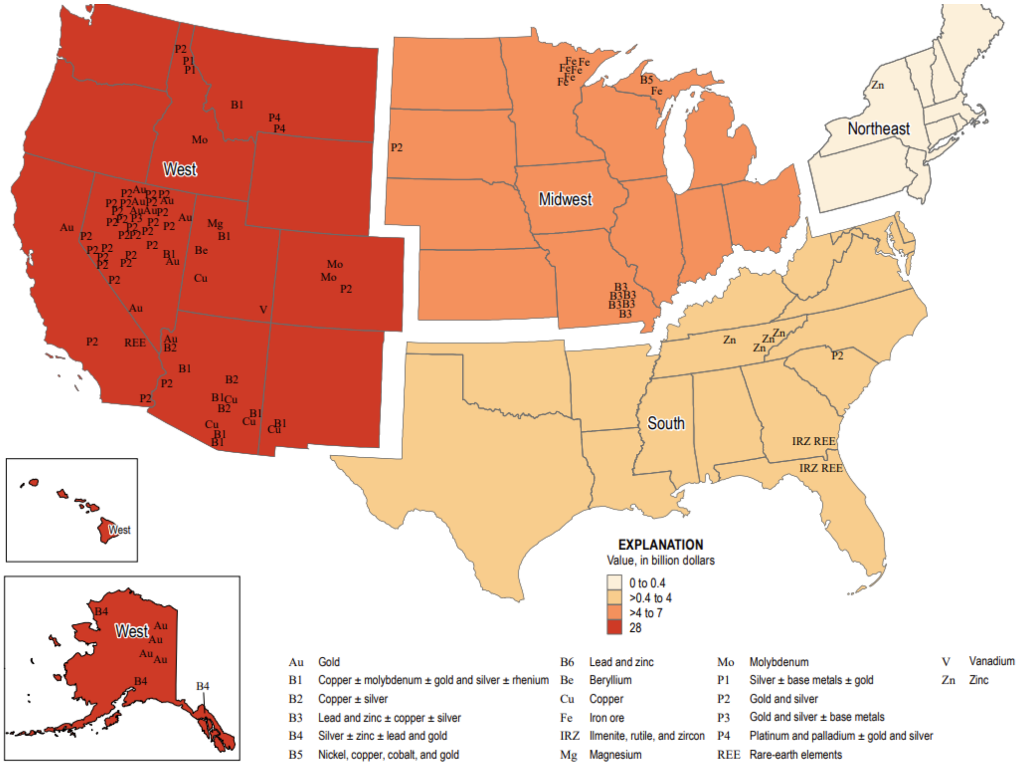


Figure 31. Metal and metallic mineral mining facilities within the U.S. in 2021 (United States Geological Survey 2022).

The challenges around decarbonizing mining are two-fold. Mining equipment is very large, requiring specialized mechanisms for maintenance. These kinds of large equipment operating at high powers are not easily conducive to electrification to reduce their environmental impacts. Creative solutions may be needed to reduce the lifecycle emissions of mined materials. The second challenge is reducing carbon emissions associated with the initial processing of mined materials. This is an area of future study and will likely have widely varying solutions as the processes may be relatively unique for each mining operation.

4.5 Oil Sands

Oil sands, also commonly referred to as “tar sands” in the U.S., are a mixture of sand, water, clay, and a thick, molasses-like substance called bitumen. These reserves are primarily found in Canada’s Alberta province and are estimated to contain one of the largest oil reserves in the world, with the potential to produce over 170 billion barrels of oil (Khakzad et al. 2022). Hence, most of the data and estimates analyzed in this section are attributed to Canada’s Alberta province oil sand production. When the concentration of bitumen in the oil sands is high, it becomes economically feasible to extract it and process it into synthetic crude oil.

Extracting oil from oil sands is an energy-intensive process and emits a large amount of greenhouse gases. In recent years, there has been increasing pressure to decarbonize the oil sands industry, either by reducing emissions from the extraction process or by developing alternative technologies to produce clean energy from oil sands resources (Janzen, Davis, and Kumar 2020). Many environmental groups have even advocated for a complete phase-out of oil sands production, predicting the full decarbonization of oil sands is not feasible and citing its significant contribution to global carbon emissions (Muzzerall 2022; Bagley 2015). However, there has been still growing interest in decarbonizing the oil sands industry. Herein, we focus on one promising approach to reduce the carbon emissions from the extraction process by using nuclear energy to generate steam instead of burning fossil fuels.

4.5.1 Oil Sands Extraction Methods

At present, the primary methods for extracting bitumen involve 1) surface mining or open-pit mining followed by thermal processing, and 2) in-situ methods such as steam assisted gravity drainage (SAGD). Surface mining involves high costs related to equipment, operations, and reclamation while in situ production is mainly dominated by the cost of natural gas used for steam injection. The profitability of both approaches has increased due to high oil prices, leading to their rapid expansion. It is important to note that both of these recovery methods utilize natural gas as an energy source, thereby contributing to the release of greenhouse gases into the environment.

The surface mining or open-pit mining process involves removing the top layer of soil and rock, known as the overburden, to access the oil sands. Once the overburden has been removed, the oil sand is scooped up and transported to a processing plant where it is mixed with hot water and chemicals to separate the bitumen from the sand and clay. In situ drilling is a method used when the oil sands are too deep to be accessed through open-pit mining. In this process, a well is drilled into the ground and steam or solvents are injected to liquefy the bitumen, which can then be pumped to the surface.

Around 80% of recoverable oil sands reserves are typically located too deep for surface mining, thus requiring in situ processes to access them (Finan 2007). Via the SAGD method, high-pressure steam is injected into the ground to heat up and decrease the viscosity of bitumen, which typically has a viscosity range of 1 million centipoise (cP) to 10 cP. This process enables the hot bitumen to flow into production wells. The process then involves pumping bitumen and water back to the surface from a well. In a field, the well pairs are positioned adjacent to one another, as illustrated in Figure 32.

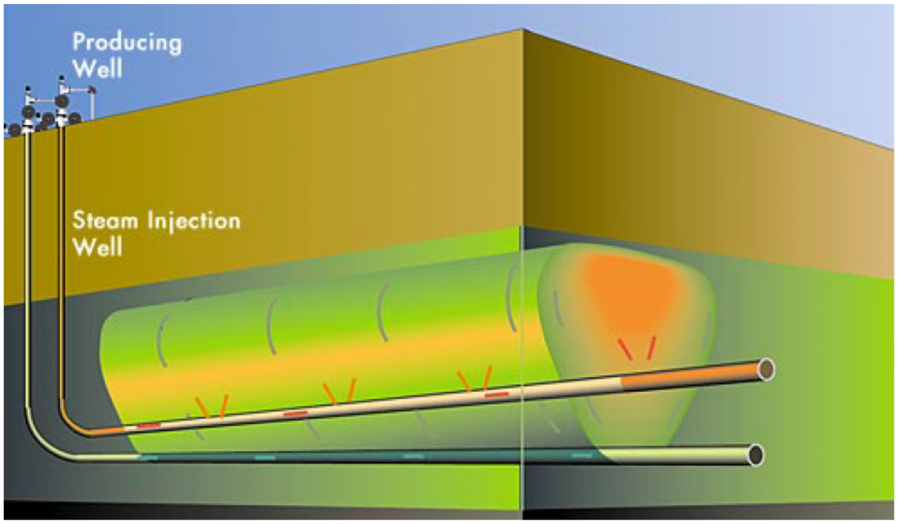


Figure 32. SAGD well arrangement (Finan 2007).

The process follows several phases:

1. The break-in phase for each well takes approximately 2 to 3 months. Steam is injected into both wells to establish thermal communication, and no bitumen is recovered.
2. Steady production period lasting between 6 to 10 years. Steady production is usually characterized by a steam-to-oil ratio (SOR) of two to three, which means that for every barrel of bitumen produced, two to three barrels of water must be heated to 100% steam and injected into the well.
3. Winding-down period of up to 4 years as the total recovered bitumen gets closer to the 50–70% threshold of the total bitumen in place that can be extracted.

Figure 33 shows a detailed block flow diagram of the conventional SAGD process (Gandrik, Patterson, and Mills 2011). The process typically includes various unit operations such as steam generation, steam transport, oil/water separation, and water treatment. In the SAGD process, both high- and low-pressure steam are required, with the former being used for injection into the well pads to recover bitumen, and the latter being used for water treatment. The high pressure, saturated steam is typically produced by combusting natural gas in a once-through steam generator at a pressure of approximately 1,450 psia (at 592°F). The steam pressure condition is usually selected to ensure it could be delivered over long distances to the SAGD well pads. The remaining heat in the hot combustion gas is utilized to generate low-pressure steam for water treatment.

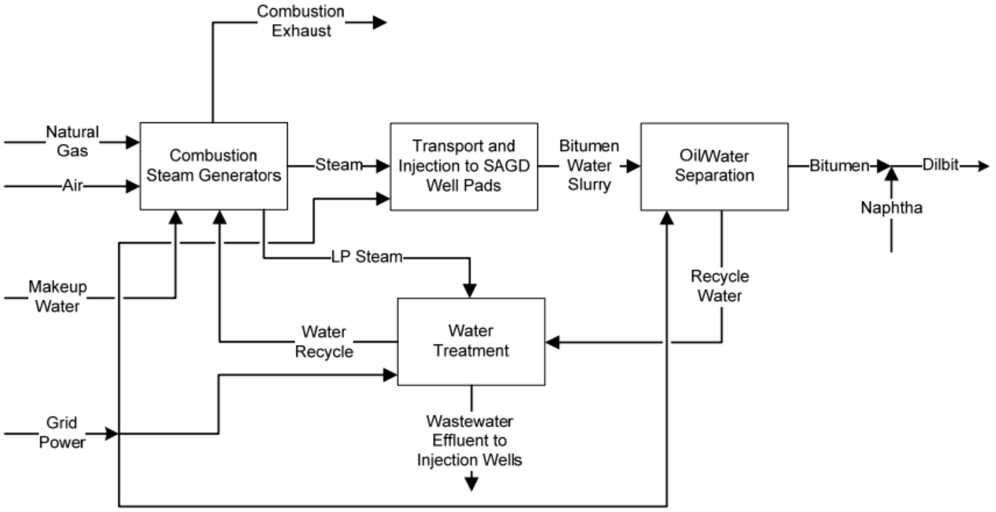


Figure 33. Block flow diagram for the conventional SAGD process (Gandrik, Patterson, and Mills 2011).

4.5.2 Bitumen Energy Production Requirements for SAGD Heat and Steam

The amount of steam needed for SAGD operations can differ significantly among fields, however, average values can be estimated from previous projects. For instance, Suncor's Firebag and EnCana's Foster Creek fields used steam generated at 9–11MPa and 310–320°C, whereas Shell's Blackrock project has had success with steam generated at about 6.0 MPa (275°C) (Nexen Inc. and OPTI Canada Inc. 2006). The steam used for SAGD operations is typically produced at a quality of around 80% and is then separated to reach 100% quality. However, due to pressure drops resulting from friction and flow splitting through several well pads, the steam pressure drops to about 4.5 to 6.5 MPa by the time it reaches an injection well. The SOR is usually between 2 and 4, with a lower ratio being desirable. It can be concluded that the steam production from most previous projects falls within the range of 6MPa to 11MPa for saturated steam with an associated SOR of 2 to 3. Therefore, over the lifetime of a well, one barrel of bitumen is recovered for every 2 to 3 barrels of steam injected.

A general estimate for in situ SAGD recovery is that each barrel of bitumen requires 1.0–1.5 Mcf of natural gas. Hence, assuming an average reasonable SOR of 2.5 requirement for a given oil sand well, that corresponds to a natural gas requirement of 1.1 Mcf per barrel. A ratio of 3.0 is used in Table 3, which results in a natural gas intensity of 1.3 Mcf per barrel. (Note that one Mcf is equivalent to 1.027 MMBtu.) Table 3 presents the daily and yearly natural gas consumption and the resulting greenhouse gas (GHG) emissions for varying levels of SAGD bitumen production per day. Note that SAGD projects require relatively little electric power relative to their required thermal power as electricity is used primarily only for pumping the fluids used in the process.

Table 3. SAGD Steam Natural Gas Consumption and GHG Emissions (Finan and Kadak 2010).

Barrels of Bitumen Per Day	Natural Gas for Steam Production (MMBtu/day)	Resulting GHG Emissions (CO_2e metric tons/day)	GHG Emissions (CO_2e kt/yr)
30,000	40,053	2,603	950
60,000	80,106	5,207	1,900
100,000	133,510	8,678	3,170
200,000	267,020	17,356	6,340
500,000	667,550	43,391	15,840
1,000,000	1,335,100	86,781	31,680
2,000,000	2,670,200	173,562	63,350

* 2 A conversion ratio of 65 kg CO_2 per MMBtu of natural gas burned is used.

4.5.3 Types of Reactors Best Suited

Several types of nuclear reactors have been proposed in the past for use in the oil sands, including the Enhanced CANDU 6, the Advanced CANDU Reactors (ACRs) ACR-700 and ACR-1000, and high-temperature gas-cooled reactors such as the pebble bed modular reactor (PBMR) and AREVA's ANTARES prismatic design. Finan et al. (Finan and Kadak 2010) analyzed the PBMR as a reference high-temperature gas reactor. In each case, the ASPEN PLUS™ program was used to model the capacity of the nuclear reactor for producing steam. The purpose of the analysis was to determine the steam production capacity of each reactor to compare its output with the requirements of an oil sands project. According to the study, the CANDU reactors were found to have low steam pressure and were too large for SAGD, while the smaller 500 MWth high-temperature pebble bed gas reactor was well-suited for steam production. The Enhanced CANDU 6 was found to be suitable for providing heat and electricity to surface mining operations. Nuclear integration in general was found to be economically viable when natural gas prices were above $10/MMBtu at the time of the study, and CO_2 emissions could be reduced significantly. Overall, the study suggested that nuclear energy integration in the oil sands business is a feasible and viable path forward.

Additional work can be performed to focus more on current advanced reactors and their applicability for nuclear integration with oil sands. Two types of nuclear reactors that are particularly well-suited for this application are microreactors and SMRs. Microreactors and SMRs are designed to be more efficient and cost-effective than traditional nuclear power plants. SMRs can be manufactured offsite and transported to the oil sands site, reducing the construction time and cost of the nuclear plant. Additionally, the modular design allows for greater flexibility in scaling up or down the nuclear power supply as needed. In previous work, NEI (2019), Shropshire et al. (2021), Abou Jaoude et al. (2021) , and other sources have discussed the use of small and micro nuclear designs as alternatives to large grid-connected stations (Nuclear Energy Institute 2019; Shropshire, Black, and Araujo 2021; Abou Jaoude et al. 2021). 28 small and micro nuclear HTR concepts that could be relevant for the Alberta bitumen sands use cases are listed in Table 4 following the classification proposed in Section 3. Small and micro-reactor concepts incorporate modularity and factory manufacturing for efficient fabrication and onsite installation.

Table 4. Overview of small modular reactors and microreactors.

Reactor	Type	SMRs	Microreactors
ALWR	PWR	- NuScale(iPWR) - Holtec(SMR-160)	- Dunedin (SMART)
—	LWR	- GE-Hitachi (BWRX-300)	—
—	BWR	- CANDU SMR	—
HTGR	—	- BWX Technologies (ANR) - General Atomics (FMR) - X-energy (Xe-100)	- HolosGen (HOLOS) - Radiant (Kaleidos) - StarCore - U-Battery - Ultra Safe Nuclear Corp. (MMR)
MSR	—	- Elysium (MCSFR) - MoltexEnergy (SSR) - TerraPower(MCFR)* - Terrestrial Energy (IMSR) - Kairos (Hermes) - fuelFlibe(LFTR) - ThorCon(TMSR) - Thorium Power (DBI Thorium Reactor)	—
LMR	SFR	- ARC-100 - GE-Hitachi PRISM) - TerraPower (Natrium)	- Oklo(Aurora) - Westinghouse (eVinci)
—	LFR	—	- LeadCold(SEALER)

While steam from Rankine cycle power plants is the main fluid considered herein for bitumen extraction, other types of fluids have also been considered. As part of the Next Generation Nuclear Plant (NGNP) project, a technical evaluation was conducted to evaluate the integration of a HTGR with the SAGD process applicable to oil sands (Mckellar, Patterson, and P.M. 2011). The technical evaluation analyzed five heat transfer fluids, including two gases, two liquids, and one molten salt, to determine their effectiveness in transferring heat from the HTGR to a remote boiler in the SAGD process. The analysis assumed that the heat is carried through a 25 km pipeline to the boiler, where 11MPa steam is generated, and then returned through another 25 km pipeline to the HTGR. The pressure and heat losses for each pipeline were calculated. The results showed that steam and FLiNaK were the most effective fluids for producing SAGD steam and servicing the SAGD well pads. However, FLiNaK had undesirable issues, including a high cost, the potential for solidifying in the pipelines, and its effects on pipe materials. In contrast, water/steam was readily available and effective in transferring heat with much less mass. Example of the steam-driven process discussed in that study is shown in Figure 34. The number of well pads serviced decreased as the distance between the reactor and well pads increased. Based on the analysis, steam at a pressure of 17 MPa and a minimum approach temperature difference of 25°C at the well pad boiler was recommended as the preferred choice for the secondary heat transfer loop.

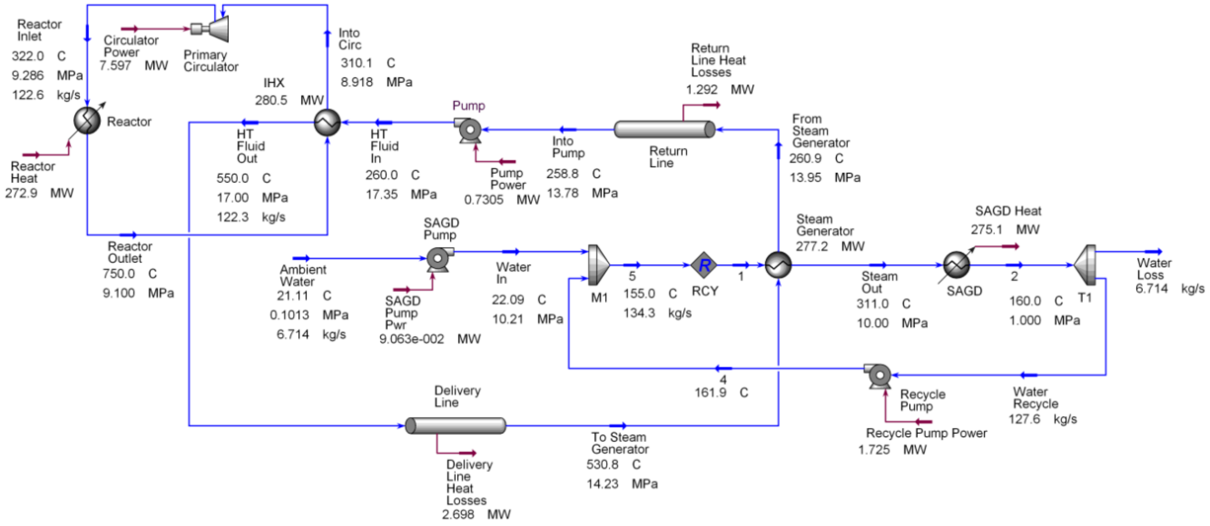


Figure 34. Process flow diagram of heat transfer loop from reactor to SAGD well pad using steam as the heat transfer fluid.

4.5.4 Nuclear Energy Integration with Oil Sands

Several options for the layout of a plant for steam and electricity generation can be considered. On option involve splitting the reactor complex into two separate islands for steam and electricity generation. Another option involved connecting the steam and electricity generation units in series with the reactor complex, though this would require a relatively high-temperature core or balance-of-plant outlet and could eliminate the feasibility of some reactor technologies. Further engineering analysis can be done to determine the exact outlet temperature and heat flow required for this layout option. A few configurations proposed by Foss et al. are shown in the Figure 35 and Figure 36 (Foss, Bryan, and Pisarra 2021).

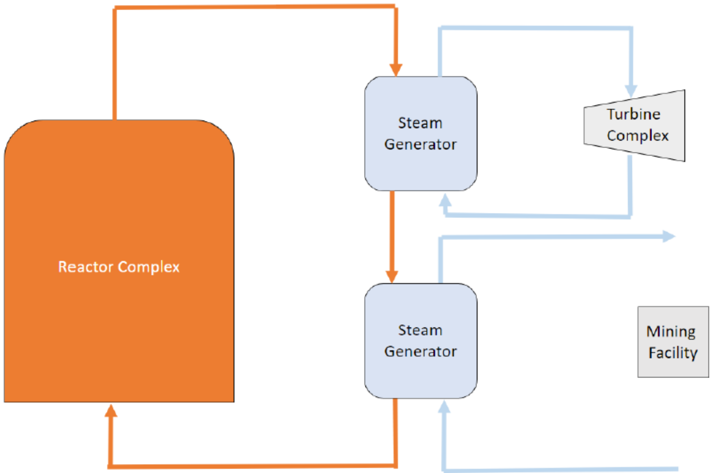


Figure 35. Possible plant configuration with steam generators in series for steam and electricity generation.

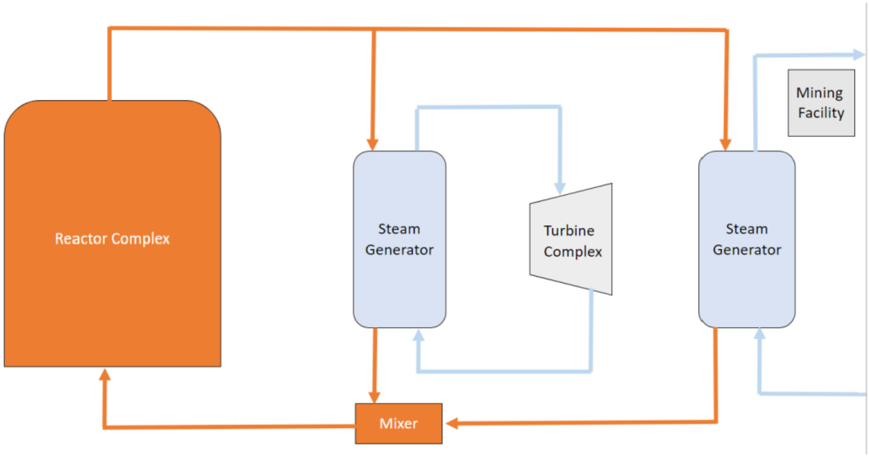


Figure 36. Possible plant configuration with steam generators in parallel for steam and electricity generation.

A nuclear-integrated steam-SAGD process was compared to a conventional SAGD process in (Gandrik, Patterson, and Mills 2011). The proposed nuclear-integrated SAGD process includes the same unit operations as the conventional process but replaces the once-through steam generator fueled by natural gas combustion with a steam reboiler. This steam reboiler, a steam-to-steam heat exchanger, uses heat supplied from a HTGR instead of combustion heat. Power is also generated from the HTGR in a Rankine cycle to supply the power requirements for the SAGD process. The steam generation for the nuclear-integrated SAGD case is similar to the conventional case, with the high-pressure, saturated steam being generated at approximately 1,450 psia (592°F) through heat exchange with the 540°C, 17 MPa steam provided from the HTGR in a steam reboiler. Heat remaining in the HTGR steam is then used to generate low-pressure steam for use in water treatment. Power consumption for the nuclear-integrated SAGD case increases from 113 MWe for the conventional case to 200 MWe due to the increased power load required for the HTGR primary circulators.

The analysis indicates a strong potential heat integration opportunity for an HTGR in the conventional SAGD case. By substituting nuclear heat for natural gas combustion in the steam generator and using an HTGR Rankine cycle to supply power, natural gas consumption and CO2 emissions are eliminated from the process. The modeling results for the nuclear-integrated SAGD case are technically promising, with a four-pack of 600 MWt HTGRs being required to produce 190,000 barrels per day of bitumen. A summary of the modeling results from the study for all cases is presented in Table 5, and a high-level material and energy balance summary for each case is graphically presented in Figure 37.

Table 5. Conventional versus Nuclear-integrated SAGD modeling case study results (Gandrik, Patterson, and Mills 2011).

	Conventional SAGD	Nuclear Integrated SAGD
Inputs		
Natural Gas Feed rate (MMSCFD)[2]	192.5	0
# HTGRs (600 MWt)	N/A	4
Naphtha as Diluent (bbl/day)	81,429	81,429
Outputs		
Dilbit Product (bbl/day)	271,429	271,429
Bitumen (bbl/day)	190,000	190,000
Naphtha (bbl/day)	81,429	81,429

	Conventional SAGD	Nuclear Integrated SAGD
Utility Summary		
Total Power (MWe)	-113.2	0
SAGD Process Consumption	-113.2	-108.9
HTGR Consumption	N/A	-83.7
HTGR Rankine Cycle Production	N/A	192.6
Water Requirments[3]	—	—
Water Consumed (gpm)	884	884
CO_2 Summary		
Total CO_2 Emitted (ton/day)	11,831	0
Nuclear Integration Summary		
Nuclear Heat Supplied[4] (MWt)	N/A	2,486
HTGR Heat to SAGD Process	N/A	2,032
HTGR Heat to Power Generation	N/A	454
Nuclear Power Supplied (MWe)	N/A	108.9

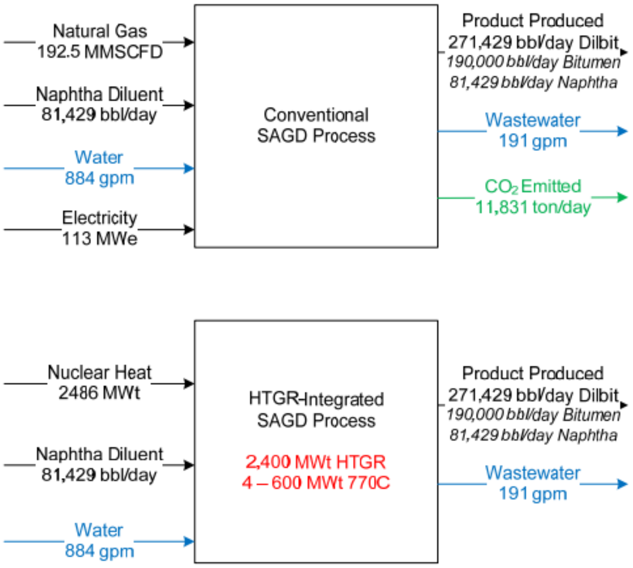


Figure 37. SAGD modeling case material balance summary (Gandrik, Patterson, and Mills 2011).

A similar detailed ASPEN model and streams analysis for the SAGD with cost analysis and technoeconomic evaluation for the nuclear-integrated SAGD cases can be conducted for other microreactors or SMRs in future work.

4.5.5 Challenges

The use of nuclear energy in the oil sands industry is not without challenges. First, the interest in extracting oil sands in the U.S. is far less than that in Canada, likely due to limited reserves in U.S. despite recent discovery of potential oil sand reserves in Utah. Additionally, though this topic are beyond the scope of the current report, the economic viability of using nuclear energy to decarbonize oil sands is also a key consideration. While nuclear power can be cost-competitive in the long run, the oil sands industry is traditionally subjected to high fluctuating oil prices and market demand, which can impact the projected profitability of nuclear projects in this sector.

On the positive side, previous studies have shown that integrating nuclear heat and power into oil sands recovery can have a positive impact by reducing natural gas consumption and associated CO2 emissions. This nuclear integration can also provide economic stability by reducing the dependence on natural gas prices, although it is reported to be more cost-effective than the conventional process only at higher natural gas prices. Additionally, the nuclear-integrated SAGD process has the potential to further outperform conventional methods when carbon tax penalties are imposed.

4.5.6 Summary and Remarks

For nuclear integration with oil sands processes, the use of nuclear energy in this industry has both benefits and challenges. While it can provide a source of clean and reliable energy, the economic viability of such projects is dependent on the fluctuating oil prices and market demand. Nonetheless, previous studies have shown that integrating nuclear heat and power into oil sands recovery can have positive impacts on reducing natural gas consumption and associated CO2 emissions, at least for the processes related to the bitumen extraction. Additional work shall be focused on conducting detailed process models and cost analyses for integration with other microreactors or SMRs to assess the potential for integration in the oil sands industry further.

4.6 Oil Refining

The United States refines approximately 12 million bbls/d of crude oil in petroleum refineries to usable products such as transportation and heating fuels, chemicals, chemical feedstocks, petroleum coke and asphalt. The refineries are located throughout the U.S. as shown in Figure 38 below. A typical refinery block diagram is shown in Figure 39 and a process flow diagram (PFD) is shown in Figure 40.

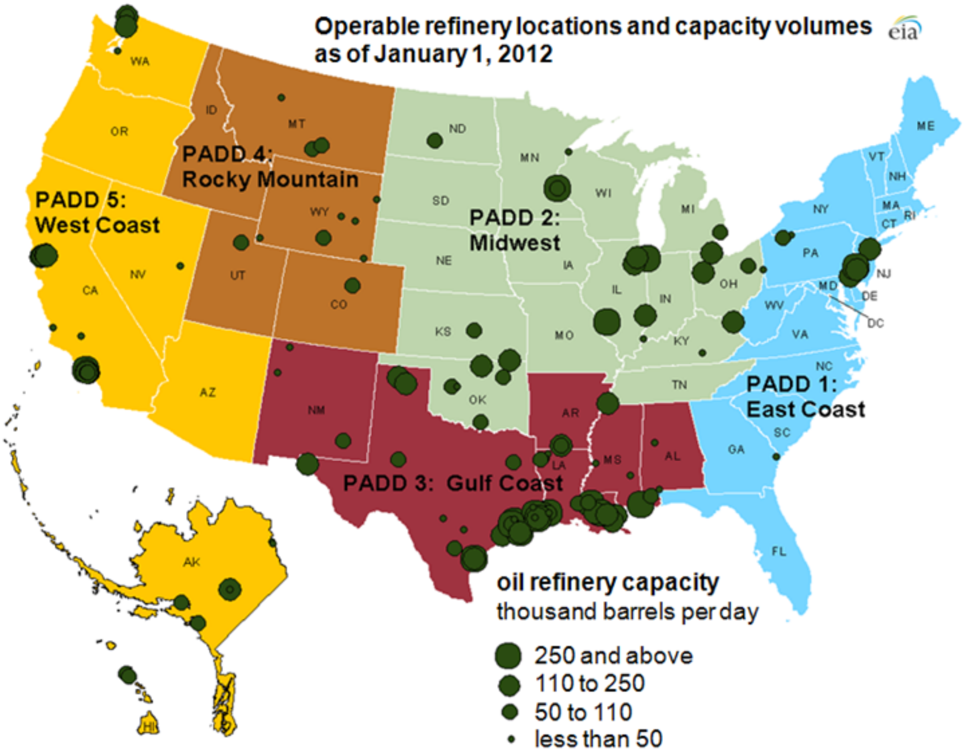


Figure 38. Locations and sizes of oil refineries in the United States.

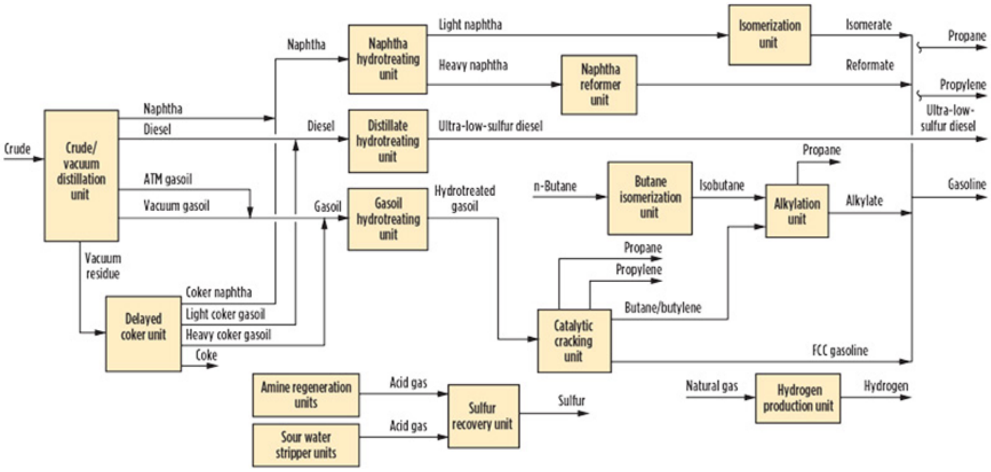
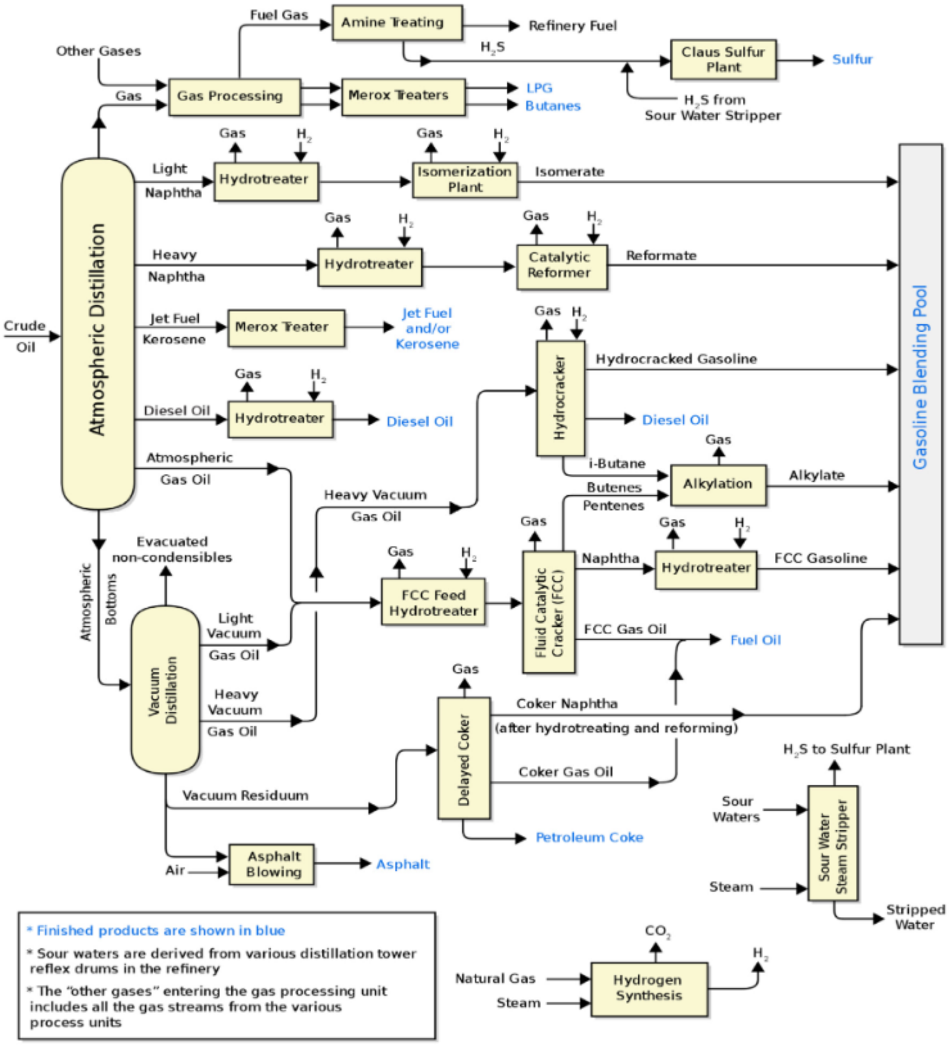


Figure 39. Refinery block flow diagram.



* Finished products are shown in blue

* Sour waters are derived from various distillation tower reflex drums in the refinery

* The "other gases" entering the gas processing unit includes all the gas streams from the various process units

Figure 40. Typical refinery PFD showing various process operations.

4.6.1 Fractionation

Fractionation is a refining step that separates components by their boiling temperature i.e., crude oil and other intermediate streams in fractionation and distillation columns. Heat is supplied to the columns with fired furnaces to enable the separation of lighter components from heavier boiling fractions. These streams are sent as component streams for product blending or further conversion and upgrading in other refining units. The first step in all refineries requires atmospheric distillation units for the initial stream separation. In more complex refineries, a vacuum-distillation column may be included to remove and upgrade heavier petroleum fractions in the refinery to higher-value products.

4.6.2 Upgrading and Conversion

Following the fractionation step, heavy, lower-value distillation fractions can be processed further into lighter, higher-value products such as gasoline, diesel fuel and other finished products.

The most widely used conversion method is called cracking because it uses heat, pressure, catalysts, and sometimes hydrogen to crack and reduce heavy hydrocarbon molecules into lighter ones. Cracking processes are employed to upgrade these lower-value streams to lighter components that can be blended to meet the product specifications. These processes use a combination of high temperatures, pressures and catalysts to accomplish these refining steps. Also, some cracking processes use hydrogen to catalytically reduce the heavy hydrocarbon streams. Complex refineries can use fluid catalytic cracking, coking and hydrocracking/hydrocracker units for the cracking process (United States Energy Information Administration 2013c). The heat energy generated in these cracking units is recovered by integrating the heat with preheat heat exchange systems and steam-generating. A cracking unit consists of one or more reactors and a network of furnaces, heat exchangers, and other vessels.

Petroleum refineries vary in complexity but include these basic steps to produce these products. In general, refining is an energy-intensive process. Intermediate oil streams require conversion and upgrading steps which are endothermic and exothermic. A table of refining operations and their respective operating conditions are provided in Table 6.

Table 6. Operating conditions for selected refinery unit operations.

Process	Temperature	Pressure	Reaction Type
Hydrotreating	300 – 425°C	735 – 1,500 psi	Exothermic
Hydrocracking	375 – 500°C	1,200 – 3,000 psi	Exothermic
Fluid Catalytic Cracking	480 – 550°C	10 – 20 psi	Endothermic
Coking	485 – 505°C	10 – 30 psi	Endothermic

Cracking is not the only form of crude oil conversion; other refinery processes rearrange and combine molecules rather than splitting them to add value. Alkylation, for example, is an exothermic process that makes gasoline components by combining some of the smaller gaseous byproducts of cracking to higher-carbon-number molecules in the range of fuel blendstock (United States Energy Information Administration 2013a). The process takes place in a series of large, horizontal vessels and tall, skinny towers. Alkylation makes gasoline components by combining light hydrocarbons in the presence of sulfuric or hydrofluoric acid (United States Energy Information Administration 2013a).

Reforming is an endothermic process that uses heat supplied by fired furnaces, moderate pressure, and catalysts to turn naphtha, a light, relatively low-value fraction, into high-octane gasoline components (United States Energy Information Administration 2013b).

4.6.3 Contaminant Removal

Crude oil contains contaminants such as sulfur and nitrogen. These contaminants need to be removed from the resultant component streams before they can be blended into the ultimate products.

Hydrotreating and hydroprocessing processes are employed for this purpose, using high-temperature and pressure in the presence of hydrogen and catalysts. These processes are exothermic and generate excess heat. The heat energy is recovered from the hydroprocessing units and efficiently used throughout the process or integrated with other refining units to conserve energy.

4.6.4 Blending

The component streams from the refining units are combined to meet the specifications for gasoline, jet, and diesel fuel products.

4.6.5 Heat Recovery

Refineries use high-temperature systems throughout the refinery. Fired furnaces are used to supply preheat to hydroprocessing units and reboil heat to distillation columns. Also, many refining units operate at high temperatures ranging from 400 to 1,500°F. Heat is efficiently recovered from these systems to generate various levels of steam and system preheat.

Steam-generated heat recovery or combustion of excess light-hydrocarbon gases is used for power generation. Depending on the steam conditions of pressure and temperature, power generation from a steam-extraction system could require 30–80 lb/hr./kW of power generation. Another power generation mode uses a condensing turbine which generates power by reducing the inlet steam pressure to a low-temperature via condensing the outlet steam to condensate. This power generation method requires 20–30 lb/hr. of steam/kW of power generation.

4.6.6 Refining CO_2 Emissions

As mentioned, refineries require a large quantity of heat and energy to accomplish the separation and low-valued intermediate oil stream upgrading. This energy is supplied from the combustion of natural gas. Also, the conversion processes consume hydrogen which is commonly produced through the steam reforming of natural gas. As a result, the refineries produce approximately 0.45 kg of CO_2 per kg of crude oil charged to a refinery. Based on the crude oil refined in the U.S., the CO_2 emissions from petroleum refining in 2022 was approximately 238 million tonnes.

4.7 Pulp & Paper

The kraft process accounts for approximately 85% of pulp production in the United States. This process, invented in 1879, has remained so dominant because its chemical recovery process can recover approximately 95% of the pulping chemicals while producing steam. The kraft process can also handle a wide variety of wood species, and the pulp strength is considered superior to other pulping processes. The other three processes principally used in chemical pulping are sulfite, neutral sulfite semichemical (NSSC), and soda (United States Environmental Protection Agency 1990). Chemical pulping processes use harsh chemicals and heat to separate plant cellulose fibers from lignin. The dissolved lignin is later burned as fuel, while the cellulose pulp is separated and washed to become paper.

An alternative to chemical pulping is mechanical pulping, which is a low cost, high-yield process in comparison. However, the products are of lower quality because the grinding process damages the fibers, as opposed to chemical processes dissolving the lignin around the fibers. Mechanical processes also require an external energy source, while chemical processes generate their own energy when the lignin is burned in the recovery process.

The suitability of pulp and paper mills for nuclear-integrated hinges on the assertion that pulp and paper production is a stable, if not growing, industry. From a high-level perspective of the paper industry, one might expect that paper demand is decreasing due to the conversion to digital platform. However, while consumption of newsprint, graphic and printer paper has greatly decreased, the demand for packaging paper and paperboard is still increasing, as shown in Figure 41. Despite the conversion of many paper products to digital, it is reasonable to assume that paper products like cardboard, paperboard, and household tissue will remain stable or increase in the future.

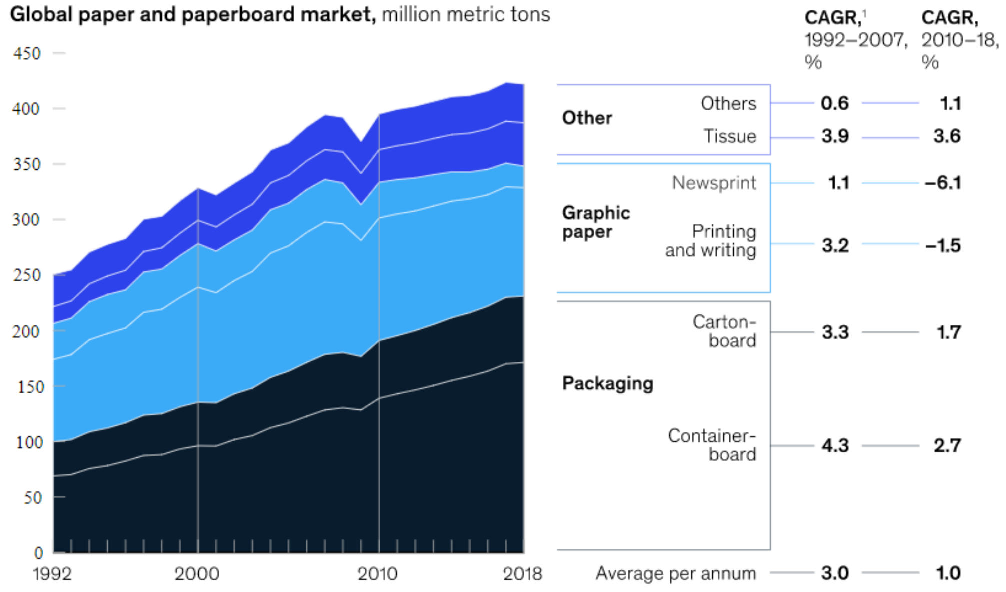


Figure 41 Global pulp and paper market evolution (Berg and Lingqvist 2019).

Because the kraft process is so dominant in the United States, it will be the main focus of integration efforts with the pulp and paper industry. Although not covered in this paper, it is expected that a mechanical pulping process could be integrated with an NPP similarly to other industries that require only electricity inputs, or potentially small amounts of heat. NPP integration with and decarbonization of the kraft process requires extensive consideration for the process byproducts, internal energy generation, steam temperature sensitivity, and the impacts of design changes. Fortunately, over 100 years of process improvements and operating experience make the kraft process a good candidate for investment in decarbonization opportunities.

4.7.1 Process Description

From a material balance perspective, pulp and paper-making is a highly efficient process. The chemical recovery process is designed to maximize the retrieval of high quality cellulose fibers and dispose of remaining solids through energy generation. Lime materials in the causticizing step can be reused many times after being heated to high temperatures. Because the cellulose fibers adhere to each other with hydrogen bonds, used paper can be effectively converted back to fibers to be pressed and used in new products. Waste material consists largely of particulate emissions of sodium salts and calcium salts from the recovery durance, lime kiln, and smelt dissolving tank. Gas emissions consist of sulfur dioxide, carbon monoxide, hydrogen sulfide, nitrogen oxides, and carbon dioxide from combustion processes and lime generation in the lime kiln.

4.7.1.1 Kraft Pulping Process

The specific design details of the Kraft pulping process will vary based on each specific facility, which is why the feasibility studies for integration are so important. The description of the process here is developed through several generic and specific descriptions of kraft pulp mill designs (United States Environmental Protection Agency 1990; Eriksson and Hermansson 2010; Thompson Equipment Company n.d.). A high-level depiction of the kraft process is given in Figure 42.

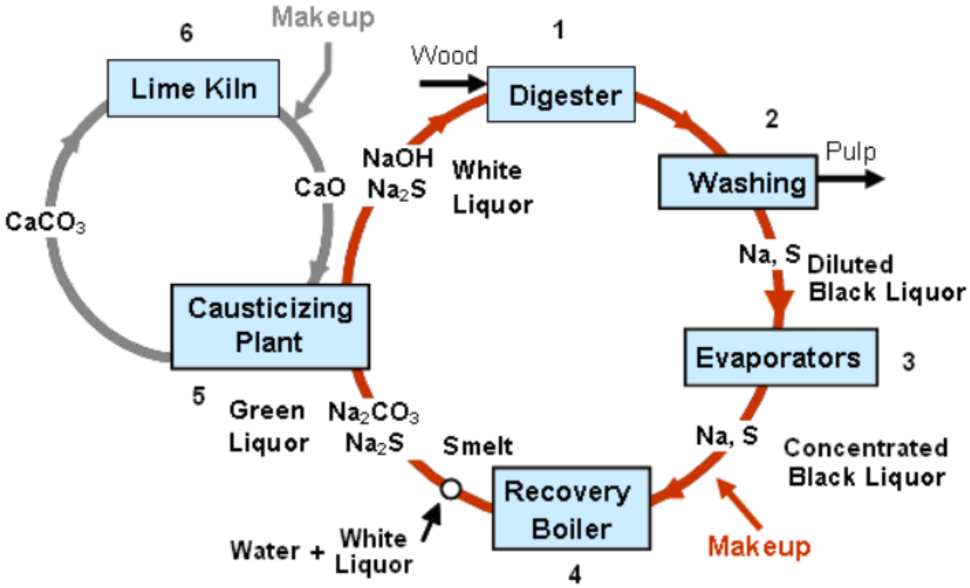


Figure 42. High-level overview of the stages of the kraft cycle (Tran and Vakkilainnen 2012).

The process begins with wood logs. The logs may be washed to remove dirt, ice, and gravel. Bark is mechanically removed in the debarking process, separated, and dried as fuel in a bark boiler. The logs are then cut into chips and preheated in a drying process.

The wood chips are mixed with white liquor, a fresh batch of sodium hydroxide (NaO) and sodium sulfite (Na_2S), for digesting, which can occur in continuous or batch processes. The digester is heated and cooked at a sustained temperature to facilitate delignification until the strong cooking liquor is displaced with a weaker liquor. When the cooking is finished, a cooling liquor displaces the weaker liquor. In the final digesting step, the pressure in the digester is lowered, which depolymerizes the fibers through rapid evaporation and a subsequent pressure increase. The various liquor stages are either cooled and stored, reused directly in the digesting cycle, or sent to the evaporation plant. The process of digesting is depicted in Figure 43.

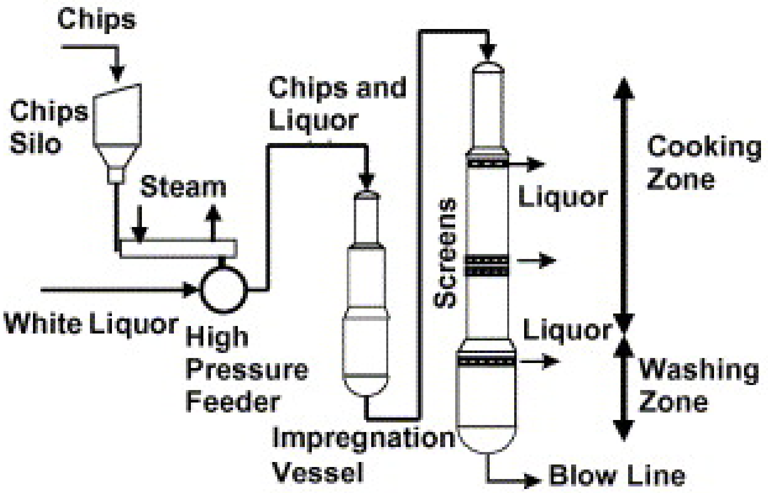


Figure 43. Depiction of a continuous digester (Pougatch, Salcudean, and Gartshore 2006).

The digested components consist of pulp and a mixture of lignin and cooking chemicals called black liquor. The weak black liquor contains about 12-15% solid lignin, oxidized inorganic compounds (Na_2SO_4 and Na_2CO_3), and white liquor (Na_2S and NaOH). The black liquor is removed in several washing steps, and the pulp is screened to remove knots and incompletely cooked fibers.

The last step of the pulping process in bleaching. Remaining lignin can be decreased by prebleaching the pulp with oxygen. This is followed with further bleaching with hydrogen peroxide, chlorine dioxide, and caustic soda. If the paper production process does not occur on-site, the pulp is dried and transported to the customer. If it is an integrated mill, the pulp will be pumped into storage.

The chemical recovery process follows the production of pulp. The weak black liquor is concentrated in a multi-effect evaporator, increased to about 50% solids, and then further concentrated in a direct-contact evaporator to 65% solids. Water removed in the evaporator is stripped and drained. Sopas can be extracted from the condensate and acidified into tall oil, which can be converted to beck oil to power the lime kiln. The highly concentrated black liquor is combusted in the recovery boiler to generate steam. The combustion itself is an important part of the recovery process, because it reduces sodium sulfate (Na_2SO_4) to sodium sulfide (Na_2S), a main component of white liquor. Unburned residuals from the black liquor form a smelt in the bottom of the recovery boiler, and the smelt is dissolved in weak white liquor creating a mixture called green liquor, a solution of carbonate salts (primarily Na_2S and Na_2CO_3) and insoluble, unburned carbon and inorganic impurities called "dregs". The "dregs" are removed in the green liquor clarifier. This process is depicted in Figure 44.

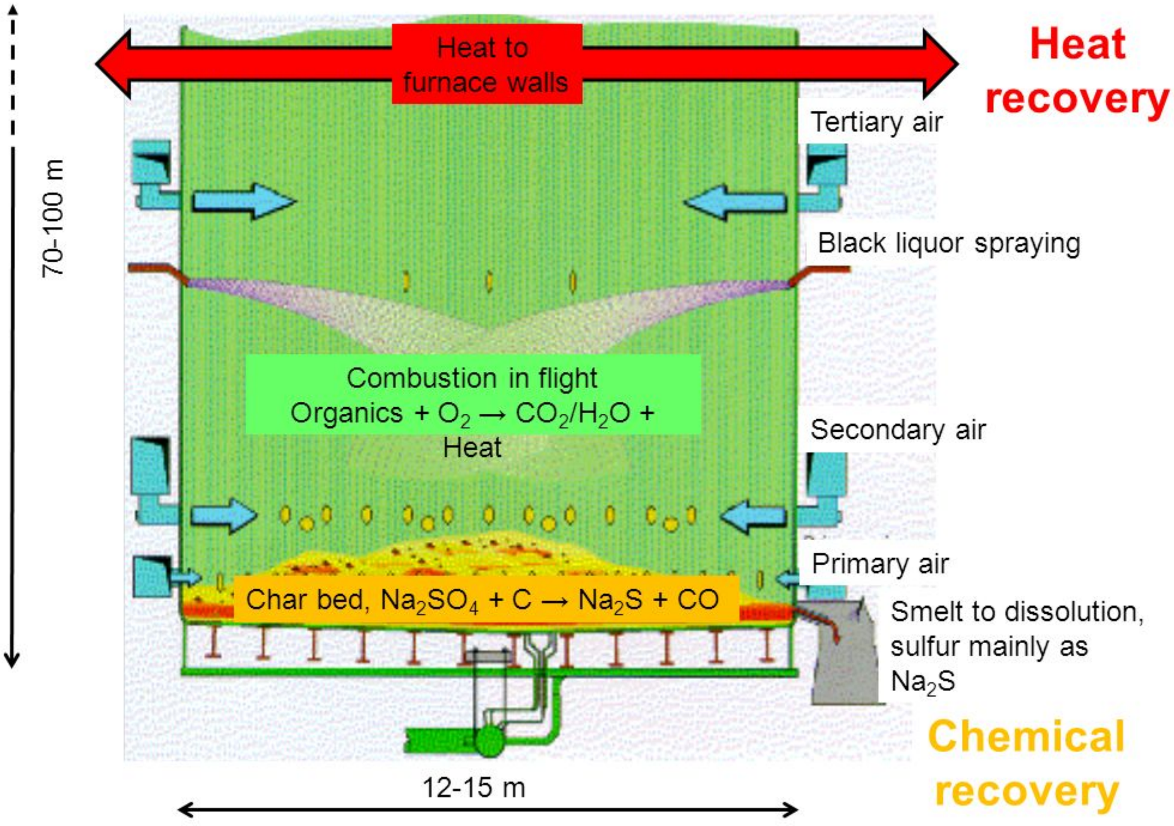


Figure 44. Chemical reactions in the black liquor recovery boiler (Jarvinen 2016).

The last step of the chemical recovery process is causticization. In the lime kiln, calcium carbonate ($CaCO_3$) is heated and split into calcium oxide (CaO), or quicklime, and CO_2. Quicklime is added to the green liquor and reacts with water to form calcium hydroxide ($Ca(OH)_2$). In a series of agitated tanks called causticizers, $Ca(OH)_2$ reacts with Na_2CO_3 to form NaOH and $CaCO_3$ to complete the causticizing reaction. A white liquor clarifier removes the $CaCO_3$ precipitate, or "lime mud" and washes it along with the dregs to remove the last traces of sodium. The mud (mostly $CaCO_3$) can be dried and added back to the lime kiln to produce "reburned" lime. The mud washer filtrate can be used to dissolve smelt. After clarifying, the resulting mixture is white liquor, and is returned to the digesters to begin the process over again. Figure 45 shows a graphical depiction of the chemical reaction cycle of causticization.

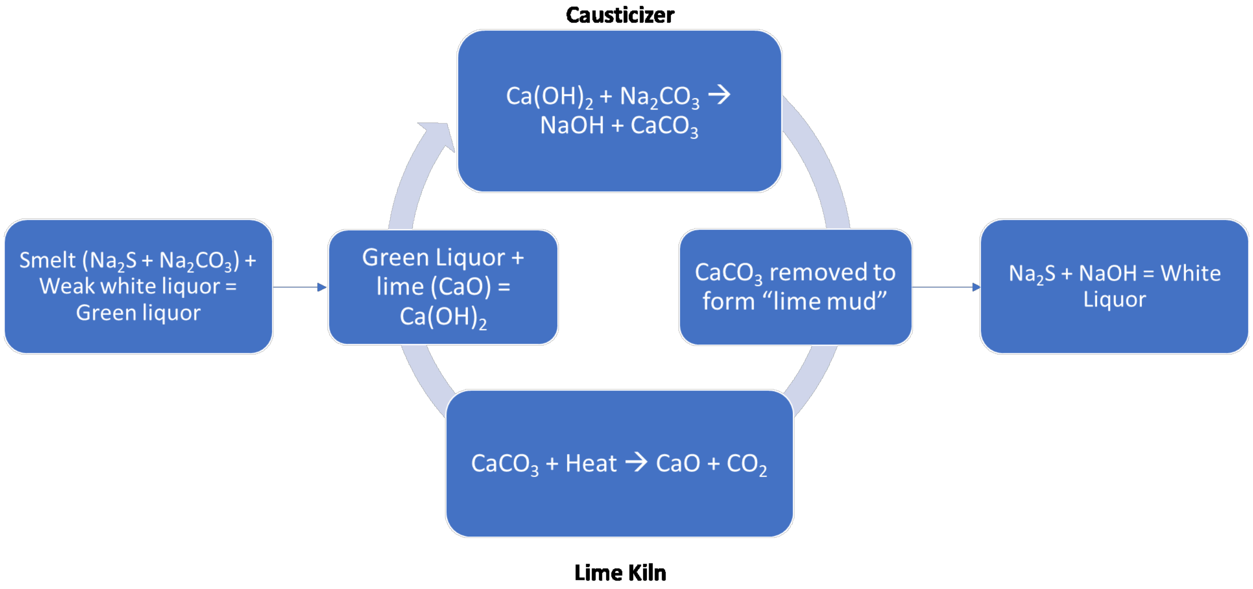


Figure 45. Chemical reactions occurring in the causticization cycle.

4.7.1.2 Paper Production Process

The paper machine consists of four sections: the wet end, press section, dry end, and calendar section. On the wet end, pulp is diluted with water and distributed onto a belt of wire mesh, which encourages all the fibers to go in one direction. Water drains from the pulp resulting in about 80% moisture content. In the press section, rollers remove the water and decrease moisture content to 50-65%. The belt in the press section is often made of felt or wool to absorb moisture. On the dry end, the pulp is run across felt-covered steam heated cylinders are used to dry the pup and reduce moisture to 5-10%. The calendar section uses rollers mounted opposite of each other to pressurize the paper for a smooth finish. This process is depicted in Figure 46. As water drains from the pulp, the fibers are forced together to form hydrogen bonds. The dry paper gets spooled into rolls to be converted to various paper products. Different types of paper or paperboard can be produced by altering the drying or calendaring process, and using different kinds of wood pulp (Eriksson and Hermansson 2010; Casey 2017).

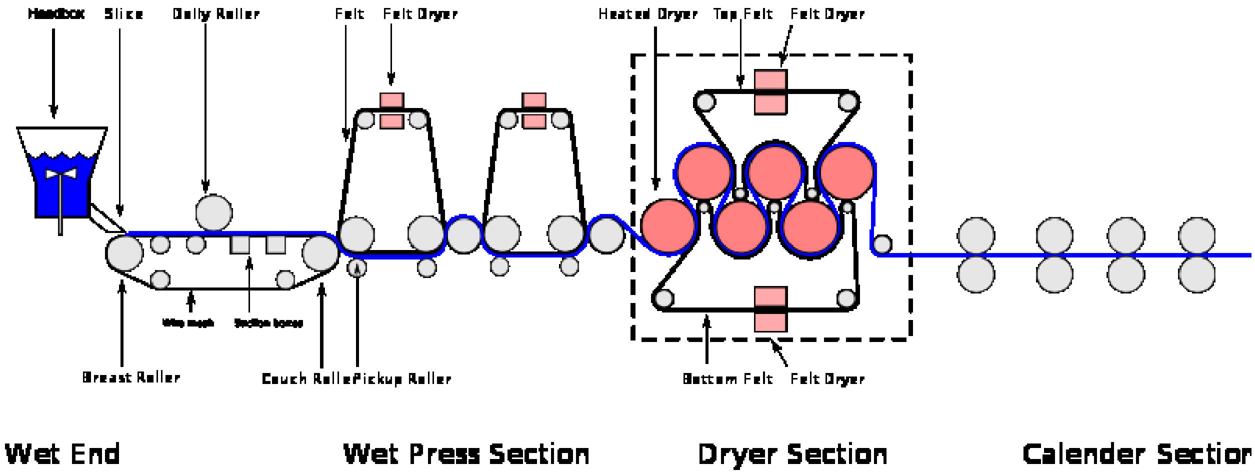


Figure 46. Depiction of a paper machine (Egmason 2010).

4.7.1.3 Recycling Fibers

The ability to recycle and downcycle cellulose fibers completes the almost entirely circular nature of pulp and paper making. According to the American Forest and Paper Association, 80% of U.S. paper mills use some recycled paper to make new products. Nearly half of all recycled paper is used to manufacture containerboard, and the rest is used for newsprint, tissue and boxboard, and about a third of the material is exported. The recycled pulping process uses mechanical shredding, water, and chemicals such as hydrogen peroxide, sodium hydroxide, and sodium silicate to break down the paper back into separated fibers. The recycling process has such a high utilization rate because contaminants like plastic, tape, and staples can be screened out in the pulping process, and ink can be removed in flotation (Greentumble 2018). It is also efficient because the paper can be returned directly to the cellulose fiber state because lignin has already been removed. The mechanical shredding processes mean that the fibers can only be recycled 5 to 7 times before they become too short to be usable (United States Environmental Protection Agency 2016). For this reason, some virgin pulp is often combined with recycled pulp to increase strength.

4.7.2 Plant Load Data

There are several publicly available data sources for paper mill heat and steam loads. This information is described here for use in future case studies.

4.7.2.1 Plant 1: Medium Integrated Mill

Plant 1 is a medium-sized integrated pulp and paper mill in the southeastern United States (Worsham 2020). A depiction of the steam systems of the plant is shown in Figure 47. Steam is generated from two black liquor recovery boilers, one bark boiler, and a natural gas boiler. The outputs of the recovery and bark boilers is dependent on the output of the plant and the chemical recovery process. The natural gas boiler can make up steam if there is a deficit in the other processes. The boiler characteristics are listed in Table 7.

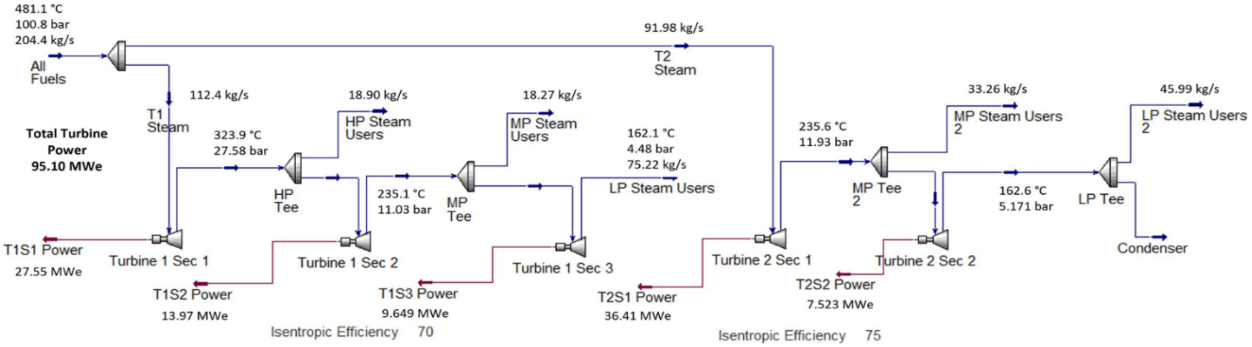


Figure 47. Model of a pulp and paper mill steam system (Worsham 2020).

Table 7. Plant steam sources (Worsham 2020).

Steam Source	Fuel	Mass Flow (kg/s)	Pressure (bar)	Temperature (°C)	Percent of Total
Recovery Boiler 1	Lignin (from black liquor)	34	101	481	17%
Recovery Boiler 2	Lignin (from black liquor)	108	101	481	53%
Bark Boiler	Bark and wood residuals	32	101	481	15%
Natural Gas Boiler	Natural Gas	30	101	481	15%

The plant produces high-temperature steam which is sent through turbines to both bring the steam to the appropriate condition for use and generate electricity. The turbine characteristics are listed in Table 4 Table 8.

Table 8. Turbine Electricity Generation (Worsham 2020).

Turbine Name	Electricity Generated (MW)	Mass Flow Rate (kg/s)
Turbine 1 Stage 1	27.6	112
Turbine 1 Stage 2	14.0	93
Turbine 1 Stage 3	9.6	75
Turbine 1	51.2	280
Turbine 2 Stage 1	36.4	92
Turbine 2 Stage 2	7.5	59
Turbine 2	43.9	151
Total	95.1	431

The plant utilizes high pressure (HP), medium pressure (MP) and low pressure (LP) steam to supply various processes. The characteristics of steam sent to plant processes is listed in Table 9.

Table 9. Plant steam demands (in terms of mass and energy) (Worsham 2020).

	Use	Pressure (bar)	Temperature (°C)	Mass flow rate (kg/s)	Total Enthalpy of superheated steam (MJ/s)	Percent of total thermal demand
HP Steam	Small secondary operations	27.6	324	19	58.1	10.7%
MP Steam	Digesting, drying, smelt recovery	11.0	235	18	52.3	9.7%
		12.0	236	33	95.8	17.7%
		Total		51	148.1	27.3%
LP Steam	Evaporator, deaerator, drying, digesting, chlorine dioxide production	4.5	162	75	208.2	38.4%
		5.2	163	46	127.5	23.5%
		Total		121	347.9	61.9%

The plant also uses natural gas to fire the lime kilns. This heat does not come from the boiler sources. The lime kiln heat demands and fuel consumption are listed in Table 10.

Table 10. Non-steam producing heat sources (Worsham 2020).

	Type of Fuel	Lime Load (mtons/day)	Heat Demand (MJ/ton)	Average Fuel Consumption (Nm3/day)
Lime Kiln 1	Natural Gas	200	7,385	40,776
Lime Kiln 2	Natural Gas	325	6,330	57,086

4.7.3 Decarbonization Opportunities

Pulp and Paper mills are not typically a priority for decarbonization because a large portion of the steam comes from burning biomass. The important balance of the chemical recovery process also limits some opportunities for replacing the biomass fuel. The various decarbonization opportunities include:

- Lime kiln
    - Alt fuel and carbon capture
- Black liquor gasification
- Chemical production (chlorine dioxide)
- Carbon capture from boiler
- Conversion of wood waste to biomaterials
- Increased use of recycled materials.

4.8 Iron and Steel

Opportunities for decarbonization by integration of nuclear reactors in the iron and steel industry, as identified to date by this study, include supply of electricity and generation of hydrogen and oxygen. Supplying heat via steam may be an additional role for a nuclear reactor, however, the extent of external fuel use in existing plants is yet unclear because quantitative information on this topic is still sought. While some fuels (such as natural gas) are unlikely to be feasibly replaced by nuclear-supplied heat, possible approaches include relegating combustion of fuels to supply topping heat for nuclear-supplied heat, and use of nuclear energy to generate synthetic fuels such as replacement natural gas.

Studies show that the iron and steel industry is a major contributor to global anthropogenic CO_2 emissions, accounting for around 8% of the annual emissions, which equates to over 2.8 billion metric tons of CO_2 annually) (Tian et al. 2018). To limit warming below 2°C, two recent emissions scenarios propose capping the CO_2 budget of iron and steel emissions at 50 Gt between now and 2050 (International Energy Agency 2016; Sun et al. 2022). Demand for steel, however, is projected to rise from 1.82 Gt in 2020 to 2.55 Gt in 2050, which adds further challenges to decarbonization (Sun et al. 2022). To achieve this 2 °C climate goal proposed in the two previous references, the iron and steel sector will need to reduce the emission intensity of crude steel to a target of 0.52 tonnes of CO_2 per tonne in 2050 as shown in Figure 48 (Sun et al. 2022). The plan to limit emissions to achieve the 2°C target (shown in green) is based on the International Energy Agency's recommendations, which mainly focuses on making short-term energy efficiency improvements and implementing scrap-based electric arc furnaces and carbon capture and storage the mid- to long-term (International Energy Agency 2016). The data for crude steel and pig iron output from 2015-2019 (shown in orange) is obtained from the World Steel Association (WSA) (World Steel Association 2022), while the data for 2020-2050 (shown in solid lines) is estimated based on the production scenario provided by the United Nations Industrial Development Organization (Birat 2010).

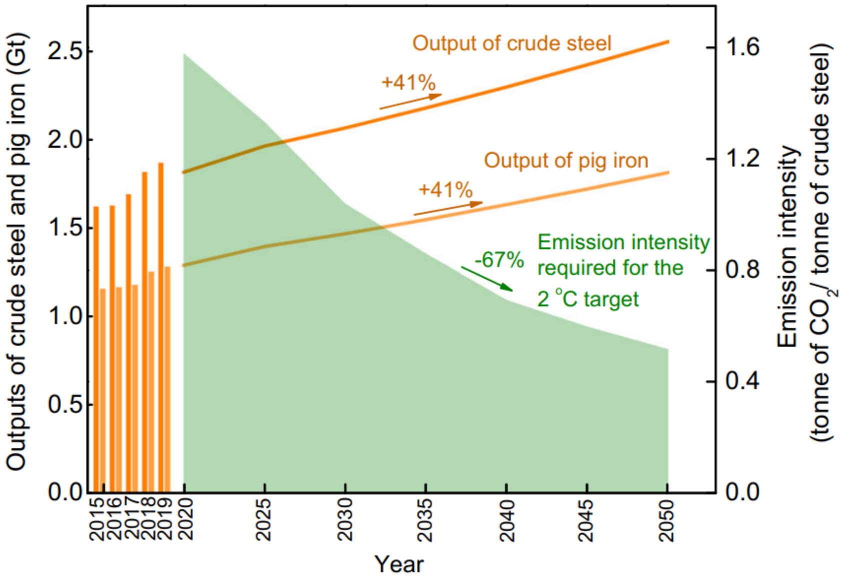


Figure 48. Required CO_2 emission intensity (tonne of CO_2/ tonne of crude steel) with the decreasing budget for the 2°C climate target versus increasing outputs of crude steel and pig iron globally from 2020 to 2050 (Sun et al. 2022).

Steel processing is dominated by two routes: blast furnace-basic oxygen furnace (BF-BOF) and direct reduction followed by electric arc furnace (DRI-EAF). Scrap steel can also be included in the charge of the latter steps. Figure 49 overviews these two routes, each of which might form an integrated steel mill; however, many other steps are not shown, and some processes such as the EAF may be sited independently.

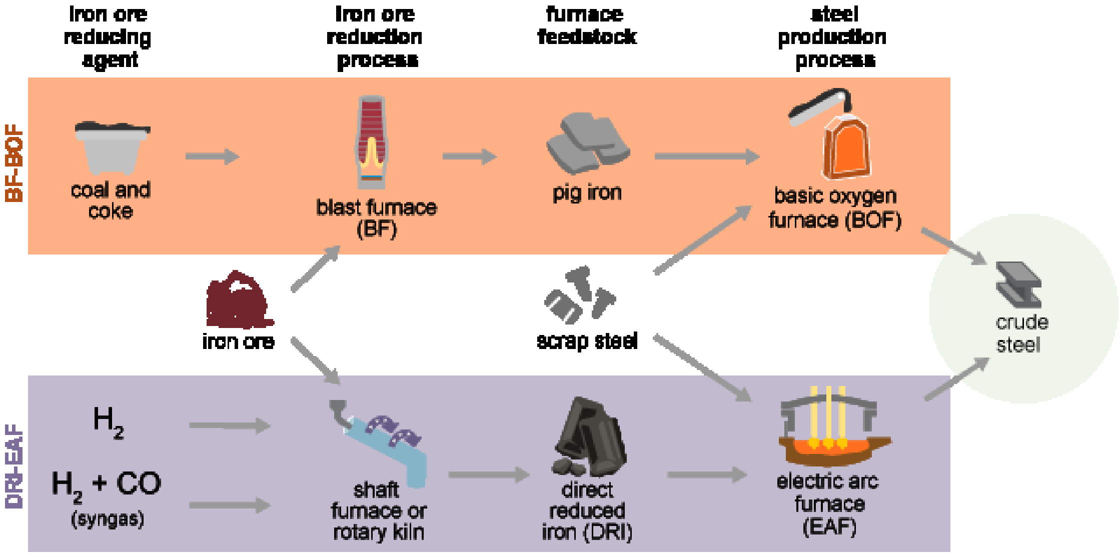


Figure 49. Main processing routes for steel at present (BF-BOF and DRI-EAF) (United States Energy Information Administration 2022b).

In many cases, steel plants utilize waste gases to reduce external fuel needs. Gases produced by the coking furnace (which converts metallurgical coal into a high-carbon form known as coke) can be burned to produce energy for other systems in the plant if harnessed, as is often the case in integrated steel mills. In the case of the blast furnace, high heat is supplied by combustion of fuels, including the furnace's own waste gases, with the hot blast air supply reaching temperatures of 870°C to 1260°C (Ricketts 2005). Free carbon is supplied by the combustion of coke. Because a carbon source is necessary for the high-carbon pig iron produced by the furnace and because the coke serves a structural role within the furnace's charge, substituting coke in the process is difficult (very limited substitution by biomass may be possible.) (Zang et al. 2023). If heat supplied by waste gases does not meet all needs of a given BF, it is plausible that nuclear reactor-supplied heat could preheat the hot blast air at lower temperature stages, thereby decreasing the use of external fossil fuels. Finally, the direct reduction furnace is an alternative to the BF and already in operation in the U.S., although direct reduction may not be suitable in every operation with a BF due to differences in feedstock requirements. Direct reduction furnaces may be operated with a mixture of natural gas and hydrogen (Zang et al. 2023).

The basic oxygen furnace (BOF) also requires external heat and will continue to be considered by this study. Supply of oxygen generated by electrolysis may increase the value proposition of nuclear-powered electrolysis on-site, as oxygen could be utilized in addition to the hydrogen produced.

A major consumer of electricity is the electric arc furnace (EAF), where present. To supply electricity to EAFs, sufficient ramping capability would be prerequisite to follow the load as one or more furnaces cycle through each heat of material (the furnace completes one cycle, thermally and electrically, to produce one heat). Many EAFs are located away from integrated steel mills, and thus are likely to draw power from a grid connection rather than from on-site power generation. The largest-by-power U.S. EAF in the Electric Arc Furnace Roundup dataset (Association for Iron and Steel Technology 2023) consumes 178 MWh of electric energy per heat, while half of EAFs consume less than 33.5 MWh. Dividing the energy consumption by the time for each heat, an average power was calculated: 178 MW for the largest-by-power, mean of 38.5 MW, and half of EAFs under 32 MW. Grouping furnaces which appear to be at a single site, these values change little: 178 MW, 41 MW, and 32.5 MW, respectively, for each group of co-located furnaces. Crucially, the average power is not the peak power reached during each heat. Looking beyond present-day industrial production, production of iron by electrolysis of its oxide is an emerging steelmaking technology that will require significant electric power if adopted industrially (Allanore n.d.).

The steelmaking process involves many more steps than described thus far, which may offer smaller yet substantial opportunities for decarbonization by integration of nuclear reactors. Further investigation under this work package is expected to lead to information on the main processes mentioned above as well as other opportunities.

4.9 Corn Wet Milling

Corn wet milling (CWM) is an energy-intensive industry which processes corn into germ, fiber, gluten feed, gluten meal, and starch, and then may further process these into feed products, corn oil, sweeteners, and ethanol (Galitsky, Worrell, and Ruth 2003). Some CWM plants have been co-located with power stations for combined heat and power, and these generators may sell electricity to the grid. Dewatering, drying and evaporation occurring in various processes make up major fractions of a plant's energy use, and occur at various temperatures ranging from 38°C to 315°C, and in some cases reaching as high as 700°C. A model of the CWM process assumed 0.07 kg of natural gas is burned to evaporate 1 kg of product (Serna-Saldivar 2019). Using the lower heating value of the fuel, the corresponding heat (including waste heat) is 3.282 MJ per kg of evaporated material, with CO_2 emissions of 0.16 kg per kg; however, this represents only one heat-consuming step in the process. For an 'average' plant processing 2,540 metric tonnes of corn feedstock per day (100,000 bushels/day), ref. (McMillan et al. 2016) gives 2,038 metric tonnes of CO_2 emissions. In terms of the stated output of 2,226 combined metric tonnes of four products (starch, gluten feed, gluten meal, corn oil), emissions are 0.9 kg of CO_2 per kg of product on average. Due to heavy use of external fuels and process temperatures well-matched to the balance-of-plant temperatures of advanced reactor designs, integration of nuclear reactors to decarbonize the CWM industry appears promising and merits further exploration.

5. FUTURE WORK

Table 11 summarizes briefly the various requirements of ammonia, chlor-alkali, corn wet milling, methanol, tar sands, oil refining, pulp and paper production, and iron and steel production. The simplicity of this table confirms the need for additional detailed process modeling to be made available to show the specifics of process operations within these industries. The specifics of thermal and electrical loads, residence times, cycle behavior, and reactant consumption are needed to identify potential nuclear power system integration with these systems.

Table 11. Summary of identified industry CO2 emissions and process conditions.

Industrial Product	Annual CO_2 Emissions or Total Domestic Energy Load	Temperature Needs	Pressure Needs (if steam)
Ammonia	4.5 million tons	50°C–1025°C	
Chlorine & Sodium Hydroxide	28.7 million tonnes	95–100°C, 177°C	0.82 MPa steam
Corn Wet Milling	0.74 million tonnes	50–121ºC, 130–168ºC, 38–315ºC, 700°C	0.7 MPa steam (50–121°C)
Methanol	4.2 million tons	170-1700°C[b]	3.6 and 10 MPa steam
Oil (or Tar) Sands	90 million tons CO2e[a]	260-600°C	4-12 MPa steam
Oil Refining	238 million tons	300-800°C	4.1, 1.2, 0.27 MPa steam
Pulp & Paper	34.9 million tons	125-325°C	0.45, 1.2, 2.6 MPa steam
Steel & Iron	89 million tons	177°C, 900–1350ºC, 1982–2316ºC	

[a] 2023 estimate for the annual equivalent CO2 emissions from oil/tar sands in North America

[b] Including some potential methanol conversion pathways

As detailed in Section 4, there is significant decarbonization opportunity across each of the technologies looked at for this report. As the United States pursues its decarbonization goals, novel integration methods will be needed to reduce the environmental impact of these significant industries. This report details how the Integrated Energy Systems program at INL is identifying these decarbonization opportunities. In the short term, only a few of these processes will be identified to continue to be researched, investigated, and detailed in such a way that front end engineering design work can provide technical analysis for integrating nuclear heat and supplanting existing carbon-emitting thermal sources. Replacing carbon-emitting energy sources may come through direct thermal substitution within processes, electrification and making electricity generation "green," or through novel chemical processes to produce an identical product.

This report includes a brief summary of advanced reactor designs with a focus on their thermal integration potential. A survey, distributed to various contacts within industrial companies, has been produced and distributed to receive input from various field experts and identify potential information partnerships.

The IES team plans to pursue five of these reviewed technologies going forward: ammonia, chlor-akali, methanol, oil refining, and pulp and paper milling. These technologies represent a significant CO_2 emissions load, totaling over 300 million tons of CO_2 emissions domestically per year. The energy requirements across these different technologies are diverse: with different kinds of thermal and electrical load ratios and different temperature requirements.

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