OVERVIEW OF COAL-TO-LIQUIDS: A HISTORICAL PERSPECTIVE

June 2020

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LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

bbl	Barrel
BP	British Petroleum
bpd	Barrels per day
CAER	University of Kentucky Center for Applied Energy Research
CCLP	Chevron Coal Liquefaction Process
CCS	Carbon capture and storage
CO	Carbon monoxide
CO_2	Carbon dioxide
CPI	Consumer Price Index
CTL	Coal-to-liquids
DCL	Direct coal liquefaction
DME	Dimethyl ether
DOD	Department of Defense
DOE	Department of Energy
EDS	Exxon Donor Solvent
EISA	Energy Independence and Security Act
Fe_5C2	Iron carbide
FT	Fischer-Tropsch
g	Grams
Gal	Gallon
GHG	Greenhouse gas
H/C	Hydrogen/carbon
H_2	Hydrogen
H_2O	Water
HRI	Hydrogen Research Incorporated
HTI	Headwaters Inc. and Hydrocarbon Technologies Inc./Headwaters Technology Incorporated
IGCC	Integrated gasification combined cycle
LPG	Liquefied petroleum gas
MESA	Mission Execution and Strategic Analysis
MHI	Mitsubishi Heavy Industries
MJ	Megajoule
MM	Million
MSG	Molten Salt Gasification
MTG	Methanol-to-gasoline
MW	Megawatt
N_2	Nitrogen
NETL	National Energy Technology Laboratory
O_2	Oxygen
OPEC	Organization of the Petroleum Exporting Countries
PRB	Powder River Basin
psi	Pounds per square inch
R&D	Research and development
RIC	Research and Innovation Center
ROI	Return on investment
RSP	Required Selling Price
Sasol	South African Synthetic Oil Limited
SRC	Solvent refined coal
STG+	Synthesis gas to Gasoline Plus
TOGAS™	Topsoe Improved Gasoline Synthesis
tonne	Metric ton
tpd	Tonnes per day
TRIG™	Transport Integrated Gasification
U.S.	United States
VCC	VEBA-Combi-Cracking
WTI	West Texas Intermediate (crude oil)
$MM	Million dollars
°C	Degrees Celsius
°F	Degrees Fahrenheit

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EXECUTIVE SUMMARY

This report provides an overview of the technology for synthesizing liquid fuels from coal, history of development in the 20th century up to early 21st century including the United States (U.S.) Department of Energy (DOE)- and National Energy Technology Laboratory (NETL)-supported work, its costs and environmental impacts, and current challenges and opportunities with particular reference to the United States.

Coal-to-liquids (CTL) technology enables conversion of abundant coal into valuable liquid fuels such as gasoline, diesel, and jet fuel. Methods include **indirect conversion** (coal to syngas, which can be converted to liquid hydrocarbons) or **direct conversion** (by various direct coal liquefaction methods). Early 20th century development of technologies gave way to wartime use in Germany and post-war commercial implementation in South Africa. The U.S. oil crisis of the 1970s gave impetus to a sustained research and development (R&D) program for CTL—by DOE in the last quarter of the 20th century, work in industry, and collaborations, which resulted in a suite of technologies for innovative CTL technologies, some of which have been deployed commercially.

NETL has been recently assessing and developing CTL technology through process feasibility, cost determinations, and lifecycle emissions studies, plus a notable collaboration with the Department of Defense (DOD)/U.S. Air Force on a set of projects in 2014–2017 aimed at technology development for reducing costs and emissions associated with synthetic jet fuel production from coal. This work has shown that carbon capture and storage and substitution of some biomass with coal in the feedstock to liquid fuels synthesis processes can reduce the lifecycle CO_2 emissions of CTL to below the baseline levels characteristic of conventional petroleum-derived fuels.

However, the future of CTL use in the United States is challenged by its relatively high cost compared to conventional petroleum-derived fuels, with cost competitiveness generally realized only with crude oil prices over $70 per barrel. As such, domestic CTL processes may have better near-term deployability in smaller modular-scale plants located strategically (e.g., at military bases) or according to special economic and environmental opportunities or needs. Further development of highly efficient, process-intensified, and moderate cost CTL technology may help target this potential.

1 INTRODUCTION

Coal-to-liquids (CTL) technology enables conversion of coal into liquid fuels like gasoline, diesel, and jet fuel. Historically, this technology is well-established, mainly by indirect coal liquefaction based on gasifying coal to produce syngas, a feedstock for Fischer-Tropsch (FT) synthesis to make liquid hydrocarbons, which, in turn, can be refined into high-value products such as liquid fuels, motor oils, and waxes. Syngas can also be made into methanol, itself a fuel and a feedstock for gasoline production, plus a wide range of other chemicals and products. There are also routes for direct conversion of coal into liquids (i.e., direct coal liquefaction [DCL]) involving reaction of coal at high pressures and temperatures with hydrogen (H_2) in the presence of solvents and catalysts, yielding synthetic crude oil that can be refined into liquid fuels.

Considering the great extent and distribution of domestic coal reserves in the United States (U.S), routes to synthesis of liquid fuels from coal add substantial diversity in transportation fuel sources and create additional capacity for fuels production, thereby increasing energy security and stability in the country. Converting inexpensive coal to valuable liquid fuels creates economic opportunities/options—given favorable market conditions. However, these coal-to-fuels routes must ultimately compete with conventional technology for liquid fuels (mainly produced from petroleum) in terms of both cost and emissions, with greenhouse gas (GHG) emissions increasingly of concern.

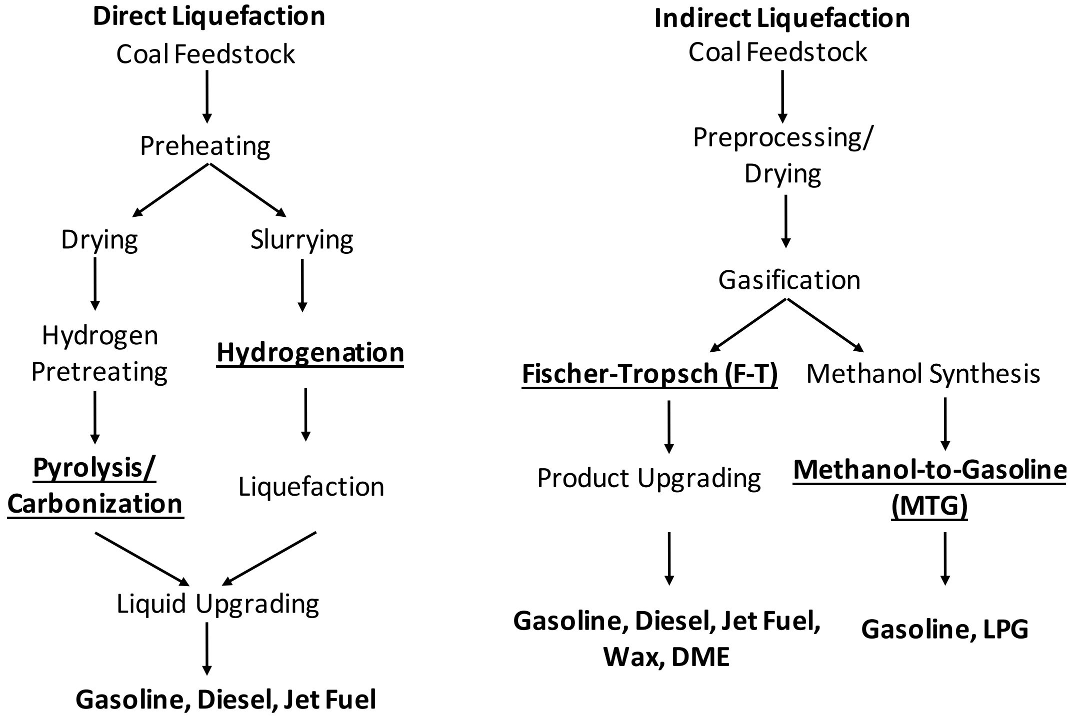
The Department of Energy (DOE) National Energy Technology Laboratory (NETL) has previously pursued technological development of cost-competitive production of coal-based ultra-clean, high-value liquid transportation fuels (gasoline, diesel, jet fuel) as drop-in fuels or refinery feedstock. This research and development (R&D) focus occurred in recent years in NETL-Department of Defense (DOD)/Air Force collaboration projects for development of modular technology and/or systems for coal or coal-biomass-to-jet fuel production. It is thought that certain opportunity markets exist in the United States and for U.S. interests for CTL in which economics may be favorable:

- Military bases (particularly forward bases) where importing fuels often involves excessively high costs and risks. In some cases, locally available coal (plus opportunity feedstocks like municipal solid waste and biomass) might be converted by CTL to synthesize fuels on-site. Modular CTL technology having deployability and portability and able to efficiently operate at smaller scales to match fuel demand at the military bases could suit the need
- Remote domestic locations suffering from high imported fuel costs (e.g., Alaska)
- Certain niche applications in the U.S. where CTL might access liability materials (waste coal, cheap biomass) to simultaneously reduce environmental liabilities while producing valuable fuels

2 BACKGROUND

Generally, methods for converting coal into liquid fuels fall into two liquefaction processes: direct and indirect. As the names imply, direct processes directly convert coal-based hydrocarbons into liquid fuels, while indirect processes use an intermediate process (gasification) to convert the coal into a gaseous fuel (syngas) before further refining the syngas into liquid fuels. Exhibit 2-1 gives a general overview of the processes involved.

Exhibit 2-1. Summary of various CTL methods



Each of the processes outlined in Exhibit 2-1 is chemically intensive compared to traditional oil refining [1], and have varying costs and potential profit margins. In terms of fundamental chemistry, the processes combine a carbon source with a H_2 source to form hydrocarbons of desired molecular weight range (synthetic crude oil or syncrude), which can be further refined into compounds that can reliably be mixed with traditional petroleum-based fuels.

2.1 DIRECT PROCESSES

The DCL approach involves reacting coal with H_2 to produce liquid hydrocarbons directly. This approach follows two main routes to achieve the desired end-products: pyrolysis/carbonization and hydrogenation. While similar, the key differences between the two are when and how the H_2 is supplied to the coal feedstock and the nature of the final liquefaction process. Both routes require some form of upgrading or refining before the obtained liquids can be used in most applications, especially for transportation [2]. In theory, DCL processes tend to be simpler and more energy efficient than indirect processes, but they require an external source of molecular

H_2. These processes are most useful for bituminous and sub-bituminous coals with high volatile matter content such as Illinois No. 6 and Powder River Basin (PRB) coals that yield more high-grade liquids and tars in the end product [3]. However, the volatiles from sub-bituminous coals tend to be high in oxygen (O_2) content, which makes them more difficult to further refine into useful liquid fuels, and these coals also tend to have high ash and moisture contents that limit yield [4].

In the pyrolysis/carbonization route, the coal is pretreated with H_2 to increase the hydrogen/carbon (H/C) ratio and volatiles, which is then followed by a pyrolysis/carbonization process. Carbonization is any process that extracts char/carbon from a solid fuel, of which pyrolysis is a primary example. Pyrolysis is also called "thermal decomposition," and is a method of separating a solid fuel into its primary components (char, volatile matter, ash, and moisture) via heat input. Through pyrolysis (which usually occurs under an inert atmosphere like nitrogen [N_2]), the volatile matter is converted into liquids and tars, which can then be further refined into gasoline- and diesel-range hydrocarbon liquids. In addition, a solid byproduct called semi-coke can be extracted for use as a smokeless fuel [2]. Before or during the pyrolysis process, the coal is usually injected with a H_2-donating solvent such as methane, toluene, or tetralin [5] to ensure a higher yield. The highest yields from this route tend to come from flash pyrolysis [5, 6], a fast, high-temperature method of pyrolysis that is often used on biomass to create bio-oils.

The hydrogenation route uses a coal slurry within a high temperature environment with a pure H_2-rich atmosphere alongside a catalyst and (usually) some recycled liquid products (as in the Bergius process discussed later). Hydrogenation generally has a higher yield than pyrolysis but loses significantly more of the energy content of the original coal, requires a much greater amount of H_2, and tends to have high costs [7].

2.2 INDIRECT PROCESSES

Indirect processes utilize gasification to produce syngas, from which desired liquid fuels are synthesized. Gasification is a process in which a solid fuel, like coal, is reacted at high temperatures (593–1260°C [1100–2300°F]), generally in the presence of limited O_2 and/or steam. The primary gaseous products are H_2 and carbon monoxide (CO), with water (H_2O) and carbon dioxide (CO_2) as substantial byproducts. Gasification is a highly versatile technology with many mainstream applications including CTL. The two main CTL processes that gasification is compatible with are FT synthesis and ExxonMobil's methanol-to-gasoline (MTG) process. Indirect processes tend to be preferentially selected because they are more self-sufficient (no external input streams aside from H_2O and O_2 are required), are cleaner (gasification allows for pollutants like sulfur, chlorine, mercury, and ash to be removed prior to liquefaction), and have higher overall yield (nearly 100 percent of the original coal is consumed by the process). However, using gasification as an interim step in the process requires more thermal energy input compared to direct processes, and the large amount of infrastructure required makes indirect processes more capital-intensive for the same scale of production.

The most commonly known method to synthesize liquid fuels from syngas in indirect coal liquefaction is Fischer-Tropsch synthesis. Invented by Franz Fischer and Hans Tropsch in the early 1920s, FT synthesis involves the reaction between H_2 and CO (the chief products of gasification and constituents of syngas) to produce higher order hydrocarbons and H_2O, with the vast majority of hydrocarbons in the form of linear alkanes that are suitable for refining into transportation fuels. FT synthesis products are easily upgraded into jet fuel, gasoline, naphtha, etc. Finally, a high melting point wax is extracted as a useful byproduct of FT synthesis, which can be mildly hydrocracked to further boost diesel production or sold for additional profit [8]. Unfortunately, FT synthesis is historically uneconomical, with the break-even cost estimated at $106 per equivalent barrel (bbl) of crude oil in 2014 dollars [9]. FT synthesis produces excess H_2O with traces of various dissolved oxygenates that requires treatment. It is also highly carbon intensive: without some form of carbon capture and storage (CCS), the process produces a large amount of waste gas that contains significant amount of CO_2 and light hydrocarbon gases. Advocates of FT synthesis often promote the use of these waste gases to provide additional power generation (such as through a Rankine cycle or gas turbine combined cycle) to offset costs and mitigate excess CO_2 emissions.

Finally, the gasification process can be adapted for methanol synthesis, which uses a catalyst to produce methanol from available H_2, CO, and CO_2 gases prevalent within syngas. The resulting methanol is a useful fuel in its own right but—thanks to Exxon Mobil's MTG process (commercialized in 1985)—this methanol can be converted into a near-zero-sulfur gasoline that requires very little end processing to meet vehicle standards [10]. The MTG process works by first dehydrating the methanol to produce dimethyl ether (DME). A downstream reactor then mixes the DME with more methanol to create lightweight olefins, which are, in turn, upgraded into paraffins, aromatics, and naphthenes (the primary hydrocarbons present in gasoline). MTG also creates liquefied petroleum gas (LPG) as a byproduct [11]. While commercially proven, it is unlikely that MTG will be generally viable in the current marketplace given its break-even cost (comparable to FT-based fuels synthesis) and current (2020) low oil prices.

3 EARLY HISTORY (1913–1950)

3.1 THE BERGIUS PROCESS

The Bergius process, originally patented by Friedrich Bergius in 1913, was the very first commercialized process designed to convert coal into alternative liquid fuels. Bergius developed the process while working alongside Fritz Haber and Carl Bosch (inventors of the Haber-Bosch process, which uses the hydrogenation of N_2 to produce ammonia). One of the key discoveries was the effect of H_2 on coal under a high-pressure atmosphere. The Bergius process saw first commercialization in 1919, after the end of World War I, at an industrial plant owned by what is now Evonik Industries. Bergius himself would be awarded a Nobel Prize in 1931 for this and other contributions to high-pressure chemistry. By the time of World War II, the Bergius process had seen considerable use throughout Germany as a part of Hitler's four-year plan and was key in supplying Germany with fuels and lubricants, especially for military applications. Near the end of World War II, many plants were destroyed by the Allies during the Oil Campaign. The remaining plants operating with Bergius's process were shut down as a part of the terms of the Potsdam Conference in 1945 [12].

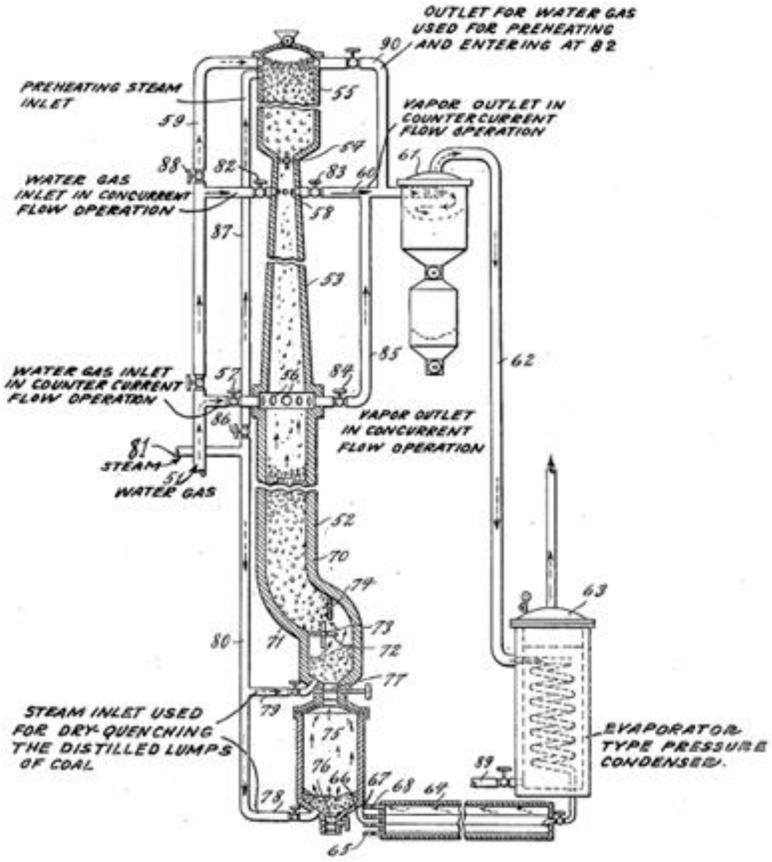
The Bergius process follows the hydrogenation route described earlier, bathing the coal feedstock in a H_2 environment alongside a portion of the final liquefied product and a catalyst. The mixture is heated to 400–500°C (~750–930°F) at pressures of up to 700 atmospheres. The process could produce gasoline as well as medium and heavy oils useful for producing both fuels and lubricants.

3.2 THE KARRICK PROCESS

In 1920, U.S. Bureau of Mines engineer Lewis Cass Karrick developed a method of refining carbonaceous material using pyrolysis. The Karrick process was designed for use with coal but can also be used for refining shale oil [7]. The Karrick process produces semi-coke (a high-quality char with trace amounts of volatile matter), gasoline, kerosene, and high-quality fuel oil. Karrick received several patents for the process from 1931 to 1942 [7].

A schematic from one of Karrick's patents is shown in Exhibit 3-1. The Karrick process operates at 450°C (~800°F) and uses high temperature steam instead of pure H_2 to raise the coal's H/C ratio. The steam and coal are supplied to a reactor vessel (called a retort) at the top of the apparatus. The mixture is heated until the pyrolysis process begins. Liquid and gas products are drained from valves at the bottom of the retort while solids like char remain inside. The liquid and gaseous fuels are cooled by the incoming steam, which is also used to quench-clean the solids, and the resulting product fuels can then be separated from one another and refined into final products.

Exhibit 3-1. Schematic of the Karrick process (U.S. patent no. 1,958,918)



Source: U.S. patent no. 1,958,918 [13]

Both FT synthesis and the Bergius process were used in Germany in WWII to produce substitute liquid fuels for use in military and civilian applications. Back in the United States, the U.S. Bureau of Mines had attempted to duplicate the German Bergius and Fischer-Tropsch processes in Missouri as a part of "Operation Paperclip" in 1939, which resulted in a source of liquid fuels competitive with contemporaneous oil refining processes. The plants that resulted from this experiment ended up getting closed after financial support from Congress was withdrawn in 1953 [14]. Finally, in 1950, South African Synthetic Oil Limited (Sasol) was founded with the goal of raising South Africa's oil independence and political autonomy. As South Africa has no natural oil reserves, SASOL's CTL plants formed a basis for the South African energy economy of the mid-to-late 20th century, and up until current times has played a large role in its industrial fleet [15].

4 MID-TWENTIETH CENTURY DEVELOPMENTS (1950–2000)

4.1 INTERNATIONAL

As the 20th century moved past its mid-point, development on converting coal to liquid fuels began to take a significant step forward, mostly driven by the oil embargo in the early 1970s. Development was not just limited to the United States, as companies across the globe advanced the technology. These included Sasol in South Africa, Mitsubishi Heavy Industries (MHI) in Japan, and Shenhua in China.

4.1.1 Sasol CTL

Sasol was the first company to develop a significant post-WWII CTL facility when the Sasol 1 complex opened in Sasolburg, South Africa in 1955. The facility, using moving bed gasifiers (Lurgi) to produce syngas and advanced circulating fluidized-bed FT reactors for syngas conversion to hydrocarbons, allowed for production yields that approached 6,500 barrels per day (bpd). Five years after the facility opened, Sasol realized a profit of $73,000 (nearly $640,000 in 2020$). This early success led the company to develop two additional facilities, Sasol 2 and Sasol 3 (now known as Sasol Synfuels West and East, respectively), both located on the same site in Secunda, South Africa. Sasol 2 began operation in 1980 and Sasol 3 began operation in 1982; combined, the facilities have a production capacity of 160,000 bpd. Sasol has not constructed a large-scale facility in South Africa since Sasol 3 but continues to advance CTL development around the globe through joint partnerships [16, 17].

4.1.2 MHI NEDOL Process

MHI, along with several other Japanese companies, developed the NEDOL process beginning in the mid-1980s through the late 1990s. The NEDOL process, considered by many to be a third-generation CTL conversion process based on its economics and technological development, converts subbituminous and bituminous coals to liquids, mainly light distillates including diesel. The NEDOL process consists of three stages: coal liquefaction, liquefied coal distillation, and solvent hydrogenation. To prove the concept, a 150 metric tons (tonnes) per day (tpd) pilot plant was developed and began operation at the Kashima Steelworks in Kashima City, Japan in 1991. During this time, a bench scale 1 tpd unit was developed to optimize the NEDOL process. The 1 tpd unit tested nine coal grades over more than 70 operating conditions to optimize the process. Nearly 25,000 hours of testing was performed on the bench-scale unit and approximately 2,000 hours at the pilot-scale unit, thereby proving the NEDOL process. Based on the success of the early pilot plant, the technology was scaled-up for use in the 250-MW integrated gasification combined cycle (IGCC) plant in Nakoso, Japan. It began as a demonstration plant in 2007 through 2013 and then transitioned to a commercial power plant [18, 19, 20].

4.1.3 Shenhua DCL

China's Shenhua Group Corporation (Shenhua) is one of the most recognized names in CTL technology development. In 2003 Shenhua began construction of the world's first modern commercial DCL plant, located in Inner Mongolia. The first phase of the facility opened in July 2009 and employs U.S.-developed catalytic two-stage liquefaction process technology from Hydrocarbon Technologies Inc. (HTI)—formerly Hydrocarbon Research Inc. (HRI)—and Headwaters Inc. in conjunction with West Virginia University and DOE. Shenhua has made further modifications: the first train, consisting of three reactors, converts 3–3.5 million (MM) tons of coal into several MM tons of oil products (20–25 MM bpd of liquid fuel); a second phase, completed in 2010, which added 7 additional reactors, expanded production to 5–6 MM tons of oil products per year (100–125 MM bpd) [21, 22, 23].

A second major Shenhua CTL facility located in Ningxia Province, China, and commissioned in 2016, uses 24 gasifier units consuming 20 MM tonnes of coal, producing 4 MM tonnes of oil products annually, including 2.7 MM tonnes of diesel, 980,000 tonnes of naphtha petroleum, and 340,000 tonnes of liquefied gas. The project drew an investment of about 55 billion yuan ($7.9 billion). The plant utilizes Synfuels China's FT technology [24].

Other companies in China also have developed CTL projects, with several plants having come online in recent years. Appendix A: New CTL Plants in China contains a more complete listing of those emphasizing production of methanol or liquid fuels.

4.2 UNITED STATES

4.2.1 Overview

CTL technology development was also being pursued in the United States during the mid-20th century. Industry, academia, and the government had interest in the technology, which took a significant jump forward during and following the oil embargo of the mid-1970s. The embargo took place in 1973 following an attack on Israel by Egypt and Syria. President Nixon agreed to help Israel during the conflict, which lead Organization of the Petroleum Exporting Countries (OPEC) nations to impose an oil embargo on the United States. The oil embargo caused the price of a barrel of oil to increase from $3 to $12 (from $20 to $80 in 2020$). The increased oil prices rippled through the economic system, resulting in higher consumer prices and shortages of fuels, notably gasoline. Long lines at gas stations across the country were commonplace and day-specific filling was instituted. This embargo lasted only a few months and was lifted in 1974 but higher prices remained. Several energy-related legislative acts were passed in the years following the 1973 oil embargo; and in 1977 DOE was created [25, 26]. Within the newly established DOE, interest in developing a coal-to-liquid program was established.

4.2.2 U.S. Department of Energy Coal Liquefaction Program

DOE established and supported the DCL program from the mid-1970s to 2000. Several commercially ready technologies to produce petroleum were developed and optimized. Following initial laboratory-scale R&D, a large-scale demonstration program was instituted to show process feasibility. Technologies were shown to be applicable to a wide range of coals in the United States. Fundamental research supported the process development effort and provided direction in optimizing process performance. The program consisted of three main elements. The first element was a large-scale demonstration of thermal/catalytic hydrogenation processes, which lasted from 1976 to approximately 1982 at a cost of $3.2 billion dollars (~$5 billion in 2020$). This amount accounted for nearly 90 percent of the entire program budget over its lifetime. Industrial partners contributed nearly as much to the overall funding of the program as technologies including the solvent refined coal (SRC) boiler fuel process, Exxon Donor Solvent (EDS), and HRI H-Coal and SRC-II distillate fuels processes were developed and demonstrated [27].

The second element consisted of funding directed to the universities, the private sector, and government laboratories, which conducted more fundamental research to determine if better alternatives to the high temperature thermal/catalytic processes like EDS and H-Coal could be identified for further development. This work involved substantial research on the chemistry of coal and associated products.

The third element was a broadly-based bench-scale and pilot-plant process development program to overcome the technical and economic deficiencies encountered in the earlier demonstration programs. While the large-scale thermal catalytic processes demonstrated were considered technical successes, liquids produced were unstable, highly aromatic, and had high concentrations of sulfur, N_2, and O_2, limiting their usefulness. Program work under this element from 1983 to 1999 targeted improving fuel quality and producing liquid fuels containing no residuals, no metals, and very low levels of sulfur, N_2, and O_2. Product quality evaluations ensured that acceptable transportation fuels could be produced by DCL. The development work also proved that direct liquefaction is a flexible process applicable to a mixed feedstock containing coal and petroleum residuals, heavy oil, bitumen, and waste polymers. This flexibility allows for a more economical plant capable of using whichever feedstock is most readily available at the lowest cost.

DOE's work on DCL lasted nearly 25 years and during that time yielded remarkably advanced technological capabilities. Initial outcomes resulted in the demonstration of the technical feasibility of the major process components but were lacking in terms of product yield and quality. Additional research resulted in substantial improvements in process performance and economics, making it possible to produce synthetic petroleum products from coal with acceptable yields. Uncertainty and risk were reduced through engineering studies and a greater knowledge of basic coal chemistry was achieved. This work provided a technically available option to produce liquid fuels from coal.

4.3 INDUSTRIAL CTL DEVELOPMENT

Industry was also developing coal liquefaction between 1950 and 2000, notably with Gulf Oil's study of solvent refined coal processes, ExxonMobil's MTG process, and Chevron's coal liquefaction process.

4.3.1 H-Coal Process

In the early 1960s, HRI, now HTI, invented the H-Coal process. This is a single-step direct catalytic hydrogenation-based coal liquefaction process. Pulverized coal is converted at elevated temperature and pressure to liquids and gases that are then separated and processed into final products. Testing began on a 25 pounds-per-day bench unit, progressed to a 3 tpd intermediate testing unit, and was demonstrated on a 200–600 tpd pilot facility in Kentucky. Early work on the H-Coal process was funded by the Office of Coal Research and later DOE. The pilot plant operated between May 1980 and November 1982, fully demonstrating the process, providing the opportunity to determine if process scale up would affect product yields and quality, and affording the opportunity to test large-scale equipment under the harsh operating conditions. H-Coal process development was so successful that the technology was later commercialized and licensed to Shenhua for their DCL production facility in Inner Mongolia [27].

4.3.2 Solvent Refined Coal Process

Gulf Oil began investigating the SRC-I process in the 1960s. The SRC-I process aimed to upgrade coal to produce a clean boiler fuel with a much lower ash and sulfur content than the original coal. SRC is considered by some to be one of the least complex of the various conversion process schemes. The SRC process occurs at elevated temperatures and pressures in the presence of H_2 to establish coal hydrogenation. An initial 0.5-ton/day plant was developed in 1965. Additional developmental work on this process was performed at Wilsonville, Alabama, in a 6-ton/day plant with funding from Edison Electric Institute, Southern Services, DOE, and Electric Power Research Institute. A 50-ton/day plant was built at Fort Lewis, Washington, and testing was performed by Gulf Oil. Modifications were made to the SRC-I process to reduce process steps and produce an all-distillate, low-sulfur fuel oil from coal rather than a solid fuel. This became known as the SRC-II process, which took condensed liquid and distilled it to produce naphtha and a middle distillate oil, which are converted to gasoline and diesel fuel, respectively. SRC-II testing was performed by Gulf Oil beginning in 1976 at the Tacoma, Washington, pilot plant, reusing the pilot facility from SRC-I testing but reducing the capacity to 25 ton/day. Funding for this work was provided by DOE. Plans for larger scale facilities were developed but never came to fruition. Testing at the Wilsonville facility continued until 1992 with funding by DOE as part of the coal liquefaction program. The SRC processes have now been abandoned in their original form, but elements have been incorporated in more recent U.S. processes [28, 29].

4.3.3 Methanol to Gasoline

This technology was developed and marketed by ExxonMobil during the 1970s. Over years of extensive studies and pilot plant operations, ExxonMobil developed an understanding of the MTG reactions and process conditions necessary to consistently produce motor gasoline from methanol. In 1979, a fixed-bed design was completed and thoroughly demonstrated at 4 bpd capacity. ExxonMobil later demonstrated the process in New Zealand with the first commercial MTG plant in 1985, capable of producing 14,500 bpd gasoline from natural gas. The plant operated until 1995 and was followed by a second generation MTG technology facility in 2009 in

China. This 2,500 bpd gasoline plant successfully demonstrated the coal-to-gasoline concept. After two years of operation, ExxonMobil agreed to license an engineering agreement for two additional MTG units at 12,500 bpd each. In March 2015, ExxonMobil and Sinopec Engineering Group announced a joint technology development agreement for advancement of a fluidized-bed MTG technology. The goal was to develop a fluidized-bed MTG design that would cost significantly less to construct and operate, and significantly improve energy efficiency versus the fixed-bed design. ExxonMobil previously investigated fluidized-bed MTG with funding from DOE in the 1980s as part of DOE's DCL program, developing and operating a 100 BPD demonstration unit in 1983 [30, 31].

An improved MTG process was developed by Haldor-Topsøe called the Topsoe Improved Gasoline Synthesis (TIGAS™) process through a collaborative effort with DOE in early 2014 [32]. The TIGAS process eliminates the methanol reactor and synthesizes gasoline directly from syngas by combining all the necessary steps in a single loop [33]. Methanol and DME are produced and then diluted with a slipstream of syngas before being sent to a set of reactors that convert the mixture into roughly 85 percent gasoline. A third process, called Synthesis gas to Gasoline Plus (STG+), developed by Primus Green Energy in 2007, can produce gasoline or jet fuel from syngas, also utilizing a single loop. Unlike MTG and TIGAS, however, STG+ integrates the process with a cleanup/purification process that removes durene impurities (the other two processes require a separate unit). While each process follows a different design, in principle, all follow the same general reaction pathway [34].

4.3.4 Chevron Coal Liquefaction Process

Chevron Research initiated several new studies on synthetic fuels with emphasis on "second generation" process options. The Middle East oil embargo of 1973–1974 was a powerful stimulant for this work, as were subsequent events in Iran and Iraq. The Chevron Coal Liquefaction Process (CCLP) consisted of two reactions, the first was a dissolution of coal followed by hydrogenation/hydrocracking to produce the product liquids. The function of the first stage is to solubilize the coal, whereas the function of the second is to stabilize the first-stage effluent and upgrade it to acceptable product and recycle oils [35].

4.3.5 VEBA-Combi-Cracking

VEBA OEL, a German refining, fuels retailing, and petrochemicals group now controlled by British Petroleum (BP), developed the VEBA-Combi-Cracking (VCC) [36, 37, 38] process in the mid-20th century. The VCC process has its roots in coal liquefaction according to the Berguis-Pier-process. Essentially, the feedstock and additives are fed to a slurry phase reactor at 200 bar, and H_2 gas is bubbled in. After the slurry reactor, a separator vessel removes unconverted material, while lighter products pass to a fixed-bed catalytic hydrotreatment vessel where additional H_2 is added, and N_2 and sulfur contaminants are thereby removed to meet clean fuel specifications. The process has been mainly targeted to conversion of refinery residues such as vacuum residuals and natural heavy crude oils but can also accommodate coal and plastics from municipal wastes. This was demonstrated in the 1980s at a former coal liquefaction demonstration plant in Bottrop (Germany), which used VCC to process vacuum residues from crude distillation and visbreaker operation with additional amounts of waste plastics and chlorinated organic compounds.

KBR, Inc. of Houston Texas has an agreement with BP to promote, market, and execute licensing and engineering services for the VCC process technology.

5 RECENT DEVELOPMENTS, UNITED STATES (2000–2020)

5.1 ENERGY INDEPENDENCE AND SECURITY ACT OF 2007

The Energy Independence and Security Act (EISA) of 2007 has been a notable factor in the United States' recent development of technology for alternative fuels. Alternative fuels derived from non-petroleum sources (coal, natural gas, biomass) could play an important role in the nation's energy security, given their substantial diversity in fuel supply capability, a large capacity for fuels production (especially considering the great extent of U.S. domestic coal reserves, possibly complemented with biomass, which constitutes a compelling feedstock source), and increased energy security that accompanies these factors. However, although coal is less expensive than other (non-waste) feedstocks being targeted for alternative fuel production, existing coal-based fuels production processes exhibit greater lifecycle GHG emissions profiles than petroleum fuels. EISA Section 526[1] prohibits federal agencies that purchase fuel (DOD being the largest) from contracting for the purchase of any type of alternative fuel unless its lifecycle GHG emissions have been moderated to the level associated with those of the comparable, conventional petroleum-derived fuel. This might be accomplished through various methods including CCS (capture of CO_2 emitted by the alternative fuel production process, and storage of the CO_2 preventing its emission into the biosphere) and using carbon-neutral or low-carbon feedstocks in alternative fuels synthesis. Additionally, DOD requires that alternative sources of fuel must be economically comparable with petroleum-based fuels, a significant challenge given the relatively high cost of low GHG emissions alternative fuels synthesis and the relatively low current price of oil.

5.2 NETL-DOD/AIR FORCE COLLABORATION—COAL/BIOMASS TO JET FUEL PROJECTS (2014–2017)

DOD was appropriated $20MM in 2013 to conduct R&D on low-emission alternative transportation fuels derived from coal. DOD requested that the Office of Fossil Energy collaborate with them in using these funds to conduct an R&D program with emphasis on coal-to-jet fuel process technology development.

The key driver for low emissions was EISA Section 526 (discussed in the preceding section), requiring that synthetic fuels purchased by federal agencies have lifecycle GHG profiles less than or equal to an equivalent petroleum-based fuel. Another key driver of obvious concern to DOD was that alternative fuels (meeting military specifications) must also be cost competitive with conventional petroleum-based fuels. Deriving emissions performance and cost-competitive liquid fuels through CTL technology was known to constitute a significant technical challenge,

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[1] SEC. 526, PROCUREMENT AND ACQUISITION OF ALTERNATIVE FUELS: "No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility-related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources." [53]

which induced the DOD to seek out collaboration with NETL given the latter's substantial experience and knowledge in coal-to-liquid fuels technology development.

Following technology gap analysis and assessment of R&D needs in the field, NETL issued DE-FOA-0000981 "Greenhouse Gas (GHG) Emissions Reductions Research and Development Leading to Cost-Competitive Coal-to-Liquids (CTL) Based Jet Fuel Production." This called for proposals under the following interest areas:

- Hybrid CTL Processes for Jet Fuel Production (using mixtures of coal and natural gas/biomass)
- Process Intensification for Coal Conversion for Jet Fuel Production
- Innovative Non-Traditional Coal Conversion Processes for Jet Fuel Production
- Commercialization Analysis for Construction of a Site-Specific CTL Facility

Except for the last area, these were intended to result in testing of pilot-scale CTL systems to produce 1 bpd of fuel or intermediates.

NETL selected seven projects that ran between 2014 and 2017. These projects focused on various conversion and fuel synthesis aspects of CTL processes, cost reductions, efficiency improvements, and reduction of carbon footprint (mainly by supplementing coal with biomass or natural gas). The projects established feasibility in terms of certain improvements of jet fuel production technologies, more modular approaches, and emissions reduction potential; in many cases, cost reductions and efficiency improvements over baseline CTL technologies were quantified.

Further information on the individual seven projects is provided in *Appendix B: NETL/U.S. DOD Air Force Coal-to-Jet Fuel Projects*.

5.3 NOTABLE RECENT R&D AT NETL

Fischer-Tropsch Fuels Synthesis—The NETL Research and Innovation Center (RIC) has addressed limitations of conventional FT synthesis by investigating nanostructured catalyst materials for coal and biomass-derived syngas conversion to the desired liquid fuel products. These innovative materials include such examples as iron oxides located inside carbon nanotubes, layered graphene catalyst supports, Hägg iron carbide (Fe_5C2) nanoparticles, etc., which demonstrate ability to fundamentally alter Anderson–Schulz–Flory product distributions and intensify reactions. Ability to tailor product distributions and intensify production of the desired hydrocarbons would be a revolutionary advance in FT fuels synthesis.

Coal-Biomass Gasification Demo/Pilot Plants Development—The program has supported design, construction, and operation of a coal/biomass-to-liquids facility at the University of Kentucky Center for Applied Energy Research (CAER), and GTI's development of an advanced pilot-scale gasifier, used in research on advanced water-gas shift processes and catalysts to support reduction of the cost of high-H_2 syngas production.

5.4 PLANNED CTL PROJECTS IN THE UNITED STATES

A number of CTL projects have been proposed in the United States in the last 20 years; most of them were proposed during times of combined high oil and natural gas prices. Many have been abandoned or cancelled; however, a few CTL projects may still be under consideration; these are listed in Exhibit 5-1.

Exhibit 5-1. CTL projects proposed in the U.S. (as of 2020) [39]

Project	Developer	Location	Products	Status
Direct Liquefaction Coal to Liquids Facility	Domestic Synthetic Fuels I, LLC	Point Pleasant, Mason County, West Virginia	2,500 tpd of coal to 6,840 bpd ultra-low-sulfur diesel fuel, 2,450 bpd reformate, 613 tpd flaked residue	Construction permit granted in September 2019.
Adams Fork Energy - TransGas WV CTL	TransGas Development Systems	Mingo County, West Virginia	7,500 tpd of coal to 18,000 bpd gasoline and 300 bpd LPG	Permitted (no new information since 2015)
Direct Coal Hydrogenation Facility	Riverview Energy	Dale, Indiana	1.6 MM tonnes of high sulfur coal and natural gas to approximately 4.8 MM bbl of ultra-low sulfur diesel and 2.5 MM bbl of naphtha annually	Granted a Title V Air Permit in 2020.

5.5 ECONOMICS OF CTL

A selection of estimated or calculated costs for production of various CTL-derived fuels and feedstocks is provided in Exhibit 5-2 by general technology type. Cost numbers original to the source documents (those in the “Cost of Production” column) are referenced to various year dollar bases; these are adjusted to the most current semiannual inflation index entry available (last half of 2019) for U.S. fuels and utilities under the U.S Bureau of Labor Statistics’ Consumer Price Index (CPI) [40] in the “Costs (adjusted)” column.

Exhibit 5-2. Estimations of costs for production of liquid fuels by CTL

Case	Cost of Production[A]	Costs (adjusted)	Source
FT Diesel	\$123.1–143.7/bbl (vent CO_2)	\$134.4–156.9/bbl	DOE/NETL-2011/1477, October 2014 [9]
	\$133.2–154.2/bbl (with CCS)	\$145.5–168.4/bbl	
Equivalent Petroleum Diesel Price[B]	**\$133.6–155.8/bbl (vent CO_2)**	**\$145.9–170.1/bbl**	
	\$144.5–167.2/bbl (with CCS)	**\$157.8–182.6/bbl**	
FT Naphtha	\$85.8–100.1/bbl (vent CO_2)	\$93.7–109.3/bbl	
	\$92.8–107.4/bbl (with CCS)	\$101.3–117.3/bbl	
Equivalent Crude Oil Price[B]	**\$106.9–124.7/bbl (vent CO_2)**	**\$116.7–136.2/bbl**	
	\$115.6–133.8/bbl (with CCS)	**\$126.2–146.1/bbl**	
Jet fuel (TRIG, FT)	RSP \$128–141/bbl[C]	\$140–154/bbl	DOE/NETL-2012/1563, September 2015 [41]
Jet fuel (entrained flow gasification, FT)	RSP \$137–159/bbl[C]	\$150–174/bbl	DOE/NETL-2015/1684, September 2015 [42]
FT Diesel (50,000 bpd scale, PRB coal)	Competitive at petroleum-derived diesel price of \$2.70 per gallon (\$94 per bbl oil price)[D]	\$3.10/gal (\$108.6/bbl oil price)	DOE/NETL-2012/1542, December 2011 [43]
Coal to crude methanol	\$1.36–1.56/gal (vent CO_2)	\$1.57–1.80/gal	DOE/NETL-341/101514, December 2011 [44]
	\$1.46–1.72/gal (with CCS)	\$1.69–1.99/gal	
FT Diesel & naphtha (50,000 bpd, Illinois No. 6 coal)	10% ROI at \$37/bbl crude price; 20% ROI at \$61/barrel[E]	10% ROI at \$48/bbl; 20% ROI at \$79/bbl	DOE/NETL-2007/1260, April 2007 [45]
Jet fuel by RTI hybrid CTL process	Competitive at \$70/bbl oil price	\$76/bbl	RTI Project Final Report [46]
Jet fuel by Altex process	Competitive at \$65/bbl oil price	\$71/bbl	Altex Project Final Report [47]
Jet fuel by Battelle CTL process	Competitive at \$48/bbl oil price	\$52/bbl	Battelle Project Final Report [48]
U.S. domestic CTL industry at 3 MM bpd	Competitive at \$60–100/bbl oil price	\$72–120/bbl	RAND research brief, 2008 [49]

[A] Cost of Production or Required Selling Prices (June 2011 dollar basis), with the first lower value based on a loan guarantee finance structure, and the second higher value based on a commercial fuels finance structure

[B] Theoretical crude oil and petroleum-based diesel prices, based on historic data that would produce the calculated Cost of Production values; the equivalent prices take into account the differences in energy content between FT and petroleum-derived fuels

[C] 25th–75th percentile spread; WTI crude oil equivalent basis; WTI spot pricing scaled to 2011 dollars was \$99.24/bbl

[D] 2009-2010 dollar basis

[E] 2005-2006 dollar basis

Most of the NETL-DOD/Air Force coal/biomass to jet fuel projects discussed in Section 5.2 (and described in more detail in *Appendix B: NETL/U.S. DOD Air Force Coal-to-Jet Fuel Projects*) included cost analyses of jet fuel production, and some offered quantitative findings on prices as noted in Exhibit 5-2. Additionally,

- Southern Research Institute did not offer CTL fuel cost estimates but did note that total plant cost for their advanced modular system vs. conventional CTL would be 10.4 percent less at 50,000 bpd capacity, improving to 31.4 percent at 5,000 bpd and 35.8 percent at 1,000 bpd. In other words, the poor economies of scale of conventional CTL at smaller plant sizes are not experienced as severely by the advanced modular system [50].
- In their analysis of the coal-biomass to jet fuel plant concept at Mississippi Power Company's retiring Plant Sweatt site in Lauderdale County, Mississippi, the Princeton group determined that it would be impossible to generate a positive net present value over a wide range in key input assumptions. In fact, a subsidy of nearly $400/bbl over a 20-year plant life was deemed necessary to achieve zero net present value under a baseline set of assumptions (including 3 percent real weighted average cost of capital and a levelized crude oil price of $80/bbl) [51].

Except for the occasional outlier, these cost numbers quite consistently suggest that CTL becomes cost-competitive compared to conventional petroleum-derived fuels only when and if crude oil prices are in the $70–125/bbl range (current prices).

5.6 ENVIRONMENTAL CONSIDERATIONS OF CTL

Emissions control operations are available for ready application to both direct and indirect CTL processes to limit or eliminate air, water, and solid emissions of concern, including sulfur and nitrogen oxides in gaseous emissions, heavy metals and toxics in gaseous and wastewater emissions, and solid waste byproducts. CTL processes are characterized by the very clean synthetic fuels that they produce; FT-synthesized fuels are inherently low in sulfur, while DCL processes rigorously purify fuels through hydrogenation and downstream treatment.

However, CTL is an energy- and CO_2-intensive proposition. The EISA Section 526 requirements mandate that fuels generated from alternative sources (such as CTL) must have lifecycle emissions below those of traditional petroleum-based fuels, or approximately 88 g CO_2/MJ. However, CO_2 emissions of CTL processes not deploying carbon capture and storage are substantially higher than this value, with an NETL study on diesel fuel synthesis from coal calculating 221 g CO_2/MJ lifecycle emissions. Robust CCS in CTL processes can greatly reduce these emissions levels. For example, recent NETL reports evaluated lifecycle emissions for converting coal to jet fuel based on coal gasification (by either Transport Integrated Gasification [TRIG^{TM}]-based coal gasification or entrained flow gasification), FT fuels synthesis, and 80–90 percent CO_2 capture by the Selexol process. Additions of biomass to the coal were also considered to attain further reductions in lifecycle CO_2 emissions. The results are summarized in Exhibit 5-3. The process scenario based on TRIG of 100 percent coal and substantial conventional capture by Selexol attains lifecycle emissions of 73 g CO_2/MJ, representing CO_2

emissions reduction of 17 percent over traditional petroleum-sourced jet fuel. (The other gasification technology results in lifecycle emissions at approximate parity with petroleum-sourced fuel).

Exhibit 5-3. Estimations of CO_2 lifecycle emissions in production of liquid fuels by CTL

Case	CO_2 Emissions ($g\ CO_2/MJ$)	Source
2007 EISA Section 526 baseline (petroleum-derived)	**88**	DOE/NETL-2012/1563, September 2015 [41]
Coal to jet fuel (TRIG, FT, 80–90% CCS)	73	
Coal/10% torrefied biomass to jet fuel	60	
Coal/30% torrefied biomass to jet fuel	34	
Coal to jet fuel (entrained flow gasification, FT, 80–90% CCS)	89	DOE/NETL-2015/1684, September 2015 [42]
Coal/10% chipped biomass to jet fuel	77	
Coal/30% chipped biomass to jet fuel	53	
Coal/10% torrefied biomass to jet fuel	76	
Coal/30% torrefied biomass to jet fuel	51	
Coal/10% pelletized biomass to jet fuel	78	
Coal/30% pelletized biomass to jet fuel	56	
Coal to diesel, no CCS	**221**	DOE/NETL-2009/1349, January 2009 [52]
Coal to diesel, simple CCS	85	
Coal to diesel, aggressive CCS	79	
Coal/15% biomass to diesel, simple CCS	60	
Coal/15% biomass to diesel, aggressive CCS	52	

These scenarios were extended to determine further reductions of CO_2 emissions that could be obtained by inclusion of biomass blended with the feedstock coal in CTL processes. Exhibit 5-3 shows substantial reductions of the emissions levels (below the petroleum baseline) by substitution of 10 percent and 30 percent of various prepared biomass types to the coal.

6 CURRENT CHALLENGES/NEXT STEPS

The main challenges for the future of CTL in the United States are economic and environmental challenges. Multiple CTL technologies and processes have been proved technically, but generally they will not be cost competitive with conventional oil refining unless crude oil prices are much higher than have been seen in recent years and being experienced currently in 2020. The other main challenge is the carbon footprint of CTL. It is possible to apply sophisticated emissions control technologies to indirect and direct coal liquefaction processes and approach a near zero emissions level for all air, water, and solid emissions of the processes (including CO_2), but at considerable capital and operating costs.

In order to eliminate some of the challenges, modular CTL processes could be explored for application in opportunity and niche applications where it has greater probability to make a viable business case. These might include remote locations suffering from high energy and fuel costs (e.g., Alaska) or special case projects that might generate a favorable business case by simultaneously remediating environmental liabilities and generating a high-value combination of products/services (e.g., a waste coal and biomass-fed polygeneration unit in economically depressed eastern Kentucky). Also, military installations requiring expensive imports of fuels might consider modular CTL processes if coal is locally available and other strategic factors are favorable.

Additionally, combinations of direct and indirect CTL conversion processes might be explored, such as remotely-located (close to combined feedstock sources) small modular scale pyrolysis units to convert combinations of coal and biomass/waste into high energy density liquid products that could then be shipped and stored at lower cost for use in larger consolidated gasification plants that would benefit from the economy of scale and from the lower costs and higher on-stream availabilities typically associated with liquids-fed (versus solids-fed) gasifiers.

R&D on process intensification approaches within the modular CTL plant could result in reducing capital cost not only through standardized designs that could be shop-fabricated but also through reduced number of capital-intensive unit operations. For example, in indirect liquefaction, the gasifier could be designed to combine gasification and elimination of tar and ammonia. Gas cleanup and water-gas shift could be combined to produce clean syngas with an appropriate H_2 to CO ratio for FT synthesis. Downstream FT synthesis might also be process intensified: instead of the conventional approach of FT synthesis (a FT reactor followed by separation of the different molecular weight hydrocarbons into finished products in a distillation column), consider a hypothetical alternative in which a distillation column is packed with FT catalyst, thereby combining FT synthesis and separations/product refining in a single step. For direct liquefaction, coal cleaning and liquefaction could be combined to produce a cleaner hydrocarbon product stream.

7 SUMMARY

CTL technology enables conversion of inexpensive and abundant coal into valuable liquid fuels such as gasoline and diesel fuel. Methods include indirect conversion of coal to syngas, which can be converted to liquid hydrocarbons (mainly by FT synthesis) or direct conversion by various DCL methods. Development of technologies in the early 20th century gave way to wartime use in Germany and post-war commercial implementation in South Africa. Furthermore, the U.S. oil crisis of the 1970s gave impetus to a sustained R&D program by DOE in the last quarter of the 20th century, work in industry, and collaborations that resulted in a suite of technologies for innovative CTL technologies, some of which have gone on to commercial implementation (e.g., ExxonMobil's MTG plants, Shenhua's DCL plant in China).

The NETL-DOD/U.S. Air Force collaboration projects of 2014–2107 emphasized various fuel synthesis aspects of CTL processes, fast pyrolysis, DCL, and direct blending and reduction of refining demand. All were aimed at reducing costs and emissions associated with non-conventional jet fuel production. They established feasibility in terms of jet fuel production technologies and emissions reduction potential, and in many cases cost reductions and efficiency improvements over baseline CTL technologies were substantiated. However, production costs were found to be relatively high compared to conventional petroleum-derived fuels, with cost competitiveness generally realized only with crude oil prices at $70–125/bbl (current prices).

In terms of emissions of CTL, the most significant concern is the high lifecycle emissions of the GHG CO_2. However, addition of CCS, and substitution of some biomass with coal in the feedstock-to-liquid fuels synthesis processes, can reduce the lifecycle CO_2 emissions of CTL to below the baseline levels characteristic of conventional petroleum-derived fuels.

The future of CTL use in the United States is challenged by its relatively high cost compared to energy/fuels from cheap and abundant domestic natural gas and petroleum. A number of CTL plant projects have been proposed in the United States in the last 20 years; however, none of them have been built and operated. Proposals that made business sense during peaking natural gas and oil prices lost any advantage when those prices fell. The huge up-front capital investment requirement and extended time frame for project development are risky and make it difficult for investors and stakeholders to commit.

These realities suggest that CTL in the United States may have more potential in the near term-as smaller modular-scale plants located according to special economic and environmental opportunities or needs. Further R&D in highly efficient, process-intensified, and moderate cost CTL technology may help target this potential.

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APPENDIX A: NEW CTL PLANTS IN CHINA

Exhibit A-1. New CTL plants in China (2015-2020), by application and feed rate

Facility Name	Application	Coal Feed Rate (tonne/day)
Shaanxi Future Energy	Coal to FT liquids	12,000
Yinchuan CTL Plant, Shenhua Ningxia Coal Co.		44,000
Luntai Methanol Plant, Eastar Group	Coal to methanol	1,200
Haohua Methanol Plant, Haohua Chemicals		2,000
Ningdong Methanol Plant, Shenhua Ningmei Group		4,000
Qinghai Yanhu		4,400
Shenhua Yulin MTO Plant, Shenhua Group		7,200
Yulin Methanol Plant, ChinaCoal Shaanxi Yulin Energy and Chemical Co.		11,500
Zhongtian Hechuang MTO Plant		15,000
Hualu Hensheng Methanol Plant	Coal to methanol & ammonia	5,000
Donying MTO Plant, Shandong Longgang Chemical Co Ltd	Coal to methanol & propylene	1,600
Mengda New Energy MTO Plant	Coal to methanol & olefins	7,200
Xingping Ethanol Plant, Shaanxi Yanchang Petroleum Group	Coal to ethanol	522

APPENDIX B: NETL/U.S. DOD AIR FORCE COAL-TO-JET FUEL PROJECTS

1. RTI International—*Breakthrough Hybrid CTL Process Integrating Advanced Technologies for Coal Gasification, NG Partial Oxidation, Warm Syngas Cleanup and Syngas-to-Jet Fuel*

   Technical focus on the Aerojet Rocketdyne advanced compact gasifier with dry solids feed pump and natural gas partial oxidation technologies (about half-coal and half-natural gas feed), mated with RTI warm syngas cleaning and novel syngas-to-liquids technologies from Axens.

2. Altex Technologies Corporation—*Green House Gas-Reduced Coal and Biomass to Liquid based Jet Fuel (GHGR-CBTL) Process*

   Technical focus on lower-temperature fast pyrolysis of mixtures of low-rank United States (U.S.) mined coal (lignite and/or subbituminous) and lignocellulosic biomass (in ratios between 51 percent and 85 percent coal) to produce a targeted liquid hydrocarbon intermediate that could be refined into liquid hydrocarbon fuel at a lower cost compared to the baseline approach (syngas produced by gasification, syngas conversion by Fischer-Tropsch (FT) synthesis, and downstream refining).

3. Battelle Memorial Institute—*Direct Coal to Liquid for Jet Fuel Using Biomass Derived Solvents*

   Technical focus on direct coal liquefaction (DCL) with innovations using novel biomass-derived bio-oil solvents having excellent hydrogen-donor capability (eliminating molecular hydrogen required in conventional DCL) and operating under milder conditions (500 psi vs. 2,500 psi in conventional DCL), producing syncrude amenable to two-stage catalytic syncrude hydrogenation/hydrotreating technologies to yield finished fuel products.

4. Southern Research Institute—*Indirect Liquefaction of Coal-Biomass Mixtures for Production of Jet Fuel with High Productivity and Selectivity*

   Technical focus on a compact high-pressure (15 atmospheres) high temperature (>900°C) autothermal catalytic transport reactor fed with Powder River Basin (PRB) coal/wood pellet blends (55–75 percent coal) to produce syngas while simultaneously reforming tar and light hydrocarbons and decomposing ammonia. Also, scope included development and testing of FT catalyst formulations and process conditions to demonstrate a hybrid FT catalyst with a target of at least 75 percent C5-C20 hydrocarbon liquid yield and with at least 65 percent jet fuel-range hydrocarbon selectivity.

5. Ceramatec, Inc.—*Technology for GHG Emission Reduction and Cost-Competitive Mil-Spec Jet Fuel Production*

   Technical focus on production of jet fuel from coal and glycerol using the unique gasification method called Molten Salt Gasification (MSG). Scope also covered a novel sulfur removal system, a hybrid FT catalyst that terminates carbon chain growth at about

C25 and provides high percentage yields in the liquids range, and deployment in an innovative FT reactor designed for shop fabrication and centralized servicing of the catalyst tubes to save on capital and operating costs.

6. Lummus Technology, Inc.—*Feasibility Study for Conversion of Wabash River Unit 1 - Integrated Gasification Combined Cycle to a Coal to Liquid Plant*

   Involved developing a feasibility study for retrofitting the Wabash River Unit 1 with its E-Gas type coal gasifier to produce liquid fuels. Study focused on evaluating options for syngas purification and conversion to jet fuel along with evaluating options for CO_2 sequestration either utilizing enhanced oil recovery or alternate methods. The main value proposition was the availability of the existing gasifier and existing plant infrastructure/brownfield site.

7. Trustees of Princeton University—*Design/Cost Study and Commercialization Analysis for Synthetic Jet Fuel Production at a Mississippi Site from Lignite and Woody Biomass with* CO_2 *Capture*

   Involved developing a feasibility study on co-gasification of lignite and woody biomass using Transport Integrated Gasification (TRIG™) technology to produce syngas that is converted via FT synthesis/refining to liquid products. The value proposition was that it would leverage use of the site of Mississippi Power Company's retiring Plant Sweatt in Lauderdale County as the host site. This brownfield site would facilitate permitting and public acceptance of a new facility.

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