United States Energy Association: Co-utilization of Coal and Mixed Scrap Plastics via Syngas Production with Carbon Capture, Utilization, and Storage (CCUS)

Prepared by:

Battelle
505 King Avenue
Columbus, Ohio 43201

Submitted to:

United States Energy Association

Technical Point of Contact:
Dr. Neeraj Gupta,
Senior Research Leader
Battelle, Columbus, OH
Email: gupta@battelle.org
Phone: 614-424-3820

Technical Point of Contact:
Ms. Christa Duffy
Project Manager
Battelle, Columbus, OH
Email: duffyc@battelle.org
Phone: 614-424-5785

Contractual Point of Contact:
Brian Wallace
Sr. Contracts Representative
Battelle, Columbus, OH
Email: wallaceb@battelle.org
Phone: 614-424-7853

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Co-utilization of Coal and Mixed Scrap Plastics via Syngas Production with Carbon Capture, Utilization, and Storage (CCUS)

PROMOTING DOMESTIC AND INTERNATIONAL CONSENSUS ON FOSSIL ENERGY TECHNOLOGIES: CARBON CAPTURE AND STORAGE AND CLEAN ENERGY SYSTEMS

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Authors:

Brandon Webster, Battelle
Priya Ravi Ganesh, Battelle
Deepti Krishnan Nair, Battelle

United States Energy
Association1300 Pennsylvania
Avenue, NW Suite 550, Mailbox
142
Washington, DC 20004
+1 202 312-1230 (USA)

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Executive Summary

The United States (U.S.) has growing volumes of single-use plastics that are a valuable scrap hydrocarbon resource and yet, they continue to be landfilled. It is apparent from the continuously increasing annual plastic production, low recycling rates, land use concerns, and energy recovery statistics that development and implementation of technologies to recycle or upcycle plastic waste is the need of the hour. Chemical recycling methods such as gasification are alternatives to combustion or incineration for resource recovery from mixed plastic waste. Utilizing coal and waste plastic together as a feedstock for gasification could potentially create a value proposition for both coal and mixed plastic waste. This system coupled with a Carbon Capture, Utilization, and Storage (CCUS) process would reduce the carbon footprint of synthesis gas (also known as syngas) or petrochemical feedstocks, as well as provide carbon dioxide (CO_2) for utilization or permanent geologic storage. This could incentivize regional economic development, creating jobs and a market for the increasing volumes of mixed scrap plastics being discarded.

This report provides a high-level assessment of the current state of the art in gasification technologies, feedstock characterization, areas of anticipated technology development, and an assessment of the potential market. The goals are to establish a foundational perspective on the potential for plastic waste gasification while co-utilizing coal, to identify areas where additional work can enable commercial-scale implementation, and to generate interest in a better end-of-life prospect for plastics waste. This report provides a high-level framework for how this synergy could be realized.

Summary table highlighting areas of focus and findings of the current study

Need	Description Statement	State of the art	Challenges/ Gaps	Chapter Reference
Reduce single-use plastics	Utilize waste plastics for syngas production via gasification and avoid landfilling	Only 8.7% of plastic solid waste (PSW) was recycled in the U.S. in 2018.	• Plastics gasification not efficient • Need significant economic and policy drivers for circular economy for plastics	1–3
Value proposition for utilization of coal while managing plastic waste	Utilize domestic coal reserves for co-gasification with mixed scrap plastics	Co-gasification with carbonaceous (coal) feedstock improves process efficiency.	• Material handling during pre-processing and syngas cleanup for different feedstock • Improved gasifier design optimized for feedstock blends • More pilot and larger-scale demonstrations to enable commercialization	4
Potential to increase syngas production	Use syngas generated during co-gasification for hydrogen or petrochemical feedstocks	Syngas production is currently predominantly from coal and natural gas.	• Commercialization of co-gasification of plastics needed to supplement increasing syngas market demand	5

Need	Description Statement	State of the art	Challenges/ Gaps	Chapter Reference
Environmentally sound source of syngas	CCUS implemented to capture CO_2 emissions from co-gasification to reduce carbon footprint of process	Well-established commercial implementation of flue gas capture and geologic storage spans multiple decades.	• Acceptance for use in co-gasification of plastic waste • Economic impact of including CCUS technologies	6

Gasification is a prominent technique used to convert biomass, coal, and carbonaceous wastes (generated from agriculture, industrial, and domestic urban centers) into valuable gas–liquid fuels and the production of chemicals. The product syngas mainly consists of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and CO_2. Gasification technologies have been around for nearly two centuries (e.g., methanol from coal). Plastic waste can be added to coal or biomass gasification without a change in the process, provided that the proportion of plastic is controlled in accordance with the processing conditions. The addition of plastic waste in the co-gasification feedstock mixture produces favorable results such as lesser tar generation. The addition of plastic improves the energy density of biomass due to higher H_2 content in plastics and ensures the continued supply of feedstock throughout the year for economical syngas generation. Co-gasification provides a degree of freedom on the product gas composition by adjusting the fuel mixture. The performance of co-gasification systems and quality of syngas are driven by critical process parameters conditions such as catalyst, temperature, gasifying medium, gasifier type, and feedstock composition (i.e., blending ratio).

Co-gasification technologies are currently at a pilot scale technology readiness level, with feasibility successfully demonstrated in multiple laboratory studies and some pilot investigations across the world. Commercial-scale gasification of municipal solid waste containing plastics has been performed in Japan since 2003. In North America, the Enerkem facility is the only full-scale gasification facility, with a number of companies such as Sierra Energy engaged at the pilot and demonstration scales, which is indicative of the increasing interest in gasification over the last decade.

In addition, coupling a CCUS system would allow the integrated system to achieve net negative emissions in operations while managing plastic waste via gasification. There are a number of carbon capture technologies compatible with the plastics/coal gasifier, such as existing, solvent-based technologies that are well-established globally in gasifier use. Geographical areas that are rich in coal reserves and have large volumes of plastic waste may present convenient potential primary targets for monetizing the coal and utilizing the PSW through co-gasification technology. The U.S. has sufficient estimated geologic storage potential in different formations deep underground and some existing regulatory infrastructure to store CO_2 from co-gasification of plastic waste. Existing financial incentives to offset project costs include the 45Q program tax credits for projects that can permanently sequester CO_2. A detailed assessment of existing infrastructure and the current gaps for recycling practices will need to be performed.

There are useful platforms and resources available to facilitate collaboration between technology and service providers and plant owners and operators within the energy, chemical, and waste management industries to help move the technology forward. These include the Global Syngas Technologies Council, with international membership and expertise on all cutting-edge technology on syngas for the industry. The Plastics Industry Association and the Plastics division of the American Chemistry Council are key industrial organizations in the U.S. that represent every segment of the plastics supply chain.

The global and domestic syngas market has exhibited strong growth and continues to have a positive outlook as reflected in various market projection reports. Rapid scale up of successful laboratory-scale demonstrations of co-gasification with mixed feedstock blends containing plastics and associated syngas cleanup technologies is needed to support this demand. Significant change in social behavior with respect to accepting responsibility in recycling programs is important to our shift away from single-use plastics and to the successful realization of a circular economy. Alignment of supportive market systems, innovative subsidies, and policy drivers can help overcome technical and economic risks for the scale up to demonstration and commercial-scale systems by incentivizing efficiency and reliability improvements in gasification technologies as well as the use of recycled plastics in the economy.

Chapter 1. Introduction and Problem Statement

Production of polymers, often referred to as plastics, requires significant energy inputs and a high volume of raw materials, creating a high demand on fossil fuels and contributing to greenhouse gas (GHG) emissions. By 2050, plastics manufacturing and processing may account for up to 20% of globally consumed petroleum and 15% of the carbon emissions budget (World Economic Forum, 2016). As shown on Figure 1-1, the global trend in primary plastics production increased from 1950 to 2015, and a vast majority of the primary production was packaging, which is more likely to be single-use than any other category.

The lifetime of consumer single-use plastics dates to the 1950s. It is estimated that approximately 8,300 million tonnes (Mt) of plastic solid waste (PSW) (e.g., polymer resins, synthetic fibers, additives) have been produced globally, as shown in Figure 1-2 (Geyer, Jambeck, & Law, 2017). The majority of PSW has historically been discarded in landfills. While the United States (U.S.) is estimated to produce the most PSW of all countries, the member countries of the European Union (EU), India, China, and Brazil are significant contributors as well (i.e., > 10 Mt) (Law et al., 2020).

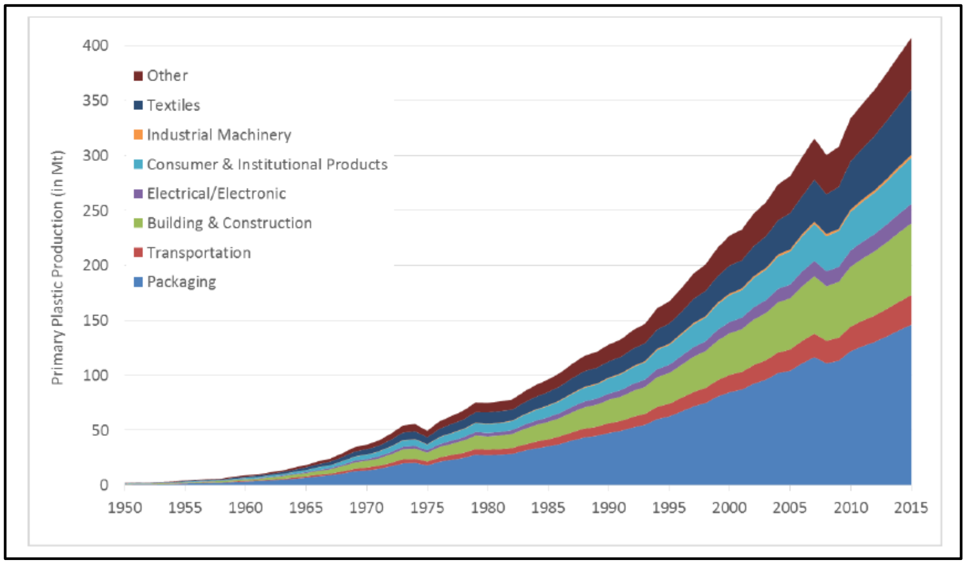


Figure 1-1. Global primary plastics production (in Mt) from 1950 to 2015 according to industrial use sector (Figure S1, (Geyer et al., 2017))

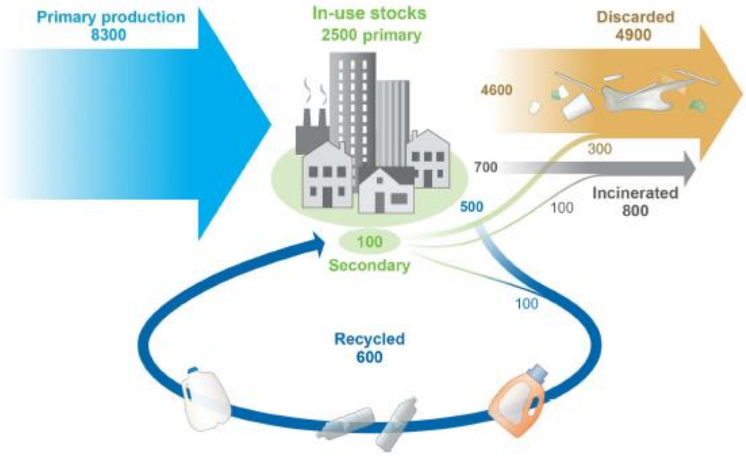


Figure 1-2. Cycle and fate of plastics from 1950 to 2015 in Mt
(Figure 1.2, (Geyer et al., 2017))

With increasing environmental awareness over the past decade, global rates of plastic's incineration and recycling are increasing. In 2014, PSW were recycled at an estimated rate just below 20% globally (of plastics produced that year) (Geyer et al., 2017). Global incineration rates were estimated to be > 25% in 2014, with landfill disposal still near 60% (Geyer et al., 2017).

The objective of this report is to compile information on the types of PSW in use and the current state-of-the-art disposal and recycling methods in the U.S. This information is combined with a study on the potential co-utilization of coal and mixed plastic waste through co-gasification technology to produce environmentally relevant sources of synthesis gas. Additionally, the reduction of carbon dioxide (CO_2) via Carbon Capture, Utilization, and Storage (CCUS) will be discussed and explored to further reduce the carbon footprint of plastic waste.

The following chapters provide a discussion of the types of plastic distribution in the U.S., the co-gasification technology that can be used in conjunction with coal for energy recovery, and the current state of CCUS, in order to consider combining these technologies for beneficial use of PSW. Chapter 2 details the types of plastic distribution in the U.S. Chapter 3 broadly focuses on one of the PSW chemical recycling treatment technologies called gasification. It briefly discusses the basic concepts of gasification, plastic gasification, and the potential benefits of co-gasification using plastic wastes. Chapter 4 discusses co-gasification in more detail. Chapter 5 focuses on the value chain of syngas, potential uses, and current market status. Chapter 6 details CCUS and its current uses in the U.S. and how it could be applied to plastics and coal co-gasification to offset GHG emissions during syngas production. Chapter 7 addresses technology gaps, research needs, and non-technical considerations to move plastics and coal co-gasification technology forward.

1.1. Plastics in the United States

Plastics to date comprise a major class of municipal solid waste (MSW) occupying landfills in the U.S. The three major routes of PSW disposal are recycling, upcycling, incineration, and landfill disposal (Geyer et al., 2017). In the U.S. in 2018, 35.7 Mt of PSW was reportedly disposed of, comprising 12.2% of all MSW ((U.S. E.P.A., 2020b), Figure 1-3); 27 Mt of PSW (75.6%) was landfilled and the remainder of PSW (8.7 Mt) was combusted or recycled (U.S. E.P.A., 2020b). In the same year, the EU produced 29.1 Mt of post-consumer PSW, comparable to the volume produced by the U.S. However, the member states of the EU only landfilled 24.9% of collected post-consumer PSW, and energy recovery comprised the most frequent disposal method for plastic wastes (42.6%) (PlasticsEurope, 2020).

The volumes of PSW in landfills have increased over the last decade largely through the contribution of the durable goods, containers, and packaging categories. When estimating GHG emission reductions from sustainable management, the EPA uses the Waste Reduction Model (WARM) tool to estimate the potential environmental benefits of recycling, composting, combusting, and landfilling for each MSW type. As of 2018, plastics in the U.S. are estimated to add GHG by 4.13 million tonnes of carbon dioxide per year—the equivalent to adding 890,000 cars on the road every year (U.S. E.P.A., 2020a).

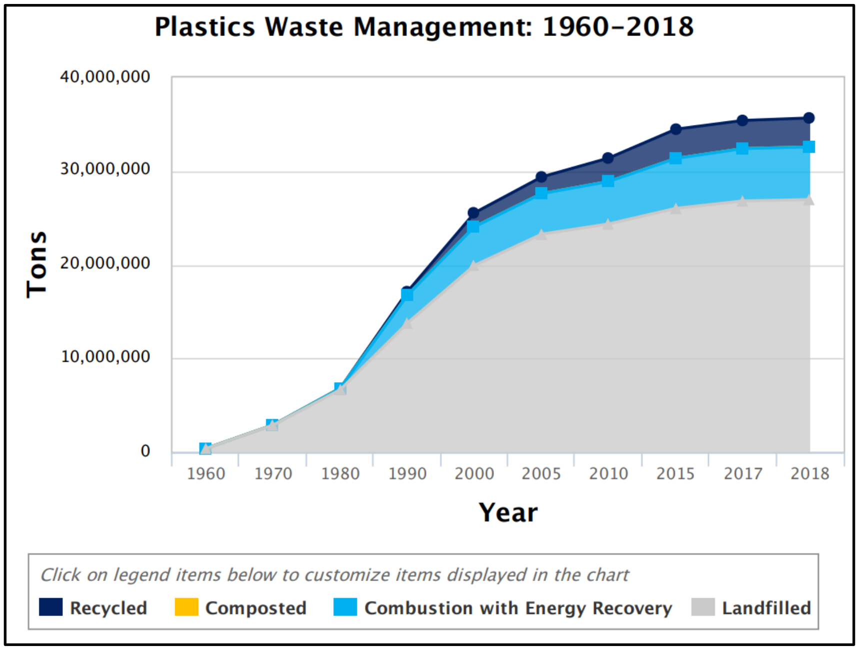


Figure 1-3. U.S.: Amount of plastics (Tonnes) in MSW recycled between 1960 and 2018 (U.S. E.P.A., 2020b)

In 2018 in the U.S., only 8.7% of all PSW was reportedly recycled. This number has increased from as low as 0.3% since the 1980s; however, PSW recycling rates in MSW have been steady for over a decade (Figure 1-4). This indicates that new technologies or methods may be needed for PSW disposal. Difficulties in recycling certain types of plastics, mixed plastic waste, lack of economic incentive, and issues with sorting render plastics recycling unattractive and sparsely utilized to date. These issues likely contribute to the overwhelming landfilling of PSW in the U.S.

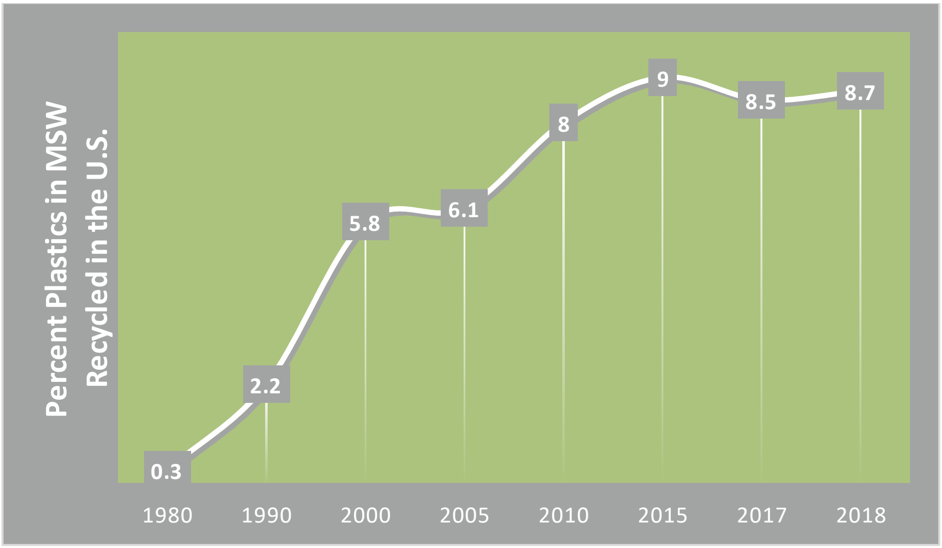


Figure 1-4. Percent plastics in MSW recycled between 1980 and 2018 in the U.S. (EPA, 2018)

1.2. Plastics in the European Union

In the EU, the fate of PSW has dramatically shifted. Between 2006 and 2018, landfilling decreased by 44%, energy recovery increased by 77%, and recycling increased by 100% ((PlasticsEurope, 2020), Figure 1-5).

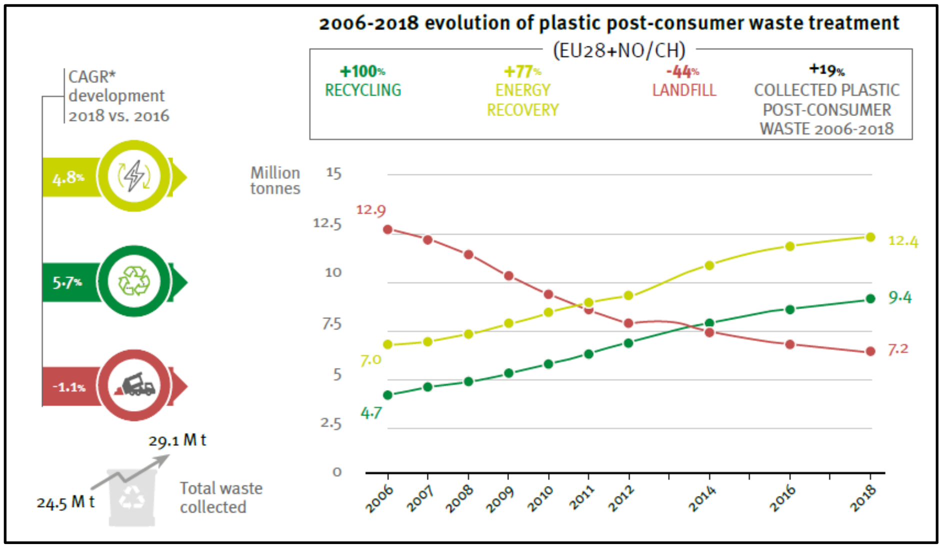


Figure 1-5. EU PSW fate from 2006 to 2018
(pgs. 30-31, (PlasticsEurope, 2020))

The PSW exports outside of the EU have decreased by 39% from 2016 to 2018. In 2018, the majority (42.6%) of post-consumer PSW were used for energy recovery, followed by recycling (32.5%), with landfilling as the least exercised option (24.9%) ((PlasticsEurope, 2020), Figure 1-6).

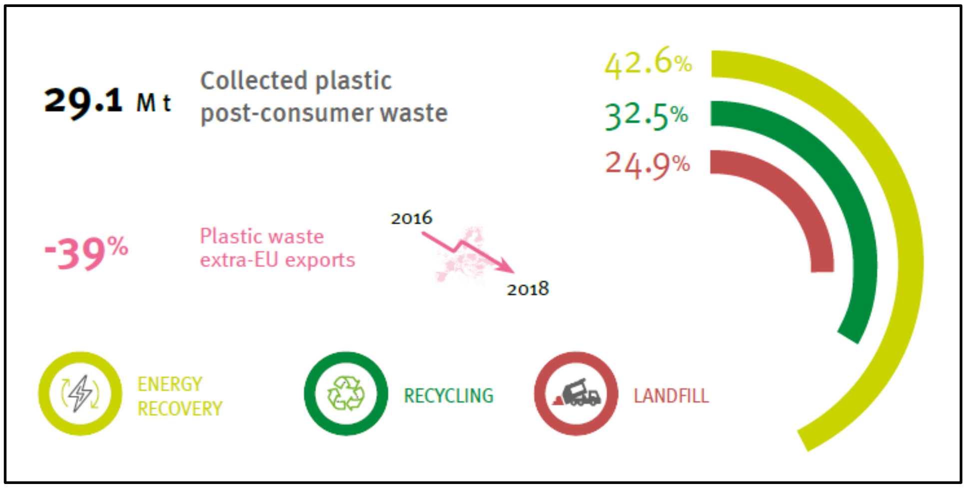


Figure 1-6. EU PSW fate from 2016 to 2018 (PlasticsEurope, 2020)

The EU and its member nations have stringent restrictions on disposal of PSW and have developed a current campaign to cease the landfilling of plastics by 2025. This campaign is a part of a larger EU directive on single-use plastics, which takes a multifaceted approach to reduce the use of single-use plastics and their disposal in landfills (European Union, 2019). Disposable cutlery, food containers, and sanitary items are among 10 items addressed by the directive. When affordable alternatives exist, the EU member states are banned from producing and selling single-use plastics in the market. Further, the volume of single-use plastics is reduced by raising awareness to decrease consumption, requiring designs that significantly lower plastics quantities in products, mandating labeling requirements to warn consumers of plastics dangers, and obligating producers to manage waste properly (European Union, 2019). Currently, eight member states already landfill less than 10% of their PSW ((PlasticsEurope, 2020), Figure 1-7), while Switzerland, Austria, and the Netherlands do not landfill at all (Figure 1-7).

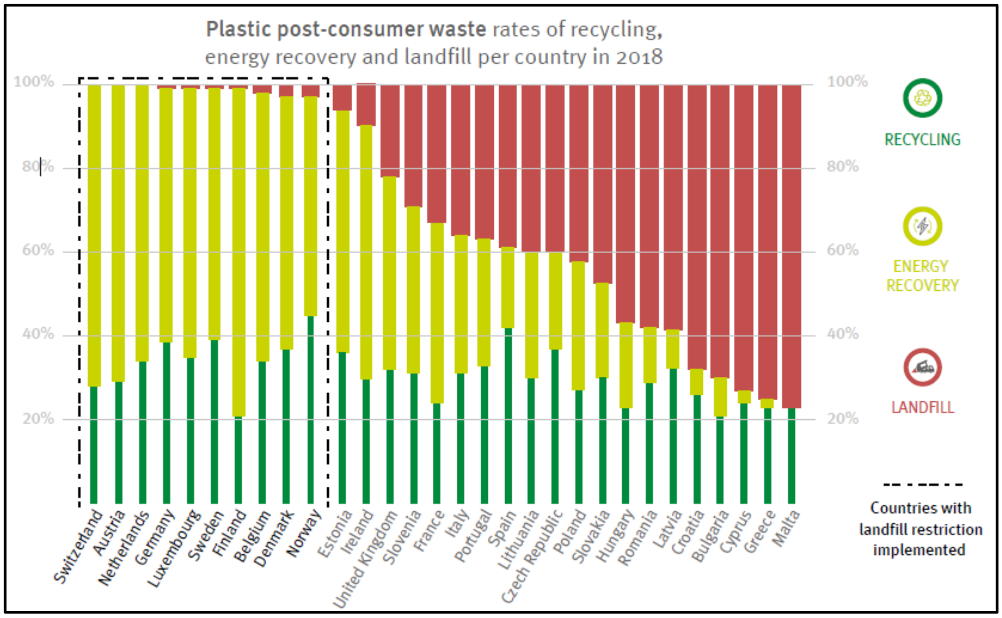


Figure 1-7. Distribution of PSW fates by country in the EU (PlasticsEurope, 2020)

1.3. Need for the Circular Economy

Traditionally, extracted resources generate synthetic products that enter the waste stream (i.e., either landfill or the natural environment) after the end of their useful product life. This is called a linear economy. An alternative to this model is the circular economy, which is based on reducing waste and pollution through design, retaining and/or regenerating products, and preserving natural systems. Figure 1-8 illustrates the pathway from a linear economy leading to a reuse economy and then moving to a circular economy. Circular economy policies have been implemented by a number of governments, including the European Commission in December 2015, to tackle climate change and environmental pollution, while boosting economic growth, job creation, investment, and social fairness (Bucknall, 2020). The Netherlands is one of the leading countries in the circular economy. The government of the Netherlands has set out to achieve a circular economy by 2050 and reduce the use of primary raw materials by 50% by 2030. Japan has been another strong advocate of a circular economy since 1991. This is due to the high population density and limited landfill space, and volcanic and mountainous terrain (Benton, 2015).

A circular economy for plastics is a critical step in managing our increasing plastic waste. In a circular economy, manufacturers will make products that are reusable. Plastics waste can be recycled into pellets and then can be made into other plastic products. Chemical recycling technologies such as gasification is often advocated for as methods to transition plastics waste into a circular economy. These methods could also reduce global warming impacts and fossil resource depletion (Meys et al., 2021). Plastics gasification presents some operational problems such as the softening and stickiness of plastic and black particle formation that chokes the feeding system, reactor, and downstream equipment (Inayat et al., 2019). These problems can be solved through the use of catalysts or potentially co-gasification of the feedstocks in different combinations such as varying ratios of biomass, coal, and plastics.

Figure 1-8. Pathway to a circular economy

1.4. Monetizing Coal and Plastic Waste

As discussed above, there is a large fraction of PSW that is not being recycled or converted to energy in the U.S. Though the U.S. is making improvements in recycling and energy recovery from waste plastics, it lags behind other developed nations. There is an urgent need to reduce the number of plastics landfilled and recover the energy value from the millions of tonnes of post-consumer plastics that are currently being landfilled. One of the potentially lucrative possibilities to empower the circular plastics economy in the U.S. is the co-utilization of the abundant PSW being generated with our rich coal reserves. This presents the opportunity to leverage the long history of coal gasification technologies in the U.S. to accomplish reliable domestic energy production with net negative carbon emissions vital to the nation's energy future.

The U.S. has abundant coal reserves that are valuable. These coal reserves are found across the U.S. as shown on Figure 1-9. Coal production in the U.S. is highly concentrated in the Appalachian region; however, Wyoming produces more coal than any other state, representing 39% of U.S. coal production in 2019, at 277 million short tonnes (Figure 1-10).

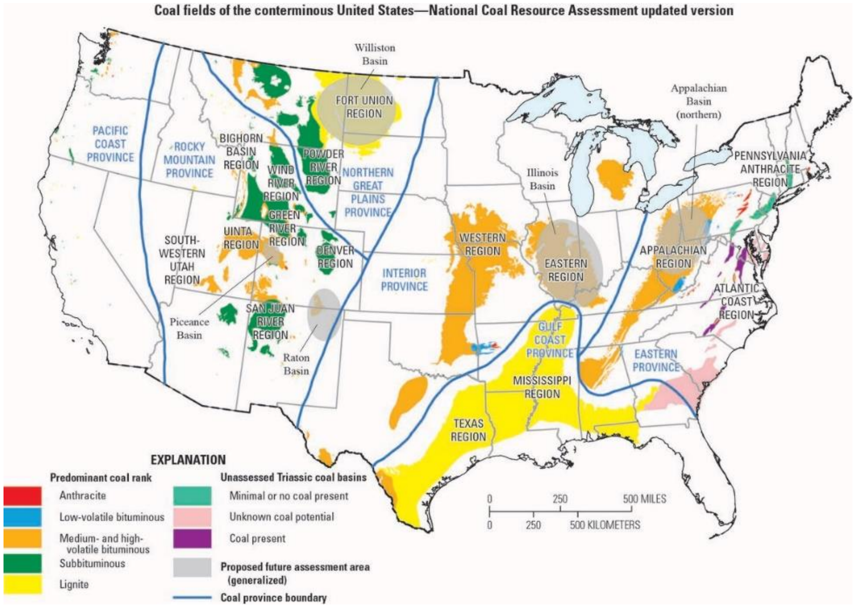


Figure 1-9. Coal field reserves of the U.S. (U.S.G.S., 2017)

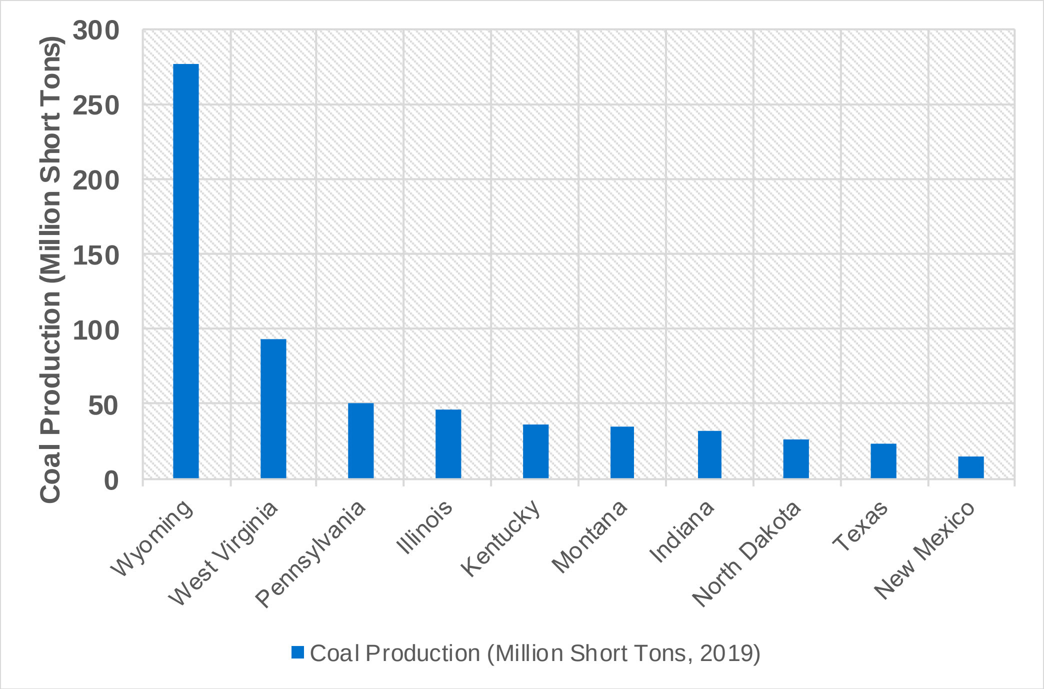


Figure 1-10. Annual coal production by U.S. state in 2019 (U.S. Energy Information Administration, 2020)

A detailed source assessment can be conducted to help identify possible scenarios for aggregation of the PSW and coal sources in different regions of the U.S. This provides an understanding of what the buildout of co-gasification of plastics with coal would be in terms of geography. Such an assessment would also provide important environmental, regulatory, and cultural considerations for proposed chemical recycling infrastructure in the different source areas. Using the co-located coal reserves and areas with large volumes of PSW for gasification may present convenient potential as primary targets for monetizing the coal and utilizing the PSW. Capturing the CO_2 emissions via CCUS subsequent to the co-gasification of coal and mixed scrap plastics could reduce the carbon footprint of synthesis gas or petrochemical feedstock production, thus potentially creating a value proposition for coal as well as mixed scrap plastics. These processes would provide regional economic development, jobs, and a market for the increasing volumes of mixed scrap plastics being discarded.

Chapter 2. Plastic Waste Types and Distribution

Production of PSW and subsequent disposal has a significant impact on the petroleum industry, GHG emissions, and landfill volumes. The U.S. is a major producer and a consumer of plastics. In 2015, 3.8% of all U.S. petroleum was utilized in the manufacturing of plastics (Di, Reck, Miatto, & Graedel, 2021). This chapter details the types and distribution of post-consumer plastics by location and volumes within the U.S. territory.

2.1. Plastic Types and Distribution

The major plastic types in the U.S. are polyethylene (PE) (e.g., high density polyethylene [HDPE] and, low density polyethylene [LDPE]), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS) (Figure 2-1).

Figure 2-1. Major types of plastics resins and common applications for each (Government of Conway Arkansas)

Recently, bioplastics such as polylactic acid (PLA) are being adopted, although these materials are still infrequently used compared to traditional consumer plastics. Over 40% of plastics produced in the U.S. are used for packaging, which often has single-use applications, followed by consumer and institutional products at 28.7%, which also may have a high turnover (Figure 2-2, (Di et al., 2021)).

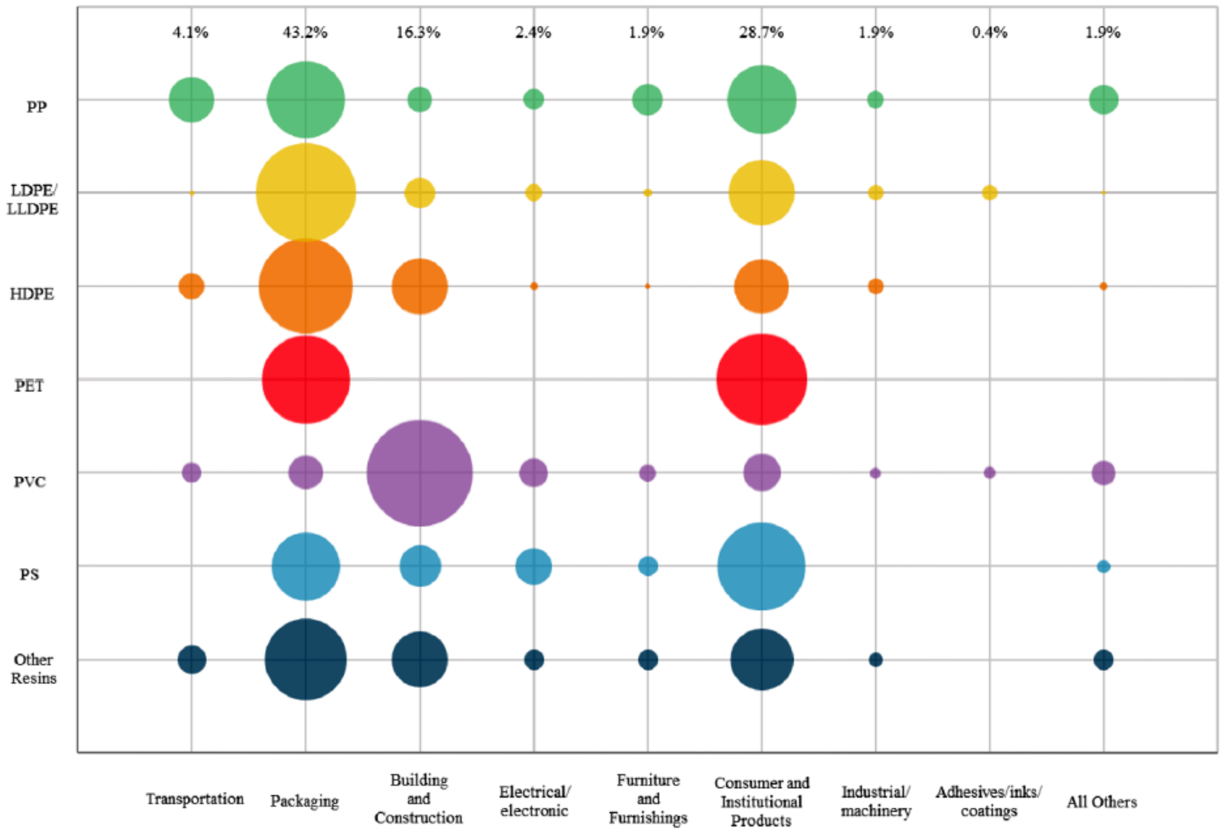


Figure 2-2. Plastic resin distribution into major end use sectors in the U.S. in 2015 (Figure 4, (Di et al., 2021))

Based on the EPA data from the past 10 years, PE is the most abundant waste plastic produced in the U.S., followed by PP and PET (U.S. E.P.A., 2020b).

- The PE family alone comprises ~42.9% of plastic production, followed by PP (18.2%), PVC (15.6%), and PET (10.2%) (Figure 2-3, (Di et al., 2021)).
- The PE family has limited recycling rates; however, this number is currently very low (Figure 2-3).
- PET has the most established and successful recycling proportions. However, in 2018 it was reported that only 18.5% of PET was recycled, leaving significant room for improvement (U.S. E.P.A., 2020b).
- Since PVC is used in building and construction, its contribution to waste streams is proportionally lower than other plastics. However, its eventual waste stream is still a concern.
- Mostly, these polymers are disposed of via landfill rather than combustion or recycling (Figure 2-3, (Di et al., 2021; U.S. E.P.A., 2020b)).
- PS and other types of plastics are produced in smaller quantities than PE/PP/PET, but also enter landfills at high rates (Di et al., 2021; U.S. E.P.A., 2020b).
- In 2018, 26.7% of "other" plastics were recycled (e.g., polycarbonate [PC], PLA), but all other plastic types (i.e., HDPE, LDPE, PVC, PP, and PS) had recycling rates under 10% (U.S. E.P.A., 2020b).

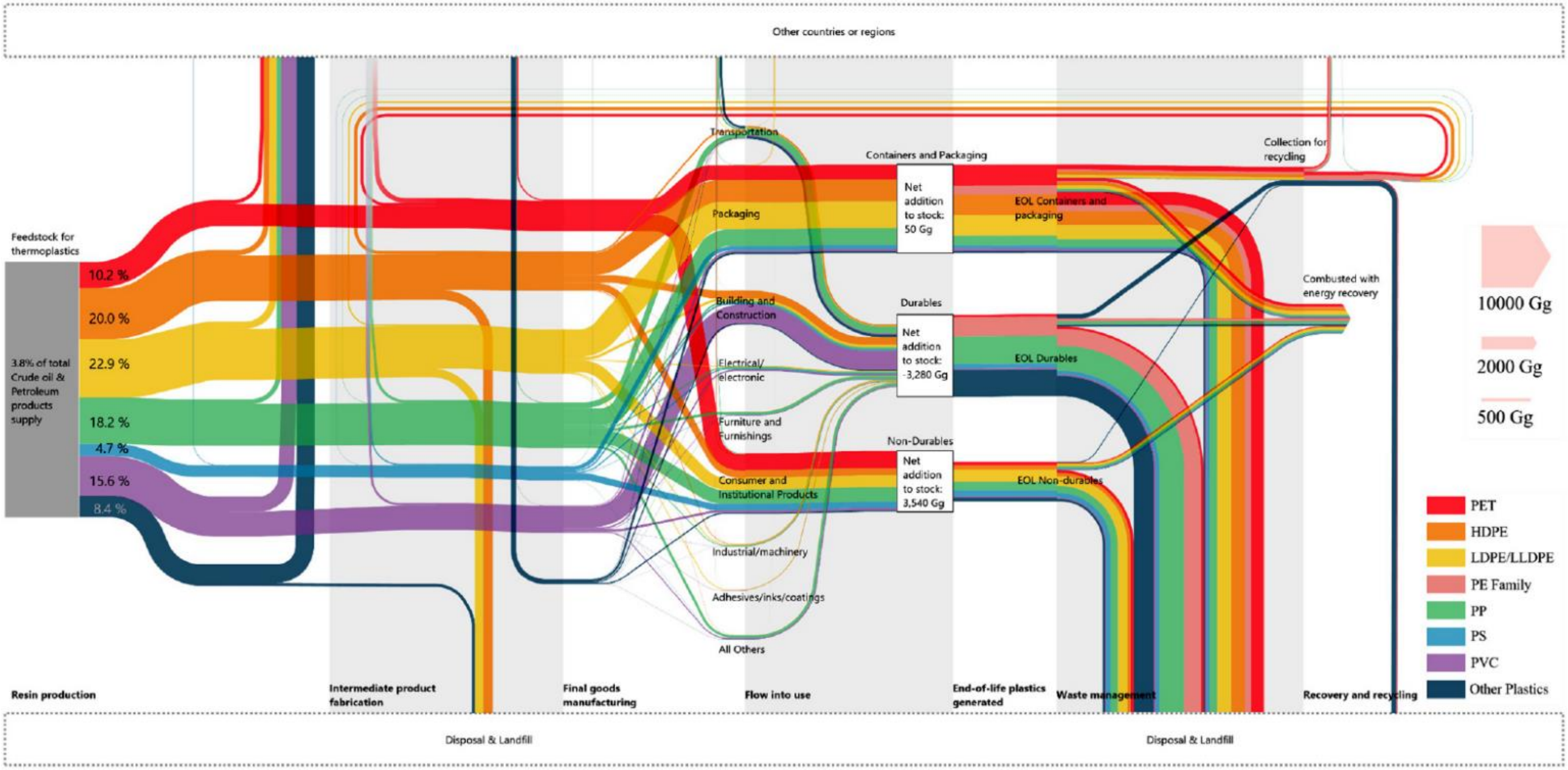


Figure 2-3. Material flows of major plastic resins in the U.S. in 2015 from production to end-of-life. Colors correspond to different plastic types as displayed in the legend. The PE family is used for recovery and recycling data since individually separated data for HD and LDPE were not available. (Figure 2, (Di et al., 2021))

Overall, difficulties in recycling certain types of plastics and mixed plastic waste, lack of economic incentive, and issues with sorting render plastics recycling unattractive and sparsely utilized to date.

The types of MSW comprising of PSW are recorded by the U.S. EPA and provide insight into post-consumer plastic products in landfills. Their major categories in 2018 include clothing and footwear (9 Mt), disposable diapers (3 Mt), miscellaneous non-durables (3 Mt), bags/sacks/wraps (3 Mt), and other plastics packaging (3.5 Mt) (Table 2-1, (U.S. E.P.A., 2020b)).

Table 2-1. MSW amounts containing PSW by category (U.S. E.P.A., 2020b)

MSW Type	Amount of Plastic Landfilled (Mt, (Inayat et al., 2019; U.S. E.P.A., 2020b))
Clothing and Footwear	9
Disposable Diapers	3
Misc. Non-Durables	3
Bags/Sacks/Wraps	3
Other Plastics Packaging	3.5

2.2. Plastics Waste by Location/Volume

In 2011, the states landfilling the most PSW were California, Florida, Georgia, Illinois, Michigan, New York, North Carolina, Ohio, and Texas (Figure 2-4, (Themelis & Mussche, 2014)). Data are reported and available for plastics production and PSW in MSW; however, data on industrial scrap (primary plastics) is sparse and incomplete.

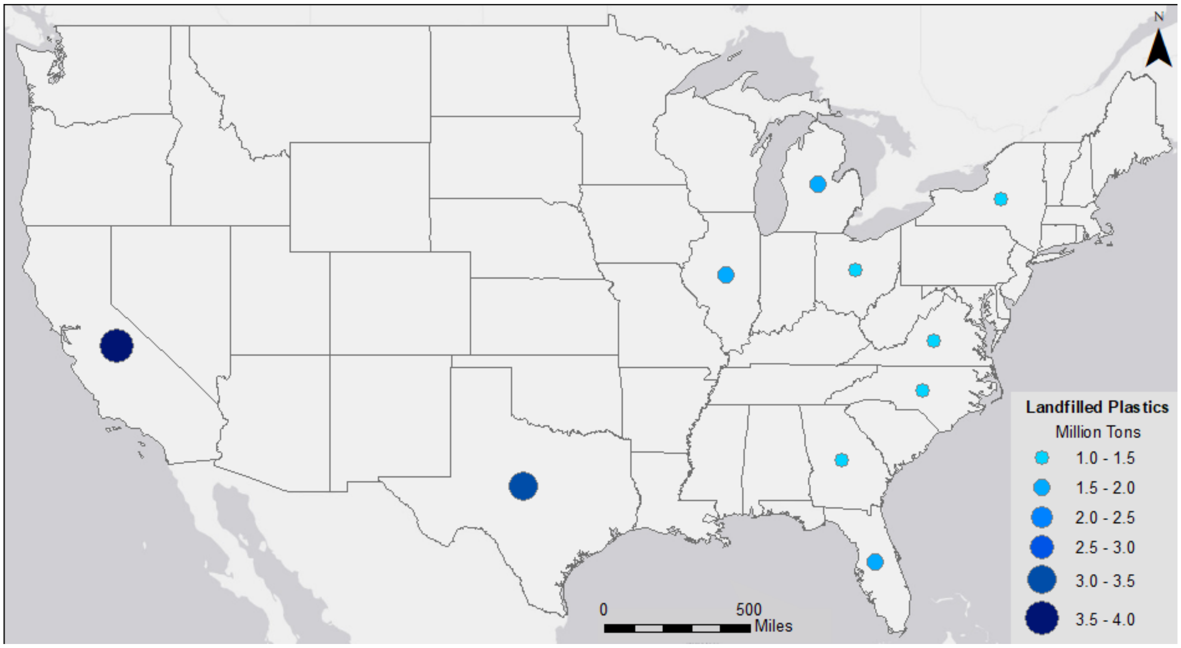


Figure 2-4. Landfilled plastics by state in 2011 (adapted from Table 8, (Themelis & Mussche, 2014))

2.3. Types of Plastics Recycling

Recycling of PSW can be divided into four categories: primary (re-extrusion), secondary (mechanical), tertiary (chemical), and quaternary (energy recovery) (Al-Salem, Lettieri, & Baeyens, 2009), as shown in Figure 2-5.

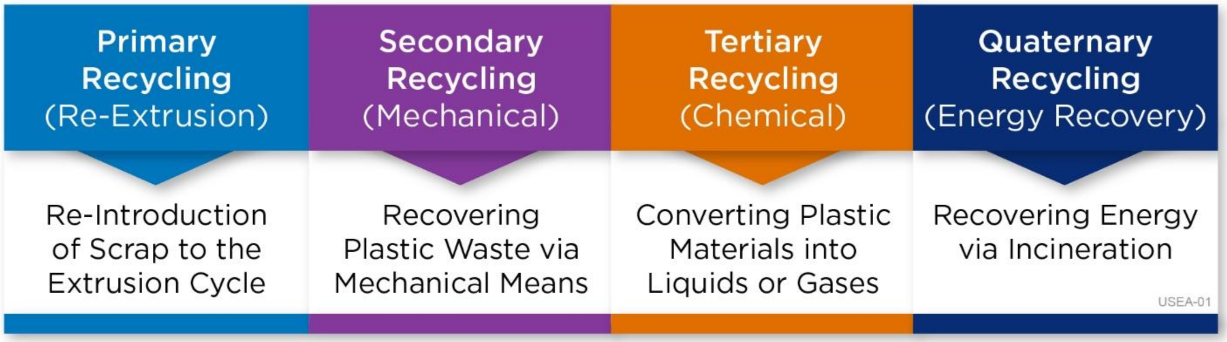


Figure 2-5. Four routes of PSW treatment

- Primary recycling, also known as re-extrusion, is the re-introduction of scrap, industrial, or single-polymer plastic edges and parts to the extrusion cycle in order to produce products of the similar material. Primary recycling is only feasible with semi-clean scrap (Al-Salem et al., 2009).
- Secondary recycling, also known as mechanical recycling, is the process of recovering PSW for the reuse in manufacturing plastic products via mechanical means. It can only be performed on single-polymer plastic (e.g., PE, PP, PS). This is an energy-intensive process and involves multiple preparatory and treatment steps.
- Tertiary or chemical recycling is a process by which plastic materials are converted into liquids or gases that are suitable for use as a feedstock for the production of distillate fuels, chemicals, and plastics. They include technologies such as pyrolysis, gasification, liquid-gas hydrogenation, catalytic cracking, etc. Gasification converts carbonaceous materials into a combustible gas, which also can be used as a synthesis gas.
- Quaternary recycling is a process by which energy is recovered from PSW by incineration. A number of environmental concerns are associated with co-incinerating PSW, mainly emission of certain air pollutants (Al-Salem et al., 2009).

This report primarily discusses tertiary and quaternary recycling technologies. More details on these recycling technologies are available in Chapter 3. Plastics are a promising material for fuel production via tertiary recycling techniques, as illustrated by some of the EU countries. In the EU between 2006 and 2018, landfilling decreased by 44%, and energy recovery increased by 77% (PlasticsEurope, 2020). Additional details on tertiary technologies are provided in Chapters 3, 4, and 5.

2.4. Summary

It is apparent from low recycling and energy recovery statistics that development and implementation of technologies to recycle, upcycle, or recover energy from PSW are needed in the U.S. Mixed plastic waste is likely to be an ongoing challenge, particularly in products such as disposable diapers or containers, which make up large proportions of waste streams. In particular, the PE family is a significant contributor to PSW with low recycling rates and may be an ideal candidate for technology development.

As mentioned in Chapter 1, plastics gasification has operational problems such as the softening and stickiness of plastic and black particle formation that chokes the feeding system, reactor, and downstream equipment (Inayat et al., 2019). Co-gasification of plastic waste with coal is a promising solution to addressing the plastic waste generated in the U.S. This technology, when combined with CCUS, is also an environmentally friendly source of synthesis gas or petrochemicals while reducing PSW in landfills. The following chapters discuss the overall gasification technology, then co-gasification technology in detail, which can be used in conjunction with coal for energy recovery.

Chapter 3. Plastics Gasification

As PSW is derived from oil, it has a recoverable energy associated with it. More recently, chemical recycling techniques have been employed to produce fuel fractions from PSW. This section broadly focuses on one of the PSW chemical recycling treatment technologies called gasification. It briefly discusses the basic concepts of gasification in general, plastics gasification, and potential benefits of co-gasification using plastic wastes.

Gasification is a prominent technique used to convert coal, biomass, and carbonaceous wastes (generated from agriculture, industrial, and domestic urban centers) into syngas, gas–liquid fuels and the production of chemicals. This technology has been applied since the mid-1800s Ciuffi et al., 2020) and the process involves thermal treatment of carbonaceous materials at a temperature above 600°C to produce solid (char), liquid (tar), and gaseous products (Shahbaz et al., 2020).

The produced gas is a valuable fuel called synthesis gas (also called syngas) and mainly consists of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and CO_2. Syngas is a valuable commercial fuel with a heating value of 200–500 Btu per cubic foot, used as a fuel for energy production or further processed into a wide variety of fuels and chemicals (Shahbaz et al., 2020). Gasification is conducted in a gasifying medium such as air, oxygen, steam, or CO_2. The quality of the syngas depends on the type of material, gasifying medium, and temperature. Figure 3-1 shows the operations involved in a typical gasification process.

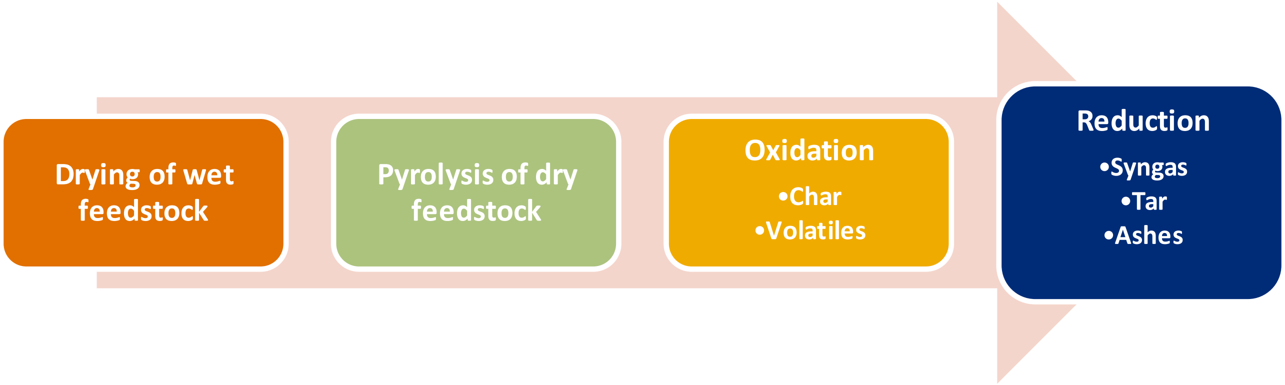


Figure 3-1. Main steps in gasification

The gasification process has been applied to different types of waste such as municipal and plastic waste in the Waste Gas Technology UK Limited (WGT) process. A demonstration plant for WGT of 500 kg/h sewage sludge capacity was installed in South Wales. A 110-kg/h unit for WGT process was installed in France in 2000 (Al-Salem et al., 2009).

In addition to coal and biomass, gasification of plastic materials has gained attention in recent years. This is particularly useful in plastics waste management and in reducing the amount of plastic waste sent to landfill. Plastics gasification has several advantages over other technologies such as incineration. It is possible to gasify a variety of feedstock such as biomass, wood, plastics and municipal solid waste providing great versatility. Plastics gasification produces various combustible gases such as H_2, CH_4, ethane, and propane in addition to syn gas that can be used for different purposes as opposed to combustion gases. Additionally, plastics are a suitable option for gasification because of the high calorific value, low moisture, and low ash content of plastics waste. Incineration of plastics waste can produce dangerous emissions, containing heavy metals, dioxins, furans, hydrochloric acid (HCl), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and hydrogen fluoride (HF) (Ciuffi et al., 2020). In comparison, gasification produces a smaller quantity of pollutants, which can be removed via established control technologies, in addition to producing a commercially viable syngas. Gasification involves several steps (as shown in Figure 3-1) and complex chemical reactions that are briefly summarized below (Ciuffi et al., 2020):

- **Drying:** Feedstock with variable moisture content is dried in a range of temperatures (100–150°C). This is a rapid process, as plastics have a very low moisture content, unlike biomass or coal.
- **Pyrolysis:** Endothermic chemical reactions take place during this process, resulting in volatile substances (gases and tars) and solid residues (char). The proportions of these products are influenced by process conditions such as the heating rate, temperature, and feedstock composition and size.
- **Oxidation:** Heterogeneous reactions occur between oxidant and raw material (char and volatiles) at elevated temperatures and sub-stoichiometric oxygen, forming CO and steam. Oxidation depends on the chemical composition of the feedstock, the nature of oxidant used, and the operating conditions. This is an exothermic reaction; the released heat is then used for the concurrent and subsequent reduction reaction.
- **Reduction:** Reduction is an endothermic process in which high-temperature chemical reactions take place in the absence of oxygen. Steam promotes two reactions that lead to the formation of H_2: the steam reforming of char and tar (endothermic) and the water-gas shift reaction (exothermic). The reduction of water in steam gasification is the most effective way of increasing H_2 production. CO_2 reacts with char to produce CO. This reaction is known as the Boudouard reaction, and it is endothermic in nature.

There are several kinds of gasification processes depending on the gasifying medium used: air gasification, oxygen gasification, steam gasification, CO_2 gasification, and supercritical water gasification. Air gasification is the most studied process, as air is an inexpensive gasifying agent, requires a simple reactor, and the reaction process is easy in comparison to other gasification processes. It also produces lower tar content in the gaseous product compared to steam gasification. There are no external energy requirements in air gasification, while in the other kind of gasification, external heating is required because the overall gasification reaction is generally endothermic. Air gasification produces a syngas with a low heating value due to dilution with nitrogen (N_2). Air gasification of plastic waste is commonly performed in fluidized bed reactors (Ciuffi et al., 2020). More relevant details in the context of plastic co-gasification are discussed in Chapter 4.

Plastics gasification presents some operational problems such as the softening and stickiness of plastics and black particle formation that chokes the feeding system, reactor, and downstream equipment (Inayat et al., 2019). These problems can be solved through the use of catalysts or potentially co-gasification of plastics with different feedstock combinations such as coal and biomass. Synergistic effects deriving from the use of mixtures of raw materials exploited in the co-gasification process could result in better product yield or gas composition, different from those calculated by linear interpolation based on the results for the pure components in the feedstock (Ciuffi et al., 2020) The co-utilization of coal and PSW to feed a gasification technology may be capable of producing a flexible and reliable source of synthesis gas.

3.1. Summary

Co-gasification provides a degree of freedom on the product gas composition by adjusting the fuel mixture. Co-gasification of coal and plastics ensures the continued supply of feedstock by varying rates of plastic waste throughout the year for economical syngas generation. Chapter 4 discusses co-gasification in more detail.

Chapter 4. Co-Gasification

The versatility of the gasification process and potential synergies with different feedstock combinations has encouraged the study of plastic waste co-gasification. Co-gasification has been studied in the last two decades by researchers at the laboratory and pilot scales for the utilization of wastes with coal and biomass. Biomass-plastic feedstock combinations form the representative components of MSW. Some important and extensively studied feedstock combinations are mixed plastic, biomass-plastic, coal-plastic, biomass-coal, and biomass-sewage sludge, as shown in Figure 4-1 (Inayat et al., 2019; Shahbaz et al., 2020). A large-scale example of coal and plastic waste co-gasification is the high-temperature Winkler (HTW) process (Renzenbrink, Wischnewski, Engelhard, Mittelstädt, & AG, 1998).

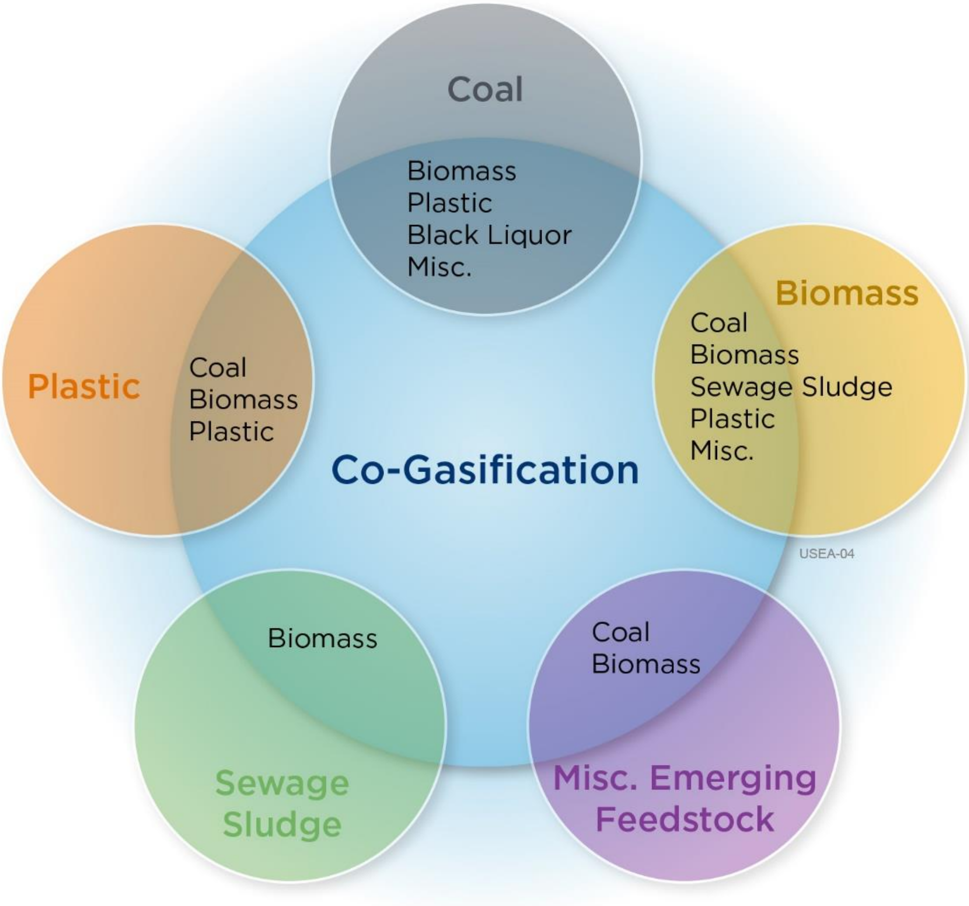


Figure 4-1. Various feedstock combinations that have been used in catalytic co-gasification

This chapter focuses on coal-plastics and coal-plastics-biomass feedstock, which present the advantage of availability and ideal combination of fossil and renewable fuels for utility as a potentially more effective technique for waste management, while producing energy and syngas for industrial products. As discussed in the previous chapter, co-gasification of coal-biomass-plastics blends presents operational advantages in comparison to gasification of individual feedstock as well as flexibility to control the product gas composition by varying the blending of feedstock. This chapter discusses the key process parameters that influence co-gasification performance based on findings reported for combinations of coal and biomass with plastics. Challenges encountered during co-gasification of plastics are reviewed, followed by a summary of the current state of the technology of co-gasification involving plastics.

Synergistic effects of co-gasification of plastics with coal and coal with biomass and plastic wastes have been reported in laboratory and pilot plant studies with high H_2 content product gas. Plastic waste can be added to coal (and/or biomass) gasification, which is a mature technology, without any major changes to the process. It is important to consider the effect of process parameter conditions to obtain desired product yield and optimal gasification performance. Different combinations of the coal, plastic, and biomass feedstock result in different compositions of volatile matter, moisture, carbon, and oxygen content. This affects critical operational requirements such as different optimal gasifying temperature conditions depending on the feedstock considered. Coal is generally gasified at higher temperatures (i.e., > 750°C), whereas the presence of plastic and biomass result in lower gasification temperatures Aznar et al., 2006; Pinto et al., 2003). The performance of a gasification system and quality of syngas are driven by critical process parameter conditions such as catalyst, temperature, gasifying medium, gasifier type, and feedstock composition (blending ratio), as shown in Figure 4-2.

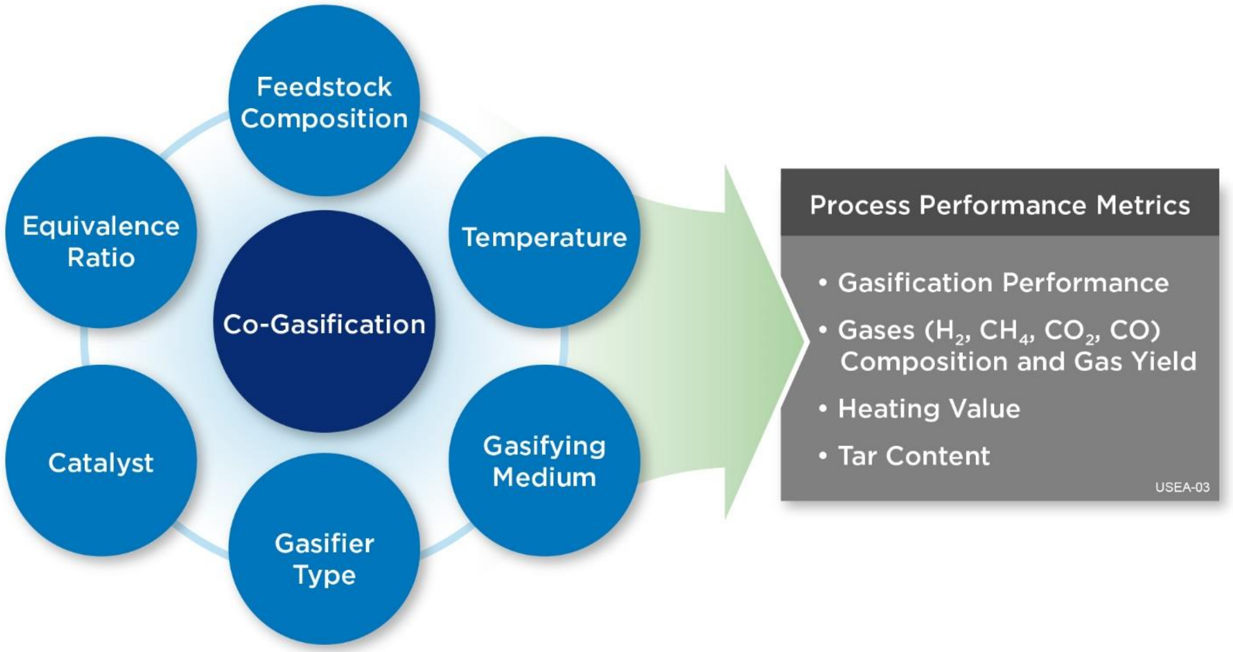


Figure 4-2. Process parameters and performance metrics in co-gasification

Some key performance metrics considered to evaluate the gasification performance include the product gas yield and composition, heating value, Carbon Conversion Efficiency (CCE), and tar content (Figure 4-2).

- Gas yield is an important parameter that defines reactivity of the gasification agent toward the feed material and the activity of all reactions. It is the measure of all gases except any inert gases such as N_2 per unit of ash-free dried feed. The gas yield drives the product gas composition obtained from the process. H_2-rich syngas is required for use as fuel, and different ratios of H_2/CO syngas can be converted to valuable chemicals for industrial use. The various syngas market applications are discussed in detail in Chapter 5.

- Product gas conversion from the solid fuel is also measured in terms of the CCE. The CCE represents the percentage of total carbon in the gasifier feedstock that is converted to product gases, which contain carbon (e.g., CO, CO_2, CH_4), and is given by the ratio of moles of carbon in the product gas to the total moles of carbon in the feed. A higher CCE is a desirable outcome of the gasification process. The presence of carbon and oxygen in the feed increases combustion and gasification, which in turn, increases CCE. The CCE is also dependent on the temperature, gasification agent, and catalyst that enhance the reactivity of carbon (Shahbaz et al., 2020).
- Heating value is defined as the energy released by burning a unit volume/mass of fuel. It is measured in terms of MJ/Nm^3 (or MJ/kg). The product gas heating values depend on the proportion of the composition of H_2, CO, sulfur, N_2, CO_2, and CH_4 in the product gases and drives its application for energy production (Shahbaz et al., 2020). Greater heating values, like gas yield, are desirable outcomes of gasification. Generally, the lower heating value (LHV) is chosen as a quality indicator of syngas. It expresses the energy of the gas without considering the latent energy of steam (i.e., heat of combustion relative to liquid water) while higher heating value (HHV) represents the heat of combustion relative to gaseous water (steam).
- Tar is an unwanted product produced during the gasification process that affects the economy of the process. Tar content dictates the cleaning of syngas to meet regulations and plant requirements for subsequent applications.

4.1. Process Parameters Influencing the Co-Gasification Performance

A number of studies have investigated the impact of the above process parameters on co-gasification performance. (Pinto et al., 2003) studied the effect of temperature and gasification medium for optimal co-gasification of coal, pine, and PE wastes with technical and economic considerations. They determined that the run temperature was the most important operating variable affecting the co-gasification performance. (Aznar et al., 2006) performed an experimental investigation of the effect of system variables such as feedstock composition, gasifier bed temperature, etc. to optimize co-gasification of ternary mixtures of coal, pinewood sawdust, and plastic waste with air. (Shahbaz et al., 2020) reviewed critical process parameters and conditions that directly affect the product yield and gasification performance. (Ciuffi et al., 2020) reviewed operating parameters of gasification and co-gasification of plastics with different types of feedstock. The following section reviews reported effects of the key process parameters on co-gasification performance.

4.1.1. Catalyst

Catalysts have been employed in the gasification process to enhance the yield of product gas by reducing tar and char formation. The use of catalysts in the co-gasification process influences the temperature and gas yield with more efficient catalysts, enabling reduced reaction temperatures and improved carbon conversion rates. The following three types of catalyst are used in co-gasification processes:

- Mineral-based catalysts such as dolomite and limestone
- Alkali and alkaline earth metals-based such as aluminum (Al), iron (Fe), and potassium
- Transition metal-based catalysts such as nickel (Ni).

Catalysts are employed in two ways, in the gasifier or downstream for product syngas cleaning and upgrading. The influence of these catalysts in the gasification process with biomass has been reviewed in detail with much focus on tar elimination. (Sutton, Kelleher, & Ross, 2001) and (Shahbaz et al., 2017) reviewed available literature for the effect of all these types of catalysts and different gasifying agents on the biomass gasification process. (Yung, Jablonski, & Magrini-Bair, 2009) studied effects of catalytic additives in production of biomass-derived syngas, with emphasis on tar destruction.

Mineral-based dolomite has been used as catalyst and bed material for tar reduction and desired gas composition. The presence of a high percentage of calcium oxide (CaO) in the dolomite enhances the product gas quality in gasification, while the presence of iron (III) oxide (Fe_2O_3) in dolomite reduces the tar production and enhances the product yield by 2 vol%. Dolomite, however, is less resistant to carbon deposition like transition metal-based catalysts, resulting in reduced catalytic activity. The mechanical strength of dolomite at higher temperatures, especially in steam fluidized conditions, is another limitation (Shahbaz et al., 2017). However, the utilization of dolomite-based catalysts has been found to be most economical and helpful in the development of tar cracking and CO_2 reduction.

Alkali catalyst appears to favor high product yield and tar elimination in biomass steam gasification. However, it is very expensive and becomes agglomerated and clogs the pipes at higher temperatures, affecting the economic viability of the process (Shahbaz et al., 2017). Additionally, it produces a large amount of ash, creating a disposal issue (Shahbaz et al., 2017).

Ni catalyst is the most significant catalyst used in coal or biomass steam gasification due to its high catalytic performance in dry and steam reforming reactions and tar reduction (Shahbaz et al., 2017). It enhances the H_2 yield at higher temperatures, while it enhances the CH_4 contents at lower temperatures. Moreover, Ni catalyst impregnated with other metals like platinum (Pt), rhodium (Rh), Al, and Fe significantly enhances the product gas yield. The catalyst has a problem of sintering due to carbon deposition, resulting in reduced catalytic activity and leading to high regeneration costs.

Despite the desirable efficiency improvements, catalytic co-gasification is an emerging technology that needs further research and development (R&D) before it can be used at large scale. Catalysts are an area of active research in co-gasification mixtures with plastics, as highly efficient catalysts in the gasifier tend to be expensive and hence cost prohibitive.

4.1.2. Gasifying Agent/Medium

There are different types of gasifying media that act as oxidizing agents, such as air, oxygen, steam, CO_2, supercritical water, and more recently, plasma, or a combination of these. Gasifying agents are indispensable for the co-gasification process and affect the composition and heating value of the produced syngas by influencing the selectivity of the gasification reactions occurring during the process.

- Pure oxygen is used as a gasifying medium when high heating value gas for combined cycle applications or when a synthesis gas for producing chemicals and distillate fuels is required.

N_2 free syngas reduces energy demand and system cost for carbon capture. However, it the high cost of pure oxygen needs to be factored in for its application.

- Air is the most common gasifying agent due to its low cost and availability and has been used in pilot plants because of economic and commercial interest. However, the use of air produces low heating value fuel gas due to the dilution by N_2.
- The use of pure steam is advantageous as it produces high H_2 content gas (50–55%). However, steam gasification has high external heat requirements and produces high tar content, which is undesirable (Aznar et al., 2006).

Generally, a combination of steam with oxygen provides an adiabatic reaction combining partial oxidation and steam reforming, which produces a high-calorific value syngas that is suitable for making distillate fuels as well as chemicals, or just H_2.

4.1.3. Equivalence Ratio (ER)

The rate of injection of the gasifying agent is also a key process consideration to ensure correct stoichiometric gasification conditions and to provide sufficient residence time to break and crack the volatiles and tar units into product gases. ER is a critical parameter that affects the syngas quality and performance of co-gasification. ER is defined as the air-to-fuel ratio used in the gasifier divided by the air-to-fuel ratio for the stoichiometric combustion. High ER results in significantly higher yield for all the gases for co-gasification. This is especially relevant in the context of air gasification, as the amount of air supplied to the gasifier directly influences the degree of gasification through the enhancement of the temperature of the reactor. Excessive air, on the other hand, is undesirable, as it results in syngas with higher CO_2 concentration. The effect of ER has been a subject of research for co-gasification of different plastics (Aznar et al., 2006; Kim et al., 2011; Shahbaz et al., 2020). A lower ER value was found to be good for plastic co-gasification. For example, a study on the effect of ER ratio from 0 to 0.2 on the co-gasification of different plastics found that increasing ER resulted in an increase in H_2 and CO content, while the CO_2 and CH_4 decreased (Aznar et al., 2006). It was determined that the gas composition and gasification performance were optimal when the (steam and oxygen)/fuel ratio was in the range of 1.3–1.5 (Pinto et al., 2003). An ER range of 0.2–0.3 was found attractive for gasification performance of mixed plastics (Shahbaz et al., 2020). They also observed a higher CCE at higher ER values for mixed plastics.

4.1.4. Temperature

Reaction temperature is one of the most important operating variables affecting the product syngas composition and yield. Both coal and biomass gasification performance are affected by this process variable since the main gasification reactions are endothermic. As previously mentioned, the gasification temperature is dependent on the feedstock, and it is directly related to the production of gases from solid carbon feed material. CO and CO_2 are the most important components of the product syngas directly affected by the temperature during co-gasification of different feedstock blends. (Pinto et al., 2003) found that the run temperature was the most important operating variable affecting gasification performance and recommended a co-gasification temperature range of 850–900°C to ensure reductions of hydrocarbons and tar contents caused by the presence of plastic wastes in the feedstock consisting of coal, pine, and PE wastes. (Aznar et al., 2006) determined that the H_2 increased from 12 to 15 vol% with the increase in bed temperature for the co-gasification of the ternary blend of coal, sawdust, and plastic, with a ratio of 60:20:20 in a fluidized bed using dolomite as a catalyst. They observed increased gas yield due to the reduction of tar with increased bed temperature.

4.1.5. Gasifier Type

While gasifier operating parameters such as temperature are important, the type of reactor used for the process also plays a role in co-gasification performance. A key component of the gasification process is thus the reactor, called the gasifier. The three main types of gasifiers based on the solid and gas interaction mode are: (a) fixed bed gasifier, (b) fluidized bed gasifier, and (c) entrained flow gasifier, as shown in Figure 4-3. Co-gasification of coal and biomass has been sufficiently demonstrated globally using all three types.

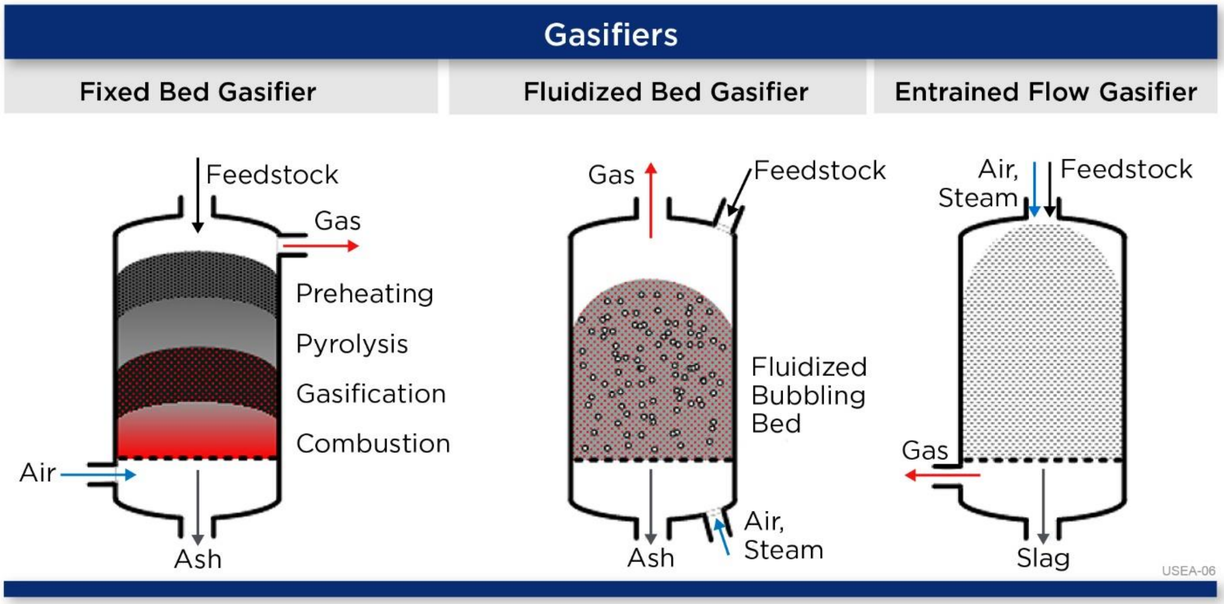


Figure 4-3. Types of gasifiers: fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier (www.substech.com)

- ***Fixed bed gasifiers*** are simple in design, where the feedstock flows downward by gravity. Therefore, it is necessary that a bulk density of the feedstock is high enough for continuous downward process. They are primarily used for small-scale applications. Tar formation is low in fixed bed gasifiers (Shahbaz et al., 2020).
- ***Fluidized bed gasifiers*** require adequately crushed and mixed uniform size coal and biomass feed and is suitable for large-scale applications. Fluidized bed (bubbling) reactors are widely used in the gasification of waste plastics for handling the typical characteristics of plastics such as low thermal conductivity, high volatile content, and sticky nature when heated (Ciuffi et al., 2020; Lopez et al., 2018).
- ***Entrained flow gasifiers*** are typically used for large-scale gasification of petroleum coke (petcoke), coal, and refinery residues, as they can handle a wide range of moisture content. High operating temperature and pressure with a short residence time and small particle size are characteristics of an entrained flow gasifier. Typically, pure oxygen is used as a gasifying agent in entrained flow gasifiers.

4.1.6. Feedstock

The mixing or blending ratio of feed materials such as plastic, coal, biomass, and sewage sludge has been extensively studied in the context of co-gasification. This provides flexibility in feedstock during situations of limited supply scenarios and seasonality, operational problems in feeding systems, and determination of feed specifications. The feedstock composition plays a significant role in influencing the purpose of co-gasification, which is the production of beneficial syngas.

The feedstock composition influences the flue gas, tar content, and working performance apart from the previously stated effects on the desired syngas yield and composition/quality. A study reviewed the effect of feedstock type and their blending ratio on syngas quality, co-gasification performance, and tar formation for catalytic co-gasification (Inayat et al., 2019). Higher hydrocarbon content or CCE is observed in the presence of PE during co-gasification of various plastics, biomass, and lignite (Pinto et al., 2003). Some researchers have observed a decrease in the gas yield or CCE with an increase in biomass content with coal, plastic, and sewage sludge (Kern et al., 2013; Shahbaz et al., 2020). The presence of biomass in the feedstock generally results in increased CO concentrations and decreased CO_2 concentrations in the product gas. Another study observed increasing CH_4 content for lignite coal-PE granulate co-gasification due to the synergetic effect of coal and plastic (Kern et al., 2013). When the plastic waste dominates in feedstock, fewer tars are generated (Aznar et al., 2006) while the presence of biomass in the feedstock increases the tar content.

Figure 4-4 shows there is an increase of hydrocarbon concentration, CH_4, and light hydrocarbons when plastic waste is included in the feedstock (Bian et al., 2020). They observed the optimal mixing ratio to be 1 for the co-gasification of lignite and various plastics (i.e., PE, PC, and PP) in supercritical water with quartz reactors. The largest magnitude of the synergistic effect was obtained at optimal mixing. This was in addition to improved total gas yield and reduced the phenol content in the liquid products. Additionally, they determined that the presence of PE and PP had a larger magnitude of the synergistic effect with lignite than that of PC, indicating that the hydrogen/carbon (H/C) ratios in plastics and lignite played an important role in the synergistic effect in co-gasification.

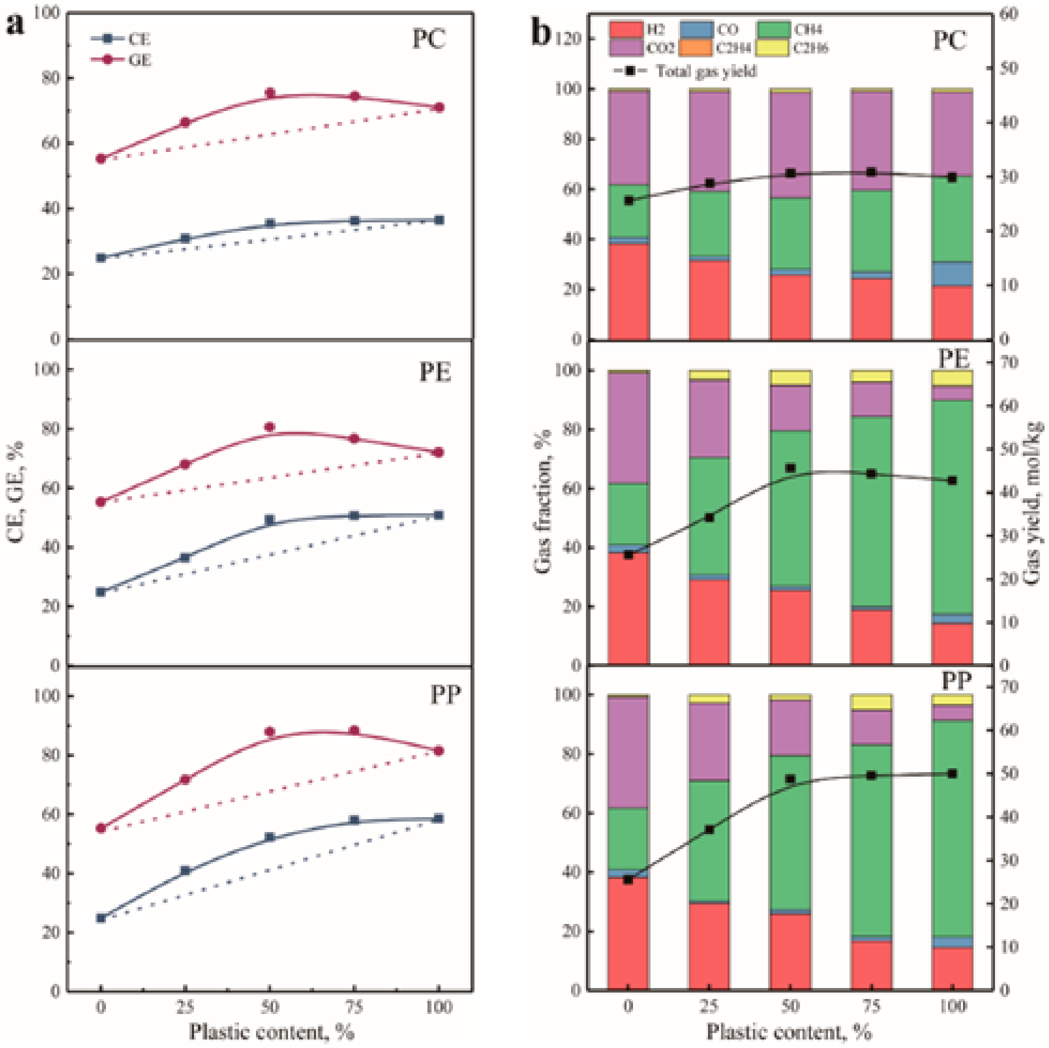


Figure 4-4. Effect of lignite/plastic mixing ratio on CCE (left) and gas yield (right) (Figure 1, (Bian et al., 2020)). H_2 and CO_2 fraction is lesser while the CH_4 fraction is higher with increasing PE and PP ratios.

Catalytic co-gasification of the ternary blend of coal, plastic, and biomass has posed an attractive option for investigation of co-gasification with plastic material. Studies have investigated the use of different combination and blending ratios of pine waste, coal/petcoke, and PE in fluidized bed gasifiers on the product syngas composition. The CO/H_2 ratio of the product gas differs with various technologies and feedstock constituents (Inayat et al., 2019). (Inayat et al., 2019) present the detailed analysis of relevant studies and conclude that the ternary blend is found to be favorable in terms of the tar reduction. The optimum gas composition was reported at a blend of 10% pine, 10% PE, 5% petcoke, and 75% coal (Pinto et al., 2007).

(Aznar et al., 2006) elicited that the effect of feedstock composition on product gas composition has opposing effects on the LHV and gas yield. This trend is because coal reacts mainly in exothermic reactions producing large gas volume but components with low LHV. Figure 4-5 shows the effect of different ternary feedstock compositions on the product syngas composition for a bed temperature of 850°C and ER = 0.36. Thus, the optimal feedstock would need to be determined by the targeted end use of the syngas. Some key trends observed are:

- The mixture with higher plastic content produces a higher LHV with a lower gas yield.
- The mixture with higher coal content produces the lowest LHV, but gas yield is the highest.
- Biomass in the feedstock causes an increase in tar content.
- Coal is less reactive and promotes char formation instead of tars.

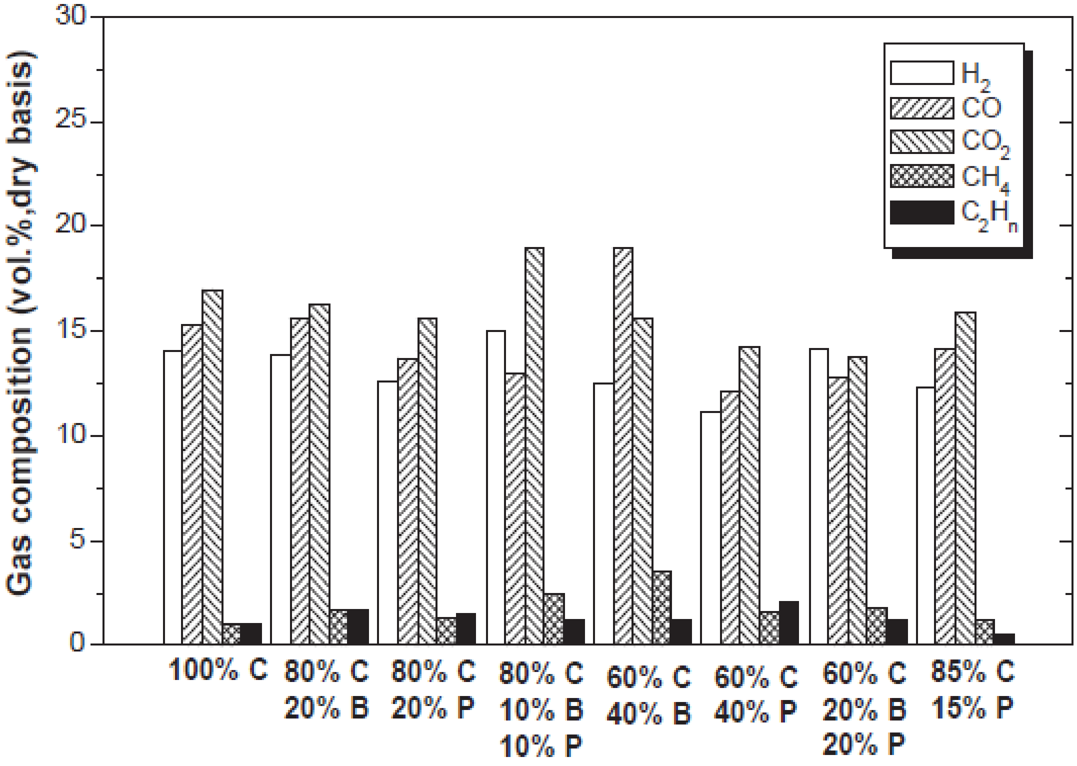


Figure 4-5. Product gas composition for various feedstock blends (Figure 8, (Aznar et al., 2006)). Coal (C); Biomass (B); Plastic waste (P). Higher coal content produces higher gas yield with the highest H_2 percentage obtained for the 80:10:10 ratio of C:B:P. The 60:20:20 blend of C:B:P has similar percentages of H_2, CO, and CO_2 with lower alkanes (CH_4, C_2H_n).

4.2. Technical and Operational Challenges

There are several technical and operational challenges during the co-gasification process. The feedstock must be prepared for the gasification stage, and the product syngas must be cleaned before it can be suitable for most end uses. Figure 4-6 shows a schematic of the operations involved in the co-gasification process. Upstream processing or feedstock pre-processing typically includes moisture removal and particle size reduction stages.

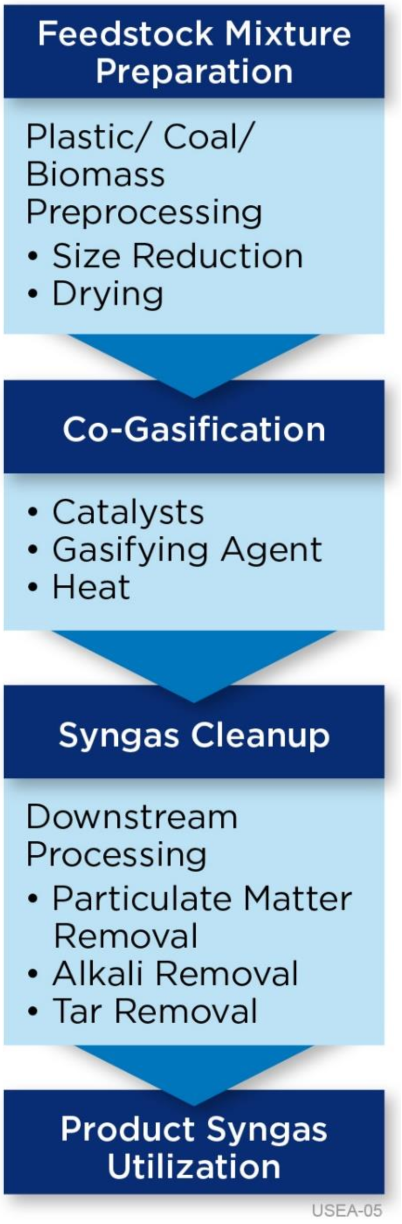


Figure 4-6. Schematic of operations involved in the co-gasification process

Some of the major technical and operational challenges are discussed below.

4.2.1. Upstream/Feedstock Pre-processing

While the commonly used fluidized bed gasifiers tolerate wider particle size ranges, feedstock component particle size considerations determine effectiveness of the co-gasification process and perform better with uniform size crushed and mixed feedstock. Size reduction processes such as grinding, crushing, and shredding involve the use of equipment such as hammer mills, knife mills, or tub grinders. These processes consume energy that depends on factors such as moisture content, initial size, screen size, and processing equipment properties. The preferred range for coal (and biomass) is 0.5–1.0 mm size. Due to the broad range of shapes and sizes of plastic waste, shredding helps create feed less than 5 cm in diameter, while some require simple agglomeration to facilitate feeding (Ciuffi et al., 2020). (Aznar et al., 2006) studied the effect of feedstock particle size on tar content and determined that coal particle size is critical because it is the major component in the feedstock mixture and is also the least reactive solid.

Some materials have a high moisture content, such as MSW and black liquor, as compared to coal and wood (Motta et al., 2018). When biomass is present in the feedstock mixture, the proportion and type of biomass and moisture content need to be considered, as these factors significantly affect the product syngas composition. Unlike coal and biomass, plastics generally have a very low moisture content. The feedstock mixture components are generally dried in order to maintain moisture content of less than 15% before being subjected to the co-gasification process so that the moisture content has a negligible effect on the process. (Ciuffi et al., 2020) highlight that co-gasification using supercritical water does not require this drying step for feedstock, thus resulting in greater energy efficiency and economic savings (especially for biomass with high water content).

4.2.2. Downstream Processing

Downstream processing includes particulate matter, alkali, nitrogen, and sulfur compounds and tar removal. Particulate matter can be removed by attaching a cyclone separator at the gas exit, while alkalis and tars can be removed by using catalysts and secondary air injection in the gasifier system, which helps in combustion of tars. Alkali elements such as sodium, potassium, magnesium, and calcium as well as sulfur present in the feedstock volatilize to form oxides and cause downstream problems such as corrosion by depositing on the downstream sections of the gasification system and deactivating catalysts used for tar removal. Nitrogen, generally present as ammonia, is removed by wet scrubbing of the cold gas and by destroying ammonia using dolomite-based, Ni-based, and Fe-based catalysts. This becomes critical in the air co-gasification processing. Sulfur is converted to SO_2 or hydrogen sulfide (H_2S) during gasification, which can be removed using limestone, dolomite, or CaO (Brar et al., 2012).

Tar Formation

Most syngas utilization processes require tar-free syngas. There have been two approaches to produce tar-free syngas:

1. Improved and efficient gasification technologies with optimized gasifier design, operating conditions, and proper selection of catalysts.
2. Downstream processing with high-efficiency tar removal techniques.

Tar content is mainly influenced by the feedstock composition and reaction conditions such as temperature. It is an undesirable product of the gasification process that affects the overall economics of the process. When the plastic waste dominates in feedstock, more tar content is generated (Kern et al., 2013). This is also summarized in Figure 4-7 from (Shahbaz et al., 2020), which illustrates the effect of feedstock on the tar content. For ternary blends of coal, biomass, and plastic, the presence of the biomass component controls the tar content. Similarly, Figure 4-8 (Aznar et al., 2006) shows that an increase of biomass percentage in feedstock causes an increase of tar content. On the contrary, coal produces less tar quantity because coal is less reactive and forms char instead of tar. (Pinto et al., 2003) determined that reductions of hydrocarbons and tar contents were achieved by increasing oxygen concentration, because partial combustion reactions were favored, and at the same time, there was a decrease in heating requirements.

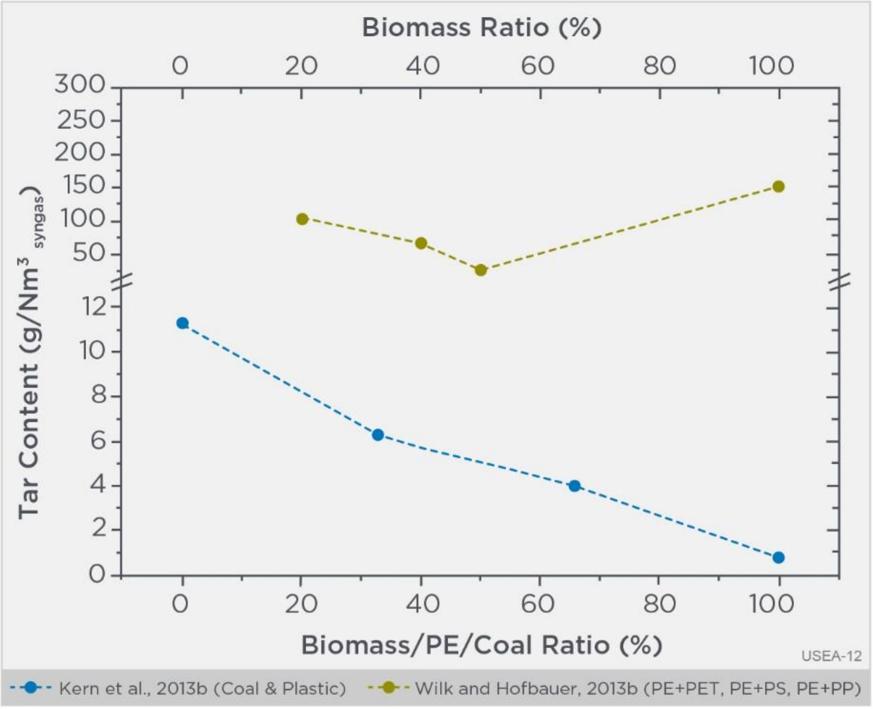


Figure 4-7. Effect of feedstock blends on tar formation (Shahbaz et al., 2020)

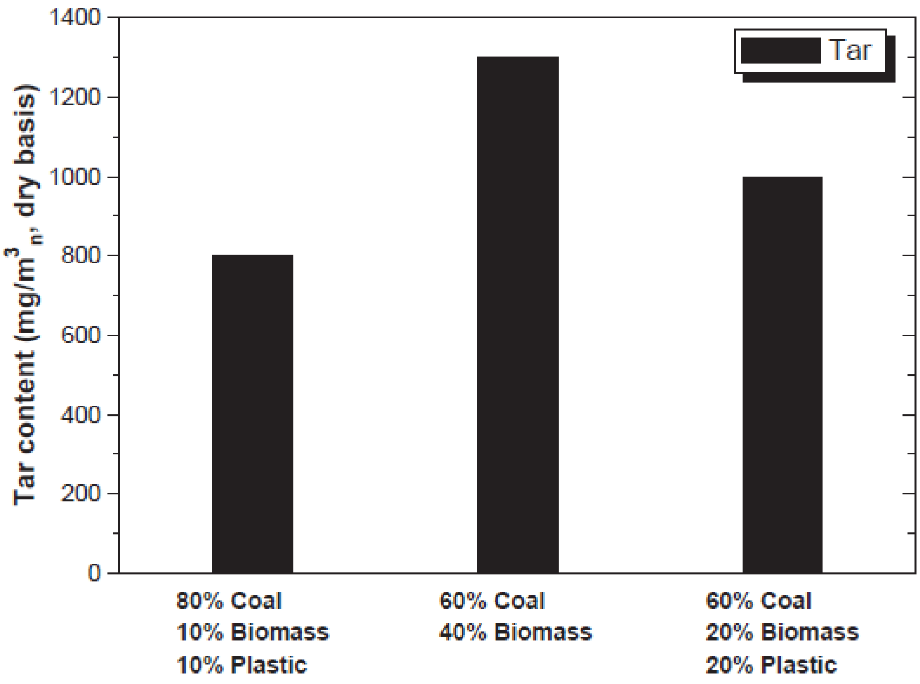


Figure 4-8. Effect of feedstock composition on tar content (Figure 10, (Aznar et al., 2006))

4.3. Current/State of the Art for Co-gasification Technologies

The Technology Readiness Level (TRL) is a systematic framework for the consistent evaluation of the technical maturity of any technology of interest along its respective innovation chain (DoD, 2005). The TRL scale ranges from TRL 1 (i.e., basic principles observed, proven technical feasibility) through TRL 9 (i.e., operational, actual system operated over the full range of expected conditions).

While coal and biomass gasification are commercially well-established technologies, studies on co-gasification have been conducted at a laboratory or pilot plant scale and are thus a TRL 3 or 4 (Figure 4-9). Multiple elements of co-gasification implementation (e.g., catalysts with different potential feedstock blends) need dedicated research and investigation to understand real-time operational issues of a full-scale operation. This is crucial to help progress on the TRL scale and accomplish the commercialization of co-gasification. Progressively higher technical and economic risks are expected to achieve the commercial-scale demonstration of TRL 6–9.

Figure 4-9. TRL of gasification versus co-gasification technologies (modified from (Shahbaz et al., 2020))

4.4. Summary

Plastic waste can be added to coal or biomass gasification without a change in the process, provided that the proportion of plastic is controlled in accordance with the processing conditions. While plastic-coal co-gasification looks to utilize domestic coal resources for effectively managing plastic waste, co-gasification with biomass involves managing these feedstock resources as part of MSW treatment. The feasibility of co-gasification with plastics waste has been demonstrated in multiple laboratory studies and some pilot investigations across the world. Key plastics co-gasification challenges of material handling of feedstock blends during pre-processing and syngas cleanup associated with different feedstock sources need to be optimized for commercial adoption of this technology. There are some successful waste gasification plants already operating in Canada (e.g., Enerkem Alberta Biofuels) and in the U.S. (e.g., Sierra's FastOx Pathfinder pilot in California) (Ciuffi et al., 2020).

The performance of a co-gasification system is determined by measuring metrics such as the CCE, gas yield, tar formation, and heating values of product gases to determine the gasification efficiency and economic viability for different applications. Table 4-1 summarizes the optimal feedstock and operational conditions in co-gasification studies.

- In general, a high H_2 content and heating value, low char yield and tar content, and high gas yield is desirable.
- Optimal process considerations typically depend on the use of the exit gas (product syngas).

- A ternary blend of coal, biomass, and plastic is found to be favorable in terms of the tar reduction (Inayat et al., 2019).
- The H/C ratios in plastics and lignite played an important role in the synergistic effect in co-gasification (Bian et al., 2020).
- Run temperature is the most important operating variable affecting the performance of gasification in co-gasification involving coal mixed with pine and PE.
- The optimal working conditions are a bed temperature of at least 850°C and an ER = 0.36, regardless of studied feedstock mixtures (Aznar et al., 2006; Pinto et al., 2003) as the presence of plastic waste favored hydrocarbon and tar release (Pinto et al., 2003).
- An increase of biomass percentage in feedstock causes an increase of tar content. On the contrary, coal produces less tar quantity because coal is less reactive and forms char instead of tar (Aznar et al., 2006). When the plastic waste dominates in feedstock, less tar content is generated (Kern et al., 2013).

Table 4-1. Summary of optimal feedstock and operational conditions in plastic/coal and plastic/coal/biomass co-gasification studies

Feedstock/Blend Ratio	Gasifier Type	Temperature	Catalyst/Bed Material	Gasifying Agent	Syngas Quality	Co-Gasification Performance	Reference
Coal (60 wt.%), biomass (20 wt.%), plastic (20 wt.%)	Air gasified bubbling fluidized bed (BFB) reactor	850°C	Silica sand with dolomite catalyst	Air	H_2: 7–15% CO: 10–20% CO_2: 14–23% CH_4: 2–10%	Gas yield: 3 m^3_n/kg feedstock Tar: < 0.5 g/Nm^3	(Aznar et al., 2006)
Coal (60 wt.%), pine (20 wt.%), PE plastic (20 wt.%)	Fluidized bed	850-900°C (890°C)		Air/Steam	H_2: 39.8 vol% CO: 17.3 vol% CO_2: 20.4 vol% CH_4: 14.9 vol%		(Pinto et al., 2003)
Coal, PE plastic	Dual fluidized bed	850°C	Olivine bed material	Steam	H_2: 40.4–49.4 vol% CO: 20.3–29.5 vol% CO_2: 3.6–12.9 vol% CH_4: 4.4-15.6 vol%	Tar: 0.8-11.2 g/Nm^3	(Kern et al., 2013)
Coal, plastics, wood **Coal (50 wt.%), mixed plastics**	BFB	850°C	Quartz sand bed material	Oxygen-enriched air	H_2: 13.8 vol% CO: 19.3 vol% CO_2: 16.3 vol% CH_4: 6.0 vol%	Tar: 13.5–21.8 g/Nm^3	(Mastellone, Zaccariello, & Arena, 2010)

Chapter 5. Synthesis Gas and the Value Chain

Synthesis gas (or syngas) is a gas mixture consisting primarily of H_2, CO, and very often some CO_2. Table 5-1 gives the typical composition of syngas. Gasification of feedstock containing carbon such as coal, plastic waste, and biomass creates syngas as explained in Chapter 3. Syngas is a versatile building block in the chemical industry that can be used for a multitude of applications such as chemicals, fuels, and power generation. More than half the syngas production (~55%) is used for the synthesis of ammonia for fertilizer production, with the H_2 from syngas consumed in the oil refining processes being the next largest application (22%), and 12% of the syngas produced is used for methanol production.

Table 5-1. Example composition of syngas from gasification of different raw materials (Table 3, (Boerrigter & Rauch, 2006; Inayat, Sulaiman, Kurnia, & Shahbaz, 2019))

Unit	Coal	Plastics	Wood
H_2, volume%	25-30	5-38	30-45
CO, volume%	30-60	5-20	20-30
CO_2, volume%	5-15	3-29	15-25
CH_4, volume%	0-5	7-30	8-12
N_2, volume%	0.5-4	5	1-3
NH_3, ppm	0-3000		500-1000
H_2S, ppm	2000-10000		50-120

Key global players include Air Products and Chemicals Inc., KBR Inc., Air Liquide S.A., Linde Plc, Sasol Limited, Haldor Topsoe A/S, Royal Dutch Shell Plc, and Siemens AG who are engaged in providing syngas and its derivatives for industrial applications around the world. The main feedstock for syngas production is currently coal in major markets such as China, U.S., and Russia. Some commercial companies such as Enerkem and Sierra Energy process waste for syngas production.

A plant that processes about 50,000 tonnes of plastic waste a year can generate up to 15,000 normal cubic meters (Nm^3) of syngas per hour or an equivalent annual output of about 20,000 tonnes of natural gas. While conventional plastics gasification can support the reuse of plastic material and has been used to produce intermediate chemicals and various plastics, for example in the Enerkem plastic waste to methanol/ethanol commercial facility in Canada, it is highly cost- and energy-intensive to produce high purity syngas for multiple possible applications. Co-gasification technologies are thus promising avenues to meet this high potential global market need.

5.1. Applications of Synthesis Gas

The clean syngas from the gasification process can be further processed to a variety of useful chemical and consumer products as shown in Figure 5-1. Syngas is a crucial base material for a variety of applications, including methanol synthesis that can be upgraded to higher commercial value chemicals such as acetic acid, formaldehyde, or dimethyl ether. Ammonia synthesis is a mature technology that constitutes the largest consumer of syngas and is recovered for urea production in the fertilizer industry. Syngas can be used as a source for H_2 production (Speight, 2015) or for the synthesis of liquid hydrocarbon fuels and other valuable chemicals such as naphthalene when subject to the well-established catalytic Fischer-Tropsch process. H_2-rich syngas can also be used directly for H_2 enrichment of fuels. It can also be used for electricity generation in many types of equipment, from reciprocating engines to turbines. Syngas used for synthetic natural gas production also finds application in the rail, marine, and road transport industries. Figure 5-2 shows the summary statistics of the Global Syngas Technology Council (GSTC) Database for various syngas capacity end uses. These statistics illustrate the predominance of gasification capacity to generate syngas (i.e., operating, under construction, and planned units as of 2016) for chemicals production over fuels and electricity end uses.

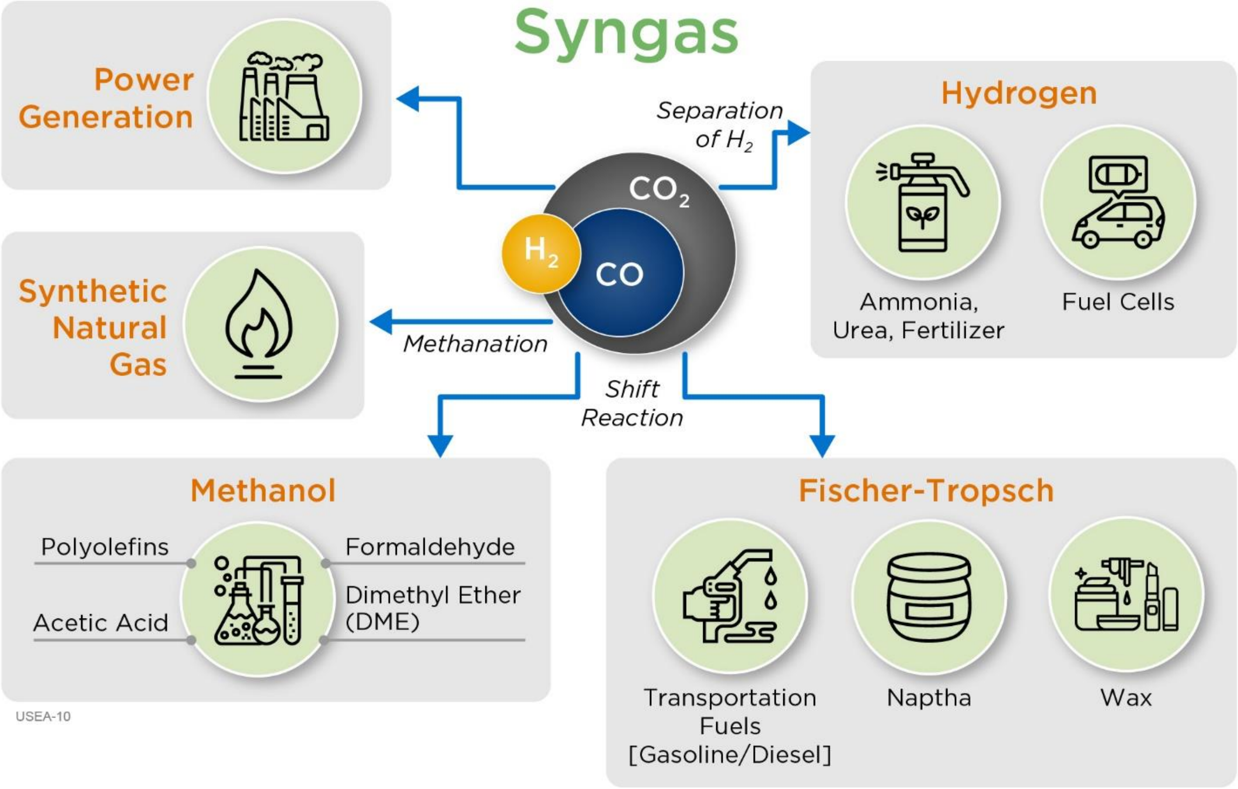


Figure 5-1. Versatile applications of syngas product of gasification

Syngas offers two main routes to industrial chemicals with different commercial effectiveness depending on the desired end product (Keim, 1987):

- Direct conversion pathways with the straight hydrogenation of CO to paraffins, olefins, and heteroatom (oxygen, N_2) containing products
- Indirect conversion pathways involving intermediates such as methanol, methyl formate, and formaldehyde.

Some of these end products can be used immediately without further processing, while others require simple or complex conditioning and/or processing before use in specialty applications. For instance, the particle and tar concentration in the syngas must be less than 50 mg/Nm^3 and 100 mg/Nm^3, respectively, for the satisfactory operation of an internal combustion engine (Copa et al., 2020). Furthermore, increasing environmental awareness and tighter Government regulations surrounding fossil fuel use are significantly driving syngas conversion technologies to produce cleaner fuels and chemicals. Syngas production from waste plastic co-gasification is thus an intensively researched pathway to address the increasing demand for green energy.

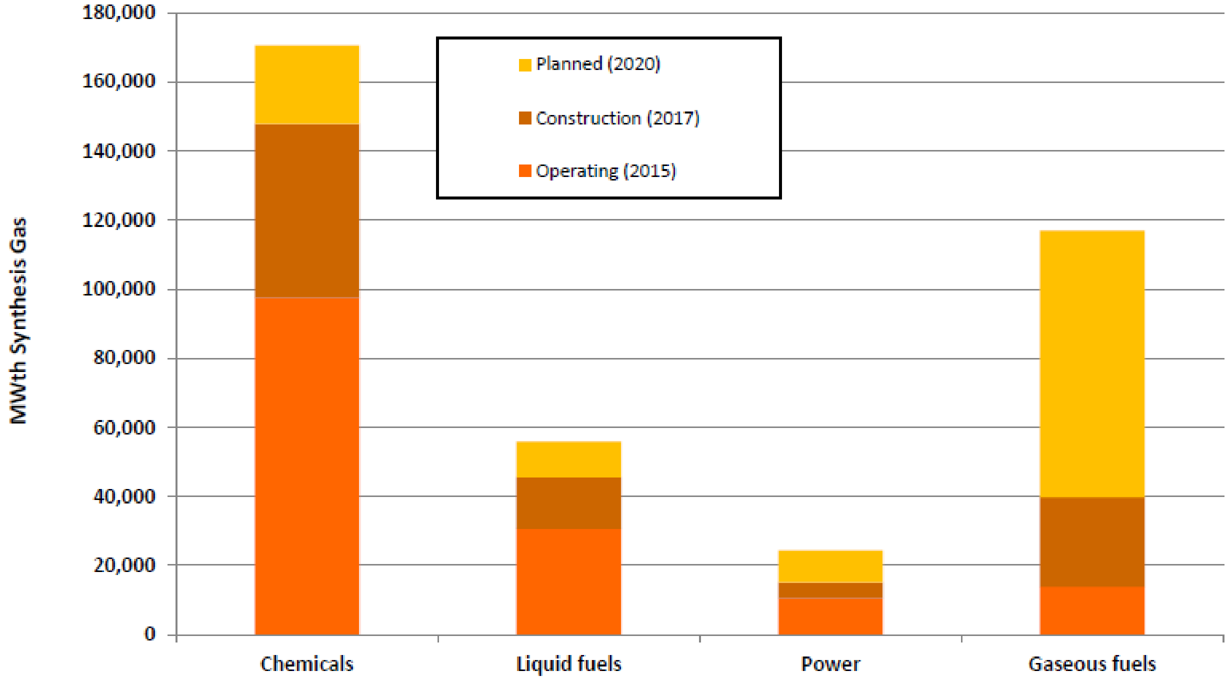
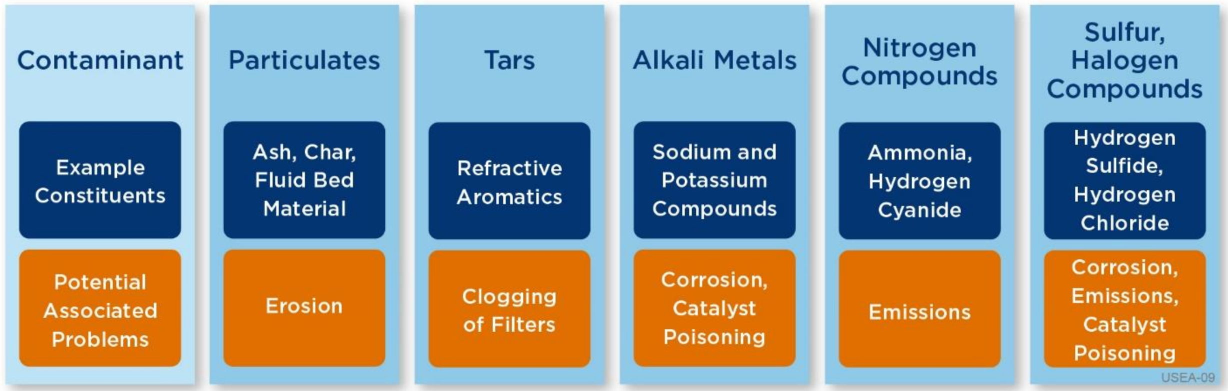


Figure 5-2. End use applications of syngas (Higman, 2016)

5.2. Impact of Impurities in Synthesis Gas – Importance of Product Processing/ Conditioning

The gasification of feedstock such as plastic waste, coal, and biomass creates syngas along with contaminants such as tars, particulate ash, hydrogen chloride, etc. as explained in Chapters 3 and 4. Figure 5-3 lists the major contaminants in this 'dirty' syngas, their typical constituents, and their associated problems to emphasize the need for cleanup to purify the syngas for various applications. Irrespective of the feedstock source or gasification technology utilized, the product syngas must be purified before its introduction into corresponding downstream utilization units. Syngas cleanup aspects are discussed in Chapter 4, Section 4.2.2. Syngas cleanup or downstream processing of co-gasification derived syngas includes the same operations needed for conventional coal gasification, including moisture removal, particulate removal, sulfur removal, alkali removal, mercury removal, etc., but is likely more complicated due to the combination of more sources than coal or plastics gasification alone.



Contaminant	Particulates	Tars	Alkali Metals	Nitrogen Compounds	Sulfur, Halogen Compounds
Example Constituents	Ash, Char, Fluid Bed Material	Refractive Aromatics	Sodium and Potassium Compounds	Ammonia, Hydrogen Cyanide	Hydrogen Sulfide, Hydrogen Chloride
Potential Associated Problems	Erosion	Clogging of Filters	Corrosion, Catalyst Poisoning	Emissions	Corrosion, Emissions, Catalyst Poisoning

Figure 5-3. Typical syngas contaminants and problems associated with their presence that warrant syngas cleanup operations

Syngas has about half the energy density of natural gas. The key combustible gases it contains are H_2 and CO whose ratio determines the product gas quality. Different ratios of H_2/CO syngas can be converted to valuable chemicals for industrial use as indicated in Table 5-2. The economics and process feasibility of syngas industry applications are influenced by the following three considerations:

- Ratio of H_2:CO
- Loss of oxygen as byproduct water or CO_2
- Interrelation of chemicals/fuels.

A high H_2/CO ratio in the produced syngas is usually desirable for liquid fuel synthesis, while lesser tar content helps increase throughput and output. Since coal is deficient in H content and rich in C content, the primary syngas from the gasifier requires a water-gas shift reaction followed by CO_2 removal for a proper H_2/CO ratio. The addition of PSW, however, reduces the extent of shift reaction required. The product syngas composition can, within limits, be conditioned to adjust the H_2/CO ratio by altering various process conditions and/or additional processing such as recycling/removal of the CO_2 stream based on the downstream processing application. Table 5-2 summarizes the desirable characteristics of syngas for a number of key applications.

5.3. Synthesis Gas Market Evaluation

Syngas has gained significant traction in the global market, owing to its varied applications (i.e., from fuels to power generation) and general advantages of feedstock flexibility. It also offers low energy costs and improved stability for power generation applications due to underground coal gasification technology that facilitates in-situ gasification of coal into syngas. One of the key factors driving the growth of the global syngas market is the surge in demand from the chemical industry over the last two decades, a portion of which is reflected in Figure 5-2. Furthermore, gasification of waste material is critical in reducing GHG and emissions from landfills. In addition to augmenting the global demand for syngas, gasification of carbonaceous feedstock also offers potential synergy to support the hydrogen economy with H_2 produced as a byproduct of this technology. However, while increased environmental awareness and stringent Government regulations are significant drivers, high capital investment and financing need to be addressed to enable the growth of the syngas market. The reported syngas market volume share in 2019 for different applications in North America establish the current dominance of the chemical industry demand for syngas in comparison to power generation and fuel applications.

Table 5-2. Desirable syngas characteristics for a number of key applications (Ciferno & Marano, 2002)

Product	Synthetic Fuels	Methanol	Hydrogen	Fuel Gas	
	FT Gasoline			Boiler	Turbine
H_2/CO Ratio	0.6[1]	~2.0	High	Unimportant	Unimportant
CO_2	Low	Low[2]	Not Important[3]	Not Critical	Not Critical
Hydrocarbons	Low[4]	Low[4]	Low[4]	High	High
N_2	Low	Low	Low	Note[5]	Note[5]
Water Vapor	Low	Low	High[6]	Low	Note[7]
Contaminants	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	Note[8]	Low Part. Low Metals
Heating Value	Unimportant[9]	Unimportant[9]	Unimportant[9]	High[10]	High[10]
Pressure, Bar	~20–30	~50 (liquid phase) ~140 (vapor phase)	~28	Low	~400
Temperature, °C	200–300[11] 300–400	100–200	100–200	250	500–600

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[1] Depends on catalyst type. For Fe catalyst, value shown is satisfactory; for cobalt catalyst, near 2.0 should be used.

[2] Some CO_2 can be tolerated if the H_2/CO ratio is above 2.0 (as can occur with steam reforming of natural gas); if excess H_2 is available, the CO_2 will be converted to methanol.

[3] Water gas shift will have to be used to convert CO to H_2; CO_2 in syngas can be removed at the same time as CO_2 generated by the water gas shift reaction.

[4] CH_4 and heavier hydrocarbons need to be recycled for conversion to syngas and represent system inefficiency.

[5] N_2 lowers the heating value, but the level is unimportant as long as turbine or boiler system efficiencies are satisfactory. Presence of excess N_2 may be unacceptable in carbon capture scenarios, however.

[6] Water is required for the water gas shift reaction.

[7] Can tolerate relatively high water levels; steam sometimes added to moderate combustion temperature to control NO_X formation.

[8] Small amounts of contaminants can be tolerated.

[9] As long as H_2/CO and impurities levels are met, heating value is not critical.

[10] Efficiency improves as heating value increases.

[11] Depends on catalyst type; Fe catalysts typically operate at higher temperatures than cobalt catalysts.

5.3.1. Current Market Size and Market Projections to 2025 and Beyond

The global syngas market exhibited strong growth from 2015 to 2020 and was valued at $43.6 billion in 2019. This market continues to have a positive outlook and is projected to reach $66.5 billion by 2027, growing at a compound annual growth rate (CAGR) of 6.1% from 2020. Owing to a surge in demand from the chemical industry, primarily from refineries, Asia-Pacific dominated the global syngas market share. Multiple market research reports on the syngas industry trends and forecasts are available, with market analysis by geographical region, end use application, gasifier type, and feedstock. The U.S. is expected to dominate the North American syngas market and is also expected to witness the fastest CAGR, estimated at 7.7% during the forecast period of 2018–2026, with growing syngas demand from the chemicals industry (Mordor Intelligence, 2020). The shifting focus towards hydrogen economy is also expected to boost the demand for hydrogen production that can be complemented by plastics co-gasification. The North America syngas market is fragmented in nature with key players such as Air Products and Chemicals, Inc., Linde plc, Air Liquide, General Electric Company, and Sasol Limited.

A 2002 National Energy Technology Laboratory (NETL) study by (Ciferno & Marano, 2002) found that bubbling fluidized bed (BFB) gasifiers are among the lowest capital cost options suitable for multiple applications (e.g., fuels, chemicals, H_2 production) for biomass gasification. The syngas market evaluation also projected the fluidized bed gasifier to be the most lucrative gasifier segment owing to its flexibility in handling potential low quality, low reactivity feedstock. Gasification R&D efforts around the world, including the Department of Energy (DOE) Gasification Systems Program in the U.S., are currently aimed at improving process flexibility to commercialize co-gasification, gasifier efficiencies, and process control while reducing costs to strategically meet projected market demand.

5.4. Summary

Syngas is a flexible carbon source and a critical base or intermediate material with varied applications from fuels to power generation. The global syngas market has exhibited strong growth and continues to have a positive outlook as reflected in various market projection reports. Co-gasification of waste plastics with coal present a lucrative, environmentally friendly alternative to be tapped to meet growing demand for chemicals and green energy.

Chapter 6. Carbon Capture, Utilization, and Storage (CCUS)

Developing a facility that can co-gasify plastics and coal while utilizing carbon capture has the potential to unlock a key solution for recycling large amounts of plastics and diverting them from landfills. Currently, plastics recycled through thermal mechanisms do not typically utilize a carbon capture and storage system, thereby releasing CO_2 directly to the atmosphere. CCUS, a well-established commercial technology that is implemented globally in other industries, could be key to progressing co-gasification of plastics in a more environmentally friendly manner.

6.1. Overview of a CCUS System

A CCUS system enables the removal of CO_2 from a stream that would otherwise be vented to the atmosphere and redirects it either to a process that utilizes the CO_2 or into permanent geologic storage.

There are three main components of a CCUS system:

1. **Capture and separation of the CO_2 from other materials in the stream at the point source of emissions**. This step also includes initial compression of the $CO_{2.}$
2. **Transportation of the CO_2 to the end use or storage site.** This is typically done via a pipeline for large quantities of $CO_{2.}$
3. **Utilization and/or storage of the CO_2.** This includes either utilization of the CO_2 to create a new product or secure, permanent geologic storage of the CO_2 in reservoirs deep beneath the surface.

A high-level depiction of a CCUS system is shown in Figure 6-1. This is representative of a CO_2 capture and storage project with pipeline transport.

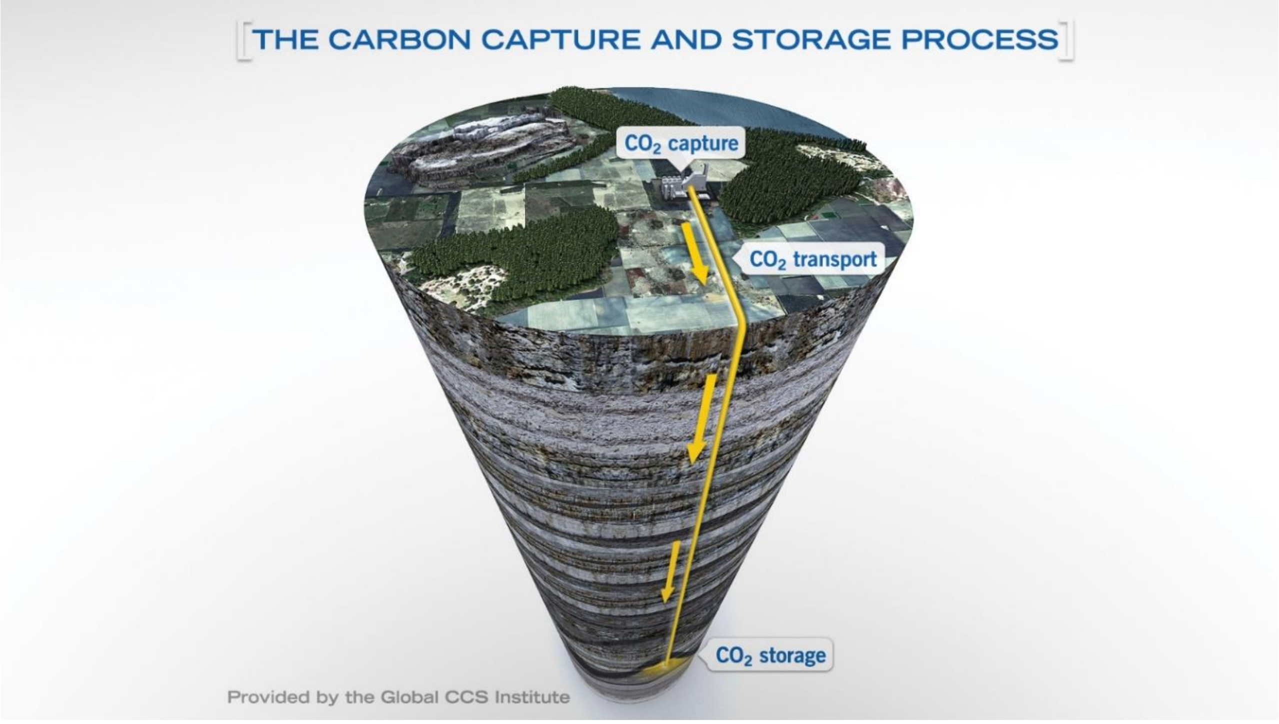


Figure 6-1. Carbon capture and storage process (GCCSI) [https://www.globalccsinstitute.com/wp-content/uploads/2018/11/1_The-carbon-capture-and-storage-process-1.jpg]

Each of these three components are discussed in more detail below.

6.1.1. Capture

The primary purpose of the capture system is to separate CO_2 from the other components so it can be compressed, transported, and ultimately utilized or permanently and securely stored in deep rock formations. Selecting the specific capture technology for a given emission source depends on a number of factors such as inlet syngas stream pressure, partial pressure of the CO_2, inlet concentrations, and outlet concentration requirements of sulfur species, economics, and other contaminant specifications.

For CO_2 removal from a co-gasification process, the capture facility is an integral part of a system designed to clean up the syngas stream. As discussed in Chapter 5.2, there are a number of cleanup operations that are required before the syngas can be utilized in subsequent operations. In one of these cleanup stages called acid gas removal (AGR), a number of the acid gases such as CO_2 and H_2S are removed (Bhattacharya et al, 2017). There are several established technologies that allow the removal of acid gases. The current technologies for CO_2 capture and separation mainly include solvent, sorbent, and membranes for varying mechanisms of the capturing approaches. The most commonly used are solvent-based systems. As shown in Figure 6-2, there are two primary families of solvents and a third that is simply a combination of chemical and physical solvents. For many gasification systems a physical solvent is selected.

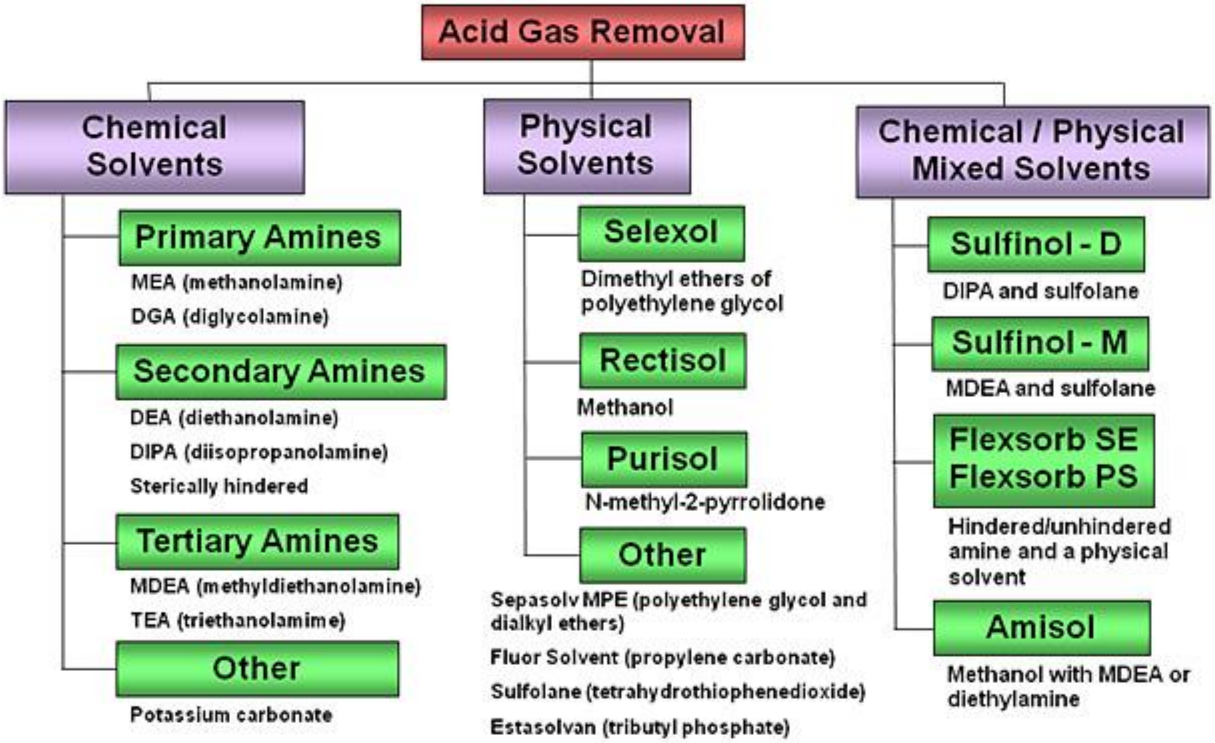


Figure 6-2. Primary solvent types for AGR [https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/agr]

In many cases, the capture component can drive the economics of a CCUS project. There can be benefits to capturing CO_2 from a gasification process versus a combustion system. Depending on the degree of water-shift performed the partial pressure of the CO_2 in the synthesis gas stream can be higher (15-40%) than if captured from a combustion system (4-12%). This allows for a lower minimum energy capture requirement and potentially a lower cost of capture all other things being equal.

The amount of CO_2 generated will depend on the carbon balance between the amount of carbon in the feedstocks (e.g., coal, plastics, other) and the amount of CO to CO_2 shift that occurs subsequent to the gasification. As discussed in Chapter 5.2, the syngas will be conditioned to deliver the optimal CO/H_2 ratios and removal of other contaminants that are not tolerable in the subsequent operations. This conditioning and specifically water shift that occurs transforms some of the CO into CO_2 or CO_2 into CO depending on the H_2/CO gas ratio requirements for the downstream process. Therefore, the amount of CO_2 captured will be a function of the feedstock, gas conditioning, and end use of the synthesis gas.

6.1.2. Transportation

The transport of CO_2 is a key step in the CCUS lifecycle. Once the capture facility has captured and compressed the CO_2 into the supercritical or liquid state, the CO_2 is transported from the source to an injection or use site. These methods of transport are regulated by the appropriate federal, state, and local entities and have shown not to pose any higher risk than transportation of other materials. Considerations such as distance to the sequestration or use site, number of sites, terrain, access, etc. can impact the ultimate transport decision and associated economics.

As further described in Table 6-1, there are four primary types of transportation utilized for CO_2:

- Pipeline
- Truck
- Rail
- Ship

Each capture project has unique requirements that are assessed, and a suitable transportation method identified. Economics plays a key role in selection of the transport method. In an established CO_2 transport infrastructure of the future, we would likely see a network of all of these types of transport designed to optimize the supply and demand of CO_2 through the use of hubs or similar approaches. However, most large-scale projects will entail pipelines and/or ships, as they provide the most-optimal economies of scale (Global CCS Institute, 2018).

Table 6-1. Methods of CO_2 transport

Transport Modality	Description
Pipeline	Pipeline transportation is one of the most economic methods of transporting large quantities of CO_2. The U.S. has about 6,500 km of CO_2 pipelines in use, currently (Global CCS Institute, 2018). Pipelines are typically the lowest cost and highest reliability option.
Truck	Truck transport is typically for small quantities and shorter distances. A tanker truck can carry approximately 18 tonnes (Mt) (National Petroleum Council, 2019). This method is typically used for beverage industries or other local users. The CO_2 is under low temperature and medium pressure for transport. For large-scale CO_2 sequestration, truck transport is an unlikely contender due to the large number of trucks required for even a moderate-sized facility.
Rail	Rail can transport larger quantities than a truck, however, it could be uneconomic if there are not already rail lines to where it needs to go. In 2017, 713,000 mt of CO_2 was safely transported (10,000 shipments) in the U.S. and Canada. The largest capacity cars can transport approximately 83 mt each (National Petroleum Council, 2019).
Ship	Ship transport is advantageous for larger quantities over longer distances and to remote locations where pipelines are impractical. Currently, there are ships that carry CO_2 for various purposes. Ships can provide significant scale but typically at a higher cost than a pipeline.

6.1.3. Utilization

CO_2 utilization has been around in at least one form, a working fluid, for decades. CO_2 has been utilized in oil fields to enhance production of those fields and capture otherwise stranded assets. This process is termed enhanced oil recovery (EOR) and was first performed in 1972 (Langston, Hoadley, & Young, 1988). Currently, about 24 million tonnes per year are stored via EOR in the U.S (National Petroleum Council, 2019).

In addition to this use of CO_2, there are numerous established and emerging technologies that could provide additional pathways to new products using the CO_2 captured from these sources, including plastics co-gasification. Figure 6-3 describes the main pathways and the resultant types of products derived from those pathways.

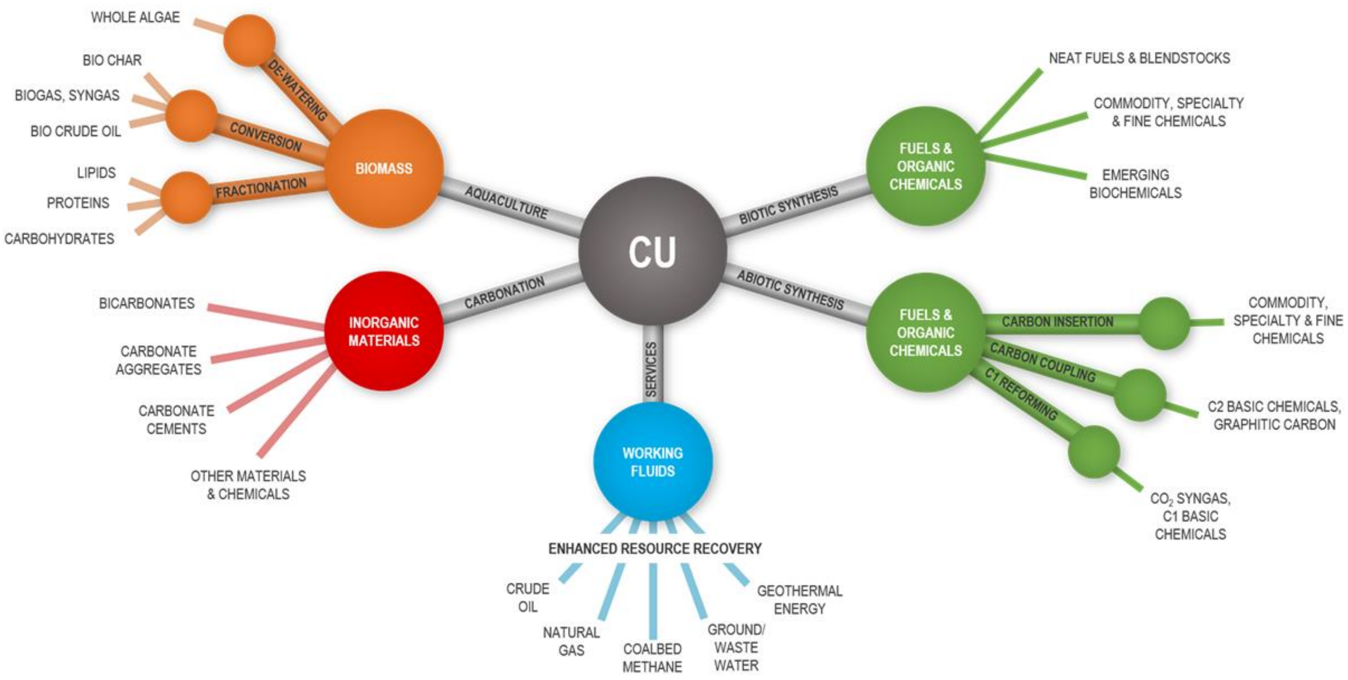


Figure 6-3. Major carbon utilization product pathways and potential products
https://netl.doe.gov/coal/carbon-utilization/about

There are numerous efforts underway to develop efficient conversion of CO_2 into useful products through both chemical and biological pathways. Some of the current research focus is to address the efficiency, economics, and environmental aspects of converting the CO_2 to useful products such as fuels, concrete, organic chemicals, and inorganic chemicals.

CO_2 utilization will be an area that will continue to develop as the world seeks to create value from the CO_2 being captured.

6.1.4. Storage

A common method of disposing of the CO_2 is to inject it into a secure reservoir deep below the surface into one of the following:

- **Saline (salt water) formation** – A porous rock that contains high salt content (salinity) water. These water deposits cannot be used for drinking water.
- **Depleted oil or gas reservoir** – A oil or gas reservoir system that is no longer producing or economically viable. Its robust caprock has served as a barrier to trap oil and gas for millions of years.
- **Un-mineable coal seam** – A coal seam that will not be mined and whose caprock can contain the injected CO_2.

Figure 6-4 shows a schematic of these different deep underground geologic storage options for CO_2. These options allow for the secure, long-term storage of CO_2.

A number of considerations need to be taken into account when selecting a reservoir for CO_2 storage to ensure its integrity and suitability for safe long-term storage. The reservoir must be contained by a competent caprock system. Injection is typically well below any drinking water formations. The capacity of the reservoir should be able to handle the large amount of injection over a 10- to 30-year period depending upon the life of the facility. The site is selected only after extensive geological and geophysical analysis and modelling. The site is then further characterized by drilling a test well to analyze a core sample and update the analysis and design of the injection and monitoring systems.

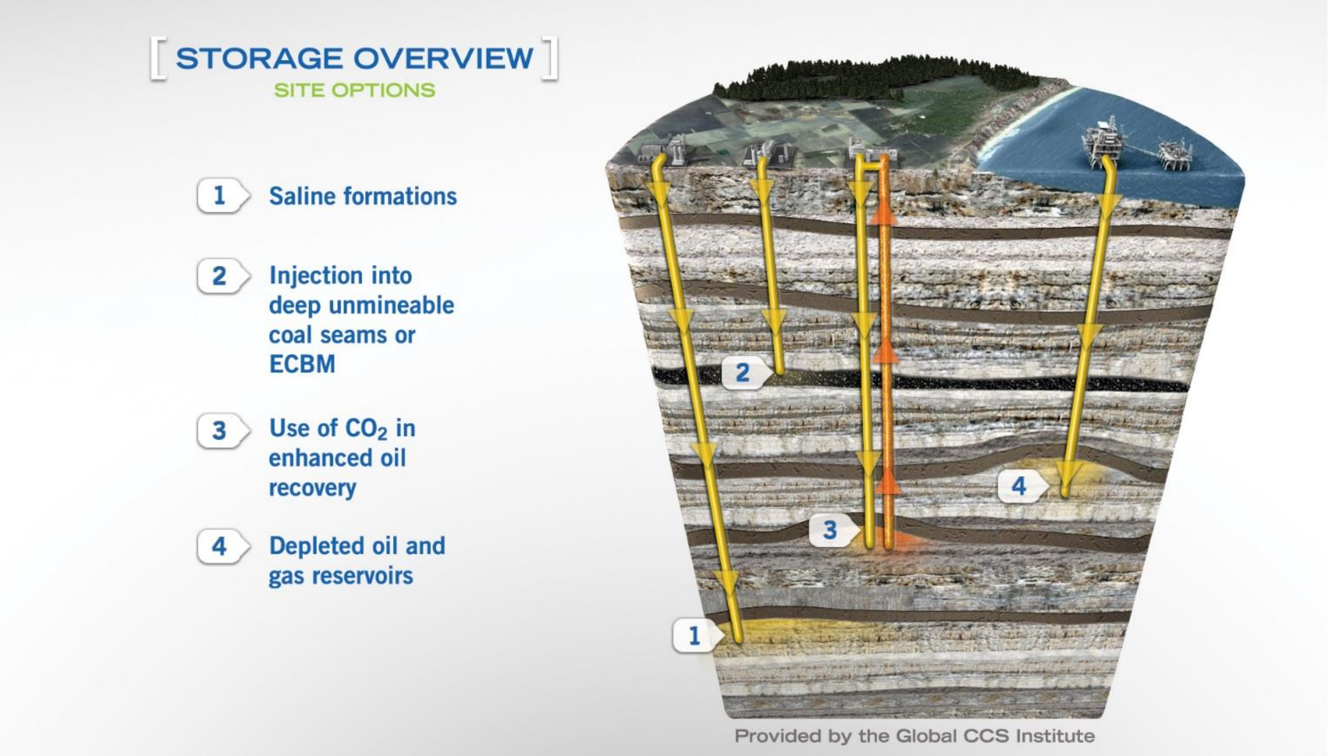
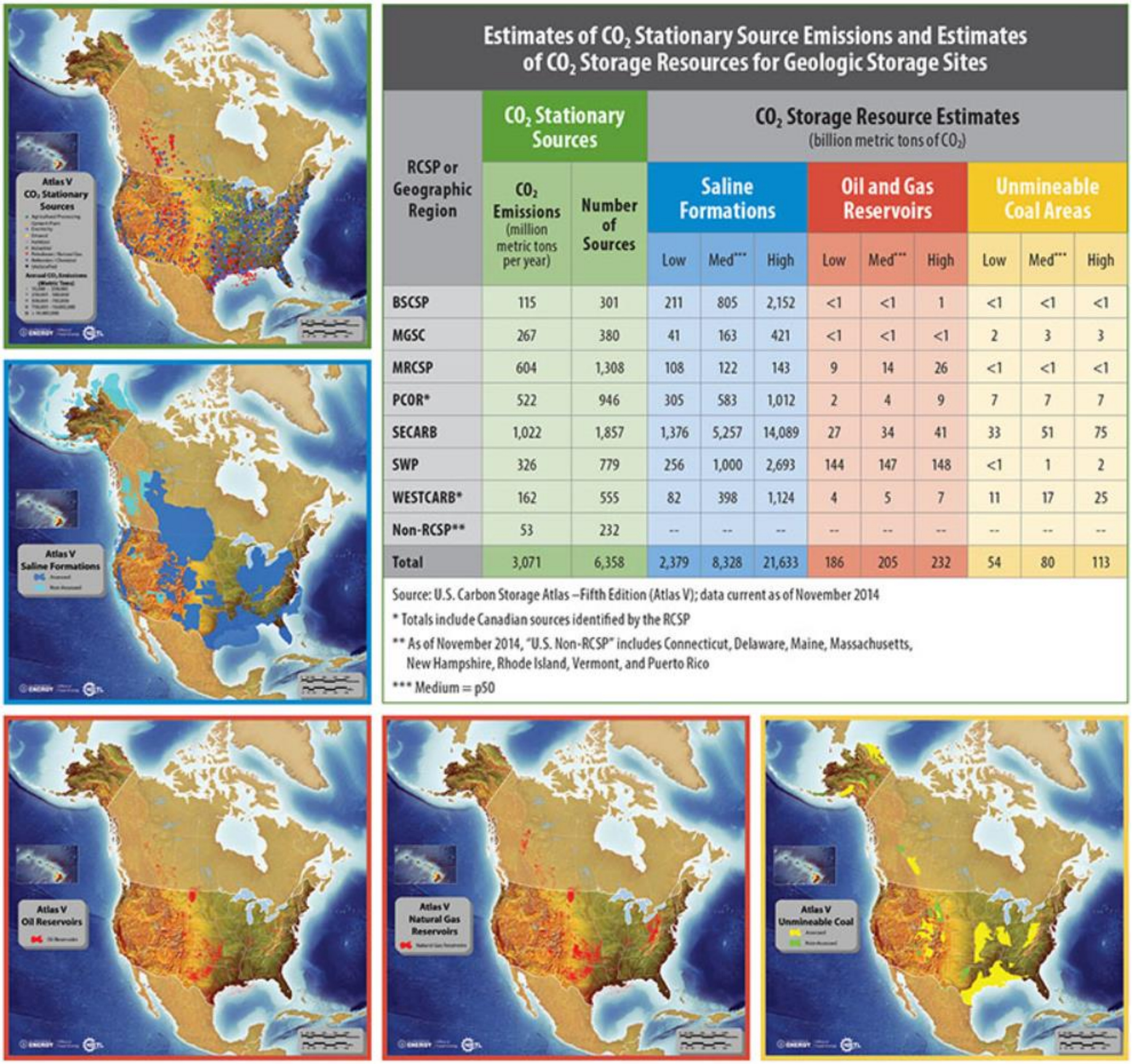


Figure 6-4. Overview of CO_2 *storage*
[https://www.globalccsinstitute.com/wp-content/uploads/2018/11/9_The-CO2-Storage-overview-1.jpg]

Federal and state regulations oversee CO_2 storage site selection and injection in the U.S. The Safe Drinking Water Act (SWDA) directs the U.S. EPA to regulate the siting, construction, operation, testing, monitoring, closure, corrective action, financial responsibility, reporting, and record keeping of sub-surface injection wells to protect underground sources of drinking water (USDW) (Congressional Research Service, 2020; U.S. E.P.A., 2021). CO_2 sequestration wells fall under Underground Injection Control (UIC) Class VI permitting requirements. There are stringent requirements for the design and monitoring programs that an operator must follow to ensure the injection will be managed appropriately. In addition, there are other regulatory requirements for various other aspects of capture and sequestration projects. For example, the Clean Air Act and the EPA's GHG emission program come into play with regard to emissions reporting.

It is estimated that the U.S. has the capacity to store hundreds of years' worth of CO_2 emissions from stationary sources (National Petroleum Council, 2019). A number of potential areas that have been identified around the U.S. are shown in Figure 6-5.



Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites

RCSP or Geographic Region	CO_2 Stationary Sources		CO_2 Storage Resource Estimates (billion metric tons of CO_2)								
	CO_2 Emissions (million metric tons per year)	Number of Sources	Saline Formations			Oil and Gas Reservoirs			Unmineable Coal Areas		
			Low	Med***	High	Low	Med***	High	Low	Med***	High
BSCSP	115	301	211	805	2,152	<1	<1	1	<1	<1	<1
MGSC	267	380	41	163	421	<1	<1	<1	2	3	3
MRCSP	604	1,308	108	122	143	9	14	26	<1	<1	<1
PCOR*	522	946	305	583	1,012	2	4	9	7	7	7
SECARB	1,022	1,857	1,376	5,257	14,089	27	34	41	33	51	75
SWP	326	779	256	1,000	2,693	144	147	148	<1	1	2
WESTCARB*	162	555	82	398	1,124	4	5	7	11	17	25
Non-RCSP**	53	232	--	--	--	--	--	--	--	--	--
Total	3,071	6,358	2,379	8,328	21,633	186	205	232	54	80	113

Source: U.S. Carbon Storage Atlas – Fifth Edition (Atlas V); data current as of November 2014

* Totals include Canadian sources identified by the RCSP

** As of November 2014, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico

*** Medium = p50

Figure 6-5. Potential sequestration resources

[Carbon Capture | Center for Climate and Energy Solutions (c2es.org)](https://www.c2es.org/content/carbon-capture/)
https://www.c2es.org/content/carbon-capture/
https://dualchallenge.npc.org/files/CCUS_V1-FINAL.pdf

6.2. Financial Incentives (45Q)

Originally added into the tax code in 2008 but modified numerous times, 26 U.S.C §45Q (otherwise known as the 45Q tax credit) is available to operators who sequester qualified carbon oxides, including CO_2, that would otherwise be released to the atmosphere (Congressional Research Service, 2021). This program pays per tonne of CO_2 geologically sequestered, increasing from $31.77/tonne in 2020 up to $50/tonne of CO_2 sequestered in 2026. The credit amounts vary depending upon the use or ultimate fate of the CO_2.There are eligibility requirements, timelines for installation, claim periods, and minimum capture amounts, among other elements (Congressional Research Service, 2021). This program is gaining momentum in certain industries as they seek a method of capitalizing on the sequestration of their emissions. This, and other such financial incentives, could potentially bolster the economics of implementing CCUS with co-gasification for plastics management.

6.3. Summary

CCUS holds the key to recycling plastics and reducing its carbon footprint. Carbon capture can be applied to the gasification process with existing, solvent-based technologies. Capture methods vary from proven to novel and are currently the focus of numerous firms and Government agencies. The U.S. has ample geologic storage and some existing regulatory infrastructure for storing significant amounts of $CO_{2.}$ There are also tax credits available for sequestration of CO_2 to offset costs.

Chapter 7. Key Considerations for Research Needs

7.1. Introduction

The production of ‘virgin plastics’ is projected to increase to around 1.1 gigatonne (Gt) by 2050 (Hanemaaijer et al., 2021). The current practice of landfilling PSW is linked to ecological and environmental damages from GHG emissions and toxic leachates. Chemical recycling technology, such as gasification, that complements recycling can help address the imminent issue of large-scale plastic waste management in the U.S. It is an attractive alternative to incineration of PSW, due to the reduced formation of dioxins and aromatic compounds. The co-utilization of coal and PSW to feed a gasification technology may be capable of producing a flexible and reliable source of synthesis gas or petrochemicals while reducing PSW in landfills. Co-gasification can debottleneck critical operational and feedstock handling issues and enable better product gas yields in comparison to plastics gasification. The CO_2 stream produced during this process may also be captured and utilized and/or securely stored deep underground, resulting in a very low carbon footprint and GHG emission offset from traditional landfilling and PSW recycling techniques. Table 7-1 summarizes the findings of this study for the four key needs identified.

Table 7-1. Areas of focus and findings of the current study

Need	Description Statement	State of the art	Challenges/ Gaps
Reduce single-use plastics	Utilize waste plastics for syngas production via gasification and avoid landfilling	Only 8.7% of PSW was recycled in the U.S. in 2018.	• Plastics gasification not efficient • Need significant economic and policy drivers for circular economy for plastics
Value proposition for utilization of coal while managing plastic waste	Utilize domestic coal reserves for co-gasification with mixed scrap plastics	Co-gasification with carbonaceous (coal) feedstock improves process efficiency.	• Material handling during pre-processing and syngas cleanup for different feedstock • Improved gasifier design optimized for feedstock blends • More pilot and larger-scale demonstrations to enable commercialization
Potential to increase syngas production	Use syngas generated during co-gasification for H_2 or petrochemical feedstocks	Syngas production is currently predominantly from coal and natural gas.	• Commercialization of co-gasification of plastics needed to supplement increasing syngas market demand
Environmentally sound source of syngas	Implement CCUS to capture CO_2 emissions from co-gasification and reduce carbon footprint of process	Well-established commercial implementation of flue gas capture and geologic storage spans multiple decades.	• Acceptance for use in co-gasification of plastic waste • Economic impact of including CCUS technologies

The following sections highlight the resource and market potential of the co-gasification technology with coal to manage PSW.

7.2. Resource Potential

Plastic Waste

There is a large fraction of PSW that is not being recycled or converted to energy in the U.S. As mentioned in Chapter 1, only 8.7% of all PSW was reportedly recycled in 2018 in the U.S while 27 Mt of PSW (75.6%) was landfilled in 2018. Landfilled plastics in the U.S., though economically convenient, present a large GHG emission burden equivalent to adding 890,000 cars on the road every year. It is apparent from low recycling and energy recovery statistics that buildout of technologies such as chemical recycling is needed in the U.S. to manage mixed plastic waste.

Coal and Plastic Waste

As mentioned in Chapter 1, Illinois, Michigan, Ohio, and Texas have substantial coal reserves of medium-high volatile bituminous rank. North Carolina, Virginia, and Georgia have unassessed but confirmed coal present. In 2019, the states producing the most coal in the U.S. were Wyoming, West Virginia, Pennsylvania, Illinois, and Kentucky. Some of the states with high volumes of landfilled PSW are also locations with potential coal reserves as shown in Table 7-2 and Figure 7-1. There is untapped potential in these states to combine coal and PSW for co-gasification and production of synthesis gas or petrochemicals.

Table 7-2. States producing the most coal in 2019, by volume and percent share (Themelis & Mussche, 2014; U.S. Energy Information Administration, 2020)

State	Million Short Tonnes Produced in 2019	% Share of Total U.S. Coal Production (2019)	PSW to Landfills (Mt) (2011)
Wyoming	276.9	39.2	0.08
West Virginia	93.3	13.2	0.24
Pennsylvania	50.1	7.1	0.78
Illinois	45.9	6.5	1.60
Kentucky	36.0	5.1	0.55

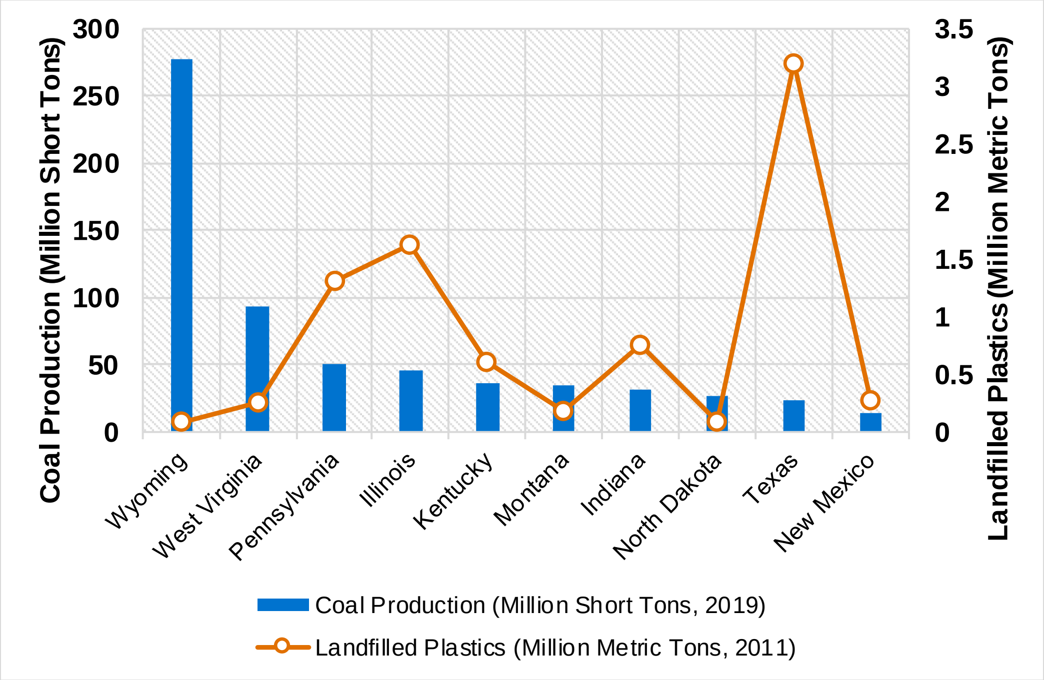


Figure 7-1. Top 10 coal producing states in 2019 (U.S. Energy Information Administration, 2020) and the total amount of landfilled plastics in corresponding states in 2011 (Themelis & Mussche, 2014)

Detailed source assessments can be done to help identify possible scenarios for aggregation of the PSW and coal sources in different regions of the U.S. for an understanding of what the buildout of co-gasification of plastics with coal would be. Such an assessment would also provide important environmental, regulatory, and cultural considerations for proposed chemical recycling infrastructure in the different source areas. Using the co-located coal reserves and areas with large volumes of PSW for gasification may present convenient potential as primary targets for monetizing the coal and utilizing the PSW.

Carbon Capture, Utilization, and Storage

Each plastic/coal co-gasification facility will produce significant amounts of CO_2. Coupling a carbon capture and sequestration system with the gasification facilities would allow for a method of reducing GHG emissions from the reuse of these plastics. This permanent geologic sequestration of the CO_2 could qualify for tax credits. As mentioned in Chapter 6, the 45Q program offers tax credits for a project that can permanently store CO_2. These credits would add economic benefit to the co-gasification project, making it more attractive to investment and potentially establishing industry momentum. There are a number of carbon capture technologies that are well-established globally in gasifier use and could be implemented on the plastics/coal gasifier.

7.3. Market Potential

Co-gasification of waste plastics with coal presents a lucrative, environmentally friendly alternative that could be tapped to meet the growing demand for chemicals and green energy. The global and U.S. syngas market has exhibited strong growth and continues to have a positive outlook as reflected in various market projection reports.

Syngas is versatile in both its end uses, as well as the feedstocks that can be used to produce the syngas. This flexibility provides syngas a particularly advantageous position as federal, state, and local governments tackle the problem of an excessive amount of plastics in landfills. In addition, the syngas market continues to grow, and projections estimate the market size at $66.5 billion by 2027, growing at a CAGR of 6.1% from 2020.

Syngas can be used as a building block to create products with higher value than just the heating value that would come from combustion. Examples include:

- Synfuels – transportation fuels
- H_2 – fuel, ammonia
- Chemical production (e.g. methanol, acetic acid).

The technical and non-technical considerations in realizing the realistic potential to augment syngas production for H_2 or petrochemical feedstocks with syngas generated during co-gasification of plastics are discussed in the sections below.

7.3.1. Technical Aspects

State of the Art: There are several projects at various scales of development that involve gasification/co-gasification with feedstock combination of agricultural biomass, municipal waste, and plastic waste. Table 7-3 lists various operational project locations that involves co-gasification technology with the feedstock and output at each of the projects. A few functional examples such as Enerkem (Canada), Showa Denko (Japan) and Sierra Energy (California) are summarized below. Many of these targets to serve waste-to-fuel applications.

Table 7-3. Key waste gasification projects in the U.S. and operational facilities around the world with plastics feedstock component (Source: company websites)

Company	Project Name, Location	Status	Plant Capacity	Feedstock	Output
Sierra Energy	FastOx Pathfinder, Fort Hunter Liggett, California, USA	Operational since 2018	10 tonnes per day gasifier capacity	MSW and biomass	Electricity and Fischer-Tropsch Diesel (FTD)
Fulcrum	Sierra Biofuels Plant, Reno, Nevada, USA	Construction completed in July 2021; full operations in Q4 2021	480 tonnes per day	MSW	Synthetic crude for transportation fuels
JGC Group	Showa Denko plant, Kawasaki, Japan	Operational since 2003	192 tonnes per day	Plastic waste	Syngas for chemical products like ammonia
Enerkem	Enerkem Alberta Biofuels, Edmonton, Alberta, Canada	Operational since 2017	274 tonnes per day (dry)	MSW	Ethanol

Enerkem's waste-to-energy (WTE) technology started as a spin-off in 2000 and scaled up the technology to a commercial scale that is currently operational in Canada. The Enerkem gasification facility obtains carbon-containing materials sorted from the city's trash, including soiled cardboard, paper, wood, textiles, and residual nonrecyclable plastics. This feedstock is shredded and dried before gasification, in a low-oxygen environment, decomposes it into a synthesis gas mostly containing H_2 and CO. Suitable catalysts are employed for converting the cleaned syngas to methanol and ethanol. The Edmonton facility converts 100,000 tonnes of MSW annually to 36 million Liter of ethanol, thus enabling CO_2 reduction.

A gasification plant, using the Ebara Ube Process (EUP) developed by Ebara Environmental Plant and Ube Industries, has been successfully operating at Showa Denko's Kawasaki plant in Japan since 2003. The plant processes approximately 70,000 tonnes of plastic waste per year to make syngas, ultimately to produce H_2 for ammonia synthesis. The EUP involves gasifying plastic waste through partial oxidation by oxygen and steam to produce syngas that can be utilized in chemical compounds. In addition, materials recovered from byproduct streams include sodium chloride, which is used to produce caustic soda; sulfur removed, which is used to produce sodium bisulfite; and $CO_{2,}$ which is recovered and used for dry ice production. The JGC Group is currently embarking on a feasibility study for a plastic waste gasification plant in South Korea by utilizing the EUP.

The Sierra Energy pilot plant was built in partnership with the U.S. Department of Defense and California Energy commission at U.S. Army Garrison Fort Hunter Liggett in Monterey County, California. It uses the FastOx® gasification technology that turns trash into syngas. Unlike most WTE systems, the FastOx gasifier has no emissions at the gasifier level and can produce electricity with minimal footprint. The company continues to advance its technology and test new applications for gasification at the Sierra Energy Research Park in Davis, California. Sierra Energy plans to further improve and scale up its gasification technology through public or private commercial projects and academic partnerships.

Challenges: Gasification technologies have been around for nearly two centuries (e.g., methanol from coal). However, as discussed in Chapter 4 and observed from the current state of operational facilities across the world, the TRL range for co-gasification technologies, especially in terms of dealing with inconsistent feedstock, are in the pilot scale. There is a need for more laboratory and pilot scale studies in the U.S. for technology readiness to support commercialization of plastic waste gasification. High costs and technological challenges have doomed biomass and WTE gasification projects as shown in Table 7-4. WTE technology is defined as confined and controlled burning with energy recovery from the waste burning process (U.S. E.P.A., 2020b). There are several kinds of WTE but the most prevalent ones under thermochemical WTE comprises of thermal gasification, pyrolysis, and incineration.

Plastics co-gasification challenges with material handling of feedstock blends during pre-processing and syngas cleanup associated with different feedstock sources need to be optimized for commercial adoption of this technology. Feed system outage is a common cause of downtime and loss of availability in gasifiers feeding biomass and wastes (Waldheim, 2018). Scale up of successful laboratory-scale demonstrations of syngas cleanup technologies is needed. (Jafri, Waldheim, & Lundgren, 2020) reported on the technology readiness assessment performed by the International Energy Agency's Bioenergy Program Task 33 on Gasification of Biomass and Waste for emerging gasification technologies for waste and biomass. The Helio Storm gasifier and the rotary gasification technologies that originated in the U.S. were among the diverse emerging technologies evaluated. Overall, an evaluation of different methodologies of chemical recycling to determine the optimal engineering and economic approach is needed.

Table 7-4. Canceled waste gasification projects in the last decade (Sources: companies)

Company/Project Location	Year Canceled	Capacity/Facility Details	Reason
Air Products, Inc., AlterNRG/ Teesside/ Billingham, U.K.	2016 (mid-construction)	Two 50 MW facilities to process 600,000–700,000 tonnes of waste per year, generating enough electricity to power up to 100,000 homes	Technical performance difficulties
Plasco Energy/ Ottawa, Canada	2015	150,000 tonnes per year capacity WTE facility using plasma arc gasification	Financial difficulties
Scotgen (Dumfries) Ltd./ Dargavel, Scotland	2013	WTE facility designed to treat up to 60,000 tonnes waste per year using combined pyrolysis and gasification technology	Operational permit revoked; technical performance difficulties
New Earth Solutions Group/ Avonmouth, U.K.	2016	13 MW facility to process 120,000 tonnes per year of refuse derived fuel using combined pyrolysis and gasification technology	Technical and financial difficulties
Range Fuels, Soperton, Georgia, U.S.	2011	40 million gallons per year biofuel facility to produce wood-based ethanol and methanol	Financial challenges
Sundrop Fuels/ Alexandria, Louisiana, U.S.	2017	Biofuel facility to produce up to 190 million L gasoline from woody biomass and H_2 from natural gas	Technical performance difficulties

In Asia, commercial-scale gasification of MSW and industrial wastes has been performed for the last two decades in Japan. In Europe, MSW gasification has been a mixed experience with several WTE gasification facilities in the U.K., Germany, and Italy receiving regional and international media coverage when they were shut down because of economic and technical performance difficulties. In North America, the Enerkem facility is the only full-scale gasification facility, with a number of companies engaged at the pilot and demonstration scales, indicative of the increasing interest in gasification over the last decade.

7.3.2. Non-technical Aspects

Current Status: Some countries have implemented strong policy measures and managed to drastically reduce or stop the use of landfills propelled by land use and environmental concerns. The WTE technology is being used by multiple countries as a means to divert waste from landfills. There are about 2,430 active WTE plants worldwide (Ling, 2019), with incineration being the predominant technology implemented in comparison to gasification. The U.S. has approximately 86 WTE facilities (Ling, 2019). The growth rate of landfills in the U.S. from 2014 to 2018 was over 10 times that of WTE facilities (Ling, 2019). The U.S. currently has over 28 times more landfills than WTE facilities (Ling, 2019).

In general, northern and western EU countries such as Austria, Belgium, Denmark, Finland, Luxemburg, the Netherlands, Sweden, Norway, and Switzerland have a higher rate of recycling, composting, and incineration with energy recovery (Waldheim, 2018). The Netherlands is pursuing a climate policy to reduce GHG by 95% by 2050 through a large-scale transformation of energy generation, carbon capture, industrial symbiosis, and becoming circular in nature. Currently, 79% of its waste is recycled, and the residual waste is mainly used for energy generation. Plastics is one of these top priorities for the Netherlands, with the goal of using only renewable (i.e., recycled and biobased) plastics by 2050. The plastics recycling market in the Netherlands has evolved significantly to adapt more circular business models due to the impact of climate change and resource scarcity. In 2019, 65 companies, including DSM and Philips, signed the Dutch Plastic Pact aiming to increase the use of recyclates (McCarville, 2019).

There have been rather strong policy measures instituted in Japan to reduce the rate of waste generation and landfilling due to limited available land. Since the 1990s, despite an increased generation of MSW, landfilling has actively decreased, while incineration and recycling has increased (Waldheim, 2018). The recycling rate of plastic waste in Japan amounted to 85% in 2019. Over half of that is burned to generate electricity or exported abroad (https://www.statista.com/statistics/1169339/japan-rate-of-recycled-plastic-waste). Incineration has been an important part of waste treatment in Japan. It also has been a leading nation in gasification technologies (International Energy Agency, 2019). Japan recently launched the "Circular Economy Partnership" with its Ministry of Economy, Trade and Industry as well as Japan Business Federation (Keidanren), aiming to promote a circular economy (https://www.env.go.jp/en/headline/2502.html). The Japanese government has committed to reducing disposable plastics by 25% by 2030. Japan has a goal of about 22–24% of total electricity generation to be met by renewable sources by 2030 (Ling, 2019).

In the U.S., as mentioned above, landfills have had a major role in waste management. In 2018, there were 1,269 landfill facilities across the U.S. (Table 7-5). However, each of the states have wide differences in recycling rate and in the use of landfills and incineration. There were 77 WTE incinerator facilities in operation in 2014, with no gasification units (Waldheim, 2018).

Table 7-5. Landfill facilities in 2018 (U.S. E.P.A., 2020a)

Regions	Number of Landfills
Northeast	105
South	491
Midwest	345
West	328
U.S. Total	**1,269**

Data represents MSW landfills open July 2019.

Northeast: Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont

South: Alabama, Arkansas, Delaware, District of Columbia, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, West Virginia

Midwest: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin

West: Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming

There are useful platforms and resources available to facilitate collaboration between technology and service providers, plant owners, and operators within the energy, chemical, and waste management industries to help move the technology forward. Some of them are summarized below.

- *Plastics Industry Association – North America* is the only organization that represents every segment of the plastics supply chain to make members more globally competitive.
- *The American Chemistry Council (ACC)* is America's oldest trade association, representing more than 190 companies engaged in the business of chemistry. The Plastics Division of the ACC represents leading companies across the entire plastics value chain. They also develop advanced recycling technologies that break down plastics and serve as building blocks for new products.
- *The Global Syngas Technologies Council*, formerly known as the Gasification Technologies Council, comprises international industrial membership and expertise on cutting-edge technology on syngas for the industry. The council also educates the public and governments about the existing worldwide syngas facilities and the value and environmental impacts of syngas capabilities through its various activities and products.
- *Plastics Europe* is a European association of plastics manufacturers that helps create a solutions-driven approach working toward the circularity and climate goals of a sustainable plastics industry.
- *European Association of Plastics Recycling and Recovery Organizations (EPRO)* is an international partnership of organizations working to develop efficient solutions for the sustainable management of plastics resources. (www.epro-plasticsrecycling.org)
- *Circular Plastics Alliance* is an initiative under the European Strategy for Plastics (2018). The European Commission launched the Circular Plastics Alliance in December 2018 to help plastics value chains boost the EU market for recycled plastics to 10 million tonnes by 2025.
- *The Chemistry Industry Association of Canada (CIAC)* includes several businesses, organizations, and governments in Canada that have come together and released a plan to eliminate plastic waste in Canada through the Canada Plastics Pact (CPP). The plan focuses on three strategic priorities to improve plastics recycling and move Canada toward a circular economy by 2025.
- *The International Energy Agency's Bioenergy Program* is a forum of countries providing information exchange and dissemination. The participating countries in this task are Australia, Germany, Ireland, Italy, Norway, South Africa, Sweden, and the U.S. The forum is currently building on activities over the past decade such as the integration of energy into solid waste management solutions as the key challenges in the material and energy valorization of waste in a society that moves toward a circular economy. The task works closely with both operating industry and with research organizations.

Challenges: The lack of policies or any incentives for chemical recycling have resulted in an inadequate market and a lack of partnerships between developers, industry, and value chain stakeholders.

The average cost of landfilling in the U.S. is considerably lower than in most countries in the EU or in Japan (Waldheim, 2018). This discourages any changes in existing behavior or policies related to plastics waste management. However, the trash ban from China has made it difficult to acquire landfill permits in densely populated parts of the U.S. Rising landfill fees in the populated parts of the country are incentivizing local municipalities to look for alternatives. While gasification technologies are more competent in safely managing plastic waste with value added products, gasification as a disposal option may not be cost-competitive to current landfill gate fees in certain regions of the U.S. (Gershman, 2013).

The end product is a crucial determinant of economic feasibility. There should be an established market for the final products to make the technology viable. For example, the FastOx gasification process at Sierra Energy can produce electricity, diesel, H_2, and/or ammonia. Table 7-3 shows the various end products currently produced during waste gasification.

Certain aspects of the existing infrastructure could be reused or repurposed. A detailed assessment of existing infrastructure and the current gaps for recycling practices will need to be performed. Since the U.S. does not have much experience in commercial co-gasification facilities, there is a challenge in collecting relevant cost information for capital and operation.

Significant change in social behavior with respect to recycling and general acceptance to responsibility in recycling programs is crucial to the success of a circular economy. Countries like Japan and Switzerland have a very strong and mandatory recycling program that is embraced by the public. Waste is sorted by citizens in Japan before it is collected. It is imperative to change people’s perception that plastic is not a waste but a valuable resource. This change will go a long way in creating a mindset for a circular economy. Sometimes, the permitting process for these gasification facilities requires a public notice and comment period where community members can raise concerns and ask questions regarding the facility. A strong public awareness program can help create community acceptance and alleviate any Environmental Justice concerns.

7.4. Current Ongoing Research Efforts

Relevant research efforts as part of the Gasification Systems Program under the U.S. DOE’s Office of Fossil Energy and Carbon Management are highlighted. This program aims to develop an innovative modular gasifier design to enable increased efficiency, and low cost and lower carbon footprint gasification technologies with coal and mixed feedstock. One of its three technology focus areas is the Process Intensification for Syngas and Hydrogen, which includes the following fields of investigation (National Energy Technology Laboratory):

- Modular gasifier technology
- Modular syngas cleanup
- Modular gasification systems market applications
- Onsite NETL research.

The DOE’s work in Gasification Systems transforms the commercially available syngas-based fuel synthesis technologies for strategic smaller-scale modular applications. New options are provided for synthesizing liquid fuels from coal as well as coal blended with biomass, MSW, and waste plastics. Technology advancements in the above aspects of gasification system components can make the technology viable at smaller remote sites for increased energy security. It can also enable design optimization that can be economically adopted for co-gasification of plastic waste.

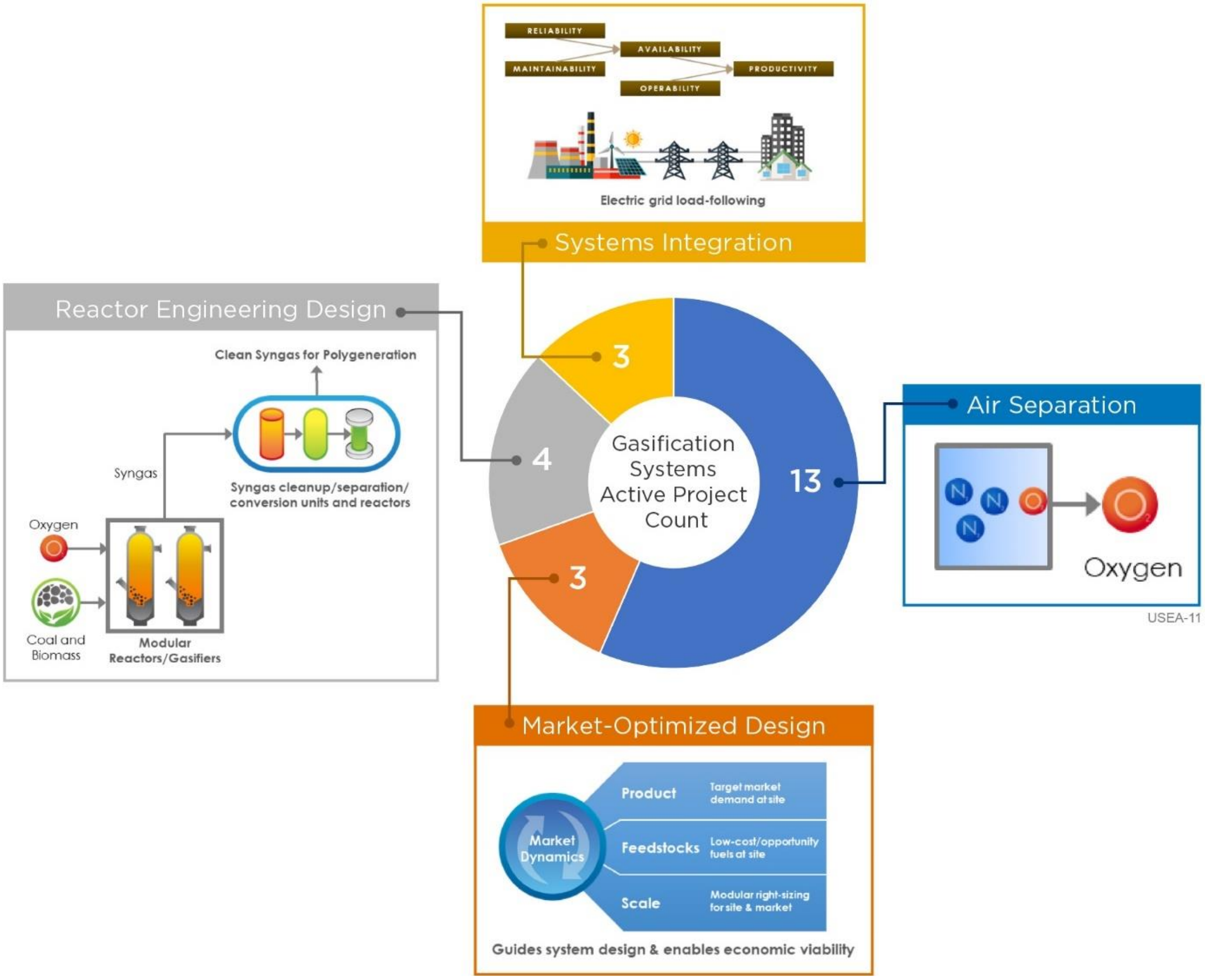


Figure 7-2. Key technology R&D areas of the Gasification Systems Program (Adapted from https://www.netl.doe.gov/sites/default/files/2019-05/2019_Annual_Reports/3%20Final%20NETL%20Gasification%20Program%20Overview%20presentation.pdf)

Gasification research supported by the DOE/NETL also includes development of next generation or advanced technologies and gasifier designs to implement coal gasification into small or modular systems for increased availability, efficiency, and reliability. Relevant co-gasification research with plastic wastes to enable net negative carbon emissions in the U.S. is currently being supported by DOE's Office of Fossil Energy and Carbon Management and is summarized below.

The U.S. DOE Office of Fossil Energy and Carbon Management has selected four R&D projects to receive $2 million in federal funding for *Enabling Gasification of Blended Coal, Biomass and Plastic Wastes to Produce Hydrogen with Potential for Net Negative Carbon Dioxide Emissions*. This funding opportunity focuses on the advancement of net negative carbon emitting technologies that aim to produce H_2 or other high-value fuels, whether as the sole product or as a co-product. The four projects selected are described below:

- *Fluidized Bed Gasification of Coal-Biomass-Plastics for Hydrogen Production* — **Auburn University** (Auburn, AL) plans to study the gasification performance of select feedstock mixtures in a laboratory-scale fluidized bed gasifier. Specific objectives are to (1) study coal-plastic-biomass mixture flowability for consistent feeding in the gasifier; (2) understand gasification behavior of the mixtures in steam and oxygen environments; (3) characterize thermal properties of ash/slag from the mixture feedstock and investigate the interaction between slag/ash and refractory materials; and (4) develop process models to determine the technology needed for cleaning up syngas and removing contaminants for H_2 production.
- *Performance Testing of a Moving-Bed Gasifier Using Coal, Biomass, and Waste Plastic Blends to Generate White Hydrogen* — **Electric Power Research Institute, Inc.** (Palo Alto, CA) plans to qualify coal, biomass, and plastic waste blends based on performance testing of selected pellet recipes in a 12 inch laboratory-scale updraft moving-bed gasifier. The testing will provide relevant data to advance the commercial-scale design of the moving-bed gasifier to use these feedstocks to produce H_2. The effects of waste plastics on feedstock development and the resulting products will be a focus of the research. The research team will review data, determine figures of merit, and interpret results to specify the range of feedstock blends that can be successfully gasified, as well as quantify gasifier outputs based on specific blends.
- *Development and Characterization of Densified Biomass-Plastic Blend for Entrained Flow Gasification* — **University of Kentucky Research Foundation** (Lexington, KY) plans to develop and study a coal/biomass/plastic blend fuel by (1) producing hydrophobic layer encapsulated biomass suitable for slurry with solid content with greater than 60 wt% of blended coal/biomass and plastic suitable for oxygen-blown entrained flow gasification with slurry feed; (2) conducting lab-scale kinetic and gasification studies on the feedstock blend; and (3) demonstrating practical operations in a commercially relevant 1 ton/day entrained flow gasifier.
- *Enabling Entrained Flow Gasification of Blends of Coal, Biomass and Plastics* — **University of Utah** (Salt Lake City, UT) plans to leverage a high-pressure, slurry-fed, oxygen-blown entrained flow system to enable co-gasification of biomass and waste plastic by creating slurries of coal, biomass pyrolysis liquids, and liquefied plastic oil. Gasification performance of the most promising mixtures will be evaluated in the University of Utah's 1 ton/day pressurized oxygen-blown gasifier fitted with a custom-built hot oxygen burner.

7.5. Path Forward for Commercial Implementation

An integrated approach to plastic waste management with multiple recycling technologies and sharing responsibility with consumers will play an important role in achieving its success. Chemical recycling technologies like gasification provide an opportunity to reduce environmental impacts and steer toward the implementation of a circular plastics economy. While simple mechanical recycling of PSW is more common in the U.S., efforts to commercialize and optimize gasification technologies tout substantial value addition and environmental advantages. A number of companies have engaged at the pilot and demonstration scales of co-gasification of coal with plastics, which is indicative of the increasing interest in this technology over the last decade.

Rapid scale up of successful laboratory-scale demonstrations of co-gasification with mixed feedstock blends containing plastics and associated syngas cleanup technologies is needed. Current gasification research in the U.S. focuses on development of next generation or advanced modular gasification technologies for increased availability, efficiency, and reliability. Overall, an evaluation of all the components involved in different chemical recycling technologies is needed for co-optimizing the engineering needs and economics. Detailed assessments of infrastructure readiness and life cycle analyses for plastics co-gasification would offer crucial insights into sustainable pathways for commercialization of this technology.

In parallel, the long-term barriers for adoption of waste gasification are related to the policies on waste management. Economics of proposed projects are driven by available policy and monetary incentives. If the energy generated from both the biogenic and non-biogenic (e.g., glass, plastics, metals) portions of municipal waste is considered renewable, it would favor the gasification market and help the widespread use of the technology (Gershman, 2013). Established versatility and positive market outlook of the product syngas can be attractive to technology adopters. Carbon credits and renewable energy credits can greatly benefit the economic feasibility of a gasification process. Significant change in social behavior with respect to recycling and general acceptance to responsibility in recycling programs is also crucial to the successful realization of a circular economy. A strong, multifaceted public awareness and education program can help create community acceptance. It is imperative to change people's perception that plastic is not a waste but a valuable resource.

Examples of policies that would constitute an opportunity to reduce the plastics waste going to landfills and shift preference to chemical recycling methods include:

- Mandatory recycling requirements
- Restructured tipping fees
- Landfill bans
- Landfill taxes.

Gasification technologies must prove, or at least make it very likely, that the performance and other conditions at least meet, and preferably go beyond, the conventional technologies by a sufficient margin. This will help motivate selection of this approach, while not generating risks that come back to the decision-makers (Waldheim, 2018). Supportive market systems can help the transition from laboratory/pilot scale to demonstration and commercial systems after overcoming technical and economic risks. The use of supportive financial benefits, innovative subsidies, and other fiscal measures can incentivize efficiency improvements in gasification technologies as well as the use of recycled plastics in the economy. Some potential drivers include:

- Federal and state incentives to promote use of chemical recycling technologies for plastic wastes
- Federal, state, and market incentives to promote reuse of mixed scrap plastics and using recylcates instead of virgin plastics
- Potential carbon reduction incentives for utilization or sequestration of the CO_2 produced during plastic waste gasification
- Technology innovation in co-gasification of plastic waste recycling technologies.

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