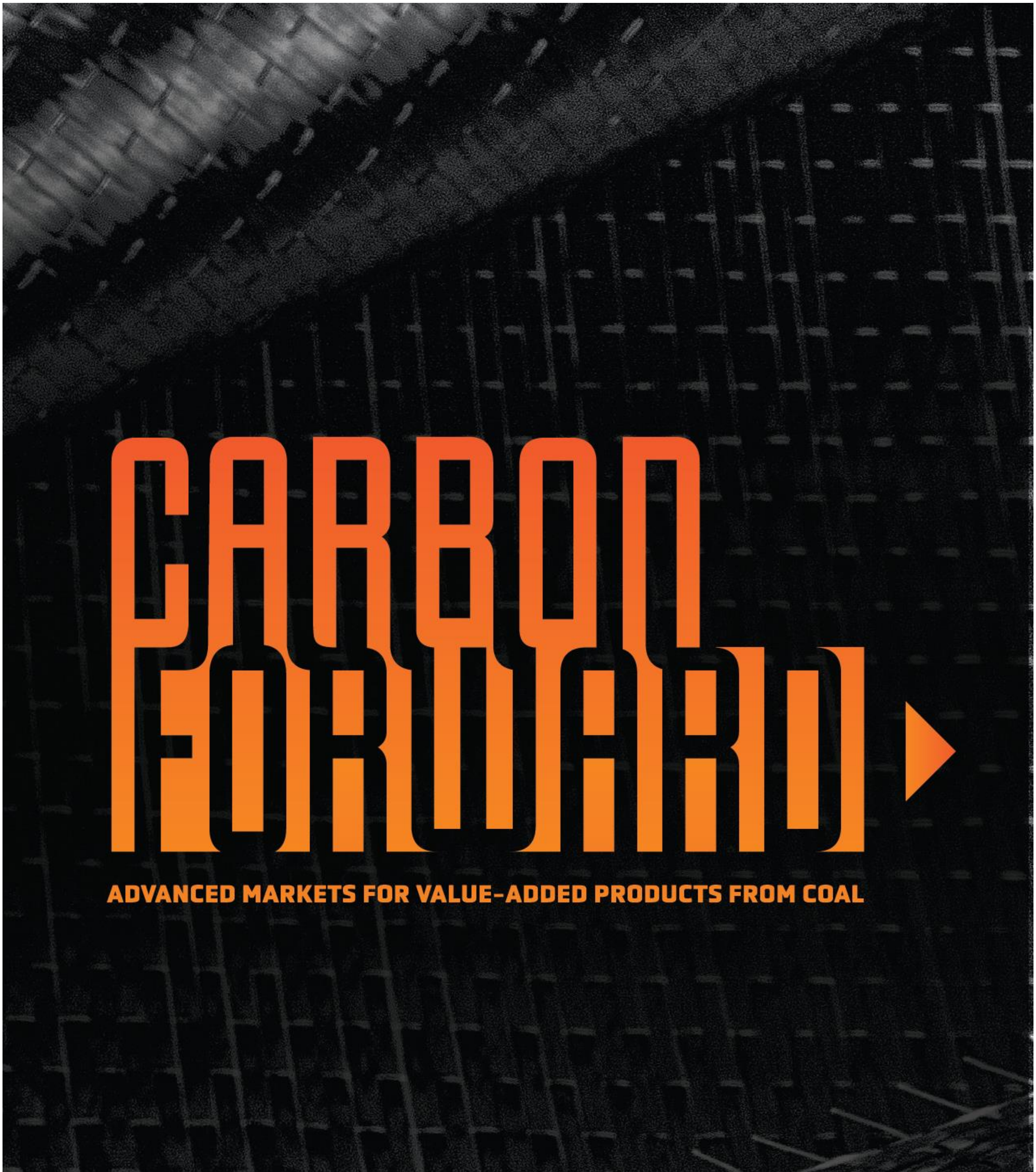

CARBON FORWARD

ADVANCED MARKETS FOR VALUE-ADDED PRODUCTS FROM COAL

NCC

CARBON FORWARD

Advanced Markets
For Value-Added Products from Coal

October 2021

The National Coal Council (NCC) 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 respective organizations.

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Advanced Markets

For Value-Added Products from Coal

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Advanced Markets for Value-Added Products from Coal

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Carbon Forward

Advanced Markets for Value-Added Products from Coal

Transmittal Letter to Secretary Granholm

Carbon Forward

Advanced Markets for Value-Added Products from Coal

Report Request Letter from Secretary Brouillette

The Secretary of Energy
Washington, D.C. 20585

September 22, 2020

Ass
Mr. Danny Gray
Chairman
National Coal Council, Inc.
1101 Pennsylvania Avenue, NW, Suite 300
Washington, DC 20004

Dear Chairman Gray:

I am writing today to request the National Coal Council (NCC) develop a white paper assessing opportunities to enlist advanced manufacturing techniques to enhance the use of U.S. coal beyond the power generation, steel making, and cement manufacturing markets.

The white paper should focus on new and expanded markets for "coal to products" and develop a roadmap of policies and approaches that would support research, development, and deployment (RD&D) of carbon-based products.

The white paper should provide an assessment of Federal and State policies, research and development investment options, and stakeholder partnership opportunities to advance these alternative markets for coal. Because advanced manufacturing techniques would be crucial to commercializing carbon-based products in the United States, advanced manufacturing techniques should feature prominently in the white paper.

Key questions to be addressed include:

• What existing or prospective Federal and State policies would support alternative markets for coal?
• What RD&D investments are needed to support alternative markets for coal?
• What opportunities should be pursued among stakeholder groups in this sector to support alternative markets for coal?
• What strategic U.S. national interests are impacted by the development of coal-to-products and advanced materials?

I ask that the white paper be completed no later than May 30, 2021.

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,

Dan Brouillette

Carbon Forward
Advanced Markets for Value-Added Products from Coal

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Carbon Forward
Advanced Markets for Value-Added Products from Coal

Acronyms and Abbreviations

°C – Degree Centigrade
°F – Degree Fahrenheit
% – Percent

ACC – Assistance to Coal Communities
AFVs – Alternative Fuel Vehicles
AM – Advanced Manufacturing
AMNPO – Advanced Manufacturing National Program Office
AMO – Advanced Manufacturing Office
AMPT – Advanced Materials Future Preparedness Task Force
AOI – Areas of Interest
ARC – Appalachian Regional Commission
ARRTA – American Recovery & Reinvestment Tax Act
ASTM – American Society for Testing & Materials

BTEX – benzene, toluene, ethylbenzene and xylenes

C_2H_2 – acetylene
CaC_2 – calcium carbide
$CaCO_3$– calcium carbonate
CH_3 – methyl
CH_3OH – methanol
CL – chlorine
CO – carbon monoxide
CO_2 – carbon dioxide

CAER – Center for Applied Energy Research (Univ. of Kentucky)
CAGR – Compound Annual Growth Rate
CATF – Clean Air Task Force
CCCC – Center for Carbon Capture & Conversion (Univ. of Wyoming)
CCP – Coal combustion products
CCR – Coal combustion residuals
CCS – Carbon capture & storage
CCUS – Carbon capture, utilization and storage
CF – Carbon Fiber
CFTF – Carbon Fiber Technology Facility
C/H – Carbon-Hydrogen Ratio
CM – Critical materials/critical minerals
CNT – Carbon Nanotubes
CO – Carbon Monoxide
CORE-CM – Carbon Ore, Rare Earths & Critical Minerals
CPC – Coal Plastic Composites
CRADA – Cooperative Research & Development Agreement
CTC – Coal-to-Chemicals
CTE – Coefficient of Thermal Expansion
CURC – Carbon Utilization Research Council

DASD – U.S. Department of Assistant Secretary of Defense
DCL – Direct Coal Liquefaction
DOC – U.S. Department of Commerce
DOD – U.S. Department of Defense
DOE – U.S. Department of Energy
DPA – Defense Production Act

EAF – Electric Arc Furnace
ECED – Energy Capital Economic Development (Wyoming)
EDA – Economic Development Administration
EERC – Energy & Environmental Research Center (Univ. of North Dakota)
EERE – Office of Energy Efficiency & Renewable Energy (Dept. of Energy)
EIA – U.S. Energy Information Administration
EO – Executive Order
EOR – Enhanced Oil Recovery
EPP – Environmentally Preferable Program
EPRI – Electric Power Research Institute
ERDC – Engineer Research & Development Center
ESG – Environmental, Social & Governance
EU – European Union
EV – Electric Vehicle

FC – Fiber Cement
FE – Office of Fossil Energy (Dept. of Energy)
FECM – Office of Fossil Energy & Carbon Management

FEED – Front-end Engineering and Design
FOA – Funding Opportunity Announcement
FOAK – First of a Kind
FOTK – First of Their Kind
FT – Fischer-Tropsch
FTD – Fischer-Tropsch Diesel
FWP – Field Work Proposals

GAO – U.S. General Accountability Office
GHG – Greenhouse gases
GRE – Great River Energy

Hg - mercury
HAB – Harmful Algal Blooms
HREE – Heavy Rare Earth Elements

IACMI – Institute for Advanced Compositive Manufacturing Innovation
iCAM – Innovation Carbon Advanced Materials
ICL or IDCL – Indirect Coal Liquefaction
IEA – International Energy Agency
IEA-CCC – IEA Clean Coal Centre
IGCC – Integrated Gasification Combined Cycle
ITC – Integrated Test Center (Wyoming)
IWG – Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization

Kg - Kilogram

Lb - Pound
LCA – Life cycle analysis

MIBP – Office of Manufacturing Industrial Base Policy
MREO – Mixed Rare Earth Oxides
MRL – Manufacturing Readiness Level
MTO – Methanol-to-Olefins
MW – Megawatt

N_2 - nitrogen
NOx – nitrogen oxide
NCC – National Coal Council
NCCC – National Carbon Capture Center
NETL – National Energy Technology Laboratory (DOE)
NIST – National Institute of Standards & Technology
NMA – National Mining Association
NSF – National Science Foundation
NSTC – National Science & Technology Council

OAM – Office of Advanced Manufacturing
OCCCM – Office of Clean Coal & Carbon Management (DOE)
OH – Hydroxy
ORNL – Oak Ridge National Laboratory (DOE)
OSB – Oriented Strand Board

PAH – Polycyclic Aromatic
PAN – Polyacrylonitrile
PDC – Polymer-derived Ceramic
PE – Polyethylene
PM – Particulate Matter
POWER – ARC's Partnership for Opportunity & Workforce & Economic Revitalization
PV - Photovoltaic
PVC – Polyvinyl Chloride

QI – Quinolone Insoluble

R&D – Research & Development
RD&D – Research, Development & Deployment
REE – Rare Earth Elements
RF – Radio Frequency
R&IC – Research & Innovation Center

S – sulfur
SiC – silicon carbide
SOx – sulfur oxides
SBC – Single Batch Composite
SDG – Sustainable Development Goals
SER – School of Energy Resources (Univ. of Wyoming)
SMR – Steam Methane Reforming
SNG – Synthetic Natural Gas

TRL – Technology Readiness Level

UCFER – University Coalition for Fossil Energy Research
UCG – Underground Coal Gasification
UCR – University Coal Research
UHM – Ultra-high Modulus
UHM-CF – Graphitic Carbon Fibers
UL – Underwriter Laboratories
U.S. – United States
USD – U.S. Dollars
USGS – U.S. Geological Survey
USDA – U.S. Department of Agriculture
USICA – U.S. Innovation & Competition Act
UV – Ultra-violet
UW – University of Wyoming

WCA – World Coal Association
WPC – Wood Plastic Composite
Wt - Weight
WVU – West Virginia University
WyIC – Wyoming Innovation Center

Carbon Forward

Advanced Markets for Value-Added Products from Coal

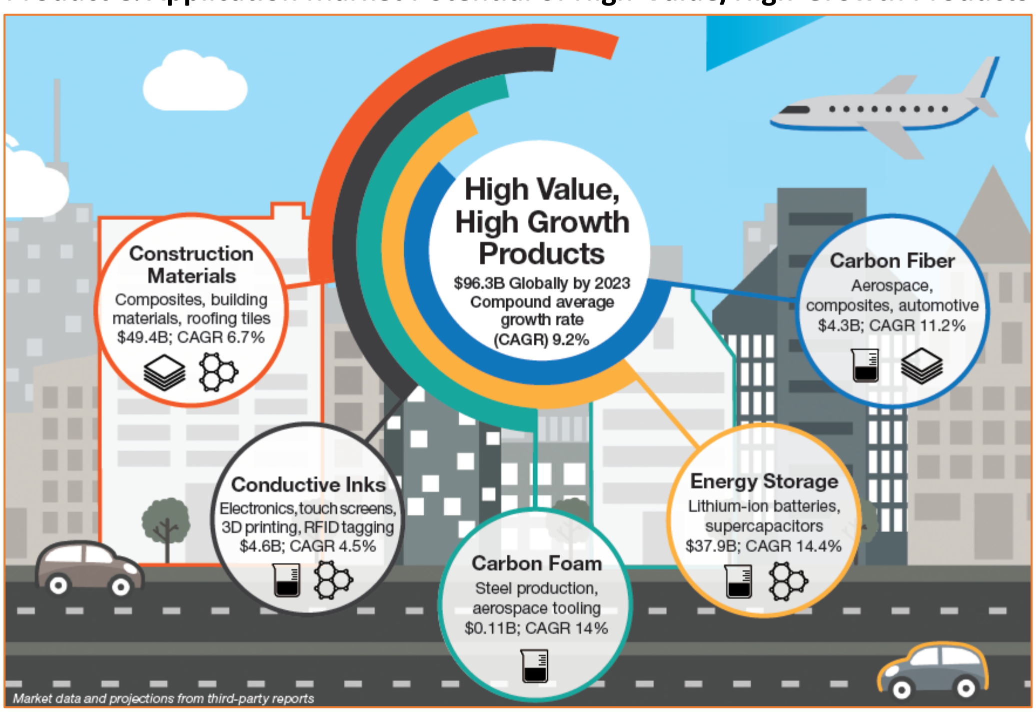
Executive Summary

The Value and Opportunity of Coal to Carbon Products

In the 20th century, coal achieved prominence in the production of electricity generation and steel, helping to establish the United States as a global industrial powerhouse. Coal's role in the 21st century new carbon age promises to be equally significant. Our nation's abundant coal resources can be used as an economic feedstock in the production of a variety of critical goods and materials.

Coal-derived products have valuable applications in the aerospace, agricultural, automotive, consumer goods, construction, defense, energy, environmental and medical sectors. These high-growth market sectors, fueled by strides in advanced manufacturing, offer the U.S. opportunities to establish its role as a global leader in next-generation industries.

Product & Application Market Potential of High-Value/High-Growth Products



National Energy Technology Laboratory

Coal’s complex chemical structure enables it to be used to manufacture:

- asphalt and ammonia
- batteries and bricks
- concrete and ceramics
- diesel fuel and 3D printing ink
- electronics and electrodes
- fertilizers and facades
- golf balls and graphene
- hydrogen and humic acid
- inks and insulation
- magnets and methanol
- pencils and pharmaceuticals
- sensors and solar panels
- tennis rackets and textiles
- wind turbine blades and water filters

Further research into the molecular genome of coal holds promise for identifying even more ways it might be used as a critical materials resource. Coal is not a monolithic material; its complex and unique chemical properties are just beginning to be identified and valued for their potential utility in production of value-added carbon products.

Many coal-derived products offer benefits vis-à-vis traditionally manufactured products:

- ***Improved Product Quality and Performance*** – stronger, more durable, lighter weight, corrosion and fire resistance, greater energy storage capacity
- ***Improved Economics*** – reduced manufacturing complexity = reduced costs, domestically abundant and affordable coal resource base, utilization of existing infrastructure
- ***Enhanced Environmental Stewardship*** – lighter weight, more energy efficient production, shorter supply chains reduce emissions, carbon dioxide (CO_2) sequestration potential, reduced water consumption, hydrogen production potential
- ***Enhanced National Security*** – improved supply chain resilience through use of domestic resources and diversified feedstock sources, reduced dependence on imports

Advancement of coal to carbon products markets offers the additional benefit of creating a significant number of well-paying jobs. The U.S. Department of Energy’s (DOE) own assessment indicates the potential for 280,000 to 480,000 manufacturing jobs in various carbon product industries. Many of these jobs can be created in economically distressed communities impacted by the decline in U.S. coal production and coal power generation.

Potential Demand for New Coal Production & Employment Associated with Markets for Carbon Products

Carbon Product	Potential U.S. Coal Industry Requirements - 2050*		U.S. Product Value -2050 (Million $) *	Employment-2050 (Mfg.)*
	Coal Production (mmt)*	Coal Mining Employment*		
Activated Carbon	22	2,641	15,979	32,437
Carbon Anodes (incl. Aluminum, Li-Ion Battery Anodes)	35	4,257	31,289	63,476
Carbon Black	14.1	1,692	5,077	10,306
Graphite Electrodes/Needle Coke	12.5	1,502	41,315	83,869
Carbon Fiber (incl. CFRP, C-C composites, cement)	47.6	5,713	24,701	50,127
Carbon Nanomaterials (incl. cement)	12.1	1,457	14,125	28,300
Conductive Inks	0.001	1	264	500
Roofing Tile	2	243	7,192	14,500
Aggregate**	**100+**	**15,000+**	**TBD**	**100,000+**
Foam - Building Mat**	**100+**	**15,000+**	**TBD**	**100,000+**
Total Carbon Products	**145 to 345+**	**17,500 to 47,500+**	**139,000 +**	**280,000 to 480,000+**

* Values reported in 2050 represent a high coal penetration scenario in which carbon-based products made from coal penetrate 80 percent of the overall product market. Additionally, several products (e.g., anodes/electrodes, CF & graphene) represent high demand growth scenarios.
** Data from project estimates with technology developers for large commodity markets

U.S. Department of Energy/Office of Fossil Energy

Finally, in considering the value associated with coal-derived carbon products, it is important to distinguish between "carbon" used to produce value-added products and the "carbon" referred to in carbon dioxide - CO_2. Carbon used for production of carbon-based products should not be confused with the carbon in CO_2 emissions. In fact, because many products made from or containing carbon have superior strength, weigh less and require less energy to produce than traditional materials, carbon-based products may have a substantially reduced environmental impact and contribute to efforts to reduce CO_2.

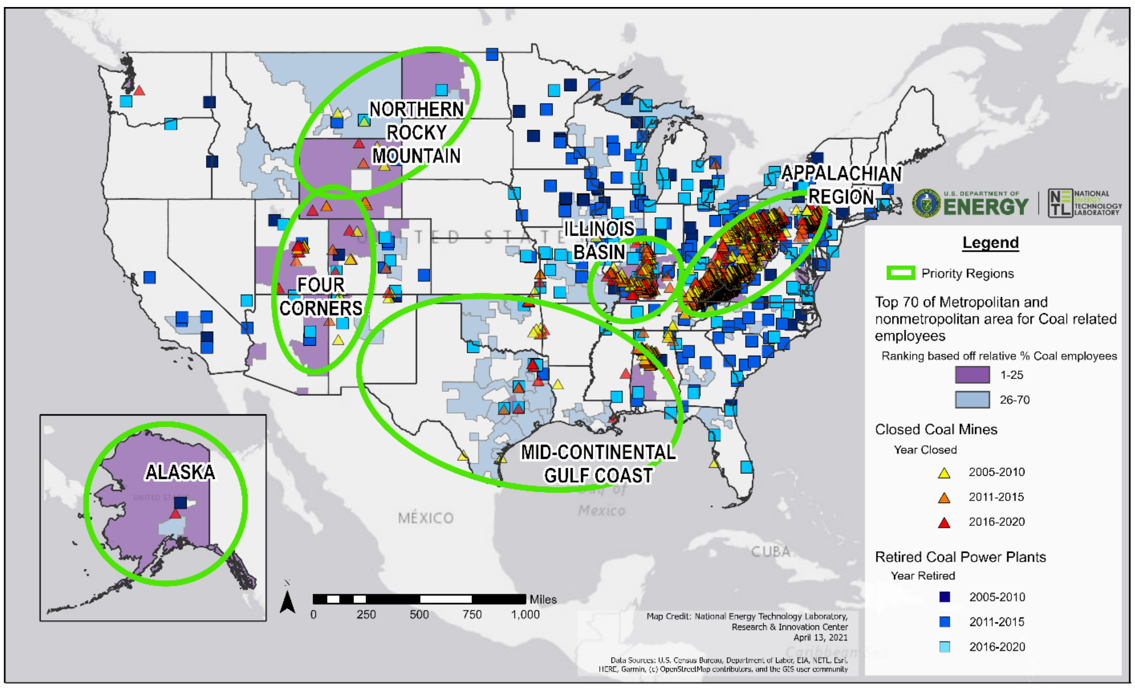
Coal-to-Products Support Biden Administration Priorities

The many benefits associated with deployment of coal-derived carbon products align with priorities established by the Biden Administration. Since taking office in January 2021, the Administration has advanced numerous initiatives supporting job creation, economic revitalization, environmental stewardship, infrastructure improvements and supply chain resilience. Chapter V of this report details how coal-derived products support the Administration's efforts in each of these areas. In summary:

Job Creation

The Administration's American Jobs Plan seeks to revitalize manufacturing and train Americans for the jobs of the future. The Plan also highlights the need to build next-generation industries in distressed communities, especially those impacted by the recent energy transition. Established by a Presidential Executive Order, the White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization has identified immediately challenged coal communities, targeting them as key locations for Federal investment for job creation, for initiatives to strengthen manufacturing supply chains for critical goods and for remediation/redevelopment of brownfield sites into new hubs of economic growth.

Coal Mining & Power Plant Impacted Areas
White House Interagency Working Group
on Coal & Power Plant Communities & Economic Revitalization



It is precisely these communities in which jobs can be readily created through deployment of coal-to-products manufacturing. Investment for research, development and demonstration (RD&D) and deployment of commercial-scale projects using advanced manufacturing technologies to produce coal-derived high-value carbon products will provide opportunities to train workers for careers in growth industries with attractive salary and benefit potential. It will also afford these workers an opportunity to remain in their established local communities.

Economic Revitalization

The American Jobs Plan calls for investment in R&D and technologies of the future, highlighting the need for public investment in breakthrough technologies to maintain the nation's economic edge in today's global economy. Enhanced investments in researchers, laboratories and universities, in partnership with the private sector, will support the carbon-based industries of the future. Recognizing the government's buying power and ability to be a first-mover in markets, the Jobs Plan also calls for jumpstarting clean energy manufacturing through Federal procurement.

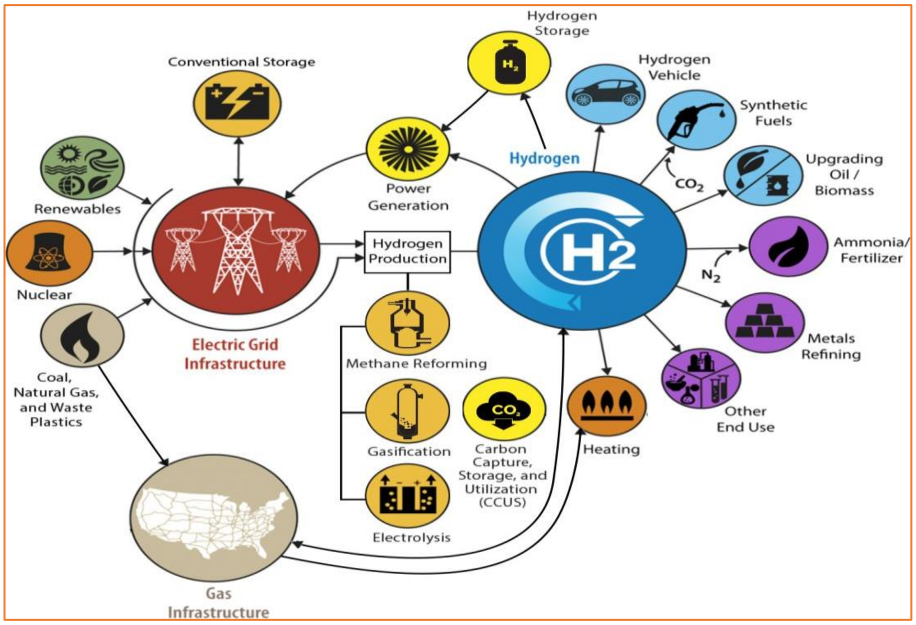
Emerging high-value carbon product markets provide materials critical to clean energy industry sectors, including those for electric vehicles and renewable energy, and have significant economic growth potential. The National Energy Technology Laboratory (NETL) projects that these products will have a global market value of over $96 billion by 2023 and a Compound Annual Growth Rate (CAGR) of 9.2%.

Environmental Stewardship

As noted earlier, coal-derived carbon products offer numerous environmental benefits. These products support the Administration's stated objectives to deliver clean drinking water, electrify the automotive industry, reduce energy consumption and emissions in both the manufacturing process and in end-use applications, and sequester CO_2.

Additionally, the Administration's initiatives to advance a "Hydrogen Economy" in which hydrogen is used for power generation, heating, transportation, fertilizer production and energy storage, can also be supported by coal. Gasification of coal, which is undertaken to produce liquid fuels, chemicals and synthetic natural gas (SNG), is one production pathway used to make hydrogen. Large centralized coal gasification facilities, equipped with carbon capture, utilization and storage (CCUS) technology, can play a major role in meeting hydrogen production needs.

Vision of the Hydrogen Economy



U.S. Department of Energy

Infrastructure Improvements

The Administration's Jobs Plan calls for investments to be made in both the construction and repair of U.S. infrastructure, including roads, bridges, rail, ports, airports and transit systems. Many of the basic commodities and construction materials needed to shore up our nation's infrastructure can be produced from coal at less cost, with enhanced technical performance, extended use life and environmental advantages vis-à-vis traditional materials.

The Jobs Plan also identifies the need to "reenergize America's power infrastructure," by creating a more resilient grid and "incentivizing more efficient use of existing infrastructure." Co-locating coal-to-products advanced manufacturing facilities with existing coal mining, transportation and power station infrastructure will provide a more streamlined and cost-effective opportunity to deploy new manufacturing plants while simultaneously incentivizing mine, transport and power station owners to invest in efficiency upgrades to their operations.

Supply Chain Resilience

In an Executive Order on "America's Supply Chains," President Biden directed the U.S. government undertake a review of U.S. supply chains with the aim of identifying risks and vulnerabilities. DOE was specifically tasked with identifying risks in the supply chain for high-capacity batteries that could be used for electric vehicles and energy storage. In response, DOE recommended establishing government policies incentivizing every stage of the U.S. battery supply chain, including securing a domestic supply of critical materials for high-capacity lithium-ion batteries. Many of the rare earth elements (REEs) and critical minerals (CMs), including carbon materials, necessary for the production of these batteries can be sourced from coal, coal ash and coal residuals. Supporting RD&D to recover REEs and CMs from coal will enable the U.S. to reduce its dependence on foreign sources for these and other materials that are critical components of the automotive, aerospace, defense, electronics and consumer goods industries.

The U.S. coal supply chain is well established and wide-ranging. Advanced manufacturing facilities for coal-derived products would benefit from utilization of established supply chains for coal production, transport (rail, port, truck) and on-site storage.

It is worth noting, that other nations are using coal-derived products to enhance their strategic supply chain resilience. U.S. supply chain resilience will be enhanced by ensuring access to all domestic coal resources, including run-of-mine coal, coal ash and coal tailings. Restricting or extending preferential treatment for RD&D funding for any of these resources, e.g., waste coal, may limit available resources and reduce supply chain resilience for critical materials.

The U.S. can benefit greatly and in many ways from efforts to support the deployment of coal-derived carbon products. Advanced manufacturing will be a critical component in the rapid deployment of coal-to-products technologies.

Pathways to Commercialization of Coal to Carbon Products

Production of coal-derived carbon products relies on both conventional and advanced manufacturing techniques. Conventional manufacturing refers to the process of converting raw materials into a finished, saleable product by manual and/or mechanized transformational techniques. Primary among these conventional processes are beneficiation, gasification, calcination, pyrolysis, injection molding and manual carbon fiber layup. With an enhanced focus on initiatives to address carbon management objectives, conventional pathways will continue to play a vital role in the production and manufacturing of coal-derived products.

Advanced manufacturing employs innovative technology to improve products and/or manufacturing processes, providing tools that can drive the rapid transfer of science and technology into manufacturing products and processes. Advanced manufacturing is critical to increasing U.S. competitiveness and facilitating technology transition in many industry sectors. The use of advanced techniques and equipment, such as automation, computation, digitization, artificial intelligence, sensing and networking, will provide the U.S. with the ability to achieve its economic, environmental and national security objectives.

Using coal to produce carbon products is a paradigm shift and advanced manufacturing will be a critical component in the rapid deployment of coal-to-products technologies. While commercial deployment of products from coal will benefit from utilizing advanced manufacturing techniques, it will also contribute to the development of both advanced manufacturing materials and advanced manufacturing processes.

Coal-derived manufacturing materials that have a vital role in facilitating the development of advanced manufacturing include critical materials/minerals, wide bandgap semiconductors for power electronics, materials for harsh service conditions, advanced materials manufacturing and composite materials.

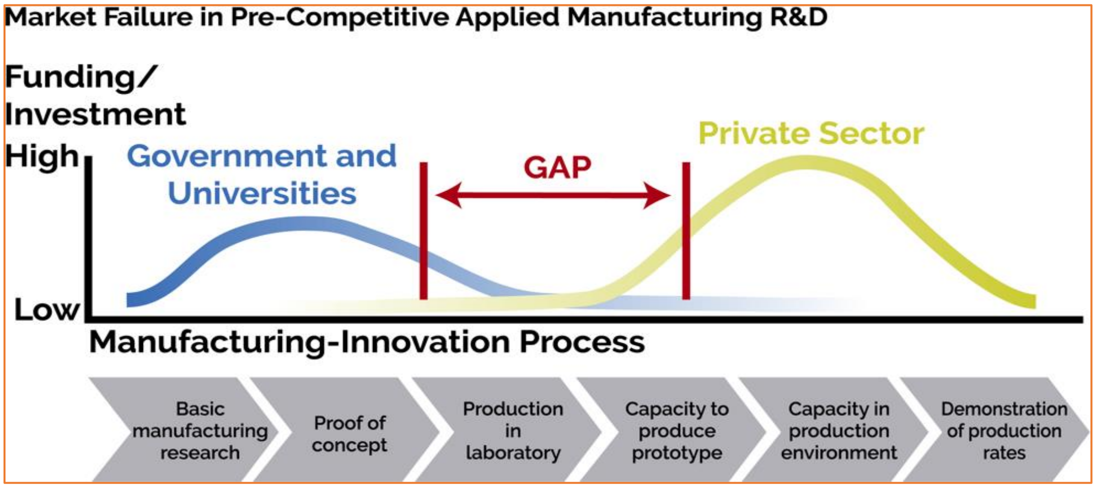
The technologies used to make materials and products from coal will require advanced manufacturing processes. These include: 1) computer technologies and high-performance computing for modeling, simulation and analysis, 2) rapid prototyping (additive manufacturing), advanced robotics and other intelligent production systems, 3) automation and control systems to monitor processes, and 4) agility to custom manufacture products and to manufacture at high or low volume. Moreover, and most important, is the capability to be sustainable, utilizing environmentally sound processes and technologies.

Examples of advanced manufacturing processes and techniques being used to produce value-added products from coal detailed in this report include carbon foam, single batch composites and thermo-chemical coal refining. Many other examples exist.

Commercialization of Coal to Carbon Products

Successful deployment of technologies for production of value-added products from coal will require addressing the gap between basic laboratory R&D typically conducted by government and universities with some support from the private sector, and the commercial demonstration of these technologies largely funded by the private sector. The major time delay and primary obstacle is a gap in the availability of funding through the so-called "development death valley." Accelerating technology innovation and deployment for value-added products from coal needs to address this gap.

Technology Development Funding Gap

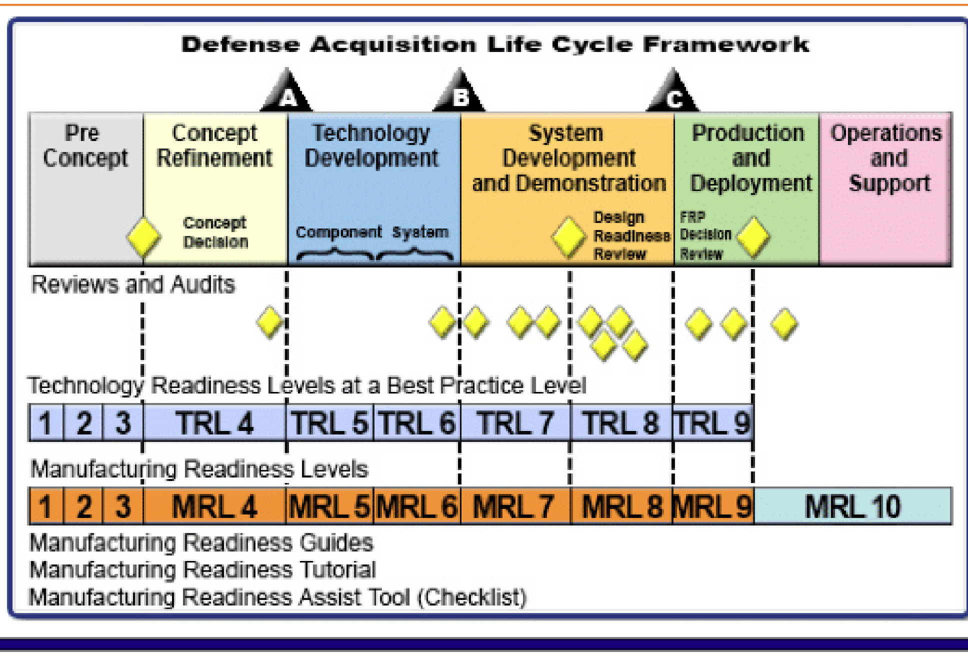


Kelvin H. Lee, Mind the Gap

Numerous initiatives can be undertaken to bridge this commercialization gap:

- DOE's Technology Readiness Levels (TRLs) and the U.S. Department of Defense's (DOD) Manufacturing Readiness Levels (MRLs) can be useful tools in developing and commercially deploying technologies, especially when used in conjunction with each other.

MRL-TRL Comparative Framework



Source: Best Manufacturing Practices Center Of Excellence [BMPCOE] under direction of Joint Defense Manufacturing Technology Panel [JDMTP], *MRL Assist Tool - User Manual Version 1.1*, College Park, Maryland, February 2007, https://www.mrlassist.bmpcoe.org/.

- Intra-governmental collaboration between departments, such as DOE and DOD, could help enhance market development for advanced carbon materials such as carbon fibers, carbon foam and graphene.

- In addition to the upstream RD&D being funded by DOE/NETL that is focused on developing products and materials from coal and associated manufacturing processes, there is a need for downstream RD&D focused on applications and end-use market development.

- It is very common for technology development to stall at the demonstration stage of technology maturity. Even very promising new technologies, especially complex and capital-intensive technologies, remain un-deployed due to the lack of an effective demonstration. The cost and risk of demonstration projects deter private investments, especially for First-of-a-Kind (FOAK) technologies. The Federal government has often shied away from technology demonstration, even when its R&D investments have brought technologies to the point of demonstration readiness. A well-funded demonstration program for various coal-derived products could help overcome technical and cost barriers.

- Lack of experienced large-scale project managers has also been noted as a challenge to the success of commercial project demonstrations. To enhance prospects for success, demonstration projects need to be managed by senior industry personnel experienced in oversight, finance and management of large-scale projects.

- The Federal government is the single largest consumer in the world, spending more than $550 billion on products and services each year. Both the Federal government and state governments have established procurement and incentives programs in place to ensure cost competitiveness, fairness and support for policy directives, e.g., the Federal Environmentally Preferable Program and DOD’s Defense Production Act, Title III. Procurement programs could be enacted for Federal and state procurement for products and minerals derived from U.S. coal.

- Programs and partnerships supporting advanced manufacturing could be pursued to enhance commercialization of coal-to-products. Prospective models and partnership opportunities include the National Science Foundation’s Advanced Manufacturing program, the National Institute of Standards and Technology’s Office of Advanced Manufacturing, the Advanced Materials Future Preparedness Taskforce, the Additive Manufacturing Coalition and the European Union’s Horizon 2020 initiative.

- The various initiatives underway in the State of Wyoming to create a “Carbon Valley,” similar in concept to “Silicon Valley” in California, provide a model for other states and an opportunity for DOE to support and showcase the value of collaboration among industry, government and academia.

Recommendations & Roadmap for Coal to Products Deployment

The abundant coal resources located throughout the U.S. are a valuable and versatile asset that can be used as a raw material in the production of high-value products critical to our nation's economic, environmental and national security. The U.S. Department of Energy, in collaboration with other Executive Branch agencies, has a vital role to play in supporting the accelerated deployment of coal-to-products technologies. An interagency effort will more quickly and efficiently advance commercialization of these vital products.

A national strategic objective in support of coal-derived products is necessary for commercial deployment. A national RD&D effort must support a full range of technologies and markets. Our ability to understand the 'materials genome' of coal can provide insight into how to use coal as an important materials resource. Funding for fundamental science is crucial to realize the full potential of coal as a feedstock for new, non-traditional uses.

Federal and state governments can support and accelerate the commercialization of coal-derived carbon markets through policies and investments in research, development and deployment, as well as through partnerships with industry, academia and stakeholder groups. Support for common user facilities, easing of cost-share restrictions that effectively exclude viable participants and availability/extension of a variety of R&D tax credits for coal-derived carbon products are among the potential initiatives that might be employed.

Initiatives are needed to minimize costs and risks associated with technology development. Grants, loan guarantees, floor pricing, long-term contracting, Federal procurement programs, "Buy American" efforts and Federal/state tax incentives could enhance opportunities for technology developers and investors. Expedited permitting for coal to products facilities and other efforts to reduce similar regulatory burdens would provide additional incentives.

Transitioning from laboratory to small and large pilot projects is often a stumbling block for many technologies. The step from laboratory scale research to deployable technology is often underfunded. Investments that allow flexible, multi-user facilities to be used for development across a wide range of scales at the pre-competitive stage help reduce risk, encourage collaboration and allow for rapid results while maximizing return on Federal investments.

Technology Commercialization Continuum

U.S. Government Accountability Office

Federal cost sharing or loan guarantees directed at reducing the risk of deployment of FOAK plants could accelerate commercialization of coal-derived products significantly. Federal government support for demonstration projects would help bridge the "Development Valley of Death" between research and commercial deployment. Government support for demonstration projects would also provide a level of reassurance for prospective financial investors.

Public acceptance and a trained workforce will be essential to successfully deploy coal to products and advanced manufacturing initiatives. Federal and state-supported education and training programs are needed in these early stages of carbon age industry commercialization. Complementing workforce development initiatives with visible government encouragement for these industry sectors will advance public acceptance of coal-derived carbon markets.

The recommendations included in this report have been organized to coincide with the Biden Administration's priority objectives to enhance job creation, economic revitalization, environmental stewardship, infrastructure improvements and supply chain resilience. In pursuit of these objectives, the National Coal Council recommends undertaking near-term initiatives within the next five years to lay a foundation for enhancing the use and deployment of critical coal-derived products and materials, enlisting advanced manufacturing techniques. Longer-term initiatives over the ensuing five to ten years will help ensure and accelerate the commercialization of coal-to-products and advanced manufacturing technologies.

These near-term and longer-term initiatives include policies, business approaches and partnership opportunities that will require the participation of Federal and state governments, academia, non-profit organizations and industry. Working together, these entities can forge a path forward for markets and technologies for value-added products from coal that will enhance our nation's economic, environmental and national security interests.

Near-Term Initiatives (within the next 5 years)
to Deploy Coal-Derived Value-Added Products in Support of:

Job Creation

- Locate coal-to-products development and advanced manufacturing facilities in regional hubs and economically distressed communities pursuant to $20 billion referenced in the American Jobs Plan.
- Provide inter-agency support for the Department of Commerce-Economic Development Administration's efforts to prioritize investments in projects that encourage economic diversification, job creation, capital investment, workforce development and re-employment opportunities.
- Extend grants through the Appalachian Regional Commission's (ARC) programs for coal-to-products initiatives that support workforce development, entrepreneurship and industry clusters. Employ the ARC program as a model for other regionally based initiatives.
- Designate shuttered and operating coal mine/power plant sites as economic revitalization zones for next generation industries.
- Support the American Jobs in Energy Manufacturing Act of 2021 (Manchin/Stabenow) and efforts of the White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization.

Economic Revitalization

- Extend Federal funding to include pre-competitive programs across a wide range of coal-derived products.
- Identify and fund Federal/state common-user facilities to enable cost-effective partnerships for technology development and commercial deployment.
- Eliminate cost-share policies that limit participation in grant programs and exclude potential researchers.
- Expand Funding Opportunities beyond rare earth elements/critical minerals to encompass other coal-derived value-added products.
- Expand fundamental research detailing the "materials genome" of coal and how it might be used as a critical materials resource.
- Host DOE/NETL workshops and other stakeholder meetings to secure input from and facilitate collaboration among Federal/state governments, academia, coal-to-products technology developers and advanced manufacturing stakeholders.

Environmental Stewardship

- Acknowledge the energy-saving, emissions-reduction and other environmental benefits of coal-derived products, emphasizing the distinction between "carbon" dioxide emissions and "carbon" used to produce value-added products.
- Incentivize inclusion of coal-derived products with CO_2 sequestration and reduced energy consumption capability as a component of U.S. initiatives to reduce greenhouse gas emissions.
- Extend the 45Q tax credit to those coal-derived products that sequester CO_2.
- Establish Federal procurement guidelines for coal-derived products to enable them to qualify under the Environmental Protection Agency's Environmentally Preferable Purchasing Program.
- Establish "Buy American" incentives for green energy and clean drinking water projects utilizing coal-derived products.
- Support the use of coal-derived soil amendments that do not add toxins, heavy metals or carcinogenic compounds to the soil.

Near-Term Initiatives (within the next 5 years)
to Deploy Coal-Derived Value-Added Products in Support of:

Infrastructure Improvements

- Recognize the superior, high-performance benefits of coal-derived products and incentivize use of these products as a component of U.S. infrastructure improvement efforts.
- Establish "Buy American" incentives for infrastructure investments utilizing coal-derived products with enhanced durability and strength.
- Secure Defense Protection Act authority for DOE under Title III to issue grants, loans, loan guarantees and other economic incentives to address critical infrastructure vulnerabilities.

Supply Chain Resilience

- Incentivize the use of domestic, abundant U.S. coal resources to produce high-value critical materials, reducing our nation's dependence on foreign sources.
- Secure Defense Protection Act authority for DOE under Title III to issue grants, loans, loan guarantees and other economic incentives to enhance supplies of critical materials.
- Execute President Biden's E.O. 14017 initiative to incentivize U.S. battery supply chain stakeholders, including coal-sourced rare earth elements and critical minerals essential for the production of electric vehicle and consumer goods batteries.
- Revitalize Section 48C Advanced Manufacturing Tax Credits and expend Section 1603 of the American Recovery and Reinvestment Tax Act (ARRTA) to support small manufacturers of batteries and associated materials suppliers.
- Extend the 48C Advanced Manufacturing Tax Credit program to include coal-derived product manufacturers.
- Utilize Department of Defense requirements for U.S. sourced materials.
- Support Congressional initiatives that promote domestic exploration, R&D and processing of critical minerals, including those derived from coal, coal ash and coal tailings, i.e., American Critical Mineral Independence Act of 2021 (H.R. 2637), the Securing America's Critical Minerals Supply Act (H.R. 1599) and the Strategic Energy and Minerals Initiative Act of 2021 (S. 1537).
- Support initiatives within the U.S. Innovation and Competition Act (S. 1260) to establish a Directorate for Technology and Innovation within the National Science Foundation and to develop a strategy to establish a critical supply chain resiliency program.
- In response to the White House Report on Building Resilient Supply Chains, DOE should collaborate with the Departments of Commerce and Transportation to address supply chain challenges associated with food supply.
- Enhance supply chain resilience by ensuring access to all domestic coal resources, including run-of-mine coal, coal ash and coal tailings.

Longer-Term Initiatives (within the next 5-10+ years)
to Deploy Coal-Derived Value-Added Products in Support of:

Job Creation

- Deploy Federal and state workforce education and training programs geared to STEM-literate high school graduates and trained technologists with skills essential to both coal-to-products and advanced manufacturing.
- Employ DOE investigator grants and contracts to support training of undergraduate and graduate science/engineering students with skills needed for technology development.
- Expand the University Coal Research program to include topics in the areas of coal-to-products and advanced manufacturing.

Economic Revitalization

- Fund demonstration projects, managed by personnel experienced in administering large-scale projects, to help bridge the "Development Valley of Death."
- Utilize Federal cost sharing and loan guarantees to help reduce the risk associated with deploying First-of-a-Kind plants.
- Offer Federal purchase agreements for coal-derived products, establishing appropriate guidelines, standards, certificates and validations to foster enhanced Federal procurement.
- Employ Federal and state tax credits to encourage private investment in new technologies.
- Extend the 48C Advanced Manufacturing Tax Credit program to include coal-derived product manufacturers to incentivize private sector investment.
- Exempt coal used for production of carbon products from severance or use taxes.
- Include coal-to-products manufacturing facilities within state high-tech incentive pools for economic development.
- Expedite Federal and state permitting of coal-derived product manufacturing facilities that support the Administration's economic revitalization and job creation objectives.
- Fund research support beyond laboratory scale for adaptation of advanced manufacturing technologies for coal conversion.
- Establish a DOE program similar to the National Science Foundation's Mid-scale Research Infrastructure program, focused on funding mid-scale capabilities to advance critical materials and coal-to-products.

Environmental Stewardship

- Utilize coal sourced from waste ponds/tailings when economically feasible and non-detrimental to end-product quality vis-a-vis use of run-of-the-mine coal.
- Pursue R&D related to utilization of coal for production of hydrogen as a carbon-free fuel for electricity generation and for vehicles.
- Pursue applications that combine coal feedstocks and renewable electricity to reduce CO_2 emissions from manufacturing and that can be deployed at the point of use, eliminating transportation costs and associated emissions.

Longer-Term Initiatives (within the next 5-10+ years)
to Deploy Coal-Derived Value-Added Products in Support of:

Infrastructure Improvements

- Pursue technology and cost-reduction R&D initiatives supporting the deployment of high-performance coal-derived asphalt.

Supply Chain Resilience

- Establish floor pricing on rare earth elements and critical minerals to incentivize private sector investment in materials critical to U.S. national security and supply chain resilience.
- Employ long-term contracting for U.S. materials to facilitate market price stability.
- Establish Federal Executive Agency Offices to monitor domestic industrial capacity and deployment of advanced manufacturing facilities to support modernization of manufacturing supply chains for critical goods.
- Locate coal-to-products technology and production/manufacturing facilities close to abundant coal supplies and affordable power generation plants. Shorter supply chains are less vulnerable to disruption.

Chapter I. The Coal to Products Opportunity

Introduction

In a previous report entitled "Coal in a New Carbon Age,"[1] the National Coal Council (NCC) provided detailed information about the opportunities to enhance the use of U.S. coal beyond the conventional markets of power generation and steelmaking. That report focused on potential markets for coal-to-products, including coal-to-liquids, coal-to-solid carbon products, rare earth elements and coal beneficiation, as well as life science, bio-tech, medical and agricultural applications. This report focuses on processes and manufacturing methods for producing these products, as well as many new and novel products from coal.

For hundreds of years, a myriad of useful products has been produced from coal. In this 21st century, advanced manufacturing methods and techniques allow the use of coal in lieu of more traditional raw materials and feedstocks in conventional manufacturing processes. In many cases, the use of coal as a raw material/feedstock results in a simplified process with lower process energy requirements, reduced end product costs, enhanced product performance and minimal environmental impact.

In considering the value associated with coal-derived carbon products, it is important to distinguish "carbon" from "carbon dioxide (CO_2)." Today, there is a focus on reducing emissions, especially carbon in the form of CO_2. Carbon used for production of carbon-based products should not be confused with the carbon in CO_2 emissions. In fact, because many products made from or containing carbon have superior strength, weigh less and require less energy to produce than traditional materials, carbon-based products may have a substantially reduced environmental impact and contribute to efforts to reduce CO_2. A vehicle fabricated with carbon fiber, for example, would be significantly lighter weight and stronger than a more traditionally constructed vehicle, enhancing safety while significantly increasing fuel efficiency.

Coal currently provides the least expensive and most readily available source of carbon.

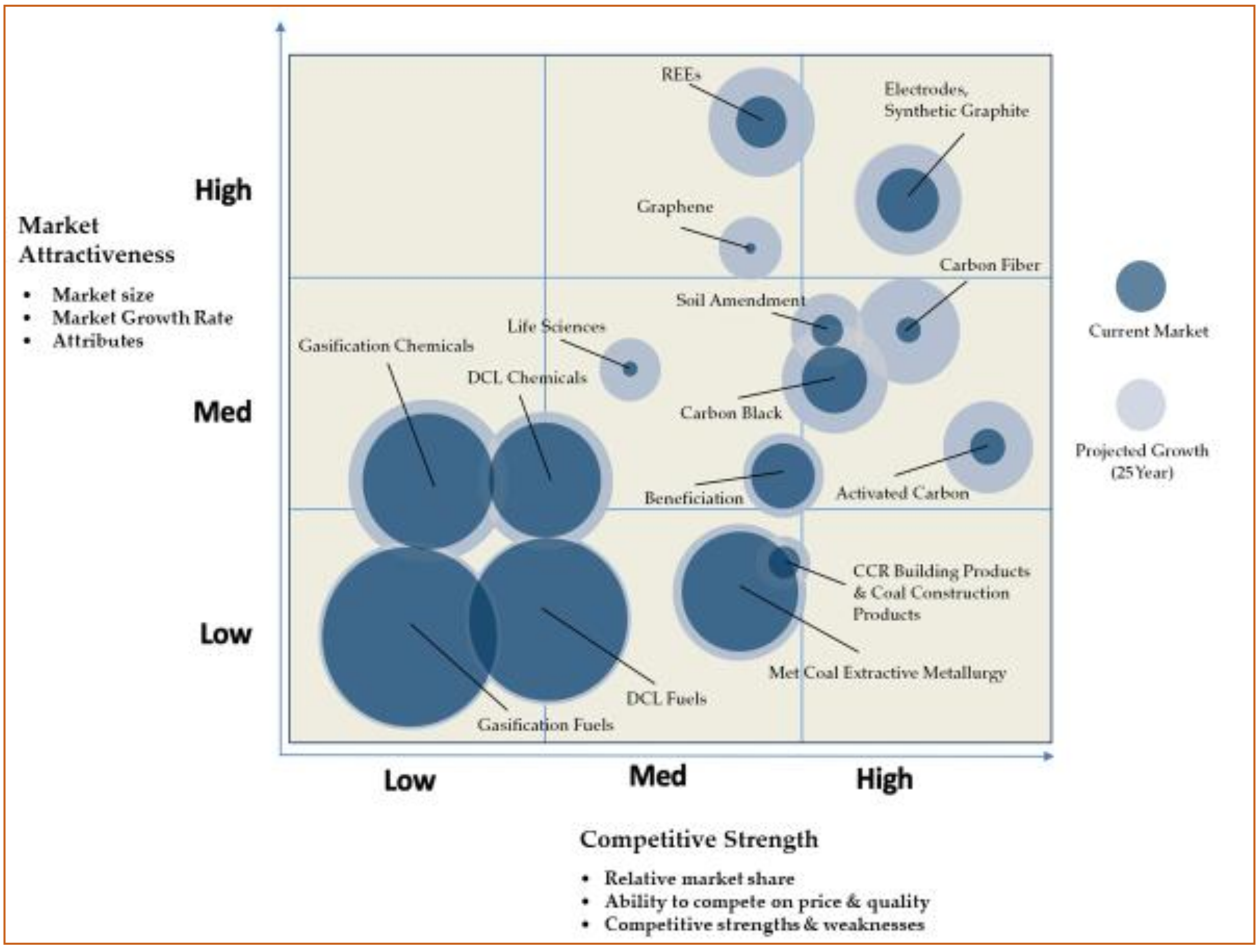
a. The Compelling Case for Value-Added Products from Coal

The U. S. possesses the world's largest supply of an extremely valuable natural resource. This resource can be used to produce a multitude of value-added products, enhance national security, bolster supply chain security, build and enhance new infrastructure, create jobs and support U.S. reemergence as a global leader in manufacturing. **That resource is coal**. Coal is this country's most abundant, valuable and versatile natural resource. Most people think of coal primarily as a fuel, but it is also a versatile raw material for manufacturing. Our nation has more than one-fifth of global coal resources, including nearly 475 billion short tons of demonstrated reserves and more than 250 billion short tons of recoverable reserves.[2]

The industrial revolution in this country, as well as throughout the world, was brought forth on energy provided by coal for power generation and steelmaking. Today, coal is a critical player in the dawning of a new, environmentally cognizant age. It is a feedstock for producing liquid and gaseous fuels. It provides chemical components for the production of plastics, fibers and other strategic minerals, including carbon fiber for use in the automotive, aerospace, defense and building industries. Because of its complex chemical structure, coal is uniquely suited to serve as a raw material, critical to the production of a broad range of value-added products.

Notably, existing and growth markets for coal-based products were identified in NCC's "Coal in a New Carbon Age" report using a nine-block analysis to assess products based on their market attractiveness and competitive strength (Figure 1A). The Council noted significant growth opportunities in producing high-value specialty materials for the automotive, aerospace, construction, electronics, low carbon energy, agricultural, environmental and life science sectors. Similar to other raw materials that are used to make engineered products, coal can only achieve and realize this growth potential as a manufacturing feedstock through technologies that minimize environmental impacts.

Figure 1A. Nine-Block Depiction of Coal-to-Product Technology-Market Pathways



Source: National Coal Council, "Coal in a New Carbon Age"

Coal-derived products support our nation's critical objectives for job creation, economic revitalization, environmental stewardship, infrastructure improvement and supply chain resilience. Coal and coal byproducts contain Rare Earth Elements (REEs) and Critical Minerals (CMs) vital to our national security and domestic supply chain resilience. Additionally, coal can be used as a feedstock for production of light-weight energy efficient building products, fertilizers and agricultural products, enhancing our ability to meet the needs of a growing global population. Finally, these coal-based products further our role as a global leader in advanced manufacturing.

Coal, as an inexpensive feedstock, can economically meet the increasing demand for raw materials used in advanced manufacturing. New materials derived from coal often have improved resiliency, strength, corrosion resistance and wear life compared with traditional raw materials, such as steel for example. They are lighter, more energy efficient and environmentally friendly. Since coal is relatively inexpensive and the U.S. has such an abundance, these new materials derived from coal can be more cost-efficiently manufactured in a domestically secure supply chain.

In addition to its availability and abundant domestic supply, coal is relatively inexpensive compared to other hydrocarbon feedstocks such as petroleum. For example, in many advance market applications, coal is less expensive ($15-50/ton) than traditional petroleum feedstocks ($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.[3] Coal's chemical structure also lends itself to inherently yielding valuable aromatic and other complex compounds and materials. As advanced carbon-containing feedstocks and materials become strategically important components in the energy, manufacturing, electronic, defense, aerospace and automotive industries, coal is poised to play an increasingly critical role in our nation's global competitiveness. Importantly, this critical role will be played out in an environmentally sustainable manner.

In addition to being abundant, coal is an extremely versatile resource. Raw coal is not a monolithic material. Various coal ranks, from anthracite to lignite, possess chemical compounds and compositions that have a myriad of uses for producing value-added products. Simply stated, coal is a unique product of nature with a complex and varied chemical composition. Coal contains an abundance of complex ring (cyclic) compounds that are extremely valuable for manufacturing value-added products. Additionally, because of its unique properties, coal is useful as a feedstock for synthesizing many new products. Moreover, coal is very rich in elemental carbon critical to the production of value-added carbon products. Simply put, coal is too valuable to burn!

Much like petroleum, coal can be refined, converted, treated and processed into valuable co-products with the removal of many harmful pollutants. The U.S. Department of Energy (DOE) is at the forefront of developing these processes for commercial applications. Moreover, while many natural resources, including petroleum, require substantial effort (exploration) to find, coal deposits tend to run in veins and are easily and readily discernible, i.e., coal is easy to find. Thus, the cost of exploration for coal is low or nonexistent. Likewise, unlike petroleum which is expensive to extract, coal is relatively inexpensive to mine. These two factors tend to make this abundant, raw resource relatively inexpensive on both a tonnage and BTU basis. It is an ideal feedstock for economically producing value-added materials.

Coal's Role in a 21st Century Economy. Coal-to-products technology will enable economic, environmentally compliant production of liquid fuels, industrial commodity products, specialty chemicals and advanced carbon containing materials from coal. These advanced materials produced from coal are an important component of clean energy and manufacturing industries in the 21st century.

An example is integration of coal into the value-chain of the advanced composites and 3D printing industries. High performance advanced polymer composites are used in many industries where both strength and weight are of critical importance (e.g., aerospace and defense industries). However, due to the extensive processing procedures required (e.g., hand-layup[i]), they suffer from high production costs and do not currently benefit from economies of scale. The use of coal-derived feedstock for production of polymer composites can greatly reduce process complexity and the cost of the products produced. This would allow sectors where carbon fiber reinforced composites are currently cost-prohibitive (e.g., consumer automobiles) to benefit from the higher performance and lighter weight of these coal-derived composites. Plus, given the lighter weight and increased strength of these coal-derived materials, automobiles could be safer and achieve greater mileage per unit of fuel. This is just one example of the value of coal-derived products.

National Security and Supply Chain Resilience. The recent COVID-19 pandemic spotlights the fragility of our domestic supply chain, which relies on foreign sources for vital material supplies. The resilience of domestic supply chains is critical to U.S. economic prosperity and national defense. In regard to coal and carbon products, this fragility is most apparent given our significant dependence on foreign sources – primarily China – for REEs and CMs. As noted in NCC's "Coal in a New Carbon Age Report," in 2014 REEs supported a market of greater than $300 billion and employed over 600,000 in North America, yet we remain nearly 100% dependent on foreign sources for these inputs.[4]

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[i] The manufacturing process known as 'hand layup' involves manually laying down individual layers or 'plies' of a form of reinforcement known as 'prepreg'. This consists of thousands of fibers, which are pre-impregnated with resin and bundled into tows and arranged either in a single unidirectional ply or woven together.

Advancing domestic production of these critical minerals from coal could greatly reduce our dependence on imports and enhance the security of domestic supply chains supporting high-tech products such as magnets, computers, and electrical and electronic products, many of which are needed for manufacturing electric vehicles (EVs). Growth in U.S. sales of EVs is constrained by the high cost of lithium-ion batteries used to power many electric vehicles (more than 50% of the vehicle cost).

Use of coal-derived carbon products can also provide an opportunity to diversify feedstock sources for our nation's material and chemical industries, many of which are currently dependent on petroleum, natural gas derivatives and off-shore markets. Coal-derived products can reduce the cost of producing feedstocks and decrease U.S. dependence on foreign suppliers.

In addition, an expected outcome in the graphite industry is the substitution of synthetic graphite derived from domestic coal for imported natural graphite. China dominates natural graphite production with 68% of the world's output; there are no operational graphite mines in the U.S. Graphitic materials are currently used in many industries, including electronics (e.g., high capacity Li-ion batteries), steel/aluminum production (electrodes), composite materials, nuclear, friction, thermal management, and paints and coatings. A further outcome is the alleviation of the shortage of high-quality carbon inputs in domestic primary metals production.

Supply chain resilience will be enhanced by ensuring access to all domestic coal resources. While the use of waste coal from mine tailings in the production of some coal-derived products may be feasible and beneficial for cleaning up waste ponds, doing so may limit available resources, notably from globally competitive mining operations in the western U.S. where there are no coal mine tailing sites.

Infrastructure. In addition to its abundance, low cost and versatility as a feedstock, coal has another very important advantage – *infrastructure*.

Infrastructure for the production, transportation and use of coal is well established. Since coal has been part of this country's energy and manufacturing infrastructure for hundreds of years, the means for transporting coal to advanced manufacturing and production facilities already exist. Moreover, permitted coal mines are available to produce an abundant supply of raw coal at low cost. In addition, chemical industries, including rail and pipeline transportation, exist for those compatible hydrocarbon-based chemicals and fuels derived from coal. Many coal-derived fuels are compatible with their petroleum counterparts and, therefore, can utilize existing transportation and distribution systems.

While at a glance this may not seem important, the coal, chemical, natural gas and petroleum transport infrastructure in this country (pipelines, railroads, trucks, ships, ship ports and stockpiling distribution centers) has a replacement value in excess of a trillion dollars. In developing the advanced process manufacturing techniques and facilities for utilizing coal to provide value-added products, consideration must be given to leveraging this historic and significant investment in infrastructure. The U.S. coal supply chain is already well established.

Jobs. A small coal-to-products plant processing 5,000 tons of coal could create 300-400 direct and indirect new jobs. Many jobs are supported by the primary and secondary effects of coal mining, including rural economies built and supported by coal mining; transportation industries such as rail and water (river and ocean); support infrastructure, supply and equipment industries which serve the coal industry; coal-based manufacturing industries such as chemical processing equipment; and other support and service industries.

A recent summary by the Department of Energy of the job potential associated with various coal-derived products (Figure 1B) illustrates that the total job potential associated with coal-to-products markets is significant.[5]

Figure 1B. Potential Demand for New Coal Production & Employment Associated with Markets for Carbon Products

Carbon Product	Potential U.S. Coal Industry Requirements - 2050*		U.S. Product Value -2050 (Million $) *	Employment-2050 (Mfg.)*
	Coal Production (mmt)*	Coal Mining Employment*		
Activated Carbon	22	2,641	15,979	32,437
Carbon Anodes (incl. Aluminum, Li-Ion Battery Anodes)	35	4,257	31,289	63,476
Carbon Black	14.1	1,692	5,077	10,306
Graphite Electrodes/Needle Coke	12.5	1,502	41,315	83,869
Carbon Fiber (incl. CFRP, C-C composites, cement)	47.6	5,713	24,701	50,127
Carbon Nanomaterials (incl. cement)	12.1	1,457	14,125	28,300
Conductive Inks	0.001	1	264	500
Roofing Tile	2	243	7,192	14,500
Aggregate**	**100+**	**15,000+**	**TBD**	**100,000+**
Foam - Building Mat**	**100+**	**15,000+**	**TBD**	**100,000+**
Total Carbon Products	**145 to 345+**	**17,500 to 47,500+**	**139,000 +**	**280,000 to 480,000+**

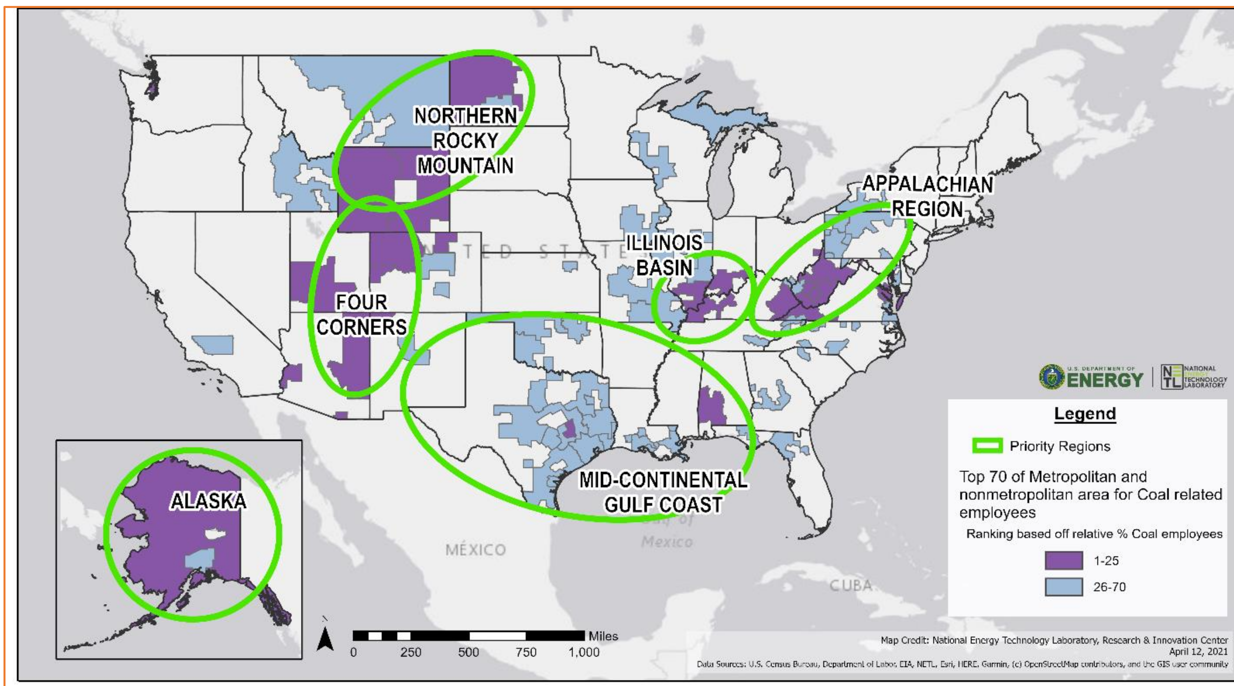
* Values reported in 2050 represent a high coal penetration scenario in which carbon-based products made from coal penetrate 80 percent of the overall product market. Additionally, several products (e.g., anodes/electrodes, CF & graphene) represent high demand growth scenarios.
** Data from project estimates with technology developers for large commodity markets

Source: U.S. Department of Energy/Office of Fossil Energy

Moreover, job creation can occur in the same communities in which coal extraction and coal-based electricity generation occur, if the conversion and manufacturing plant is located at a coal mine mouth or on the site of an existing or shuttered coal electric power plant. Thus, the communities most economically harmed by the decline in thermal coal production and use will benefit the most from emerging coal-to-products industry and associated new high-value value chains.

The White House Interagency Working Group (IWG) on Coal and Power Plant Communities and Economic Revitalization established by President Biden (Executive Order 14008) released an initial report to the President on empowering energy communities in April 2021.[6] The report identified 25 priority energy communities as key locations for Federal investment for job creation, including coal communities identified as immediately challenged (Figure 1C). It is precisely these communities in which jobs can be readily created through deployment of coal-to-products.

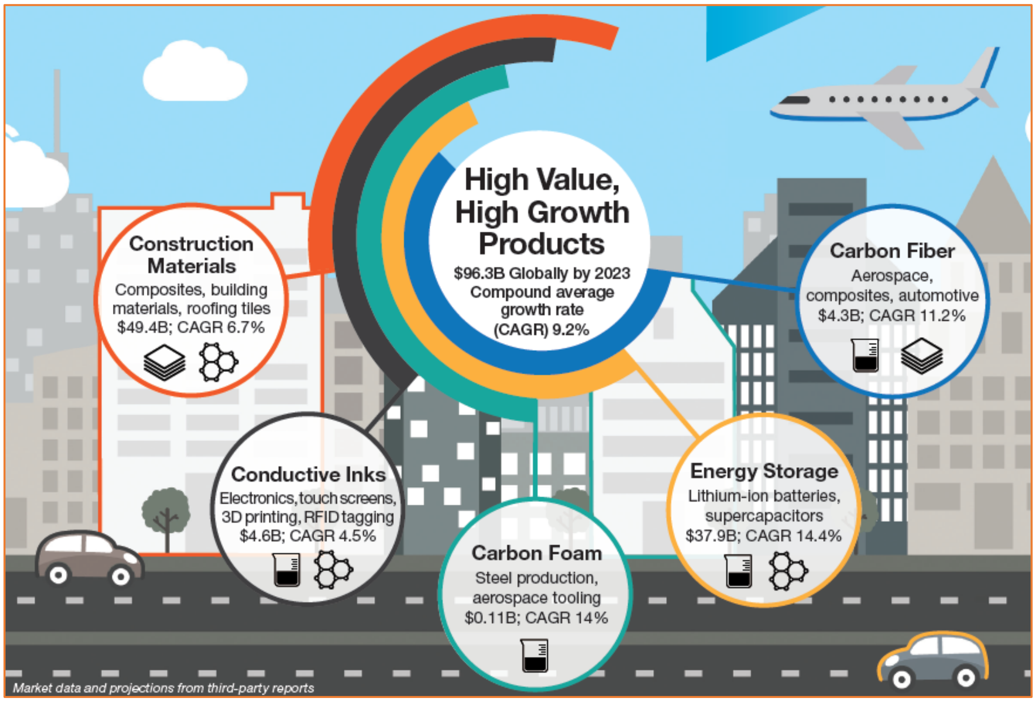
Figure 1C. IWG Recommended Federal Investment Areas



Source: White House Interagency Working Group on Coal & Power Plant Communities & Economic Revitalization

Economic Value. The high-value product markets in which coal can contribute have significant future high-growth potential. (Figure 1D) The National Energy Technology Laboratory (NETL) projects that these products will have a global market value of over $96 billion by 2023 and a Compound Annual Growth Rate (CAGR) of 9.2%.

Figure 1D. Product & Application Market Potential of High-Value/High-Growth Products



Source: National Energy Technology Laboratory

Utilization of coal as an inexpensive feedstock for manufacturing of value-added products will reduce the price pressure on competing feedstocks. This is especially true with regard to hydrocarbon feedstocks such as petroleum and natural gas. The high carbon content of abundant low-cost coal can reduce the cost of manufacturing high carbon content products (e.g., carbon fiber) as compared to lower carbon content petroleum and biomass resources.

In addition to reduced costs attributable to raw feedstock price differentials (e.g., $500/ton for petroleum versus $15/ton for Powder River Basin coal), the integration of coal into advanced composites and the use of 3D printing to manufacture carbon composites for use in the automotive industry could potentially replace parts made from more capital and energy intensive processes, such as rolling and milling steel. This is one example of the benefits of more cost-efficient, environmentally friendly advanced manufacturing processes associated with coal-derived products.

Environmental Stewardship. As detailed throughout this report, coal-derived carbon products support efforts to electrify the transportation sector, reduce air emissions, provide clean drinking water and decrease energy consumption. Advanced manufacturing holds promise for continued improvements in energy consumption and emissions reduction associated with production of value-added products from coal.

The environmental benefits associated with coal-derived products may offer opportunities for commercial entities that are increasingly evaluating options to reduce their carbon footprint. The Greenhouse Gas (GHG) Protocol Corporate Standard[7] classifies a company's GHG emissions into three "scopes," the last of which covers "indirect GHG emissions" such as those deriving from end-use of the company's products. The potential to use coal for production of products, provides environmental benefits in terms of essentially capturing carbon in the product as well as avoiding emissions associated with burning coal.

Refiners, for example, who can divert fuels to chemicals can capture the carbon in the chemical product and avoid emissions from the combustion of fuels. Recently, Exxon/Mobil announced plans to address their Scope 3 GHG emissions in response to increasing stakeholder interest in tracking Scope 3 data.[8] The company noted that while many Scope 3 emissions resulting from consumption and use of a company's products occur outside of its control, "ultimately, changes in society's energy use coupled with the development and deployment of affordable lower-emissions technologies will be required to drive meaningful Scope 3 emissions reductions."

Examples of environmental benefits of coal-derived products:

- Ammonia (Fertilizers/Plastics/Transportation Fuels) – advanced manufacturing approaches and process intensification are enabling small-scale distributed plants which are carbon neutral.
- Methanol (Marine Fuels) – methanol offers an alternative fuel for ships, helping the shipping industry to meet increasingly stringent emissions regulations.
- Activated Carbon (Air/Water Purification) – significant global demand for activated carbon is being driven by its use for water treatment and air/gas purification.
- Graphite (Energy Storage) – graphite's electrical conductivity properties are in demand for energy storage applications, including those for electric vehicles.
- Carbon Fiber (Light-Weight/High-Strength Critical Materials) – properties of carbon fiber are in demand in the aerospace, civil engineering and defense sectors, offering notable improvements in transportation industry carbon emissions and energy consumption.
- Graphene (High Strength/Durable Performance Products) – graphene's beneficial properties enhance energy storage capacity in Li-ion batteries, decrease energy consumption for water purification and desalination of water, and increase durability of infrastructure building materials thus reducing CO_2 emissions since fewer products need to be manufactured.

- Building/Construction Materials (Concrete, Panels, Asphalt) – many coal-derived building materials can be manufactured with less energy consumption and lower emissions than conventional products; others enable CO_2 to be fully sequestered in the process and the product; still others provide non-toxic alternatives.
- Rare Earth Elements/Critical Minerals (Batteries) – these minerals are critical components for use in electric vehicles and battery storage.
- Agriculture (Fertilizers) – coal-derived soil amendments do not add toxins, heavy metals or carcinogenic compounds to the soil.

Improved Product Performance. Coal-derived carbon can deliver superior performance for certain products. For example, carbon nanotubes (CNT) made from coal have demonstrated superior performance to more traditional metal components in certain applications in industries including aerospace, electronics, medicine, defense, automotive, energy, construction and fashion. Coal-derived CNTs greatly enhance the energy capacity in lithium ion batteries, increase transistor density, build stronger and lighter sporting equipment and personal armor, and more efficiently conduct electricity than copper, thus reducing transmission line losses.[9]

As detailed in Chapter III of this report and in NCC's "Coal in a New Carbon Age" report,[10] other carbon-based products made from coal include medical products which improve patient care, disease diagnosis and pathogen detection. Graphene derived from coal, has a physical structure and unique physical properties which make it ideal for use in biosensor technologies. Coal-derived agricultural products, such as soil additives, including coal char and fertilizers, enhance water retention, growth of beneficial micro-organisms, root growth and plant yield, and also support soil carbon sequestration. As noted earlier, certain ranks of coal have specific compounds and/or properties which enhance their use in particular applications. For example, lignite coal contains natural humic acid-based soil amendments. Humic acid compounds play an important role in counteracting the deterioration of fertile land, a challenge caused by intensive farming, erosion and drought.

b. Coal-to-Products Benefits of Specific Applications

Following are examples of benefits associated with specific coal-derived products. Noted throughout are examples of coal-derived products that can provide performance advantages over existing products (e.g., steel, aluminum, petrochemicals) and meet the needs of emerging markets (e.g., conversion of the automotive fleet to electric vehicles).

- **Chemicals and Chemical Feedstocks**

  Coal-to-chemicals (CTC) is the fourth largest use of coal behind electric power, steel and cement production, yielding over 40 million metric tons per year.[11] Coal tar, the primary product for CTC, is used in the production of aromatic chemicals, building materials and carbon anodes for aluminum smelting. The second largest and growing usage of CTC is for the production of polymers using methanol-to-olefins (CTO/MTO) technology. Most of this market is currently based in China.[12] Emerging technologies, which refine coal, are focused on the direct production of chemicals as feedstocks for a number of petrochemical materials. Also emergent is the direct production of aromatics, including BTX (benzene, toluene, and xylene isomers), from coal in an environmentally benign manner, removing pollutants, reducing the carbon footprint and requiring no processing water. In areas where water availability may be limited, careful consideration of plant siting is required for coal-to-products processes requiring large water consumption. In some processes, using sub-bituminous coal can ameliorate water shortage challenges.

- **Coal Derived Products for Gas, Liquid and Solid Fuels**

  Beginning as early as the 1900s, coal-derived liquids were used for transportation fuels, kerosene and various chemical-derived products, such as plastics and detergents.[13] Coal-to-fuels processes are currently focused on improving energy efficiency and reducing processing costs through changes in catalyst, reactor and process design, often through exploiting the nature of coal which lends itself to the concurrent co-production of fuels and chemical products. Coal refining has the ability to produce fuel and chemical products traditionally derived from petroleum and natural gas in order to seamlessly use existing fuel supply and delivery infrastructure, as well as conventional internal combustion engines, including jet engines. When utilized with CO_2 capture, coal refining results in reduced emissions associated with production of both fuels and chemicals.

  Utilization of coal for production of hydrogen holds potential as a transportation fuel. Today, virtually all of world's hydrogen is derived from fossil fuels via gasification or steam reforming, followed by the water gas shift. A growing anticipated use of hydrogen is as a carbon-free fuel for electricity generation and for vehicles.

- **Rare Earth Elements (REEs) and Critical Minerals (CMs)**
  As noted earlier, in 2014 rare earth elements supported a market of greater than $300 billion, employing over 600,000 in North America. Yet, in the U.S. we remain nearly 100% dependent on foreign sources for these inputs. China controls over 85% of REE production with the remainder mined in Australia and Mongolia. In a U.S. Department of Energy (DOE) white paper summarizing findings from a 2019 workshop[14], it was noted that of the 35 minerals identified as critical by the Secretary of the Interior, the U.S. is 100% net import-reliant for 14 and is more than 50% import-reliant for 17 of the remaining 29 mineral commodities.

  REEs can be extracted from coal, coal tailings overburden and/or coal combustion residues. Among the various REE recovery technologies being tested by DOE, is a reduced cost method in which all the volatile co-products are removed from the coal by refining, leaving pure carbon (char) without any of the pollutants (N_2, S, Hg, and Cl). The char is then combusted in an oxygen-blown gasifier to produce electricity, capturing all of the produced carbon dioxide (CO_2) (no carbon footprint) and a prilled or pelletized inorganic residue. The REEs can then be extracted from this small amount of material by conventional methods. An additional benefit gained by removing REEs from coal tailings is a reduction in contaminant heavy elements from aqueous waste streams.[15] Given the initial success of trial projects, the DOE's Office of Fossil Energy & Carbon Management, in conjunction with NETL is supporting the next phase of commercial deployment.[16]

- **Coal-derived Building Products**
  One of the largest market segments for solid products derived from coal is building and construction materials. The use of coal in these applications can enhance the mechanical properties (e.g., durability, strength, fire/mold/corrosion resistance, reduced water absorption), economics and environmental profile (e.g., reduced manufacturing energy requirements) of the finished product.

- **Carbon Fibers and Films**
  About 90% of the carbon fiber currently produced is made from petroleum-based polyacrylonitrile (PAN); the remaining 10% is made from coal tar pitch or petroleum heavy oil feedstocks. Given that on a per ton basis, Powder River Basin coal is about 3% of the cost petroleum, manufacture of carbon fiber from coal could be transformative for the aerospace, defense and automotive industries amongst others. New advanced materials could enhance or replace basic metals, such as steel or aluminum, and conventional building products, such as cement, asphalt, rebar or roof shingles.

- **Electrodes, Synthetic Graphite, Battery Anodes, Capacitors**

  Industrial electrodes are generally made from petroleum needle coke, a growing market with rising prices. Demand for high purity graphite or porous carbons is increasing in markets for lithium ion batteries, large scale battery pack and carbon electrode materials for energy storage and electric vehicles. The use of coal feedstocks in new battery technologies, such as synthetic graphite produced from coal tar pitch, is evolving. The inherently higher carbon content of coal derivatives, relative to oil or biomass sources, can help reduce manufacturing costs.

- **Carbon Nanotubes and Graphene**

  Carbon nanotubes (CNT) are highly sought after for applications in many industries, including aerospace, electronics, medicine, defense, automotive, energy, construction and fashion. In a report prepared by the International Energy Agency (IEA) on "Non-Energy Uses of Coal,"[17] author Ian Reid notes CNTs can be used to double the energy capacity in lithium ion batteries, increase transistor density, build stronger and lighter sporting equipment and personal armor, and more efficiently conduct electricity than copper wiring, thus reducing losses of electricity on the grid.

  For example, increased availability of carbon materials for electric vehicle applications with a dramatically improved sustainability profile would improve the emissions profile of the U.S. vehicle fleet, which is responsible for 30% of the nation's CO_2 emissions. Availability of the key component of high-performance batteries (25% graphite by weight) would directly support growth of the electric vehicle (EV) fleet. Additionally, availability of low-cost, low-weight composites derived from coal would support gains in gasoline vehicle fleet efficiency. Even a 10% reduction in vehicle weight would lead to an 8% improvement in fuel economy gains.

  Coal-derived ultra-high modulus carbon fibers (UHM CF) have exceptional strength; they could potentially serve as a replacement for steel and aluminum in certain applications. The high cost of continuous fiber and parts manufacturing with manual lay-up presently preclude carbon composite adoption outside of high-performance (e.g., aerospace) applications. Discontinuous carbon fiber may offer a route to achieve lower costs than traditional continuous low fiber, and would be suitable for industry-standard injection molding production lines. The dramatic reduction in capital intensity of the composites supply chain could reduce cost of the final parts from $100/kg to $10/kg, driving adoption of coal-derived carbon composites by the automotive industry.

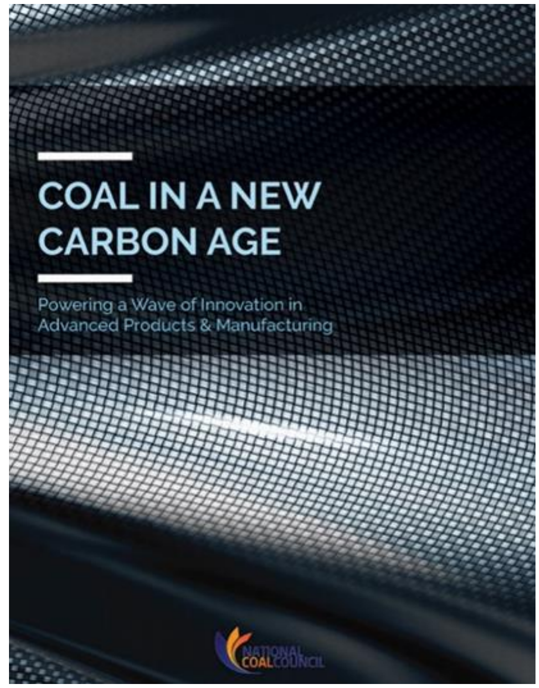
- **Fertilizers and Other Agricultural Products**
  Coal-derived agricultural products, such as humic soil additives, soil amendments and fertilizers, enhance water retention, growth of beneficial micro-organisms, root growth and plant yield. Lignite coal contains natural organic compounds known as humate. Organic fertilizer made from lignite coal is used increasingly to improve soil fertility and the efficiency of mineral fertilizers, and to overcome drought and salinity impacts. 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. Similarly, coal-derived charts can possess exceptional porosity and purity, lending themselves to support nitrogen retention in soils and also prevent water run-off, in turn improving the soil carbon sequestration potential.

The following four pages provide a summary of NCC's earlier report on the topic of coal to value-added products.

Coal In a New Carbon Age

Powering a Wave of Innovation in Advanced Products & Manufacturing

SUMMARY OF NCC 2019 REPORT ON COAL-TO-PRODUCTS



In May 2019, the National Coal Council (NCC) completed a report for then Secretary of Energy Rick Perry in response to his request to assess opportunities to enhance the use of U.S. coal for applications outside of power generation and steelmaking. The report identified significant market-scale opportunities for new markets for coal and highlighted the associated economic, national security, societal and environmental benefits.

Advanced markets for coal-derived products, materials and technologies, referenced in the 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 and soil amendments

As the United States embarks on a "New Age of Carbon," coal, and the carbon it contains, will be a valuable resource in powering a wave of innovation in advanced products and manufacturing. The benefits to the U.S. of employing these coal-derived products are compelling.

Economic Benefits – In early 2019, the global market for coal-to-products was 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 advanced 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.

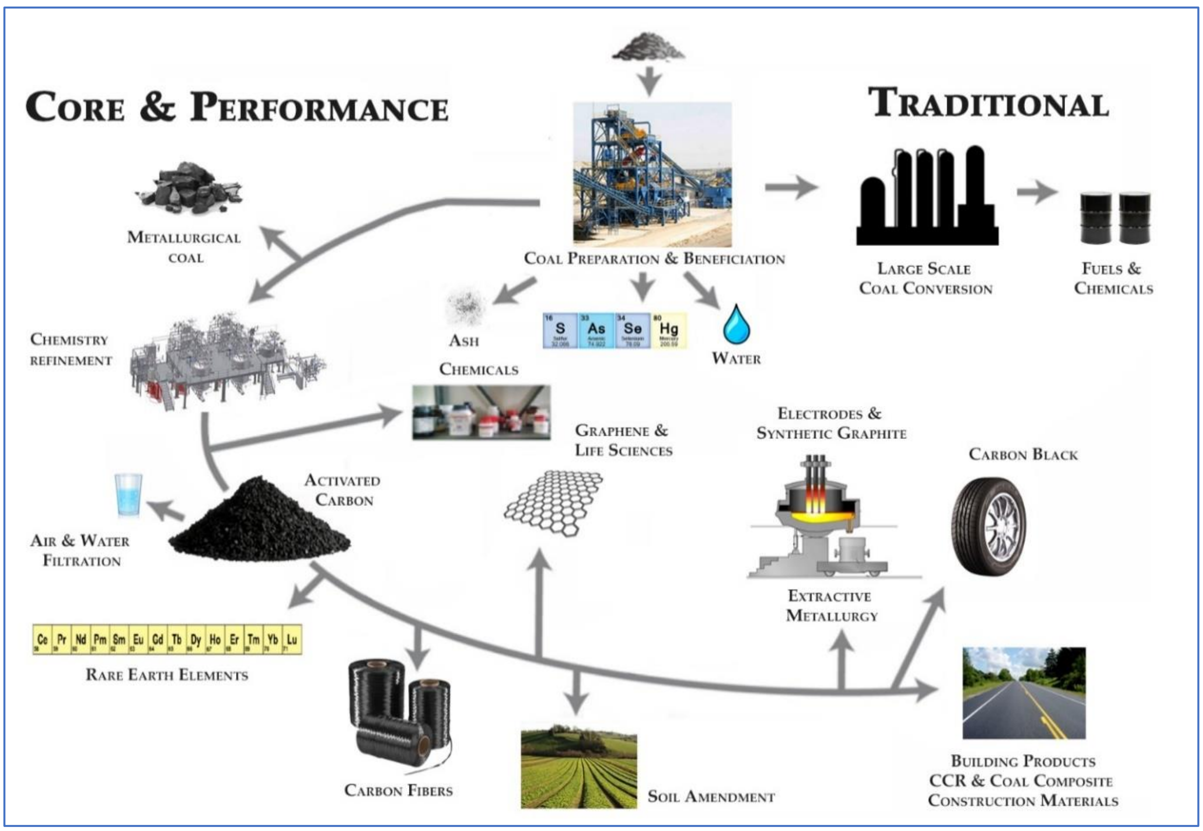
The analysis undertaken by the NCC indicated that coal tonnage utilization of domestic U.S. coal for coal-to-products applications has the potential to be on the same order of magnitude as that projected for coal power generation applications in the coming years. The markets for carbon products, in particular, 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 could 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 light-weighting; 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.

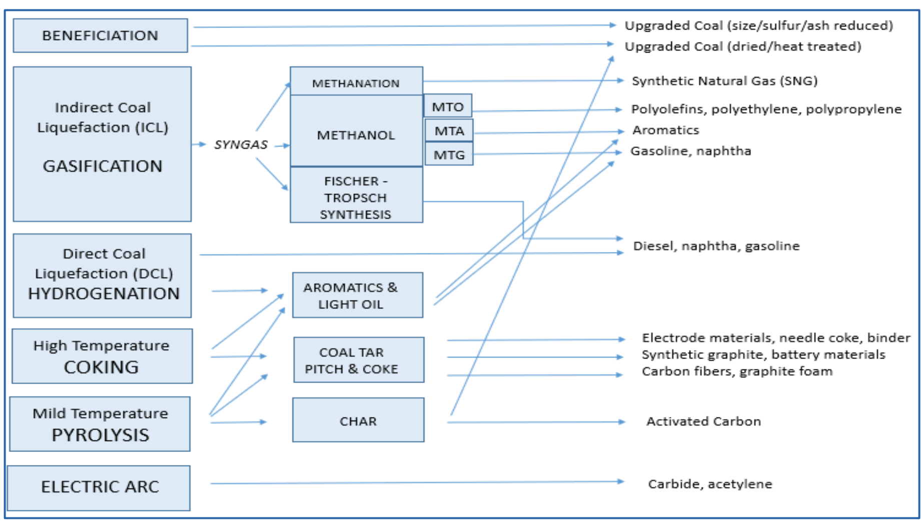
National Security Benefits – Rare earth elements support critical sectors of the U.S. defense industry. Advancing domestic market production of these critical minerals from coal and coal ash could greatly reduce the nation's significant dependence on imports from China.



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

In its report, NCC undertook a systematic approach for characterizing, assessing and prioritizing market and product attractiveness for these coal-to-products markets using a nine-block analysis. Each of the 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). The analysis detailed 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 U.S. opportunity. 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.



The conclusions of the NCC's nine-block analysis 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.

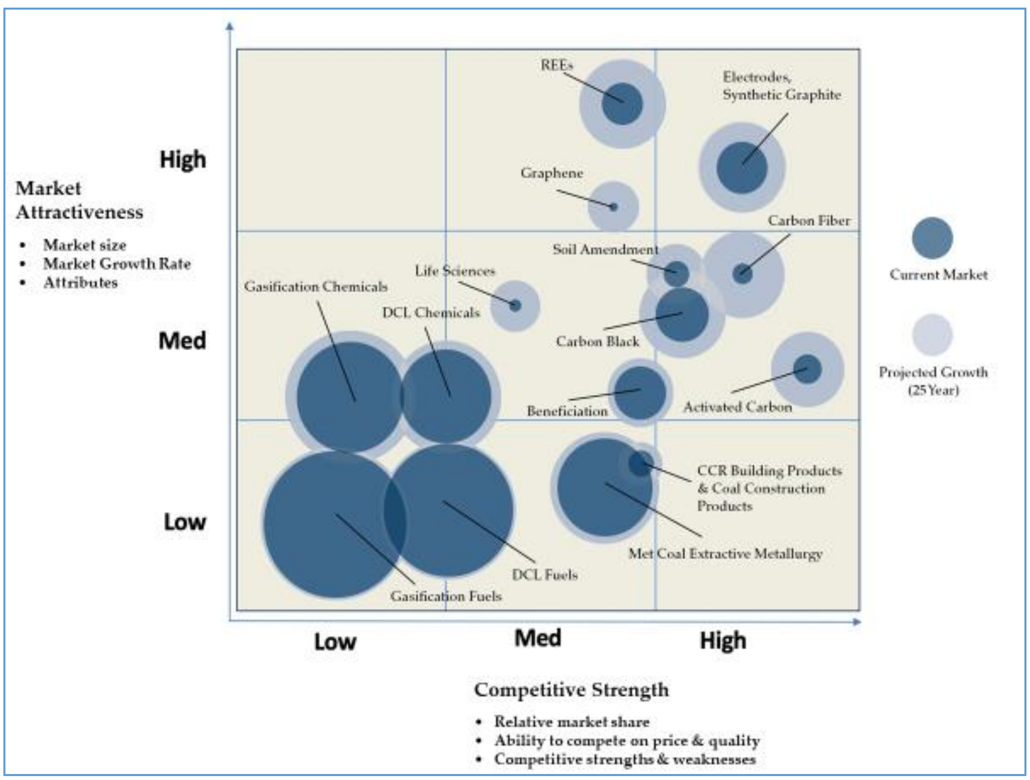
The most significant growth opportunities for U.S. coal are in producing high-value specialty materials and products at reduced costs that will accelerate and spearhead large-scale applications. Coal has the potential to become a new, innovative, low-cost solution to creating advanced materials and products across many important sectors, including automotive, aerospace, construction, electronics, low carbon energy, agricultural, environmental and life sciences.

Recommendations

To advance and accelerate the commercialization of domestic markets for coal-to-products, the NCC recommended three primary strategic objectives be pursued by the U.S. Department of Energy.

- **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.

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.



Qualitative Nine-Block Analysis of Coal-to-Products Markets

Chapter II. Production Pathways for Coal-Derived Products: Conventional and Advanced Manufacturing

Introduction

In May 2019, the National Coal Council (NCC) produced a report for then Secretary of Energy Rick Perry assessing opportunities to enhance the use of U.S. coal for new coal to product markets. The "Coal in a New Carbon Age"[18] report focused on what markets and opportunities exist for coal to products.[ii]

NCC's current report, "Carbon Forward," addresses how to advance these markets, including:

- What existing and prospective Federal and state policies would support and accelerate coal to products technology commercialization.
- What research, development and deployment (RD&D) investments are needed to support coal to products markets.
- What opportunities should be pursued among stakeholder groups in this sector.
- How coal to products markets can be used to advance U.S. national strategic objectives.

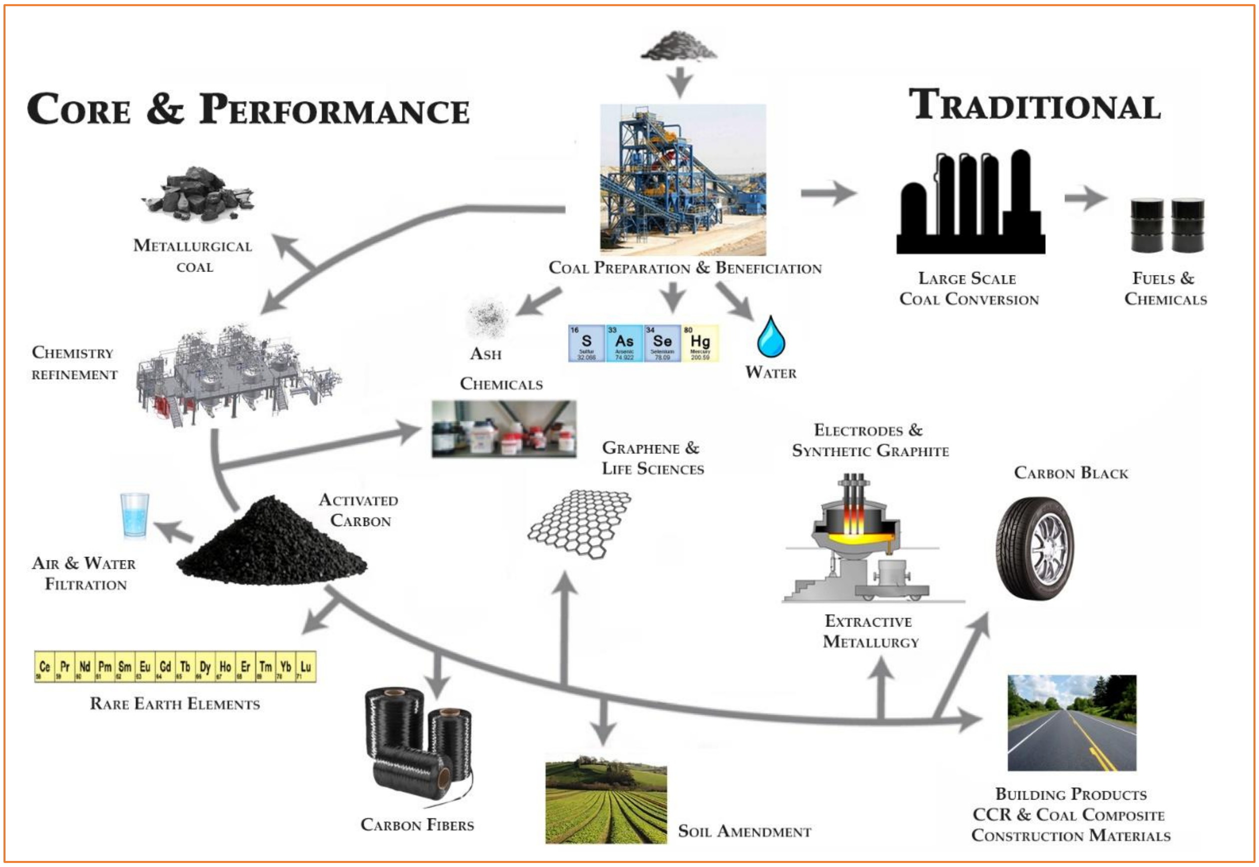
In response to the Secretary's request, this report also focuses on pathways for production of coal-derived products, including both conventional and advanced manufacturing. Conventional manufacturing refers to the process of converting raw materials into a finished, saleable product by manual and/or mechanized transformational techniques. Advanced manufacturing employs innovative technology to improve products and/or manufacturing processes, providing tools that can drive the rapid transfer of science and technology into manufacturing products and processes.

Finally, a discussion of production pathways should also take into consideration sourcing of the coal resource. The quality and cost of coal-derived products can be affected by the quality of the coal input. The use of coal from mine tailings in the production of some coal-derived products may be feasible and beneficial for cleaning up waste ponds, but may not be optimal for all applications in terms of carbon and mineral content, or given the associated cost of recovery. Extending preferential treatment for use of coal waste may jeopardize deployment of high-value coal-derived products, especially in the western U.S. where there are very limited mine tailings sites.

Figure 2A graphically presents the use of both conventional and advanced techniques for production of coal-derived value-added products.

[ii] Chapter III of this report provides an update on various coal-derived products, including a discussion of their commercial significance, advantages and opportunities.

Figure 2A. Coal-Derived Products: Conventional & Advanced Pathways



Source: National Coal Council

This chapter provides an overview of both conventional and advanced manufacturing pathways for producing various coal to value-added products.

a. Conventional Production/Manufacturing Pathways

Today, coal is primarily used for power generation and steelmaking. Coal is combusted to produce electricity; coal is heated to produce coke for steelmaking. By-products derived from these processes can be recovered and further processed into valuable products from coal.

- Coal combustion products (CCPs) are the materials that remain after pulverized coal is burned to generate electricity. These materials have a wide range of uses in construction, manufacturing, environmental remediation and other industries, including recovery of rare earth elements and critical minerals.

- Coking of coal generates volatile materials as byproducts: coke oven gas, tar, ammonium sulfate and light oils. These by-products are further processed to produce valuable chemicals used in the production of plastics, tires, aluminum and pharmaceuticals.

Conventional pathways will continue to play a vital role in the production and manufacturing of coal-derived products. As is the case with all manufacturing industries today, these processes will, of course, need to address how to meet carbon management objectives. Primary among these conventional processes are beneficiation, gasification and calcining. Additional production pathways include pyrolysis, solvolysis and hydrolysis (all with or without catalysis), as well as injection molding and carbon fiber layup. Depending on the product slate, multiple processes might be integrated or combined in the manufacturing process.

Beneficiation

Beneficiation relates to the upgrading of coal quality and/or the conversion of coal into higher value products. Utilization of coal in conventional processes begins with coal preparation (beneficiation) to improve the quality of raw, mined coal to make it suitable for a given process. Much beneficiation of coal involves removing inorganic impurities (i.e., ash reduction). For coals that contain a significant amount of moisture (i.e., low-rank coals), reducing the moisture content through thermal dewatering is also sometimes useful.

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). These are important intermediate processing steps needed for production of a wide-range of established products.

Mechanical separation to remove ash-bearing mineral matter is the most common beneficiation operation. Typically, the raw coal is crushed and separated by size. Gravity separation processes are used on different size fractions in which the coal is suspended in a fluid with a certain specific gravity (air, water, organic liquids) and then separated into “clean” coal and “refuse” coal.[19,20] The smallest particles may be separated into clean coal and refuse based on surface properties using technologies such as froth flotation or oil agglomeration. Clean coal from mechanical cleaning operations typically has an ash content of 5-15%, depending on the mineral distribution in the coal.

The concentrations of certain inorganic elements associated with the mineral matter (e.g., sulfur, trace metals) are also reduced.[21] Ultra-clean coal (1-2% ash) can be produced by high-energy milling followed by density separation.[22] Various leaching or solvent extraction methods have been reported as well with the goal of reducing the ash content to 1% or less.[23,24] Production of ultra-low-ash coal has not been widely used for combustion applications because of the cost relative to existing ash management technologies; for the production of high-value products, however, these methods might be justified economically.

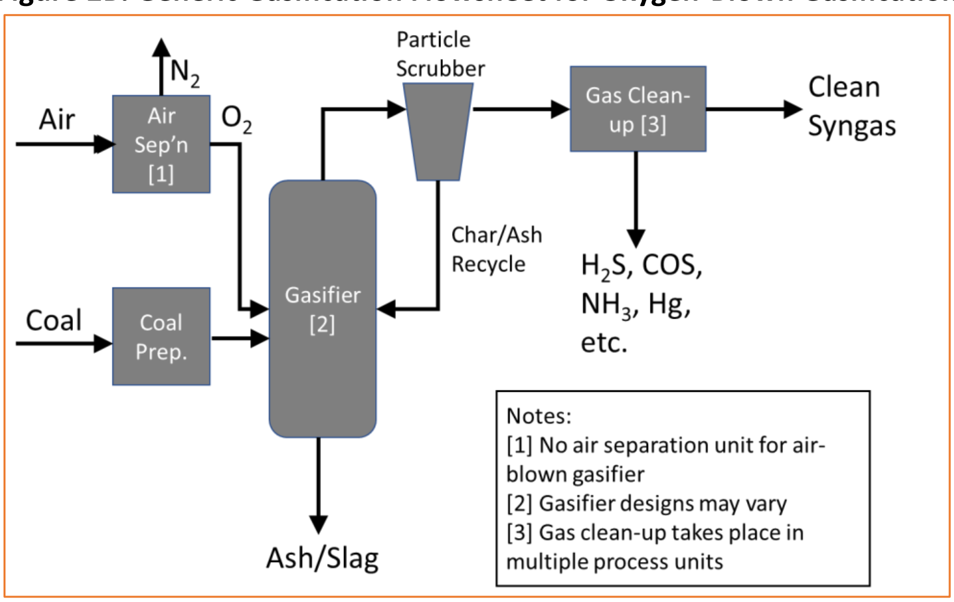
Moisture can be removed evaporatively (i.e., released into the gas phase) or non-evaporatively (e.g., hydrothermal dewatering) from coal with efficiencies of 50% to 75%. A high-temperature medium (200-600°C) transfers heat to the coal either directly or indirectly. Examples of dewatering media are flue gas, hot air, steam or hot water. Dewatering can take place over a range of pressures: vacuum, atmospheric or high pressure. A variety of commercial processes have been used for dewatering,[25] which can also remove some components of the coal. For example, thermal drying of lignite removed 70% to 80% of the mercury at a temperature of about 290°C,[26] because most of the mercury in lignite is organically bound and thus easily vaporized at relatively low temperatures.

Gasification

Gasification is used to produce liquid fuels, chemicals and synthetic natural gas. This process typically involves conversion of coal to syngas, a process also known as indirect coal liquefaction as compared to direct coal liquefaction, also used to produce fuels and chemicals, which involves the solvent extraction (and possibly hydrogenation) of organic materials from coal.

Broadly speaking, gasification takes place at high temperatures, in either atmospheric or high pressure systems, to convert coal to a syngas that requires sulfur and metals removal, and will require CO_2 capture, to be used either for electricity production or chemical production. Figure 2B provides a generic process flowsheet for gasification.

Figure 2B. Generic Gasification Flowsheet for Oxygen-Blown Gasification



Source: Connie Senior

The gasifying medium can be either air or oxygen. The coal can be fed into the gasifier dry or as a coal-water slurry, depending on the gasifier design. The physical and chemical characteristics of the coal feedstock determine the gasifier technology that is most suitable.

Depending on operating conditions (i.e., temperature, pressure, gasifier design), gasifying medium and the coal composition, the major products of gasification will include carbon monoxide, carbon dioxide, methane, hydrogen, water and, in some cases, dinitrogen. Syngas from gasification of coal can produce CO_2 at higher pressures than from typical industrial combustion processes, which is more compatible with CO_2 capture and compression processes.

Cleaned syngas can be used for electricity production in a combined-cycle system known as integrated gasification combined cycle (IGCC). IGCC systems produce lower air emissions and higher generating efficiencies compared with conventional pulverized coal plants. Cleaned syngas can also be used to produce a variety of chemical products, including ammonia, hydrogen, synthetic natural gas, alcohols, olefins and liquid fuels.

There has recently been considerable interest in combining electricity generation and chemical production in a gasification system. As the electricity system changes to accommodate more variable renewable energy (i.e., wind and solar), thermal systems for generating electricity are called upon to ramp load up or down quickly and on an intermittent basis. Gasification systems are complex and gasifiers have considerable thermal inertia, which means gasification systems do not cycle quickly. However, if a gasification system had the flexibility to produce both electricity and chemicals, the gasifier could operate at high capacity while splitting syngas between electricity generation and chemical production.

For example, research has been done on a gasification system for producing electricity and hydrogen, as well as capturing CO_2.[27] Researchers found that electricity and hydrogen costs for the integrated plant were lower than either electricity-only or hydrogen-only fossil-fueled plants. Others have proposed a flexible design to produce ammonia, synthetic natural gas and electricity.[28] The gasifier output was split between a conventional ammonia synthesis process, a methanation unit to increase the methane content of the gas, and a heat recovery steam generator for production of electricity.

While gasification of coal has been studied for many decades and deployed around the world, commercial deployment in the U.S. has lagged behind that of other countries. The concept of poly-generation – production of electricity <u>and</u> chemicals from gasification of coal – while capturing CO_2, might fit into America's changing energy landscape.

Activated Carbon Production

Activated, or porous, carbons are used for a variety of industrial applications, including purification of air and water streams; food and pharmaceutical separations; solvent recovery; and production of catalysts and catalyst supports. Use in capacitors and batteries for energy applications and as a CO_2 sorbent and hydrogen storage are emerging applications. Water treatment accounts for about 40% of activated carbon used worldwide, followed by air and gas purification (25%) and food processing applications (20%).[29] Activated carbons are also used in life science applications such as blood dialysis.

Activated carbon can be made from a variety of organic feedstocks, with coal of various ranks being one traditional starting material. Activated carbon from coal is produced by a two-step process: carbonization (i.e., pyrolysis) followed by partial gasification. This is also called the physical activation process, to distinguish it from the chemical activation process that is commonly used with feedstocks such as wood, coconut shells and other biomass (lignocellulosic) sources. In some cases, flash calcination can be used to produce activated carbon from Powder River Basin coals.

Activated carbon can be produced from bituminous, subbituminous or lignite coals. The choice of coal rank depends on local availability (and cost) as well as the desired properties of the product. Broadly, the carbonization process drives off most of the non-carbon elements at temperatures on the order of 800-1000^{o}C in the absence of oxygen.[30] During this step, the Carbon/Hydrogen (C/H) ratio increases to the range of 10-20.[31] Partial gasification takes place at similar temperatures to pyrolysis with the addition of steam, CO_2, air or a combination of these. During gasification, the initial pore structure from carbonization is further developed through oxidation and rearrangement of the carbon structure. The final C/H ratio is in the range of 15 to 40, and surface areas may range from a few hundred to a few thousand square meters per gram (m^2/g). Industrially, activated carbon is produced from coal using either a rotary kiln or a multiple hearth furnace (shaft kiln).

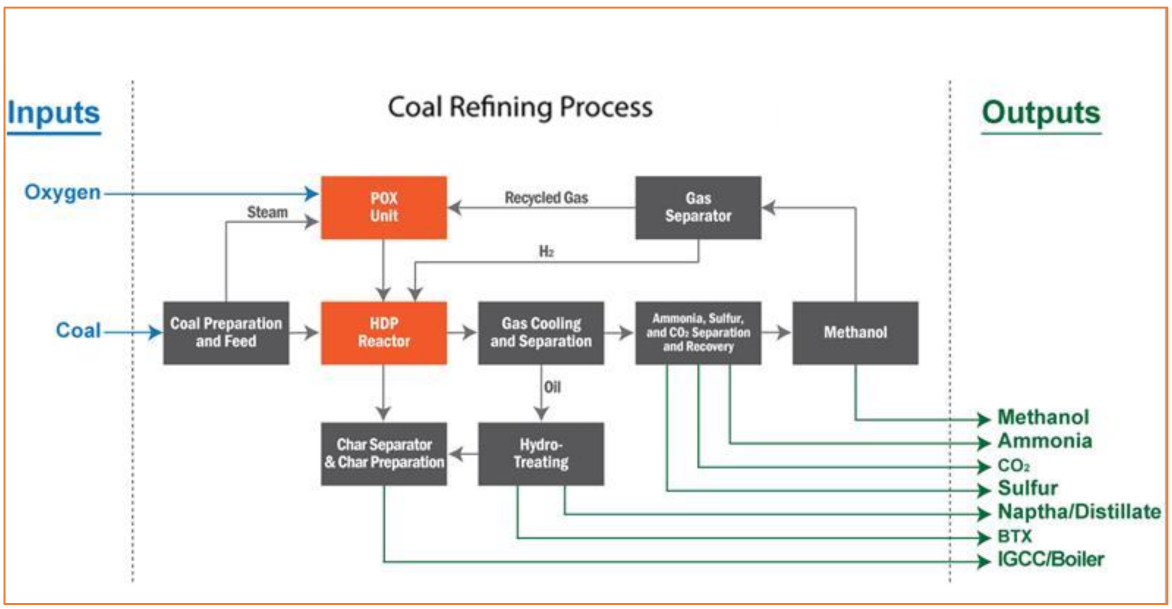
Following are examples of select conventional manufacturing processes and techniques being used to produce value-added products from coal; many other such examples exist.

Charfuel Coal Refining

Carbon Fuels LLC[32] employs a Charfuel® coal refining process that processes coal into transportation fuels, electricity generation feedstock and petrochemicals, as well as ammonia and sulfur, while inexpensively removing pollutants. The process involves rapidly removing volatile material in the coal particle, selectively "cracking" that material and hydrogenating free radicals with internally generated process hydrogen (hydro-disproportionation) to form a variety of stable compounds. During the process, inherent pollutants, such as fuel nitrogen, sulfur and mercury, are released in a manner that allow ready conversion to salable co-products in a manner similar to petroleum refining.

As noted in Figure 2C, a coal refinery facility, like an oil refinery, can be designed to yield many products. The "char" product can be used for a myriad of conventional purposes, including as a gasifier feedstock, an IGCC feedstock, a clean product for reduction in metallurgical processes, a soil treatment, feedstock for carbon fibers and materials, and as a feedstock for economically recovering rare earth elements.

Figure 2C. Coal Refining Process

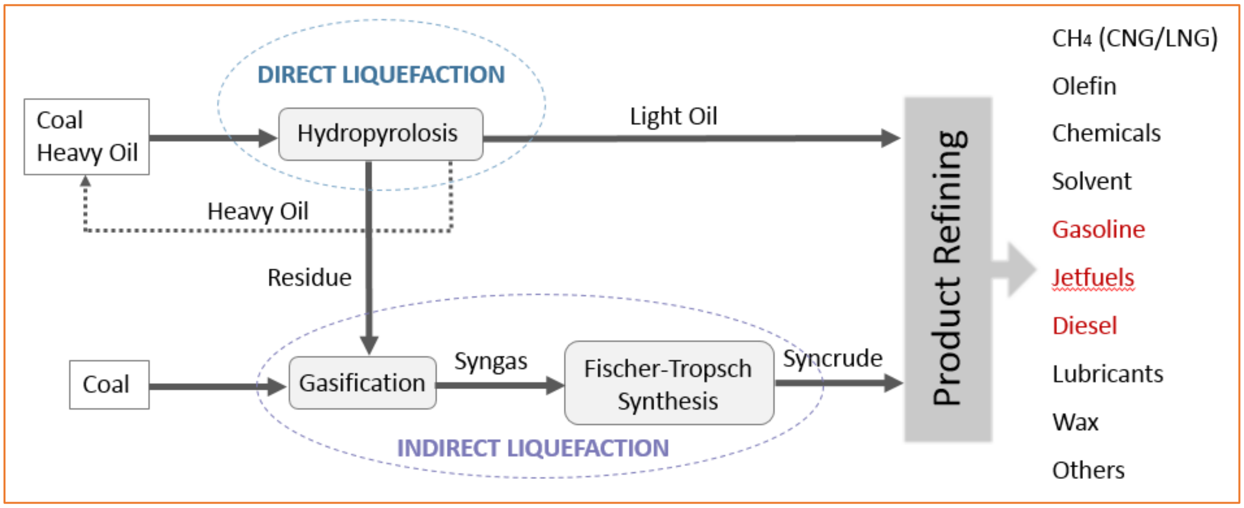


Source: Carbon Fuels LLC

Stepwise Liquefaction

Synfuels Americas' Stepwise Liquefaction[33] process integrates low temperature coal pyrolysis, modern gasification technology and the advanced slurry bed Fischer-Tropsch (FT) process for an improved energy efficient coal-to-liquids technology. Developed by affiliate Synfuels China, Stepwise Liquefaction utilizes both Direct Liquefaction (DCL) and Indirect Liquefaction (IDCL) technology which are run in parallel.

Figure 2D. Simplified Stepwise Liquefaction Process



Source: Synfuels Americas

As noted in Figure 2D, in DCL, solid coal is pulverized to a powder, mixed with heavy oil and hydrogen, and then reacted to form liquid hydrocarbons through hydropyrolysis. Liquid hydrocarbons can be divided into three groups: light oil (refined into value-added fuels such as naphtha, gasoline and diesel), heavy oil (used as a solvent) and residue (sold for heat value or transferred to the IDCL stage to be converted to liquid hydrocarbons). For IDCL, the coal is first gasified with steam to form syngas and then reacted to form hydrocarbons through the FT process.

b. Advanced Manufacturing Pathways

The field of manufacturing continues to evolve with new processes, tools and equipment that allow manufacturing companies to produce products more efficiently. Advanced manufacturing is critical to increasing U.S. competitiveness and facilitating technology transition in many industry sectors. The use of advanced techniques and equipment, such as automation, computation, digitization, artificial intelligence, sensing and networking, will provide the U.S. with the ability to achieve its economic, environmental and national security objectives.

Using coal to produce products is a paradigm shift and advanced manufacturing will be a critical component in the rapid deployment of coal-to-products technologies. While commercial deployment of products from coal will benefit from utilizing advanced manufacturing techniques, it will also contribute to the development of both advanced manufacturing materials and advanced manufacturing processes, both of which are described in the following pages.

Advanced Manufacturing - Materials

Coal-derived manufacturing materials that will have a vital role in facilitating the development of advanced manufacturing include critical materials/minerals, wide bandgap semiconductors for power electronics, materials for harsh service conditions, advanced materials manufacturing and composite materials.

Critical Materials/Minerals. Technology solutions that enable the increased and consistent availability of materials/minerals essential to clean energy applications. These materials and minerals support diversification of energy supply, development of cost-effective substitutes, and improvements in reuse and recycling of critical and near-critical materials/minerals.

NETL has identified domestic coal resources that contain rare earth elements (REEs) and demonstrated the ability to produce high purity REEs from these coal sources in bench- and small pilot-scale facilities. The program is now poised to take the next step in demonstrating the feasibility of producing REEs and, potentially, critical minerals (CMs) through the design, construction and operation of an engineering-scale prototype facility. The operation of this facility, in conjunction with complementary R&D efforts to develop advanced transformational separation and production processes, will establish our nation's path forward for the operation of economically viable, domestic commercial-scale REE-CM separation and production facilities.

Wide Bandgap Semiconductors for Power Electronics. Wide bandgap semiconductor materials and devices, technologies and applications that result in improvements in energy efficiency, enable cost-efficient integration of power systems and accelerate the adoption of clean energy technologies.

- Carbon and graphitic materials have always impacted optical and thermal sensors primarily due to the low coefficient of thermal expansion and high thermal conductivity. Coal feedstock materials are suitable for manufacturing low-cost materials for stable mirror surface substrates or solid-state cooling components. Graphitic foams, carbon fibers, composites and graphene all have an impact on improving the performance of various devices, as well as enhancing efficiency and lowering manufacturing costs.

- Carbon substrates in batteries, super capacitors, ultra-capacitors and chemical capacitors, as well as their enabling capabilities in fuel cells, have been demonstrated for decades. Even today, the high cost and difficulty in manufacturing carbon products contributes to the slow rate of vehicle electrification globally. Recent advances in processing of coal to provide tailorable properties in synthetic graphite anode materials is only one example of a multitude of possibilities for lowering cost and increasing availability for these critical materials. The combinations of high thermal and electrical conductivity, along with the ability to achieve high surface area while remaining chemically inert, contribute to increased charge-discharge rates, cycle life and overall lower battery manufacturing and operating costs.

Materials for Harsh Service Conditions. Technologies that increase the durability and reduce the cost of materials and components operating in harsh and extreme environments (e.g., high temperature, corrosive, hydrogen and radiation). These materials enable technologies that lower energy use and greenhouse gas (GHG) emissions.

Carbon-carbon composites are well established as the most efficient material for hypersonic and re-entry vehicle hot structures. The application of carbon fiber and pitch-based graphitic carbon matrix composites was developed in the 1960s and is still used today. The utilization of coal feedstocks for mass production of pitch for both the fiber and matrix materials of these critical composite structures has potential to dramatically lower cost and increase availability for use in commercial spacecraft and defense applications.

Advanced Materials Manufacturing. Technologies that accelerate the research, development and demonstration of new materials that are ultimately integrated into applications for cost-effective, advanced clean energy applications.

- Carbon products have a direct impact on metals processing in many ways beyond the fundamentally important commodities of coke in steelmaking and graphite electrodes in aluminum smelting. Composites of graphene in metal have illustrated remarkable properties, including improved electrical and thermal conductivity. Binders and media for sand casting, including those utilized in 3D printed mold and form-making machines, can be produced from coal. This could enable rapid, on-demand part manufacturing in the field in a small foundry, as well as rapid design-to-manufacturing capability on the shop floor.

- The hardness, durability and impermeability of coatings and films may be significantly improved by the inclusion of low-cost bulk graphene nano-platelet materials produced at massive scale from coal. The benefits of this application could impact all paint and coating markets, including consumer, commercial, military and industrial. These may also aid process facilities for coal processing to improve performance.

Composite Materials. Composite material production technologies that: 1) reduce energy and GHG emissions and 2) enhance the cost-competitiveness of composites vis-à-vis current materials and manufacturing methods, enabling widespread use of composite materials in clean energy applications.

- Coal to carbon fiber is a critical enabler for low-cost composites and affordable crash resistant lightweight structures. It has been promoted for some time and is reaping significant benefits. Market predictions for increased utilization of carbon fiber across all industries are impressive for the currently predicted price points, although there will be a balance between performance and cost in some applications. The recent advances in process automation allow rapid manufacturing of parts with process cycles under one minute.

- A less obvious contributor is the potential of low-cost resins resulting from advanced coal processes. There are significant economic benefits associated with a self-contained facility in which the only required input is coal to produce a wide assortment of end-use products or even the majority of what a community/industry may need.
- A distributed, versatile manufacturing capability may be established through modular shipping container-sized processing units and mobile expandable architectural components. Deployment in areas where coal is present may provide immediate self-reliance and productive output to improve coal communities or establish new industrial hubs.

Advanced Manufacturing - Processes

The manufacturing technologies used to make materials and products from coal will require advanced manufacturing processes. These include: 1) computer technologies and high-performance computing for modeling, simulation and analysis, 2) rapid prototyping (additive manufacturing), advanced robotics and other intelligent production systems, 3) automation and control systems to monitor processes, and 4) the ability to custom manufacture products and to manufacture at high or low volume. Moreover, and most important, is the capability to be sustainable, utilizing environmentally sound processes and technologies.

Additive Manufacturing. Additive manufacturing technologies: 1) improve the reliability at which parts can be produced at specifications required by industry, 2) increase the range of high-performing materials and processes and 3) advance characterization and modeling techniques for qualification and certification of parts. The technologies help to reduce lifecycle energy use and costs and enable more innovative products compared to conventional manufacturing methods.

- A number of active coal-based product demonstration projects have been implemented and some have been proposed to utilize large-scale additive manufacturing.
- By using large fractions of beneficiated coal filler in thermoplastic composite large-scale extrusion deposition, the cost may be reduced significantly and the process scaled to architectural sizes as demonstrated with concrete printers.
- The advantage of a coal-based whole-house printer is that all feedstocks could be produced from coal and produced locally if the production facility is located near a coal mine.
- The development of containerized modular process facilities could be particularly useful for military deployments in remote regions or where supply routes are difficult.
- The deployable additive manufacturing capability described above is directly applicable to sustainment of all types of vehicles in the field and understood to be one of the best first applications of 3D printing in support of operations. The ability to eliminate the need for supply lines and facilitate maintenance through on-demand replacement part production is remarkably being demonstrated today. It is possible to design facilities at a variety of scales that only require an input of coal to continue producing an unimaginable variety of products indefinitely.

Process Heating. Cost effective technologies for process heating that improve the properties of manufactured products, and offer low thermal budget alternatives that reduce the energy requirements of materials processing.

Lightweight and optimally efficient heat exchangers from highly-aligned graphitic carbon foams may be produced from coal utilizing well established methods. These products enable high-powered electronics and radio frequency (RF) devices to be cooled efficiently at all scales. Many applications have been demonstrated; lower costs from new novel processing methods that enable coal feedstocks to be utilized will enable widespread adoption.

Smart Manufacturing. Sensors, controls, platforms and modeling technologies that are interoperable, secure and able to function under the harsh conditions specific to certain manufacturing facilities. Smart manufacturing technologies allow systems to operate less expensively than incumbent technologies, aggressively reducing the energy intensity of complex processes through data-driven prediction, control, optimization and artificial intelligence.

- Process Monitoring and Control – Coal refining facilities and advanced processes utilize and implement advanced process controls and sensors. Intelligent process control and machine learning are being integrated into operations systems.
- Non-Destructive Evaluation/Inspection – Critical structures of process facilities, as well as products, utilize advanced inspection and verification tools to ensure quality and safety.
- Advanced Robotics and Automation – Automation in the process industry has always been at the forefront of design efforts to improve performance.

Direct Thermal Energy Conversion Materials, Devices and Systems. Technologies that improve materials, devices and systems that directly convert energy from one form to another (e.g., waste heat to electricity), in order to realize lifecycle energy efficiency benefits on an economically effective basis.

Roll-to-Roll Processing. Technologies to reduce cost, increase precision, and enable in-line quality control and defect detection, resulting in expanded use of roll-to-roll processing to produce clean energy technologies.

Process Intensification. Technologies that significantly improve industrial process productivity and energy efficiency through optimized molecular level kinetics, thermodynamics, and heat and mass transfer.

Waste Heat Recovery Systems. Advance technologies for waste heat recovery systems that enable the cost-effective capture and use of energy from industrial waste heat in order to reduce overall energy demands of manufacturing facilities.

Sustainable Manufacturing. Technologies and tools to improve resource efficiency in the manufacturing industries, including recycling and reuse, and lower the lifecycle cost and cross-sectoral energy impacts of manufactured products.

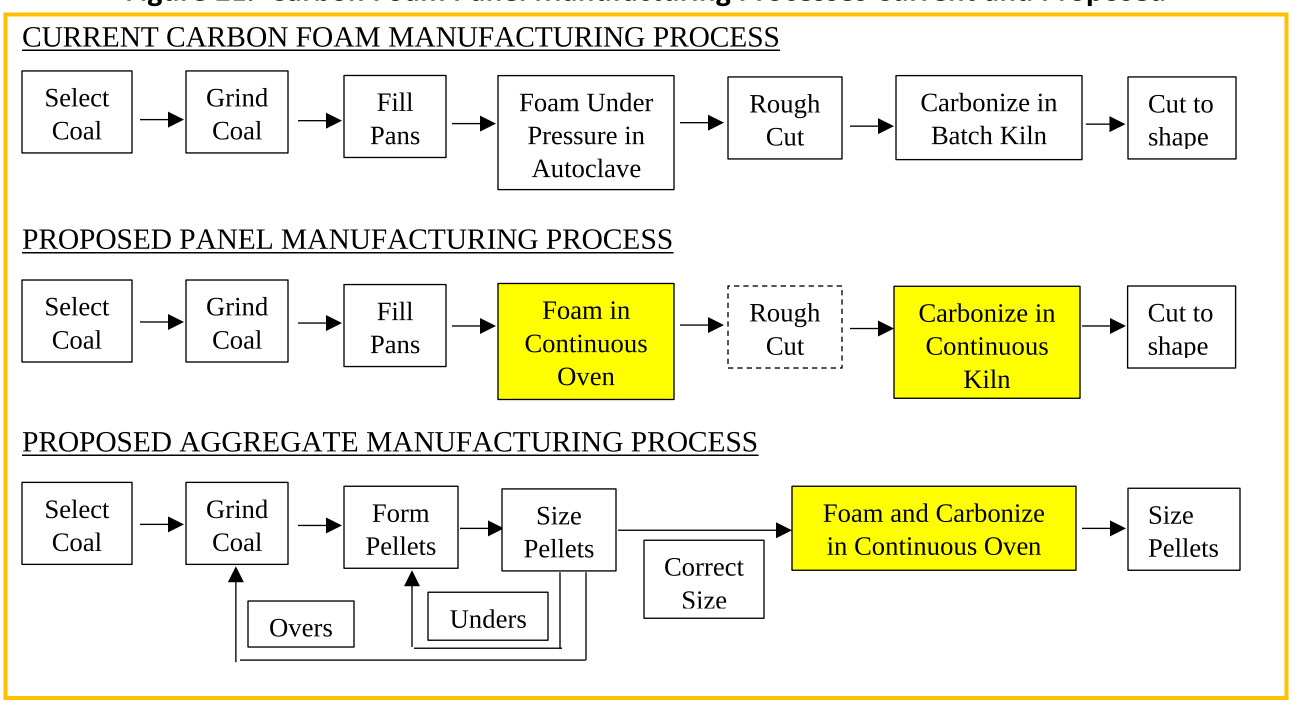
Following are examples of select advanced manufacturing processes and techniques being used to produce value-added products from coal. These examples are illustrative of the benefits associated with advanced manufacturing of high-value products; many other examples exist.

Carbon Foam Advanced Manufacturing

CFOAM® Carbon Foam[34] uses enabling technologies to produce a host of carbon products, including carbon foam panels for military, industrial, aerospace and commercial markets. CFOAM can replace conventional materials in existing systems to increase product life cycle and to provide enhanced product performance properties.

Carbon foam panels can be produced directly from the heating of coal under pressure. The current manufacturing process involves seven steps as noted in Figure 2E. Carbon foam in the form of light-weight aggregate could also be produced by first pelletizing coal in a granulator or fluidized bed which would not require machining and allow low waste, net-shape manufacture. In a future, large-scale manufacturing process, the batch steps (autoclave and batch kiln carbonizing) would be replaced with foaming at atmospheric pressure and carbonizing in a continuous kiln. A continuous process to manufacture carbon foam at atmospheric pressure would reduce costs by as much as 90%.

Figure 2E. Carbon Foam Panel Manufacturing Processes Current and Proposed



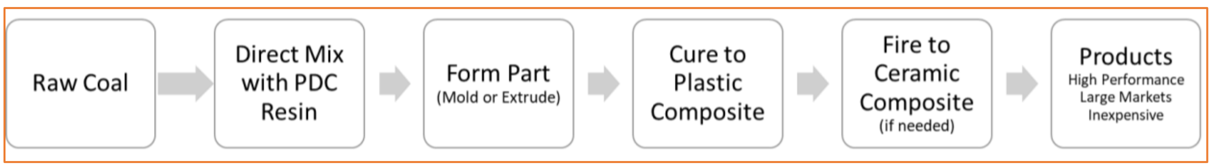
Source: CFOAM

Single Batch Composites

Semplastics[35] supplies precision plastic engineered components to a broad range of industries, including semiconductor, medical, aerospace and oil and gas. The company employs the single batch composite (SBC) process to produce novel composite materials using computation and software capabilities to customize materials for unique applications. SBC produces components without burning or otherwise modifying raw coal, and sequesters carbon in the process providing an environmentally, sustainable end product.

SBC is a quick, simple fabrication process in which filler particles are directly mixed with polymer-derived ceramic (PDC) resin and bonded to make bulk parts via low-pressure molding or extrusion at room temperature. The SBC process noted in Figure 2F can be tailored to each specific filler material being used, the target application and the desired properties of the final product. A key aspect of the SBC process is the utilization of the whole coal particle without any chemical modification or conversion to intermediates which add complexity, require more energy and increase cost.

Figure 2F. Single Batch Composite Processing



Source: Semplastics

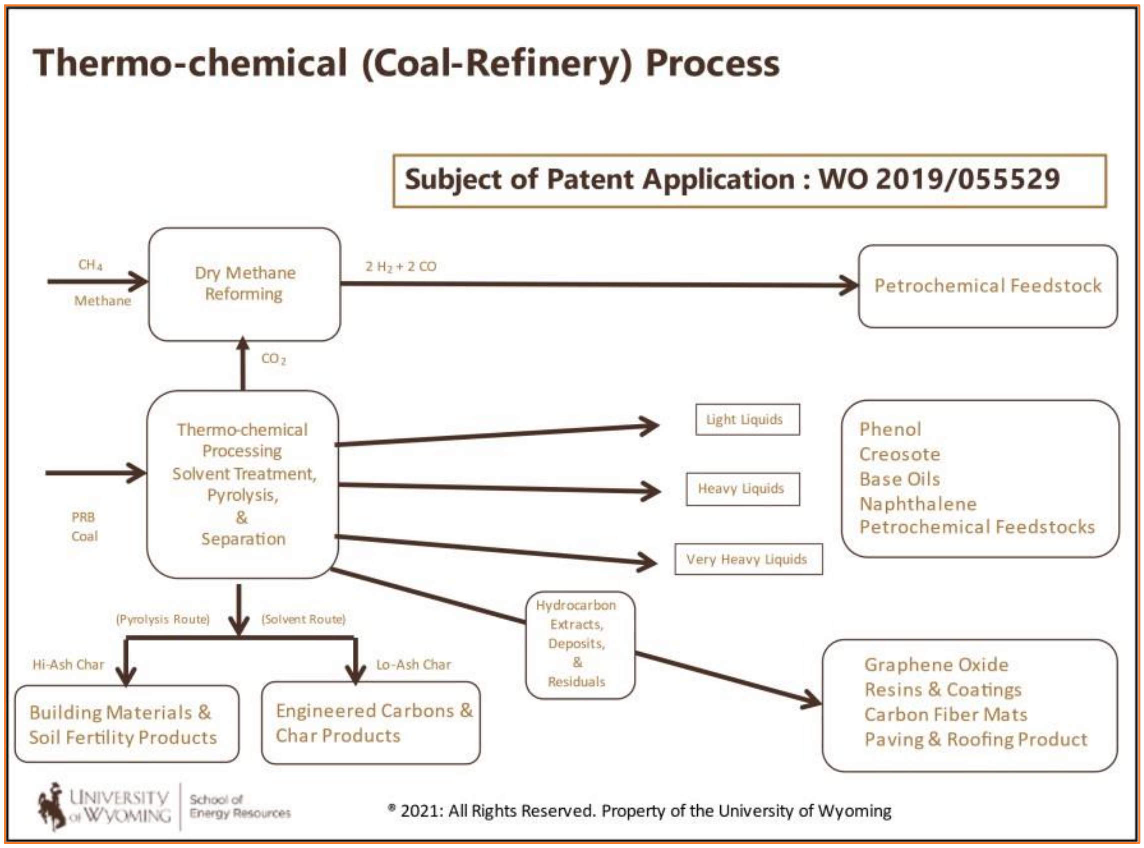
The SBC process can also be leveraged to produce high-strength, light-weight aggregate for concrete with significantly higher strength than existing aggregates.[36] Additionally, one of the newest developments is the use of coal/ceramic composite particles as a light-weight, low-cost filler for 3D printing applications. Finally, the SBC process is a fully closed loop, sustainable process in that all products are fully recyclable. Any waste or failed parts can be re-used to feed the next generation of materials in the process.

Thermo-Chemical Coal Refinery

The School of Energy Resources at the University of Wyoming[37] is engaged in "Deliberate Decomposition of Coal" to produce high-volume, environmentally friendly, non-combustion products integrating three technology platforms. The thermo-chemical process combines thermal pyrolysis with solvent extraction and dry methane reforming to produce engineered materials and chemical products as noted below in Figure 2G and in Chapter III, Figure 3F.

The main technology platform is capable of processing very large quantities of coal on a continuous basis, targeting the on-purpose production of a wide range of goods together that have a low carbon footprint. The process is designed to minimize the production of gaseous products and maximize liquid and solid yield. Essentially all the molecules from the coal feed are available to make product, while the water extracted can be re-used.

Figure 2G. Thermo-chemical (Coal Refinery) Process



Source: University of Wyoming, School of Energy Resources

Chapter III. Coal-Derived Products and Markets

Introduction

This chapter provides an overview of the various products that can be produced from coal, including coal to gas, coal to liquids, coal to solid carbon products, building and construction materials, rare earth elements/critical minerals and agricultural products. For each, details are provided on their significance, advantages and opportunities. Information on current production and manufacturing pathways for each product can be found in Appendix C.

Coal-derived carbon products offer many benefits that are highlighted in this chapter. In considering the value associated with coal-based carbon products, it is important to distinguish "carbon" from "carbon dioxide (CO_2)." Carbon used for production of carbon-based products should not be confused with the carbon in CO_2 emissions. In fact, because many products made from or containing carbon have superior strength, weigh less and require less energy to produce than traditional materials, carbon-based products may have a substantially reduced environmental impact and contribute to efforts to reduce CO_2.

A summary of the potential benefits of each coal-derived product is included in the matrix on the following page. Benefits include:

- Reduced Energy Consumption – products require less energy to produce than traditional production method
- Decarbonization/Reduce GHG-CO_2 – products contribute to reductions in emissions of greenhouse gases, including CO_2, including sequestering CO_2
- Reduce Import Dependence – products enhance domestic U.S. manufacturing and supply chain capabilities, reducing the need to import products and/or product components from foreign sources
- Reduce Criteria Emissions – products contribute to reductions in emissions of mercury, sulfur dioxide, nitrogen oxide, particular matter and other criteria pollutants
- Improved Production Efficiency – products can be manufactured more efficiently than through traditional production processes
- Improved Quality and Performance – products have notably higher quality and performance attributes than traditional products
- Other Environmental – products offer additional environmental benefits such as lighter weight (reducing fuel consumption), purification value (enhanced water and air filtration qualities) and insulation (enhanced fire proofing and insulating capabilities) among others
- Cost Savings – products can be manufactured at a lower cost than traditional products
- Batteries Energy Storage – products are critical to the production of batteries for electric vehicles and energy storage

The final section of this chapter summarizes the results of a survey of companies and organizations engaged in the development of coal-derived products, evaluating their respective technologies' stage of maturity and market potential. Comprehensive survey results are included in Appendix A – Technology Compendium.

Potential Benefits of Coal to Value-Added Products									
	Reduce Energy Consumption	Decarbonize Reduce GHG/CO^2	Reduce Import Dependence	Reduce Criteria Emissions	Improved Production Efficiency	Improved Quality & Performance	Other Environmental	Cost Savings	Batteries Energy Storage
COAL TO GAS									
Acetylene	X	X							
Syngas/Hydrogen		X							
Ammonia/Urea		X		X					
COAL TO LIQUIDS									
Methanol				X					
BTEX			X						
Coal Tar		X			X				
Diesel Fuel		X	X	X		X			
Jet Fuel			X						
COAL TO SOLID CARBON PRODUCT									
Activated Carbon							X		
Char						X	X		
Carbon Black		X			X			X	
Synthetic Graphite					X	X		X	X
Needle Coke						X			
Carbon Fiber		X			X	X	X	X	X
Graphene	X	X	X	X		X	X		X
BUILDING & CONSTRUCTION									
Decking & Piping	X	X		X		X		X	
Cladding	X			X		X	X	X	
Panels & Facades	X	X				X			
Concrete, Bricks	X	X				X	X	X	
Roofing, Asphalt		X				X	X		
REEs & CMs			X						X
AGRICULTURAL		X			X	X	X	X	

a. Coal to Gas – Acetylene, Syngas, Hydrogen, Synthetic Natural Gas & Ammonia

Coal gasification enables production of a variety of downstream products, including various platform chemicals[iii], hydrogen and fertilizers.

Acetylene

Background and Significance

Acetylene (C_2H_2) is a colorless combustible gas first discovered in the 19th century. Coal was the feedstock of choice for acetylene production until the second half of the 20th century, when low-cost petroleum products displaced coal for economic reasons.

Acetylene is used industrially as a fuel for cutting and welding operations as well as a key intermediate in chemical manufacturing. In 2020, the global market for acetylene was $5.8 billion (USD).[38] The largest use for acetylene in the chemical industry is the production of vinyl chloride monomer, which accounts for about 85% of use as a chemical intermediate, followed by vinyl monomer and 1,4-butanediol, widely used in the synthesis of polyurethane and polyester plastics.[39] Bulk acetylene can also be used as a raw material to produce acetaldehyde, acetic anhydrite and acetic acid.[40] It can also be hydrogenated to yield ethylene, one of the five top platform chemicals, with excess energy yield. In 2019, about 90% of acetylene produced in the world was consumed in China.[39]

The global market for calcium carbide (CaC_2) was $14.06 billion (USD) in 2019.[41] Growth in demand for calcium carbide is driven by demand for acetylene, which accounts for about 80% of calcium carbide production.[42] The market for calcium carbide in North America is expected to grow during the period 2020-2027 because of growing demand from chemical, steel and other industries.[41] However, owing to the relative abundance of natural gas and petroleum for the production of acetylene, the coal market for calcium carbide production will not grow as much in North America as in Asia.

Advantages and Opportunities

Direct pyrolysis of coal could reduce the energy needed to produce acetylene from coal. Direct pyrolysis produces acetylene from coal by taking advantage of the thermodynamic properties of acetylene, which is stable at temperatures above 1200^{o}C.[40] Plasma-based processes for direct production of acetylene often include the addition of hydrogen to increase yield. These processes have been scaled up to the megawatt (MW) level in some cases.[43,44,45]

[iii] "Platform" chemicals are commodities used as precursors or components in the production of industrial and consumer goods, such as plastics, pharmaceuticals and textiles among many other products.

However, the economics of acetylene production do not currently favor coal as a feedstock in the U.S. Coal must compete with other hydrocarbon feedstocks (natural gas, petroleum coke, etc.) and the indirect process (via calcium carbide) has a high energy demand. Furthermore, acetylene, as a precursor to other chemicals, competes with ethylene; thus, the relative prices of acetylene and ethylene determine which is preferred for manufacture of certain chemicals.[40] Improvements in the electric arc process for indirect production from coal or the pyrolysis process for direct production from coal will be needed for coal-based acetylene to compete economically. Most work on reducing the cost of calcium carbide manufacture and on direct production of acetylene from coal is largely being carried out in China at present.

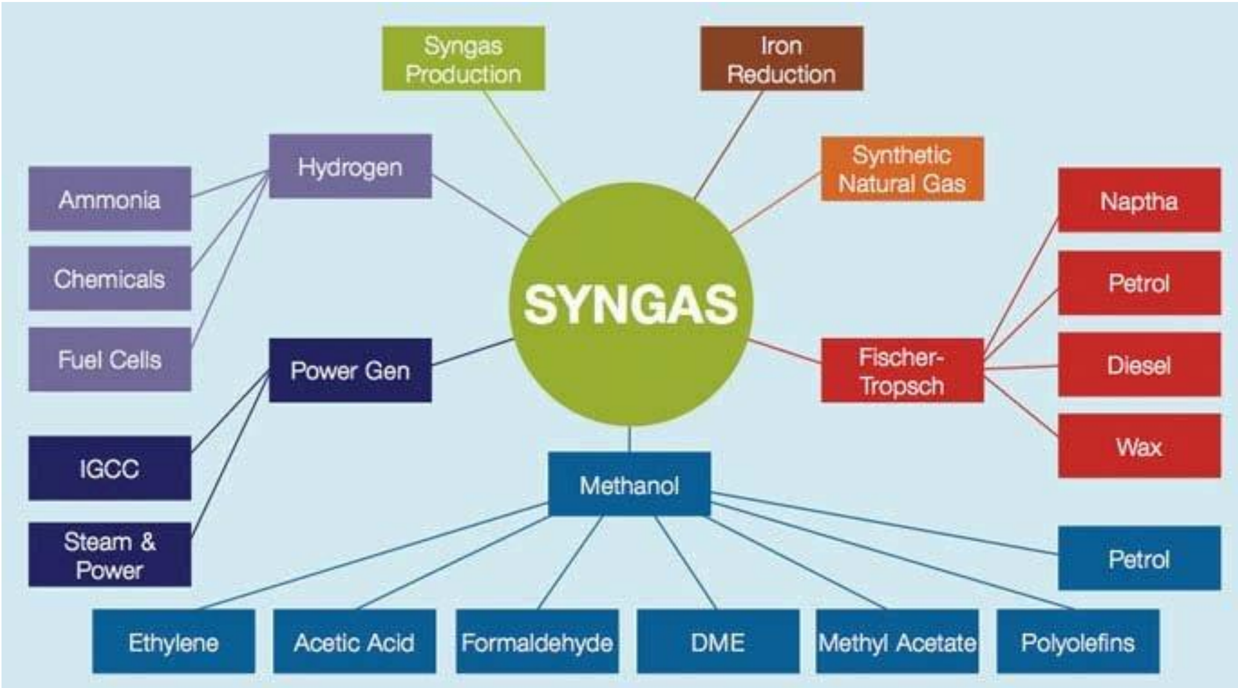
In the U.S., capacity growth and falling costs of renewable electricity supports acetylene production from domestic coal resources. Zero CO_2 coal-derived acetylene can support decarbonization of the chemical industry via an ethylene pathway. Conventional naphtha and ethane cracking facilities in this sector reported emitting 764 million tons of CO_2-equivalent in 2018 in the U.S. alone, an 8% increase since 2016.[46]

Syngas and Synthetic Natural Gas

Background and Significance

Syngas, also called a synthesis gas, generally refers to a mixture of hydrogen and carbon monoxide (CO) molecules. It is the main product of gasification and a majority product of high temperature pyrolysis carried out on coal, biomass, petroleum coke, residues or waste. A small fraction of methane, CO_2 and water vapor, as well as trace amounts of sulfur and nitrogen containing impurities, ash and tar are the byproducts of gasification. When produced in pyrolysis, syngas is created by the vaporization of volatile compounds from the raw material in response to heat, which induces a set of complex reactions.

Figure 3A. Syngas Production Pathways & Products



Source: Pratiwi, Ragil, Kurniawan, Widya and Nugroho, Hadi, Preliminary Study Of Underground Coal Gasification (UCG) Potential In Muara Wahau Area, Kutai Basin, 2013/05/01

Historically, syngas was used as early as the 19^{th} century by consumer for fuel and lighting (town gas), but was later replaced with cheaper natural gas. Today, syngas is used for in a variety of applications (Figure 3A).

- Methanol - Most methanol is made from syngas. While the majority of methanol synthesis is based on natural gas as a feedstock, coal-derived syngas is also used. In 2003, coal/solid feedstocks were used to make 9% of the worldwide output of methanol, but increased sharply in the recent decade due to rapid expansion of capacities in China. (See also Chapter III, Coal to Liquids – Fuels & Chemicals, Methanol.)

- The Fischer-Tropsch (FT) process enables conversion of syngas to fuels. (See also Chapter III, Coal to Liquids – Fuels & Chemicals.)

- Power generation - Integrated gasification combined cycle (IGCC) technology relies on syngas to generate coal-derived electricity with much higher efficiencies than conventional pulverized coal combustion.

- Synthetic natural gas (SNG) – SNG can be created by hydrogenation of CO, the reaction opposite of steam methane reforming (SMR). Although the shale oil and gas revolution has resulted in a glut of natural gas in North America, this process may be applicable. In the U.S., the Great Plains Synfuels Plant injects approximately 4.1 million m^3/day of synthetic natural gas (SNG) produced from lignite coal into the national gas grid.[47] The production process of SNG at the Great Plains plant involves gasification, gas cleaning, water-gas shift and methanation. About two-thirds of the CO_2 from this plant is transported via pipeline to the Weyburn oilfield in Saskatchewan for injection for enhanced oil recovery (EOR). In China, approximately 80 SNG production projects are in the development pipeline with a total capacity of 300 billion cubic meters of production.[48]

Advantages and Opportunities

Although coal is a hydrocarbon material, its high carbon content (5+ C for every 4 H atom) gives it a natural advantage as a source of carbon rather than hydrogen. Conversion of coal into carbon materials would necessarily result in output of excess hydrogen. Indeed, pyrolysis processes produce significant amounts of hydrogen or hydrogen-advantaged methane and/or acetylene. For instance, coke oven gas is 51% hydrogen and 34% methane by composition. In the past, coke oven gas has been refined and used as a source of hydrogen for use in chemical production and oil refining.[49] Small-scale pyrolysis plants powered by renewable electricity coupled with carbon capture could offer a source of blue hydrogen for local use.

Although conventional gasification/FT plants have poor thermal efficiencies, significant capital intensity and a large greenhouse gas (GHG) footprint, carbon capture and utilization or storage (CCUS) process intensification and availability of renewable electricity can enable small scale coal-derived syngas production with a favorable carbon footprint relative to traditional fuels. For example, syngas may be produced at small scale while reducing CO_2 emissions by electrically powered steam reforming of coal: instead of partially combusting the coal, the high temperature can be achieved with microwaves or resistive heating. The renewable electricity inputs can be augmented by the highly exothermic FT reactions. Similarly, pyrolysis gas can be catalytically reformed with CO_2 to produce syngas with a high hydrogen ratio.

Hydrogen

Background and Significance

Hydrogen is not a naturally occurring element. To produce hydrogen, it must be separated from the other elements in the molecules where it occurs. There are many different sources of hydrogen and ways for producing it. The methods in use today for producing hydrogen are:

- Steam-methane reforming (SMR) of natural gas
- Gasification of coal, petroleum or biomass
- Electrolysis (splitting water with electricity)

Today, virtually all of world's hydrogen is derived from fossil fuels via gasification or SMR, followed by the water gas shift process. Of the 70 million metric tons of hydrogen produced globally, 76% is produced via by SMR, 22% by gasification and 2% by electrolysis. Local economics dominate the hydrogen generation mix. For example, in the U.S., with abundant and cheap natural gas supplies, 96 % of the production is via SMR of natural gas. A small fraction of the current production capacity includes CCUS.

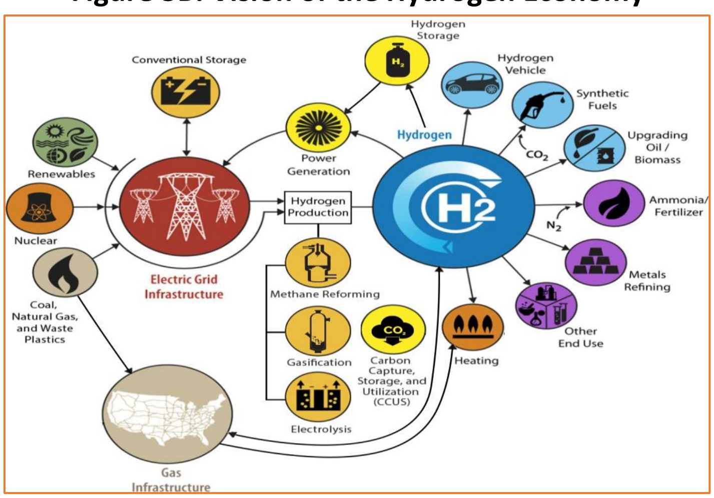
Nearly all of the hydrogen consumed in the U.S. is used by industry for refining petroleum, treating metals, producing fertilizer, and processing foods. U.S. petroleum refineries use hydrogen to lower the sulfur content of fuels. Hydrogen is an important raw material for the chemical industry,[50] in particular for ammonia synthesis.

Gasification and SMR necessarily combust some of the feedstock to generate heat to drive the reactions; the water-gas shift reaction, which is required to increase hydrogen content, increases the CO_2 footprint further. This puts coal at a disadvantage for syngas-mediated production of hydrogen, as it is lower in hydrogen content as compared to a natural gas feedstock, requiring selective CO_2 removal to be competitive on a carbon footprint basis.

Advantages and Opportunities

The advantage and opportunity for hydrogen are evident in the appeal of a "Hydrogen Economy." Hydrogen is a clean fuel. There are no GHG emissions from its combustion, only water (H_2O). The hydrogen economy is a term used to cover using hydrogen as the main fuel for heat, vehicles, energy storage and the long distance transport of energy. DOE's website provides a graphic illustration of its vision of a hydrogen economy. (Figure 3B)

Figure 3B. Vision of the Hydrogen Economy



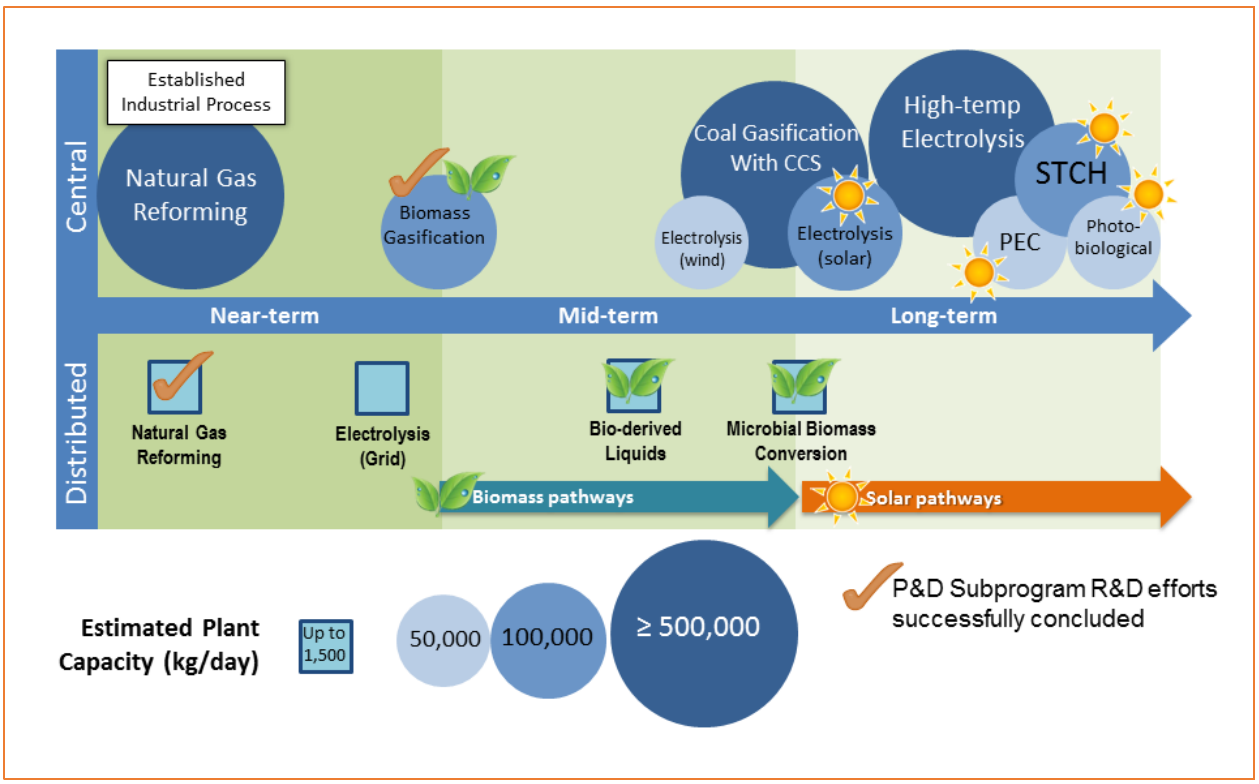
Source: U.S. Department of Energy – https://www.energy.gov/eere/fuelcells/h2scale

Hydrogen can enable U.S. GHG emission goals, energy security, sustainability and economic prosperity for numerous reasons:

- Hydrogen can be produced from diverse domestic resources for use in multiple sectors, or for export.
- Hydrogen has the highest energy content by weight of all known fuels – 3X higher than gasoline – and is a critical feedstock for the entire chemicals industry, including liquid fuels.
- Hydrogen and fuel cells can enable zero or near zero emissions in transportation, stationary or remote power, and portable power applications.
- Hydrogen can be used as a “responsive load” on the grid to enable grid stability and gigawatt-hour energy storage, and increase utilization of power generators, including nuclear, coal, natural gas and renewables.
- Hydrogen can enable innovations in domestic industries (such as steel manufacturing and energy storage) and in transportation (e.g., in vehicles, rail, aviation and marine applications) and iron making.

At the core of a hydrogen economy are the hydrogen production pathways. The following figure (Figure 3C) provides a roadmap for current and future hydrogen supply. Large centralized coal gasification facilities with CCUS will play a major role in meeting the hydrogen production needs.

Figure 3C. Hydrogen Production Pathway



Source: U.S. Department of Energy
https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php

Ammonia

Background and Significance

Ammonia is among the top five commodities both by volume and by energy consumption. Annual global production of ammonia was estimated to be 144 million metric tons in 2020. It is crucial to address ammonia supply issues to ensure global food security; 80% of the annual global production of ammonia is used to produce fertilizers. The U.S. was estimated to produce 14 million metric tons in 2020, where approximately 88% of ammonia was used in fertilizer production. 30% of agricultural nitrogen in the U.S. is in the form of anhydrous ammonia.[51]

Ammonia serves directly or indirectly as the precursor to virtually all nitrogen-containing compounds. An important derivative is nitric acid, which is used for the production of fertilizers, explosives and plastics such as polyacrylonitrile, a precursor of both textile and carbon fiber. An emerging use for ammonia is as a fuel; it is an effective hydrogen carrier for fuel cells or internal combustion engines for both stationary and transportation applications.[52] Importantly, ammonia can be mixed with carbon dioxide to produce urea.

Advantages and Opportunities

Advanced manufacturing approaches and process intensification are enabling small-scale, distributed plants which are carbon neutral. The move to distributed production of "green" ammonia from small-scale plants is also driven by a desire for localized self-sufficiency. Over half of U.S. ammonia is currently imported. Domestic, distributed ammonia production would significantly mitigate supply vulnerabilities.[53] Zero-CO_2 hydrogen, derived from coal with CCUS as described above, can be complementary and enabling for the small-scale ammonia production, especially in the agriculture-intensive rural areas, where coal mining communities are located. Growth of ammonia use as a transportation fuel will further support this distributed pathway, as it would avoid delivery costs from the point of centralized production.

b. Coal To Liquids – Fuels and Chemicals

Coal-derived fuels first came to prominence in the 1850s when kerosene was distilled from coal tars for use in lighting lanterns. Today, coal is liquified and gasified to produce liquid fuels and chemicals, primarily through:

- Direct Coal Liquefaction (DCL) – which involves the solvent extraction of organic material from coal and the catalytic hydrogenation of the extracted material, usually at high pressure. Among the fuels that can be produced directly are diesel fuel, gasoline and jet fuel; platform chemicals that can be produced include aromatic compounds (BTEX isomers) used to make plastics and synthetic fibers.

- Indirect Coal Liquefaction (ICL) – which involves conversion of coal to syngas through coal gasification. Syngas can be converted to methanol which is used as a feedstock for production of chemicals such as olefins, aromatics and ammonia. ICL processes can be used to convert coal into methanol-derived gasoline, Fischer-Tropsch (FT) diesel and jet fuel or synthetic natural gas.

- Thermo-chemical Conversion – which employs various processes, such as pyrolysis, solvolysis and hydrolysis, to produce coal-derived tars and pitches that are used as feedstocks for industrial chemicals and materials, as well as for production of carbon anodes used in making aluminum and graphite electrodes for electric arc steelmaking.

Described herein is the conversion of coal to various feedstocks used in the production of industrial chemicals, including methanol and BTEX platform chemicals. Also addressed is the use of coal-derived tars and pitches to produce chemicals, as well as carbon anodes which are vital for aluminum and steel production. The section concludes with a description of the conversion of coal to liquid fuels, using diesel and jet fuel products as examples.

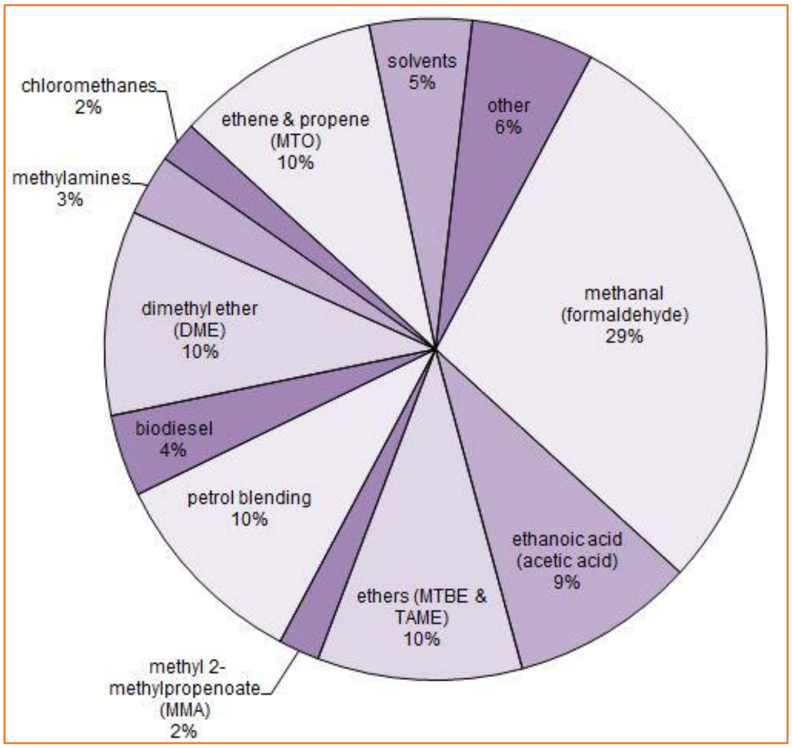
Methanol

Background and Significance

Methanol (CH_3OH), also called methyl alcohol, wood alcohol or wood spirit, is the simplest of a long series of organic compounds called alcohols, consisting of a methyl group (CH_3) linked with a hydroxy group (OH).

As noted in Figure 3D, the largest use for methanol is as a feedstock for the plastics industry. Pure methanol is an important platform chemical, serving as a feedstock for synthetic dyestuffs, resins, pharmaceuticals and perfumes. Large quantities are converted to dimethylaniline for dyestuffs and to formaldehyde for synthetic resins. It is also used in automotive antifreeze solutions, in rocket fuels and as a general solvent.

Figure 3D. Methanol-derived Products



Source: The Essential Chemical Industry

In China, methanol fuels industrial boilers, which are used extensively to generate heat and steam for various industrial applications and residential heating. Its use is displacing coal, which is under pressure from increasingly stringent environmental regulations. It offers a cost-competitive fuel source, and as a liquid fuel, requires only a moderate infrastructure investment. Methanol is also a widely used fuel for camping and boating stoves.

The U.S. methanol production in 2019 was 6.1 million metric tons per year (M Mt/y), and was expected to increase to 9.4 M Mt/y in 2020 (EIA), representing a 3-fold increase since 2015[54]. Worldwide, over 90 methanol plants have a combined production capacity of about 110 million metric tons (almost 36.6 billion gallons or 138 billion liters). According to IHS,[55] global methanol demand reached 70 million metric tons in 2015 (24 billion gallons/91 billion liters), driven in large part by emerging energy applications for methanol which now account for 40% of methanol consumption. Each day, nearly 200,000 tons of methanol are used as a chemical feedstock or as a transportation fuel (67 million gallons/254 million liters).

In 2000, China accounted for about 12% of the world's consumption of methanol while North America and Europe consumed 33% and 22%, respectively. By 2015, China consumed 54% while North America and Europe consumed 11% and 10%.

Advantages and Opportunities

Methanol is a high-octane, clean-burning fuel that is a potentially important substitute for gasoline in automotive vehicles. Given the growing demand for cleaner marine fuel, methanol offers an alternative fuel for ships, helping the shipping industry meet increasingly stringent emissions regulations.[56] Its use significantly reduces emissions of sulfur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM). Methanol can be used with high efficiency in marine diesel engines after minor modifications using a small amount of pilot fuel. Additionally, methanol is important in the production of biodiesel; as the market grows for this renewable fuel to replace diesel, there will be a corresponding increase in the need for methanol.

BTEX (Fuels and platform chemicals)

Background and Significance

The basic aromatic compounds – BTEX = benzene, toluene, ethylbenzene, and xylene(s) – are the primary precursors of petrochemical products. BTEX aromatic compounds are used in the production of a variety of industrial and consumer products. Toluene, for example, is used as a solvent in producing coatings, adhesives, textiles, pharmaceuticals, inks, photographic film and metal degreasers. It is also used in the manufacturing of polyurethane plastics and rubber products. The xylene group of aromatics are used to produce coatings, plastics and polyester fibers. A variation of benzene is used in the process of creating styrene, a chemical precursor to polystyrene used to manufacture rubber, plastic, insulation, fiberglass, pipes, automotive components and food containers.

Advantages and Opportunities

BTEX compounds can be refined to produce high purity benzene and paraxylene which are the largest volume commodities in the BTEX family of aromatic chemicals and of highest value. Benzene demand is expected to grow at an annual rate of 2.7% between 2018 and 2028; paraxylene is expected to grow at 4.4% annually for the same period.[57]

The production of these aromatics as a by-product of the direct coal liquefaction process can potentially enhance the economic profile of a DCL facility which is particularly well suited to the co-production of fuels and chemicals. Since the U.S. is a net importer of benzene, development of a domestic resource for this vital chemical compound would help reduce the nation's import dependence.

Coal Tar

Background and Significance

Coal tar is a complex mixture of aromatic and polyaromatic compounds that is captured and condensed from coke oven exhaust. It serves as a feedstock for production of a wide range of chemicals and materials. In particular, coal tar is the most significant feedstock in the production of complex aromatic chemicals, including bi- and tri- aromatic forms. Coal tar is also a major feedstock for the production of carbon black.

Coal tar composition varies, but contains approximately 50% pitch; the remaining light tar fraction has over 300 components, principally phenolic compounds such as light aromatic oils (2%), naphthalene (10%) and creosote (33%). These lighter fractions can be hydrotreated to produce low-sulfur marine fuels, low-temperature operable diesel fuel and thermally-stable jet fuels. The heavier pitch contains insoluble matter that is an important supply chain component for a wide range of industrial materials and processes.

Electrode pitches are the most important products derived from coal-tar pitch. They are used as reactive binders, especially for the production of carbon anodes used in manufacturing aluminum and in the production of graphite electrodes for electric steelmaking. Coal-tar pitch is the preferred agent for large-scale electrode production due to its good coking behavior resulting from its high content of condensed aromatics and fixed carbon. Coal-tar pitch has the highest carbon content of comparable bituminous binding agents, including those of petroleum asphalt and coal extracts.

In addition to being used for the production of carbon and graphite electrodes, pure carbon pitch coke is used in other carbon and graphite materials, especially for high-temperature and chemically resistant equipment. It is also used as conductive filler in carbon brushes, batteries, plastics and brake linings; as a carburizing agent in steel and cast-iron production; as adsorption coke for water purification; as a nearly ash-free solid reducing agent in metallurgy and chemistry; and for the production of highly isotropic graphite for nuclear reactors.

Soft pitches with increased coking values are used as refractory binders. They are reactive binding agents for the production of dolomite and magnesite bricks used especially for the lining of steel converters. Use of these soft pitches in brick-making increases the compressive strength and counteracts corrosive slags.

Hard pitches can be modified for use in the production of anticorrosive protective coatings. These plasticized pitches are used for long-term anticorrosion pipe coatings and as sealing compounds. The products offer advantages in their resistance to moisture, bacteria, fungi, mineral oils and gasoline.

Mesophase pitches and high-melting isotropic pitches are used as intermediates in the production of new forms of technical carbon products, such as anisotropic and isotropic carbon fibers, mesocarbon microbeads and sinterable carbon powders. In recent years, these carbon materials have been used in a wide range of energy and transport technology applications. They offer advantages associated with low density, compared with metals such as steel and aluminum; mechanical strength over a wide temperature range; and tolerance to high temperatures, up to 4000° C, if protected against oxidation.

Advantages and Opportunities

Decline in production of conventional coal tar, coupled with growth in demand for carbon rich feedstocks for the advanced materials and energy storage industries, presents an attractive opportunity to produce 'synthetic' coal tars with significantly higher efficiencies (as much as 50% or more of coal can be converted into tars) and reduced environmental impact. Of particular interest are electrically-powered processes which have a zero CO_2 footprint when powered with non-fossil derived electricity.

Continuous, rapid (< second residence time) electrically-powered pyrolysis or direct solvolysis processes supported by other advanced manufacturing elements can enable clean, distributed production of 'bespoke' coal tars from a wide range of coals, including lignite and sub-bituminous. These 'bespoke' tars can be optimized for specific applications. For example, tars with higher phenolic contents derived from subbituminous coals may be utilized in the synthesis of polyurethane and epoxy coatings, while methylated tars with zero quinolone (QI) insoluble particles would be an optimal feedstock for mesophase and graphitic carbon materials.

Diesel Fuel

Background and Significance

Diesel fuel is an important commodity that economies around the world depend on for transportation of products via trucks, trains and ships. According to the Energy Information Administration (EIA), as of 2019, the U.S. transportation sector alone consumed about 47.2 billion gallons or 1.1 billion barrels of diesel per day, accounting for 15% of total U.S. petroleum consumption and 23% of total energy consumption by the transportation sector.[58]

Diesel fuel is also used to power heavy machinery and construction equipment and is, therefore, critical to the development of infrastructure. Additionally, diesel generators are used to generate backup power for hospitals, schools, stores other facilities and used as the primary power source for remote locations that are off the electrical grid. Many sectors of society depend on diesel fuel; a consistent supply is critical to our nation's economy and well-being.

Advantages and Opportunities

Gasification followed by a Fischer-Tropsch-like process provides numerous advantages over traditional crude oil refining techniques. Diesel fuels produced with FT synthesis can be of very high quality due to low aromaticity and zero sulfur content. The carbon footprint of these fuels can be reduced when coupled to a carbon capture, utilization and storage (CCUS) system. This allows for cleaner and more environmentally friendly fuels and products to be used for commercial and private use. For example, FT diesel burns cleaner and has proven to be effective in dramatically reducing emissions of sulfur dioxide, nitrogen oxides and particulate matter, as compared to conventional diesel fuels. Lastly, FT technology can be an alternative source of liquid fuels for places that lack petroleum resources.

The products produced through the FT process contain no sulfur or nitrogen contaminants and are therefore cleaner than petroleum feeds. The syngas produced from the feedstock gets purified to remove sulfur, mercury, carbon dioxide and other impurities. The purified syngas reacts with a catalyst in the FT reactor and produces a wide range of hydrocarbons. The hydrocarbons are fractionated and sent to product upgrading for refining into value-added products. This process results in a cleaner and superior product than is produced through traditional refining of crude oil.

Diesel-powered heavy-duty trucks and more efficient diesel cars have been widely used in industrialized nations, especially in European countries, with the number continuing to rise. Increasingly stringent environmental regulations, however, dictate the need for a 'super-clean' diesel – that is, a carbon-neutral fuel with low emissions and a higher combustion efficiency relative to petrodiesel. As an alternative fuel to the conventional, crude oil-based diesel, Fischer–Tropsch diesel (FTD), which has a high cetane number and almost zero sulfur content, has been proven to be effective in dramatically reducing vehicle emissions as compared to conventional diesel fuels. Consequently, automobile manufacturers worldwide are increasingly viewing FTD as a feasible alternative diesel engine fuel, given its two primary differentiating attributes, namely a high fuel efficiency and a low impact on the existing distribution infrastructure. Use of FTD can support environmental objectives for cleaner and more efficient vehicles, particularly for diesel-powered heavy-duty trucks which are essential for the transportation of goods.

Many countries do not have substantial oil reserves and therefore do not have a secure, adequate source of petroleum-based products. The FT process can mitigate petroleum resource constraints since it makes use of coal and other carbonaceous materials to produce synthetic fuels and petroleum-based products. The conversion potential of FT technology allows a nation to maximize use of its inherent natural resources and decrease its dependence on foreign petroleum-based products. A reliable and stable source of liquid fuels, such as diesel and jet fuel, can be a matter of national security. Finally, FT technology can also maximize the potential of products which would otherwise have had little use, such as municipal waste and other biomass materials.

Jet Fuel

Background and Significance

In 2019, 300 million tons of jet fuel were used by commercial airlines worldwide to transport 4.5 billion passengers[59] and 61.3 million tons of freight[60]. Aviation provides the worldwide rapid transportation network essential for global business and tourism. Air travel is set to grow at a fast pace in response to global market growth driven by socio-economics, tourism, political interaction and comprehensive business trading.

The U.S. Air Force consumes approximately 2 billion gallons (7 million tons) of aviation fuels annually. About 81% percent of the total Air Force energy budget is for fuels, including about 17% used for facilities and 2% for ground vehicles.[61] Coal conversion to jet fuel via direct coal liquefaction can be employed today; DCL processes are fully developed and commercialized in China, but have yet to be deployed at commercial scale in the U.S.

Advantages and Opportunities

Coal conversion to liquid fuels provides a market opportunity to utilize U.S. coal resources to reduce and/or eliminate the net import balance of crude oil and petroleum products, produce strategic fuels for national security and create new employment opportunities in economically distressed coal producing regions of the U.S.

A notable feature of coal-based jet fuel is its remarkable versatility. What is required as the coal portion of the feedstock is a material rich in two-ring aromatics. Any coal conversion process whatsoever that provides such a material can be used as the "front end" for the coal-based jet fuel production. Options include direct liquefaction, tars from coal carbonization (coking), solvent extracts, coker liquids from coking coal/petroleum blends, and by-product tars from fixed-bed coal gasification. Provided that any of these materials is suitably fractionated to give the desired two-ring aromatic product stream, it can be used interchangeably or in combination as the source of coal-derived feedstock.

c. Coal to Solid Carbon Products

The production of solid carbon products from coal has a long history, as reflected in the ubiquitous "Coal Tree" figure.[62] Traditional applications where coal is directly converted into a solid product range from metallurgical coke for steel and aluminum manufactory to activated carbons for water purification to foundry coke and graphite. Alternatively, many solid carbon products result from the use of an intermediary based on coal liquids and pitch. These coal-derived carbons have found broader markets with the expansion of carbon fiber use into aerospace and automotive applications and the development of specialty porous carbons used in water purification, gas cleaning and energy storage. Of note has been the development of carbon foams and other construction materials derived from coal.

More recently, mechano-thermal and chemical processes have been developed to produce nanomaterials from coal, including carbon nanotubes, graphene and quantum dots.[63] Coal is a reliable, low-cost feedstock with a structure amenable to the formation of sp^2 carbon allotropes that form the fundamental structure of these nanomaterials. Such materials, due to their 1- and 2-dimensional morphology, lend themselves easily to advanced manufacturing technologies where they may be incorporated into resins, printing filaments or inks. Their use in additive manufacturing, including both contact and non-contact printing, has been the focus of much recent R&D[64,65,66] with particular emphasis on the development of molecular circuits, organic electronics, electrostatic discharge materials and low-cost sensors.

This section summarizes production technologies and current markets for coal-derived solid carbon products.

Porous Carbon

Activated Carbons

Background and Significance

Activated carbon is used for a variety of industrial applications including: purification of air and water streams; food and pharmaceutical separations; solvent recovery; production of catalysts and catalyst supports. Use in capacitors and batteries for energy applications and as a carbon dioxide (CO_2) sorbent are emerging applications. Water treatment accounts for about 40% of activated carbon used worldwide, followed by air and gas purification (25%) and food processing applications (20%).[67]

In 2019, the global activated carbon market stood at $4.7 billion USD; the U.S. had the largest market value ($1.1 billion USD) followed by China ($873 million USD).[68] China was the largest activated carbon producing country (801 metric tons or 35% of total volume), followed by India (13%) and the U.S. (11%).

Advantages and Opportunities

Activated carbon can be produced from bituminous, subbituminous or lignite coals. The choice of coal rank depends on local availability (and cost) as well as the desired properties of the product. The demand for activated carbon has been and will continue to be driven by environmental regulations, related to water and air purification, in both mature and rapidly developing economies. The global average annual growth rate for activated carbon is forecast be about 4.3% through 2025.[6]

Char-derived Porous Carbons

Background and Significance

Coal-char type porous solid spherical products are an important building block that results from the thermal treatment or pyrolysis of run-of-mine pulverized coal, driving off organic compounds. These types of products have multiple applications. Porous carbons have been widely explored and utilized in the fields of adsorption and have found applications in water and air filtration (activated carbons), when often their performance is enhanced by the further surface treatment or modification to the pyrolyzed porous carbon surface. Use in agriculture as an alternative to bio-char and also to make light-weight, porous char-bricks is also emerging. Due to their shape, porous carbons are easily dispersed and do not agglomerate, unlike flake and laminar like products such as graphene and graphene oxide, and therefore can self-reinforce polymeric-resin systems.

Advantages and Opportunities

Electrochemical Devices: Porous carbons have a large surface area to volume ratio and in their purest form, when pressure and heat are applied, in the presence of a reactive matrix, can be used to make battery electrodes and energy storage devices, if they are further thermo-chemically treated or sintered. Applications include supercapacitors, metallurgical and energy storage electrodes. One of the advantages of coal-derived electro-chemical devices is that they can be custom engineered by tuning the manufacturing conditions, which can impact electrical impedance, capacitance, discharge and charging rate. At this time most of these electro-chemical devices are supplied by other fossil energy resources such as natural gas and petroleum. That said, coal does currently hold a high-volume position in serving the metallurgical coke market, served almost exclusively from the conversion of bituminous coals.

Agricultural Products: The high surface-area-to-volume ratio and the dispersive nature of coal char, has been shown to benefit soil fertility when added in moderate dosage levels. Tests have shown that coal-derived soil amendments can perform as well as the industry standard product at this time, which is bio-char, and can be made appreciably cheaper adopting simple thermo-chemical processes. One of the important attributes of coal-derived soil amendments is that they do no harm to the soil and do not add toxins, heavy metals and carcinogenic compounds to the soil. This necessitates that the cleaner coals are more suited to make soil amendment products. Further, high-oxygen-content coals have been shown to perform better, because of the homogeneous nature of the inherent porosity that is derived from these types of coal.[69] Soil amendment products change the structure of the soil and can improve crop fertility over many years, without the need for regular additions of coal-char derived product. Clay-like soils have shown the ability to retard nitrogen fertilizer run-off and have an affinity to retain moisture in sandy soils. (See also section “f” of this chapter for more on coal to agricultural products.)

Silicon Carbide Products: It has been shown that coal-derived silicon carbide (SiC) powders can be made of comparable quality to commercial grades manufactured today, which are derived from mixing sand and other high quality sourced carbon solids, generally derived from natural gas and petroleum sources. Commercially, SiC is formed by heating the C/Si mixtures to high pressure and temperature, and then hot -isostatically pressing. From the powder form, SiC can be compounded to make abrasive papers and wheels used in manufacturing. If these powders are cold-isostatically pressed, then they can be formed into tubes, sheets and bocks and then sintered and used as machine tools and in high temperature applications. A most appealing property of SiC is that it is capable of sublimation, which means that it turns into a vapor instead of melting, enabling it to be used in furnace, bearing and brake applications. This property also lends itself to making single crystal SiC devices. As a semiconductor, SiC can be doped with nitrogen, aluminum, boron, phosphorous, gallium and beryllium. Its inherent strength has found use in applications such as protective armor, and because of its inherent high temperature electrical properties is used to manage high-voltage power systems and power electronics.

Carbon Black

Background and Significance

Carbon black represents an important group of industrial products, categorized further into thermal, furnace, channel and acetylene blacks. These materials essentially consist of elemental carbon in the form of near-spherical particles of colloidal size, coalesced into particle aggregates and agglomerates, and are obtained by the partial combustion or thermal decomposition of hydrocarbons. The use of carbon blacks dates back many centuries to when the Chinese and Indians used them as pigment in black ink in the third century B.C.

Carbon black is widely used as a filler in elastomers, plastics and paints to modify the mechanical, electrical and optical properties of the materials in which they are dispersed and consequently determine their applications in a given market segment. Carbon black, when compounded with plastics imparts unique properties such as ultra-violet (UV) protection, electrical conductance, range of darkness (jetness), opacity and reinforcement; when used in rubber these fillers change fracture behavior and improve abrasion and failure properties. About 90% of worldwide production of carbon black is used by the tire industry; the carbon black enhances tire strength and improves modulus and wear characteristics of the tires.

The other 10% of the production goes toward the so-called specialty blacks. Carbon blacks are an important pigment used in inks, toners and coatings. Carbon blacks are also electrically conductive and impart good conductivity to thermoplastic polymers. The electrical and dielectric behavior of a polymer-carbon black compound depends upon the concentration, the nature and the characteristics of the carbon black, the nature and the molecular weight of the polymer and the mixing and finishing conditions. These properties also make them important for energy storage applications.

The global carbon black market was valued at $17.5 billion in 2018 and is projected to reach $23 billion by 2026, growing at a Compound Annual Growth Rate (CAGR) of 3.5% from 2019 to 2026.[70] The average price for the tire rubber blacks is $1.25/kg. The specialty carbon blacks typically range in price from $3/kg to $5/kg, with some grades commanding prices of $20/kg.

Advantages and Opportunities

Coal, owing to its carbon-rich composition, can be an advantageous feedstock for production of both acetylene and furnace blacks. While coal tar fractions are a preferred feedstock for furnace blacks, presently petrochemical oils are much more available. Availability of aromatic-rich coal tar feedstocks can be quickly increased with deployment of novel coal pyrolysis processes, in particular those employing microwaves and non-thermal plasmas, powered by renewable electricity. Eliminating the CO_2 footprint of the feedstock process and improving efficiency and yields of carbon black production thanks to the advantageous chemical structure of coal-derived liquids would reduce the overall CO_2 footprint of the carbon black industry.

Coal feedstocks and low cost renewable electricity can combine to reduce CO_2 emissions for manufacturing of acetylene blacks, remove supply bottlenecks, increase their market availability and reduce costs. Electrically powered thermal arc processes can be employed to generate acetylene from both coal and coal-derived feedstocks, in particular pyrolysis chars. Such processes can be deployed at the point of use, eliminating transportation costs and reducing the CO_2 footprint compared to fossil-energy intensive conventional acetylene generation processes.

Synthetic Graphite

Background and Significance

Graphite is a naturally-occurring form of crystalline carbon. It is extremely soft, cleaves with very light pressure and has a very low specific gravity. In contrast, it is extremely resistant to heat and nearly inert in contact with almost any other material. These extreme properties give it a wide range of uses in metallurgy and manufacturing. Graphite is used in pencils, lubricants, crucibles, foundry facings, polishes, arc lamps, batteries, brushes for electric motors and cores of nuclear reactors, and is on the list of strategic materials.

The global graphite market is estimated to have been $11.9 billion in 2015, growing to $12.5 billion in 2016, and is projected to be $18.2 billion in 2021, at a CAGR of 7.7% from 2016 through 2021.[71] Graphite's electrical conductivity properties are ushering in a large new market for graphite in the field of energy storage applications, which are growing rapidly thanks to the ubiquitous consumer electronics and the growing market share of electric vehicles and intermittent (renewable) power generation.

Synthetic graphite is a man-made substance manufactured by the high-temperature processing of amorphous carbon materials. The types of amorphous carbon used as precursors to graphite are many, and can be derived from petroleum, coal or natural and synthetic organic materials.

Lithium-ion batteries for automotive and other applications typically contain about 1 kg of graphite per kWh of battery capacity. There is 54 kg of graphite in the battery anode of each Tesla Model S.[72] Graphite demand for the electric vehicle market was projected to reach 40,000 tons per year in 2020.[73]

Advantages and Opportunities

Typical precursors for synthetic graphite production are petroleum and coal tar pitches, which are high-carbon, aromatic feedstocks, produced as by-products of petroleum refining or metallurgical coke making. The source of petroleum-derived pitch, however, is shrinking due to supply pressures from two directions.

First, heavy oils are increasingly becoming sourer (i.e., their sulfur content is increasing). Most of the petroleum pitches currently produced are not suitable for the production of advanced graphitic carbon materials, due to high sulfur, metal and asphaltene contents. Thus, the long-term shift in the conventional oil supply towards sourer oils with high asphaltene contents sharply reduced the availability of high-quality pitches. More recently, the shale revolution has shifted the U.S. refining slate toward the lighter shale oils with low content of high-molecular-weight aromatics, reducing the need for catalytic cracking, which in turn further reduces the supply of aromatic-rich petroleum pitches.

The coal pitch must first be extracted in a direct liquefaction process (liquid yields ranging 5%wt-50%wt), with pitch accounting for 20%wt-50%wt of the final liquid weight. It may be assumed that another 20-40%wt are lost in further processing, purification and graphitization. Hence a single ton of coal at the extremes could yield between 5 and 200 kg of graphite, depending on the process yields.

Needle Coke

Background and Significance

One major industrial graphitic material that serves both energy storage and industrial electrode market is the so-called needle coke.

Needle coke is usually produced from highly aromatic petroleum pitch feedstocks and is by far the highest value coke. Most of the petroleum coke currently produced is not suitable for the production of electrode-grade graphite, which requires needle coke – the highest quality, most “crystalline” coke available. For a coke to be classified as a premium needle coke to be used in high-capacity industrial electric arc furnaces (EAF), it must have a coefficient of thermal expansion (CTE) less than 1^{-7}/°C and sulfur content below 0.4%.[74]

The needle coke market in North America is anticipated to expand at a considerable pace due to the higher demand for super premium grade needle coke for steel, as well as for the aluminum and nuclear power industries. Needle coke is the principal material for graphite electrodes used in EAF in the steel industry, accounting for roughly two thirds of the electrodes’ cost of production. From 1 to 3 kg of graphite is needed to produce a ton of steel, resulting in an estimated global demand of 0.75 million tons per year. As EAFs continue to replace conventional blast furnaces as well as induction furnaces in the steel industry, the market for needle coke is projected to grow at 5.5% CAGR, and reach $4.4B by 2025. In 2017, needle coke prices have increased 7-fold from $450 to $3,200 per ton, reflecting the pent-up demand for this premium material and reduction in capacities in China due to strengthening environmental regulations.

Advantages and Opportunities

Presently, needle coke is predominantly produced by the delayed coking of decant oils which are a by-product of fluid catalytic cracking of heavy petroleum to gasoline. However, coal-tar derived needle coke has superior physical properties to petroleum-based coke, such as lower coefficient of thermal expansion (CTE) and electrical resistance, along with lower spalling and breakage. Coal tar feedstock is commercially used by Mitsubishi, Baostee and C-Chem.

Carbon Fiber

Background and Significance

Carbon fibers are fibers about 5–10 micrometers in diameter and composed mostly of carbon atoms. Carbon fibers have several advantages, including high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made carbon fiber very popular in aerospace, civil engineering, military and motorsports applications, along with other competition sports. However, they are relatively expensive when compared with similar fibers, such as glass fibers or plastic fibers.

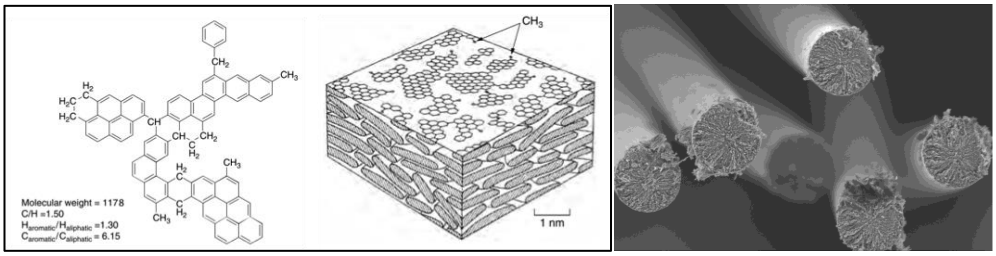
Advantages and Opportunities

The graphitic pitch-based carbon fibers have the most commercially desirable properties, being distinguished by high mechanical stiffness (high modulus), high heat and electric conductivity, zero coefficient of thermal expansion and high dimensional stability. The use of pitch-based carbon fibers can improve the efficiency of electronics, energy storage solutions and industrial processes across the board, and enable and support adoption of new construction and energy technologies. The use of pitch-based carbon fiber, however, is currently limited to the most demanding applications in aerospace, defense and high-end sports equipment industries, because of its very high cost of production (>$80/kg).[75]

In Japan, subsidiaries of Mitsubishi and Nippon Steel have commercialized coal-pitch-derived graphitic carbon fiber under trademarks DIALEAD and GRANOC respectively.

With the transportation sector responsible for 27% of the nation’s carbon emissions, 29% of total energy consumption and 70% of petroleum consumption, improving transportation’s energy efficiency through vehicle light weighting will significantly reduce reliance on imported energy and vehicle-related pollution. Carbon fiber (Figure 3E) has the highest weight reduction potential (it is 50% lighter than steel for same strength and stiffness), but its use in the automotive industry is currently hindered by the high cost (570% the cost of steel today[76]). A cost-effective method for conversion of coal to a graphitic carbon fiber precursor would satisfy the unmet demand while providing a new established market for coal with low environmental impact.

Figure 3E. Carbon Fibers



Source: Courtesy University of Kentucky Center for Applied Energy Research 2021

Thermal conductivity of pitch-based fibers (up to 1000 W/K-m) is better than that of silver and copper. It is used in thermal control applications (heat pipes) on space satellites, but its high cost has so far precluded use of pitch fibers to improve heat dissipation or transport in electronics, high capacity batteries, concentrated solar power generators and other industrial applications. The price-point at which industrial thermal management applications become viable has been reported to be $100/kg.

Currently, chopped pitch-based carbon is widely used as an additive to plastics to improve their thermal conductivity and thermal interface materials (heat grease) in electronic applications.

Higher stiffness and lower mass are crucial parameters for wind turbine blades exceeding 40 m in length. Use of carbon fiber allows blades to reach lengths of 100 m, increasing generation efficiency and allowing more wind energy to be harvested per generator. A reduction in the cost of higher modulus fibers would promote its use in wind blades and in the support structures, thus not only further increasing structural stiffness, but also improving vibration damping characteristics to suppress destructive resonance effects. Other energy applications include cryogenic pressure vessels for transportation of hydrogen, LNG and other industrial gases and fuels; efficient, temperature-resistant heat conductors for solar concentrators; high-conductivity and high-purity electrodes for energy storage solutions; and corrosion-resistant, chemically inert heat exchangers and conduits for various energy and chemical processes.

At present, the use of pitch-based carbon fiber in manufacturing is restricted to industrial applications where high dimensional stability and vibration damping are absolutely required: precision assembly and professional printing. As the pervasiveness of robotic and additive manufacturing continues to grow at a stunning rate (3D printing market CAGR is estimated to be 103%), the need for mechanical components with improved deformation and vibration characteristics will drive demand for the high modulus carbon fiber in the industrial setting. In automotive applications, chopped ultra-high modulus (UHM) carbon can be employed in existing plastic injection molding processes, allowing production of carbon fiber body panels using existing process flows and dramatically reducing costs compared to conventional carbon fiber part production.

Finally, UHM carbon fibers have been widely used in Japan for seismic reinforcement and repair of concrete structures, and have been piloted in the U.S. for non-disruptive reinforcement of concrete overpasses. Reduction of cost for the high-modulus fibers would spur explosive growth of use in construction and civil engineering, allowing reduction in use of steel and concrete for new construction, and non-intrusive repairs in reinforcement projects. UHM reinforcement of steel beams is another high impact application in the infrastructure space. As the carbon fiber does not corrode, cost-effective carbon laminate reinforcement would be an attractive alternative to costly capital repairs or bridge replacement.

The global market for carbon fiber is anticipated to triple in one decade and exceed 100 thousand tons in 2020 with a value of more than $3 billion.[77]

An efficient coal conversion process that can be deployed at small scale to produce a high quality coal pitch feedstock with low impurities and stable and consistent material properties will address the present needle coke shortage while reducing environmental impact and creating new markets for the vast domestic coal resources.

Graphene

Background and Significance

Though graphene, and its more common form graphene oxide, is generating a lot of excitement and attention recently, the existence of this material has been known to the scientific community for more than 70 years. However, it was not until 2004, when graphene was first isolated by researchers from the University of Manchester, that its true significance was discovered. So, what is graphene? It is a two-dimensional, single atomic layer of carbon and is the thinnest and strongest material ever discovered. In fact, graphene's properties were considered so revolutionary upon its isolation, that the two research scientists, Konstantin Novoselov and Andre Geim, were awarded the Nobel Prize in Physics six years later.

Below are some of the key properties identified:

- 200 times stronger than steel
- Conducts electricity better than copper
- Transparent – allowing 97.3% of light to pass through
- Flexible – stretching up to 25% of its length
- Conducts heat better than any other metal

The problem with graphite is the market is dominated by China which accounted for more than 60% of the graphite market in 2020. By contrast, U.S. production of graphite was zero. U.S. graphite imports were an estimated 41,000 tons in 2020. Though the U.S. continues to lag other countries in the commercialization of graphene, the emerging markets for graphene powder are ever growing and provide significant opportunity for coal to carbon products.

Advantages and Opportunities

While graphene has yet to enter fully developed markets, its unique and attractive properties offer many possible applications across a range of use sectors. Below is a brief summary of possible application pathways for low cost graphene.

Energy: Graphene-enhanced lithium-ion batteries are shown to have superior performance, increased output, longer lifecycles and greater operating tolerance at higher temperatures than “plain” lithium-ion batteries.[78] Graphene-based supercapacitors offer energy storage at higher levels and can hold hundreds of times the amount of electrical charge as standard capacitors, providing a suitable replacement for electrochemical batteries in many industrial and commercial applications. Graphene’s superior conductivity also makes it a feasible candidate as an alternative to the rare and expensive cadmium telluride typically required for photovoltaic panels.

Water Desalination and Purification: Graphene membranes have proven to be quite effective in desalination of seawater, with commercial products on the market showing promise to produce safe drinking water with less energy than the reverse-osmosis technique currently used to treat seawater. Researchers from U.S. Army Engineer Research and Development Center (ERDC) - Environmental Laboratory received a patent in 2019 for using graphene oxide to develop membrane technology for water treatment of biological, chemical and radiological contaminants.[79]

Automotive: Graphene’s use in automotive applications gained prominence in 2018 when XG Sciences announced that its collaboration with Ford Motor Company[80] had yielded graphene enhanced polyurethane foam parts. In 2019, the Ford Motor Corporation began to incorporate graphene enhanced foams for their Ford Mustang and F-150 models. The addition of graphene resulted in improvements of 17% reduction in noise and double-digit improvements in heat endurance and strength. As of February 2020, all Ford vehicles are using graphene seat cushion foam and under-hood insulation and over five million graphene-enhanced Ford automobiles have been sold.

Infrastructure: Graphene is showing significant promise in both concrete and asphalt. Data consistently shows that a small addition of graphene can reduce the weight, increase the strength and increase the overall life of roads and other critical infrastructure. Graphene is proven to make concrete 25% stronger – this means a potential to use less and “reduce global CO_2 emissions by 2%.”[81] Furthermore, graphene has the potential to double the service life of asphalt roads. With asphalt comprising 93.99% of the 2.8 million miles of roads in the U.S., that is significant.

Aerospace: Graphene's properties are showing unique applicability for composite parts, fire retardant technologies for aircraft interiors and conductive coatings to provide better protection against lightning strikes. Furthermore, graphene is showing promise in space applications such as using a solar sail as a propulsion system.

Coatings: Graphene can greatly enhance the anti-corrosion properties of coatings.[82] Of its many properties discussed previously, graphene is also impermeable, lending a significant benefit to coatings used in harsh environments. This is particularly important for the maritime industry. Moreover, conductive ink has been developed using graphene that allows for the creation of electronic circuits on a variety of surfaces.

Sensors: Graphene-based sensors can be used to detect gas and other biological agents as well as explosives. Its heat and conductive properties can be used in coatings to detect changes in temperature and wirelessly submit those changes to a handheld receiver. Biomedically, graphene can be used to detect changes in the human body.

Apparel and Sporting Goods: Early graphene commercialization focused on retail, primarily sporting goods, markets. Many retail graphene-enhanced products have surfaced over the past 18 months. Callaway Golf balls, Head tennis rackets, Inov8 running shoes and Anker wireless earbuds are but a few. Great Britain even used a graphene-enhanced sled for the Skeleton event in the 2018 Winter Olympics.

d. Building and Construction Materials

One of the largest market segments for solid products derived from coal is building and construction materials. This includes products such as decking, piping, cladding, facades/panels, bricks/blocks and concrete, roof tiles and asphalt.

Decking and Piping

Background and Significance

Coal can be used as a filler for building and infrastructure products, including decking and piping. These high-volume applications have the potential to incorporate a large percentage of coal into the overall formulation. Coal-derived carbon-based pigments and filler materials are currently produced and sold commercially for a variety of applications, including those in the rubber, tire, plastics and coatings industries, among others. These fillers are typically derived from low-volatile bituminous or anthracite coals and provided in dry powder form.[83,84] The use of coal in such applications enhances the technical performance, economics and/or environmental profile of the finished product.

Composite decking is a growing market arising from consumer demand for building products possessing long service life and minimal maintenance compared to the more conventional pressure-treated lumber option. The global market for composite decking and railing estimated at US$2.9 billion in 2020, is projected to reach US$6.5 billion by 2026.[85] Currently, composite materials account for about 20% of all U.S. deck construction, providing significant growth potential.

Plastic piping is a critical infrastructure component used in non-pressurized and pressurized conveyance of liquids, gases and multiphase fluids. In 2019, the U.S. plastic piping and fitting market was valued at $20 billion, and is expected to grow at 2.5% annually through 2026.[86] Sewage and drainage account for the largest market share (35%); other growing market segments include piping used for irrigation, oil and gas, and building and construction, with rural water management and rapid urbanization driving growth.

Advantages and Opportunities

Recent studies have demonstrated that Coal Plastic Composites (CPCs) offer equivalent mechanical properties with a host of potential advantages over existing WPC composite decking[87,88] including:

- Equivalent or greater oxidation resistance (>15% increase),
- Slower surface burning rate (≈50% slower),
- Lower water absorption (>75% reduction), and
- Reduced manufacturing energy requirements and emissions savings (>30% reduction).

Additionally, recent research supported by the U.S. Department of Energy (DE-FE0031809) has demonstrated the economic feasibility of manufacturing CPC decking utilizing commercial-scale processes. The use of low-cost coal provides potential manufacturing cost-savings when compared to the current use of WPCs. Finally, CPCs have the potential to create manufacturing jobs and benefit the economies of coal-producing regions such as those in Appalachia.

Coal plastic composite piping can be manufactured using coal as a filler agent, providing both rigidity and UV resistance. Coal as filler (14.3 kg CO_2/ton) for plastic pipe manufacturing would offer significant embodied carbon reductions in comparison to $CaCO_3$ (50-265 kg CO_2/ton) and carbon black (2,200 kg CO_2/ton). Replacing existing pipe filler materials with coal can meet mechanical performance requirements for non-pressure applications while providing manufacturers with significant cost savings.[89,90]

Conventional plastics may be replaced with coal-derived resins. Pyrolysis char has been evaluated as a filler with various systems for blending to make structural and load-bearing members.

Cladding

Background and Significance

Cladding refers to the application of one material over another to provide a skin or layer and is used to furnish a degree of thermal insulation and weather resistance, as well as to improve the appearance of buildings. Cladding materials are a critical component for both residential and commercial properties as they protect building structures from the elements (sun, rain, snow, wind), while deterring dirt, moisture and insect infestations.

Vinyl and fiber cement (FC) siding products dominate the U.S. market, with 2.6 and 2.1 billion square feet, respectively, installed in 2018.[91] However, vinyl siding is losing market share to FC products due to consumer desire for a more robust and appealing product. Currently, the FC siding market is valued at $13.2 billion and is expected to reach $20.3 billion by the end of 2025.[92]

Advantages and Opportunities

One proprietary process under development[93] applies commercial thermal processing techniques to directly convert coal into a lightweight cladding material. To date, the coal-derived material has been demonstrated to meet or exceed mechanical strength requirements for cladding applications. Potential advantages of coal-derived cladding over FC-based materials include less energy use and emissions (>60% reduction) and lower-weight cladding material (40%-70% reduction), with likely lower manufacturing water usage, as well as lower sales and installation costs.

Panels and Facades

Coal-derived panels and facades provide a high-volume, high-value application for coal, offering high-performance, competitively priced products. Two approaches to production of these products are featured here: Carbon Foam and Single-Batch Composite.

Carbon Foam Panels

Background and Significance

Carbon foam, produced as described in Chapter II, can be used to manufacture panels for the construction industry. It is projected that the world will need to build more than 2 billion homes over the next 80 years (25 million per year on average).[94] Innovations in residential building materials will be required to meet this demand and the CO_2 emissions associated with this level of construction. The use of coal to manufacture carbon foam for construction products could help address both of these issues. A moderately-sized modern house utilizing carbon foam could use an estimated 42.5 tons of coal, delivering over 12,000 ft^2 of panels assuming a thickness of 1-inch. If carbon foam could be utilized for 10% of the projected home building demand, over 100 million tons of coal would be utilized annually.

Advantages and Opportunities

Carbon foam fire resistant panels were originally intended for use on Navy ships. Since the carbon foam production process involves stripping organics from the coal, the resultant products possess excellent fire resistant qualities. Carbon foam will oxidize above a temperature of 370°C, but will not combust.

Carbon foam has passed numerous performance tests, including:[95]

- ISO 1182 – 1382°F (750°C) for 30 minutes, Certified "noncombustible"
- ASTM E1354 (Cone Calorimeter), Heat and Visible Smoke Release
- ASTM E162 (Radiant Panel), Surface Flammability

With its high porosity, the material is also very insulating; the thermal conductivity for carbon foam having a density of about 17 pounds per cubic foot is relatively low at about 0.25 W/m-K. Given its open-cell structure, carbon foam can be easily coated with a variety of materials.

Carbon foam is also resistant to UV rays, corrosion, mold, mildew and rot, which are excellent properties for a construction panel. Materials made from carbon foam are also impermeable to water damage which, in 2017, cost the U.S. $13 billion.[96] While several companies have considered using carbon foam as a fire and water resistant panel in building, aircraft and ship construction, high cost and low manufacturing capacity were cited as obstacles to adoption.

Single-Batch Composite Facades and Panels

Background and Significance

Single-Batch Composite (SBC) building materials are manufactured by mixing a composite, pressing it in large mold and curing it. The material can be molded and cured to produce fireproof components such as ceiling panels, facades, and extruded underlayment, blocking, and backer boards, as well as other architectural design components such as moldings. A description of the manufacturing process is detailed in Chapter II.

SBC panels would utilize 55% coal by mass (71% carbon by mass) and would be comparable in dimensions to commercially available materials. Assuming a market penetration of 1% in 2025, growing to 5% by 2030, coal utilization over that time period would be ~667,000 tons of coal.[97]

The total estimated market size for fire-resistant building materials is $20.3 billion[98], and the total market for panels, facades and architectural structural components is $2.9 billion, with a total potential coal usage of 559.0 million tons annually (at 55% coal by mass). The introduction of SBC panels at the target price of $2.80/square foot would enable standard housing, including manufactured and mobile homes, to adopt fire-resistant materials into their design, thereby increasing the addressable market.

Advantages and Opportunities

Coal-based SBC materials display an array of high-performance characteristics, including light weight, mechanical durability, temperature stability and water resistance. Compared to commercially available alternatives, SBC panels have far superior mechanical strength (three to five times stronger), significant weight savings (30% to 50% lower density), and better insulating ability (at least three times the R-value) at a competitive cost. With current materials, a 4-hour-rated concrete firewall must be 7” (17.8 cm) thick, but a comparable firewall using SBC material only needs to be 3.5” (8.9 cm) thick.

SBC materials require less energy to produce than comparable commercial products and can be produced on existing conventional plastic resin processing equipment in large quantities, enabling rapid scale-up and competitive pricing. The ceramic-based materials system developed for the SBC panel can offer a reduction in energy consumption during the fabrication process of about 20% when compared to commercially available alternatives.

In addition to the environmental benefits associated with enabling light-weight insulation, nearly zero CO_2 emissions are created during the SBC fabrication process. The concrete-equivalent SBC panel products will be considered CO_2-negative building materials owing to the sequestering of CO_2 within the material.

Concrete, Bricks and Blocks

In addition to their use for producing building panels, Carbon Foams and Single-Batch Composites can be used to manufacture products analogous to conventional clay bricks and concrete blocks and pavers. Concrete production with coal-based aggregates is an especially promising market for coal with attractive performance benefits.

Concrete is one of the most widely used products on the planet. It is a central element of building and construction. Unfortunately, concrete is very heavy weight and is of low strength relative to its density, properties which impose limitations on the size, shape and applications of structures made from concrete. Additionally, failures and flaws in concrete are very often a function of failures and flaws in the aggregate or the aggregate-cement interface. Concrete’s properties are governed greatly by its aggregate components, as these make up most of the volume of the concrete.[99,100,101,102,103] To improve the properties and performance of concrete, it is necessary to improve the aggregate materials used to make it.

Carbon Foam Aggregates for Concrete

Background and Significance

Carbon foam can be used to manufacture lightweight aggregates for the production of concrete for building and construction applications. About 10 billion tons of concrete is produced every year, which is more than one ton per person on the planet. It is the second most used material, surpassed only by water.[104] Approximately 70% of the volume of concrete is composed of aggregate, putting the projected usage volumes of aggregate on the scale of billions of tons per year (matching the annual global production of coal at 7-8 billion tons).

The spectrum of concrete products is quite broad and a wide variety of designs exist. One efficient and well-engineered product is Structural Lightweight Concrete, a material that uses lightweight aggregate to achieve property improvements over those of heavier, more conventional concrete designs. Examples of improvements include enhanced thermal properties and fire ratings, reduced autogenous shrinkage, excellent freezing and thawing durability, better contact zone between aggregate and cement matrix, less micro-cracking as a result of better elastic compatibility, more blast resistance, better shock and sound absorption, less cracking, improved skid resistance and easier placement via concrete pumping.[105] Examples of specific applications for Structural Lightweight Concrete include those for heat insulation on roofs, insulating water pipes, construction of partition walls and panel walls in frame structures, general insulation of walls, surface rendered for external walls of small houses and manufactured stone veneer.[106]

Advantages and Opportunities

Low-density coal-derived carbon aggregate has certain properties that set it apart from other conventional, low-density aggregates:

- Lightweight. The density of vitreous carbon is only 1.6 g/cc. This is much lighter than the density of more common silicates and aluminosilicates that make up expanded clay, shale and pumice, which are closer to 2.6 g/cc.
- Strength. The vitreous carbon is quite strong and has good resistance to friability, unlike some of the weaker and more irregularly shaped aggregates like pumice and volcanic tuff.
- Non-reactive. Danger of alkali silica reaction in concrete would be eliminated given its carbon composition.
- Flexibility. Selection of aggregate size for a given mix design could be easily provided through its forming process.
- Non-wetting. Vitreous carbon is relatively non-wetting to water, whereas all other conventional lightweight aggregates are largely wetting to water. This could enable performance improvements related to permeability, drying shrinkage and lifetime.

Blending pyrolysis char and coal liquids derived from subbituminous coals were shown to result in light-weight bricks, which can be laid using traditional building techniques and tools. Thermally superior to clay bricks, this coal-derived product benefits from low-cost manufacturing and a neutral or carbon negative footprint.

Single-Batch Composites for Concrete Aggregates

Background and Significance

The SBC process can be used to produce a coal-based composite ceramic material with high strength and low density that can be used as an aggregate filler in current standard concretes.[107,108] The composite is made from raw coal powder, as-is, and is combined with proprietary pre-ceramic polymer resins to form a matrix composite of coal and polymer. The coal-based ceramic composite "aggregate" takes the place of the quartz, silica, sand and mineral aggregates currently used in concrete. The aggregate accounts for 60-75% of the total mass of the concrete.

The market for precast concrete structures in the U.S. and Canada is $21.2 billion or 106 billion lbs. or 48.2 million tons annually.[109] Of this amount, 60% is aggregate, which is 28.9 million tons. Coal composite aggregate is 70% coal, so 20.2 million tons of coal could be used annually for this product.

Advantages and Opportunities

Among the many advantages associated with using coal-derived aggregates:

- Lower density material (typical aggregates ~2.2g/cc, coal composite aggregate 1.65 g/cc) leads to overall lower weight concrete.
- Lower density would be beneficial in seismic environments where lower inertial mass is desirable.
- Lower weight enables concrete structures to be built bigger and taller than ever before, along with lowering transportation and construction costs.
- Improved strength over standard aggregates; highest compressive strength for concrete using coal composite aggregate thus far is ~7500 psi. The compressive strength for standard concrete used in residential applications is 3,000 psi.
- Lowers costs of construction at the endpoint; cost range for coal composite aggregate (depending on the resin used) = $0.25-0.50/pound.
- Cost range of concrete tiles using coal composite aggregate = $1-2 per tile (4 lb. tile); cost for 130-tile square of concrete tiles using coal composite aggregate = $130-260.
- CO_2 is fully sequestered in the process and the product. Carbon is not burned. Any volatiles that are released during pyrolysis can be scrubbed and recycled.
- Coal ceramic composite aggregate is fully recyclable.

Single-Batch Composites for Bricks and Blocks

Background and Significance

SBC bricks and blocks are coal-based versions of conventional bricks and concrete blocks with the same size and shape as their commercially available analogs. The SBC construction materials would be used in the same way and be drop-in replacements for conventional materials.

The U.S. market alone uses $6.2 billion of clay bricks[110] and $3.7 billion of concrete blocks.[111] Based on sizes and weights of each, the result of using the coal-based technology could translate into 36 million tons of coal at full market adoption.

Coal-based materials would be stronger and lower weight, but available at a higher price than conventional products. It is anticipated, therefore, that the first customers for SBC products would be users of higher-end products, such as decorative face-brick or face-blocks and pavers.

Advantages and Opportunities

SBC bricks and blocks are 50% lighter and have over five times the flexure strength and three to five times the compressive strength of conventional products. The coal-based product's superior strength enables higher walls to be constructed without the need for beams; higher earthquake stresses could be withstood. At half the weight of conventional products, transportation and lay-up of SBCs would be easier. Additionally, the coal-based SBC materials are more resistant to salt, acid rain, and freeze/thaw cracking.

SBC bricks lower energy input by 20% (no heated drying cycle, comparable heating cycle to ceramic bricks). SBC blocks lower energy input by ~30% compared to the process for making concrete. There are no CO_2 emissions associated with the manufacture of these products; the manufacturing process sequesters carbon from the coal, making it CO_2 negative compared to concrete.

Roofing Tiles and Asphalt

The roofing shingle market has historically grown at a healthy pace, expanding by 2.4% over the past ten years with a combined industry market size of $13.6 billion in 2017.[112] The growing incidences of severe weather and wildfires in the U.S. has increased interest in fortified materials, particularly roofing materials. To better protect homes from severe weather and fires, new roofs need to be mechanically strong and durable, fireproof and non-combustible, and able to achieve an Underwriter Laboratories (UL) Class 4 Impact Rating.

Conventional roofing materials include metal, calcium carbonate, porcelain, plastics, slate and ceramics. Asphalt is also used in the production of roofing materials and sealants, as well as for its more familiar use in paving roads.

Two approaches to coal-derived production of these products are featured here: Carbon Foam and Single-Batch Composite.

Single-Batch Composite Materials for Roofing Tiles

Background and Significance/Current Pathways

SBC-based roof tiles use coal-derived composite materials which are pressed into molds with desired roof tile features, and cured in an oven. The cured tiles are then fired in a furnace to produce a lightweight, high-strength ceramic.

The SBC material, composed of between 60% and 75% coal by weight, is very low density at 1.5-1.7 g/cc (aluminum is 2.7 g/cc). Based on the size of an average 6” × 10” roofing tile, each tile would use roughly 1.75 lbs. of coal; a roofing “square” (10’ × 10’) of SBC material would contain approximately 434 lbs. of coal powder.[113]

Advantages and Opportunities

The unique nature of the coal-based SBC composite structure provides key features that are highly valued by those in the roof tile market. Included among the features in demand: 1) fireproof and non-combustible, 2) light weight, 3) high tensile and flexural strength, 4) great impact resistance, 5) low porosity, 6) high wind resistance and 7) high sound dampening. The competitive advantage of SBC-based roof tiles is summarized in Table 3A.

Table 3A. Comparison of competitive roof tile products in the high-end market

Product	Weaknesses	Strengths
Metal with Granule Coatings	Granules flake off over time	Lightweight, Durable, Long Life
Calcium Carbonate Tiles	Surface Easily Scratches Upon Heating, Only a 10-year Warranty	Excellent Slate or Shake Look
Porcelain Tiles	Expensive	Unbreakable / Walkable
Reused Plastic or Tire Tiles	Deforms in Extreme Hot Weather	UV Resistant, Environmentally Friendly
Slate Tiles	Very Heavy, Faster Degradation of Roof Structure	Durable, Long Life
Ceramic Tiles	Heavy	Durable, Long Life
SBC-Based Roof Tiles	**Dependent on Source of Coal**	**Lightweight, Durable, Long Life, UV Resistant, Unbreakable / Walkable**

Source: Semplastics

SBC-based roof tiles permanently sequester the carbon in the ceramic matrix and thereby prevent the release of CO_2 into the atmosphere.

Carbon Foam for Asphalt-based Products

Background and Significance

According to the National Asphalt Pavement Association, the U.S. has more than 2.7 million miles of paved roads and highways, 94% of which are surfaced with asphalt. The nation has around 3,500 asphalt plants, at least one in every Congressional district. These plants annually produce a total of about 400 million tons of asphalt pavement material valued in excess of $30 billion. The industry supports employment for more than 400,000 Americans in the asphalt production, aggregate production and road construction sectors.[114]

Advantages and Opportunities

Coal products are applicable to all aspects of asphalt manufacturing and application. Coal tar was the original cement in the 'tarmac.' High-temperature coal tar pavement and roof sealants continue to be used around the world, owing to their deep black color, water impermeability, and chemical and mechanical resistance. However, their market share has been significantly reduced due to environmental concerns stemming from their high polycyclic aromatic (PAH) content.

Liquid coal products derived at lower temperatures through pyrolysis or the solvolysis processes, however, can have minimal PAH contents, and therefore are well-suited for such applications. Tests have shown consistent product quality compared to petroleum asphalt products, exhibiting similar characteristics.

Solid coal products may provide high-performance alternatives to conventional aggregates. Given a carbon sphere could be engineered to have a specific size, it could be included in an asphalt mix as an intermediate, which is a size range between coarse and fine aggregates and is often lacking in asphalt mixes because aggregate in this size range is often more difficult to obtain. Aggregate size must be precisely engineered to achieve good properties and performance,[115] which is easy to attain with engineered aggregate.

The largest obstacle to adoption of alternative aggregates is cost. Average pricing for conventional lightweight aggregates is approximately $67.5 per ton,[116] which is quite low, but these markets also represent great potential for very high volumes and high value. Carbon aggregate would be a very unique product in this space given its unique structure, properties and performance. Note much of the cost and utilization of lightweight aggregate depends on transport; location of carbon aggregate manufacture could initially be located in a strategic manner. Manufacturing would be relatively similar to methods currently used for conventional lightweight aggregate. If 5% of the aggregate supplying the markets described herein could be displaced by carbon foam aggregate, the annual coal demand would be over 400 million tons.

Additional Building Products Pathways and Opportunities

Additional opportunities exist to produce building products using pyrolysis and coal extraction techniques, including char bricks, carbon wallboard, structural and load-bearing materials and asphalt products. The applications, attributes and development status of some of these opportunities are summarized in Figure 3F.

Figure 3F. On-Purpose Manufactured Coal-Derived – Product Technologies, Qualities & Development Status

On-Purpose Product	***Primary Technology***	***Application***	***Qualities & Attributes***	***Status***
Char bricks	Coal-pyrolysis solids blended with coal- extract material as binder and polymer.	Low rise residential and commercial buildings	Light weight, thermally superior to clay bricks, low-cost manufacture, nontoxic and leaching, recyclable. Neutral of carbon negative footprint	Sample bricks have been made and can be laid using traditional building techniques and tools. Preparing to manufacture large batch (400 to 500) and build demonstration building for long-term performance testing. Demonstration house project expected to start late 2021
Carbon wall board	Pyrolysis gas blended with coal derived solids & extract	Low rise residential and commercial buildings	Strong – resistant to shock, thermally efficient, high level of noise abatement and application tolerant. Neutral or negative carbon footprint	Product development phase complete, scaling up large batch quantities (100kg) which will be utilized in demonstration building project for long term performance and durability testing, starting late 2021.
Carbon structural & Load bearing members	Pyrolysis solids reacted with coal derived resin and other mineral resources sourced in Wyoming	Low rise residential and commercial buildings	Coal derived ingredients that provide strength component benchmarked favorably against industry standard materials, and can be produced at much lower cost while exhibiting superior strength in structural members	Various formulations are being evaluated and being tested in loaded beam apparatus. Best performing load bearing beams will be used in demonstration building project. Different designs will be evaluated for various applications e.g., lintels, roof trusses etc. Field evaluation in demonstration house to start late 2021
Asphalt Products	Coal extract intermediates, blended with residuals that are further reacted.	Building roofing, paving and road surfaces	Consistent product quality compared to petroleum asphalt products, exhibiting similar characteristics. Non-toxic containing minimal poly-cyclic hydrocarbons and toxic ingredients.	Coal derived whole asphalt products have been developed with acceptable performance in industry favored tests. Manufacturing costs need to be reduced, and sustainable engineering practices introduced. Plan in place to deliver next generation products (in 1 year) with superior environmental acceptable and comparable or cheaper in cost to petroleum derived products.
Soil Amendment	Modified Pyrolysis solids augmented with Wyoming sourced nutrients	Agriculture and Land restoration	Better in performance to bio-char and can be produced at lower cost. Carbon life cycle analysis shows negative impact on the environment due to enhanced CO2 uptake in the soil; product can act as a carbon sink when applied.	A field test program is underway which is now in its 3rd year. A database of information on soil and crop quality and yield improvements is being compiled. Material being evaluated in land restoration applications, and coal mine remediation. Significant improvement in soil fertility achieved for a number of crop and soil types. Products generate carbon negative opportunity in agriculture which is superior to bio-char on a cost benefit analysis.
Engineered-carbons	Surface-modified raw-coal, pyrolysis and solvent extracted coal- carbons, including graphitic processed low cost graphene oxide,	Engineered composite materials, electrical and electronic applications	Exceptional electrochemical properties, very high surface area to volume ratio, structurally strong, can be surface modified easily and are cheap to produce, exhibiting comparable qualities and superior properties compared to gas and oil based derived carbons, and are advantaged in having low carbon footprint	Engineered carbons are being evaluated in a number of product applications and benchmarked against industry standards, to identify the full potential of the wide array of engineered carbons being produced, and to understand the full extent of applications. Very promising results achieved using coal derived porous carbons as reinforcement in composite materials. Prototype energy storage devices built (button cells, super capacitors and redox batteries); which are now being engineered for demonstration. Purity of carbons are food grade.

Source: University of Wyoming, School of Energy Resources

e. Rare Earth Elements and Critical Minerals

Background and Significance

As noted in Figure 3G, the U.S. is dependent on foreign sources of materials vital to our nation's security and economic prosperity. In 2018, the U.S. Secretary of the Interior identified 35 minerals or mineral material groups (including rare earth elements) as "critical minerals," noting that they serve an essential function in the manufacturing of various defense, energy and consumer products, and are susceptible to supply chain disruptions, owing primarily to heavy reliance on imports. [117]

Figure 3G. U.S. Import Reliance on Critical Materials 2019

2019 U.S. NET IMPORT RELIANCE[1]

Commodity	Percent	Major import sources (2015–18)[2]
ARSENIC (all forms)	100	China, Morocco, Belgium
ASBESTOS	100	Brazil, Russia
CESIUM	100	Canada
FLUORSPAR	100	Mexico, Vietnam, South Africa, China
GALLIUM	100	China, United Kingdom, Germany, Ukraine
GRAPHITE (natural)	100	China, Mexico, Canada, India
INDIUM	100	China, Canada, Republic of Korea, Taiwan
MANGANESE	100	South Africa, Gabon, Australia, Georgia
MICA, sheet (natural)	100	China, Brazil, Belgium, Austria
NEPHELINE SYENITE	100	Canada
NIOBIUM (columbium)	100	Brazil, Canada, Russia, Germany
RARE EARTHS[3] (compounds and metal)	100	China, Estonia, Japan, Malaysia
RUBIDIUM	100	Canada
SCANDIUM	100	Europe, China, Japan, Russia
STRONTIUM	100	Mexico, Germany, China
TANTALUM	100	Rwanda, Brazil, Australia, Congo (Kinshasa)
YTTRIUM	100	China, Estonia, Republic of Korea, Japan

Source: U.S. Geological Survey

In a 2019 assessment, the U.S. Geological Survey (USGS) reported that the U.S. is 100% import reliant on 14 minerals on the critical minerals (CMs) list – including graphite, manganese, niobium, rare earth elements (REEs) and tantalum, among others. According to USGS, the nation is more than 75% import reliant on an additional 10 critical minerals – including antimony, barite, bauxite, bismuth, potash, rhenium, tellurium, tin, titanium concentrate and uranium.[118]

Due to their unique properties, the rare earth elements – lanthanide series elements and scandium and yttrium – are essential components in energy systems, in military applications and in production of consumer goods. (Figure 3H) These elements support a market of greater than $300 billion and employ more than 600,000 in North America.[119] Many of the REEs and CMs imported by the U.S. are sourced from China, the global leader in REE production and use.[120] The U.S. considers development of a domestic REE/CM market a matter of national security. There is, however, only one active rare earth mine in the U.S., in Mountain Pass, California. Coal reserves, coal byproducts, such as coal combustion residuals (coal ash), and coal mine water drainage have been identified as promising resources for domestic sourcing of REEs and CMs.

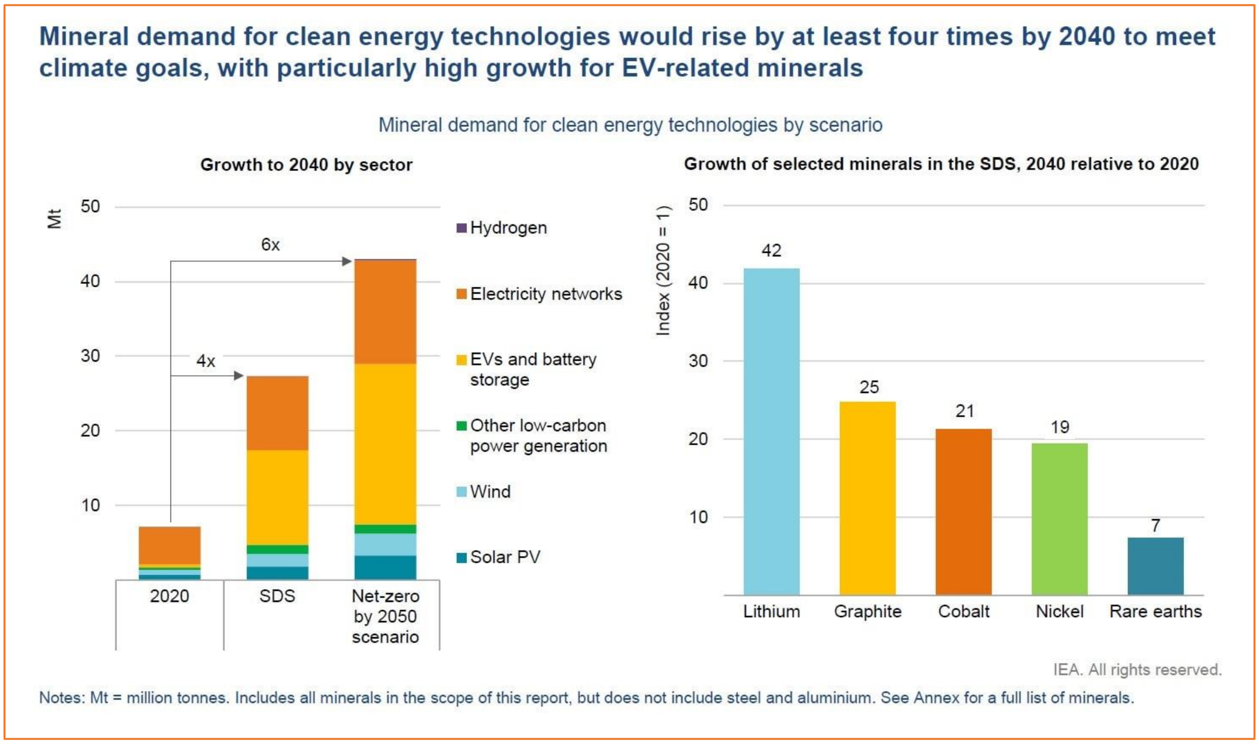
Figure 3H. Applications of Rare Earth Elements

REE	Application
Lanthanum (La)	Battery alloys, metal alloys, auto catalysts, petroleum refining, polishing powders, glass additives, phosphors, ceramics, and optics
Cerium (Ce)	Battery alloys, metal alloys, auto catalysts (emissions control), petroleum refining, polishing powders, glass additives, phosphors, and ceramics
Praseodymium (Pr)	Battery alloys, metal alloys, auto catalysts, polishing powders, glass additives, and coloring ceramics
Neodymium (Nd)	Permanent magnets, battery alloys, metal alloys, auto catalysts, glass additives, and ceramics
Promethium (Pr)[a]	Watches, pacemakers, and research
Samarium (Sm)	Magnets, ceramics, and radiation treatment (cancer)
Europium (Eu)	Phosphors
Gadolinium (Gd)	Ceramics, nuclear energy, and medical (magnetic resonance imaging, X-rays)
Terbium (Tb)	Fluorescent lamp phosphors, magnets especially for high temperatures, and defense
Dysprosium (Dy)	Permanent magnets
Holmium (Ho)	Permanent magnets, nuclear energy, and microwave equipment
Erbium (Er)	Nuclear energy, fiber optic communications, and glass coloring
Thulium (Tm)	X-rays (medical) and lasers
Ytterbium (Yb)	Cancer treatment and stainless steel
Lutetium (Lu)	Age determination and petroleum refining
Yttrium (Y)	Battery alloys, phosphors, and ceramics
Scandium (Sc)	High strength, low weight aluminum scandium alloys

Source: Cambridge University Press[121]

The International Energy Agency (IEA) issued a report in May 2021 addressing the increasingly critical role of minerals in the production of electric vehicles (EV), wind turbines and solar panels. In the report – "The Role of Critical Minerals in Clean Energy Transitions"[122] – IEA noted that demand for critical minerals such as lithium, cobalt and REEs would soar, highlighting mineral demand for use in EVs and battery storage which could be expected to increase at least 30 times by 2040. (Figure 3I) Additionally, the expansion of electricity grids arising from mass electrification of the transportation and industrial sectors is expected to double the demand for copper for power lines through 2040.

Figure 3I. Mineral Demand for Clean Energy Technology by Scenario



Source: International Energy Agency

Among the challenges to meeting increased critical mineral demand is the long lead times for permitting and launching mining projects (typically 16 years).[123] To avoid production shortfalls, IEA recommends the following initiatives be undertaken:

- Ensure adequate investment in diversified sources of new supply
- Promote technology innovation at all points along the value chain
- Enhance supply chain resilience and market transparency
- Maintain higher environmental, social and governance (ESG) standards
- Scale up recycling

Domestic mining and recovery of REEs and CMs have previously been conducted but pose significant challenges associated with economics of extraction. Traditional ore resources for some of the most critical and valuable REEs are scarce, resulting in a lower value ore as substitutes. Of these valuable REE resources, nearly 100% of the global market is produced from a single resource in China (ion-adsorbed clays). Projections of this reserve anticipate only 10-20 years remaining of economically extractable reserves.[124]

The REEs and CMs supply chain is currently not independent from foreign interests. The supply chain involves resource extraction (mining), concentration (beneficiation), separation (into individual mineral oxides), refining (into metals and alloys) and manufacturing (finished products). Mining companies currently ship any produced concentrate to a foreign country for further processing and refining. Because of the nonexistent domestic supply chain in the U.S., the vertically integrated foreign supply chain dominates markets for manufactured finished products that U.S. consumers, the U.S. Department of Defense (DOD), and U.S. technology and manufacturers depend upon.

Advantages and Opportunities

Developing a domestic source of REE/CM production would lessen U.S. dependence on foreign supply. Extracting REEs and CMs from coal reserves and coal byproducts that are readily available throughout the country could stimulate industrial development and begin to establish the lost supply chain that the U.S. enjoyed during the 20th century.

Additionally, the use of coal-based resources for REE/CM extraction could substantially reduce potential supply delays if sourced at existing, active mines. The wide-ranging location of coal mines throughout the U.S. could also provide a broad-based distribution of REEs/CMs.

Studies conducted in recent years by USGS and private concerns noted that REEs and CMs are present in coal strata throughout the U.S. These appear to be concentrated in the associated strata that make up the waste produced during processing of coal, such as the finely mixed clays, coal-partings, under-clays or waste rock, and fly or bottom ash (waste remaining after combustion).

A DOE National Energy Technology Laboratory (NETL) report entitled "Assessment of Rare Earth Elemental Contents in Select United States Coal Basins"[125] states that the formation of coal generally occurs in a basin that may also contain REE-enriched sediments from the deposition and/or erosion of volcanic, intrusive and detrital sources. The results of this study support the contention that REE occurrences in coal and associated waste materials have the potential to be important and viable sources of REEs and CMs, especially if mining costs can be minimized by coupling the extraction process with conventional coal mining practices.

Sourcing REEs/CMs from domestic coal supply activities could enhance the economics associated with REE/CM production, while also providing an added revenue stream for current and future coal mining operations. In most mining operations, the extraction and amassing of the commodity represents the bulk of the mining expense. When REEs are concentrated in coal waste rock, the additional expense of mining the REEs would likely be low, as the coal is already being mined, whether or not the REEs are utilized. Based on this scenario, the grade of REEs required for profitable exploitation would most likely be lower than that of a traditional REEs mine not associated with coal.

In North Dakota, lignite coal has been identified with high REE concentrations, particularly heavy rare earth elements (HREE).[126] In lignite coal, the REEs are weakly bound as organic complexes, rather than contained in hard mineral forms typical of higher-rank coals. These organic associations permit a simple dilute acid leaching process to be highly effective in extracting REEs from pre-combustion lignite coal. The technology is less complex than most REE mineral processing methods, potentially offering significant cost savings.

The leaching processes is also a coal beneficiation process, offering value-added opportunities for the upgraded lignite byproduct. Preliminary techno-economic assessments and feasibility studies have demonstrated evidence for a cost-effective method of generating a REE-concentrate from North Dakota lignites with the sale of multiple by-products, including CMs and upgraded coal products such as activated carbon and humic acid. Results show strong economic potential for the process. The proposed technology is capable of making a disruptive impact on domestic REE markets, in large part due to the novel extraction methodology and substantial lignite reserves in North Dakota.

Another distinct opportunity lies in accessing coal waste reserves containing carbon and REE-rich materials. Since the 18th century, coal mining practices in the U.S. have resulted in billions of tons of lower energy coal products being discarded in thousands of coal waste disposal ponds throughout the country. The Appalachian mountain chain region, in particular, is thought to contain some of the richest reserves of REEs in the world.[127] Both lignite and bituminous coal have higher ash contents and are expected to contain higher levels of both CMs and REEs, as compared with higher BTU-lower ash coals, such as anthracite.

Recovering REEs from coal waste resources would have numerous advantages. Mining and logistics costs would be negligible compared with traditional REE/CM mining methods. The carbon resources are "shovel ready" in that they are surface mine reserves and the material is already finely ground for the most part, requiring less energy and expense to produce an optimal grind required for efficient beneficiation. These factors significantly reduce the cost of extraction and separation. Distributed REE separation plants sited at or near the reserve sites would eliminate the need for extensive transportation. Finally, REE recovery from carbon material would aid in the mitigation of legacy environmental issues associated with waste coal disposal ponds.[128]

REE/CM Processing Synergies with Coal to Products

Synergies exist between extraction of REEs/CMs and the production of other value-added products from coal. By way of example, chemical leaching, which is a standard in the mining industry, can be used to selectively extract and concentrate REEs from low-rank coal (e.g., lignite), resulting in a residual coal product with characteristics that are beneficial for use in applications such as production of activated carbon, humic soil amendments and pharmaceuticals.

The leaching process employed under conditions relevant for the REE/CM extraction maintains the organic structure of the coal, while removing the bulk of the organic-bound constituents. This results in a number of potential benefits for value-added coal use, such as increased pyrolysis fractions and pore volume for high-value activated carbon and reduced organic content of associated humic acid, for fertilizer, pharmaceuticals, or high-purity carbon applications.

Additionally, the post-leached residual coal has improved properties compared to the unleached coal. Leached coal has a lower ash content and a larger pore structure. By utilizing the upgraded coal, a higher quality, higher value activated carbon product can be produced as the larger pore size in the residual coal provides additional surface area for increased adsorption. The decreased ash content of the residual coal also improves the quality of the activated carbon as the presence of ash in activated carbon decreases its effectiveness.

Conversely, many of the coal conversion processes described previously, particularly liquefaction and pyrolysis, yield an ash residue as a reject stream from selective removal of the carbon containing compounds. This serves to concentrate REEs into the solid residue, similar to coal combustion byproducts.

In the case of humic acid production from the residual coal, the lower ash content is also beneficial. Without the reduction in ash content provided from the REE recovery process, additional processing would likely be required during humic acid production to remove the ash material from the coal. High ash content in humic acid reduces the purity and also the value of the humic acid. Therefore, reduction in ash content during REE extraction improves the quality of the final humic acid product.

f. Agricultural Products

Background and Significance

Today’s global population is fast approaching 8 billion people.[129] Population models predict reaching 10 billion in the next 50 years and a two-fold increase in food demand. Soil and water are essential natural resources for our food production systems.

While soil is frequently referred to as the "fertile substrate," not all soils are suitable for growing crops.[130] Ideal soils for agriculture are balanced with a combination of mineral components, organic matter, air and water. The balanced contributions of these components allow for water retention and drainage, oxygen in the root zone, nutrients to facilitate crop growth and physical support for plants. Poor or infertile soils are characterized by water repellence, subsoil acidity, subsoil compaction and poor water and nutrient holding capacity.

Agriculture accelerates soil erosion at rates that exceed that of soil formation. Erosion is often accelerated by agricultural practices that leave the soil exposed to surface runoff or wind. It is evident that, in order to maintain and increase food production, efforts to prevent soil degradation must become a top priority of our global society.

In modern, industrially supported agricultural practices, farmers counteract soil depletion and erosion with chemical fertilizers, which provide crops with the nitrogen and phosphorus necessary to grow and produce the food we eat. However, chemical fertilizers contribute to nutrient pollution, which is one of America's most widespread, costly and challenging environmental problems, caused by excess nitrogen and phosphorus.[131]

Excess nitrogen and phosphorus can be washed from farm fields into waterways during rain events or when snow melts, and can also leach through the soil into groundwater over time. High levels of nitrogen and phosphorus can cause eutrophication of water bodies. Eutrophication can lead to hypoxia ("dead zones"), causing fish kills and a decrease in aquatic life. Excess nutrients can cause harmful algal blooms (HABs) in freshwater systems, which not only disrupt wildlife but can also produce toxins harmful to humans.

Fertilized soils, as well as livestock operations, are also vulnerable to nutrient losses to the air. Nitrogen can be lost from farm fields in the form of gaseous, nitrogen-based compounds, such as ammonia and nitrogen oxides. Ammonia can be harmful to aquatic life if large amounts are deposited from the atmosphere to surface waters. Nitrous oxide is a potent greenhouse gas.

Slow-release fertilizers attempt to counteract this problem by using fertilizer pellets coated with polymers. These polymer-coated pellets oxidize and break down over time, releasing the fertilizer – and presumably degraded polymer – into the soil. Their use, however, only slows down rather than prevents runoff.

The most naturally fertile soils around the world – terra preta in Amazon region, black dirt in New York/New Jersey, chernozem in the Eurasian steppes and mollisols in the North America prairies – have one thing in common: a thick top layer of organic, black carbon-rich matter. Rich in carbon and humic contents, these soils have a high water-holding capacity, and high inherent contents of potassium, phosphates and nitrogen. They support a healthy animal and plant ecology resisting soil compaction. Addition of bio-char (charcoal) has been shown to partially replicate these effects, and thus has been adopted by the organic farming industry. Increased consumer demand for organic produce contributes to the rapid growth for carbon-rich soil additives.

Advantages and Opportunities

Coal and peat, due to their origin and organic nature, have been long used in agriculture as sources of humus or organic matter.[132] In this context, not all types of coal are useful. Mostly "younger" types, such as peat, lignite and sub-bituminous coals, have found their niche in agriculture. Since the 1920s, there have been attempts to create organic fertilizers based on coal.

The "younger" coals possess chemical structures that are found in composted organic matter. Humic and organic acids in the coal-based products have a positive influence on plants, helping them to endure stressful situations (e.g., drought and heat), serving as a bio-stimulant.[133]

The fact that peat and lignite are by nature relatively poor in plant macronutrients (nitrogen, phosphorous and potassium) explains why using pure lignite as an "organic fertilizer" has not been successful. Nevertheless, some coal-based products have found their way into the market as soil improvers, e.g., leornadite[134] granulates.

The processes for enhancing the consistency and nutrient capacity for these products continue to improve. The present global market size is estimated between 500 million and 1 billion US$ per annum.[135]

In Australia, it was it reported that lignite-derived low molecular weight organic compounds have been evaluated as a low-cost bio-stimulant fertilizer liquid. Trials conducted at application rates between five liters per hectare to 70L/Ha found that at rates of between 5-35L/Ha, crops developed at around three times the rate of the untreated control group. There was a similar improvement in total fresh mass and a doubling of plant total dry mass per plant compared with the control group. The bio-stimulant fertilizer liquid was produced via a proprietary oxidative hydrothermal dissolution process applied to lignite from Australia's Gippsland Basin. In this process the coal is crushed, turned into a slurry and subjected to heat, pressure and liquefied oxygen in a process that is clean and recovers mostly water. Reportedly, bio-stimulant fertilizers have typically been too expensive to use on anything other than higher value crops; the use of inexpensive coal as a feedstock reduces the cost by almost 90%.[136]

Another beneficial aspect of coal amelioration with carbon additives derives from the physical properties of porous, chemically-inert carbon materials. The high surface-area-to-volume ratio and the dispersive nature of coal char has been shown to benefit soil fertility when added in moderate dosage levels. Tests have shown that coal-derived soil amendments can perform as well as the industry standard product at this time, which is bio-char, and can be made at appreciably less cost using simple thermo-chemical processes. It should also be noted that the addition of coal char can inhibit soil erosion as it provides structure to the soil.

One of the important attributes of coal-derived soil amendments is that they do no harm; they do not add toxins, heavy metals and carcinogenic compounds to the soil. Soil amendment products change the structure of the soil and can improve crop fertility over many years, minimizing the need for regular re-applications of coal-char derived product. Clay like soils have shown the ability to retard nitrogen fertilizer run-off and have an affinity to retain moisture in sandy soils. Similar beneficial properties would be expected in coal-derived amendments.

This necessitates that the cleaner coals, compliant with specific levels for certain compounds (e.g., heavy metals), are more suited to make soil amendment products. Further, high oxygen content coals have been shown to perform better, because of the homogeneous nature of the inherent porosity that is derived from these types of coal.

There are approximately 1.5 billion hectares of cultivated land worldwide; 12 million hectares are being lost every year.[137] Soil amelioration with coal products would help retain and deliver much needed nutrients , prevent harmful fertilizer runoff, reduce CO_2 emissions associated with energy intensive fertilizer production and contribute to the long-term stability of the soils. In fact, reversing and reclaiming desertification with abundant coal-derived soil additives can arrest erosion, retain water and nutrients, and reinvigorate arable land. These efforts can significantly contribute to capturing atmospheric CO_2 and reversing effects of climate change.

g. Status of Coal to Products Technologies Development and Deployment

The National Coal Council undertook a stakeholder survey of entities engaged in researching, developing and deploying various coal-derived products. Survey results are included as a Technology Compendium in Appendix A of this report.

Approximately 25 private industry and university stakeholders[iv] submitted self-assessments of more than 35 technologies and products currently under development, providing an evaluation of their respective technologies' maturity and market potential based on the following range of metrics (Figure 3J).

[iv] A number of those engaged in RD&D for coal-derived products declined to participation in the stakeholder survey due to the proprietary nature of their technology/product. The NCC survey should not be construed as representative of the full universe of those involved in this sector.

Self-Assessed Metrics

Development Stage Assessment

- Technology Stage – ranging from concept/white paper stage through commercial ready
- Scale Demonstrated – ranging from yet-to-be-completed through fully completed
- Timing of Prototype – ranging from more than a year to completed
- Timing of Pilot – ranging from more than 3 years to completed
- Timing of Full-Scale – ranging from more than 5 years to completed
- Timing of Commercial Deployment – ranging from more than 10 years to completed
- Economics Stage – assessing cost accuracy on a range of unknown to +/- 10%
- Investment Stage – assessing investment caliber ranging from unknown to investment grade/financeable

Business Case/Benefit Assessment

- Potential U.S. Coal Utilization – assessing magnitude of coal tonnage/year use ranging from less than 1 million tons to more than 100 million tons
- Price Comparison – assessing advantages vis-à-vis alternative products ranging from more expensive to greater than 20% less expensive
- Competitiveness – assessing key benefits, such as jobs, enhanced utilization of resources, environmental and national security, on a scale of 1 to 9
- Environmental Impacts – ranging from a net increase to a net benefit
- National Security – assessing key benefits, such as reducing import dependency, providing redundancy of sourcing and/or improving trade, on a scale of 1 to 9

The technologies and products represented in the Technology Compendium include carbon fibers, carbon resins, rare earth elements, building materials, agricultural applications, transportation fuels, and chemicals and petrochemicals, as well as pigments, manufactured carbon, mineral fiber, nanoparticles, carbon allotropes and sorbents.

Technology Compendium Survey Results

A summary of the survey participants' self-assessments (Figure 3K) indicates that of those technologies represented, the following Development Stage and Business Case Benefits can be discerned.

Development Stage Assessment

- Technology Stage – a majority of the technologies are in the mid-development stage in which feasibility has been confirmed and are poised for investment. This is typical of the "development valley of death" referred to in Chapter IV of this report's discussion on technology commercialization. This is the stage at which many technologies fail to advance for lack of funding and opportunities to demonstrate their engineering and commercial viability.

- Scale Demonstrated – the development valley of death is here, again, evident as most of the technologies in the survey fall in the mid-range of demonstration (bench-scale to small/large pilot-scale). Most technologies have achieved completion of prototype development and many have either completed some pilot testing or are poised to do so within 1-2 years. Fewer have completed full-scale demonstrations, with many indicating at least 1-2 years are yet ahead.

- Timing of Commercial Deployment – a majority of survey participants indicated commercial deployment is at least 3-5 years out.

Business Case/Benefit Assessment

- Potential U.S. Coal Utilization – technologies represented in the survey reflected a wide-range of potential coal use, with transportation fuels and chemicals indicating larger tonnage utilization than other coal-derived products.

- Price Comparison – survey results suggest potential for coal-derived products to be cost-competitive or cost-advantaged over alternative products.

- Competitiveness, Environmental Impacts and National Security Benefits – survey respondents indicated significant benefits of their technologies associated with job creation, resource utilization, net environmental advantages, reduced import dependency and enhanced national security.

See Appendix A. Technology Compendium for a complete overview of the survey participants' responses.

Figure 3J. Technology Compendium Metrics

	Topic	Matrix Entry 1	2	3	4	5	6	7	8	9
Dev phase	Technology Stage	Concept / White paper			Feasibility confirmed; commercial case promising			Investment ready		Commercial
	Scale Demonstrated	None	Lab	Bench	Small Pilot	Large Pilot		Demo/FOAK		Commercial
	Timing of Prototype	> 1 year				<6 mo				Complete
	Timing of Pilot	>3 year		2-3 year		1-2 year		<1 year		Complete
	Timing of Full-scale	>5 year				1-2 year		<1 year		Complete
	Timing of commercial deployment	>10 year				3-5 year		1 year		Complete
	Economics Stage (Cost accuracy range, e.g., +/- 30%)	unknown				+/-50%		+/-30%		+/-10%
	Investment Stage	unknown		Govt Grant		Subsidy Required				Investment Grade-Financeable
Business Case	Potential U.S. coal utilization, magnitude ton/yr	<1MM	>1 MM	>5 MM	>10 MM		25-50 MM		50-100 MM	>100 MM
	Price comparison - advantage over alternative	More expensive				Neutral		10% less		>20% less
	Competitiveness (benefits other than price)	None				1 key benefit				2+ key benefits
	Environmental Impacts	net increase				Neutral				net benefit
	National Security	Neutral				1 benefit				2+ benefits

Figure 3K. Technology Compendium Matrix Responses

Technology Compendium Matrix Technology	Technology Stage	Scale Demonstrated	Timing of Prototype	Timing of Pilot	Timing of Full-scale	Timing of commercial deployment	Economics Stage	Investment Stage	Potential U.S. coal utilization	Price comparison	Competitiveness	Environmental Impacts	National Security
Carbon Fibers													
Carbon Fuels	6	5	9	9	5	3	9	9	8	9	9	9	9
University of Kentucky	4	4	1	5	5	5	5	3	9	9	9	9	9
University of Wyoming	4	4	1	3	1	1	5	5	3	7	7	9	9
Carbon Resins													
Carbon Fuels	6	5	9	9	5	3	9	9	8	9	9	9	9
University of Kentucky	4	4	1	5	5	5	5	3	9	9	9	9	9
University of Wyoming	4	4	1	3	1	1	5	5	3	7	7	9	9
Rare Earth Elements													
Carbon Fuels	6	5	9	9	5	3	9	9	8	9	9	9	9
CTC Foundation	6	3	6	7	7	7	5	4	6	8	9	9	9
Ram Rock	8	8	8	8	8	8	8	8	6	5	9	9	9
SonoAsh	1	1	3	3	3	2	1	3	5	9	9	9	9
University of Kentucky	4	4	1	5	5	5	5	3	9	9	9	9	9
University of North Dakota & Microbeam	4	4	9	7	5	5	5	5	3	7	9	9	9
Building Materials													
Boral Resources	7	7	9	9	9	7	7	9	1	9	9	9	9
CarbonBuilt	7	7	9	9	5	6	7	7	n/a	9	9	9	1
Carbon Fuels	6	5	9	9	5	3	9	9	8	9	9	9	9
CFOAM	4	4	4	7	3	6	3	3	9	4	9	9	5
CTC Foundation	6	4	6	6	5	5	7	5	6	6	8	9	4
GCS Fibers	9	9	9	9	9	9	9	9	4	9	9	9	9
Green Cement	7	9	9	9	7	7	7	9	8	9	9	9	9
New Steel	7	9	9	9	9	7	9	9	9	9	9	9	9
Ohio University - Decking	7	7	9	9	8	7	8	7	2	9	9	9	1
Ohio University - Piping	4	5	4	5	5	5	7	3	3	8	7	8	1
Ohio University - Cladding	4	3	2	3	5	5	5	3	1	9	8	9	1
Ram Rock	8	8	8	8	8	8	8	8	6	5	9	9	9
SEFA	9	9	9	9	9	9	9	9	4	4	9	9	9
Semplastics - Single-Batch Building Materials	4	4	5	5	3	5	5	5	2	4	9	9	5
Semplastics - Single-Batch Coal Based Concrete	3	3	5	3	3	5	5	3	4	5	9	9	5
SonoAsh - Sonic Platform Technology	8	9	8	9	8	5	7	6	7	5	9	8	8
SonoAsh - Cementitious Material	4	5	5	5	8	5	7	6	7	5	8	9	5
SonoAsh - Carbon Abrasives	1	1	1	1	3	2	2	2	7	7	6	7	1
SonoAsh - Proppants (Artificial Sand)	2	1	3	2	3	3	2	3	2	8	8	7	3
University of Kentucky	4	4	1	5	5	5	5	3	9	9	9	9	9
University of Wyoming	4	4	1	3	1	1	5	5	3	7	7	9	9
Agriculture-Life Science Applications													
NOVIHUM	9	7	9	9	3	5	8	n/a	3	5	9	9	5
Transportation Fuels													
C3H LLC Beneplus	5	4	9	9	7	5	7	7	9	9	9	9	9
Carbon Fuels	6	5	9	9	5	3	9	9	8	9	9	9	9
CTC Foundation	8	4	6	7	6	6	6	4	7	7	8	9	8
HTI	7	7	9	9	9	7	9	7	6	7	9	9	9
Riverview Energy	9	9	9	9	9	9	9	9	9	9	9	9	9
Synfuels Americas Fischer-Tropsch Synthesis	9	9	9	9	9	9	9	5	9	5	5	9	9
Synfuels Americas Stepwise Liquefaction	9	9	9	9	9	9	5	5	9	5	9	5	9
Chemicals & Petrochemicals													
HTI	7	7	9	9	9	7	9	7	6	7	9	9	9
Synfuels Americas Fischer-Tropsch Synthesis	9	9	9	9	9	9	9	5	9	5	5	9	9
Synfuels Americas Stepwise Liquefaction	9	9	9	9	9	9	5	5	9	5	9	5	9
Conductive Carbon-Pigments-Polymers													
Minus 100 LLC	7	4	5	4	5	5	7	5	2	9	9	9	9
Manufactured Carbon													
Morgan Advanced Materials	2	3	2	5	4	4	3	4	1	4	7	7	9
Mineral Fiber-Paper Pulp-Insulation													
GCS Fibers LLC	9	9	9	9	9	9	9	9	4	9	9	9	9
Nanoparticles & Nanotubes													
CTC Foundation	4	3	5	7	5	5	7	5	4	8	8	9	8
Pure Carbon Allotropes													
CLWV Holdings	3	3	5	2	2	5	3	1	n/a	6	6	7	7
Sorbents													
University of Wyoming	4	4	1	3	1	1	5	5	3	7	7	9	9

Chapter IV. Approaches to Coal-to-Products Commercialization

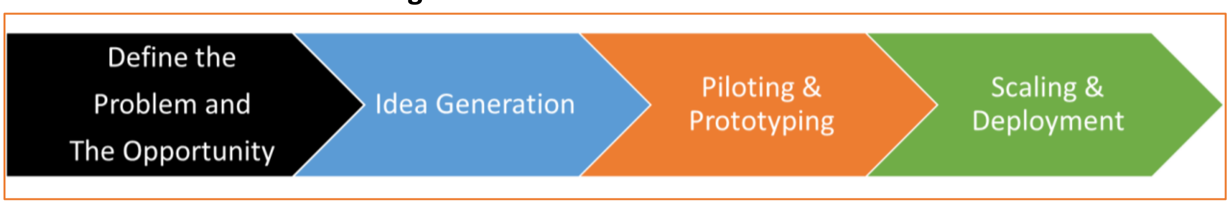
Successful deployment of technologies for production of value-added products from coal will require addressing the gap between basic laboratory research and development (R&D) that is typically funded and undertaken by government and universities with some support from the private sector, and the commercial demonstration of these technologies largely funded by the private sector. This chapter examines opportunities and challenges associated with the research, development and demonstration (RD&D) continuum, with a particular focus on deployment of coal-derived products via advanced manufacturing techniques.

a. From Lab to Fab(rication): The RD&D Continuum to Market Deployment

In Chapter III of this report, a number of very promising applications have been identified that would enhance beneficial use of our nation's existing coal resources and coal production infrastructure, to retain and create jobs and to strengthen our domestic supply chain for critical resources.

How does this happen? How does technology progress from fundamental research, through development to fabrication and full commercial deployment … from Lab to Fab. At a high level, this is the continuum of the process for technological innovation and change.

Figure 4A. The RD&D Continuum



Source: Stanford Social Innovation Review

- **Define the Problem and the Opportunity** – The fundamental starting point is identifying the problem and the benefit(s) of technological solutions. Should we do it?

- **Generate Ideas to Solve the Problem and Capture the Opportunity** – This is the basic science and chemistry to identify potential technological solutions. Can we do it?

- **Develop the Technology through Piloting and Prototypes** – Here is where the fundamental science and engineering come together to develop a complete technology platform, from raw material to viable product. Can we make all of the pieces fit?

- **Deploy the Technology at Commercially Relevant Scale** – The final step of scaling the piloting and prototypes to something commercially meaningful.

The U.S. government is quite sophisticated in its approach to the process of technology innovation and commercialization. In August 2016, the U.S. Government Accountability Office (GAO) published, “Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs.”[138] This guide assembled inputs across a large number of government agencies, universities and private industry contactors in order to establish a methodology based on best practices to apply broadly within the Federal government for evaluating technology maturity. The methodology can be employed particularly as it relates to determining a program or project’s readiness to move past key decision points that typically coincide with major commitments of resources.

The U.S. Department of Energy (DOE) has adopted “The DOE Technology Readiness Assessment Guide”[139] that provides a methodology and ranking to define where a technology falls along this continuum. The intent of this guide is to ensure a systematic process that clearly defines not only the state and status of a technology under development, but also defines the level of work necessary to advance the technology development. The ranking is termed Technology Readiness Level (TRL) and is graphically illustrated in the following figure.

Figure 4B. Technology Readiness Level

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof-of-concept validated	Basic technology components integrated and validated in a laboratory environment	Basic technology components integrated and validated in a relevant environment	Prototype validated in a relevant environment	System prototype validated in an operational system	Actual technology successfully commissioned in an operational system	Actual technology operated over the full range of expected operational conditions

Source: Figure based on information contained in DOE Technology Readiness Assessment Guide

TRL 1 - Basic principles observed and reported

- Core Technology Identified.
- Scientific research and/or principles exist and have been assessed.
- Translation into a new idea, concept and/or application has begun.

TRL 2 - Technology concept and/or application formulated

- Invention Initiated.
- Analysis has been conducted on the core technology for practical use.
- Detailed analysis to support the assumptions has been initiated.
- Initial performance attributes have been established.

TRL 3 - Analytical and experimental critical function and/or characteristic proof-of-concept validated

- Performance requirements that can be tested in the laboratory environment have been analytically and physically validated.
- The core technology should not fundamentally change beyond this point.
- Performance attributes have been updated and initial performance requirements have been established.

TRL 4 - Basic technology components integrated and validated in a laboratory environment

- The basic technology components have been integrated to the extent practical (a relatively low-fidelity integration) to establish that key pieces will work together, and validated in a laboratory environment.
- Performance attributes and requirements have been updated.

TRL 5 - Basic technology components integrated and validated in a relevant environment

- Basic technology component configurations have been validated in a relevant environment. Component integration is similar to the final application in many respects.
- Data sufficient to support planning and design of the next TRL test phase have been obtained.
- Performance attributes and requirements have been updated.

TRL 6 - Prototype validated in a relevant environment

- Component integration is similar to the final application in most respects and input and output parameters resemble the target commercial application to the extent practical.
- Data sufficient to support planning and design of the next TRL test phase have been obtained.
- Performance attributes and requirements have been updated.

TRL 7 - System prototype validated in an operational system

- A high-fidelity prototype, which addresses all scaling issues practical at pre-demonstration scale, has been built and tested in an operational environment.
- All necessary development work has been completed to support actual technology testing.
- Performance attributes and requirements have been updated.

TRL 8 - Actual technology successfully commissioned in an operational system

- The actual technology has been successfully commissioned for its target commercial application, at full commercial scale.
- In almost all cases, this TRL represents the end of true system development.
- Actual technology operated over the full range of expected operational conditions.

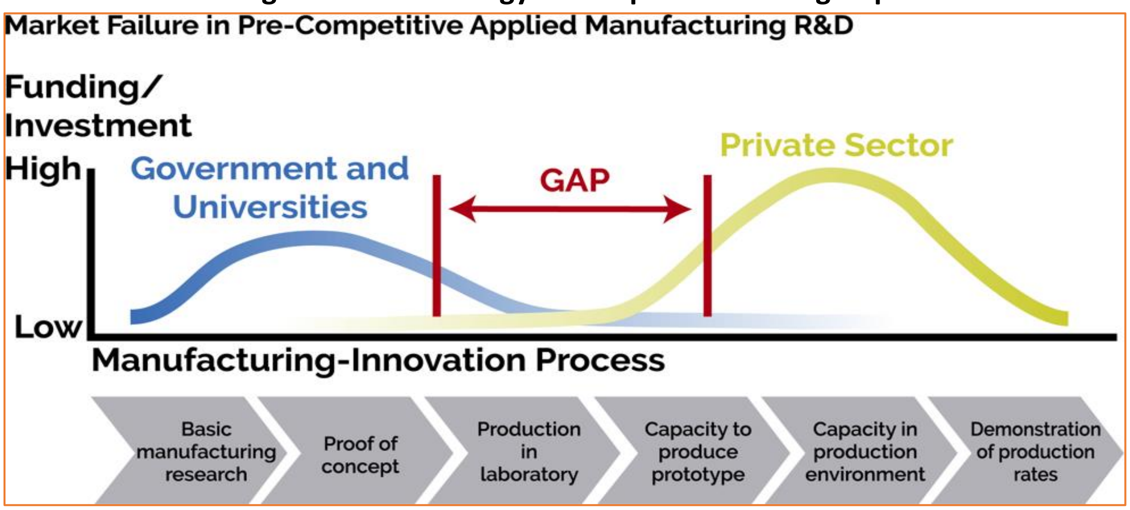
TRL 9 - Commercially operated

- The technology has been successfully operated long-term and has been demonstrated in an operational system, including (as applicable) shutdowns, startups, system upsets, weather ranges and turndown conditions.
- Technology risk has been reduced so that it is similar to the risk of a commercial technology if used in another identical plant.

Figure 4B above illustrates the orderly stepwise progression in the TRL RD&D continuum. Historically, at TRL 1 – TRL 3, innovations originate in universities and other research organizations, and are supported through public sector funding. At TRL 7 – TRL 9, technology development is largely funded by the private sector. It should be noted that this technology development, from TRL 1 to TRL 9, can take decades to complete. For an overview of current DOE RD&D initiatives on coal-to-products, see Appendix B.

The major time delay and primary obstacle is a gap in the availability of funding through the so-called "development death valley," illustrated in Figure 4C. Accelerating technology innovation and deployment for value-added products from coal needs to address this gap.

Figure 4C. Technology Development Funding Gap



Source: Kelvin H. Lee, Mind the Gap[140]

Another tool for tracking the development and deployment stages of a technology is the U.S. Department of Defense's (DOD) manufacturing readiness level (MRL). (Figure 4D) The MRL, adopted by DOD in 2005, is used to assess the maturity of manufacturing readiness through the application of quantitative measures. The U.S. GAO has identified the use of MRLs as a best practice for improving acquisition outcomes.[141]

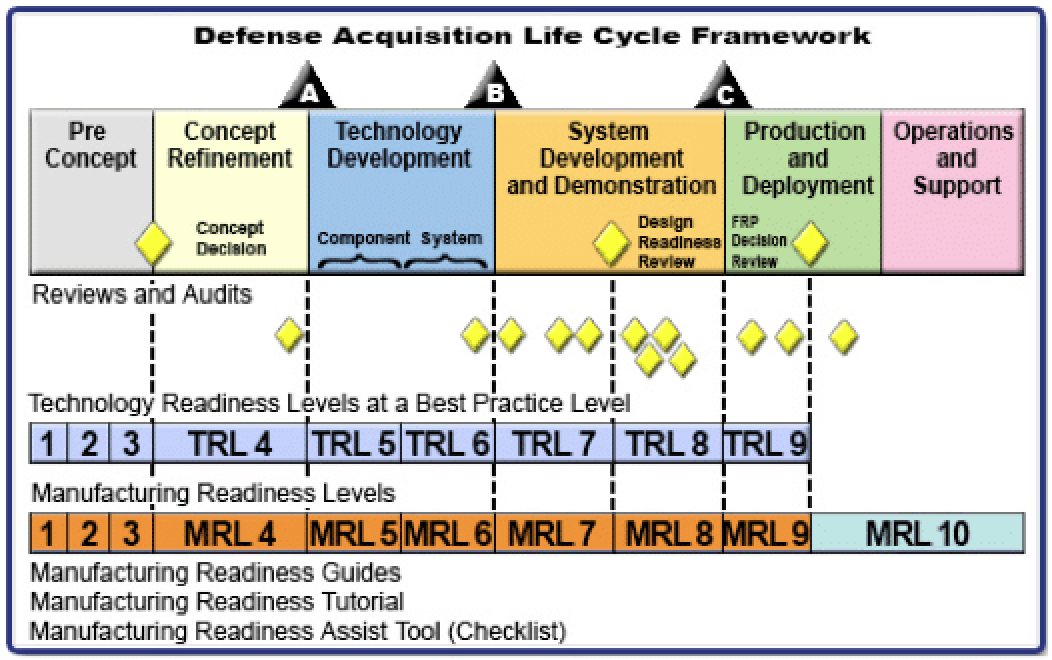
Figure 4D. Manufacturing Readiness Levels

MRL 1	Basic manufacturing implications identified
MRL 2	Manufacturing concepts identified
MRL 3	Manufacturing proof of concept developed
MRL 4	Capability to produce the technology in a laboratory environment
MRL 5	Capability to produce prototype components in a production relevant environment
MRL 6	Capability to produce a prototype system or subsystem in a production relevant environment
MRL 7	Capability to produce systems, subsystems or components in a production representative environment
MRL 8	Pilot line capability demonstrated. Ready to begin low rate production
MRL 9	Low Rate Production demonstrated. Capability in place to begin Full Rate Production
MRL 10	Full Rate Production demonstrated and lean production practices in place

Source: U.S. Department of Defense

MRLs enable industry and government decision makers with a common understanding of relative maturity and attendant risks associated with manufacturing technologies, products and processes. The MRL numbering system was designed to coincide with comparable levels of TRLs. An example of a comparative framework between MRL and TRL levels is noted in Figure 4E.

Figure 4E. MRL-TRL Comparative Framework



Source: Best Manufacturing Practices Center Of Excellence [BMPCOE] under direction of Joint Defense Manufacturing Technology Panel [JDMTP], *MRL Assist Tool - User Manual Version 1.1*, College Park, Maryland, February 2007, https://www.mrlassist.bmpcoe.org/.

DOE's TRL and DOD's MRL can be useful tools in developing and commercially deploying technologies. In addition to the upstream RD&D being funded by DOE/NETL that is focused on developing products and materials from coal and associated manufacturing processes, there is also a need for downstream RD&D focused on applications and end-use market development. Intra-governmental collaboration between departments, such as DOE and DOD, could help enhance market development for advanced carbon materials such as carbon fibers, carbon foam and graphene.

Solidia Technologies: Use of Existing RD&D

Solidia Technologies provides an example of how the U.S. Department of Energy's use of RD&D programs can successfully advance the deployment of value-added products from coal.

CO_2-cured Solidia Concrete™ from EP Henry Newark, DE

In 2002, DOE awarded Solidia Technologies located in Piscataway, New Jersey, R&D funding to study "Utilization of CO_2 in High Performance Building and Infrastructure Products." The overall objective of the award (DE-FE0004222 [142]) was to demonstrate that calcium silicate phases, in the form of either naturally-occurring minerals or synthetic compounds, could replace Portland cement in concrete manufacturing. The calcium silicate phases would be reacted with gaseous CO_2 to create a carbonated concrete end-product. If successful, the project would offer a pathway to a significant reduction in the carbon footprint associated with the manufacture of cement and its use in concrete (approximately 816 kg of CO_2 is emitted in the production of one tonne of Portland cement).

In the initial R&D phases, Rutgers University teamed with Solidia Technologies to demonstrate that natural minerals could be used as a cement and would both eliminate the CO_2 emitted during cement production altogether and store CO_2 during concrete curing. This new approach enabled the new cement material to be made using existing cement industry raw material supply chains, capital equipment and distribution channels. It would also offer faster and more complete access to the concrete marketplace.

In the subsequent Demonstration of Commercial Development phase, the characteristics and performance of Solidia Cement made at LafargeHolcim cement plants were established. This Solidia Cement was then used to demonstrate the CO_2-curing process within operating concrete plants. The culminating activity of the Demonstration of Commercial Development phase was the conversion of 10% of the manufacturing capacity at a concrete paver and block company from Portland cement-based products to Solidia Cement-based products.

The successful completion of the Demonstration of Commercial Development phase clearly illustrated the environmental benefits associated with Solidia Cement and Solidia Concrete technologies.

- The industrial production of Solidia Concrete reduces CO_2 emissions at the cement kiln from 816 kg of CO_2 per tonne to 570 kg per tonne of Solidia Cement clinker.
- Industrial scale CO_2-curing of Solidia Concrete sequestered a net of 183 kg of CO_2 per tonne of Solidia Cement used in concrete pavers.
- Taken together, these two effects reduced the CO_2 footprint associated with the production and use of cement in concrete products by over 50% (a reduction of 430 kg of CO_2 per tonne of cement).

"As an alternative building material with a lower carbon footprint, Solidia Cement is an excellent example of the innovative technologies DOE's Carbon Storage Programme advances in its mission to promote solutions for reducing CO_2 emissions," said Traci Rodosta, NETL Carbon Storage Technology Manager. "We're hopeful that the commercial success of Solidia Cement will encourage the view that CO_2 has untapped value as a commodity."[143]

b. Demonstration Projects: Value, Need and Funding

Demonstration is the part of the technology RD&D continuum that links research with commercial reality. Before commercial deployment of a new technology, all of the innovative elements of the technology must be demonstrated in as close to a market/manufacturing setting as possible.

The primary objective of a demonstration project is to provide technology developers, investors and users with relevant information about the performance, costs, reliability and safety of the new technology in circumstances that approximate actual conditions of use. A successful demonstration resolves technological, regulatory and business risks to levels that would allow the first few commercial projects to proceed with private investment. In TRL terms, a demonstration project advances technology from a TRL 4 level to a TRL 9 level. In other words, from the stage in which basic technology components have been integrated to establish that key pieces will work together and are validated in a laboratory environment, to commercial operation.

A demonstration project scale/capacity is set to minimize capital expenditures while using commercial equipment and integrating the necessary processing sequencing and components. The demonstration project confirms the up-scaling of the technology.

Also, by design, demonstration projects are undertaken at a scale and scope that allows for quicker and easier planning, financing and implementation than for full-size projects. This makes it possible for a shorter project cycle, so that the technology benefits may be quickly verified while the technical and financial risks of commercial implementation are mitigated.

It is very common for technology development to stall at the demonstration stage of technology maturity. The major time-delay and primary obstacle is a gap in the availability of funding through the so-called, “development death valley,” illustrated previously in Figure 4C.

Even very promising new technologies, especially complex and capital-intensive technologies, remain un-deployed due to the lack of an effective demonstration. The cost and risk of demonstration projects deter private investments, especially for First-of-a-Kind (FOAK) technologies. The Federal government has often shied away from technology demonstration, even when its R&D investments have brought technologies to the point of demonstration readiness. Currently, large-scale demonstration is among the biggest gaps in the energy innovation process for deployment of technologies such as carbon capture and transformational low-carbon power generation technologies. A similar gap will need to be bridged for successful commercial deployment of value-added products from coal.

Financing of demonstration projects in today's market is an impediment to advancing these technologies. Commercial-scale demonstration projects currently require industry contributions of up to 50%; Federal support is to comprise the additional 50%. However, the 50%-50% cost-share arrangement only works if the full 50% Federal funding is actually received. In their Energy Technology Roadmap (July 2018)[144], the Carbon Utilization Research Council (CURC) and the Electric Power Research Institute (EPRI) highlighted non-receipt of full Federal cost share for commercial scale projects as a challenge to the ultimate success of various Clean Coal Power Initiative projects. (Figure 4F) These lessons may be instructive in moving forward with funding support for coal-to-products commercial demonstration projects.

Figure 4F. Federal Cost-Share of CCPI Projects

Project	Total Federal Grant	Total Project Cost	Federal Cost Share
Hydrogen Energy California	$408 M	$4 B	10%
Summit Texas Clean Energy	$450 M	$2.5 B	18%
NRG Energy (Petra Nova)	$167 M	$1 B	19%
Southern Plant Ratcliffe (Kemper)	$293 M	$5.6 B	5%
Total ($) or Average (%)	$1.752 B	$13.1 B	13%

Source: CURC-EPRI Advanced Fossil Energy Technology Roadmap

Lack of experienced large-scale project managers has also been noted as a challenge to the success of commercial project demonstrations. To enhance prospects for success, demonstration projects need to be managed by senior industry personnel experienced in oversight, finance and management of large-scale projects.

A well-funded demonstration program for various coal-derived products could help overcome technical and cost barriers, more expeditiously advancing the many socio-economic, environmental and national security benefits noted in Chapter I of this report.

UCLA CarbonBuilt
NRG COSIA Carbon XPRIZE Winner

In April 2021, XPRIZE announced two winners of the $20 million NRG COSIA Carbon XPRIZE – CarbonCure Technologies and CarbonBuilt. The Carbon XPRIZE, launched in 2015, was a five-year global competition challenging innovators around the world to develop technologies that convert CO_2 into value-added products. Both winning companies represent efforts to utilize CO_2 in the production of concrete. Canadian CarbonCure demonstrated a technology enabling the production of concrete with a reduced water and carbon footprint without sacrificing the material's reliability.

Los Angeles-based UCLA CarbonBuilt developed technology that reduces the carbon footprint of concrete by more than 50% while reducing raw material costs and increasing profitability. CarbonBuilt's technology was researched at the University of California-Los Angeles and tested at the Wyoming Integrated Test Center.

UCLA researchers first developed a new formula for cement, which is the binding agent in concrete. They used hydrated lime, or portlandite, which can absorb carbon dioxide (CO_2) quickly, to replace traditional calcium silicate cement, known as ordinary Portland cement. The team then created a method in which CO_2 taken directly from flue gas is quickly absorbed by portlandite as the concrete hardens.

In addition to absorbing CO_2 into the concrete, CarbonBuilt's Reversa process reduces the amount of ordinary Portland cement needed to produce concrete by between 60% and 90%. The process also occurs at ordinary temperatures and pressures. As a result, CarbonBuilt concrete has a much smaller carbon footprint than conventional concrete. That could go a long way toward reducing the world's greenhouse gas output, since the production of traditional cement used in concrete is the cause of nearly 9% of the world's CO_2 emissions.

Another compelling advantage of the new technology is that it is cost-effective. Unlike other carbon-mitigation technologies that require an expensive setup to capture the CO_2 emissions or purify them, the CarbonBuilt process allows for CO_2 in power and industrial plants' flue gas to be utilized directly and converted at its source without those extra steps.

https://newsroom.ucla.edu/releases/ucla-nrg-cosia-carbon-xprize-concrete

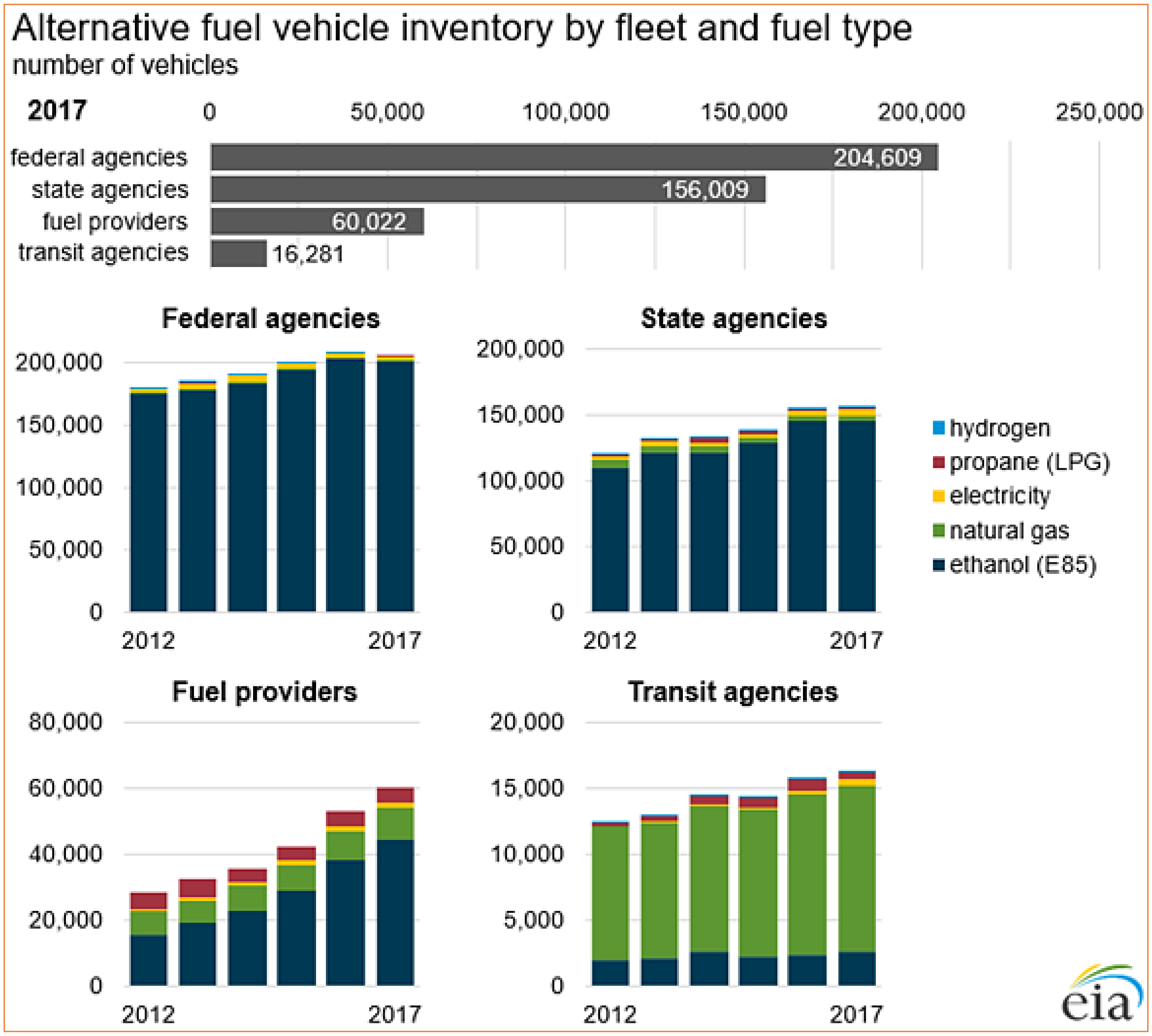
c. U.S. and State Government Guaranteed Purchase Agreements: Value and Need

The Federal government is the single largest consumer in the world, spending more than $550 billion on products and services each year. And, of course, Federal procurement procedures are very demanding to ensure cost competitiveness and fairness in the process. Included within Federal procurement guidelines is the Environmentally Preferable Program (EPP), designed to help Federal agencies purchase greener products and use its spending power to support these efforts. Several Federal and state requirements and incentives are in effect for the production, sale and use of ethanol, biodiesel and other fuels made from biomass. The Federal Energy Independence and Security Act of 2007 requires that 36 billion gallons of biofuels be used in the U.S. each year by 2022. In addition, several states have their own renewable fuel standards or requirements.

The State and Alternative Fuel Provider Fleet Program is a good example of public procurement practices, requiring covered fleets to acquire alternative fuel vehicles (AFVs) as a percentage of their annual light-duty vehicle acquisitions or to employ other petroleum-reduction methods in lieu of acquiring AFVs. EPAct 1992 – as amended by other key Federal statutes – directed DOE to regulate and guide State and Alternative Fuel Provider Fleets and Federal fleets. DOE also created Clean Cities to provide informational, technical and financial resources to EPAct-regulated fleets and voluntary adopters of alternative fuels and vehicles. EPAct authorizes DOE to add fuels to the list of EPAct-defined alternative fuels by making a final rule after a petition process. Petitioners must demonstrate fuel composition, environmental and energy security benefits before DOE will undertake a rulemaking. The State and Alternative Fuel Provider Fleet Program compiles annual reports that show how covered fleets meet their EPAct 1992 annual requirements for each model year. Figure 4G shows annual reported data from 2012-2017.

Similar procurement policies could be enacted for Federal and state procurement for products and minerals derived from U.S. coal. The availability of domestic production capabilities for critical defense technologies is an essential element of national security.

Figure 4G. EPAct 1992 Annual Report Data from 2012-2017



Source: U.S. Energy Information Administration

The Department of the Assistant Secretary of Defense (DASD) Office of Manufacturing Industrial Base Policy (MIBP) Defense Production Act (DPA) Title III Program Office[145] is designed to create, maintain, modernize, protect, expand or restore industrial capabilities required for national defense using the powerful DPA Title III authorities. A key objective of the Title III Program is to accelerate the transition of technologies from research and development to affordable production and insertion into defense and other government systems. To create the needed industrial capacity, Title III authorities provide the use of financial incentives in the form of purchases, purchase commitments, the purchase or lease of advanced manufacturing equipment for installation in government or privately owned facilities, the development of substitutes, and loans or loan guarantees. Title III activities strengthen the economic and technological competitiveness of the U.S. defense industrial base and can reduce U.S. dependency on foreign sources of supply for critical materials and technologies.

Coal Core Composite Building and Infrastructure Products
Made from the Single Batch Composite (SBC) Process

A demonstration project to build an **entire Coal Building** out of coal-derived materials is currently underway in Bluefield, West Virginia. Coal-derived building materials that will be used in this exhibit include roof tiles, bricks, building blocks, panels, facades, building columns and architectural structural components. The plan is to use the Coal Building demonstration project to prove the feasibility and practicality of using coal-derived building materials. Coal-derived building products that successfully meet performance, customer and financial metrics will be advanced into the marketplace.

The Single Batch Composite (SBC) process uses whole particles of raw coal coated with polymer-derived ceramic resins to produce lightweight, high strength ceramic composites. Typically, these products are produced using 55-70 % coal by mass with comparable dimensions to commercially available products. Most importantly, the carbon in coal is sequestered by the SBC process allowing for an environmentally, sustainable product. Surprisingly, building products derived from coal core composites are fire-resistant, because the coal particles have now been transformed into an inert ceramic composite. Some of the characteristics of improvement include: superior mechanical strength (*three to five times stronger*), significant weight savings (*20% to 50% lower density*) and better insulating ability (*at least three times the R-value*) in some form factors. Other important properties are improved mechanical durability, abrasion resistance and high resistance to chemicals such as acids, salts and dilute caustics in water.

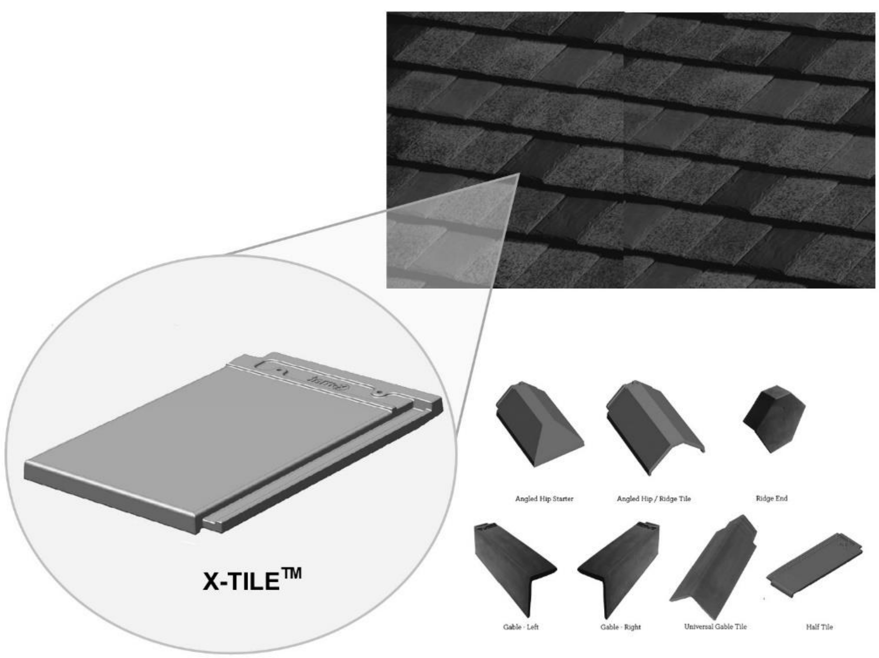
Recent developments have produced a path to use coal core composite particles without curing in a furnace as the final manufacturing step. This allows the processing of components at room temperature, such as in the making of concrete. Coal-core composite aggregates, which can be sustainably recycled from scrap coal core composite building materials, will make high strength concrete when mixed with cement. This lightweight, high strength coal-derived concrete will be used as both the building foundation and the structural cast beams of the Coal Building.

The use of coal-core composite aggregates in concrete opens up a large market for high performance concrete applications. The coal-ceramic aggregate properties of high strength and lighter weight will be translated into the properties of the concrete. High performance concrete requires properties such as those noted earlier, including improved mechanical durability, abrasion resistance and high resistance to chemicals. These high-performance properties offer significant improvements over conventional bricks, structural concrete block and concrete pavers, and precast/poured concrete.

Semplastics

The SBC process and coal building are being deployed by Semplastics - https://semplastics.com/

Coal Building



Coal-Derived Roof Tiles

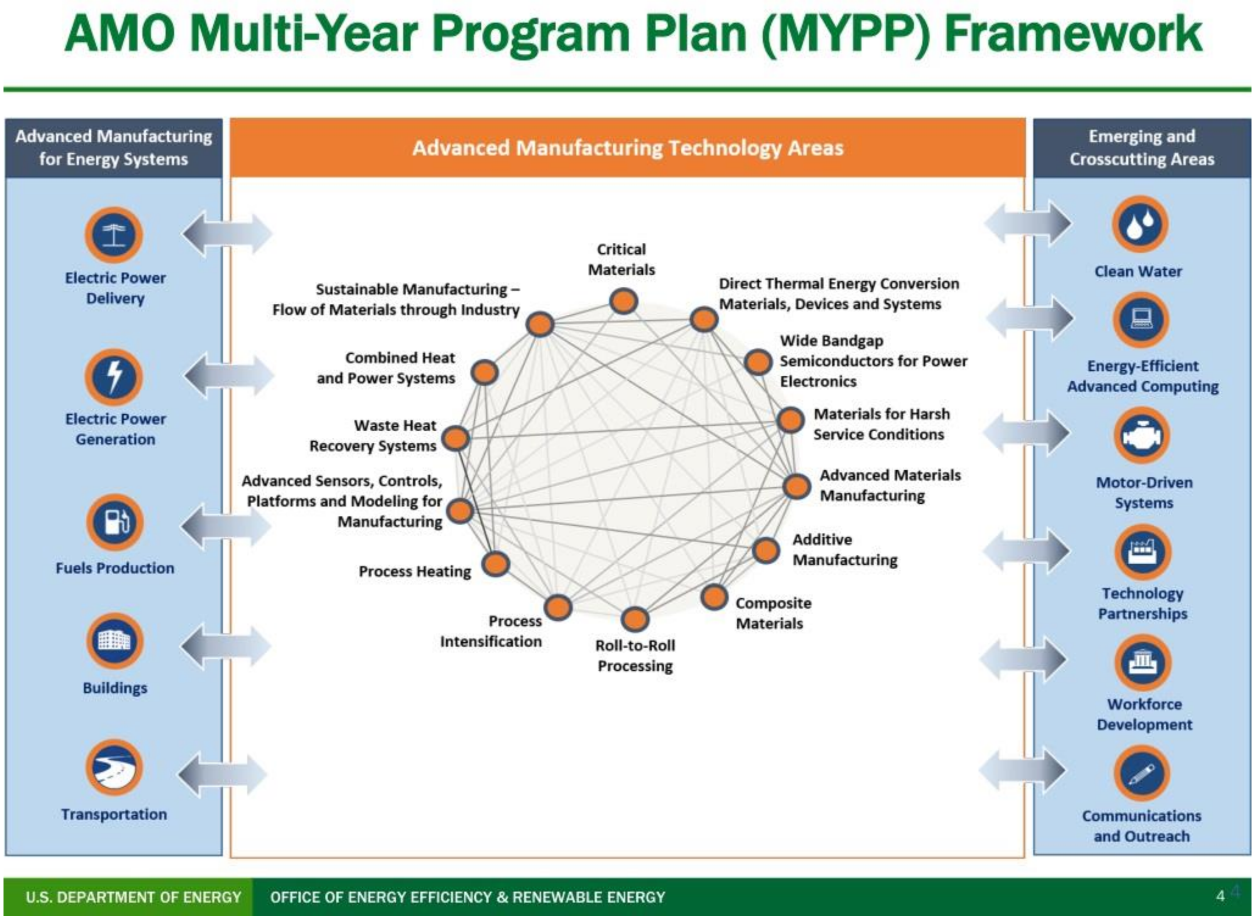
d. Advanced Manufacturing for Coal-to-Products: Enablers and Opportunities

The American Industrial Revolution of the late 18th-early 19th centuries transformed our nation's economy and the daily lives of our citizens. Technological innovations fostered advancements in communications, transportation and industrial production. Today, the U.S. is poised to assume a leadership role in advanced manufacturing processes and production of advanced materials. These processes, technologies and products will support national objectives for economic prosperity and environmental protection, while bolstering our national security through a robust domestic supply chain.

Numerous government agencies are engaged in developing and using innovative technologies to more efficiently produce existing products or to create new products.

The U.S. Department of Energy's (DOE) Advanced Manufacturing Office (AMO),[146] a division of the Office of Energy Efficiency & Renewable Energy (EERE), supports R&D projects/consortia, as well as early-stage technical partnerships with national labs, for-profit and non-profit organizations, state and local governments and universities. AMO's objective is to enhance the efficiency of the U.S. manufacturing sector through improvements in energy productivity, efficient utilization of abundant and available domestic energy resources, and support for manufacturing of clean energy products. These AMO objectives are an obvious fit with the various coal-derived products addressed in this NCC report, which details how enlisting advanced manufacturing techniques can be used to enhance the efficiency, cost and environmental benefits associated with the manufacturing of these products. Figure 4H shows the various advanced manufacturing technology areas that are the focus of AMO.

Figure 4H. AMO and Advanced Manufacturing



Source: Advanced Manufacturing Office, DOE Office of Energy Efficiency and Renewable Energy

The National Science & Technology Council (NSTC),[147] the Executive Branch entity that coordinates science and technology policy across diverse Federal research and development (R&D) enterprises, has established a Subcommittee on Advanced Manufacturing responsible for planning and coordinating Federal programs and activities in advanced manufacturing R&D and developing a quadrennial national strategic plan for advanced manufacturing. In October 2018, the Subcommittee issued a "Strategy for American Leadership in Advanced Manufacturing,"[148] detailing three key goals:

- Develop and Transition New Manufacturing Technologies
- Educate, Train and Connect the Manufacturing Workforce
- Expand the Capabilities of the Domestic Manufacturing Supply Chain

In its report, the Subcommittee highlighted the critical role manufacturing plays in supporting the U.S. economy and national security. Advanced manufacturing, defined in the report as including both new manufacturing methods and production of new products enabled by innovation, was cited as providing opportunities to increase productivity, enable new products, establish new industries, and create new, higher-paying jobs. As described throughout this report, coal to products, enabled by advanced manufacturing, can fulfill these goals while creating good jobs in the coal communities hit hardest by the ongoing energy transition.

In addition to government agency efforts, various organizations are also engaged in advancing markets for advanced manufacturing techniques and materials. The Institute for Advanced Compositive Manufacturing Innovation (IACMI),[149] for example, is pursuing opportunities to create new mass markets for low-cost, high-modulus carbon fibers derived from coal. IACMI notes that these composites may offer significant cost savings for composite applications requiring high stiffness and low-to-moderate strength and strain capacity, such as those in high-volume vehicle, infrastructure and electronic industries.

e. Model Initiatives in Advanced Manufacturing Deployment and Funding

Coal-derived carbon products will contribute significantly to the future of advanced manufacturing in the U.S. and support efforts to address global supply chain challenges. Following are examples of programs and partnerships in support of advanced manufacturing that could serve as models to enhance commercialization of coal-to-products.

National Science Foundation - The Advanced Manufacturing (AM) program at the National Science Foundation (NSF) supports the fundamental research needed to revitalize American manufacturing in an effort to enhance national security and economic prosperity, expand our advanced manufacturing workforce, and reshape our strategic industries. The AM program accelerates advances in manufacturing technologies with an emphasis on multidisciplinary research that fundamentally alters and transforms manufacturing capabilities, methods and practices.

NSF has funded groundbreaking discoveries such as nanomaterials, computer-aided design and 3D printing. The Foundation provides grant opportunities for academic liaison with industry, stimulating collaboration between academic research institutions and industry. NSF-industry partnerships are aimed at more quickly moving products to market through innovative manufacturing processes and systems. Finally, NSF invests in strategic educational programs to expand and nurture the advanced manufacturing workforce, such as the Advanced Technological Education program and the Manufacturing USA Network for Manufacturing Innovation.

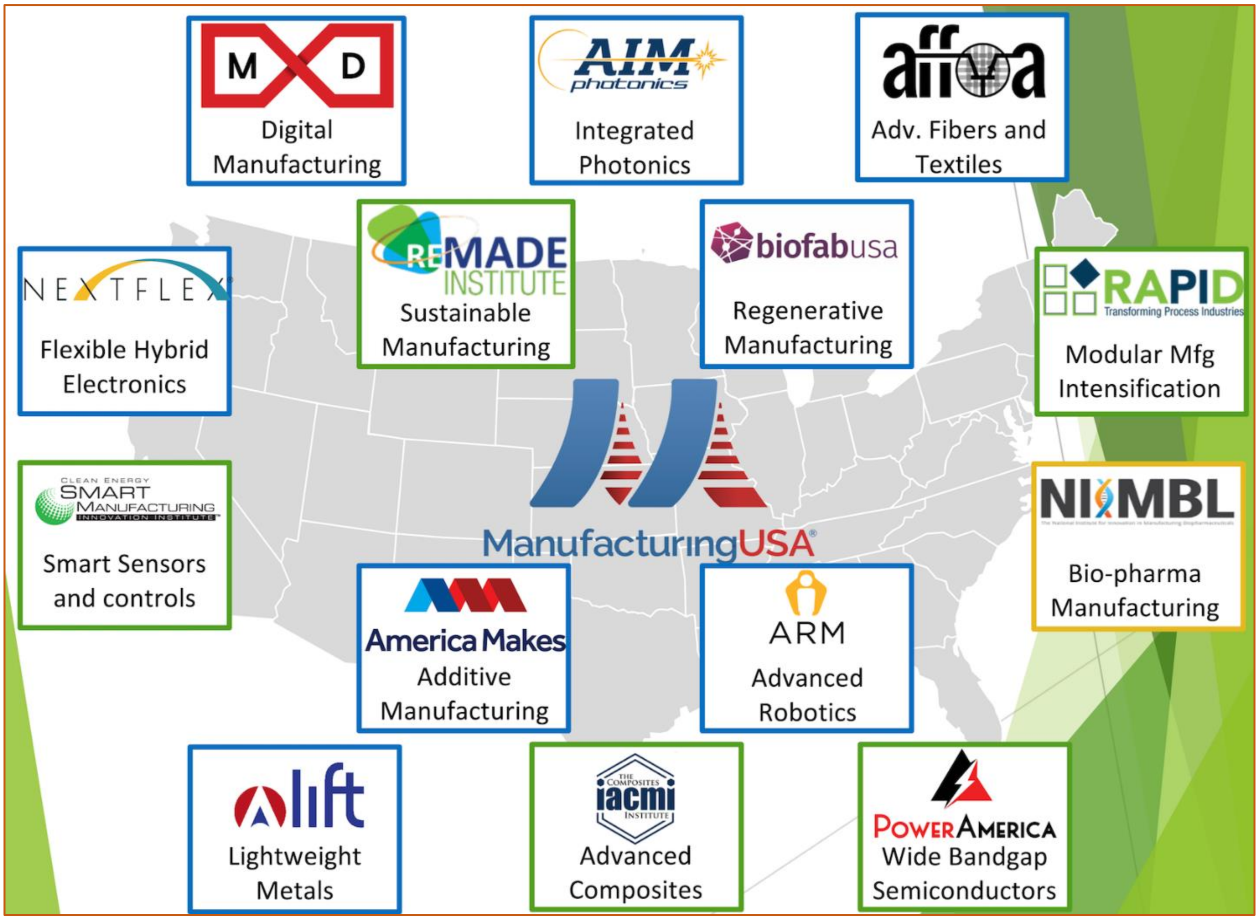
Advanced Technological Education Program
https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5464
Manufacturing USA Network for Manufacturing Innovation
https://www.manufacturing.gov/glossary/national-network-manufacturing-innovation
National Science Foundation
www.nsf.gov/; https://www.nsf.gov/about/congress/factsheets.jsp

National Institute of Standards and Technology - The National Institute of Standards and Technology (NIST) is part of the U.S. Department of Commerce. The NIST Office of Advanced Manufacturing (OAM) manages outreach in the area of advanced manufacturing, including providing Federal financial assistance through programs such as AMTech and the Manufacturing USA Institutes. The OAM also serves as headquarters for the interagency Advanced Manufacturing National Program Office (AMNPO), staffed by representatives from Federal agencies with manufacturing-related missions as well as fellows from manufacturing companies and universities. AMNPO staff work in close partnership with advanced manufacturing offices in the Department of Defense, the Department of Energy, NASA, the National Science Foundation, the Department of Education and the Department of Agriculture.

In 2016, NIST issued the first competition to establish new Manufacturing USA Institutes. Like the other institutes that are part of the Manufacturing USA network, the NIST institutes are private-public partnerships that foster collaboration among industry, academia, nonprofits and government agencies. Through the Institutes, stakeholders work to accelerate U.S. innovation and to increase U.S. competitiveness by investing in industrially relevant, cross-cutting advanced manufacturing products and resources. As noted in Figure 4I, Manufacturing USA consists of a national network of linked manufacturing institutes. Each has a unique technological concentration, but is also designed to accelerate U.S. advanced manufacturing as a whole.

National Institute of Standards and Technology - https://www.nist.gov/
NIST Office of Advanced Manufacturing - https://www.nist.gov/oam
NIST Advanced Manufacturing Technology Consortia – AMTech Program -
https://www.nist.gov/oam/programs/advanced-manufacturing-technology-consortia-amtech-program
Manufacturing USA - https://www.manufacturingusa.com/

Figure 4I. Manufacturing USA Institutes



Source: NIST Manufacturing USA Highlights Report, December 2020

Advanced Materials Future Preparedness Taskforce – The Advanced Material Future Preparedness Taskforce (AMPT) is an international public-benefit initiative focused on using Advanced and Frontier[v] Materials to help solve some of humanity's most pressing challenges. Initially formed in response to addressing issues associated with the COVID-19 pandemic, AMPT is designed as an international multi-disciplinary platform that is building a global infrastructure and ecosystem network that enables the advanced materials community to respond swiftly and effectively to global challenges when a need arises.

[v] The term "Frontier Materials" was adopted and gained use by AMPT in 2020 to introduce a class of materials distinguished from the classical and much broader term "advanced materials."

Founded in 2020, the global alliance currently includes 15 country chapters and 8 working groups. AMPT is developing a library of knowledge and a network of advanced materials resources and expertise that will provide a pathway for collaboration, knowledge and resource sharing, facilitating interdisciplinary research and commercial development of advanced materials in service of global needs.

Advanced Materials Future Preparedness Taskforce - https://www.amptnetwork.com/

Horizon 2020

Horizon 2020 is the largest European Union (EU) Research and Innovation program ever, with nearly €80 billion (about $100 billion) of funding available over 7 years (2014 to 2020). It was an initiative aimed at securing Europe's global competitiveness and intended to drive economic growth and create jobs. In establishing this program, Europe's leaders agreed that research is a fundamental investment in a smart and sustainable future and a requirement for economic growth and jobs. The long-term goal was to ensure Europe's ability to:

- produce world-class science
- remove barriers to innovation, and
- make it easier for the public and private sectors to work together in delivering innovation.

Technology innovations often face difficulties in accessing financing for new ideas or continued development. Horizon 2020 helped to fill this "innovation gap" (see Figure 4C: Technology Development Funding Gap) through loans and guarantees, and by investing in innovative companies. This support provides companies with the ability to attract private finance and venture capital for research and innovation. The EU has estimated that every €1 invested generated €5 in additional financing.[150]

One Horizon 2020 project is illustrative of the value of this initiative. The "3D" project (for DMX™ Demonstration in Dunkirk[151]) brings together 10 partners from research and industry from 6 European countries. The project, which aims to demonstrate an innovative process for capturing CO_2 from industrial activities, has a €19.3 million budget over 4 years, including €14.8 million in European Union subsidies. The objectives are:

- Demonstrate the effectiveness of the DMX process on an industrial CO_2 emission source. The pilot will be able to capture 0.5 metric tons of CO_2/hour from steelmaking gases by 2021. The DMX process uses an innovative solvent that reduces the energy consumption for CO_2 capture by nearly 35% compared to the reference process.

- Prepare the implementation of a first industrial unit that could be operational starting in 2025 and will be able to capture more than 125 metric tons of CO_2/hour (more than one million metric tons of CO_2/year).

The project will validate a solution for industrial deployment of CO_2 capture and storage technology around the world. It will enable industries with high-energy consumption and CO_2 emissions, such as the steel industry, to reduce emissions, and provide a technology solution for meeting the targets of the Paris Agreement on global warming.

Horizon 2020 - https://ec.europa.eu/programmes/horizon2020/
Enabling Technologies
https://ec.europa.eu/programmes/horizon2020//en/area/key-enabling-technologies

Additive Manufacturing Coalition

The Additive Manufacturing Coalition is a national organization dedicated to helping its members navigate funding and legislative challenges confronting those involved in the additive manufacturing sector. Additive manufacturing is a "3D printing" process which involves the use of various metals, plastics and composite materials to produce parts and products for industries such as aerospace, automotive, machinery, medical and sports, to name a few.

Among the key issue areas being addressed by the Coalition:

- Research Funding
- Additive Manufacturing Policies
- Workforce Development
- Standards
- Federal Acquisition Rules
- Policy Maker Education

Additive Manufacturing Coalition - https://www.addmfgcoalition.org/

Wyoming's Emerging Carbon Valley

The State of Wyoming is a leader in initiatives designed to advance the research, development and deployment of coal to carbon products. Various entities working within the state are creating a "Carbon Valley" akin to that of the high tech industry's Silicon Valley in Northern California. Wyoming is a logical choice for deployment of a Carbon Valley as it has the largest reserves of coal in the U.S. Among the many initiatives of note:

The Wyoming Innovation Center (WyIC) is an initiative of Wyoming's Energy Capital Economic Development (ECED) which is working to diversify and expand local economies within the state. A ground-breaking ceremony was hosted In June 2021 to launch the WyIC as a development facility for high-value, coal-based carbon processes and products. The $3.48 million Center offers businesses with coal-based technologies an open-access platform to host pre-commercial scale-up to foster the continued utilization of Wyoming coal. http://www.energycapitaled.com/about/services/

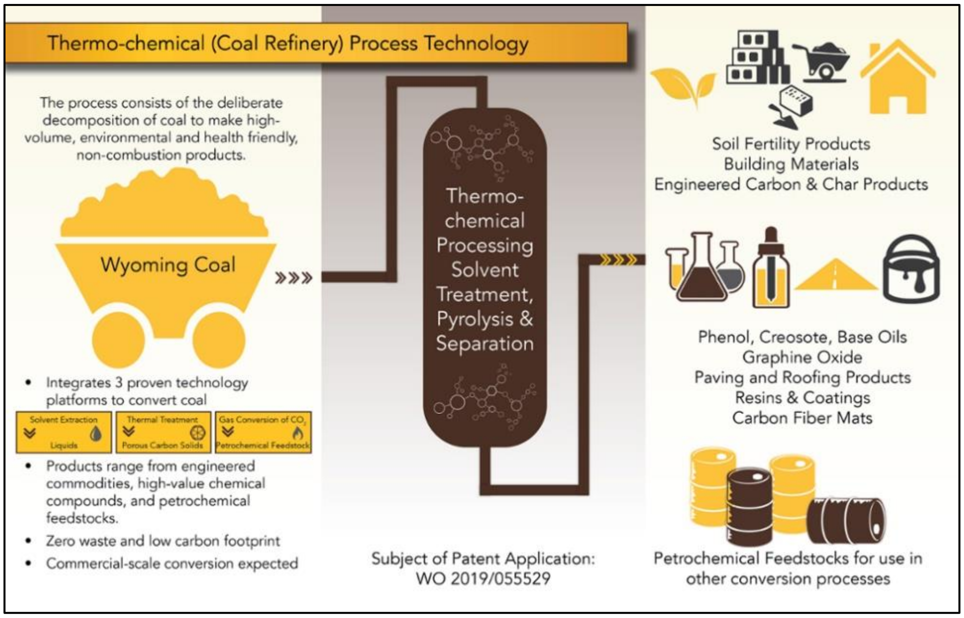
Ramaco Carbon is privately investing to create an ecosystem of innovation, building a vertically integrated carbon resource-based research, development and production facility in Sheridan, Wyoming. The company's vision is to advance the development of a coal to carbon products industry in Wyoming's Carbon Valley to support the efforts of researchers to commercialize their work. https://ramacocarbon.com/

Among the components of this vision:

iCAM – The iCAM (Innovating Carbon Advanced Materials) center will host research professionals from national laboratories, universities, private research groups and manufacturing organizations in laboratory, pilot-plant and permanent operating facilities. The facility will foster research that allows strategic manufacturing partners to conduct applied research and development with the goal of using carbon found in coal to create advanced manufactured products.

iPark – The iPark center is planned as a next generation mine-mouth coal to products manufacturing facility with zero net emissions. Operations at iPark will use coal from the adjacent Brook Mine to create high-value carbon products, including carbon fiber, graphene, graphite, carbon nanotubes, carbon dots, carbon-based resins, carbon-based building products, medical products and activated carbon.

The School of Energy Resources (SER) at the University of Wyoming (UW) was created in 2006 to enhance the University's energy-related education, research and outreach. SER directs and integrates cutting edge energy research and academic programs at UW and bridges academics and industry through targeted outreach programs. http://www.uwyo.edu/ser/



SER's Center for Carbon Capture and Conversion (CCCC) is engaged in developing novel, marketable products derived from coal and investing in carbon engineering processes and product technologies that consume large volumes of Wyoming coal. The initiative is designed to grow the demand for coal as a feedstock that can be converted into chemical and high-performance engineered products that have greater value than that of the Btu component of the coal itself.

The Wyoming Integrated Test Center (ITC), officially opened at the Dry Fork Station power plant in Gillette in 2018, provides space for researchers to test carbon capture, utilization and storage (CCUS) technologies. ITC allows for real world testing at an active power plant, helping to address concerns typically associated with being able to transfer technology from a lab to a plant. https://www.wyomingitc.org/

The ITC served as the testing site for CarbonBuilt, the April 2021 winner of the NRG COSIA Carbon XPRIZE. CarbonBuilt used the ITC to further develop its technology to reduce the carbon footprint of concrete by more than 50% by directly absorbing CO_2 into the concrete, reducing the amount of Portland cement needed to produce concrete.

Chapter V. Coal-Derived Markets Support Biden Administration Priorities

Since taking office in January 2021, the Biden Administration has advanced a number of initiatives geared toward advancing U.S. economic recovery, creating jobs, addressing global climate and environmental objectives, improving our infrastructure and securing our domestic supply chains of critical minerals and materials, including strategically important carbon materials. Fortunately, our nation's abundant coal resources and their potential for conversion to vital coal-to-carbon products, provide us with significant opportunities to advance each of these initiatives.

Job Creation:
How coal-derived products can support the Biden Administration's job creation efforts.

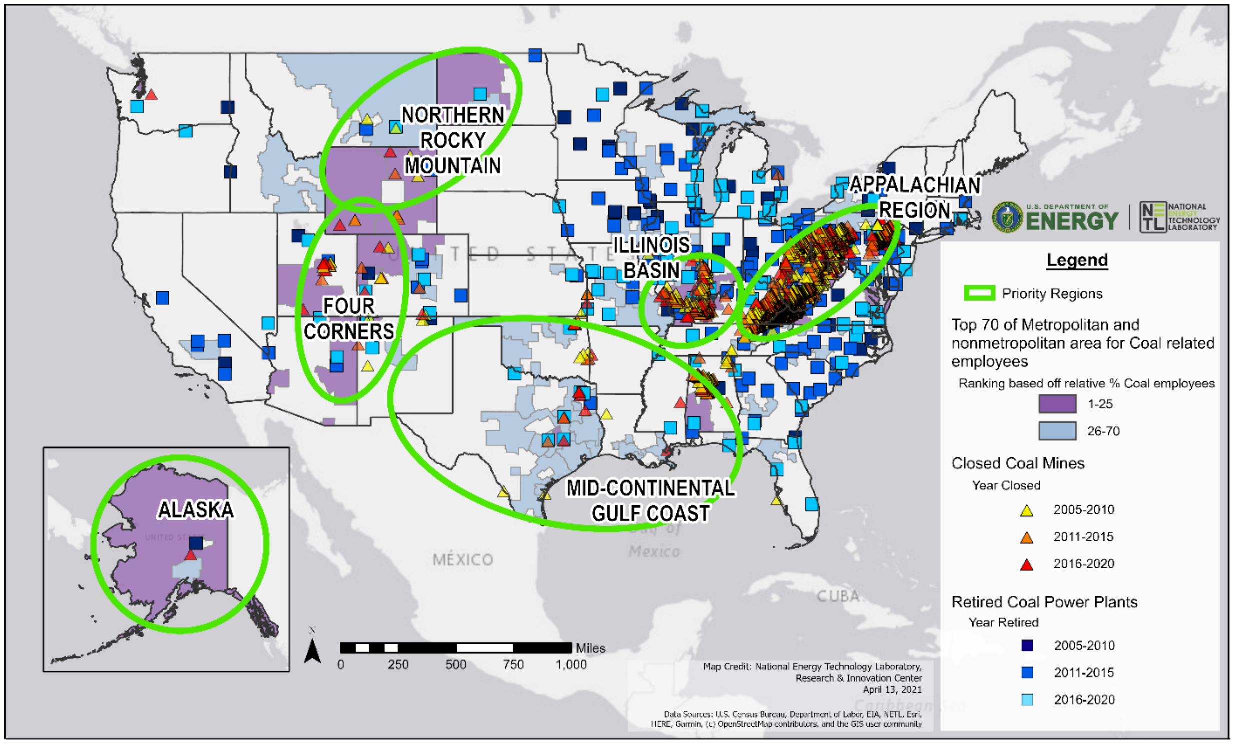
- The American Jobs Plan highlights the Administration's intent to revitalize manufacturing and small businesses and to train Americans for the jobs of the future. The rise of advanced manufacturing for the production of coal-derived products can create new job opportunities in markets with high-growth potential.

- The Jobs Plan also calls out the need to build next-generation industries in distressed communities, especially those impacted by the recent energy transition. Locating coal-to-products facilities in impacted coal mining and coal power generation communities will provide opportunities to train workers for careers in growth industries with attractive salary and benefit potential. It will also afford these workers an opportunity to remain in their established local communities.

- An investment of $20 billion in regional innovation hubs is called for in the American Jobs plan, with plans for at least ten hubs to leverage private investment in technology development and create new businesses in regions beyond the current handful of high-growth centers. The deployment of coal-to-products industrial hubs can provide an opportunity to advance new technologies and create jobs in regional/rural communities.

- In January 2021, President Biden signed Executive Order 14008 establishing the White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization designed to catalyze economic revitalization, create jobs and support workers in energy communities, especially those impacted by the recent energy transition.[152] In April 2021, the Interagency Working Group released a report[153] with initial recommendations in support of these objectives, including investing in initiatives to strengthen manufacturing supply chains for critical goods, increasing access to capital for domestic manufacturers and investing in remediation/redevelopment of brownfield sites into new hubs of economic growth and job creation.

Figure 5A. Coal Mining & Power Plant Impacted Areas
Source: White House Interagency Working Group
on Coal & Power Plant Communities & Economic Revitalization



Investment for RD&D demonstration and commercialization projects using advanced manufacturing technologies to produce coal-derived high-value carbon products will support the revitalization of distressed communities in those areas targeted by the Biden Administration's IWG. (Figure 5A)

- The U.S. Department of Energy estimates that significant opportunities exist for preserving and creating new employment associated with these new markets for coal: coal mining employment could range from 17,500 to 47,500+ jobs; coal to carbon products employment coal could range from 280,000 to 480,000+ jobs. (Figure 5B)

Figure 5B. Potential Demand for New Coal Production & Employment Associated with Markets for Carbon Products

Carbon Product	Potential U.S. Coal Industry Requirements - 2050*		U.S. Product Value -2050 (Million $) *	Employment-2050 (Mfg.)*
	Coal Production (mmt)*	Coal Mining Employment*		
Activated Carbon	22	2,641	15,979	32,437
Carbon Anodes (incl. Aluminum, Li-Ion Battery Anodes)	35	4,257	31,289	63,476
Carbon Black	14.1	1,692	5,077	10,306
Graphite Electrodes/Needle Coke	12.5	1,502	41,315	83,869
Carbon Fiber (incl. CFRP, C-C composites, cement)	47.6	5,713	24,701	50,127
Carbon Nanomaterials (incl. cement)	12.1	1,457	14,125	28,300
Conductive Inks	0.001	1	264	500
Roofing Tile	2	243	7,192	14,500
Aggregate**	**100+**	**15,000+**	**TBD**	**100,000+**
Foam - Building Mat**	**100+**	**15,000+**	**TBD**	**100,000+**
Total Carbon Products	**145 to 345+**	**17,500 to 47,500+**	**139,000 +**	**280,000 to 480,000+**

* Values reported in 2050 represent a high coal penetration scenario in which carbon-based products made from coal penetrate 80 percent of the overall product market. Additionally, several products (e.g., anodes/electrodes, CF & graphene) represent high demand growth scenarios.

** Data from project estimates with technology developers for large commodity markets

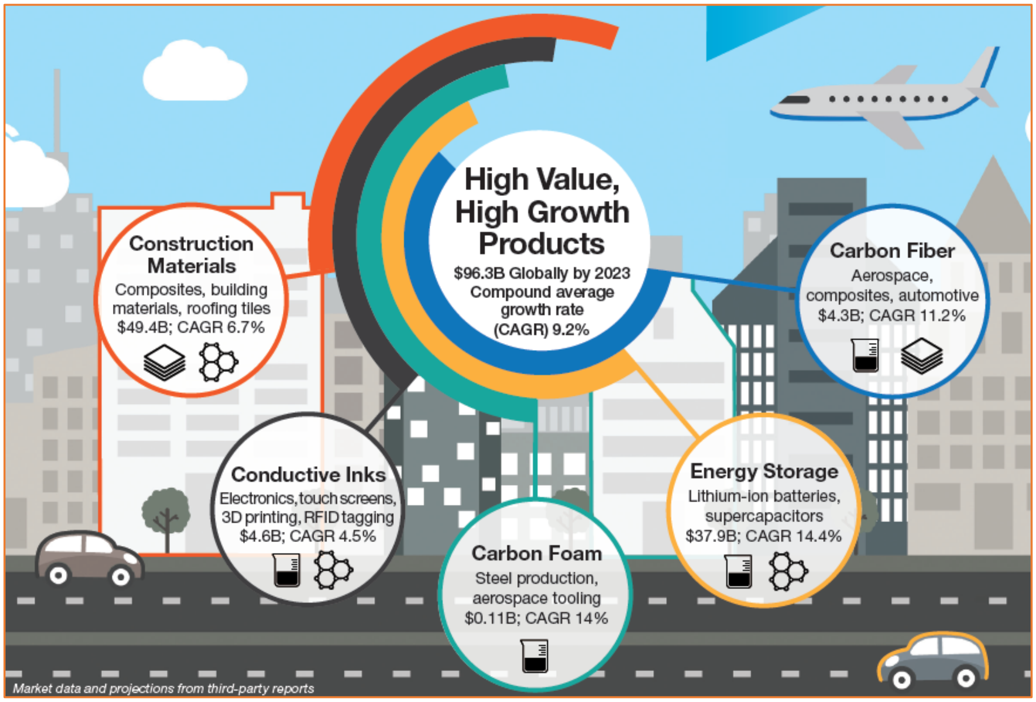
Source: U.S. Department of Energy/Office of Fossil Energy

Economic Revitalization: How coal-derived products can support the Biden Administration's economic recovery efforts.

- President Biden's "American Jobs Plan"[154] calls for investment in R&D and the technologies of the future, highlighting the need for public investment in breakthrough technologies to maintain our nation's economic edge in today's global economy. Enhanced investments in researchers, laboratories and universities, in partnership with the private sector, will support the carbon-based industries of the future.

- Emerging high-value carbon product markets have significant economic growth potential. As noted in Figure 5B, the National Energy Technology Laboratory projects that these products will have a global market value of over $96 billion by 2023 and a Compound Annual Growth Rate (CAGR) of 9.2%. (Figure 5C)

Figure 5C. Product & Application Market Potential of High-Value/High-Growth Products



Source: National Energy Technology Laboratory

- Recognizing the government's buying power and ability to be a first-mover in markets, the American Jobs Plan calls for jumpstarting clean energy manufacturing through Federal procurement. Advanced manufacturing of critical coal-derived products would support this Administration initiative and accelerate deployment of coal-to-products markets that have economic, environmental and national security benefits.

Environmental Stewardship:
How coal-derived products can support the Biden Administration's climate and environmental objectives.

- The Biden Administration's Jobs Plan identifies the need to deliver clean drinking water to all Americans. Coal-derived activated carbon provides a water purification product utilizing a widely available and abundant domestic product. Graphene membranes have proven to be effective in desalination of seawater to produce safe drinking water with less energy than reverse-osmosis.

- The Administration's objectives to electrify the automotive industry require the use of lithium-ion batteries and other engineering components that require the use of rare earth elements (REEs) and critical minerals (CMs). Recovery of REEs/CMs from coal and production of graphene-enhanced Li-ion batteries would enhance efforts to deploy electric vehicles, while also reducing our dependence on foreign sources for critical materials. Similarly, next generation energy storage technologies will require high purity coal-derived synthetic graphite and porous carbons.

- Light-weight carbon fibers and carbon-based composites used in the automotive, aerospace, energy, construction and consumer goods industries reduce end-use product energy consumption and emissions, i.e., light-weight cars use less fuel and emit fewer emissions.

- Many coal-derived carbon products require less energy to produce than products produced using conventional techniques. Advanced manufacturing holds promise for continued improvements in energy consumption, emissions and economic competitiveness.

Infrastructure Improvements:
How coal-derived products can support the Biden Administration's infrastructure improvement initiatives.

- The American Jobs Plan calls for investments to be made in both the construction and repair of U.S. roads, bridges, rail, ports, airports and transit systems. Many of the basic commodities and construction materials needed to shore up our nation's infrastructure can be produced from coal at less cost, with enhanced technical performance, extended use life and environmental advantages vis-à-vis traditional materials.

- Coal-derived carbon foam and single batch composite construction materials have enhanced fire-resistant and insulating qualities, greater mechanical strength, are lighter weight and require less energy to produce than comparable commercial products.

- Bricks and concrete blocks and pavers derived from coal are lighter, stronger, more flexible and more durable than conventional products.

- Coal tar pavement can be used to increase durability in asphalt applications, including road and highways. Coal-derived aggregates used in these applications could provide high-performance alternatives to traditional products while remediating waste coal or coal combustion residue impoundments. Reducing damage to roads and highways is an infrastructure concern of national importance.

- The use of graphene in concrete and asphalt can reduce the weight, increase the strength and increase the overall lifespan of roads and other critical infrastructure.

- The American Jobs Plan identifies the need to "reenergize America's power infrastructure," by creating a more resilient grid and "incentivizing more efficient use of existing infrastructure." Co-locating coal-to-products advanced manufacturing facilities with existing coal mining, transportation and power station infrastructure will provide a more streamlined and cost-effective opportunity to deploy new manufacturing plants while simultaneously incentivizing mine, transport and power station owners to invest in efficiency upgrades to their operations.

Supply Chain Resilience:
How coal-derived products can support the Biden Administration's efforts to shore up our nation's vital supply chains.

- The COVID pandemic highlighted many imbalances in our nation's supply chain that leave the U.S. vulnerable to supply disruptions and at a significant economic disadvantage. In February 2021, President Biden signed an Executive Order (E.O. 14017) "America's Supply Chains," directing the U.S. government "… to undertake a comprehensive review of critical U.S. supply chains to identify risks, address vulnerabilities and develop a strategy to promote resilience."[155] The E.O. specifically called on the U.S. Department of Energy (DOE) to identify risks in the supply chain for high-capacity batteries, including electric vehicle batteries. The E.O. also requested that the Secretary of Defense identify risks in the supply chain for critical minerals and other strategic materials, including rare earth elements.

  Supporting RD&D to recover REEs and CMs from coal and coal ash will enable us to reduce our dependence on foreign sources for these materials that are critical components of our automotive (electric vehicles), aerospace, defense, electronics and consumer goods industries.

- In response to the President's E.O., a White House report was released in June 2021 – Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth.[156] The report's recommendations from DOE included establishing government policies incentivizing every stage of the U.S. battery supply chain, including securing a domestic supply of critical materials for high-capacity lithium-ion batteries, i.e., nickel, lithium and cobalt. To promote sustainable domestic battery materials, DOE recommending catalyzing private capital with grants and loans, introducing supportive tax credits (e.g., a revitalized IRS 48C manufacturing tax credit and a revived and expanded Section 1603 of the American Recovery and Reinvestment Tax Act (ARRTA)) to support small manufacturers for batteries and associated materials suppliers.

DOE operates two loan programs – Energy Policy Act of 2005 (Public Law 109-58) and the Energy Independence and Security Act of 2007 (Public Law 110-140), which can support domestic production of critical minerals. Additionally, the Energy Policy Act of 2020 (Public Law 116-260) provides authorization for DOE to expand critical material R&D efforts to include demonstration and commercialization to support sustainable production and a technically skilled workforce.

- The June 2021 White House report included recommendations as well from the Department of Defense (DOD) to address national military and economic vulnerabilities associated with the supply of critical materials. DOD recommended expanding sustainable domestic production and processing capacity, including recovery from unconventional sources, i.e., coal, coal tailings and coal ash. DOD also highlighted the opportunity for the President to deploy the Defense Production Act (DPA) Title III authority to issue grants, loans, loan guarantees and other economic incentives to establish industrial capacity, subsidize markets and acquire materials, noting that any Federal agency responsible for critical infrastructure may request use of DPA to mitigate shortfalls to national defense. DOD notes that the use DPA has the potential to spark private sector investment and send a strong signal to market participants.

- President Biden's Jobs Plan calls for creation of a new office at the Department of Commerce (DOC) "dedicated to monitoring domestic industrial capacity and funding investments to support production of critical goods." Including initiatives to advance research, development and deployment of critical materials derived from coal within the purview of this new DOC office, in conjunction with the Department of Energy, would accelerate efforts to shore up supply chain capacity.

- The American Jobs Plan includes support for modernizing supply chains, including extending the 48C Advanced Manufacturing Tax Credit program.[157] Coal-derived product manufacturers that supply critical components to advance clean energy projects would benefit from inclusion in an expanded tax credit program of this nature.

- The U.S. currently remains dependent on petroleum and off-shore markets for feedstock and chemical sources for production of various products for the aerospace, automotive, defense, energy, environment, electronics, medical, agriculture and consumer goods markets, including carbon fiber and carbon fiber composites for the aerospace and automotive industries. Use of coal-derived carbon products can reduce the cost of producing these feedstocks and decrease U.S. dependence on foreign suppliers.

- The U.S. coal supply chain is well established and wide-ranging. Advanced manufacturing facilities for coal-derived products would benefit from established supply chains for coal production (mines located in 20+ states[158]), transport (rail, port, truck), and on-site storage (stockpiling distribution).

It is worth noting, that other nations are using coal-derived products to enhance their strategic supply chain resilience. In a recent report,[159] the International Energy Agency's (IEA) Clean Coal Centre noted that the coal to chemical sector in China is emerging as a major source of commodity chemicals as part of China's strategy for independence on chemical feedstocks. New plants for coal-based chemicals and fuels production have been constructed in Africa and Asia, partly associated with China's Belt and Road Initiative. Plans are also underway to develop coal gasification facilities in India to make chemicals and fuels and North Korea is reportedly developing a coal gasification industry to avoid oil import sanctions.

U.S. supply chain resilience will be enhanced by ensuring access to all domestic coal resources, including run-of-mine coal, coal ash and coal tailings. Restricting or extending preferential treatment for RD&D funding for any of these resources, e.g., waste coal, may limit available resources and impede efforts to enhance supply chain resilience for critical materials.

International Energy Agency
"Advances in Non-Energy Products from Coal"

INTERNATIONAL CENTRE FOR SUSTAINABLE CARBON

In June 2021, the International Energy Agency's (IEA) Clean Coal Centre[vi] published a report on "Advances in Non-Energy Products from Coal" authored by Dr. Ian Reid.[160]

In support of the United Nations' Sustainable Development Goals (SDG) to promote global prosperity while addressing climate and environmental challenges, the report noted the potential value of coal as a feedstock, highlighting ways in which coal-derived products could "positively affect society and more effectively use resources," including:

- An expanding population is exerting excessive demands on raw materials for construction. If these could be augmented by new coal-derived products there is an opportunity to enhance construction quality and reduce climate impact using an abundant resource.
- The relatively low production cost of coal offers a means to overcome cost barriers of new materials such as carbon fibre (CF) in auto transport. This is necessary for key aspects such as vehicle range, while high strength, lightweight CF is essential to the next generation of wind turbine blades for an important renewable energy sector.
- Minerals present in coal can be an alternative source of rare earth elements that are critical for a host of high technology industries, especially the manufacture of electric motors, and is currently subject to a near-monopoly in supply.
- Of carbon nanomaterials, graphene is the most patented and is rapidly being deployed into a host of novel commercial applications that cover batteries, concrete, inks, coatings, and electronics. Additional routes to graphene from coal are very encouraging and the quality of graphene derived from coal is sufficiently pure to create computer memory chips.
- Coal to hydrogen is already practiced in China within the chemical industry but, if selected as the primary product, may facilitate the formation of an affordable hydrogen-fuelled economy using lignite while awaiting lower cost electrolysis.
- A rising population requires more food, raising concern over the decline in global soil fertility. The adoption of lignite humate products in agriculture is currently modest but offers one of few long-term solutions to counter soil deterioration and more serious desertification.

Source: International Energy Agency, Clean Coal Centre, https://www.sustainable-carbon.org/report/advances-in-non-energy-products-from-coal-ccc-311/

[vi] IEA's Clean Coal Centre was renamed the International Centre for Sustainable Carbon in July 2021.

Chapter VI. Recommendations & Key Questions Addressed

Guiding Principles

The National Coal Council's (NCC) recommendations in support of advancing technology and markets for value-added products from coal are premised on the following guiding principles:

- The abundant coal resources located throughout the United States are a valuable and versatile asset that can be used as a raw material in the production of high-value products critical to our nation's economic, environmental and national security. The U.S. must make use of our national resources to ensure the resilience of domestic supply chains for critical materials.

- While the U.S. Department of Energy (DOE) has a vital role to play in supporting the accelerated deployment of coal-to-products technologies, an interagency effort will more quickly and efficiently advance commercialization of these vital products. Collaboration with the U.S. Departments of Commerce (DOC), Defense (DOD), Agriculture (USDA) and others can significantly enhance DOE's efforts.

- A national strategic objective in support of coal-derived products is necessary for commercial deployment. A national research development and deployment (RD&D) effort must support a full range of technologies and markets. While the recent focus on the vital need for domestic supplies of rare earth elements (REEs) and critical minerals (CMs) is warranted, other coal-derived high-value products are also critical to achieve our nation's economic, environmental and national security objectives and should also receive significant Federal investment.

- Advanced manufacturing techniques offer significant opportunities to enhance the economic, environmental and job creation potential of coal-derived products. These production and manufacturing pathways will increase U.S. competitiveness and facilitate technology transfer in many industrial sectors. Conventional production and manufacturing pathways will, however, continue to play a vital role for many valuable coal-derived products and should not be dismissed out of hand.

- Employing advanced manufacturing that is localized to source materials, customers and a trained workforce will support the most efficient and cost-effective manufacturing processes from ideation to commercialization.

- The quality of the coal input used to produce high-value coal-derived products will affect the quality and economic viability of the final product. While the use of coal from mine tailings in the production of some coal-derived products may be feasible and beneficial for cleaning up waste ponds, doing so may not be optimal for all applications in terms of carbon and mineral content, or given the associated cost of recovery. Extending preferential treatment for use of coal waste may jeopardize deployment of high-value coal-derived products, especially in the western U.S. where there are very limited mine tailings sites.

Key Recommendations

Job Creation

High-value carbon product markets have significant employment and job creation potential.

- Locate coal-to-products development and advanced manufacturing facilities in regional hubs that can maximize workforce employment and infrastructure at existing coal supply, power generation and transportation sites.
- Next generation industries can provide good-paying jobs, especially for those in distressed communities impacted by the recent energy transition.

Economic Revitalization

High-value carbon products markets have significant economic growth and cost-savings potential.

- Ensure adequate investment in a full range of coal-derived carbon products, including supporting demonstration projects, managed by personnel experienced in administering large-scale projects, to bridge the gap between research and commercial deployment.
- Establish appropriate guidelines, standards, certifications and validations to foster enhanced Federal procurement of coal-derived products.
- Harness the abundant, low cost and inherent carbon content of domestic coal resources to reduce the current high costs associated with carbon-based materials and products.

Environmental Stewardship

High-value carbon products can provide environmental benefits, supporting efforts to electrify the transportation fleet, reduce air emissions, provide clean drinking water and decrease energy consumption.

- Acknowledge the energy-saving, emissions-reduction and other environmental benefits of coal-derived products and incentivize inclusion of these products as a component of U.S. initiatives to reduce greenhouse gas (GHG) emissions.
- Emphasize the distinction between "carbon" dioxide (CO_2) emissions and "carbon" used to produce value-added products.

Infrastructure Improvement

High-value carbon building and construction materials can be produced at less cost, with enhanced technical performance and environmental advantages vis-à-vis traditional products.

- Recognize the superior, high-performance benefits of coal-derived products and incentivize inclusion of these products as a component of U.S. initiatives to improve the nation's infrastructure.

Supply Chain Resilience

Domestically sourced and produced high-value carbon products can shore up vulnerable supply chains and reduced U.S. dependence on foreign sources for critical materials.

- Incentivize the use of low-cost, abundant U.S. coal resources to produce high-value carbon materials to enhance supply chain resilience, including run-of-mine coal, coal ash and coal tailings.

Key Questions Addressed with Recommendations

As detailed in Chapter V, many of the Biden Administration's priorities for economic recovery, job creation, environmental stewardship, infrastructure improvement and supply chain enhancement can be advanced with deployment of coal-derived products, technologies and markets. In the Secretary of Energy's letter to the NCC requesting an assessment of opportunities to enhance the use of U.S. coal for new and expanded markets, four key questions were posed:

- What existing or prospective Federal and state policies would support alternative markets for coal?
- What RD&D investments are needed to support alternative markets for coal?
- What opportunities should be pursued among stakeholder groups in this sector to support alternative markets for coal?
- What strategic U.S. national interests are impacted by the development of coal-to-products and advanced materials?

NCC's recommendations are organized within the parameters of these key questions.

Federal & State Policies

Key Question: What existing or prospective Federal and state policies would support alternative markets for coal?

a. Initiatives to Advance RD&D

Opportunities exist to enhance initiatives in support of research, development and deployment (RD&D) to accelerate U.S. commercialization of coal-to-products technologies and markets. For example, Federal funding should include pre-competitive programs that support development across a wide range of coal-derived products focusing particularly on advanced manufacturing of high-value or nationally strategic materials.

Similarly, funding should support common user facilities to enable cost-effective partnerships for technology development with entities that can provide for broad access (this may be at national laboratories, universities or technology development centers). This initiative could be supported through the Biden Administration's American Jobs Plan[161] which proposes a $20 billion investment in regional innovation hubs to leverage private investment in technology development.

To maintain American leadership in science and technology, participation in Federal RD&D funding must be open to all participants. The U.S. Department of Energy's (DOE) cost-share policies currently limit participation in grant programs, and unnecessarily exclude researchers who might otherwise bring new ideas and technologies forward, such as small technology developers, universities and non-profits. Rather, broad participation should be encouraged in early-stage R&D, leaving it to the market to ultimately determine the value in supporting development once past early stage. Other Federal agencies have determined that cost share at early technology levels (TRL <= 4) are contrary to national interests and counterproductive.[162] DOE, and particularly the Office of Fossil Energy & Carbon Management, should fully remove this unnecessary cost-share burden on small technology developers, universities and non-profits, similar to existing rules for national laboratories.

Federal and state government should employ R&D tax credits at all levels to encourage continued private investment in new technologies. In particular, programs that reduce risk for investors would encourage capital availability for commercialization. For example, in response to President Biden's Executive Order 14017[163] addressing America's Supply Chains, DOE recommended incentivizing those engaged in U.S. battery supply chains. Revitalization of the section 48C Advanced Manufacturing Tax Credit and expanding section 1603 of the American Recovery and Reinvestment Tax Act (ARRTA) would support small manufacturers of batteries and associated materials suppliers. In general, extending the 48C Advanced Manufacturing Tax Credit program to include coal-derived product manufacturers could support U.S. efforts to shore up critical supply chain components.

Additionally, since many coal-derived products, such as cement and building materials, sequester CO_2, consideration should be given to extending the 45Q tax credit to these materials. Recently, the National Carbon Capture Center (NCCC), in conjunction with CarbonBuilt, announced that it had successfully injected CO_2 into 5,000 concrete blocks where it is now permanently bound.[164] The intent of the 45Q tax credit is to incentivize efforts to store CO_2. Extension of the credit to those coal-to-carbon products that effectively store CO_2 could accelerate their commercial deployment.

b. Initiatives to Minimize Cost and Risk

Federal and state governments can play an active role in reducing hurdles to technology development and technology acceptance through policies and programs that minimize risk and encourage capital flow to new projects and industries. These may include:

- Provide grants or loan guarantees for coal-to-product projects similar to other energy development projects to minimize capital risk.
- Establish floor pricing on rare earths and other critical minerals.

- Utilize U.S. Department of Defense (DOD) requirements for U.S. sourced materials which would aid in reducing demand volatility.
- Employ long-term contracting for U.S. materials which would contribute to market price stability.
- Jumpstart advanced manufacturing industries through Federal procurement initiatives that exert the government's buying power and first-mover market-maker capacities.
- Establish appropriate standards, certifications and validation practices to facilitate Federal procurement of coal-derived products. Establish Federal procurement guidelines for coal-derived products to enable them to qualify under the Environmental Protection Agency's Environmentally Preferable Purchasing Program.[165]
- 'Buy American' for infrastructure investments, such as roads, bridges, and Federal and state government buildings, utilizing coal-derived products.
- 'Buy American' for Federally supported green energy projects (e.g., wind or solar), including direct investments, indirect investments and loan guarantees, utilizing U.S. coal-derived products.
- Consideration should be given by relevant Federal entities to rebate Federal severance and/or use taxes for coal used in the manufacture of non-fuel products. State governments should consider economic incentives, including exclusion from or rebate of severance/use taxes, for coal used in the production of non-fuel products.
- Include coal-to-product plants within state high-tech incentive pools for economic development.
- Enhance efforts to strengthen and modernize manufacturing supply chains for critical goods through creation of Executive agency offices to monitor domestic industrial capacity and funding investments that support these efforts.

c. Initiatives to Support Economic Revitalization and Infrastructure Modernization

Initiatives to fund critical infrastructure investments in coal country should take into consideration opportunities to utilize coal-derived building and construction materials. The Department of Commerce's (DOC) Economic Development Administration (EDA) is managing the Assistance to Coal Communities (ACC)[166] initiative which provides grants to coal communities for a range of activities, including economic diversification, job creation, capital investment, workforce development and re-employment opportunities. DOC is revising its EDA investment priorities to promote projects that meet the needs of coal and power plant communities. Inter-agency collaboration between DOE and DOC would ensure support for use of coal-derived products and projects that would benefit impacted coal communities.

Coal-to-products industries can also play a role in advancing economic revitalization initiatives. The Appalachian Regional Commission's (ARC) Partnership for Opportunity and Workforce and Economic Revitalization (POWER)[167] initiative, for example, could benefit from collaborative efforts with businesses seeking to deploy coal-to-products projects. ARC's grants program supports Appalachian communities that have experienced job losses in coal mining, coal power plant closures and coal-related supply chain and logistics industries. The programs funding priorities include workforce development, entrepreneurship and industry clusters. The program could serve as a model for other regionally based initiatives in impacted coal communities seeking opportunities in next generation industries.

The Biden Administration's infrastructure modernization plans[168] address the need to rebuild bridges, highways, roads and main streets in need of critical repair while simultaneously improving air quality and limiting greenhouse gas (GHG) emissions. Plans also call for redevelopment of brownfield sites with the aim of turning idle real property into new hubs of economic growth. The Biden plan also calls for building next generation industries in distressed communities. The performance and environmental benefits associated with many coal-derived products as noted in Chapter I, could contribute significantly to these goals.

Designating shuttered and operating coal mines and coal power plants as economic revitalization zones for manufacturing centers would support the President's efforts to build next generation industries in distressed communities.

The American Jobs in Energy Manufacturing Act of 2021[169] co-sponsored by Senator Joe Manchin (D-WV) and Senator Debbie Stabenow (D-MI) lends Congressional support to this initiative. The Act would drive investment in clean energy manufacturing, recycling and industrial facilities, including the expansion or retooling of now-shuttered sites and furthers investment in economically impacted coal-producing and manufacturing areas.

These investment initiatives, in both the Administration's Jobs Plan and the Manchin-Stabenow Jobs in Manufacturing Act should be reinforced through the efforts of the White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization.[170]

d. Initiatives to Reduce Regulatory Burdens

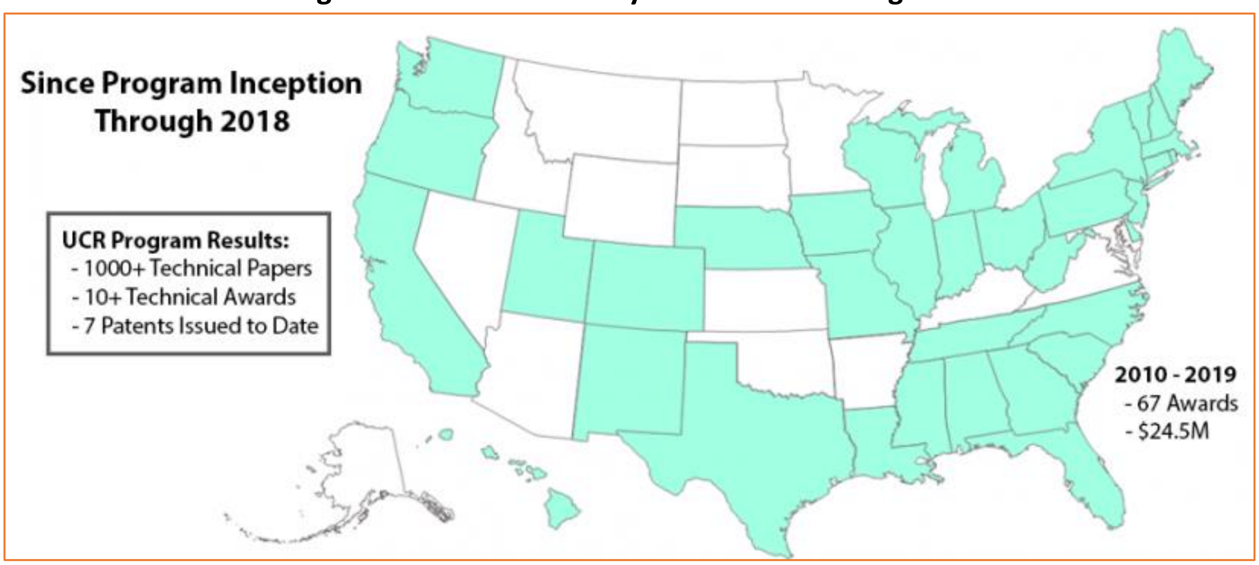
Providing expedited permitting for the use of former mining, preparation or processing facilities that will be used for coal to carbon products projects will support the Administration's economic revitalization and infrastructure modernization objectives noted above. These goals would also be supported by ensuring that Federal and state environmental standards are no more stringent on manufacturing processes using coal than for any other feedstocks (e.g., no separate carbon penalty).

e. Initiatives to Support Workforce Development and Public Acceptance

In addition to supporting the workforce development initiatives noted above in relation to economic revitalization and infrastructure modernization, efforts are needed to ensure availability of a workforce skilled in advancing manufacturing. A trained workforce will be essential to successfully achieve the future development and deployment of both coal-to-products and advanced manufacturing. This will require development of education and training programs geared to STEM-literate high school graduates and trained technologists most logically derived from industry specific programs within community and technical colleges. This will require support at both the Federal and state levels to be initiated, but should be self-sustaining into the future through support from the specific 'end users.'

At the technology development phase, it is imperative to support the education and training of the next generation of scientists and engineers who will develop the materials and processes of the future. Traditional single investigator grants and contracts from DOE can allow support and training of graduate and undergraduate students. An obvious vehicle for support in this area is the University Coal Research (UCR)[171] program (Figure 6A) which was launched by DOE in 1979. The UCR program has three objectives: 1) sustain a national university program of research in energy and environmental science and engineering related to coal through innovative and fundamental investigations pertinent to coal conversion and utilization, 2) maintain and upgrade the coal research capabilities and facilities of U.S. colleges and universities and 3) support the education and training of next generation scientists and engineers. The University Coal Research program should be expanded to include topics in the areas of coal to products and relevant advanced manufacturing technologies.

Figure 6A. DOE University Coal Research Program



Source: U.S. Department of Energy

Research, Development and Deployment Investments

Key Question: What RD&D investments are needed to support alternative markets for coal?

A national program of RD&D investments directed toward support of alternative markets for coal must necessarily range across the full spectrum of research, development and deployment if technologies are to transition from concept to commercialization.

In the 1990s and early 2000s, DOE had several programs investing in conversion of coal to value-added products, such as chemicals and materials. For example, Penn State and West Virginia University (WVU) led the U.S. DOE-funded Consortium for Premium Carbon Products from Coal[172] with a focus on various non-fuel uses of coal. However, these programs were short-lived and had relatively low funding levels. Over the last decade, Federal fossil energy related RD&D support has focused on carbon capture and storage and other approaches to decarbonization of fossil thermal plants. Only recently has that focus turned to "how else do we realize the value of coal?" This has resulted in several Funding Opportunity Announcements (FOAs) focused on coal-derived carbon products, primarily driven initially by the need for Rare Earth Elements and now the more inclusive topic of Critical Minerals in which "carbon ore" features prominently (DE-FOA-0002364).[173]

The "Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) Initiative for U.S. Basins" (DE-FOA-0002364) seeks to catalyze regional economic growth and job creation by realizing the "full potential value" of coal across basins throughout the U.S. It targets "the upstream and midstream critical minerals supply chain and downstream manufacturing of high-value, nonfuel, carbon-based products, to accelerate the realization of full potential for carbon ores and critical minerals within the U.S basins. U.S. coals and associated by-products and waste streams can be used as feedstocks for domestic production of REE and CM to enhance our national and economic security. They can also be used as sources of carbon for production of high-value, nonfuel, [carbon based products]."

While these new investments are a reasonable first step, further investments are needed if coal-to-products are to become a commercially competitive reality. Coal-to-products research must be supported on its own rather than as secondary products from REE programs. These necessary investments, in the context of this report, must include both advanced manufacturing technologies, fundamental coal science, product development and prototyping and de-risking of First of Their Kind (FOTK) demonstrations.

a. Research

Our ability to understand both the interactions that take place during coal conversion processes as well as the composition-structure-property relationships for the many varieties of coals have advanced considerably in the last 20 years. National labs and universities possess computational capabilities and analytical techniques today that were not available in the past. Both idealized and complex models for coal and its interactions in various systems can now be modeled at the molecular level allowing a more thorough understanding of both the processes and the possibilities offered by the diverse range of coals found in the U.S.

This is a key point when looking at needs for research funding: despite the long history of coal utilization, we have only now gained the abilities to study and predict its behavior and properties at the atomic and molecular level. Our ability to understand the 'materials genome' of coal can provide insight into how to use coal as an important materials resource.[174] Funding for such fundamental science is crucial to realize the full potential of coal as a feedstock for new, non-traditional uses (e.g., resins for additive manufacturing, electrochemical energy storage materials, new high strength fibers and composites, electronic components, etc.).

As noted throughout this report, many coal-to-products technologies will benefit from further research investments in fundamental science, including but not limited to:

- synthetic graphite and demineralization for energy storage
- high temperature materials
- process control and intensification
- molecular models and computational materials science

Adaptation of advanced manufacturing technologies into coal conversion and utilization processes also require continued support at the research stage. There have been frequent announcements of the use of coal to make novel materials,[175] but in most cases these have been at very small laboratory scale. While process intensification has been around for a long time, improvements continue to yield new benefits. Further research support, at an increased level, is required to transition these from novelty to scalable processes.

Areas for further advanced manufacturing investments may include but not be limited to:

- resins and inks for 3D printing
- development of high temperature printing techniques
- separations for carbon capture and hydrogen production
- controllable microstructure of coal-derived fibers (spinning technologies)
- lower cost resins for carbon-carbon components
- molecular self-assembly, graphene applications, carbon foams and X-ogels
- process control and intensification

As noted previously, the future R&D workforce in coal science and technology must also be trained, maintained and retained. With reduced investments over the last decades, few students, and therefore few graduates, have focused on coal utilization. One existing program into which increased funding could play a role in overcoming this shortfall is the University Coal Research Program referenced above. However, to be effective, the technology portfolio supported in the program will need to be expanded to include increased funding for coal-derived materials development as well as coal-focused computational materials development.

b. Development

Transitioning from laboratory to small and large pilot projects is often a stumbling block for many processes. While laboratory scale research has offered a range of possible new uses for coal, the step from there to a deployable technology is often underfunded. Universities and national labs are good at producing new ideas and converting them to research projects, but often struggle with funding for piloting these processes. Investments need to be made that allow flexible, multi-user facilities to be used for development across a wide range of scales at the pre-competitive stage. Such investments reduce risk, encourage collaboration and allow for rapid results while maximizing return on Federal investments.

An example of such a capability is the Carbon Fiber Technology Facility (CFTF) at Oak Ridge National Laboratory (ORNL). CFTF operates a complete fiber production line capable of producing up to 20 tons/yr of finished fiber. This facility is operated to support both ORNL R&D and that of industry and university partners, avoiding the unnecessary cost of duplicative facilities and providing the technically trained staff.

Such facilities require investments in the $10s of millions range and are prohibitive under many existing funding opportunities. An Office of Fossil Energy & Carbon Management program similar to the National Science Foundation's (NSF's) Mid-scale Research Infrastructure program (NSF 21-505)[176] could maintain national competitiveness in critical materials and coal-to-products research. The Mid-scale RI program brings together diverse disciplinary perspectives to support convergence research with the aim of providing NSF with an agile process to fund experimental research capabilities in the mid-scale range.

c. Deployment

Federal cost sharing or loan guarantees directed at reducing the risk of deployment of first of a kind plants could accelerate commercialization of coal-derived products significantly. Federal government support for demonstration projects would help bridge the "Development Valley of Death" between research (TRL/MRL 1-4) and commercial deployment (TRL 9-MRL 9-10).

Given the current mindset associated with coal utilization, capital markets may be hesitant to invest in this industry. Government support for demonstration projects would provide a level of reassurance for prospective financial investors. Additionally, as noted in Chapter V, Federal procurement activities can provide market stability and increase the attractiveness for capital flow into new projects.

Partnership Opportunities

Key Question: What opportunities should be pursued among stakeholder groups in this sector to support alternative markets for coal?

To fully develop and commercialize alternative markets for coal, a variety of stakeholder partnerships will be required, including DOE technology development and demonstration partnerships with academia, industry and national laboratories across the spectrum of fundamental and applied research to demonstrations and deployments. Similarly, public-private partnerships will be necessary to meet both the necessary financing and workforce needs of this nascent industry.

DOE's Office of Fossil Energy & Carbon Management and National Energy Technology Laboratory (NETL) can play a critical role by organizing stakeholder groups; funding pre-competitive research and technology demonstrations; providing access to unique user facilities within the Laboratory; and partnering to commercialize intellectual property developed at the Laboratory. DOE, through NETL, is positioned to most effectively work with a broad spectrum of stakeholders to develop common road maps to address technical or market gaps, identify possible partnering arrangements and foster precompetitive research consortia. Similarly, DOE can identify needs for major user facilities that would be common to the industry. This latter capability is especially needed to bring advanced manufacturing technologies into the coal products arena.

Included below is a brief summary of current activities being developed with NETL support, other partnering opportunities which DOE may consider in developing coal-derived carbon products and an illustrative example of key contributions DOE can make in developing new coal-to-products industries in economically depressed coal producing regions.

a. Partnership Models: Overview of Current NETL-Stakeholder Partnerships

Overseen by the National Energy Technology Laboratory, DOE's Office of Fossil Energy & Carbon Management manages a range of projects relating to coal products and processes with industry, university and national lab partners.[177] A number of these initiatives were highlighted in testimony provided by NETL's Director, Dr. Brian Anderson, before the Senate Energy and Natural Resources Committee in a hearing on Carbon Utilization in April 2021.[178]

Initiatives currently supported under DOE's Advanced Coal Processing program include (with number# of awards supported):

- Production of pitches from coal (isotropic and mesophase) #1
- Coal to fuels and co-products #1
- Graphene production #3
- Activated/porous carbons #1
- Coal to carbon fiber #3
- Coal-plastic composites #1
- Electrochemical energy storage utilizing coal or coal products #2
- Building materials from coal #4
- Carbon foams #1
- Conductive inks, fillers and coatings #2
- Coal combustion residues for construction materials #1
- Rare Earth Elements from combustion byproducts #2
- Rare Earth Elements from acid mine drainage #2
- Rare Earth Elements analytical tools #1

These represent a range of partnership models, including direct grants, Cooperative Research and Development Agreements (CRADA) and Field Work Proposals (FWP). While this is a cross-section of projects currently active, other opportunities are either under development or pending.

NETL has hosted a number of workshops and other stakeholder meetings, such as the CarbonX Summit[179] to discuss coal-to-products, however, these have not focused on advanced manufacturing aspects as addressed in this report. An obvious opportunity exists for DOE to further extend stakeholder engagement; stakeholder meetings not only bring together the coal-to-products community, but also connect this group with other DOE supported activities in advanced manufacturing. Such exchanges would offer an opportunity to shape NETL programs that would facilitate collaboration and technology development at the intersection of these areas through road map development or similar initiatives.

b. NETL Partnership Opportunities

NETL has the opportunity to continue to expand partnerships with industry, academia and other national laboratories for research on coal-to-products and development of enabling advanced manufacturing technologies. Current funding in this area is primarily on a per-project basis (with the exception of the Critical Materials Institute), and often limited in scope and funding.

Some consortia type arrangements do exist, but are underfunded for the number of partners involved, making it difficult to attract participants due to the relatively low probability of funding (an example being the University Coalition for Fossil Energy Research (UCFER)).[180] Development of industry-academia consortia more narrowly focused on coal-to-products (or a sub-set, such as carbon products), with sufficiently robust funding levels, could expand national capabilities and competitiveness, develop the requisite workforce and allow rapid transition of discoveries to industry.

Of particular concern when considering the opportunities offered by bringing advanced manufacturing technologies and methodologies to the uses of coal for high-value products is the perceived level of risk. In many cases, products would be competing in existing markets against established, relatively low-cost materials (such as building materials) or in niche applications of extraordinary value but low volumes (graphene). In either case, development and commercialization of products face the so called "valleys of death" in the transition from proof of concept to pilot process and from pilot to commercial scale (Figure 6B). For technology development, this is the point where traditionally small levels of grant support are insufficient for the leap to a scalable pilot process but too early in the development phase for commercial or venture investment. For commercialization, this is where the process is proven out at scale, but financing for full-scale production and roll-out is difficult to obtain.

In the first case, formation of large "hub" or consortia programs offer one approach to expanding NETL's role in this area. More directed efforts that are sufficiently resourced would allow for rapid development of technologies, particularly where a continuum of laboratory-to-commercial product are emphasized. In this way, NETL could take the lead in forming and guiding partnerships not only with NETL, but between early-stage ideas and companies capable of placing them into the market. Here also, as described above, NETL could take the lead in formation of user facilities which address the constraints of moving from laboratory to pilot either within NETL, other national laboratories, or academic or industrial host sites, avoiding substantial duplicative costs.

Figure 6B. Technology Commercialization Continuum

Source: Figure based information from U.S. Government Accountability Office

In the latter case, DOE could develop programs to reduce the burden of raising capital through guarantees or loans. In this case, NETL would play a crucial role in management and oversight. A partnership approach would position NETL to bring its considerable expertise in project management as a benefit to companies seeking to commercialize technology as well as serve as a conduit for identifying appropriate external partners or "match-making."

Most significantly, DOE and NETL have the opportunity to form partnerships with other Federal, state and local entities (e.g., Appalachian Regional Commission). As many areas have been devastated by the rapid decline in the demand for thermal coal, new industries based on uses of coal for production of carbon products could play a key role in offering new economic opportunities. These areas offer a workforce familiar with coal mining, handling and preparation, but would benefit from workforce development investments to transition workers into a trained advanced manufacturing base.

Similarly, joint investments between multiple Federal agencies, state governments and local entities to incent development in these areas would be a significant tool in seeing coal-to-products industries developing in these depressed areas. Here, NETL could play a direct role in facilitating development of incubator activities, providing technology development funding and development and licensing of its own intellectual property.

c. Partnership Example: Carbon Ore, Rare Earth and Critical Minerals Initiative (DE-FOA-0002364)

In April 2021, DOE's Office of Fossil Energy & Carbon Management announced 19 projects funded under the "Carbon Ore, Rare Earth and Critical Minerals Initiative for U.S. Basins" program.[181,vii] This program serves as a model for steps DOE can take to facilitate the development of a coal-to-products industry.

The required program elements provide a framework for the complex components DOE seeks to support in order to establish this new industry in economically depressed coal basin areas and could form the basis for future programs directed at uses of coal for production of high-value carbon products.

The program description includes a vision to "catalyze regional economic growth and job creation by realizing the full potential value of natural resources, such as coal, across basins throughout the U.S. It has been designed to address the upstream and midstream critical minerals supply chain and downstream manufacturing of high-value, nonfuel, carbon-based products, to accelerate the realization of full potential for carbon ores and critical minerals within the U.S basins." In this, DOE is able to leverage RD&D investments into drivers of economic growth with far reaching impacts on economically depressed coal producing regions.

[vii] See also Chapter IV.

Specific key element requirements more clearly illustrate the partnership approach DOE and NETL are taking within this proposed program:

- Funding to support infrastructure assessments and gap analysis
- Funding to support development of regional technology centers to provide a platform for product development, ***including advanced manufacturing capabilities***
- Outreach to stakeholders and identification of educational needs
- Formation of regional coalitions or consortia

Partnering activities already undertaken by DOE for this program:

- *Teaming Partner List*: DOE compiled a Teaming Partner List to "facilitate the formation of new project teams for this FOA. The teaming partner list allows organizations who may wish to participate on an application, but do not wish to apply as the Prime applicant to the FOA, to express their interest to potential applicants and to explore potential partners."
- *REE Researcher List*: DOE compiled and provided a list of researchers with relevant expertise in rare earth element aspects of the solicitation, serving the role as advisor and partner in developing successful programs.
- *NETL Resource Availability*: Included within the solicitation were details on the NETL Research and Innovation Center data sets on REEs, as well as information on expanding this data set through cooperative data sharing.

d. Interagency and Government-wide Opportunities

As noted in the Guiding Principles in the opening section of this chapter, collaboration between government agencies and international/national organizations will facilitate accelerated deployment of coal-derived technologies and markets. Chapter IV of this report provides an overview of a number of initiatives in support of advanced manufacturing and production of advanced materials, including:

- National Science Foundation (NSF) – Advanced Manufacturing Program
- National Institute of Standards and Technology (NIST) – Department of Commerce, Office of Advanced Manufacturing
- Advanced Materials Future Preparedness Taskforce (AMPT)
- European Union's Horizon 2020
- Additive Manufacturing Coalition

Chapter IV of this report also highlights additional opportunities for collaboration in support of advanced manufacturing and markets for coal-derived products, including:

- The White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization
- U.S. Department of Defense – Defense Production Act (DPA), Title III
- U.S. Department of Commerce – pending office to oversee funding of production of critical goods

Also of note are the collaborative efforts underway in the State of Wyoming to deploy a "Carbon Valley." State government, state university, local communities and industry are working together for the mutual benefit of all stakeholders. Their efforts serve as a model of collaboration.

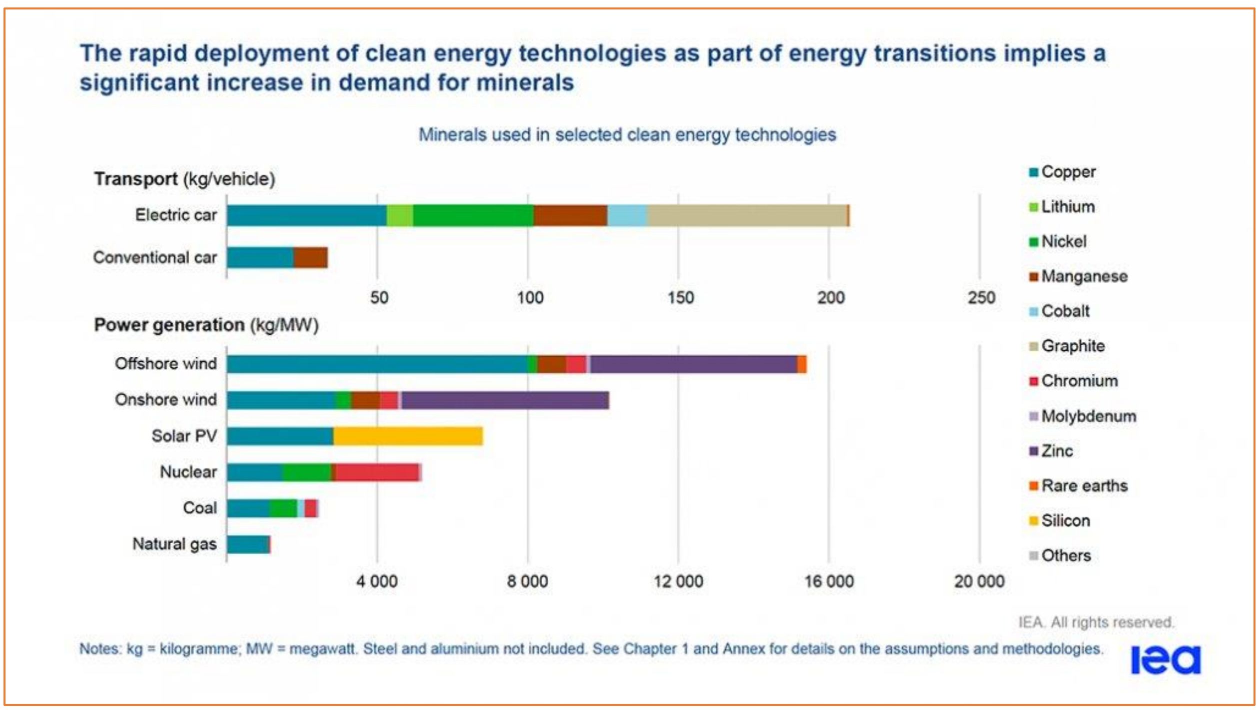
U.S. Strategic National Interests

Key Question: What strategic U.S. national interests are impacted by the development of coal-to-products and advanced materials?

The International Energy Agency (IEA) released a report in May 2021 on "The Role of Critical Minerals in Clean Energy Transitions,"[182] noting that:

> *An energy system powered by clean energy technologies differs from one fuelled by traditional hydrocarbon resources. Solar photovoltaic (PV) plants, wind farms and electric vehicles (EVs) generally require more minerals to build than their fossil fuel-based counterparts. A typical electric car requires six times the mineral inputs of a conventional car and an on onshore wind plant requires nine times more mineral resources than a gas-fired plant. [See Figure 6C] Since 2010 the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables in new investment has risen.*

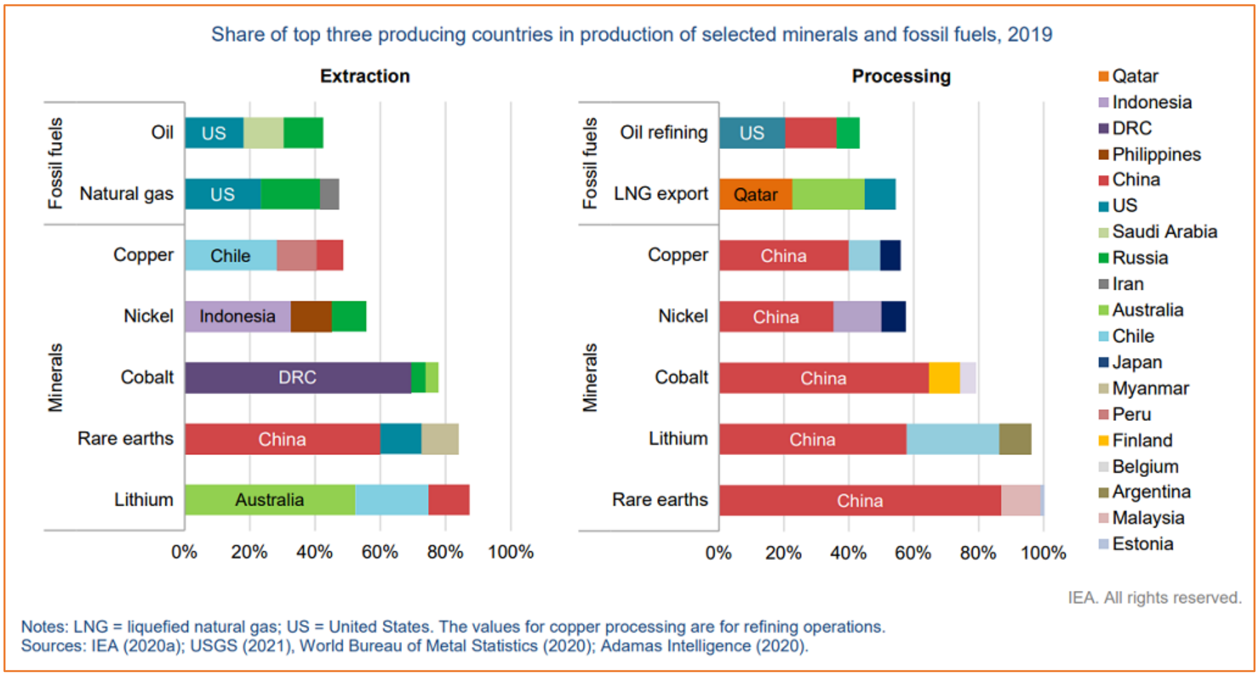
Figure 6C. Minerals Used in Transport Vehicles & Power Generation



Source: International Energy Agency

In its report, IEA warns that demand for critical minerals is poised to increase significantly over the next two decades, jeopardizing efforts to achieve decarbonization in the power generation and transportation sectors. A pending critical minerals supply shortage may not only delay or derail these low-carbon objectives, but could increase costs associated with doing so in addition to heightening geo-political destabilization as a result of the concentration of mineral production within select nations. (Figure 6D)

Figure 6D. Critical Minerals Extraction & Processing in Top Three Producing Countries



Source: International Energy Agency

In its response to President Biden's E.O. 14017 addressing America's Supply Chains, the DOD[183] highlighted the opportunity for the President to deploy the Defense Protection Act (DPA) Title III and issue grants, loans, loan guarantees and other economic incentives to enhance supplies of critical materials. To address military, economic and critical infrastructure vulnerabilities, any Federal agency, including DOE, may request DPA authority to spark private sector investment.

As noted in Chapter I of this report, the U.S. has significant national security concerns associated with its reliance on foreign sources for rare earth elements (REEs) and critical minerals (CMs). The U.S. possesses the world's largest supply of coal which can be used to produce a domestic supply of REEs and CMs, reducing our import dependence.

This foreign dependence also extends to petroleum and off-shore markets for platform chemicals and materials that have potential to be produced here in the U.S. from our nation's abundant coal resources. The U.S. is increasingly reliant on imports of carbon feedstocks necessary to produce defense, aerospace, automotive and consumer goods.

Locating coal-to-products technology and production/manufacturing facilities close to abundant coal supply and affordable power generation plants would support efforts to establish resilient supply chains and reduce costs and emissions. Shorter supply chains offer reduced energy and transportation costs with less GHG emissions. Shorter, less complex supply chains with fewer intermediaries also reduce potential for disruption.

Supply chain resiliency also requires investment in diversified sources of advanced materials. A number of bills have been introduced in Congress to promote the domestic exploration, R&D and processing of critical minerals:

- American Critical Mineral Independence Act of 2021 (H.R. 2637)[184]
- Securing America's Critical Minerals Supply Act (H.R. 1599)[185]
- Strategic Energy and Minerals Initiative Act of 2021 (S. 1537)[186]

These initiatives must include opportunities for sourcing and processing critical minerals from coal, coal ash and coal tailings as part of our nation's efforts for strategic diversification of supply chains. Funds authorized in the Energy Act of 2020, Title VII Critical Minerals[187] ($150 million for 2021-2026[188]) need to be expended by DOE to conduct R&D to develop and assess advanced separation techniques for extraction and recovery of REEs and CMs from coal and coal byproducts.

The U.S. Innovation and Competition Act (USICA – S. 1260)[189] - formerly The Endless Frontiers Act – would establish a Directorate for Technology and Innovation within the National Science Foundation (NSF). The legislation would require preparation of a strategy and report on economic security, science, research, innovation, manufacturing and job creation to establish a critical supply chain resiliency program. It would also establish regional technology hubs across the U.S. in key technology focus areas, including:

- Advanced Manufacturing
- Biotechnology and Medical Technology
- Advanced Energy, Batteries and Industry Efficiency
- Advanced Materials, including composites and 2D materials

As detailed in Chapter III of this report, many coal-derived products can be encompassed within these areas.

Finally, our nation's ability to meet the needs of a growing population are enhanced by the availability of fertile agricultural land, providing a measure of national security in feeding our citizens. Coal-derived fertilizers and humic soil additives can help counteract the effects of crop land deterioration, erosion and drought. In supporting enhanced agricultural production in other nations, these products additionally contribute to global stability. While the White Report on Building Resilient Supply Chains[190] did not include recommendations from the USDA, the report did address the need for the Department to engage with the Departments of Commerce and Transportation to address supply chain challenges associated with food supply and other critical commodities.

Chapter VII. Coal-to-Products/Advanced Manufacturing Roadmap

The recommendations included in this report can advance the Biden Administration's priority objectives to enhance job creation, economic revitalization, environmental stewardship, infrastructure improvements and supply chain resilience, utilizing one of our nation's greatest natural resources – coal.

In pursuit of these objectives, the National Coal Council recommends undertaking near-term initiatives within the next five years to lay a foundation for enhancing the use and deployment of critical coal-derived products and materials, enlisting advanced manufacturing techniques. Longer-term initiatives over the ensuing five to ten years will help ensure and accelerate the commercialization of coal-to-products and advanced manufacturing technologies.

The following near-term and longer-term initiatives,[viii] organized to align with the Administration's top priorities, include policies, business approaches and partnership opportunities that will require the participation of Federal and state governments, academia, non-profit organizations and industry. Working together, these entities can forge a path forward for markets and technologies for value-added products from coal that will enhance our nation's economic, environmental and national security interests.

[viii] Initiatives in the roadmap have been summarized; more detailed descriptions of these initiatives are included in the report, most notably in Chapter VI. Recommendations.

Near-Term Initiatives (within the next 5 years)
to Deploy Coal-Derived Value-Added Products in Support of:

Job Creation

- Locate coal-to-products development and advanced manufacturing facilities in regional hubs and economically distressed communities pursuant to $20 billion referenced in the American Jobs Plan.
- Provide inter-agency support for the Department of Commerce-Economic Development Administration's efforts to prioritize investments in projects that encourage economic diversification, job creation, capital investment, workforce development and re-employment opportunities.
- Extend grants through the Appalachian Regional Commission's (ARC) programs for coal-to-products initiatives that support workforce development, entrepreneurship and industry clusters. Employ the ARC program as a model for other regionally based initiatives.
- Designate shuttered and operating coal mine/power plant sites as economic revitalization zones for next generation industries.
- Support the American Jobs in Energy Manufacturing Act of 2021 (Manchin/Stabenow) and efforts of the White House Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization.

Economic Revitalization

- Extend Federal funding to include pre-competitive programs across a wide range of coal-derived products.
- Identify and fund Federal/state common-user facilities to enable cost-effective partnerships for technology development and commercial deployment.
- Eliminate cost-share policies that limit participation in grant programs and exclude potential researchers.
- Expand Funding Opportunities beyond rare earth elements/critical minerals to encompass other coal-derived value-added products.
- Expand fundamental research detailing the "materials genome" of coal and how it might be used as a critical materials resource.
- Host DOE/NETL workshops and other stakeholder meetings to secure input from and facilitate collaboration among Federal/state governments, academia, coal-to-products technology developers and advanced manufacturing stakeholders.

Environmental Stewardship

- Acknowledge the energy-saving, emissions-reduction and other environmental benefits of coal-derived products, emphasizing the distinction between "carbon" dioxide emissions and "carbon" used to produce value-added products.
- Incentivize inclusion of coal-derived products with CO_2 sequestion and reduced energy consumption capability as a component of U.S. initiatives to reduce greenhouse gas emissions.
- Extend the 45Q tax credit to those coal-derived products that sequester CO_2.
- Establish Federal procurement guidelines for coal-derived products to enable them to qualify under the Environmental Protection Agency's Environmentally Preferable Purchasing Program.
- Establish "Buy American" incentives for green energy and clean drinking water projects utilizing coal-derived products.
- Support the use of coal-derived soil amendments that do not add toxins, heavy metals or carcinogenic compounds to the soil.

Near-Term Initiatives (within the next 5 years)
to Deploy Coal-Derived Value-Added Products in Support of:

Infrastructure Improvements

- Recognize the superior, high-performance benefits of coal-derived products and incentivize use of these products as a component of U.S. infrastructure improvement efforts.
- Establish "Buy American" incentives for infrastructure investments utilizing coal-derived products with enhanced durability and strength.
- Secure Defense Protection Act authority for DOE under Title III to issue grants, loans, loan guarantees and other economic incentives to address critical infrastructure vulnerabilities.

Supply Chain Resilience

- Incentivize the use of domestic, abundant U.S. coal resources to produce high-value critical materials, reducing our nation's dependence on foreign sources.
- Secure Defense Protection Act authority for DOE under Title III to issue grants, loans, loan guarantees and other economic incentives to enhance supplies of critical materials.
- Execute President Biden's E.O. 14017 initiative to incentivize U.S. battery supply chain stakeholders, including coal-sourced rare earth elements and critical minerals essential for the production of electric vehicle and consumer goods batteries.
- Revitalize Section 48C Advanced Manufacturing Tax Credits and expend Section 1603 of the American Recovery and Reinvestment Tax Act (ARRTA) to support small manufacturers of batteries and associated materials suppliers.
- Extend the 48C Advanced Manufacturing Tax Credit program to include coal-derived product manufacturers.
- Utilize Department of Defense requirements for U.S. sourced materials.
- Support Congressional initiatives that promote domestic exploration, R&D and processing of critical minerals, including those derived from coal, coal ash and coal tailings, i.e., American Critical Mineral Independence Act of 2021 (H.R. 2637), the Securing America's Critical Minerals Supply Act (H.R. 1599) and the Strategic Energy and Minerals Initiative Act of 2021 (S. 1537).
- Support initiatives within the U.S. Innovation and Competition Act (S. 1260) to establish a Directorate for Technology and Innovation within the National Science Foundation and to develop a strategy to establish a critical supply chain resiliency program.
- In response to the White House Report on Building Resilient Supply Chains, DOE should collaborate with the Departments of Commerce and Transportation to address supply chain challenges associated with food supply.
- Enhance supply chain resilience by ensuring access to all domestic coal resources, including run-of-mine coal, coal ash and coal tailings.

Longer-Term Initiatives (within the next 5-10+ years)
to Deploy Coal-Derived Value-Added Products in Support of:

Job Creation

- Deploy Federal and state workforce education and training programs geared to STEM-literate high school graduates and trained technologists with skills essential to both coal-to-products and advanced manufacturing.
- Employ DOE investigator grants and contracts to support training of undergraduate and graduate science/engineering students with skills needed for technology development.
- Expand the University Coal Research program to include topics in the areas of coal-to-products and advanced manufacturing.

Economic Revitalization

- Fund demonstration projects, managed by personnel experienced in administering large-scale projects, to help bridge the "Development Valley of Death."
- Utilize Federal cost sharing and loan guarantees to help reduce the risk associated with deploying First-of-a-Kind plants.
- Offer Federal purchase agreements for coal-derived products, establishing appropriate guidelines, standards, certificates and validations to foster enhanced Federal procurement.
- Employ Federal and state tax credits to encourage private investment in new technologies.
- Extend the 48C Advanced Manufacturing Tax Credit program to include coal-derived product manufacturers to incentivize private sector investment.
- Exempt coal used for production of carbon products from severance or use taxes.
- Include coal-to-products manufacturing facilities within state high-tech incentive pools for economic development.
- Expedite Federal and state permitting of coal-derived product manufacturing facilities that support the Administration's economic revitalization and job creation objectives.
- Fund research support beyond laboratory scale for adaptation of advanced manufacturing technologies for coal conversion.
- Establish a DOE program similar to the National Science Foundation's Mid-scale Research Infrastructure program, focused on funding mid-scale capabilities to advance critical materials and coal-to-products.

Environmental Stewardship

- Utilize coal sourced from waste ponds/tailings when economically feasible and non-detrimental to end-product quality vis-a-vis use of run-of-the-mine coal.
- Pursue R&D related to utilization of coal for production of hydrogen as a carbon-free fuel for electricity generation and for vehicles.
- Pursue applications that combine coal feedstocks and renewable electricity to reduce CO_2 emissions from manufacturing and that can be deployed at the point of use, eliminating transportation costs and associated emissions.

Longer-Term Initiatives (within the next 5-10+ years)
to Deploy Coal-Derived Value-Added Products in Support of:

Infrastructure Improvements

- Pursue technology and cost-reduction R&D initiatives supporting the deployment of high-performance coal-derived asphalt.

Supply Chain Resilience

- Establish floor pricing on rare earth elements and critical minerals to incentivize private sector investment in materials critical to U.S. national security and supply chain resilience.
- Employ long-term contracting for U.S. materials to facilitate market price stability.
- Establish Federal Executive Agency Offices to monitor domestic industrial capacity and deployment of advanced manufacturing facilities to support modernization of manufacturing supply chains for critical goods.
- Locate coal-to-products technology and production/manufacturing facilities close to abundant coal supplies and affordable power generation plants. Shorter supply chains are less vulnerable to disruption.

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