COAL IN A NEW CARBON AGE

Powering a Wave of Innovation in Advanced Products & Manufacturing

NATIONAL COAL COUNCIL

COAL IN A NEW CARBON AGE

POWERING A WAVE OF INNOVATION IN ADVANCED PRODUCTS & MANUFACTURING

National Coal Council Draft Report

May 2019

The National Coal Council is a Federal Advisory Committee established under the authority of the U.S. Department of Energy. Individuals from a diverse set of backgrounds and organizations are appointed to serve on the NCC by the U.S. Secretary of Energy to provide advice and guidance on general policy matters relating to coal and the coal industry. The findings and recommendations from this report reflect a consensus of the NCC membership, but do not necessarily represent the views of each NCC member individually or their respective organizations.

Coal in a New Carbon Age

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NCC Overview – 1984|2019

In the fall of 1984, Secretary of Energy Don Hodel announced the establishment of the National Coal Council (NCC). In creating the NCC, Secretary Hodel noted that "The Reagan Administration believes the time has come to give coal – our most abundant fossil fuel – the same voice within the federal government that has existed for petroleum for nearly four decades."

The Council was tasked to assist government and industry in determining ways to improve cooperation in areas of coal research, production, transportation, marketing and use. On that day in 1984, the Secretary named 23 individuals to serve on the Council, noting that these initial appointments indicate that "the Department intends to have a diverse spectrum of the highest caliber of individuals who are committed to improving the role coal can lay in both our Nation's and the world's energy future."

Throughout its 35-year history, the NCC has maintained its focus on providing guidance to the U.S. Secretary of Energy on various aspects of the coal industry. NCC has retained its original charge to represent a diversity of perspectives through its varied membership and continues to welcome members with extensive experience and expertise related to coal.

The NCC serves as an advisory group to the Secretary of Energy chartered under the Federal Advisory Committee Act (FACA). The NCC is incorporated as a 501c6 non-profit organization in the State of Virginia. Serving as an umbrella organization, NCC, Inc. manages the business aspects of running the Council.

The Council's activities include providing the Secretary with advice on:

- Federal policies that directly or indirectly affect the production, marketing and use of coal;
- Plans, priorities and strategies to address more effectively the technological, regulatory and social impact of issues relating to coal production and use;
- The appropriate balance between various elements of Federal coal-related programs;
- Scientific and engineering aspects of coal technologies, including coal conversion, utilization or environmental control concepts; and
- The progress of coal research and development.

The principal activity of the NCC is to prepare reports for the Secretary of Energy. The NCC's members, Executive Committee, Chair's Leadership Council and Coal Policy Committee develop prospective topics for the Secretary's consideration as potential subjects for NCC reports. During its 35-year history, the NCC has prepared more than 35 studies for the Secretary, at no cost to the Department of Energy. All NCC studies are publicly available on the NCC website.

The NCC is a totally self-sustaining organization; it receives no funds from the Federal government. The activities and operations of the NCC are funded solely from member contributions, the investment of Council reserves and generous sponsors.

The Secretary of Energy
Washington, DC 20585

August 31, 2018

Mr. Deck Slone
Chairman, The National Coal Council
1000 Independence Avenue SW, Room 4G-036
Washington, DC 20585

Dear Chairman Slone:

I am writing today to request the National Coal Council (NCC) develop a white paper assessing opportunities to enhance the use of U.S. coal beyond power markets.

The white paper should focus on new markets for "coal to products" including coal conversion (coal to liquids, coal to gas, coal to chemicals); carbon engineered products (value-added non-Btu products); rare earth elements; coal combustion products, methanol; biotechnology approaches (agriculture, liquid fuels); and beneficiated coal for non-power uses, among others.

The key questions to be addressed include:

- What significant market-scale opportunities exist for new markets for coal?
- What are the economic, energy security, trade, and other issues the U.S. faces now that can be addressed with new markets for coal?
- Considering the current uses for coal overseas (syngas, chemicals, synthetic oil, transportation fuels, etc.), where and how are these markets operating today and what is the outlook for these markets going forward?
- What has been the domestic history of coal utilization and what can be learned from past successes/failures in coal utilization?
- How can domestic markets for utilization (other than for CO_2) be developed similar to those underway in other countries?

The white paper should be managed under the auspices of the Executive Advisory Board within the NCC. I ask that the white paper be completed no later than April 12, 2019.

Upon receiving this request and establishing your internal working groups, please advise me of your schedule for completing the white paper. The Department looks forward to working with you in this effort.

Sincerely,

Rick Perry

Rick Perry

COAL IN A NEW CARBON AGE
POWERING A WAVE OF INNOVATION IN ADVANCED PRODUCTS & MANUFACTURING

Executive Summary

The United States is embarking on a "New Age of Carbon" which will usher in significant opportunities for coal beyond conventional markets for power generation and steelmaking. Coal, and the carbon it contains, is on the crest of powering a wave of innovation in advanced products and manufacturing.

Advanced markets for coal-derived products, materials and technologies, referenced in this report as "coal-to-products," include:

- Coal to Liquids – fuels and chemicals
- Coal to Solid Carbon Products – carbon fiber, activated carbon, graphite, electrodes, graphene, building and construction products, carbon foam and carbon black
- Rare Earth Elements – component minerals for health care, military, transportation, power generation, petroleum refining and electronics applications
- Coal Beneficiation – quality enhancements to coal for specialty product applications
- Life Science, Biotech and Medical – prosthetics and biosensors
- Agricultural Uses – fertilizer

The opportunity for the U.S. represented by these markets is compelling. Advancing new markets for coal can enhance U.S. national defense security, bolster the nation's energy and mineral security, enhance our nation's environmental objectives and contribute to America's economic prosperity.

<u>Economic Benefits</u> – Currently, the global market for coal-to-products is estimated to consume between 300-400 million tons per year of coal, mostly in the areas of chemicals, fuels and fertilizers in emerging economies. As a frame of reference, the U.S. produced roughly 750 million tons of both thermal and metallurgical coal in 2018. In many advance market applications, coal is less expensive ($12-$50/ton) than traditional feedstocks such as petroleum ($400-$500/ton), offering opportunities for both reducing the cost of manufacturing carbon products as well as, in many cases, providing a superior quality carbon feedstock.

The analysis undertaken by the National Coal Council (NCC) for this report, indicates that coal tonnage utilization of domestic U.S. coal for coal-to-products applications has the <u>potential</u> to be on the same order of magnitude as that projected for coal power generation applications in the coming years. The markets for carbon products, in particular, are growing at attractive above average metrics of an approximately 18% compounded annual growth rate (CAGR).

Social Benefits – The economic growth potential of coal-to-products provide social benefits in the form of new mining and manufacturing job creation, especially in regions of the country adversely impacted by the recent downturn in coal production and power generation. Indeed, many future coal-to-product manufacturing sites might be advantaged to be located in repurposed areas of former mining production to take advantage of both coal feedstocks and logistical economies.

Additional social benefits accrue through the use of advanced medical products that improve patient care, early disease diagnosis and pathogen detection. Coal-derived agricultural products enhance water retention, growth of beneficial micro-organisms, root growth and plant yield.

Environmental Benefits – Coal-to-products support and enhance our nation's environmental objectives through their unique performance characteristics. Advanced forms of carbon now serve as key building blocks for a host of new solutions that result in cleaner energy, cleaner water and cleaner air. These benefits are realized 1) through the potential widespread alternative uses of coal that do not have the same carbon emission characteristics as other current uses; 2) through the use of coal to create durable, light-weight carbon products for the aerospace and automotive industries with the potential for a corresponding reduction in fuel use because of lightweighting; 3) through the use of coal to create high-strength advanced composite materials and high-efficiency rare earth element components for the wind and solar power industries; 4) through the use of coal to create sorbents used to capture CO_2 from fossil fuel power plants, cement kilns and industrial sources; 5) through the use of sorbents for water purification, and 6) through the use of coal to create composite products for infrastructure, concrete and building materials.

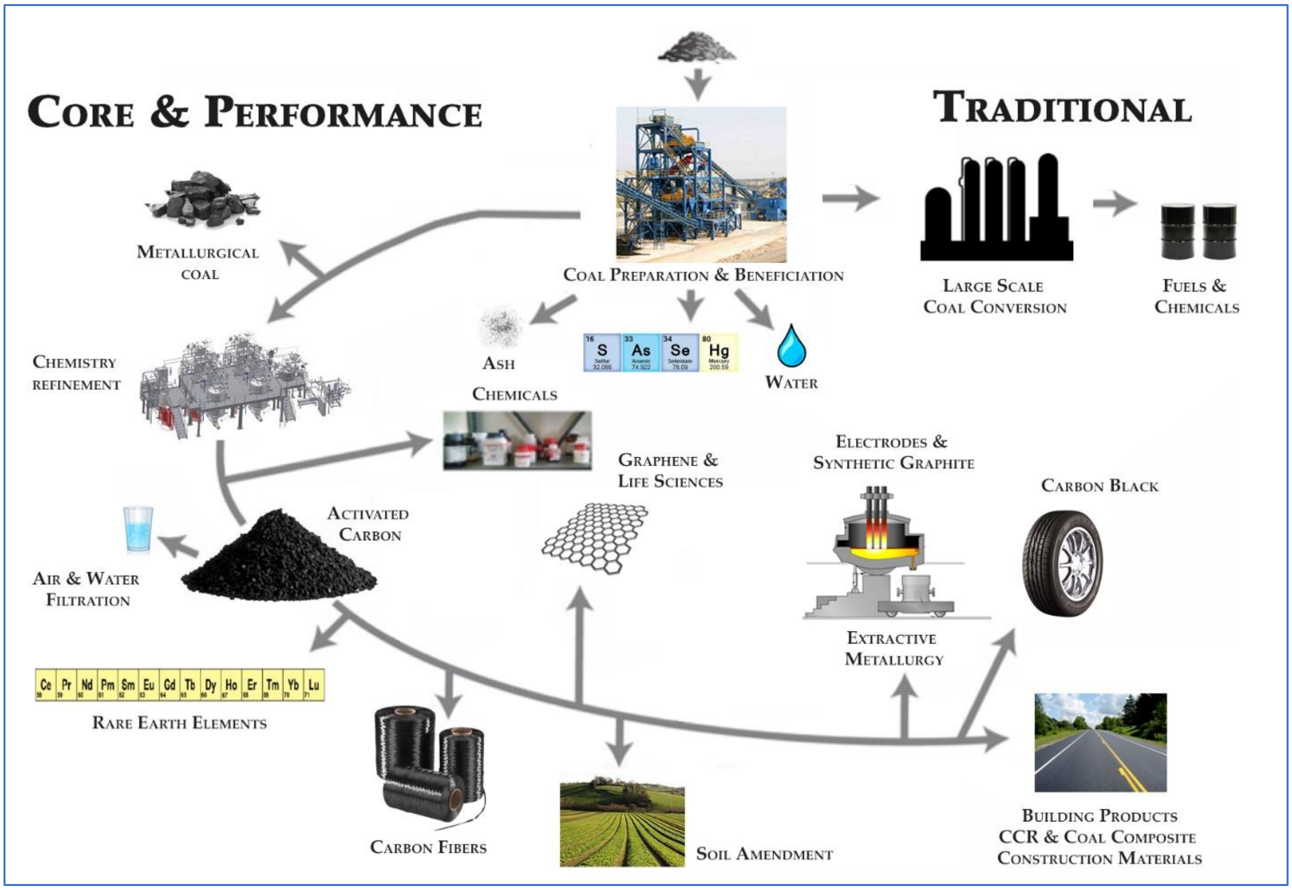
National Security Benefits – Rare earth elements support critical sectors of the U.S. defense industry. Advancing domestic market production of these critical minerals from coal and coal ash could greatly reduce the nation's nearly 100% dependence on imports from China.

To capitalize on the significant opportunity afforded by these new markets for coal, the National Coal Council undertook a systematic approach for characterizing, assessing and prioritizing market and product attractiveness using a nine-block analysis. Each of the coal-to-products markets was assessed based both on their market attractiveness (market size, market growth rate, attributes) and competitive strength (relative market share, ability to compete on price and quality, competitive strengths and weaknesses). This resultant analysis details pathways in three primary categories:

- **TRADITIONAL** – *Low Market Attractiveness-Low Competitive Strength*
  This sector is characterized by high commodity volumes, technically and technologically proven, requiring high capital expenditures and providing marginal economic opportunity in the U.S. due to cost competition from other resources, specifically lower cost natural gas and petroleum feedstocks. Products in this category include bulk chemicals and fuels.

- **CORE** – *Medium Market Attractiveness-High Competitive Strength*
  This sector is characterized by moderate industrial-scale volumes, technically proven, requiring moderate capital expenditures and providing a sizeable opportunity in the U.S. Specialized products in this category include extractive metallurgy, coal beneficiation, activated carbon, carbon black and coal-derived building products.

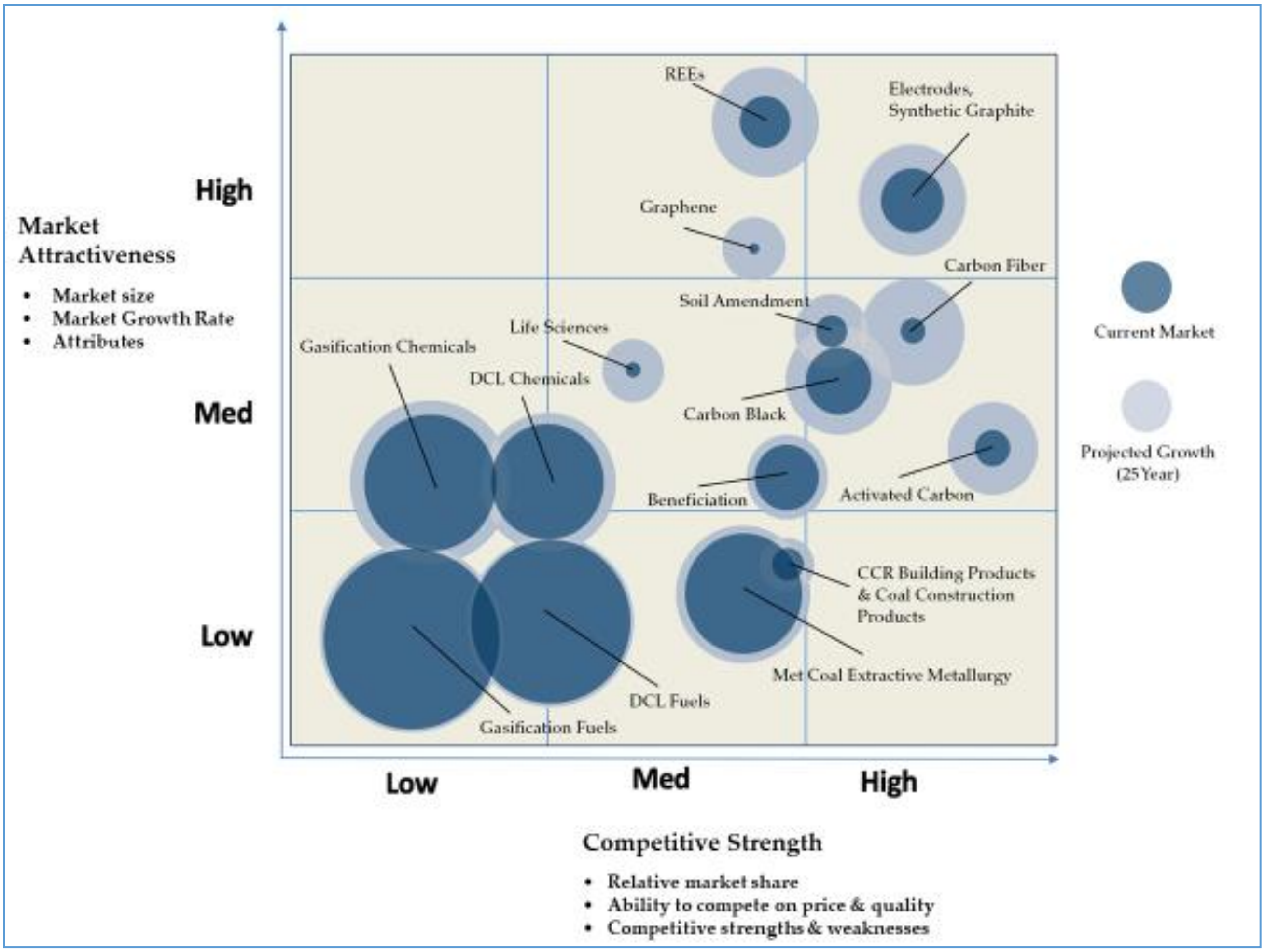
- **PERFORMANCE** – *High Market Attractiveness-High Competitive Strength*
  This sector is characterized by specialty volumes of high-performance materials utilizing coal's inherent and unique chemistry advantages, optimistically poised for rapid commercialization from small-scale modular to larger industrial scale. Products in this category include rare earth elements, carbon fiber, synthetic graphite and electrodes, graphene, soil amendments and life-science biosensors.



Non-Conventional Uses of Coal:
CORE & PERFORMANCE routes (left and lower) and TRADITIONAL routes (upper right)

The conclusions of the NCC's nine-block analysis shown below provide a qualitative, directional assessment of market opportunities. As graphically represented, the analysis depicts each data point with two concentric bubbles. The size of the darker blue inner bubble is a qualitative representation of the total size of the market (in annual revenues) that coal is able to address; the size of the lighter blue outer bubble is a qualitative representation of potential market growth over the next 25 years.

Based on NCC's nine-block analysis, the most significant growth opportunities for U.S. coal are in producing high-value specialty materials and products at reduced costs that will accelerate growth and spearhead large-scale applications. This could constitute a step-change in turning coal into the future 'carbon ore' mineral asset. Coal could become a new, innovative, low-cost solution to creating advanced materials and products across many important sectors, including automotive, aerospace, construction, electronics, low carbon energy, agricultural, environmental and life sciences.



In his request to the NCC, Secretary of Energy Rick Perry asked how domestic markets for coal-to-products could be development and commercialized in the U.S. The NCC recommends three primary strategic objectives be pursued by the U.S. Department of Energy to accelerate U.S. manufacturing of coal-derived solid carbon products, chemicals, fuels and rare earth elements.

- **Establish a focused R&D program on coal-to-products.**
  Additional research and development (R&D) is needed to achieve commercially viable technical performance-to-cost ratios for the manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs in the U.S.

- **Accelerate research-to-commercial deployment in coal-to-products markets.**
  Competing successfully in a global economy requires that the U.S. bring new technologies and related manufacturing to market much faster via replicable modular systems. To avoid being out-paced by other countries, gaps in funding and delays in progression from research to commercial deployment, including new-skills workforce development, must be eliminated.

- **Incentivize private sector investment in coal-to-products production and manufacturing sectors.**
  Efficient use of public and private sector financial capital requires alignment of private sector interests and investment readiness with government public sector R&D and economic development investment plans, as well as with defense procurement schedules. Steps must be taken to establish a stronger private sector investment appetite for first-of-a-kind (FOAK) and subsequent single-digit coal conversion plants and end-product factories, in order to quickly move DOE supported coal-to-products technologies into commercial operation, to create jobs and to improve U.S. balance of trade.

Specific tactics to achieve these objectives are detailed in Chapter 3 of this report.

The nation's abundant coal resources are well-suited to securely support the U.S. as it enters the New Carbon Age, powered by innovation in both advanced products and manufacturing.

Chapter 1. Overview of Opportunities for Coal-to-Products*

Introduction

The United States is embarking on a "New Age of Carbon" which will usher in significant opportunities for coal beyond conventional markets for power generation and steelmaking. Coal, and the carbon it contains, is on the crest of powering a wave of innovation in advanced products and manufacturing.

The opportunity for the U.S. represented by these markets is compelling. The market landscape is an evolving mosaic of products, covering everything from undifferentiated commodities to advanced nano-carbon structured specialties, ranging from multi-billion-dollar coal conversion systems to novel single-use hand-held biosensors.

Currently, the global market for coal-to-products (including fuels, chemicals and carbon products) is estimated to consume between 300–400 million tons per year of coal.[i] As a frame of reference, the U.S. produced roughly 750 million tons of both thermal and metallurgical coal in 2018. The analysis undertaken by the National Coal Council (NCC) for this report indicates that utilization of domestic U.S. coal for coal-to-products applications has the potential to be on the same order of magnitude as that projected for coal power generation applications.

In addition, most of the coal-to-products considered in this report create associated and additive economic opportunities by providing secure, domestic feedstocks to support industry. The economic growth potential of coal-to-products provide social benefits in the form of new mining and manufacturing job creation, especially in regions of the country adversely impacted by the recent downturn in coal production and power generation. The markets for carbon products, in particular, are growing at attractive above average rates of approximately 18% compound annual growth rate (CAGR), based on 2011-2018 data presented in Table 2.2 of this report.

Coal-to-products also support and enhance our nation's environmental objectives through their unique performance characteristics. A host of newly emerging and existing coal-to-carbon product technologies are changing the way energy is generated, used and conserved. Advanced forms of carbon now serve as key building blocks for a host of new solutions – including cleaner energy, cleaner water and cleaner air – that will benefit our society and our economy. Criteria and CO_2 emissions reductions are achieved 1) overall through the potential widespread use of coal in alternative uses that do not have the same carbon emission characteristics as other current uses; 2) through the use of coal to create durable, light-weight carbon products for the aerospace and automotive industries with the potential for corresponding fuel reduction; 3) through the use of coal to create high-strength advanced composite materials and high-efficiency rare earth element components for the wind and solar power industries; 4) through the use of coal to create sorbents used to capture CO_2 from fossil fuel power plants, cement kilns and industrial sources; and 5) through the use of coal to create composite products to be used in infrastructure, concrete and building materials.

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* The term "coal-to-products" as used throughout this report refers to coal-derived products, materials and technologies beyond conventional markets for coal in power generation and steelmaking.

To grapple with the strategic perspectives and with the main objective of developing a coherent outlook, a systematic approach for characterizing and prioritizing opportunities was chosen as a means of mapping out "directional opportunities." The chosen tool was the GE-McKinsey nine-block framework[ii]. The approach recognizes the complexities of comparing a diverse portfolio of business units – in this case a diverse set of product opportunities – and resolves the challenges of putting everything on the same basis by considering two common features; namely, *market attractiveness* and *competitive strength*. The results of this analysis are shown below in Figure 1.1. Additional supporting commentary is presented in Chapter 2.

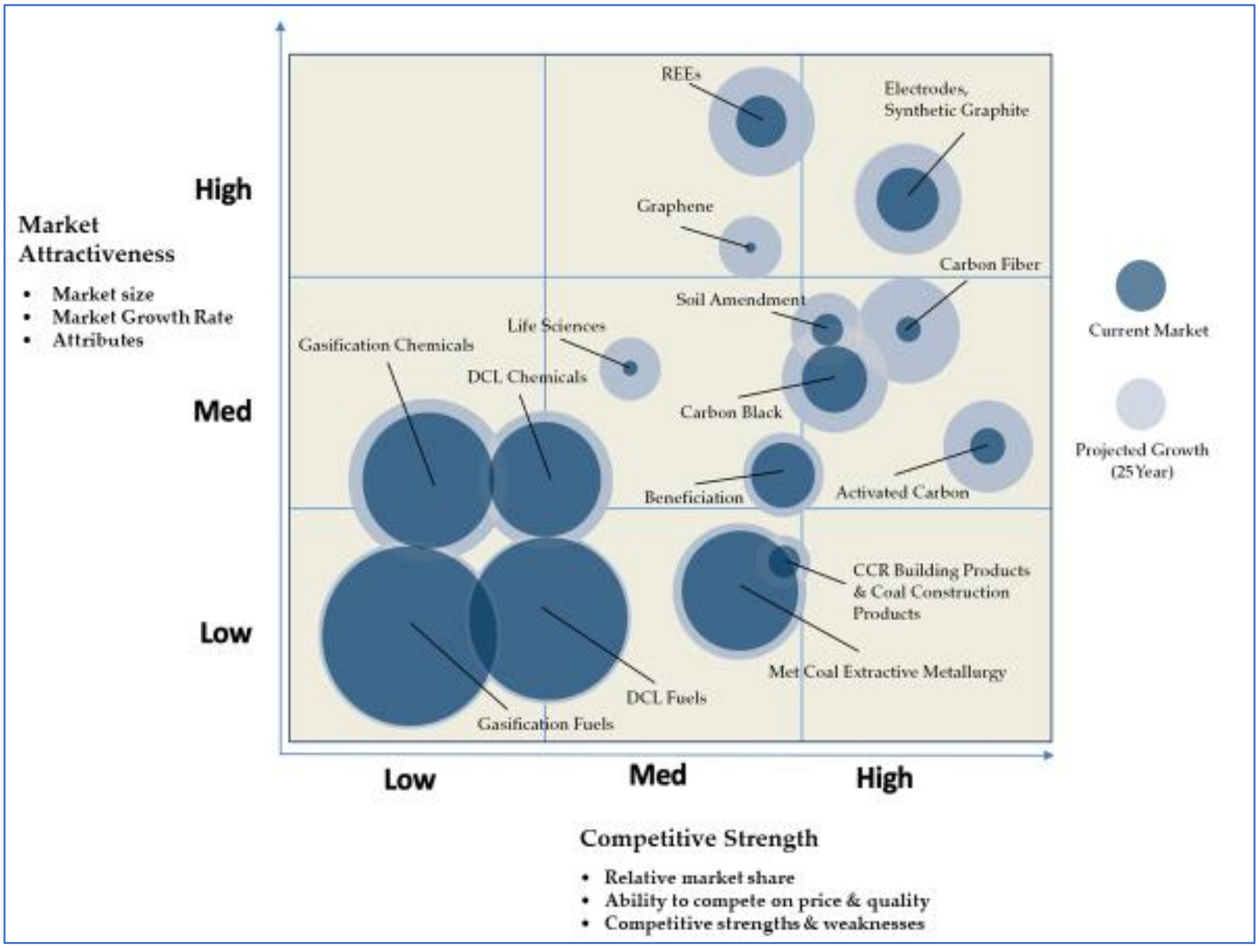

Figure 1.1 A Nine-Block Depiction of the Main Coal-to-Product Technology-Market Pathways

Additional considerations for these market opportunities also include:

- Arbitrage between the Price of Coal and Petroleum in Carbon-related Products.
  Both a ton of coal and a ton of petroleum each contain roughly 70% carbon matter. A ton of thermal coal, however, sells for between \$12 and \$50 in the U.S., while a ton of petroleum sells for roughly \$400-\$500.

- China already has a strong foothold in some of these markets.
  Should the U.S. stand idly by, American carbon product producers and manufacturers may not win the global battle to lead in the New Carbon Age. Should that happen, China could control more than half of the world's supply of advanced carbon products, including batteries, graphene sensors, graphite, carbon fibers and other strategically important products. China would once again have the potential to disrupt supply chains and free-market pricing for strategically important solid carbon materials, as that nation already did before with rare earth elements (REEs).

These coal-to-products opportunities should be enhanced, encouraged, invested in, developed and fully commercialized in the U.S. They hold the promise of not simply replicating China's or other countries' gasification-based coal economy, but of initiating a new and different carbon-based technology and carbon manufacturing renaissance in the U.S.

At the request of U.S. Secretary of Energy, Rick Perry, the National Coal Council (NCC) is providing this assessment of opportunities to enhance the use of U.S. coal in various coal-to-products markets. This report identifies:

- Significant market-scale opportunities that exist for new markets for coal.
- Employment, economic, energy security, trade and other issues the U.S. now faces that can be addressed with new markets for coal.
- Objective criteria that can be employed to assess new opportunities, including:
  - Market readiness
  - Market acceptance
  - Technology readiness
  - Economic and investment feasibility
  - Environmental and sustainability market acceptance

New and pre-existing markets for coal are being pursued worldwide for a host of applications. Countries such as China, Korea, South Africa and Japan who are not endowed with significant oil and gas reserves are already pursuing conversion of coal to synthetic oil, transportation fuels, synthesis gas (syngas), hydrogen and industrial chemicals. They are doing so at full industrial scale using more than 300-400 million tons[iii] of coal per year.

In the U.S., efforts are already underway to convert coal into advanced materials, such as carbon fibers (that can be used in aerospace, infrastructure, automotive and energy applications), carbon resins (which can be used in advanced manufacturing such as 3D printing), basic building materials (such as roads, roofing, rebar and infrastructure) and even life-science applications (such as diagnostic sensors and personalized medicine). Numerous initiatives are also being pursued in the U.S. to convert coal into cleaner and greener transportation fuels, such as low sulfur diesel and naphtha.

Coal has significant potential beyond its use to fuel power plants or produce steel. Advancing new markets for coal can enhance U.S. national defense security, bolster our nation's energy and mineral security, and contribute to our economic prosperity.

The Value of Advancing New Markets for Coal

Why examining opportunities for coal-to-products is not only important but essential?

- New and existing opportunities must not be lost for a host of reasons, including national employment, energy security, defense, economic, competitive, technological, trade and financial reasons.
- Our vital coal industry has been severely hampered over the past decade by regulatory and market competitive pricing pressures and the thermal coal markets are in pronounced decline. Non-conventional uses of coal offer the opportunity to revitalize and transform both the thermal and metallurgical coal industries in America.
- This report demonstrates that taking advantage of two significant resources in the U.S. – its people and its coal – can contribute greatly to both our nation's materials and manufacturing future, as well as to its economic vitality over the next century.

What are the opportunities for coal-to-products markets and technologies?

- This report details prior efforts and activities in the U.S. to develop non-conventional uses for domestic coals. The U.S. Department of Energy (DOE) has supported substantial advancements in sciences and technologies that provide the foundation to establish coal-to-products industries that can support numerous jobs in the distressed coal mining communities throughout the U.S.
- The report also details the use of coal for a wide range of productive uses being pursued internationally. Roughly 300-400 million tons[iv] of coal are used every year outside of the U.S. for the production of goods rather than power.
- The U.S. has an opportunity to establish a global leadership role in areas of production and market sectors in which our nation has clear material advantages.
- Low-priced natural gas and low-priced heavy oil can be used as a productive co-feedstock with coal in the production of highly valued-added products. Certain carbon-based products offer opportunities to blend America's cheap and plentiful natural gas and oil in the production of undifferentiated commodity fuels and solid carbon material products.
- This report further details the wide range of technologies and the techno-economic outlook for those technologies here in the U.S. These include:

    - Coal conversion technologies and beneficiation/upgrading processes (coal to liquids, coal and gas/CO_2 to liquids, carbon fibers, resins and chemicals, and precursor compounds used to make advanced carbon materials)
    - Non-combustion products (building products, infrastructure uses) and advanced materials from coal (including carbon fiber, graphite, graphene, carbon nanotubes, and activated carbon)
    - Rare earth elements (REEs) from coal, ash and coal overburden
    - Coal combustion products (CCPs)
    - Life science and medical uses (possible collaboration with NIH)
    - Biotechnology and agricultural applications

    Each of these areas represents a considerable opportunity for American enterprise and the U.S. economy, as well as a significant opportunity for the U.S. coal industry to bolster production to serve those markets, be they domestic or international.

Who may benefit by taking advantage of the coal-to-products opportunities that exist?

- The U.S. coal-to-products opportunity is a win-win landscape benefitting both new and existing market sector participants.
- Use of coal for the purposes detailed in this report will benefit coal miners, coal mining communities, domestic manufacturing and the American economy, strengthen our international competitiveness and help secure America's role as a global leader in the coming 21st century's Carbon Age where carbon-based advanced materials (carbon fiber, carbon nanotubes, carbon dots, graphene, graphite etc.) and carbon-based lightweight manufacturing is poised to dominate industry.
- There are also secondary and tertiary benefits associated with increased utilization of coal for the purposes detailed in this report. For example, the transportation industry will benefit from increased utilization of new carbon materials with less weight which can be used in the construction of more efficient vehicles for road, rail, water and air transportation. Mine-site carbon product manufacturing will not only improve the economics and logistics of the U.S. coal industry, but will revitalize communities that have been negatively impacted by the recent downturn in U.S. coal demand and production. Developing robust coal-to-products industries will enable our nation to not only bring back mining jobs, but provide former miners with high wage manufacturing jobs.
- Society will also benefit from reduced emissions enabled through the use of durable, light-weight, high-performance, high-efficiency coal-derived advanced carbon products used in aerospace, automotive, renewable energy, construction and other industries, as well as in new medical, technical and advanced manufacturing applications.
- Due to the compositional and chemical differences between coal and other carbon-based feedstocks, such as oil and gas, there are uses where one feedstock has inherent advantages over the other. The increased use of coal for carbon-based product manufacturing will leverage the respective strengthens of our nation's vast coal, oil and gas feedstocks to achieve the best overall economic competitive position for the U.S.

Where will the benefits of increased utilization of coal-to-products be realized?

- Geographically, the greatest initial benefit of the increased use of coal for products will be felt in those areas of the U.S. that have been most adversely impacted by the downturn in coal production and coal power generation.
- These impacted states have historically been some of the strongest contributors to the nation's economic growth. The opportunity exists to revitalize and reinvigorate these local economies by developing coal-to-products manufacturing industries at the sites of many now shuttered facilities.
- Unemployment in these areas remains well above national averages and provides one of the few areas in the U.S. where capable workers, abundant inexpensive land and underutilized industrial facilities are available.

How could the U.S. Department of Energy and the U.S. government work together with industry to accelerate deployment of coal-to-products technologies?

The NCC recommends three primary strategic objectives which could be pursued by the Department of Energy, in concert with private industry, to accelerate U.S. manufacturing of coal-to-products, including coal-derived solid carbon products, chemicals, fuels and rare earth elements.

- Establish a dedicated Research and Development (R&D) program within the U.S. Department of Energy focused on coal-to-products, in a way that builds upon the centers of excellence that DOE already has established for both carbon products and their critical uses in energy efficiency programs.
- Accelerate research-to-commercial manufacturing deployment in coal-to-products market sectors.
- Incentivize private sector investment in coal-to-products sectors.

In Chapter 3 of this report, the NCC details specific approaches and tactics to achieve these strategic objectives in an effort to encourage, enhance and accelerate the commercialization of coal-to-products markets. Many of these tactics are based on an examination of international developments in coal-to-products markets and on lessons learned from previous initiatives undertaken in the U.S.

Specific to the U.S., there have been a number of historic coal upgrading and coal conversion projects that were proposed and developed to various stages before ultimately being suspended. The obstacles that derailed these projects were predominantly some combination of the following:

- Successful financing of coal conversion projects requires a level of certainty regarding sustained long-term (20+ years) price differentiation between coal and competitive oil or natural gas feedstocks to offset inherently higher capital costs associated with handling, transporting and converting a solid feedstock (coal) into a gas or liquid.

- Delays due to obtaining project financing and/or environmental and construction permits that tend to drive up overall costs, causing the commercialization process to go through multiple re-evaluations with resultant cost escalation.

- First-of-a-kind (FOAK) development and deployment risks tend to lead to extra mitigation costs that can ultimately cause projects to become non-viable.

- Coal conversion projects tend to be large in scale and cost and can take a number of years to proceed through development, engineering and design, permitting, financing, construction and startup. It is not unusual for market conditions to change during such extended time periods, which may lead to reassessment of, and changes to, overall project attractiveness. It may also be difficult to maintain the commitment and momentum of project owners/developers over such extended timeframes.

- Companies driving new advanced technologies into markets that may also be new to them, such as coal companies seeking to drive coal products into chemical or carbon fiber markets, may not have the internal expertise, or adequate access to external expertise, needed for such new technology directions.

- Technology hurdles or roadblocks can sometimes occur along the development pathway. These can generally be overcome by dedicated and talented teams of scientists and engineers, although not always in an economically viable manner.

Lessons learned from assessment and analysis of previous U.S. coal upgrading and coal conversion technology development and deployment efforts include the following:

- The most successful efforts have primarily been the result of cooperative partnerships between public entities and private industry.

- Public entities often conduct or support fundamental research that enables private industry to develop and successfully deploy new technology advances into the marketplace.

- First-of-a-kind (FOAK) technology deployments carry risks that are often difficult and costly to mitigate, making it hard for private industry to move such projects forward. Federal assistance to help mitigate such risks can be effective to encourage such projects to move forward.

- Redirection from traditional coal markets to new coal-to-products markets often requires expertise outside that of existing coal-based companies. Universities and federal and state governments and their lab and research facilities can help provide trained and qualified researchers and technologists to fill such needs.

- Coal conversion technologies that can compete with alternative petroleum- or natural gas-based technologies often require some level of value addition to offset inherently higher capital costs due to solids handling of coal and the costs of converting a solid to a liquid or gas. This offset often comes from advantages in the relative raw material costs of coal versus the alternatives. This advantage can come from a differential in relative energy costs (cost per BTU basis), which is often difficult to sustain with adequate certainty over the long (20+ year) financing timeframes of such projects. But it can also be the result of an inherent advantage of coal, such as in the production of products that are heavily dependent on the carbon content of the feedstock (e.g., graphite, graphene, carbon fibers, or carbon-heavy chemicals such as acetyl chemicals) or are dependent on other components that exist in greater levels in coal (such as rare earth elements (REE) or critical minerals (CM)).

- Coal upgrading technologies, if adequately cost and energy efficient, can open up new domestic and export markets for U.S. reserves, for both lower-rank western coals and higher-rank eastern coals.

- As seen from an historical review, federal support for coal upgrading and coal conversion technologies has tended to be cyclical, with various crises or economic or national security concerns serving as primary drivers. Such cyclical efforts can lead to losses of critical expertise and program momentum during periods of reduced support. It is recommended that some base level of federal support be continuously maintained so that critical needs can be addressed more rapidly and more effectively as they arise.

The nation's abundant coal resources are well suited to securely support the U.S. as it enters the New Carbon Age, powered by innovations in both advanced products and advanced manufacturing.

Coal-to-products technologies and markets addressed in this report include the following. More detailed descriptions are provided in Appendix A.

Coal Beneficiation – Coal beneficiation relates to the upgrading of coal quality and/or the conversion of coal into higher value products. The three primary technology options for coal upgrading are: (1) physical or gravity separations (e.g., conventional coal preparation); (2) thermal treatment (e.g., coke production); and (3) chemical extraction (e.g., production of low ash carbon products).

Coal to Liquids, Natural Gas and Chemicals – Processes that produce liquid fuels, chemicals, and synthetic natural gas (SNG) from coal can involve prior conversion of the coal to syngas (through coal gasification), a process also known as indirect coal liquefaction (ICL). Cleaned and chemically adjusted syngas can be used as a feedstock for chemical reactions that can produce fuels and chemicals. Among the fuels that can be produced directly are diesel fuel, gasoline and methane (synthetic natural gas). Primary chemicals that can be produced include methanol and ammonia. Methanol can then be converted to higher-value products such as olefins (such as ethylene and propylene), aromatics (such as benzene, toluene and xylene), monoethylene glycol (MEG) gasoline, or dimethyl ether (DME), among others. Ammonia, either itself or following conversion to urea, is a building block for fertilizers for agricultural markets.

Direct coal liquefaction (DCL) involves the solvent extraction of organic material from coal and the hydrogenation of the extracted material. Similar to ICL, DCL can produce fuels (diesel, gasoline, jet fuel) and chemicals (plastics products and synthetic fibers).

Coal to Products – The inherent carbon content of coal lends itself to the use of coal to produce carbon-based products. Current existing applications for carbon products include electrodes, seals, bearings, refractories, fishing rods, golf clubs, nuclear reactors, various automotive materials, and aircraft parts such as the fuselage of the Boeing 787, and increasingly in automotive parts and building materials. Carbon materials are also used in environmental applications, such as the removal of contaminants from water and flue gases (activated carbon) and the purification of municipal drinking water (anthracite filter media).

Detailed descriptions of the following coal-to-products markets are included in Appendix A:

- Electrodes, Graphite Products and Carbon Fibers
- Activated Carbon
- Coal Use in Non-ferrous Metal Smelting
- Coal to Graphene and Carbon Nanotubes
- Coal to Building Products
- Coal to Carbon Foam
- Coal to Carbon Black

Coal Derived Critical Minerals and Rare Earth Elements – Critical minerals (CMs), including rare earth elements (REEs) are used in end products in critical sectors of the U.S. economy that include health care, military, transportation, power generation, petroleum refining, and electronics. Specific clean energy related REE applications include magnets for wind turbines, batteries and vehicles, and phosphors for lighting products.

Metallurgical Coal Sector Use of Coal Products – The term "metallurgical coal" is commonly applied to coal that is used to make coking coal. The resultant coke is used primarily in ironmaking blast furnaces and, to a lesser extent for other iron and steel applications and in non-ferrous extractive metallurgy. However, coal products are used in other metallurgical processes with coking. Two key potential uses for coal in extractive metallurgy are anode coke and needle coke. Activated carbon also finds use in the metallurgical sector.

Life Sciences and Medical Uses – The history of coal in the chemical and pharmaceutical industry can be traced to the discovery and development of synthetic dyes from coal tar – a byproduct of town gas and the steel industry. Modern pharmaceuticals have their origins in apothecaries that commenced to produce and sell drugs extracted from flora and fauna as well as in the organic chemical companies – especially dyestuffs that moved from manufacturing dyes through extraction from coal tar to other organic chemicals, using the organic building blocks extracted from coal and coal byproducts.

Graphene MedTech Uses – Graphene's unique physical structure, as well as its chemical and electrical properties, make it ideal for use in medical sensor technologies. Several of these platforms have been used to immobilize biomolecules, such as antibodies, DNA and enzymes, to create highly sensitive and selective biosensors with high specificity which can significantly enhance patient care, accurate early diagnosis of diseases and pathogen detection in clinical practice.

BioTech and Agricultural Uses – Lignite contains natural organic compounds known as humate, which derive from the decomposition of plants and are found in soil, peat, as well as lignite. Application of humates to soils is beneficial, promoting increased water retention, growth of beneficial micro-organisms, root growth, and plant yield serving as a source of natural nutrients. Humic acid products could play an important role in counteracting the deterioration of fertile land, a challenge caused by intensive farming, erosion and drought.

Chapter 2. Trends and Future Outlook for New Coal-Derived Products in the U.S.

Key Findings

- **Opportunities exist to use coal more productively beyond its conventional applications in power generation and steelmaking. These new opportunities span a mosaic of products, with the most significant near-term growth potential in the production of high-value specialty materials and products.**
- **Industry analysis tools used to assess the market attractiveness and competitive strength of various markets sectors, indicate the relative value of three classes of products: Traditional (gasification- and liquefaction- derived fuels and chemicals), Core (metallurgical coal/coking, beneficiation, activated carbon, carbon black and building products) and Performance (carbon fibers, graphite, electrodes, graphene, rare earth elements, soil amendments and life science applications).**
- **Today, about 300-400 million tons of coal per year is consumed for non-conventional uses worldwide. The U.S. has an opportunity to take a leadership role in and benefit economically from participation in the anticipated future growth of these new markets for coal.**

Executive Highlights

The importance of coal to the U.S. economy is evolving. A significant opportunity for the U.S. exists to dramatically increase and diversify its coal use beyond conventional electric power generation and coking applications to also include a broad range of coal-to-product categories. The future growth outlook for coal will be tied to new innovations and new advanced product introductions.

Based on the analysis conducted for this report, the most significant growth opportunities for U.S. coal are in producing high-value specialty materials and products at reduced costs that will accelerate growth and spearhead large-scale applications. This could constitute a step-change in turning coal into the future 'carbon ore' mineral asset. Coal could become a new, innovative, low-cost solution to creating advanced materials and products across many important sectors – automotive, aerospace, construction, electronics, low carbon energy, agricultural, environmental and even life science sectors.

New opportunities exist for coal to become the precursor for advanced materials to augment or replace steel, aluminum and concrete materials, supplying high volume materials to a broad swath of U.S. industrial sectors.

Introduction and Background

An expanding opportunity for coal exists as a mineral asset that can be more productively used beyond its conventional applications as a combustion fuel or in the production of steel. An internal survey identified more than a dozen pathways to markets for coal-derived products that belie the notion that coal's only useful purposes are for steam and electric power generation or for producing coke for steelmaking and other metallurgical applications. These results are as compelling as they are complex. The market landscape is an evolving mosaic of products, covering everything from undifferentiated commodities to advanced nano-carbon structured specialties, ranging from multi-billion-dollar liquefaction fuel assets to novel single-use hand-held biosensors.

To grapple with the strategic perspectives and with the main objective of developing a coherent outlook, a systematic approach for characterizing and prioritizing opportunities was chosen as a means of mapping out "directional opportunities." The chosen tool was the GE-McKinsey nine-block framework[v]. The approach recognizes the complexities of comparing a diverse portfolio of business units – in this case a diverse set of product opportunities – and resolves the challenges of putting everything on the same basis by considering two common features; namely, *market attractiveness* and *competitive strength*.

Market attractiveness was quantified based on the current size of the targeted market, forecasted growth rates of the overall market and market pull factors. Competitive strength was quantified based on current coal-derived market share, coal's competitiveness versus incumbents and individual product strength attributes, including perceived technical viability, perceived commercial viability, U.S. strategic implications, environmental impact and future potential growth opportunities. This exercise was intended to be directional in terms of identifying clusters and commonality among them. The results showed groupings of product classes essentially along three main themes: Traditional, Core and Performance.

> **TRADITIONAL** – This group is characterized by high commodity volumes, is technically and technologically proven, requires high capital expenditures and provides only marginal economic opportunity in the U.S. as oil and gas currently out-compete coal in the U.S. This group would benefit from improvements in conversion efficiency, hybridization with natural gas co-feed synergies and deployments at smaller modular scale. NCC recommends further and continued techno-economic assessment of this area of opportunity.

> **CORE** – This group is characterized by moderate industrial-scale volumes, is technically proven, requires only moderate capital expenditures and provides a sizeable opportunity in the U.S. It would benefit both from process efficiency gains to reduce production costs and from new investments in product application research to serve growing needs for more advanced products in the specialty sectors currently being served. NCC recommends more investment in product application R&D and in new systems and processes for manufacturing. This group needs to grow.

PERFORMANCE – This group offers specialty volumes of high-performance materials that utilize the inherent and unique chemistry advantages embedded in coal, which cannot easily be replicated by other generic carbon sources. Many products in this cluster can out-compete petroleum- and natural gas-derived surrogates. These products enable a new economy for lightweight, high-strength, energy-saving, electrically- and thermally-conductive materials. The optimistic outlook for this product class is one of rapid commercialization from small-scale modular facilities to larger industrial facilities with production volumes and economics of scale that reduce costs, driven by the ultimate ability to supply commodity volumes of coal-derived materials that meet or exceed the cost and performance of existing materials to established and new markets in the construction, automotive, electronics and environmental sectors. This group offers innovation and disruption opportunities, unique chances to shape the future, high upside potential for large-volume consumption premised on price elasticity of demand and the potential ease of substitution with low-cost coal-derived materials in large commodity sectors such as steel, aluminum, cement, asphalt and building products. NCC recommends additional research, development, investment and encouragement of commercialization opportunities in this group.

The compass for growth opportunities is now being set, and it is imperative that stakeholders consider implications associated with each of the three broadly-classed opportunities.

Market Attractiveness and Product Strength Assessments

The leading coal-to-products technology/market pathways were identified by researching the historical conventional uses of coal, summarizing known pathways in operation currently, and envisioning a future characterized by both modest commercialization of new coal-derived products and re-commercialization of some existing coal-based processes.

One of the first coal-to-product processes brought kerosene to the market more than 150 years ago. Since that time, coal has been utilized and considered in a variety of non-conventional uses. These range from the steel and cement sectors, to use in early synthetic dye manufacturing, to large-scale liquefaction and chemicals manufacturing. Indeed, overseas countries, especially China, are using coal today for such purposes in volumes approaching 50% of the U.S. consumption of coal for power generation. See Table 2.1 for volumes of coal utilized.

		Coal Consumed	Yield to Liq. products [vi]	Coal Products
		million TPY	%	million TPY
Indirect Coal Liquefaction	Gasification Fuels and Chemicals [vii], [viii], [ix]	270	40%	108
Direct Coal Liquefaction	DCL Fuels and Chemicals [x], [xi]	2	55%	1
	DCL Fuels and Chemicals [xii], [xiii], [xiv] via Low -Temp Pyrolysis Route	28	14%	4
Coking of Metallurgical Coal	Coal Tar Pitch [x] as precursor liquids for Carbon Black, Electrodes and Chemicals		4%	16

Table 2.1 General Estimates for Non-Conventional Usage of Coal

As a point of reference, the Energy Information Administration (EIA) reported 2018 U.S. coal production at 755 million tons[xv]. Rough estimates from Nexant indicated that 300-400 million tons/year of coal is consumed globally for non-conventional uses. This estimate does not include coal consumed for metallurgical coke making, nor does it include the coal consumed in calcining of cement. Of the 300-400 million ton/year estimate, roughly 95% of that amount is used in China, and 95% of the China total is for gasification-based production of liquid fuels and chemicals.

These estimates are based on non-proprietary information available from public sources. They are presented here to show the general coal consumption structure, for comparison purposes, as a qualitative indication of relative size, and have not been independently verified or peer reviewed in terms of their accuracy.

An additional view is presented in Table 2.2 to show the existing worldwide market for carbon products, which includes the production of activated carbon, carbon black, carbon fiber, synthetic graphite and carbon electrodes among others; some but not all of these carbon products are made from coal currently. The worldwide annual sales volumes shown represent the amounts of the carbon products sold globally.

Many of these products are heavily reliant on two key feedstock sources; namely coal tar pitch and petroleum pitch, and to lesser extent mined graphite. However, both petroleum-based pitch feedstocks and coal-based pitch feedstocks have declined in the U.S. Petroleum-based pitches have declined due to lighter refinery feeds and higher levels of contamination. Coal tar pitches have declined as a result of new less coke-intensive steelmaking processes and off-shoring. Nonetheless, the markets for the carbon products listed have continued to grow, and, as necessary, together with the requisite process technology development work, coal-based pitch can be used to replace petroleum-based pitch as a feedstock.

Recent higher technology innovations involve coal used in the development of high-value nanomaterials, in advanced carbon materials in the med-tech sector and in battery storage applications. Other emerging technologies are seeking to develop coal core composites for roofing, coal plastic composites for decking and carbon foams for use in building material and structural applications. These processes are characterized by a minimal number of processing steps and high-volume infrastructure application opportunities. The novel extraction of rare earth elements (REEs) from coal, and the use of modified lignite coal for agricultural soil amendment purposes, are also in the development and commercialization stage.

<table>
<tr><th>Product</th><th>Primary Feedstocks</th><th>Main Applications</th><th>Y2011[xvi] Worldwide Sales, tons</th><th>Y2018[xvii] Worldwide Sales, tons</th></tr>
<tr><td>Activated Carbon</td><td>Coal
Biomass, other</td><td>Sorbents, air and water purification</td><td>na</td><td>1,380,000</td></tr>
<tr><td>Binder Pitch</td><td>Coal Tar Pitch
Petroleum Pitch</td><td>Anodes (Al Smelting)
Arc Furnace Electrodes (steelmaking)</td><td>1,500,000</td><td rowspan="3">5,500,000</td></tr>
<tr><td>Impregnation Pitch</td><td>Petroleum Pitch
Coal Tar Pitch</td><td>Electrodes, Composites</td><td>380,000</td></tr>
<tr><td>Mesophase Pitch</td><td>Petroleum Pitch
Coal Tar Pitch</td><td>High Performance Composites, Fibers</td><td>3,700</td></tr>
<tr><td>Anode Coke
Uncalcined
Calcined</td><td>Petroleum Resid</td><td>Anodes (Al Smelting)</td><td>
8,000,000
6,200,000</td><td>26,000,000</td></tr>
<tr><td rowspan="2">Needle Coke</td><td rowspan="2">Petroleum Pitch (US)
PP + CTP (Japan)</td><td>Arc Furnace Electrodes (steelmaking)</td><td>1,300,000</td><td>1,000,000</td></tr>
<tr><td>EV Batteries</td><td>na</td><td>600,000</td></tr>
<tr><td>Graphite</td><td>Natural Graphite</td><td>Electrodes, others</td><td>na</td><td>1,200,000</td></tr>
<tr><td>Carbon Fiber (PAN)</td><td>Petrochemicals</td><td>Non-graphitic composites</td><td>24,000</td><td>78,500</td></tr>
<tr><td>Pitch Fibers</td><td>Coal Tar Pitch
Petroleum Pitch</td><td>Graphitic composites</td><td>3000</td><td>4,000</td></tr>
<tr><td>Calcium Carbide</td><td>Coal derived coke</td><td>Acetylene, PVC, BDO, VAM</td><td>na</td><td>30,000,000</td></tr>
<tr><td>Carbon Black</td><td>Petroleum Pitch, Coal Tar Pitch</td><td>Rubber additives, various other</td><td>8,000,000</td><td>16,000,000</td></tr>
<tr><td>Carbon Foam</td><td>Petrochemicals, Coal, Coal Tar Pitch</td><td>Structures, Electrochem. Systems</td><td>200</td><td>151</td></tr>
<tr><td>Coal Soil Amendment</td><td>Lignite Coal</td><td>Soil Nutrient, Fertilizer, Remediation</td><td>na</td><td>1,000</td></tr>
<tr><td>TOTAL</td><td></td><td></td><td>25,410,900</td><td>81,763,651</td></tr>
</table>

Table 2.2 General Estimates of Existing Worldwide Markets for Carbon Products

The schematic representation shown in Figure 2.1 is a simplified depiction meant to cover the main production pathways and markets under consideration. These are not meant to be exhaustive. While more than a dozen coal process technology/market pathways are addressed in this report, a number of processing pathways were not considered to be within the scope of the report; e.g., the conversion of coal-derived CO_2 to products is not covered.

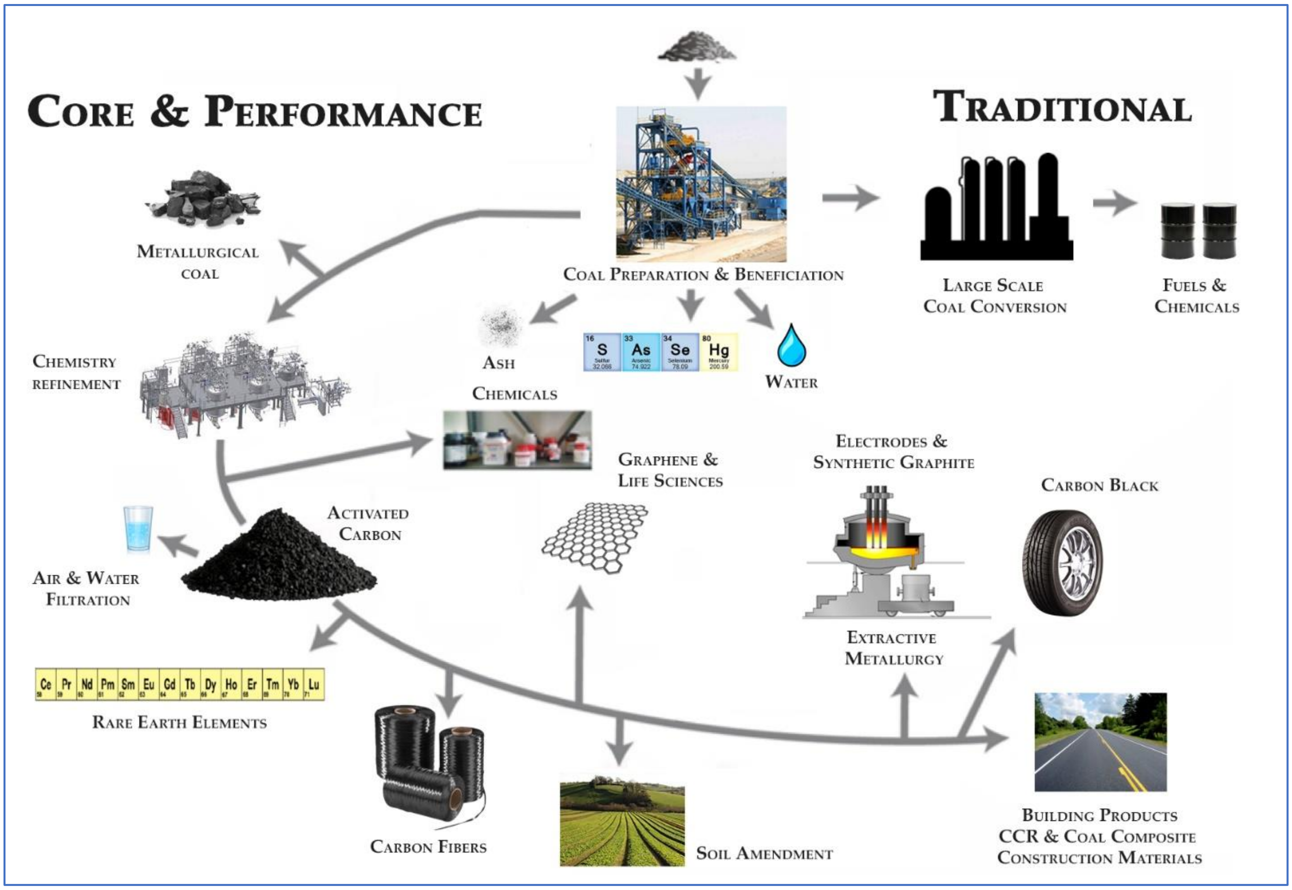

Figure 2.1 Non-Conventional Uses of Coal:
CORE & PERFORMANCE routes (left and lower) and TRADITIONAL routes (upper right)

In conducting this report, NCC first gathered key attributes for each of the major coal process technology/market pathways, and then characterized these with respect to product competitiveness and market attractiveness/viability.

It should be noted that the published literature is incomplete when it comes to emerging coal-to-products technologies, particularly with respect to economics and quantitative performance attributes. Some techno-economic studies have been concluded for coal conversion processes, and these were used as references where available. However, these studies were relatively narrow in scope given the wide spectrum of potential alternative applications for coal. Therefore, detailed references are not available for all the technologies covered in this report, and as such this remains an area that could benefit from more detailed analysis by the DOE and other organizations. Until that can be accomplished, a certain amount of extrapolation is needed to execute and evaluate the qualitative rankings versus purely quantitative comparisons.

The results of the GE-McKinsey nine-block analysis are graphically represented in Figure 2.2 and detailed below. In the graphic, each data point consists of two concentric bubbles. The size of the darker blue inner bubble is a qualitative representation of the total size of the market (in annual revenues) that coal is able to address; the size of the lighter blue outer bubble is a qualitative representation of potential market growth over the next 25 years. The addressable markets are defined as those which according to precedent may be served by coal, where in many cases, however, are primarily served by oil and gas, depending on prevailing market dynamics and relative competitiveness among these feedstocks.

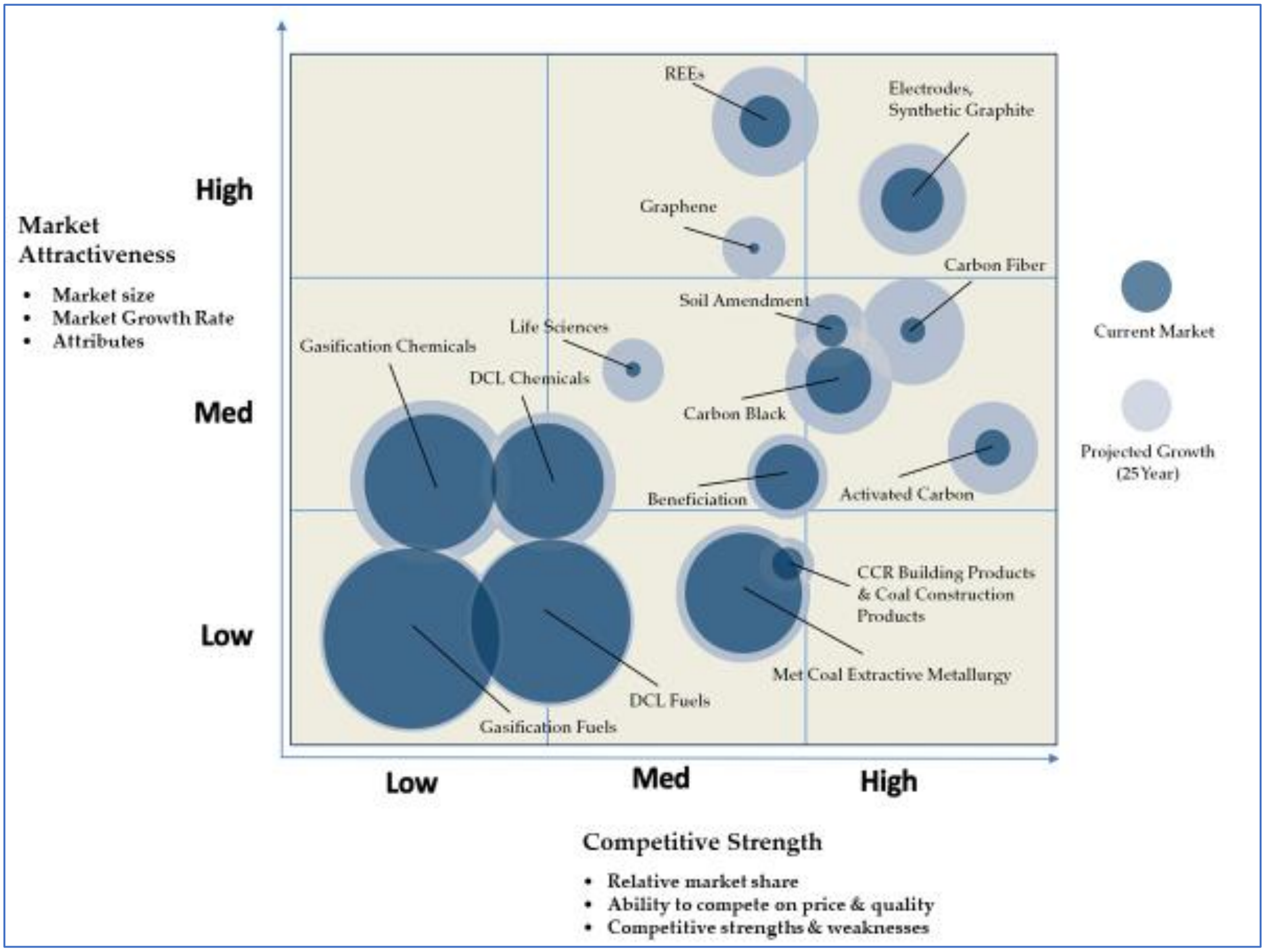

Figure 2.2 A Nine-Block Depiction of the Main Coal-to-Products Technology-Market Pathways

It should be noted that the results of the GE-McKinsey nine-block analysis are not intended to serve as a substitute for business planning purposes. To be sure, there are a multitude of attractive opportunities that this simple process does not capture well, especially those associated with the newest emerging technologies which have not yet established a sizeable market presence and, in some cases, have not yet established the new markets that they will create. For example, new coal carbon-based building materials could emerge in the future in ways that are not reflected in today’s assessment.

<u>TRADITIONAL</u> - Coal commodity products, including bulk chemicals and fuels, qualitatively fall in to the Low Market Attractiveness - Low Competitive Strength classifications.

- **Gasification-based Liquid Fuels and Chemicals** - Although technically feasible, and widely practiced in China, the feedback gathered from this report did not indicate that these products from coal have the economic potential to compete with natural gas and petroleum-based fuels in the near to mid-term in the U.S. This is due in large part to the success of the U.S. oil and gas industry in driving down petroleum and natural gas feedstock costs through technological advances such as hydraulic fracturing. It is also due to the significant capital costs required to build the multi-billion dollar coal-based facilities that can produce products at the economies of scale needed to compete with the already-competitive oil and natural gas refining industries. If petroleum or natural gas costs were to significantly increase in the future, then coal could potentially become a competing source of these products. Larger market potential for these coal-based products could also be possible if new lower-cost processes significantly drove down processing and conversion costs.

- **Direct Coal Liquefaction-based Fuels and Chemicals** – Although direct coal liquefaction (DCL) is technically feasible, it is not widely practiced. Overall production costs, especially those associated with hydrogen consumption, are lowered with use of low-cost natural gas co-feed to produce fuels and aromatic chemicals. The information gathered for this report indicate that this technology approach is more competitive than indirect coal liquefaction (ICL). However, the NCC report did not undertake a detailed comparison with leading competition from petroleum-derived fuels and aromatic chemicals.

<u>CORE</u> – The specialized products identified below qualitatively fall into the Medium Market Attractiveness - High Competitive Strength classifications.

- **Metallurgical Coal and Coke (for extractive metallurgy uses) –** This is an established processing technology, mainly serving the steelmaking industry and lower-volume non-ferrous metal smelting processes. Overseas markets are growing in comparison to U.S.-based operations, which face competition with imported steel products. No major upturn in the domestic demand for the combined consumption of metallurgical coke and direct use of coal extractive metallurgy is foreseen during the periods of interest to this study. Though a relatively small co-product of coke-making, coal tar pitch has risen in demand and shortened in supply in recent years as a precursor for specialized carbon-based product applications.

- **Coal Beneficiation –** This is a well-established and important intermediate processing step that enables products rather than being a product itself. Traditionally, this includes the first processing step for raw coal, including sizing and physical removal of unwanted non-carbon bearing mineral (rock). Increasingly sophisticated new advances now target significant reductions of unwanted moisture, trace elements, and sulfur and enable the ability to purify very fine coals including, for example, the cleanup of coal from tailing ponds. Coal beneficiation holds the promise of providing higher-quality coal feedstocks to the increasingly higher-purity demands across all coal consumption sectors.

- **Activated Carbon –** This product derives from established processing routes using coal and biomass feedstocks, mainly serving the specialty sorbent market for water purification and air purification demands, which are growing at or above global GDP rates. New specialized uses include areas such as low-cost industrial gas separations, CO_2 removal from mixed gases and other energy-saving applications that could spur future demand.

- **Carbon Black –** Established processing routes from coal and petroleum residues are used to produce this product which mainly serves the tire industry as a toughening additive to automotive rubber. China has built its carbon black industry on coal-derived co-products (from coking) while the rest of the world continues to use petroleum residues as feedstock. The opportunity for substitution requires further assessment.

- **Coal Combustion Residuals (CCRs) and Coal to Building Products –** There is an established processing route for converting fly ash into value-added construction products, cement additives and other novel uses. It is price-competitive versus on-purpose production of substitutes, i.e., from energy-intensive calcining routes. New emerging technologies are also seeking to develop direct coal core composites and direct coal plastic composites for use in building material and structural applications. Market demand and attractiveness could potentially surge, especially if the promise of low-cost coal-sourced materials meet high performance demands in these new and potentially high-volume applications.

PERFORMANCE – This sector includes engineered advanced products and rare earth elements, which qualitatively fall into the High Market Attractiveness - High Competitive Strength characterization.

Coal has a variety of specialized uses, most of them currently low-volume applications but growing at rates significantly exceeding global GDP. Many of these depend on coal tar pitch and its inherent carbon chemistry to be fully formed into advanced carbon materials which can outperform other known alternatives from petroleum, biomass and natural gas derivatives. Much of the past R&D on these niche applications has taken place, and continues to take place, in U.S. national labs and established U.S. research centers for specialized aerospace and defense applications.

At the present time, new domestic markets are being catalyzed by greater market demands for high-performance advanced carbon materials in high-performance applications requiring, in some cases, ultra-light-weight, ultra-high-strength and high electrical- or thermal-conducting materials. High-performance products are enabling a new economy that is being built in areas such as the automotive sector, with trends toward higher capacity, lighter weight electric vehicle (EV) batteries, high-pressure fuel storage tanks and lighter weight body panels as several examples.

- **Carbon Fiber –** First developed in the 1960s for demanding applications as a space age material for satellites and military aircraft, carbon fiber is now finding its way into the infrastructure, energy and transportation sectors. A burgeoning new role is in reducing the use of energy-intensive materials such as steel and concrete. It is widely used in Japan for seismic strengthening and repair of concrete structures, and holds promise as a potential component in asphalt, lumber composites and even roofing materials. Market demand could potentially surge, especially in the automotive and aviation sectors, if the promise of low-cost coal-sourced precursor materials come to fruition.

- **Synthetic Graphites and Electrodes –** This is another strategic material, first developed to serve the needs of two core industries: aluminum smelting (anodes and cathodes) and electric arc furnace (EAF) steelmaking (electrodes). These products are now finding their way into Li-ion battery applications and as conductive pastes in electronic applications. Market demand is poised to surge if the promise of low-cost coal-sourced materials begins to outcompete natural graphite at disruptive production costs.

- **Graphene and Graphene Oxide –** Recently discovered atomic-layered carbon, found in coal, holds promise as a “wonder material” exhibiting the highest known material strength ever recorded. As a lab fascination it is already getting traction in performance markets and will find its way into new applications that have not been fully envisioned at present. Some of these applications include uses such as a toughening agent in building materials and as an electrical conductivity enhancer in new metal alloy systems. Both hold promise in terms of efficiency gains. These products are worthy of additional study and application research.

- **Rare Earth Elements (REEs) –** Produced extensively and almost exclusively in China from enriched ore deposits, rare earth elements are not “rare” but of high strategic value. Single-source basis (China) has led to market availability concerns worldwide. Research efforts now point toward residual coal ash and mining residues as potentially abundant and low-cost feedstocks. A proportion of coal deposits are naturally rich in REEs, which are essential for the construction of an array of products such as batteries and electromagnetic motors, and most importantly numerous defense applications. The extraction of REEs from raw coal or coal by-products (tailings, ash and aqueous effluent) holds significant promise as an important method to secure the industrial supply of critical elements. A number of different groups are pursuing various technical paths that will result in viable options for commercial domestic production of REE oxides.

- **Soil Amendment (Humic Acid and Humate) –** Lignite coal has a long history of use as a fertilizer; it is currently being assessed as a large-scale solution to help counter the problem of desertification with remediation. If upgraded lignite coal performs as an effective agricultural additive, then this could be a significant alternate high-volume use of a valuable coal resource. Lignite contains natural organic compounds known as humate, which are from the decomposition of plants and are found in soil and peat, as well as lignite. Application of humates to soils is beneficial, promoting increased water retention, growth of beneficial micro-organisms, root growth and plant yield serving as a source of natural nutrients and replacement of lost top soil. Humate and humic acid products could play an important role in counteracting the deterioration of fertile land, a challenge caused by intensive farming, erosion and drought.

- **Life Science (Biosensors) –** Specialty carbon materials are used in prosthetics and implants and as carriers in drug delivery. In another example, graphene is very suitable for use in sensor technologies. Moreover, like all life forms it is carbon based, making it an ideal platform for biological applications. In the past several years, novel sensing platforms have been proposed with graphene. Several of these platforms were used to immobilize biomolecules, such as antibodies, DNA and enzymes to create highly sensitive and selective biosensors. These coal-based biosensors can be particularly useful in life sciences and medicine, since biosensors with high sensitivity and specificity can significantly enhance patient care, early diagnosis of diseases and pathogen detection in clinical practice.

Although the quantities of coal consumed may initially be relatively small, the value uplift and rate of growth for the Performance product category is forecast to be the highest. A recent study by McKinsey[xviii] shows that by 2030, the use of lightweight materials in automotive production will approach the levels currently used in aviation. As an essential light weighting component, carbon fiber will experience two decades of strong growth, with carbon fiber growing at a CAGR rate of almost 20% – an impressive number though starting from a low base. This number could increase dramatically if certain conditions occur, such as greater CO_2 reduction pressure or further cost decreases of carbon fiber.

Based on carbon product data presented in Table 2.2, a combined total of about 50 million tons of carbon black and carbon anodes are produced globally from coal pitch and petroleum pitch. If all 50 million tons of products were made from coal tar pitch, assuming a 25% yield of carbon products from coal, then this would represent 200 million tons per year of coal consumption based on existing addressable markets. As a point of reference, EIA reported U.S. coal production at 755 million tons in 2018.[xix]

It is often difficult to project the size of rapidly growing markets that benefit not only from organic growth but from price drops that result from increased volumes. In the past, all “expert” market forecasts for silicon chips, photo-voltaic cells and lithium-ion batteries were proven to be woefully conservative. Moreover, the market, job creation and overall infrastructure impact may ultimately outsize initial estimates resulting in greater long-term economic benefits for coal communities.

Chapter 3. Recommendations

To realize the opportunities for using domestic coals to produce coal-to-products (e.g., solid carbon products, chemicals, fuels, and rare earth elements) will require a coordinated national commitment. Making such a commitment will benefit the U.S. economy and environment, our nation's trade balance, domestic manufacturing of both defense and non-defense products, and, in particular, mining and manufacturing jobs in critical coal-producing states. The following strategic objectives and action items are recommended for consideration and implementation by the U.S. Department of Energy.

Strategic Objectives

The National Coal Council has reviewed the supply chains for manufacturing products from coal in the U.S. and is recommending that the U.S. become a competitive producer and supplier of coal-derived carbon products, rare earth elements (REEs) and select chemicals and fuels. Accomplishing this objective will require significant investment and development, both at the governmental and strategic industrial levels. It will also require productivity and efficiency improvements in infrastructure and process technologies throughout the coal-to-products supply chain in order to successfully commercialize these opportunities.

The NCC recommends three primary strategic objectives be pursued by the U.S. Department of Energy to ramp up U.S. manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs.

Establish a focused R&D program on coal-to-products.
Additional research and development (R&D) is needed to achieve commercially viable technical performance-to-cost ratios for the manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs in the U.S.

Accelerate research-to-commercial deployment in coal-to-products market sectors.
Competing successfully in a global economy requires that the U.S. bring new technologies and related manufacturing to market much faster via replicable modular systems. To avoid being out-paced by other countries, gaps in funding and delays in progression from research to commercial deployment, including new-skills workforce development, must be eliminated.

Incentivize private sector investment in coal-to-products production and manufacturing sectors.
Efficient use of public and private sector financial capital requires alignment of private sector interests and investment readiness with government public sector R&D and economic development investment plans, as well as with defense procurement schedules. Steps must be taken to establish a stronger private sector investment appetite for first-of-a-kind (FOAK) and subsequent single-digit coal conversion plants and end-product factories, in order to quickly move DOE supported coal-to-products technologies into commercial operation, to create jobs and to improve U.S. balance of trade.

Tactics

Specific tactics and action items recommended to achieve these strategic objectives are detailed below and specify ***WHAT*** must be done and ***WHY***.

A. Strategic Objective: Establish a focused R&D program on coal-to-products.

- Establish a national R&D program for advanced carbon products and manufacturing within the U.S. Department of Energy.

  A committed R&D effort to advance coal-to-products technologies would enhance prospects for commercialization in an efficient and timely manner. It is recommended that screening tools are established so that R&D investments can be directed toward those technologies that are most likely to commercially succeed and have a positive impact.

- Sustain a multi-decade base level of Federal commitment and support.

  From a historical perspective, Federal support for coal upgrading and coal conversion technologies has tended to be cyclical, with various crises or economic or national security concerns serving as primary drivers. Such cyclical support can lead to losses of critical expertise and program momentum during periods of reduced support. It is recommended that an adequate base level of Federal support be continuously maintained so that critical needs can be addressed more rapidly and more effectively as they arise.

- Implement a broad-based interagency coordinated program to accelerate coal to fuels and products development.

  Similar to the Biomass Research and Development (BR&D) Board[xx] created through enactment of the Biomass Research and Development Act of 2000, bring together in a formal intergovernmental team the required agencies and departments to work concurrently on positioning all the necessary elements for success, including U.S. Export Administration Regulations (EAR) and International Traffic in Arms (ITAR) compliance.

- Elevate the priority of and increase R&D funding for coal-to-products technologies.

  Establish a national commitment to develop and deploy U.S. coal-to-products conversion technologies and U.S. manufacturing capabilities to revitalize the coal industry and communities. Such a commitment goes beyond typical Department support for energy plant development and scale up and adds Department support for development and deployment of new manufacturing methods and processes to achieve robust economic and job growth from manufacture of carbon products derived from coal. The DOE Office of Fossil Energy can leverage existing programs within the National Institute of Standards and Technology (NIST), the Department of Defense (DOD) and the Department's own Advanced Manufacturing Office (AMO) to jump start and place coal-to-products on a fast-track program.

B. Strategic Objective: Accelerate research-to-commercial deployment in coal-to-products market sectors.

- An Office of Carbon Products within the U.S. Department of Energy would establish the required national commitment and empower DOE program managers to pursue the strategic objectives and achieve the desired economic growth, job creation (such as the American Jobs Project's report entitled, The Wyoming Jobs Project: A Guide to Creating Jobs in Carbon Tech[xxi]) and national security benefits. The Office of Carbon Products would be tasked with building one or more Carbon Advanced Material, Manufacturing and Production (CAMP) centers at coal mining sites in key coal states to accelerate the pace of research-to-commercial deployment of coal-to-products and to develop repeatable modular plant designs.

  Past designs for commercial facilities have focused on extremely large plants for converting a solid (coal) to a gas (chemicals) or liquids (fuels). Although technically successful, the U.S. benefits from very low cost and plentiful carbon liquids (crude oil) and carbon gases (syngas, natural gas). Since the 1950s almost all of its carbon solids (coal) have been burned. With the advent of carbon-based advanced materials, the time has now come to focus on direct coal to solid carbon product processing facilities and to do so with a focus on advanced manufacturing. One or more CAMP centers need to be built to spearhead the effort and to bring together America's best and brightest to achieve this important national objective.

- Support multiple first-of-a-kind projects throughout the U.S.

  The U.S. is blessed with a diversity of coal compositions that are geographical distributed throughout the country. Each coal resource provides different commercial strengths and weaknesses and different technical challenges for successful operation that need to be understood in order to be successfully leveraged. Geographical distribution of industries critical to defense applications provides greater survivability of critical economic and defense industry assets against adversary attacks. Lessons learned from the Nth-of-a-Kind version of each technology will reduce the cost of deployment and provide an economic advantage for U.S. manufacturers.

- Expand DOE Loan Guarantee Program.

  Review the eligibility criteria for the existing DOE Loan Guarantee Program and affect changes needed to allow loan support for coal-to-products conversion plants and factory opportunities.

- Dramatically reduce DOE Loan Guarantee Program costs, red tape and processing time.

  Uncertainty and risk associated with the DOE Loan Guarantee Program approval process time and possible delays elevates private sector investor risk assessments such that opportunities are not selected for investment.

- Apply U.S. Department of Defense Manufacturing Readiness Levels to DOE programs.

  The DOD developed manufacturing readiness levels (MRLs) to provide better coordination between technology development efforts and U.S. capability to affordably manufacture new technologies. Likewise, the DOE can apply MRLs to improve coordination between science and technology development and alignment with U.S. manufacturing method and process development. DOE can also use MRLs as a program and project progress and management evaluation tool.

- Target defense applications and national critical materials to avoid "Valley of Death" stall-out.

  Many of the products highlighted in this report have substantial defense applications that are quality early-adopter premium market opportunities that can support private sector investment justification for first-of-a-kind (FOAK) coal conversion plants and end-product factories. Coordination with the DOD should be pursued to jointly identify and prioritize the chemicals, fuels, materials and products most desired by the DOD and to align DOE R&D program timelines.

- Target dual-use applications to quickly grow markets and demand for coal.

  Review DOD dual-use programs to quickly grow total market demand for coal-derived solid carbon materials, chemicals, fuels and REEs.

- Ensure U.S. developed technologies are deployed in the U.S.

  Unfortunately, many of the new uses and applications of coal and coal products technologies are now being exploited in China but are based upon technology originally developed in the U.S. and other countries. These new uses and applications of coal technology have not been replicated here in the U.S. due to historically restrictive environmental and regulatory issues and the availability of low cost and plentiful oil and natural gas resources. However, there are high-value wealth and job creation opportunities available here in the U.S. in which coal has a material advantage over oil and natural gas.

- Address U.S. Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR).

  Many of the advanced carbon materials identified in this report require EAR and ITAR compliance that inhibit academic institution participation in recommended R&D programs when projects do not fall under the basic research exclusion.

C. Strategic Objective: Incentivize private sector investment in coal-to-products production and manufacturing sectors.

- Establish public-private partnerships.

  Facilitate early engagement and commitments to ensure the necessary entrepreneurial and investment communities buy in and are prepared to lead manufacturing and commercialization of technologies advanced by the Department to convert coal into solid carbon materials, chemicals, fuels and REEs. All government departments and agencies must work together with the private sector in a tightly coordinated manner to achieve maximum economic value, job creation, trade deficit reduction and national security benefits.

- Provide tax and other investment incentives and subsidies to facilitate the rapid development and commercialization of coal-to-carbon products.

  In previous National Coal Council reports[xxii], the success of tax and policy incentives in facilitating the rapid growth and commercialization of renewable energy technologies has been documented. There is a precedent for the use of these measures to advance technology commercialization.

- Validate revenue and business models and management strategies in addition to technology performance and cost.

  Revenue and business models, as well as management strategies can be more critical to commercial success than just validation of technology performance and cost. It is essential that the Department incorporate development and validation of credible revenue/business models and management strategies concurrent with technology development activities.

- Expedite environmental and permit approvals.

  Delays and cost overruns associated with the National Environmental Policy Act (NEPA) reviews can add several years to commercialization of DOE-supported technologies and hence delay job creation and national security benefits. Pre-approved project templates could be developed by DOE and tailored for individual projects to provide faster NEPA review cycle time at less expense.

- Analyze the condition and suitability of existing infrastructure assets.

  Reliable, efficient and affordable infrastructure is essential to grow sustainable coal to carbon solid products, chemicals, fuels and REEs economic sectors. Infrastructure repairs, upgrades and improvements will likely be required for successful U.S. competitiveness and job creation in the global economy.

- Use shuttered and producing mines, coal power plants and coal communities as economic revitalization zones for new coal to fuels and products production and manufacturing centers.

  Brownfield coal mines, power plants and communities with existing infrastructure assets offer low startup costs to establish coal to chemicals, fuels, REEs and carbon products.

- Update regulations, legislation and permitting.

  Commercial deployment of the many new technologies and manufacturing capabilities envisioned in this report are at risk of being delayed due to lack of inclusion within existing laws, regulations and permitting requirements. Given that changes to existing laws, regulations and permitting requirements are generally a multi-year endeavor, it is recommended that the Department immediately identify and begin work to resolve gaps and barriers within existing laws, regulations and permitting requirements three to five years in advance of filing first plant and factory permit applications.

- Provide DOE financial support for pre-FEED and FEED projects.

  Preliminary front end engineering and design (pre-FEED) and FEED assessments can facilitate financing and development of commercial coal-to-products facilities. DOE support for FEED initiatives can strengthen and accelerate commercialization.

Chapter 4. Overseas Coal-to-Products Markets and Outlook

Key Findings

- **Nations worldwide are using coal in a variety of non-combustion applications, including production of chemicals, carbon products, transportation fuels, critical minerals and high-quality beneficiated coal.**
- **Development of technologies and markets for coal-based products can create new markets for U.S. coal exports, expanded employment opportunities in the U.S., and potential for improvements in the U.S. balance of trade.**
- **An examination of research and development (R&D) activities for non-conventional coal-based technologies in overseas markets may aid identification for similar U.S. R&D and commercialization pursuits to expand domestic markets for U.S. coal products.**

Overview

Coal has seen a multitude of uses worldwide that may be considered as non-conventional applications, here defined as those outside of power generation and steelmaking markets. Although coal has historically been used in the U.S. as a feedstock for various non-conventional applications, other feedstocks, such as petroleum and natural gas-derived products, have more recently been substituted. In international markets, however, these alternative feedstocks are often less available and more costly.

In many countries, this has led to the use of coal as a feedstock for numerous non-combustion production processes. This provides export potential for U.S. coal and coal-derived products. Additionally, coal use outside the U.S. for these applications, has led to continued new overseas R&D associated with coal-based production processes. An examination of this international research work, especially where it has led to commercial facilities, may lead to the identification of opportunities for similar deployments in the U.S. to expand both domestic and export markets for U.S. coal products.

Some current markets for coal have the potential for expansion through the type of R&D activities that produce both commercial improvements and next generation (NextGen) technologies. Among these are coal-to-liquids (CTL), fuels and coal-to-chemicals (CTC) applications, and selected materials that are currently derived to some extent from coal, such as synthetic graphite products and carbon fibers (CF).

The development of new and NextGen technologies for coal-based products can create new markets for U.S. coal producers. Examples include the production of graphenes from coal and extracting critical mineral (CM) commodities, such as rare earth elements (REEs) from coal byproducts and over/under burden.

The following is a summary examination of uses for coal outside the U.S., in key areas such as the production of CTLs, transportation fuels and chemicals, carbon products, REEs and the metallurgical sectors. A discussion of coal beneficiation with respect to these markets is also presented.

In addition to expanding the market potential for U.S. coal products, R&D within these market sectors can also lead to expanded employment opportunities within the U.S., as well as the potential to improve the U.S. balance of trade (reductions in import requirements and trade deficits).

Coal Conversion

Coal to Liquids, Fuels, Natural Gas, and Chemicals

The use of coal-derived syngas for fuels production, known as indirect coal liquefaction (ICL), dates back to the discoveries associated with the Fischer-Tropsch (FT) process in the 1920s. Developments in Germany were the subject of extensive investigation by the U.S. Bureau of Mines following World War II.[xxiii]

Sasol (South African Synthetic Oil Liquids) was formed by the South African government in 1950, with a charter to develop the capability to produce liquid fuels from South African coal reserves. In 1955, the Sasol-I plant was constructed in Sasolburg to demonstrate the technology to produce liquid fuels from coal via gasification and FT synthesis. Sasol subsequently undertook a massive program to build two large ICL facilities, Sasol II and III in Secunda. These facilities started operations in 1980 and today produce 160,000 barrels per day (BPD) of liquid fuels from about 40 million metric tons per year (MMTPY) of coal.[xxiv]

In China, R&D activities into the FT process have led to several commercial ICL projects using the FT technologies developed by Synfuels China Technology Co. Ltd. These include plants in stages ranging from development to operational, such as the Yitai Dalu and Guizhou Projects (50,000 BPD each), the Yitai HJQ Project (25,000 BPD), the Luan Project (25,000 BPD) and the Shenhua Ningxia Project (100,000 BPD).[xxv]

The combined aggregate production capacity of the referenced plants in China and South Africa is over 410,000 BPD. By comparison, U.S. crude oil refining capacity in January 2017 was more than 45 times larger at 18.6 million BPD.[xxvi]

Among the other products that can be produced from syngas is synthetic natural gas (SNG). In India, a large coal gasification project is being undertaken by Reliance Industries, Limited, which will produce multiple products from syngas, including SNG and hydrogen.[xxvii] The plant is designed to use approximately 29,000 metric tons per day (MTPD) of petroleum coke as feedstock, with the flexibility to accommodate 35% coal as feedstock[xxviii]. As such, in addition to pioneering polygeneration of SNG with other products, the facility has the potential to use significant amounts of coal.

In addition to synthetic fuels, the conversion of coal-derived syngas to chemicals is a significant practice overseas. Both methanol and ammonia are produced from coal, as products themselves or as intermediates used in turn to produce fuels and olefins, in the case of methanol, and fertilizers and urea, in the case of ammonia.

Methanol Production from Coal

As of 2017, coal accounted for 85% of the feedstock for methanol production in China.[xxix] Three years earlier, China accounted for over half of both world methanol production and consumption.

In 1985, a plant was commissioned in New Zealand, using the then Mobil (now ExxonMobil) methanol-to-gasoline (MTG) process, with a capacity of 14,500 BPD.[xxx] This technology has also been adopted in China, with a 2,500 BPD, coal-based MTG plant entering service in 2009. In China, numerous operating plants for the production of olefins and polypropylene from coal-derived methanol were reported in 2013, with more under development.[xxxi] In 2017, the Jiangsu Sailboat Petrochemical Co. Ltd. started up a methanol-to-olefins (MTO) plant with a production capacity of 833,000 MMTPY. A technology vendor for the project (UOP) forecast at the time (2017) that China would be investing $100 billion in CTC technology over the next five years.[xxxii]

Coal to Fertilizer

China, India, and the U.S. are, in that order, the largest consumers worldwide of nitrogen fertilizers.[xxxiii] By 2016, China had become both the largest producer and exporter of nitrogen and phosphate fertilizer products.[xxxiv] In 2014, 86% of Chinese ammonia production capacity was based on coal,[xxxv] and, according to China's 13th Five Year Plan, by 2020, 81% of China's urea production capacity was forecast to be coal-based.

An example of a recently constructed urea production facility based on coal gasification is the China XLX Fertilizer's Plant V in Xinjiang Province, which started up in 2015. This plant has a 520,000 MTPY production capacity.[xxxvi]

Coal-based fertilizer production in India is a decades-old practice.[xxxvii] An example of a newer project is the development of a coal gasification-based fertilizer plant by Talcher Fertilizers, Limited, at the site of an older gasification-based fertilizer plant that closed in 2002. The projected production rate for this project is 1.27 MMTPY. Feedstock is to be high ash content Indian coal, with the provision to also use up to 25% petroleum coke in the plant feed.[xxxviii]

Direct Coal Liquefaction

Direct coal conversion processes convert coal into liquids by directly breaking down the organic structure of coal. Since liquid hydrocarbons have a significantly higher hydrogen-carbon molar ratio compared to coal, DCL technologies use hydrogenation processes (with application of solvents and/or catalysts in a high pressure and temperature environment) or carbon-rejection processes (carbonization or pyrolysis). Like the family of IDCL processes, it can produce both fuels and chemicals.

DCL processes date back to the work of Friedrich Bergius from 1912 to 1926, and commercial production began in Germany in 1926[xxxix]. In 1931 Bergius was awarded a Nobel Prize for his work on chemical reactions under high pressure. By 1944, 12 DCL plants were in operation in Germany. The DCL process has been the subject of a significant body of R&D work since then, including major developments under both the U.S. Bureau of Mines and the U.S. Department of Energy (DOE).

Like other countries with vast coal reserves China had research activities in coal-to-liquids technologies dating back to the 1930s, and similarly reduced this activity when oil was cheap and plentiful and renewed interest in response to supply and price disruptions. In the 1990's China became a net importer of crude oil. Coal conversion to liquid fuels became a strategic energy supply issue and the incentive to renew development of coal-to-liquids became a priority.

In 1997 the Shenhua Group began their initial development of a DCL project. Shenhua's DCL project was initially discussed between the top leadership of the USA and China. The Chinese visited the United States' DOE and resulting from that visit, the coal liquefaction project was regarded as one of the major cooperation projects between the two countries. DOE introduced Shenhua to DOE's long-term technology partner (Hydrocarbon Technologies Inc. - HTI) in developing DCL in the US, and HTI immediately began experimentation on Shenhua's coal, and HTI signed a process license agreement with Shenhua Group for the direct coal liquefaction plant in China. However, it was ultimately decided that the DCL technology was too important to be controlled by a foreign entity and Shenhua negotiated the rights to apply the HTI technology and to further develop their own "China Shenhua DCL Technology." The plant construction was completed in 2008 and started operation in December 2008. The plant processes 6,000 tons per day of coal and produces 20,000 barrels per/day of liquid fuels (LPG, gasoline and diesel).[xl]

A second DCL project in China was started in 2015 by Yanchang Petroleum Company at their Yulin City refinery. This plant processes 1,500 TPD of coal and petroleum derived oil (about 45 % of the feed is coal).

Synfuels China Technology Co. Ltd. has been developing a hydro-liquefaction technology, known as "Stepwise". This process has been tested with low rank coal[xli] and may offer opportunities for reduced cost liquid fuels and chemical production based on U.S. low rank coal.

Coal Conversion Outlook

Syngas production for synthetic fuels, fertilizer and methanol – including that produced from coal – is expected to continue to increase through 2030.[xlii] Asia is expected to dominate the growth in coal-based syngas production.

The DCL process, which bypasses the intermediate step of producing syngas, may offer opportunities, notably with low rank coals which can present gasification challenges.

Carbon Products

Electrodes, Graphite Products and Carbon Fiber

Coal has a long history of use as a feedstock for the production of carbon materials. Parallel with this history has been R&D activities oriented toward coal use as feedstock for carbon materials. Coal products are used as feedstock for amorphous and graphite furnace electrodes used in metallurgical applications, activated carbon products and carbon fibers. New applications such as graphene and carbon foams can present new market opportunities for coal as a feedstock for these products.

The most significant international developments related to synthetic graphite products have included the diminishing U.S. production of coal-derived pitch products, along with needle coke shortages. Current U.S. production capacity of coal tar pitch is likely less than 250,000 MTPY, compared with world coal tar pitch production in 2016 estimated at 6.7 MMTPY, and projected at that time to grow to 8.1 MMTPY by 2020.[xliii]

Another international development of note has been the tightening of the needle coke market. In addition to use for furnace electrodes, needle coke is used in the production of graphite for lithium-ion batteries. In 2012, the worldwide petroleum-derived needle coke market was estimated to be 1.2 MMTPY.[xliv] Demand for needle coke for battery applications has been growing, leading to a tight market.[xlv] The demand for both furnace electrodes and graphite for batteries is expected to grow through 2028,[xlvi] which, absent additional production capacity, is expected to further tighten the needle coke market.

While developments such as diminished domestic pitch production and tightening of the needle coke market will have potential impacts on U.S. production of synthetic graphite products, there have been significant R&D activities overseas related to both of these topics. In Japan, Mitsubishi Chemical Corporation developed pitch coke, anode coke and CF precursors based on coal tar (pitch-based fibers). In the case of pitch coke, the product is used in the production processes for semiconductors and solar panels.[xlvii] The company manufactures carbon anodes for lithium-ion batteries and pitch for CFs, produced from coal products. While the majority of carbon fiber production is not based on pitch, this is notable as synthetic graphite products and carbon fibers can share a common coal-derived feedstock.

An additional development that has originated in Japan is the investment in two new CF plants in South Carolina (by Teijin and Toray Industries), adding production capacity in a region that has hosted CF production plants since 1981.[xlviii]

Himadri Specialty Chemical Ltd. produces coal tar pitch and other carbon products, and has a significant R&D activity aimed at expanding their product offerings. Results include the development of special pitch products, including one that has been developed for aerospace applications. Development of anode materials for lithium-ion batteries is among the company’s current R&D activities.[xlix]

Amorphous carbon electrodes for ferroalloy and silicon metal furnaces, and cathodes for aluminum reduction furnaces, use calcined anthracite, produced in electric calcining furnaces. While U.S. production capacity for electrically calcined anthracite (ECA) has been disappearing, overseas ECA production facilities remain an important export outlet for U.S. anthracite producers.

While U.S. aluminum production from primary smelters has been declining for decades, worldwide primary aluminum production in 2016 was 59 MMTPY.[l] Were U.S. coal products to be available with the properties required of anode cokes (notably low ash content), this could result in the development of a new export market for the U.S. coal industry.

Activated Carbon

Environmental and health considerations are the key drivers of activated carbon use to provide clean air and water. Developing countries are expected to expand their activated carbon consumption as environmental controls are implemented. The global activated carbon market in 2017 was reported at $2.8 billion.[li]

The global activated carbon market is expected to grow to over $6 billion by 2023. According to the IEA[lii] global production of activated carbon was greater than 3.7 billion pounds in 2017. Production is documented by the U.S. International Trade Commission (ITC)[liii] in China, India, Indonesia, Japan, Philippines, Sri Lanka, Australia, The Netherlands and Germany, in addition to the significant U.S. production discussed in Chapter 5. This important coal-derived product has several emerging growth markets.

Carbon Products Outlook

Worldwide growth in demand is forecast for the range of synthetic graphite products, including furnace electrodes and battery applications, as well as other products requiring the material such as refractories and shapes.[liv] While needle coke derived from petroleum is preferred for high-end applications, such as ultra-high power (UHP) furnace electrodes[lv], needle cokes derived from coal find other applications. With the forecast growth in demand for premium needle coke, the development of coal-derived needle coke products for the high-end market could assist U.S. coal producers and manufacturers in accessing this market, where the product sells for a considerable premium.

The decline in U.S. coal tar pitch production has resulted in constraints in both supply and demand. However, increased demand due to global production of graphite products, absent dramatic reductions in demand from the worldwide aluminum industry, will likely at least maintain the market for pitch. The use of alternate technologies to extract pitch from coal within the U.S. may create export opportunities for the product.

Currently, carbon fibers are generally higher cost but CFs are experiencing the fastest growth rate in the overall fiber market. Pitch-based CFs offer greater strength than polyacrylonitrile (PAN)-based CFs. This provides an opportunity for coal to meet the high-strength-to-weight ratio needs in aerospace, automotive, civil engineering, military and motorsports.

Market opportunities for coal-to-products could allow for U.S. coal products to enter the value supply chains for significant and, in some cases, growing markets. Work has been undertaken in these areas with respect to U.S. coal by both the U.S. Bureau of Mines and DOE. Building on this body of research, which is reviewed elsewhere[lvi], could offer early opportunities to get research results into the marketplace, with attendant jobs benefits for the U.S. economy and coal industry.

Rare Earth Elements

International Rare Earth Element Research and Coal

Currently, the U.S. is virtually 100% import-dependent for raw materials for its rare earth element-based manufacturing sector, mostly from China. In May 2018, the Department of Interior (DOI) published its "Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy"[lvii], which was compiled in response to White House Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals." Some items on the Critical Minerals list, such as vanadium and germanium, have been commercially extracted directly from coal products. In other cases, coal is used as a reagent in the extractive metallurgy processes used to produce these commodities.

The concept of producing REEs from coal, over/under burden and coal byproducts has attracted attention internationally. A review of the presence of REEs in coal measures worldwide was the subject of a publication by the China University of Mining and Technology and the Russian Academy of Sciences in 2012.[lviii]

With respect to international technology development, activities have the potential to impact both REE extraction from coal, over/under burden, and coal byproducts, as well as the use of coal as a reagent in extractive metallurgy processing.

An example of the former – which would allow for REE extraction from REE-rich underclays – is the pressure leaching process developed by Orbite Technologies in Canada.[lix] This process, for which a pilot plant has been constructed in Quebec, is intended to co-produce multiple products, including alumina, gallium, and scandium, along with an REE concentrate. Aluminum smelter feedstock, gallium and scandium, are also on DOI's CM list.

International technology development activities have also involved coal use in REE extractive metallurgy. Frontier Rare Earths (Luxembourg) and Outotec (Finland and Germany) have developed an integrated, coal-based acid roasting and calcination process, currently envisioned for use at a REEs production project in South Africa.[lx]

Rare Earth Elements Outlook

Rare earth elements that are commercially produced include 14 different elements that occur together in nature and are produced together. Different elements find uses in different applications and the market is complex. However, market forecasts are available for the suite of REEs in aggregate. Examples of these market forecasts are also work products of overseas research.

One forecast from China's University of Science and Technology Beijing produced aggregate demand growth forecasts for REEs, ranging from 70% to 140% between 2012 and 2030.[lxi] The growth in worldwide demand for REEs is expected to produce opportunities for new mineral sources. New extractive metallurgy operations that use coal in the process can also drive increases in world coal demand. Should sufficient REE concentrations be found in the U.S. coal reserves, this will create a new market for the materials produced by coal mining operations. The development of coal-based extraction technologies, in pyrometallurgical operations such as roasting and calcining, can produce new market opportunities for U.S. coal products.

The Metallurgical Sector

Coal products are used today in both ferrous and non-ferrous metals production worldwide. Many of the metallurgical processes that have resulted in the development of markets for U.S. coal product have been the result of overseas technology development activities. These activities date back to the original blast furnace installations in the U.S. that used hot blast furnace technology imported from the United Kingdom in the 19th century.

International technology development work resulting in markets for coal products in metallurgy applications include the following examples:

- The Waelz Kiln - This process was developed in Germany, originally for the recovery of zinc from low-grade ores. More recently, the listing of EAF dust, a steelmaking byproduct, under the Resource Conservation and Recovery Act (RCRA), has led to the adaptation of the Waelz kiln for the recovery of lead and zinc from a RCRA listed material. As such, elimination of hazardous waste became a new market of U.S. coal products.
- The Quebec Iron and Titanium (QIT Fer et Titane) (QIT) Process - Is a pre-reduction-electric arc smelting system for the production of pig iron and titanium-rich slag from ilmenite, and has resulted in a significant market for U.S. anthracite.
- The Basic Oxygen Furnace (BOF) - Also known as the Linz–Donawitz (LD) vessel, this oxygen-blown version of the Bessemer Converter was developed in Austria by a precursor of Voestalpine AG (Austria). In addition to being the workhorse converter for integrated steelmaking worldwide, practices have developed where coal products are added directly to the BOF, to allow for higher scrap charges to the converter. This has resulted in a new application for U.S. coal products.
- Oxygen/Carbon Lance Technologies for EAF Steelmaking - The injection of coal products with oxygen into an EAF can speed up scrap melting, reduce tap-to-tap times, and reduce electric power consumption. In the U.S., the electric arc furnace accounts for two-thirds (2/3) of domestic steel production. An example system was developed by Danieli (Italy). While EAF steelmaking eliminates the need for the blast furnace and its coke requirements, the adaptation of EAF lance coal injection by the steel industry has led to the development of a new coal market.
- The Elkem Electric Calcining Furnace - The Elkem (Norway) calcining furnace is used to calcine anthracite for use in cathodes and ramming paste at primary aluminum smelters, as well as for electrodes for ferroalloy and silicon metal smelters. This development has led to a significant market for U.S. anthracite.
- Top Submerged Lance Technology - This is an Australian development with numerous applications in non-ferrous metallurgy, including the production of lead, zinc, copper and nickel. Depending on the application, coal can be a requirement. One type, the Ausmelt system, has been installed 64 times at worldwide locations.

Metallurgical Applications Outlook and Opportunities

New extractive metallurgy technologies are continuously under development worldwide. These have had a nearly two century impact on the U.S. coal industry and new developments can continue to provide new markets for U.S. coal products. The production of some metals can be expected to grow as new applications are found, notably in applications such as electronics.

Worldwide technology developments can provide opportunities to leverage additional work aimed at optimizing new processes around characteristics of U.S. coal products, such as:

- Silicon metal smelting, where low ash coal with special properties is required.
- Carbothermic aluminum reduction process development, as an alternative to the Hall-Heroualt Process.
- Coal-based roasting processes for high value metals, such as the REE process discussed earlier.
- Direct steelmaking processes.

Summary: How Technology Development has Expanded Coal-to-Products Markets Internationally

International technology development activities have resulted in the growth of substantial markets for coal in non-conventional uses, such as chemicals, fertilizers, fuels, REEs and other products. While coal products are used in some applications in the carbon industries, there is potential for market growth in that sector through R&D activities, notably involving the production of needle coke and anode coke, and pitches as precursors for CFs and other carbon products.

International technology development in the extractive metallurgy field has resulted in expanded market reach for U.S. coal products, notably in non-ferrous metals production.

Chapter 5. Historical Perspective on U.S. Coal-to-Products Efforts

Key Findings

- **Coal has a long history in the U.S. as a versatile carbon feedstock used for production of various products ranging from chemicals, synthetic natural gas, metals and building materials, to plastics, medications and photographic film.**
- **Abundant, low-cost U.S. coal reserves, in combination with both advanced material and advanced manufacturing technologies, hold significant promise for the future use of coal as a feedstock for carbon-based, value-added products, including new carbon products, chemicals, fuels, critical minerals and rare earth elements key to national security interests.**
- **Historically, U.S. coal conversion and coal-to-products initiatives have achieved varying levels of success. The most successful efforts have resulted from cooperative public-private partnerships. Among the factors that have delayed or hindered initiatives are the risks and costs associated with First-of-a-Kind (FOAK) technology deployments, changing market conditions, extensive environmental and construction permitting requirements, and difficulties obtaining project financing.**
- **Redirecting the use of U.S. coal resources into new markets outside of power generation and steel/coke-making has potential to open up new domestic and export markets for the U.S.**

Introduction and Overview

Coal is a very versatile feedstock and technologies exist to convert coal by various means into almost any end product achievable from oil or natural gas, and in some cases into products unique to coal. Development of these coal technologies reach back to the earliest years of U.S. republic and have been driven over time by a combination of private industry funding, as well as public funding from state and federal governments and agencies, and academia.

Historically, coal in the U.S. has been used as feedstock for chemical, carbon and metal products. Coal combustion byproducts have, among other uses, been incorporated into cements and concrete mixes used in construction. The use of coal products in fertilizer production has added it to agricultural value chains. Consumer products derived from coal span a wide spectrum of products including photographic film base, performance polymers, flat-screen televisions, pain relief medications, adhesive tape, high-end fashion fibers, shampoo, wood preservatives, graphite, activated carbon and carbon fibers (CFs).

In the U.S., the production of numerous commodities was, in the past, based on coal feedstocks. Technology and infrastructure advances associated with petroleum and natural gas over time yielded more favorable and cost-effective competitive positions of those feedstocks compared with coal in a number of domestic markets, such as chemicals and fuels production. In other U.S. markets – notably those associated with metals production – the introduction of newer technologies, such as the electric arc furnace (EAF), created an alternative to the traditional large volume coal product (furnace coke in the case of metals). Ironically, the availability of low-cost electric power from coal in the U.S. also played a role in the adoption of EAF technologies.

U.S. coal products are well established in domestic power generation and steel/coke markets, as well as in export markets based on these applications. Coal also has some inherent advantages in non-fuel coal markets, including the offering of a full range of coal ranks (involving volatile matter and moisture contents). Recently, coal-based power generation has been under domestic market pressure due to competition from cheap abundant natural gas. U.S. coal consumption has gone from a peak of about 1.2 billion tons to 700 million tons in recent years and could fall to as low as 400 million tons by 2030.[lxii] Reducing the production and transportation costs and/or improving the quality of various coal products can help enhance the competitive positions of the end uses of coal-derived products, in turn helping to preserve these markets for U.S. coal producers and improving the competitive position of U.S. coal for these and other applications in export markets.[lxiii]

The continued abundance of low-cost U.S. coal reserves and recent advances in technology are once again favorably positioning coal as a potential feedstock for higher value-added products, particularly those that are heavily carbon-based, and as a source of critical minerals (CMs), including rare earth elements (REEs). Potential technology advances related to coal upgrading are also making U.S. coals more attractive for export markets.

This chapter addresses the historical perspective and recent developments related to U.S. efforts for coal-to-products applications.

Coal Beneficiation

Overview

Coal beneficiation, as included in this report, refers to upgrading coal quality characteristics. Coal quality requirements for non-conventional markets can differ significantly from those required for power generation applications. Coal in the latter use is a source of energy with its calorific value being the key quality parameter. Coal quality requirements for non-conventional markets, on the other hand, are governed by its use in equipment such as gasifiers, its use as a metallurgical reductant, and its use as a source of carbon.

Coal ash content/composition, volatile matter content and moisture will all have an effect on coal utilization for fuels, chemicals, carbon products and extractive metallurgy. These coal quality characteristics are addressed in Appendix A.

R&D activities associated with coal upgrading have a long history and range from basic research to attempts at commercialization. Basic research aimed toward improved understanding of physical phenomena in commercial coal prep systems has led to substantial operational improvements, notably led by the work of the U.S. Bureau of Mines and Department of Energy (DOE).

An abundance of fundamental information has been generated on the behavior of coal in thermal processing systems and on the subject of coal interactions with solvents.[lxiv] Many successful commercial technology introductions have occurred over the past couple of centuries, often involving coal mining companies working in cooperation with federal agencies. More recent technology development efforts have led to a number of demonstration projects.

Market conditions, notably the potential for new applications for materials produced through coal mining, may create new opportunities for processes that have been either the subject of R&D or past commercial application. Examples could include the extraction of pitch for CF applications, or the production of coal with a very low ash content.[lxv]

The DOE published a comprehensive report[lxvi]in March 2018 on the history and opportunities associated with coal upgrading technologies. This report informed much of this chapter section and can be referenced for additional details on the subject.

Physical (Gravity) Separations

The dominant method by which coal upgrading has taken place in the U.S. coal industry is through physical or gravity separation of non-coal particles from run of mine material, which results in an ash content and sometimes a sulfur (S) and/or mercury (Hg) content reduction of the finished coal product.

Physical separations can be broken into several major categories:[lxvii]

Dry Processes	**Water-Only Processes**	**Dense Medium Processes**	**Froth Flotation**

• Crushing, screening, sorting
• Dry spirals
• Air tables
• Electrostatic
• Magnetic
• X-ray luminescence
	• Jigs
	• Concentrating tables
	  ○ Bumping table
	  ○ Reciprocating motion table
	• Hydrocyclones
	• Wet spiral separators
		• Static bath
		• Dense medium cyclones
		• Dense medium types:
		  ○ Sand
		  ○ Magnetite
		  ○ Pyrite cinders
		  ○ Ferrosilicon
		  ○ Organic liquids
		  ○ Salt solutions
			• Traditional tank systems
			• Column flotation systems
			• Various additives used to enhance performance

These separation processes have been developing for over a century. In the 1800s, dry processes predominated, including crushing and screening, often with hand sorting of coal from rock. Mechanical dry processes were introduced starting in the early 1920s. More modern dry separation processes include electrostatic separation processes, dry magnetic processes and X-ray transmission sorting processes.[lxviii] Electrostatic separation has been used to make low ash feedstock for carbon products and has been examined for both coal upgrading and recovery of REEs from coal byproducts.[lxix]

Water-only separation systems work with suspensions of the feedstock in water. The earliest of these processes, jigs, were introduced in the early 1870s[lxx]and are primarily used for cleaning coarse coal sizes.

Dense medium systems, now used broadly for coal upgrading, use liquids with specific gravities greater than water to create a suspension. The first dense medium system in the U.S. was installed in 1921.[lxxi] More recent R&D work on dense medium systems has included attempts to separate coal and rock with liquid carbon dioxide[lxxii] and the development of a process using micronized magnetite.[lxxiii]

Froth flotation, selectively removes as a floating product the solids that adhere to introduced bubbles. The use of such froth flotation separation dates to the late 19th century.[lxxiv] U.S. commercial application for coal cleaning dates back to 1930.[lxxv]

As of 2015, there were 268 coal prep plants in the U.S., with an aggregate installed capacity of over 200,000 tons per hour (TPH). Current physical separation methods include dense medium vessels, jigs, and large-diameter dense medium cyclones for coarse coal (>10 millimeter (mm)), dense medium cyclones and jigs for intermediate (10 - 1 mm) sizes, spirals and water-only cyclones and tables for fines (1 - 0.15 mm), and flotation for ultra-fines (<0.15 mm).[lxxvi]

Thermal Treatment Processes

A reduction in coal moisture by thermal drying improves the heating value of the coal, reduces coal flow to boilers, improves unit efficiency, plant operation and economics, and reduces emissions. Configurations for coal thermal drying systems include fixed bed, rotary bed, fluid bed, and entrained flow systems.[lxxvii] However, many traditional thermal processes were either mechanically complex or required costly primary energy or steam to remove the moisture. Thermal drying of bituminous and anthracite coal products has been a commercial practice for decades, including for the production of carbon products and steel.

Recent innovations in coal drying have included the successful demonstration of the use of low-grade power plant heat for moisture reduction of lower rank coals.[lxxviii] Advanced thermal drying of low rank coal has been in continuous commercial practice by Great River Energy since 2009.[lxxix] This DryFining™ system, the result of a DOE-sponsored demonstration, uses low-grade heat from a power plant to dry 1100 TPH of lignite in a 2-stage moving fluid-bed drying process and has operated with over 95% availability.[lxxx]

Carbonization processes in the U.S. are currently used for the production of metallurgical coke. Low-temperature carbonization was first commercially practiced in 1933[lxxxi] and in the 1950s collaboration among the U.S. Bureau of Mines, Alcoa, and Texas Power and Light led to the construction of a prototype low temperature carbonization system for lignite.[lxxxii] The plant was built to produce tar for market studies, and a pilot plant was added to investigate the upgrading of recovered tar to salable products.[lxxxiii] More recent developments in low-temperature carbonization have included demonstrations of the liquids from coal (LFC) and advanced coal conversion process (ACCP) technologies.[lxxxiv]

Thermal processes at temperatures above those for carbonization can be used to produce carbon aggregates. The typical application is mixing with a binder and further high-temperature processing to produce electrodes and refractories. Calcination is used commercially to heat treat carbon products, with an attendant improvement in electrical conductivity.[lxxxv]

Research into graphitization has included the use of coal, notably anthracite. The current aggregate used in graphite electrode formulations – needle coke typically derived from petroleum – has been subject to adverse price and availability constraints. Graphite electrodes are used in the U.S. steel and aluminum smelting industries, and any electrode cost reductions that could result from the production of coal-based graphite electrodes could help improve the competitiveness of the U.S. domestic steel industry.[lxxxvi]

Chemical Extraction Processes

Chemical extraction processing of coal products involves the use of a solvent to selectively extract constituents from the rock. Extraction with organic solvents can be applied to produce organic products such as liquids or pitches from coal, and inorganic solvents can be used to extract metal values and remove mineral constituents associated with coal sediments.

The application of inorganic solutions to leach metal values from rock is a commercial practice that dates back over 100 years.[lxxxvii] Inorganic solvents have been used at an industrial scale for the production of low-ash anode carbon for aluminum smelting. Extraction of coal with organic solvents dates back to U.S. Bureau of Mines work in the early 20th century.[lxxxviii] Extraction with organic solvents at elevated temperatures and pressures can be used to produce pitch[lxxxix], and when hydrogen is also added to the system can be used to produce feedstocks for liquid transportation fuels (e.g., DCL).

Chemical extraction processes offer the potential to significantly broaden the slate of products that can be produced at U.S. coal mines.

New Technology Developments

Examples of some of the more promising new technology developments in the coal upgrading area include the following:[xc]

- Clean Coal Technologies, Inc. Pristine™ Technologies[xci]- Processes that remove moisture and volatiles from lower rank coals, then reabsorb some of the volatiles into coal pores to produce a stable high quality and cleaner burning dry coal product.

- LP Amina BeneficiationPlus™ Process[xcii]- A thermal process that pyrolyzes coal in a fluid-bed system, producing liquids, gases, and a dry, partially devolatilized char. Liquids and gases can be refined to make value-added products or generate heat or power.
- Western Research Institute's WRITECoal™ Process [xciii]- A thermal process for water and Hg removal. Products are a dried power plant fuel with reduced Hg content and recovered water that can be used for process purposes. As an alternative to power generation, the solid process product can be pyrolyzed and the volatile products processed to produce feedstock precursors for production of CF and other carbon products.
- H Quest Vanguard, Inc.'s Wave Liquefaction™ Process[xciv]- This thermochemical process involves use of microwave/radio frequency (RF) plasma to enable rapid pyrolysis (carbonization) of coal and natural gas in a modular reactor to produce value-added liquid products and a char that can be used as fuel or for carbon product applications.
- Great River Energy's DryFining™ Process[xcv]- This process integrates thermal processing and physical separation. The heart of the system is a two-stage moving fluid-bed dryer accomplishing two functions: it cleans the coal by removing a significant portion of S and Hg from the coal in the first stage via an air jig and dries the coal in the second stage. The cleaning function, accomplished by gravitational segregation in a fluidized bed, distinguishes this technology and provides a very important co-benefit of emissions reduction. As mentioned previously, this technology has been in successful operation using low-grade heat from a power plant since late 2009.
- Minerals Refining Company's Hydrophobic-Hydrophilic 2-Liquid Separation Process[xcvi] – This novel process, developed at Virginia Polytechnic Institute and State University, utilizes a combination of hydrophobic and hydrophilic liquids to separate very fine (too fine for froth flotation) coal and mineral particles from non-coal/ash particles and provides a dry coal product following solvent recovery.

In addition to these technology developments, the DOE National Energy Technology Laboratory (NETL) has been developing an American Coal Properties Database, drawing on data and expertise from the DOE National Labs and academia to provide detailed technical information on the impact of coal properties and composition on power plant performance and emissions. The database will centralize detailed information on U.S. produced coal to facilitate its use domestically and abroad by helping potential users understand the impacts of its use in a wide variety of applications including value-added products from coal.[xcvii]

Coal Conversion to Fuels and Chemicals

Early History

U.S. development of coal-to-products market applications for coal began as early as 1816, when the Gas Light Company of Baltimore was founded and began providing town gas (early SNG) made from coal to light the streets of Baltimore, Maryland.[xcviii] By the 1850s, many small to medium-sized cities had a coal-based gas plant to provide for street lighting and eventually for gas cookers and stoves. Byproducts of town gas production were eventually recovered and utilized for chemical and dye applications. However, developments in oil and gas exploration led to the eventual phase out of coal-based town gas by the early-mid 1900s.

In the winter of 1922-23, a major disruption in U.S. coal supply due to labor disputes led to an increased shift by consumers to oil and natural gas.[xcix] Developments from World War I had also led to an increased use of petroleum fuels for vehicles and aircraft. This placed a strain on domestic oil and gas production and led to concerns about long-term resource availability of oil and gas. At the same time, new developments were occurring in Germany for the conversion of coal-to-liquids (CTL) fuels through processes such as the Bergius direct coal liquefaction (DCL) direct coal hydrogenation process and the Fischer-Tropsch (FT) indirect coal liquefaction (ICL) process for conversion of syngas (from coal) to liquid fuels.

The U.S. Bureau of Mines took the lead in exploring two potential substitutes for petroleum: liquid fuels from oil shale and liquid fuels from coal. At the Pittsburgh Experiment Station, chemists organized a small group to work on CTL conversion, and by 1926, had equipped a laboratory for producing small quantities of water gas (consisting of CO and H_2) and observing how the gas components reacted to different catalysts at varying temperatures and pressures.[c]

The synthetic liquid fuels group initially chose to study the synthesis of alcohols (such as methanol) and liquid hydrocarbons from water gas. Its experiments verified that the process could yield methanol of high purity and that this methanol could be further converted into DME that had potential as a motor fuel. The synthetic liquid fuels group also began investigating the Bergius direct coal hydrogenation process in 1928 and did preliminary work on the conversion of water gas into methane. However, the coming of the Great Depression halted the research program. Some work on low-temperature coal carbonization, synthetic methanol, and the Bergius-I. G. Farben process continued, but a shortage of funding after 1931 obliged the scientists to concentrate on other projects. The economic collapse coincided with the great petroleum discoveries in Oklahoma and East Texas, with the result that energy prices fell and the likelihood of petroleum shortages seemed more remote than ever.[ci]

Concerns over Germany's military build-up prior to World War II, and use of coal to fuel it, led U.S. Secretary of the Interior Harold Ickes to identify coal hydrogenation as a top research priority for the Bureau of Mines, and in 1935 he asked Congress to fund a 100 pound per day hydrogenation pilot plant at the Pittsburgh Experiment Station and to conduct a hydrogenation assay of domestic coals. Crude oil from the pilot plant yielded up to 7 gallons per day of gasoline. The hydrogenation assay confirmed that hydrogenation could work across a wide range of coals, indicating that most of the country's vast coal reserves qualified as raw material for synthetic liquid fuel production.[cii]

Synthetic Liquid Fuels Act (1944)

Following War World II and Germany's successful program for converting coal to liquid fuels, the U.S. Synthetic Liquid Fuels Act was approved on April 5, 1944.[ciii] The Act authorized $30 million in funding over a five-year period to construct and operate demonstration plants to produce synthetic liquid fuels from coal, oil shale and renewable raw materials. The Act directed that the demonstration plants be of a size suitable to provide the necessary cost and engineering data for the development of a synthetic liquid fuel industry. In 1948, Congress extended the Act to eight years and doubled the funding and in 1950, Congress approved a second amendment adding another $17.6 million.

To begin implementing its new program, the U.S. Bureau of Mines expanded laboratory work it had been conducting near the Carnegie Institute. The work was transferred to new laboratories created in Pittsburgh, Pennsylvania and Morgantown, West Virginia. In addition, two coal-to-oil plants were constructed at a renovated site in Louisiana, Missouri:

- A 200 BPD direct coal hydrogenation plant that produced 1.5 million gallons of synthetic gasoline from 1949-1953.
- An 80 BPD FT plant, started up in 1951 that transformed coal into a gas, then chemically rearranged the gaseous molecules into liquid fuels and chemicals, and produced 40,000 gallons of liquid products.

The Morgantown facility also built and ran a pilot scale gasifier capable of processing 500 pounds per hour of coal. In parallel to these efforts, in 1952, the nation's first privately built and operated coal hydrogenation plant began operating at Institute, West Virginia. Constructed by the Carbide and Carbon Chemical Company (later to become Union Carbide), the plant could process 300 tons of coal daily. From 1952 to 1956, the plant produced chemicals from coal.

In 1953, Congress ceased funding for the Synthetic Liquid Fuels Program as America’s energy sights and supplies were shifted towards massive oil reserves that had been discovered in the Middle East. For the remainder of the 1950s and early 1960s, coal and synthetic fuels research was relegated to low-priority fundamental studies, but the knowledge gained during this period proved to be valuable when the nation's coal research program was rejuvenated in 1961, with creation of a new Office of Coal Research within the U.S. Department of the Interior (DOI).

1970s Oil Crises

The oil crises of the 1970s – results of the 1973 Arab Oil Embargo and the 1979 Iranian Revolution – led to severe shortages of oil, and drove prices to record levels. In 1975, the Energy Research and Development Administration (ERDA) was created and brought together for the first time the major programs of research and development for all forms of energy.[civ]

From the DOI came the Office of Coal Research and from the Bureau of Mines the energy centers and the coal liquefaction and gasification programs. In 1975, the first national energy plan from ERDA was developed, including plans to accelerate capabilities to extract gaseous and liquid fuels from coal and shale.

Starting in 1977, the energy crisis stimulated several major new pieces of legislation, including the Energy Security Act of 1980 (ESA). On April 18, 1977 President Jimmy Carter announced a new National Energy Plan. His plan called for the establishment of an energy department in the executive branch, in order to assure coordinated and effective administration of federal energy policy and programs. In August of that year, Congress enacted the DOE Organization Act, which established the U.S. DOE, supplanting the short-lived ERDA.[cv]

The new DOE embarked on a major DCL campaign which lasted over two decades. Results of this campaign are described in a report prepared by experts from Consol Energy and Mitretek Corporation and published by DOE in 2001.[cvi] In the report, the experts analyzed the costs and benefits of the DOE DCL effort and concluded that the program achieved many of its objectives, resulting in substantial improvements in process performance (e.g., yields), economics and the risk level reduction associated with commercial deployment, to the extent that DCL represented a technically available option for the production of liquid fuels. In addition, considerable research was directed toward a better fundamental knowledge of coal chemistry, and to identify and explore novel liquefaction concepts.

The ESA created the congressionally chartered United States Synthetic Fuels Corporation (SFC). The SFC was established to create a financial bridge for the development and construction of commercial synthetic fuel manufacturing plants that would produce alternatives to imported fossil fuels. The ESA established a national goal of achieving a synthetic fuel production capability of at least 500,000 BPD of crude oil by 1987 and at least 2,000,000 BPD of crude oil by 1992. The projects were to convert the nation's coal, oil shale, and tar sands resources into synthetic fuels as substitutes for natural gas and petroleum. Congress planned to fund the corporation with up to $88 billion during its expected period of existence from 1980 to 1992. The SFC had authority to provide financial assistance via purchase agreements, price guarantees, loan guarantees, loans and joint ventures. The SFC funded four synthetic fuels projects, none of which survive today, but at least two of the projects (Coolwater and Dow Syngas projects) helped support future coal gasification projects in the U.S. and abroad. With the election of Ronald Reagan as President, coupled with a return to more normal oil prices and supply, emphasis on the SFC diminished and it closed its doors in 1986.[cvii]

However, the 1970's oil crises did spur two ultimately successful commercial coal conversion deployments and served as a driver for several other early coal conversion developments. Eastman Kodak Company, concerned that it would lose access to the oil needed for producing its valuable photographic film base, decided to construct a coal gasification facility at its Kingsport, Tennessee manufacturing site (now Eastman Chemical Company) that at the time used Texaco-design (later acquired by GE) gasifiers to produce syngas for conversion into methanol and acetyl chemicals (methyl acetate, acetic acid, and acetic anhydride). Acetyl chemicals are attractive for coal-to-chemicals (CTC) conversion because they are able to utilize a high percentage of the coal's carbon, reducing by-product CO_2 emissions. The Eastman facility started up in 1983 and has been very successfully operated ever since that time. The plant has had one of the best coal gasification operating records in the world, consistently achieving on-stream availabilities of 98-99% and achieving over 150% of its original nameplate capacity.[cviii] In 1997, a DOE-sponsored liquid-phase methanol process commercial demonstration facility was constructed and operated at the Eastman site (further described below).

In parallel to the efforts by Eastman, the Great Plains Synfuels Plant (Synfuels Plant), owned and operated by Dakota Gasification Company (Dakota Gas) – a subsidiary of Basin Electric Power Cooperative, and located near Beulah, North Dakota – began operation in 1984.[cix] The project benefited from a DOE federal loan guarantee, which enabled the project to move forward after struggling to obtain adequate commercial financing for such an FOAK project.

DOE also owned and operated the facility for a brief period (July 1986 until December 1988) after the original financing fell through and before selling it to Dakota Gas.[cx] The Synfuels Plant converts North Dakota Lignite into pipeline quality natural gas and is integrated with the adjacent Antelope Valley Station (AVS) electrical generating plant. The Synfuels Plant produces and sells more than 54 billion standard cubic feet (SCF) of SNG per year.[cxi] In addition, Dakota Gas has an ever-expanding product line that has helped improve the economics of the plant and reduce the sensitivity to natural gas prices. These non-SNG products include liquid nitrogen and krypton and xenon gases captured from the air separation unit, fertilizers (including anhydrous ammonia, ammonium sulfate, and urea), CO_2, and chemicals such as dephenolized cresylic acid, naphtha, phenol, and tar oil.[cxii]

The Synfuels Plant began selling CO_2 for enhanced oil recovery (EOR) and geologic storage in the Weyburn and Midale oil fields in Southern Saskatchewan in 2000, transported via a 205-mile pipeline with a daily capacity of up to 165 million SCF. About 2.5 million tons of CO_2 per year is captured, which is ultimately stored in geologic formations as a result of the EOR operations. Additional targets for CO_2 EOR from the Synfuels Plant, as well as from potential carbon capture at nearby power plants, are under consideration in conventional oil fields of the region. Technology for use in the Bakken and Three Forks shale oil formations is under development.[cxiii]

Clean Coal Technology (CCT) Demonstration Program (1987)

The CCT Demonstration Program, adopted in 1987, was established to demonstrate the commercial feasibility of new advanced coal-based technologies with enhanced operational, economic, and environmental performance. The program consisted of 40 cost-shared projects selected through five competitive solicitations. These projects resulted in a combined commitment by the federal government and the private sector of more than $5.6 billion (DOE's cost-share was approximately 34%).[cxiv]Two of the most successful projects produced liquid fuels from coal:

- ENCOAL® Liquids from Coal (LFC™) Process[cxv]– This 1,000 TPD mild coal gasification facility was built near Gillette, WY in 1992. The process technology utilized low-sulfur Powder River Basin (PRB) coal to produce two new fuels: Process-Derived Fuel (PDF™) and Coal-Derived Liquids (CDL™). The products, as alternative fuel sources, are capable of significantly lowering current sulfur emissions at coal boiler sites. CDL is also an acceptable substitute for heavy industrial fuel without further processing, or can be fractionated into major constituents, including valuable chemicals. The facility processed 246,900 tons of coal and produced 114,900 tons of PDF™ and 4,875,000 gallons of CDL™.

- Liquid-Phase Methanol (LPMEOH™) Demonstration Project[cxvi]– This commercial demonstration project was sponsored by an Air Products and Chemicals, Inc. and Eastman Chemical Company partnership. The project utilized Air Products' LPMEOH™ technology and was located at Eastman's chemicals-from-coal complex in Kingsport, TN. The process was developed to enhance electric power generation using integrated gasification combined cycle (IGCC) technology, by co-producing methanol when full power generation capacity was not needed. The demonstration project reached nameplate capacity (260 TPD of methanol) just four days after initial startup and produced more than 100,000,000 gallons of methanol that Eastman used to produce valuable acetyl chemicals, making it one of DOE's most successful demonstration projects. The facility is still in commercial operation today.

Other Private Industry Initiatives

In mid-2000, Farmland Industries started up a 1,084 TPD, petroleum coke-fueled gasification facility to produce hydrogen for conversion to ammonia and urea ammonium nitrate fertilizers. The facility utilized the original gasifier from the SFC's Coolwater project, but in modified form, as one of its two gasifiers. Although the facility has been primarily fueled by petroleum coke, it is essentially identical to coal-fueled facilities and thus worthy of mention here. The facility is now operated successfully at high on-stream availability by CVR Partners LP, a subsidiary of Coffeyville Resources.[cxvii]

In the past couple of decades, there have been a number of other projects for conversion of coal (or in some cases coal and/or petcoke) to fuels or chemicals that progressed to significant levels of project development, but each failed to reach commercial reality because of cost economics and economic conditions. Some of the most promising of these proposed projects were:

- Eastman Chemical Company's proposed polygeneration project in Beaumont, TX:[cxviii] Planned to produce hydrogen, methanol, ammonia, and electric power and steam from over 2 MTPY of coal and/or petcoke, with 90+% CO_2 capture for use in EOR. The project made it through detailed front-end engineering and design (FEED) and received a number of federal and state incentives, including a DOE loan guarantee, before being dropped as a consequence of the 2008 financial collapse.
- Summit Power's proposed Texas Clean Energy Project near Odessa, TX:[cxix] Planned to co-produce 400-Megawatt (MW) of electric power and 700,000 TPY of urea, along with 90% CO_2 capture for use in EOR. The project received a $450 million award from DOE under the Clean Coal Power Initiative (CCPI) and proceeded through FEED and permitting before folding due to construction cost escalation, key partnership changes, and failure to obtain final financing.
- A proposed Lake Charles Methanol, LLC project near Lake Charles, LA:[cxx] Planned to produce methanol, hydrogen and capture CO_2 from pet coke and/or coal. The project received a conditional commitment from DOE in 2016 for a loan guarantee, but has languished since that time with an uncertain future.
- DKRW Energy LLC's proposed ICL plant near Medicine Bow, WY:[cxxi] Planned to produce transportation fuels, with CO_2 capture for EOR. First conceived in 2004, the project struggled amid numerous changes and delays and was indefinitely suspended in 2016 after oil prices collapsed and failed to recover to revenue levels sufficient to justify the project's expected cost.

- Baard Energy's proposed 50,000 BPD coal-to-diesel project in Ohio:[cxxii] The project received approved permits, but faced a number of obstacles, including declining oil prices, and was officially suspended in 2011.

There have been a number of other U.S. coal conversion projects besides the above that were also proposed and developed to various stages before being suspended.

Recent DOE Initiatives

In the past decade or so, DOE has come to recognize the growing potential value of coal as a conversion feedstock, versus its primary use as a fuel for power and steam generation. The DOE efforts to support utilization of coal for conversion to fuels or chemicals have primarily been focused in the advanced gasification program and/or in the coal/biomass to liquids (CBTL) program (recently combined under the gasification program).

A number of Funding Opportunity Announcements (FOAs) have included areas of interest related to coal conversion. Recent DOE efforts to drive development of radically engineered modular systems (REMS) for gasification have a side benefit of reducing the economy of scale of gasification technology, thus making it more economically attractive for coal conversion projects that often tend to be smaller in overall scale than large power generation projects.[cxxiii] A recent DOE NETL project award was made to CarbonFuels, LLC to employ their novel Charfuel® Coal Refining Process at its existing, permitted 18 TPD pilot plant, to refine coal and produce an upgraded coal product and a number of organic and inorganic coproducts, in order to produce engineering and product data that can be used to design a commercial-scale integrated facility.[cxxiv]

Coal to Carbon-Based Products

Overview

Carbon products such as pitches, foams, fibers, and graphite have been produced over many years using petroleum cokes derived from the production of fuels and chemicals. Germany in World War II, and South Africa in the era of oil embargos, successfully demonstrated that coal can be transformed to fuels and chemicals. Applied research on the use of coal to produce solid carbon-based products have been conducted by many academic and industrial teams. Specific topics of interest are to determine if products made from coal have better properties than the same products produced via petroleum routes, as well as the economics of such processes.

Coal tar pitch is produced from a byproduct of coke making (coal tar distillation). As noted in Chapter 4, U.S. coal tar pitch production has been declining, along with needle coke shortages, likely due to a combination of byproduct coke plant closures and reduced primary aluminum production in the U.S., producing constraints in both supply and demand. A 2008 estimate of U.S. coal tar distillation capacity was in the range of 1.1 MMTPY.[cxxv] Since then two of the cited plants, in Pennsylvania and West Virginia, have closed, further reducing the distillation capacity by half. Assuming a pitch yield of 50% of the distilled tar, the current U.S. production capacity of coal tar pitch is likely less than 250,000 MTPY. By comparison, world coal tar pitch production in 2016 was estimated to be 6.7 MMTPY and estimated at that time to grow to 8.1 MMTPY by 2020.[cxxvi] While increases in coke plant coal tar production in the U.S. may not be on the horizon, the use of alternate technologies to extract pitch from coal within the U.S. may create export opportunities for the product.

Steam-activated carbon is produced in the U.S., primarily from lignite, bituminous, and subbituminous coal feedstocks. Manufacturing capacity has grown over the past decade, with capacity over 500 million pounds per year (0.25 MMTPY) in 2017 and a market size of about $500 million.[cxxvii] This corresponds to potential coal consumption on the order of 0.7 to 1 MMTPY. Domestic capacity exceeds actual production, with an overall production of about 71% of capacity in 2017. Historical industry, Electric Power Research Institute, U.S. Environmental Protection Agency (EPA), and DOE initiatives have enabled the development of new applications for activated carbons, expanding its domestic market and enabling the development of new products and formulations, such as for Hg capture emissions control. Both domestic and worldwide markets for activated carbon are expected to grow over the next few years, and capturing this share for U.S. suppliers and maintaining their competitiveness will depend on continued product and application development.

Such market opportunities could allow for U.S. coal products to enter the value chains for significant and, in some cases, growing global markets. Work has been undertaken in these areas with respect to U.S. coal by both the U.S. Bureau of Mines and DOE.

New market opportunities can extend the reach of U.S. coal products outside of traditional markets, notably where these products compete with petroleum products. These include the processing of coal into feedstocks for CF, graphite, and graphene production. These precursors can represent a significant product value compared with feedstock costs. Industrial interest in CFs is growing, as evidenced by the recent investment by Japan in two new CF plants in South Carolina (see Chapter 4 under Carbon Products section for more details).

In addition, potential exists for the use of coal in the value chains of products such as anodes for aluminum smelters and graphite furnace electrodes for the EAF-based portion of the steel industry. These represent research opportunities toward the development of new markets. Such development efforts have been and are being led by combinations of academia, federal agencies such as DOE, and industry.

The manufacture of graphite products requires very high process temperatures, use of binders such as pitches derived from petroleum as well as from coal tar[74], and aggregates that include needle coke (petroleum product) and cokes produced from the carbonization of coal tar pitch.[cxxviii] Notable among graphite products are furnace electrodes for the steel industry (EAF application). The reliance of the graphite electrode industry on petroleum-derived needle coke has recently been an area of concern, as constraints in needle coke supply have helped drive an unfavorable electrode cost and availability situation in the steel industry.[cxxix] This situation presents opportunities for the substitution of coal products for petroleum products in the graphite manufacturing process. Graphite production using coal as an aggregate and graphitization of coal itself have been demonstrated in the laboratory[cxxx] and some process-related R&D may be required to fully match the properties of other graphite products. There is also the potential for the manufacture of a needle coke product from coal-derived pitch, especially pitch that has been solvent-extracted from coal[cxxxi], rather than pitches produced through distillation of coal tar recovered from carbonization (i.e. from byproduct coke production).

Academic Initiatives

The DOE's Office of Fossil Energy (FE) entered into long-term collaborative agreements with two groups – consisting of academic institutions and industry participants – to advance technologies for producing carbon products from coal. The Consortium for Premium Carbon Products from Coal (CPCPC) was one such program, led by Penn State over a period from 1998 to 2010.[cxxxii] A related program was conducted by West Virginia University (WVU) from 2003 to 2009.[cxxxiii] Recently, the Massachusetts Institute of Technology (MIT) has also been doing leading-edge research into utilization of coal as a feedstock for advanced carbon-based materials.[cxxxiv]

The results of these low technology readiness level programs demonstrated that coal products such as pitches for electrode manufacture, foams for insulation, fibers for enhanced strength of light-weight materials and other products, such as graphite and carbon black, could be made economically from coal using advanced chemical and heat-based extraction processes. As with the DOE investments in coal-to-liquids programs, the funding provided to academic researchers also resulted in the development of NextGen researchers and technologists to succeed our aging workforce of coal chemistry experts.

Industrial Initiatives

By including industry partners in participatory and/or advisory activities led by academic researchers, the advanced technology developed was transferred to the private sector where larger-scale plants could be constructed and tested through pilot plant and demonstration plant stages. The university and industry communities have further advanced the results obtained in the Penn State and WVU programs to stages ready for commercial deployment. Further investments in exploring the markets for coal-based products are warranted.

One of the largest and most visible current industry initiatives is being driven by Ramaco Carbon, a subsidiary of Ramaco Coal, founded in 2011.[cxxxv] Its main objective is to create large volume and high margin product uses for coal-based carbon by pursuing an integrated resource, technology and manufacturing based approach to new coal uses. Based in Wyoming, the company owns 1.1 billion tons of thermal coal near Sheridan, Wyoming (Brook Mine) that is under final permit review. It has obtained approval to break ground on a new Carbon Advanced Materials Center (iCAM) research park. The iCAM will house researchers from national laboratories, universities, private research groups, and strategic manufacturing partners, and will conduct applied research (bench to pilot scale) to commercialize coal-based carbon products.

Ramaco also has plans to create a 100+ acre C2P mine-mouth industrial park called Wyoming iPark. Plants in the Innovation Park (iPark) would use research from the iCAM and coal from the Brook Mine to manufacture advanced carbon products. Some of Ramaco Carbon's current research and strategic partners include the Western Research Institute, Carbon, Inc., Fluor Corporation, Oak Ridge National Laboratory, MIT- The Grossman Materials Group, the Southern Research Institute, and the DOE. Ramaco Carbon is focusing on four broad uses: coal to chemicals, coal to CF, coal to medical technology and coal to building products.[cxxxvi]

Recent New DOE-Funded Programs

Relatively recent R&D results in the area of coal to carbon products include the use of pitch – a solvent extracted from coal – for carbon electrode production, including graphite furnace electrodes. Such a graphite furnace electrode has been tested in a commercial EAF at a U.S. mill.[cxxxvii] Other products such as carbon foams and needle coke can also be produced from the extracted pitch.[cxxxviii] Additionally, pitch has been used to produce CFs.[cxxxix]

Last year, the DOE announced awards to several coal to carbon products projects under DE-FOA-0001849, including:[cxl]

- Touchstone Research Laboratory, Ltd. – Development of new silicon carbon (SiC) foam utilizing coal feedstock that meets system performance requirements suitable for application temperatures > 1000°C, such as for concentrated solar power systems and supercritical-CO_2 turbine operations.
- Minus 100, LLC – Development of new or improved methods of manufacturing conductive ink pigments using coal as a primary feedstock at significantly lower cost than existing silver-based conductive inks.
- Semplastics EHC LLC – Development of coal core composites for low cost, lightweight, fire resistant panels and roofing materials.
- Physical Sciences, Inc. – Development of high-conductivity carbon material (HCCM) for electrochemical applications and generation of valuable byproducts such as minerals and low-emission gaseous fuels.

Very recently, DOE issued DE-FOA-0001992, “Maximizing The Coal Value Chain” to provide up to $9.5 million for research projects aimed at maximizing the coal value chain. The FOA seeks research to develop innovative uses of domestic U.S. coal for upgraded coal-based feedstocks for power production and steel-making, and for making high-value solid products.[cxli]

The DOE has also launched a new multi-lab collaboration, led by NETL in cooperation with other national labs, universities, and industry. The goal is to develop & demonstrate pathways for high-value materials and their use in making products.[cxlii]

Rare Earth Elements (REEs) and Critical Minerals (CMs)

Overview

Should sufficient REE and CM concentrations be found in U.S. coal resources or mining by-products, this will create a new market for materials produced by coal mining operations. The development of coal-based extraction technologies, in pyrometallurgical operations such as roasting and calcining, can produce new market opportunities for U.S. coal products. Acid mine drainage (AMD) has also been found to contain relatively high levels of desirable heavy REEs.

The U.S. Congress has recognized the national security risks associated with being solely dependent on imports for REEs and CMs. Starting in fiscal year (FY) 2014 and again in FY15, they authorized DOE funding for the assessment and analysis of the feasibility of economically recovering REEs and CMs from coal and coal byproduct streams, such as fly ash, coal refuse, and aqueous effluents. In FY16-17, Congress authorized expansion of external agency activities to develop and test commercially-viable advanced separation technologies at proof-of-concept or pilot scale that could be deployed near term for the extraction and recovery of REEs and CMs from U.S. coal and coal byproduct sources. In FY18 Congress authorized external agency activities to continue to develop and test advanced separation technologies and to accelerate the advancement of commercially-viable technologies for the extraction and recovery of REEs and CMs from U.S. coal and coal byproduct sources.[cxliii]

REE Research and Technology Development – Historical and Current Efforts

As follow-up to a 2017 DOE-led workshop[42] to discuss technical developments that might improve the reach of U.S. coal products in domestic and international markets, a survey was made of the coal industry and academia. One of the most frequently cited topics for critical research needs was the production of strategic REE and CM concentrates. The production and sale of these concentrates can offset the costs associated with producing coal, and preliminary research results have shown potential for concentrating them using physical separations. These results have also shown that elements are found in specific gravities that are between those of pyrite and coal, offering opportunities to recover them from what would otherwise be refuse (minimizing process waste). Integration of physical separations with subsequent chemical extraction argues for hydrometallurgy research regarding the phase assemblages found in physical separation products.[cxliv]

With respect to the recovery of strategic materials and CMs from coal byproducts, a significant body of work began in the 1940s, undertaken by the U.S. Bureau of Mines, focused on the potential to produce alumina feedstocks for aluminum smelters from central Pennsylvania underclays (floor rock under coal), the concern being the wartime security of the domestic aluminum production supply chain involving imported bauxite.[cxlv] This body of work also led to the development of pressure leaching data[cxlvi], and process technology elements for the recovery of salable alumina from the pressure leach liquor.[cxlvii] This type of process can render alumina-rich coal byproducts as economic feedstocks for the domestic aluminum industry. Additionally, where these byproducts contain elevated contents of strategic and critical elements, recovery of these from the leach liquor could further improve process economics.

Following recent Congressional authorizations, the DOE NETL established a REE program with a mission to develop an economically competitive and sustainable domestic supply of REE and CMs to assist in maintaining our nation's economic growth and national security. The program's objectives are to recover REEs from coal and coal byproduct streams, such as coal refuse, clay/sandstone over/under-burden materials, aqueous effluents and power generation ash. It also aims to advance existing and/or develop new, second-generation or transformational technologies to improve process systems economics and reduce the environmental impact of a coal-based REE value chain. The program's primary goal is, by 2020, to validate the technical and economic feasibility of small, domestic, pilot scale, prototype facilities as well as to generate, in an environmentally benign manner, 10 pounds per day, 1,000 pounds total, high-purity (90-99wt%), salable, rare earth oxides (REOs) from 300 part per million (ppm) coal-based resources.[cxlviii]

The DOE NETL REE program now has over 25 active projects from a series of FOAs, covering enabling technologies, separation processes, and process systems for economically viable recovery of REEs and CMs from coal and coal byproducts. They have also formed a cooperative partnership with other national laboratories, including Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Idaho National Laboratory.[cxlix]

Some of the most promising accomplishments/developments to date from this program include the following:[cl]

- University of Kentucky - Produced small quantities of 80wt% total REEs on a dry basis and more than 98wt% REOs. Critical elements such as neodymium and yttrium (used in national defense technologies and the high-tech and renewable energy industries) represented more than 45% of the total REE concentrates. They also started up a pilot plant in late 2018 that is currently producing a few grams per day of a REO concentrate containing greater than 90wt% total REOs (dry basis). The products were from processing leachate collected from a coarse refuse area.
- West Virginia University - Achieved lab recovery of nearly 100% REEs from coal AMD sludge as 5-6wt% mixed REE concentrates and are now commissioning an extraction bench/pilot-scale facility for recovery of REEs from AMD feedstock.
- University of North Dakota – Identified that approximately 80% to 95% of the REE content in lignite coals is organically associated, primarily as coordination complexes as opposed to mineral forms typically found in the older/higher-rank coals.
- Physical Sciences Inc. (PSI) – In cooperation with the University of Kentucky, the University of Wyoming, and others, achieved >30wt% mixed REE pre-concentrates from coal-based materials. Built a micro-pilot facility that produced >15wt% concentrates of mixed REEs from post-combustion ash resulting from burning East Kentucky fire clay coal in a power plant boiler. PSI is now building a pilot facility in Sharon, PA to be operational by June/July 2019.
- Marshall Miller & Associates – Received a Phase I award to develop a process design and techno-economic analysis for a proposed 90-99wt% REE recovery facility (extraction and separation system) based on conventional technologies. If successful, in a subsequent Phase II down-select, they would then construct and operate a facility to produce 10 pounds per day and 1000 pounds total of a salable REE product (90-99wt% purity REOs).

- NETL – Developed a fiber optic sensor for detection of ppm levels of REEs in liquid samples. Developed immobilized amine and organo-clay sorbents for REE recovery from liquid sources. Produced 2wt% REE pre-concentrates in a lab-scale facility.

On the industrial front, Crazy Horse Coal has an automated technology for mining from deep formations that would otherwise be unrecoverable by other mining methods.[cli] Their technology offers opportunities for the integration with coal upgrading technologies, notably those involving physical separations. They recently completed a successful proof-of-concept well project. In addition to representing a novel method for producing coal, this system may also be useful for the recovery of strategic and critical elements from geology that are too deep to mine.

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