2024 CARBON ORE PROCESSING

PROJECT PORTFOLIO

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

CONTENTS

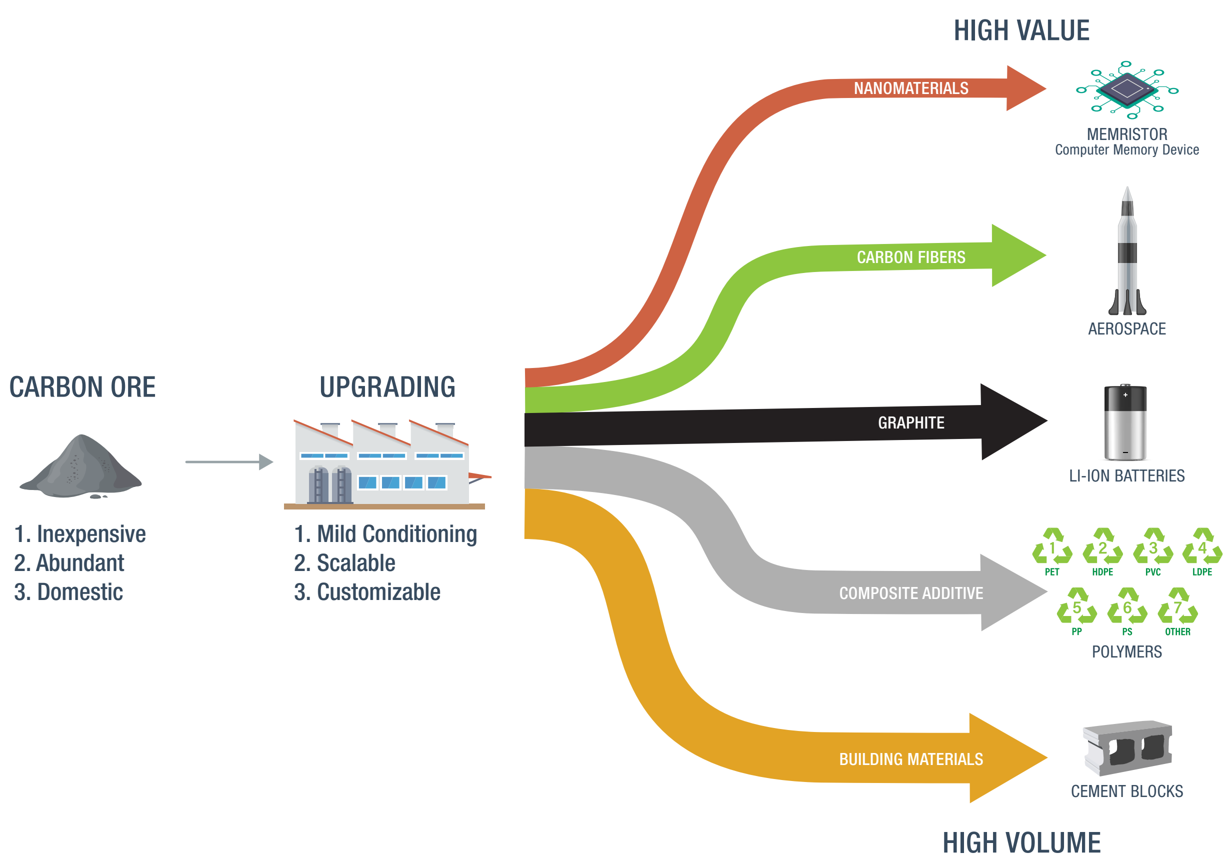
INTRODUCTION

Coal is a domestic resource that has contributed to U.S. economic growth for over a century . However, under a shifting energy generation paradigm, innovation is needed to extract the full economic value from coal and to remediate legacy impacts associated with coal extraction and utilization. The Carbon Ore Processing Program at NETL delivers solutions to this challenge with novel technologies for producing valuable products from coal and coal wastes. Laboratory and pilot-scale research and development (R&D) supported by the program aims to elevate the value of our nation's coal resources and transform their use for the future. The program focuses on developing a range of coal-derived products, spanning the entire value spectrum from high volume through high value.

Coal's unique structure and composition makes it well suited as a feedstock for high¬value carbon products such as carbon fibers, graphite for batteries, additive manufacturing filaments and resins, and carbon nanomaterials for advanced electronic and metal alloy applications. Coal is also abundant and low-cost, making it an attractive feedstock for high-volume applications such as building materials, as a concrete additive, and polymer composites. These markets, which are outside of coal's traditional thermal and metallurgical roles, expand the U.S. coal value chain and sustain jobs within a critical sector of the U.S. economy.

Examples of products pursued by R&D within the Carbon Ore Processing Program include:

- Graphite for electrochemical applications and carbon fibers for carbon-carbon composites and polymer enhancement.
- Carbon fibers/foams and modified coal and coal wastes for building materials such as roofing tiles, siding, decking, insulation, joists/studs, sheathing, tiles and carpet, wraps and veneers, and architectural block.
- Carbon nanomaterials such a graphene, quantum dots, and nanotubes for additive manufacturing (filaments, resins, and conductive inks), battery anodes, supercapacitors, memristors, and carbon-metal alloys.



COAL TO CARBON PRODUCTS

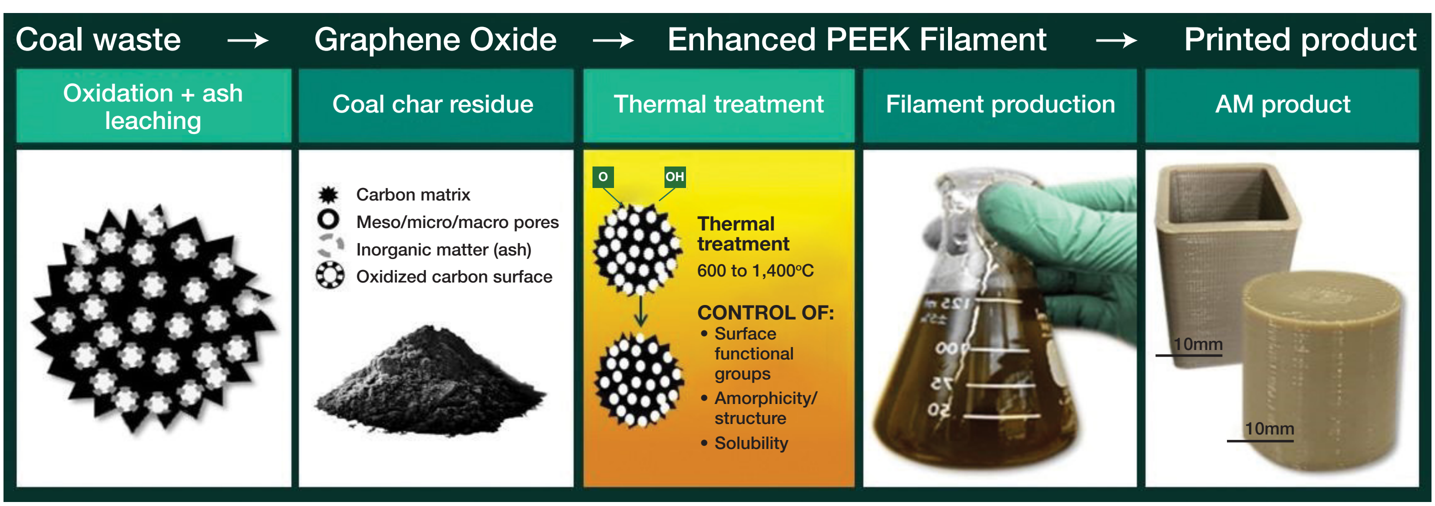
Coal Enhanced Polyether Ether Ketone (PEEK) Filament Production for Additive Manufacturing in Industrial Services

Performer	**Baker Hughes Energy Transition, LLC**
Award Number	FE0032146
Project Duration	07/12/2022 – 07/11/2024
Total Project Value	$ 1,118,348
Collaborator	University of Wyoming

The main objective of this study is to additively manufacture a suite of selected parts using traditional polyether ether ketone (PEEK) and coal-enhanced PEEK, baselining and comparing the overall performance of the two approaches. Graphene oxide will be developed from coal char and will be incorporated into PEEK to broaden its applicability. The goals of the project include identifying how the graphene oxide can be sufficiently distributed into PEEK and testing the coal-enhanced PEEK properties on product life and performance to promote the supply chain usage of additive manufacturing.

This project will include the development of a coal-enhanced PEEK filament, investigation of the printability of the coal enhanced filament in a commercially available 3D printer, and printing in a fused deposition modeling (FDM) modality. Prototype parts will be tested to quantify the properties of the new filament.

The coal enhanced PEEK will provide value by creating a circular economy for coal waste and extending markets for additive manufacturing products due to improved performance and reduced disruptions to the supply chain, achieved in a cost-effective manner.



Transforming coal waste into commercially valuable products through additive manufacturing.

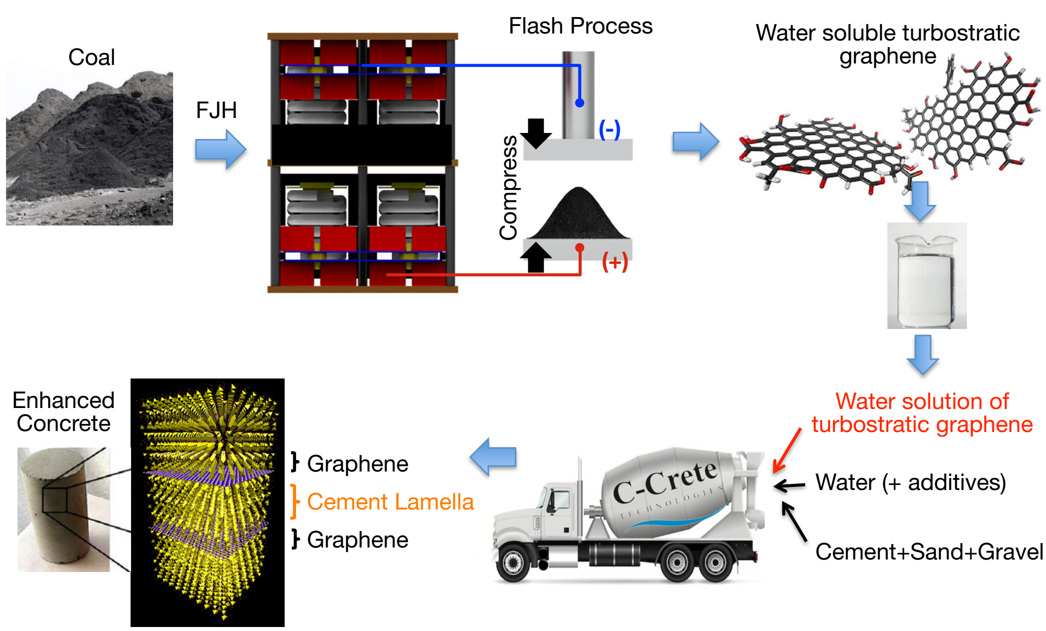
Low Cost Conversion of Coal to Graphene: Bench-Scale Testing, Modeling and Techno-Economical Analysis

Performer	**C-Crete Technologies, LLC**
Award Number	FE0031999
Project Duration	03/01/2021 – 02/29/2024
Total Project Value	$ 625,000

The overall objective of this project was to demonstrate the techno-economic feasibility of a 250 ton/day manufacturing facility to convert coal to high-quality graphene. The first objective (Tasks 1-3) was bench-scale testing of flash Joule heating (FJH) and parametric study of FJH processes on various coal ranks. The second objective (Task 4-5) was to accelerate process optimization in real time via machine learning and in-line characterizations, followed by small-scale demonstration of an optimized graphene/concrete composite as end product. The third objective (Task 6) was to use the collected performance data and design criteria in objectives 1 and 2 to perform process modeling, a techno-economic analysis and a technology gap analysis for a 250 ton/day manufacturing facility. The core technology is based on FJH to convert various coals to high quality graphene.

The advantage of FJH is that it requires no reactive gases or furnace, is exceedingly fast, works with various coal compositions, is self-purifying, and is tolerant to ashes and moisture.

This project provided key technical information on the scaled-up FJH process and bench-scale dynamic data to turn various coals to value-added graphene to be used in the concrete market. The high-value graphene, along with the demonstrated high potential for large markets such as concrete, could increase demand for domestic coals, increasing the value chain across the entire coal industry. The target is to improve the process until all coal ranks can be converted to graphene, with a yield of 90% or greater and a purity of greater than 99%, for less than $40/ton.



Manufacturing concrete composites reinforced with graphene.

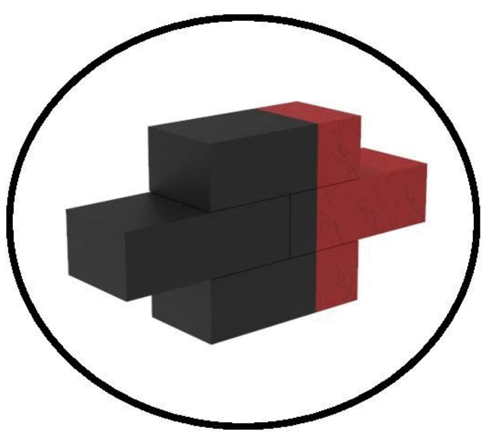
Low Cost, Rapid and Scalable Microwave Carbon Ore Melt-Casting for Modular Carbon-Based Buildings

Performer	**C-Crete Technologies, LLC**
Award Number	FE0032085
Project Duration	08/01/2021 – 10/31/2023
Total Project Value	$ 687,537

The project will demonstrate the feasibility of modular building prototypes where key building components have greater than 70 weight percent carbon from coal and components have physical, chemical, and thermal properties exceeding those of conventional construction materials. The first objective is to optimize microwave fabrication protocols to bench scale, followed by technical and environmental tests of representative building components. The second objective is to conduct a conceptual design of a carbon- based building prototype and perform technoeconomic, life cycle, and technology gap analyses to determine feasibility for use in modular, precast buildings.

This project will perform structural and environmental bench-scale testing on microwave melt cast building materials necessary to construct a conceptual design. A techno-economic assessment and life cycle modeling will be developed to demonstrate the feasibility of coal-based building prototypes.

Technical results will enable a detailed assessment for commercial feasibility of large-scale coal feed manufacturing facilities to produce carbon-based building materials. The project will overturn the notion of coal as a polluting and combustible energy source and may help introduce a “Carbon Age” whose most abundant source is coal. High-value building materials will significantly drive demand for domestic coals, raising their value across the entire coal industry.

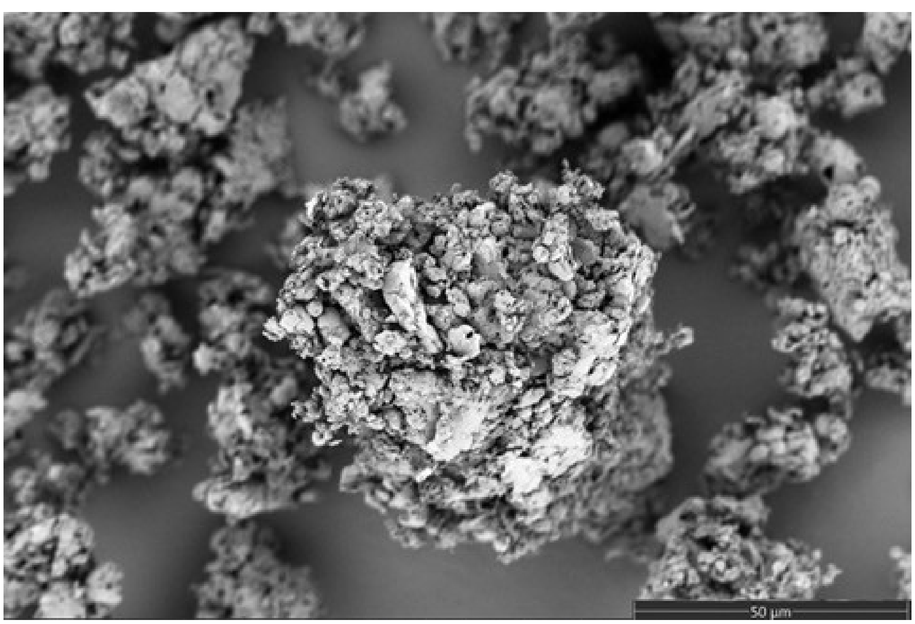


Bricks.

Conversion of Coal to Li-Ion Battery Grade (Potato) Graphite

Performer	**George Washington University**
Award Number	FE0031797
Project Duration	09/01/2019 – 08/31/2024
Total Project Value	$ 949,030

The main objective of this project is to further develop George Washington University's recently discovered process to efficiently transform low-cost coal (lignite) into high-performance, high-value lithium-ion (Li-ion) battery-grade "potato" graphite, so called because potato-shaped agglomerates result from the process. This transformation represents an approximately 1,000-fold increase in the coal's value. The initial phase of the project will be devoted to improving the graphite yield by optimizing reaction conditions and improving first-cycle Coulombic efficiency to greater than 90 percent by optimizing potato size and porosity and increasing the purity level. Efforts to transition the process from batch to continuous production will run concurrently and synergistically, with results from one effort informing the others. In addition, electrochemical testing of the graphite produced will be conducted with the ultimate goal of demonstrating long-term (500-plus) cycle performance that meets or exceeds commercial graphite. At the end of the project, solutions that valorize domestic coal will have been found, and conversion of domestic lignite coal to Li-ion battery-grade graphite will have been demonstrated.



Graphite agglomerates made from coal.

Coal-Derived Graphene Materials for Industrial Applications

Performer	**Iowa State University**
Award Number	FE0032274
Project Duration	09/01/2023 - 08/31/2025
Total Project Value	$ 1,249,915
Collaborator	University of Wyoming

The objective of this project is to further develop and demonstrate the feasibility of coal derived graphite oxide (GO), reduced graphite oxide (rGO), and graphene nanosheets with application to battery anode materials and cement filler. This work is designed to demonstrate the production process from coal feedstock to end-use product and show effectiveness of the anode material and concrete applications. The three overall objectives of this project are to improve production of GO using Powder River Basin coal as feedstock, conduct continued testing and improvement of a hard carbon sodium-ion battery prototype and test device, and determine the properties and performance of concrete using GO and rGO as a concrete additive or cement replacement.

Conversion of coal and coal wastes (the carbonaceous solid portion of waste resulting from the cleaning of coal) into value-added products that are outside of traditional thermal and metallurgical markets can provide great societal benefits. These products can contribute to the U.S. gross domestic product while providing a stable and sizable market for U.S. coal and a path for utilizing coal wastes. The unique structure and composition of coal and coal wastes make them well suited as feedstocks for various carbon products such as building materials, carbon fibers, carbon foams, and carbon nanomaterial.

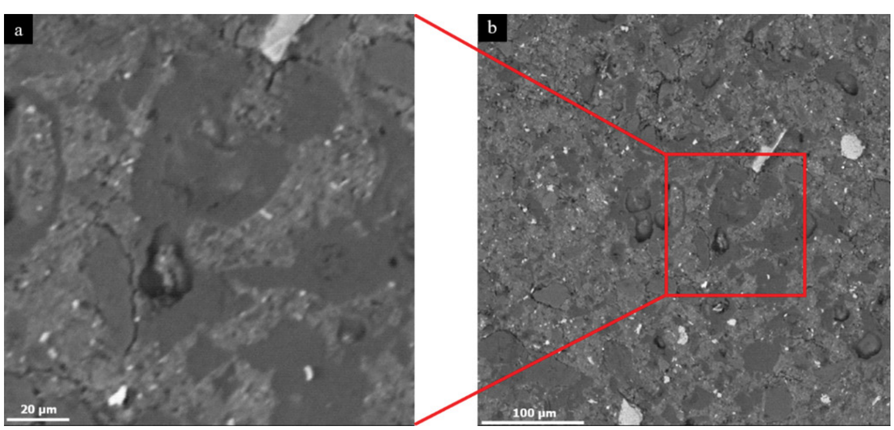
Powder River Basin coal, which will be used as a feedstock to produce GO, rGO, and graphene nanosheets.

Development of Novel Sintered Carbon-Ore Building Materials

Performer	Microbeam Technologies, Inc.
Award Number	FE0032083
Project Duration	10/01/2021 – 02/29/2024
Total Project Value	$ 649,407
Collaborator	University of North Dakota

The objective of this project was to develop and establish a novel method for the flexible production of low-temperature sintered coal building materials. Microbeam Technologies Incorporated and the University of North Dakota have developed a method to produce high-value carbon-based building materials using a flexible manufacturing process to produce products such as blocks and foams that are greater than 70 weight percent (wt%) carbon with more than 51 wt% carbon from coal. The project team identified feedstock materials, optimized material development and performance, developed process flow diagrams, performed life cycle analysis for the flexible process, and completed a technical and economic assessment (TEA) of the product. Following these tasks, the team performed additional materials testing to demonstrate compliance with all relevant building codes under relevant methodologies and updated the TEA of the products.

This technology will create value-added products from coal, in particular high-value carbon-based building materials, by using a low-temperature continuous manufacturing process. These coal-derived products have tailorable material properties and are greater than 70 wt% carbon with more than 51 wt% carbon from coal. The sintered lignite and lignin composites products, developed using sintered coal building materials technology, can be used for various applications such as insulation, masonry brick, tiles, and architectural block. Three main types of products can be produced from this technology: (a) low-strength foams, (b) medium-strength products, and (c) high-strength premium products. In addition to mechanical properties, the appearance of these materials can be modified to add aesthetic value.



(a) High magnification backscattered electron (BSE) scanning electron microscope (SEM) image showing sintering and bonding between carbon-ore and additive material, (b) low magnification BSE SEM image showing morphological structure of cross-sectioned high-strength carbon-ore composites.

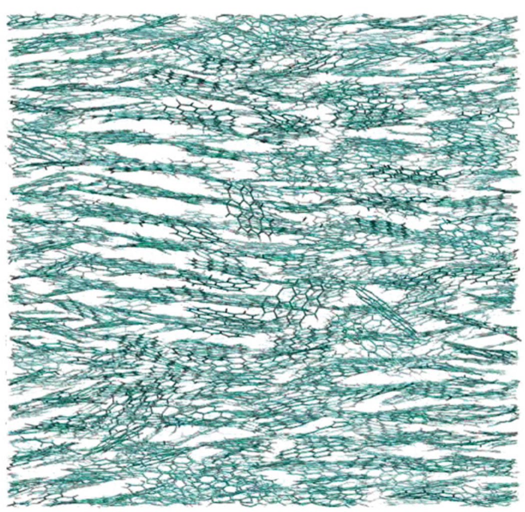
C4WARD: Coal Conversion for Carbon Fibers and Composites

Performer	**Oak Ridge National Laboratory**
Award Number	FWP-FEAA155
Project Duration	05/12/2020 – 04/30/2024
Total Project Value	$ 10,000,000
Collaborator	University of Kentucky Research Foundation

The Oak Ridge National Laboratory (ORNL) C4WARD Field Work Proposal will develop the underlying and translational science to establish processing- structure-properties relationships for coal-derived fibers, thus enabling the development of energy-efficient and cost-effective processes for manufacturing carbon fibers with tunable properties. This project will address challenges associated with coal processing, variability in feedstocks, and scaling up of carbon fiber manufacturing from the laboratory bench scale to semi-production scale at ORNL's Carbon Fiber Technology Facility.

The scope of this project includes classification of coals based on their molecular makeup rather than on their rank; identification of the best coals for obtaining precursors for manufacturing carbon fibers; carbon fiber manufacturing; and manufacturing of carbon fiber-reinforced composite prototypes. The molecular representation of coal will inform computational chemistry models to identify the most energy-efficient and cost-effective pathways for processing coal into precursors that have molecular structures best suited for manufacturing carbon fibers. At the end of this project, ORNL will demonstrate a clear path for competitive industrialization of coal-derived carbon fibers and composites for a wide range of applications.

By identifying alternative pathways for processing carbon fiber precursors not from coal tar, but directly from coal, ORNL mitigated the risk associated with potential disruptions in the availability of coal tar pitch in the United States. Another key element of this project is the successful demonstration of manufacturing coal-derived carbon fibers with tunable properties at semi-production scale. This effort is a major step toward providing a low-cost carbon fiber product from coal for potential use in automotive and other important markets and will also lead to new economic development opportunities for communities with coal-based economies.



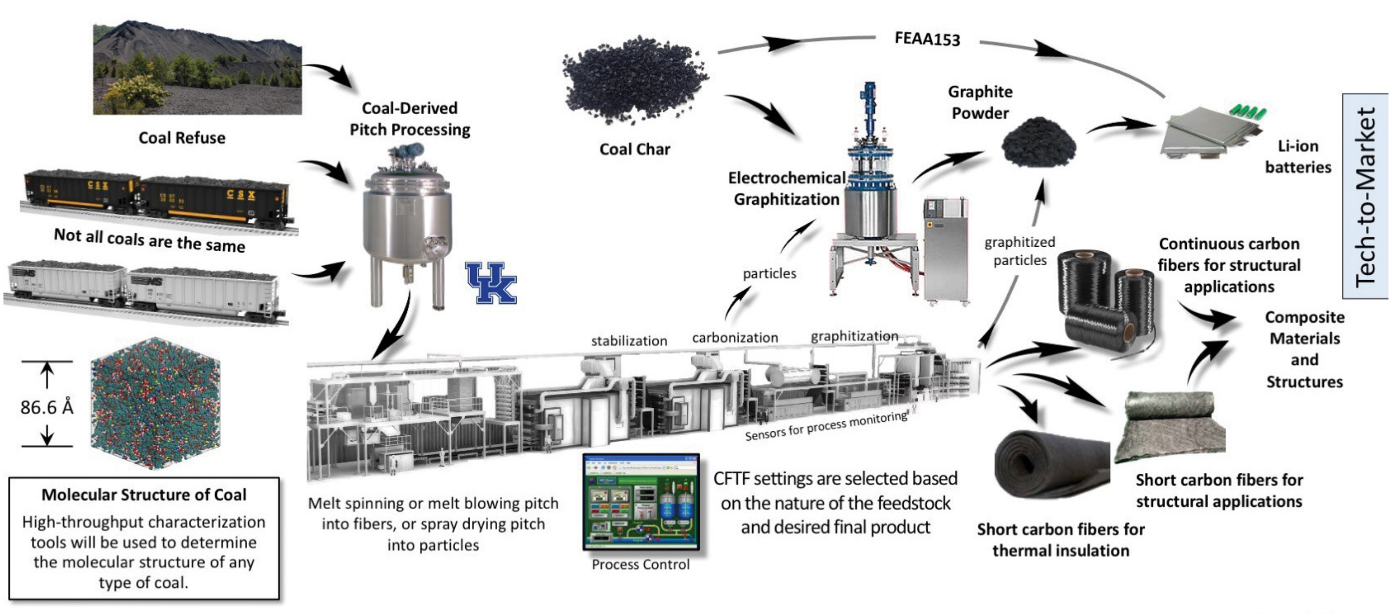
A molecular dynamics simulation of 500 disk-shaped molecules in an isotropic pitch at high temperature, showing how the molecules become aligned in transition to mesophase pitch.

Scale Up Production of Graphite and Carbon Fibers from Carbon Ore and Coal Refuse

Performer	**Oak Ridge National Laboratory (ORNL)**
Award Number	FWP-FEAA157
Project Duration	10/01/2021 – 09/30/2024
Total Project Value	$ 5,000,000
Collaborator	University of Kentucky Research Foundation

The objective of this field work proposal is to develop and demonstrate processes for scaling up the production of graphite and carbon fibers from carbon ore, coal refuse, and waste streams associated with previous coal mining activities. The proposed work builds upon the results obtained by ORNL in FWP-FEAA153, which demonstrated the feasibility of using coal char, obtained by the mild gasification of Blue Gem coal, for fabricating anodes for lithium-ion batteries, and on current work by ORNL and the University of Kentucky as part of FWP-FEAA155, establishing processing-structure-properties relationships for carbon fibers derived from carbon ore.

The knowledge generated will enable the development of energy-efficient and cost-effective processes for scaling up the manufacturing of carbon fibers with tunable properties up to semi-production scale at ORNL's Carbon Fiber Technology Facility. The successful completion of this project will help address a national priority by developing domestic sources of graphite for lithium-ion batteries.



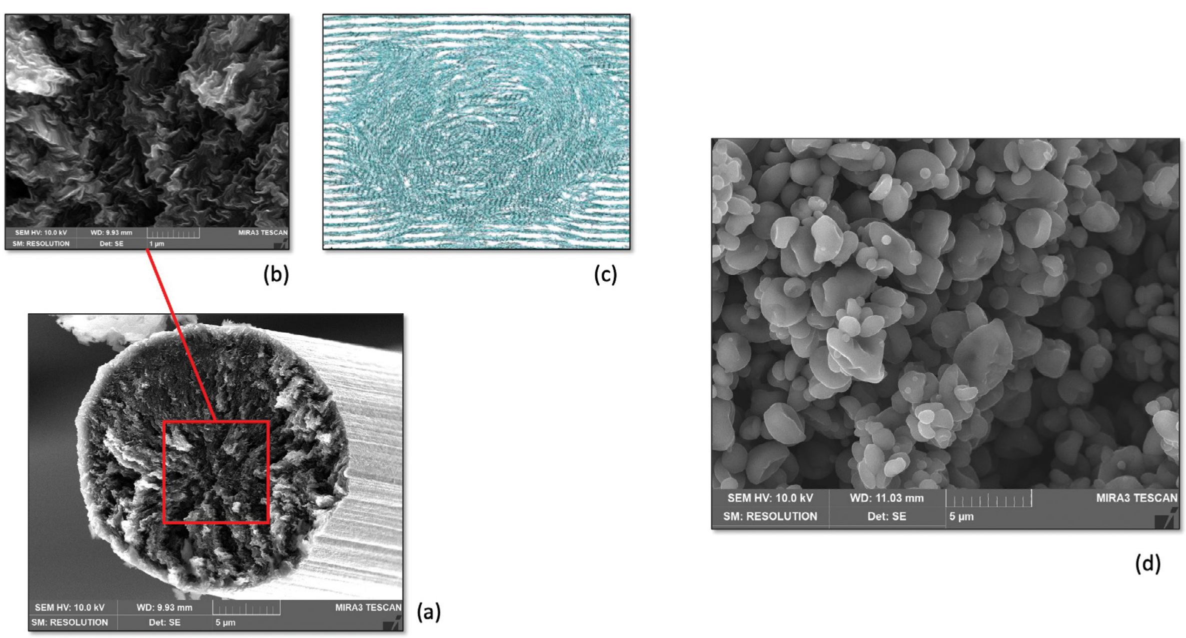
Carbon Ore and Coal Refuse-to-Products at ORNL's Carbon Fiber Technology Facility.

Scale-up Production of Graphite, Carbon Fibers and other Products from Coal and Coal Refuse

Performer	**Oak Ridge National Laboratory**
Award Number	FWP-FEAA302
Project Duration	08/01/2023 – 09/30/2026
Total Project Value	$ 5,000,000
Collaborator	University of Kentucky Research Foundation

The objectives of this field work proposal are to demonstrate the use of coal and coal refuse feedstocks to manufacture carbon and graphite fibers at semi-production scale at Oak Ridge National Laboratory (ORNL) Carbon Fiber Technology Facility and to manufacture graphite particles for lithium-ion battery anodes and other energy storage applications at multi-kilogram scale. This work builds on the activities and results associated with projects FWP-FEAA155 and FWP-FEAA157 that ORNL has led in collaboration with the University of Kentucky's Center for Applied Energy Research, which identified multiple pathways to utilize coal and coal refuse as feedstocks to manufacture carbon fibers, graphite fibers, and graphite particles for energy storage devices. This project will also conduct market, technical, economic, and environmental analyses to assess the market viability of carbon fibers, graphite fibers, and anodes for lithium-ion batteries derived from coal and coal refuse.

The successful completion of this project will help address a national priority by developing domestic sources of graphite for lithium-ion batteries, as well as developing technologies to valorize waste streams from previous coal mining and coal processing.



(a-b) Scanning electron micrographs of graphite fibers obtained from coal refuse via solvent extraction. Note the radial graphitic structure. (c) Atomistic simulations illustrating the effect of shear flow during melt spinning on molecular orientation, leading to radial graphitic structure. (d) Spherical carbonaceous particles obtained by spray drying of coal-derived pitches for use as anodes in lithium-ion batteries.

Electrochemical Coal to 2-Dimensional Materials (e-Coal2D) Process to Enable Renewable Energy Storage

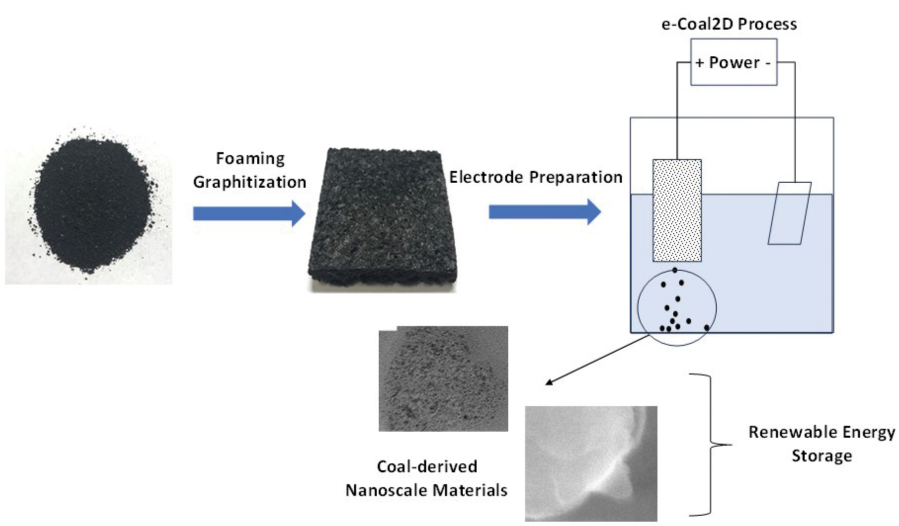
Performer	**Ohio University**
Award Number	FE0032275
Project Duration	08/01/2023 – 07/31/2025
Total Project Value	$ 1,248,276
Collaborators	Capacitech Energy, Inc.; CONSOL Innovations, LLC

The goal of this 24-month project is to develop electrochemical processes to convert coal and waste coal to two-dimensional nanoscale carbon material such as graphene and carbon quantum dots. These materials have unique electronic properties that make them of interest for use in energy storage devices including supercapacitors. Use of these materials in electrochemical energy storage devices could enhance device capacity and could help enable renewable energy by providing more efficient energy storage.

The team consists of Ohio University and industrial partners CFOAM and Capacitech Energy. Together, the partnering organizations will develop coal- and waste coal-derived materials that can be converted by electrochemical processes to the two-dimensional, nanoscale carbon materials. The outcome of this project is utilization of coal and waste coal in energy storage applications.

Conversion of coal and coal wastes (the carbonaceous solid portion of waste resulting from the cleaning of coal) into value-added products that are outside of traditional thermal and metallurgical markets can provide great societal benefits. These products can contribute to the U.S. gross domestic product while providing a stable and sizable market for U.S. coal and a path for utilizing coal wastes. The unique structure and composition of coal and coal waste make them well suited as a feedstock for various carbon products such as building materials, carbon fibers, carbon foams, and carbon nanomaterials.

Graphitic carbon can have electronic, mechanical, chemical, or surface properties that produce new classes of high-value carbon products or superior versions of existing high-value carbon products. The market value of these products exceeds the thermal and metallurgical value of coal, representing an opportunity to offer value to both manufacturers and consumers of coal-derived carbon products.



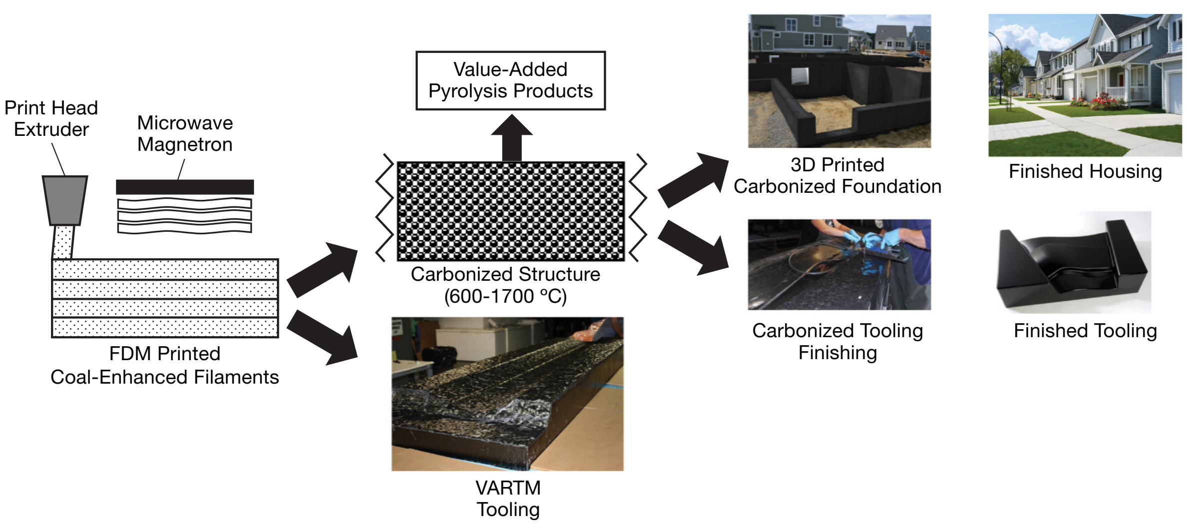
e-Coal2D process overview.

Fused Deposition Modeling Additive Manufacturing of Carbonized Structures Via Waste-Enhanced Filaments

Performer	Ohio University
Award Number	FE0032143
Project Duration	04/15/2022 – 04/14/2025
Total Project Value	$ 1,250,000
Collaborators	CFOAM, LLC; CONSOL Energy, Inc.; IC3D, Inc.; JuggerBot 3D, LLC

The objective of this project is to develop carbonizable, coal-enhanced filaments that can be used in commercial fused deposition modeling (FDM) printers to manufacture articles for construction, tooling, and metals-casting industries. Coal-enhanced filament formulation and filament 3D printing trials with commercial FDM printers will be conducted to quantify both filament and printed article properties. Thermal processing of printed materials will also be investigated to generate carbonized products for a host of commercial applications. Computational tools including molecular dynamic simulation and finite element analysis will be utilized to investigate coal-enhanced filament processing chemistry and predict bulk mechanical and thermal properties of printed materials to aid product design. Process simulations will be developed and validated using bench-scale information to support techno-economic and market analyses to identify required selling prices and resources necessary to scale and commercialize coal-enhanced filament materials.

Coal-enhanced filaments offer a host of environmental, industrial, and 3D printing advantages, including transforming the nation's coal resources into low embodied energy and low emission construction materials, development of carbonizable coal-enhanced filaments that integrate with commercially available FDM printers, reduction of U.S. construction-sector greenhouse gas emissions, diversifying and securing U.S. construction supply chains, enabling environmentally affordable housing construction for disadvantaged communities, and converting Appalachian mining brownfields into advanced manufacturing hubs with prevailing-wage jobs.



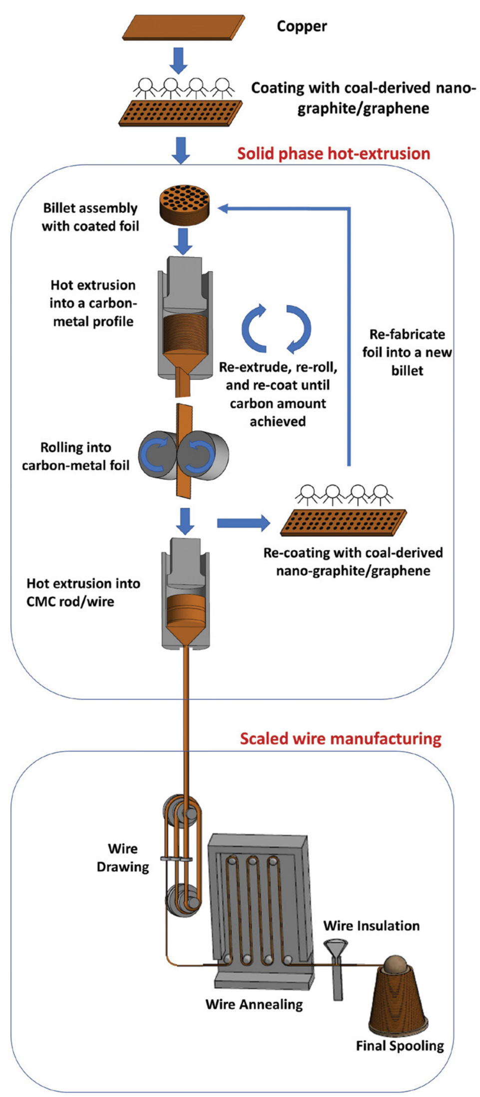
FDM additive manufacturing using carbonizable coal-derived enhanced filaments for construction materials and tooling applications.

Ultra-Conductive Carbon Metal Composite Wire for Electric Motors

Performer	Ohio University
Award Number	FE0032277
Project Duration	07/26/2023 – 07/25/2025
Total Project Value	$ 1,250,000
Collaborators	AmeriCarbon, LLC, Clear Skies Consulting, LLC, CONSOL Innovations, LLC, Fisk Alloy, Inc., Hydro Precision Tubing North America, MetalKraft Technologies, LLC, SP2 Technology Co.

The objective of this project is to develop cost-effective carbon metal composites (CMCs) with enhanced bulk electrical properties for use in electric motors to increase American energy efficiency and reduce greenhouse gas emissions. The CMC materials will be made using primary conductor materials (including copper and aluminum) and coal-derived graphitic carbons, such as nano-graphite and/or graphene. CMC wire formulations will be synthesized using unique solid and liquid phase methodologies and their performance will be assessed with respect to method and process parameters to establish material-process-structure-property relationships.

Conversion of coal and coal wastes (the carbonaceous solid portion of waste resulting from the cleaning of coal) into value-added products that are outside of traditional thermal and metallurgical markets can provide great societal benefits. These products can contribute to the U.S. gross domestic product while providing a stable and sizable market for U.S. coal and a path for utilizing coal wastes. The unique structure and composition of coal and coal waste make them well suited as feedstocks for various carbon products such as building materials, carbon fibers, carbon foams, and carbon nanomaterials.



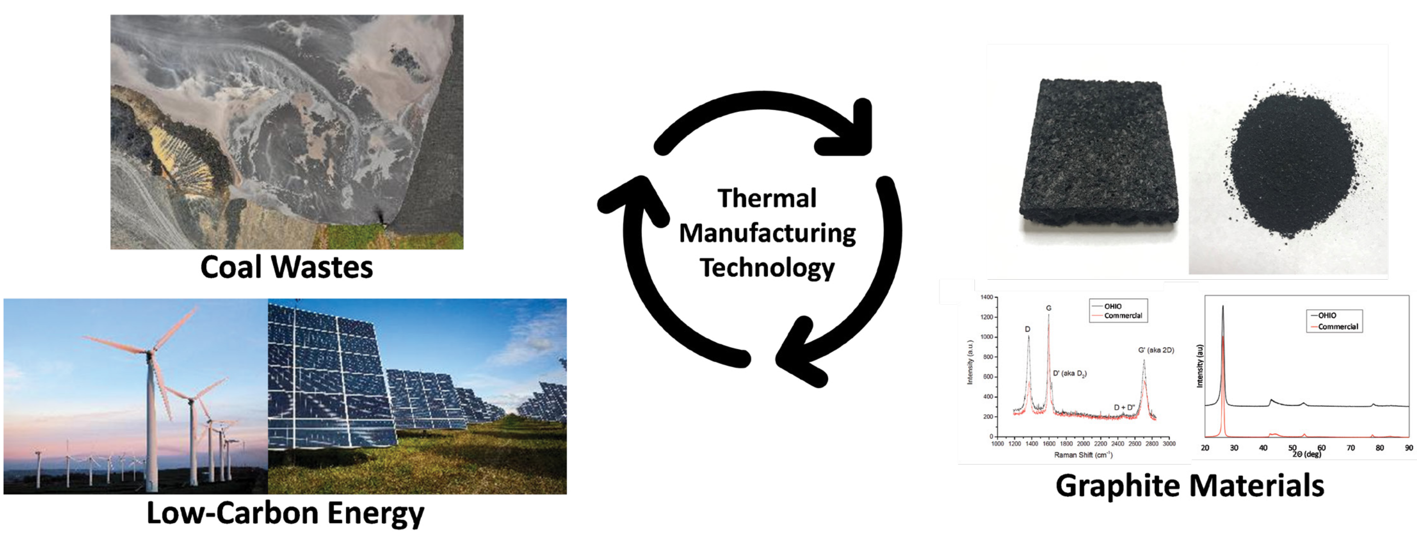
Process flow diagram of the production of ultra-conductive carbon metal composite wire.

Utilization of Carbon Supply Chain Wastes and Byproducts to Manufacture Graphite for Energy Storage Applications

Performer	Ohio University
Award Number	FE0032144
Project Duration	02/15/2022 – 02/14/2025
Total Project Value	$ 1,337,920
Collaborators	American Electric Power Service Corporation; CFOAM, LLC; CONSOL Energy, Inc.; Engineered Profiles; General Motors, LLC; Koppers, Inc.; OMNIS Bailey, LLC

The overall objective of this project is to develop graphite materials (greater than 51% coal derived) for transportation and grid-scale energy storage applications utilizing a continuous engineered foaming process. Specific project objectives include conducting bench scale coal foaming and graphitization trials, electrochemical performance testing of coal derived graphite materials in coin cells, and application of computational tools to demonstrate that coal derived graphite can be successfully utilized in energy storage applications. The best performing parameters will be translated to a prototype extruder to demonstrate a commercially viable pathway for coal derived graphite production to produce sufficient material to construct single cell batteries to evaluate performance under energy storage conditions. Information from the prototype-scale trials will be used to conduct more thorough techno-economic analyses to estimate coal-derived graphite manufacturing costs and assess market potential.

If successful, the coal-derived graphite manufacturing (CGM) process will support the establishment of a domestic graphite manufacturing supply chain to support the continued growth of the burgeoning U.S. electric vehicle and grid-scale energy storage sectors. In addition, the CGM process will utilize reclaimed coal from mining wastes, addressing adverse environmental impacts by the energy industry, while creating new clean energy manufacturing jobs in economically distressed power plant and coal communities.

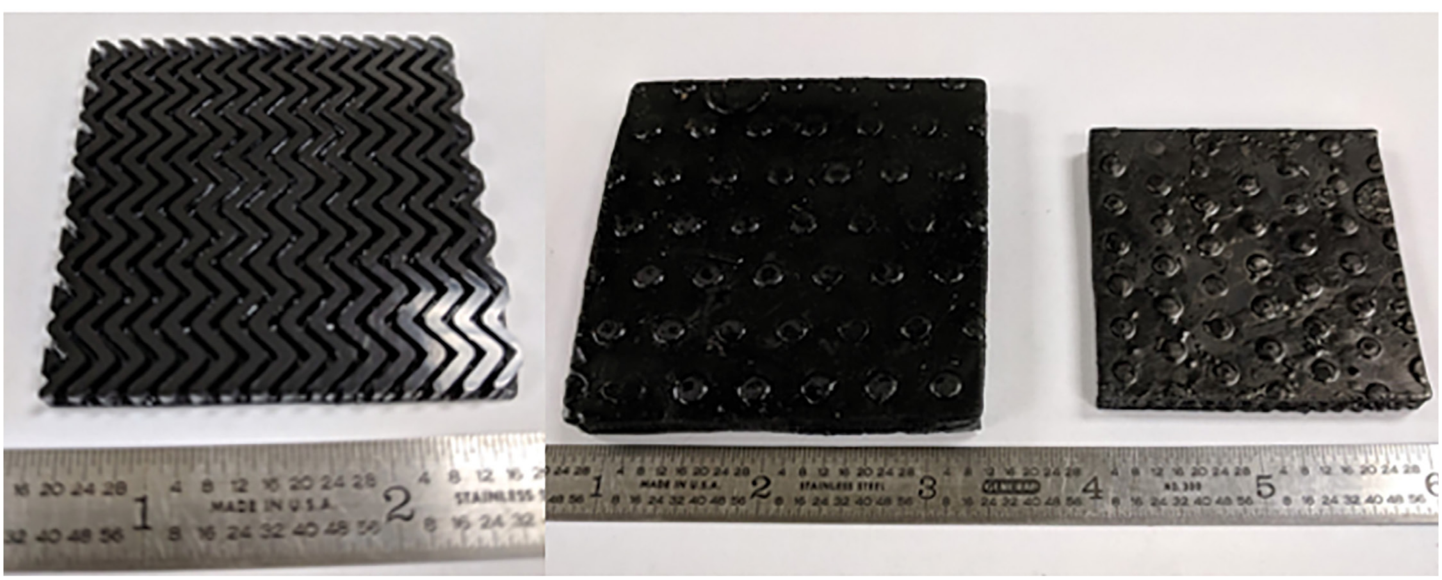


Coal-Waste-Enhanced Filaments for Additive Manufacturing of High-Temperature Plastics and Ceramic Composites

Performer	**Semplastics EHC, LLC**
Award Number	FE0032145
Project Duration	02/01/2022 – 01/31/2025
Total Project Value	$ 1,258,789
Collaborators	Clemson University; Industrial Commission of North Dakota - Lignite Energy Council; University of North Dakota Energy and Environmental Research Center (UNDEERC); Virginia Polytechnic Institute and State University

For this work, Semplastics will apply its materials technology to develop and test filament material suitable for use in a commercially available 3D printer, using two different kinds of coal waste. Several demonstration objects will be produced using the best filament formulation. Commercialization and performance modeling will be performed for the technology as a precursor to establishing a market for resulting products.

If this technology is commercially deployed, the use of coal waste as precursors to high-value end use applications will have numerous environmental justice benefits. A conduit for full waste utilization will be created, which will result in the cleanup and remediation of legacy environmental issues. This presents a significant benefit to coal communities, where large waste impoundments constitute a significant long-term environmental liability. Moreover, this technology has the potential to create high paying advanced manufacturing jobs, promote economic development within depressed regions, and facilitate increased stakeholder engagement between resource owners, manufacturers, and local communities.



a) b) c)

3D printed parts utilizing coal fines: parts made from Semplastics' (a) UV-curable resin, (b) cured (plastic) part, (c) fired (ceramic) part.

Spray Deposition of Coal-Derived Graphene-Copper Nanocomposites for Advanced Conductors

Performer	Tennessee Technological University
Award Number	FE0032273
Project Duration	08/01/2023 – 07/31/2025
Total Project Value	$ 1,255,742
Collaborators	Tennessee State University (TSU); Copperweld Bimetallics LLC; Eastern Plating LLC

Tennessee Technological University (TTU), partnering with Tennessee State University (TSU), Copperweld Bimetallics LLC, and Eastern Plating LLC, will focus on the optimization of the spray deposition process for the synthesis of high-performance copper-matrix nanocomposites with uniformly distributed graphene particulates. To control the amount of graphene and achieve a uniform distribution of graphene in the nanocomposites, the team will systematically investigate several key atomizing parameters for a better understanding of their synergistic effects on the microstructural development in the processed nanocomposite. Conversion of coal and coal wastes (the carbonaceous solid portion of waste resulting from the cleaning of coal) into value-added products that are outside of traditional thermal and metallurgical markets can provide great societal benefits. These products can contribute to the U.S. gross domestic product while providing a stable and sizable market for U.S. coal and a path for utilizing coal wastes. The unique structure and composition of coal and coal waste make them well suited as feedstocks for various carbon products such as building materials, carbon fibers, carbon foams, and carbon nanomaterials.

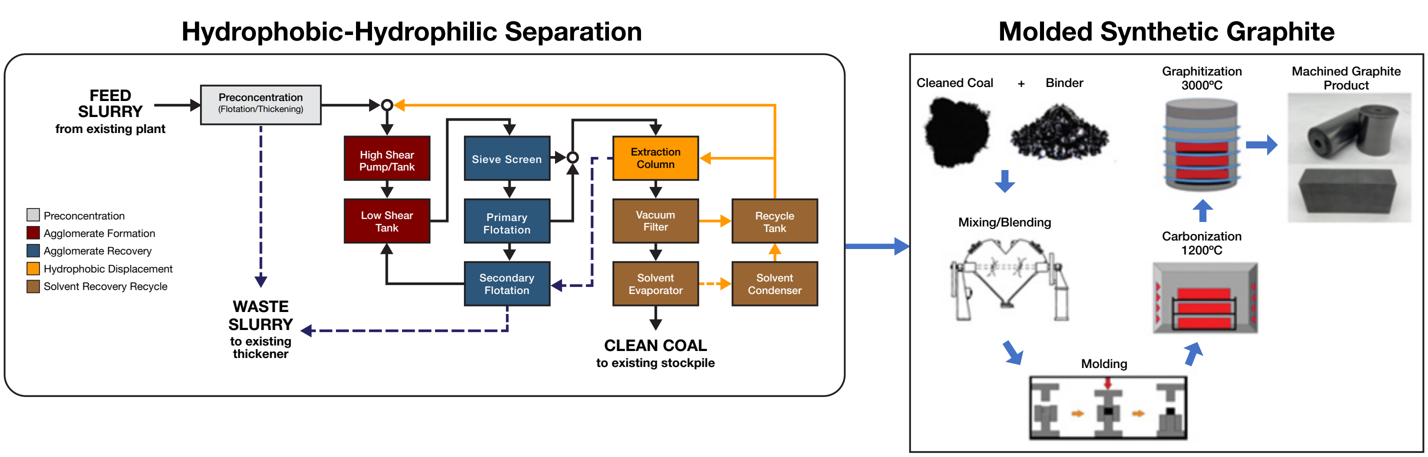
Spray deposition system at TTU for Cu-graphite nanocomposite manufacturing.

Molded Graphite Products Synthesized from Waste-Coal

Performer	**Touchstone Research Laboratory, Ltd.**
Award Number	FE0032141
Project Duration	06/01/2022 – 05/31/2024
Total Project Value	$ 1,250,000
Collaborators	Touchstone Research Laboratory, Ltd.; Blaschak Anthracite; CONSOL Innovations, LLC; Minerals Refining Company, LLC; United Coal Company, LLC; Virginia Polytechnic Institute and State University; Warrior Met Coal, Inc.

The project team will implement the Hydrophobic-Hydrophilic Separation (HHS) process that was developed at Virginia Tech for reducing mineral deposits in coal. The research and development will focus on cleaning low, medium, and high rank coals and resulting waste-coal streams generated when cleaning coals via froth flotation. The objective is to clean waste coal to sufficient levels, thereby making it suitable for feedstock in high-value synthetic graphite processes. Touchstone will determine coal candidates based on degree of graphitization attainable, high capacity for ash impurity reduction via HHS, and demonstration that the cleaned waste-coal feedstock can be successfully molded and graphitized to meet application requirements and specifications through test and validation. An objective is to transition the HHS coal-derived graphite technology processes from laboratory-scale proof of concept to pilot system validation in a relevant environment.

Successful outcomes of this project will enhance the process for making waste-coal-derived graphite that meets or exceeds current state-of-the-art petroleum coke-based synthetic graphite. Furthermore, waste-coal fines may be procured from coal cleaning facilities prior to waste disposal, thereby contributing to the environmental justice initiatives for a cleaner environment. The proposed technical approach and related processes are expected to reduce manufacturing cost, thereby making synthetic graphite more affordable and benefiting the automotive, aerospace, energy, industrial, and space industries.



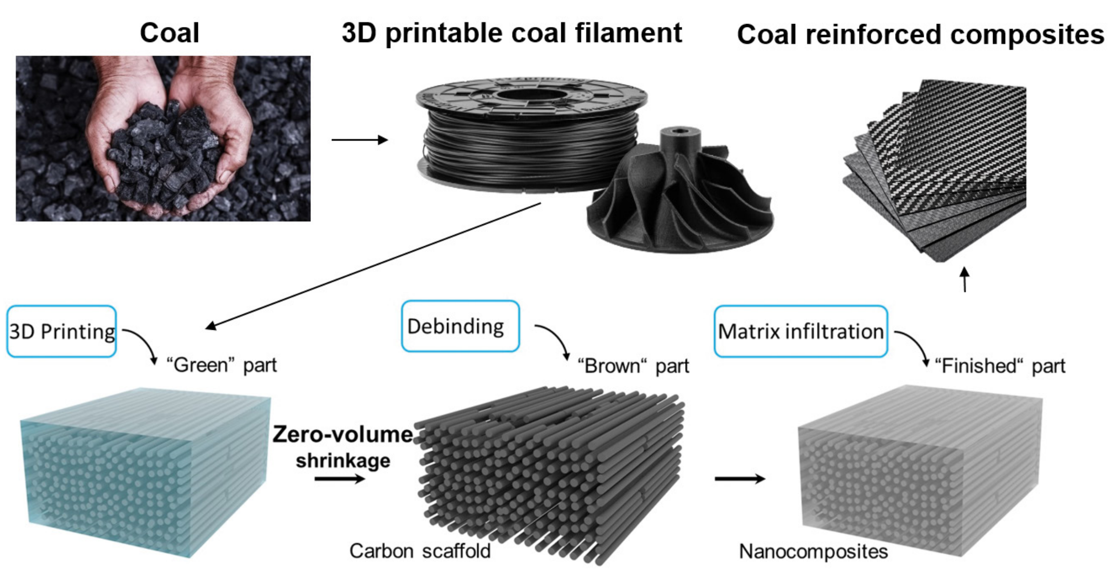
Schematics of the Hydrophobic-Hydrophilic Separation (HHS) and Molded Synthetic Graphite processes. The HHS process will be used to remove mineral deposits from waste coal that may be used as feedstock for production of high-value carbon and graphite products.

Lab-scale Additive Manufacturing of Coal-derived Carbon-Metal Composites for High-Performance Heat Sinks

Performer	**University of Delaware**
Award Number	FE0032280
Project Duration	09/01/2023 – 08/31/2025
Total Project Value	$ 1,250,000
Collaborators	University of Southern Mississippi

The goal of this project is to develop a lab-scale additive manufacturing (AM) process to fabricate carbon-copper composites with a high heat dissipation rate and low thermal stress and demonstrate highly-efficient and compact heat sinks for electrical applications. Graphene derived from domestic US coal shall be used as a carbon feedstock for the carbon-metal composite heat sink development. The specific project objectives are to (1) develop a new feedstock material system based on coal-derived graphene and high-carbon-yielding polymers to additively fabricate three-dimensional (3D) coal-derived graphene scaffolds, (2) develop a post-processing method to impregnate copper into graphene scaffolds, (3) develop coal-derived graphene-copper composites with high heat dissipation rate and low thermal stress, (4) design, develop, optimize, and demonstrate highly-efficient and compact graphene-copper heat sinks enabled by AM, (5) perform a full techno- economic analysis to inform technology development and assess the potential of coal-derived graphene for rapidly growing and high-value AM and carbon-metal composite markets.

Conversion of coal and coal wastes (the carbonaceous solid portion of waste resulting from the cleaning of coal) into value-added products that are outside of traditional thermal and metallurgical markets can provide great societal benefits. These products can contribute to the U.S. gross domestic product while providing a stable and sizable market for U.S. coal and a path for utilizing coal wastes. Coal's and coal waste's unique structure and composition make them well suited as feedstocks for various carbon products such as building materials, carbon fibers, carbon foams, and carbon nanomaterials.



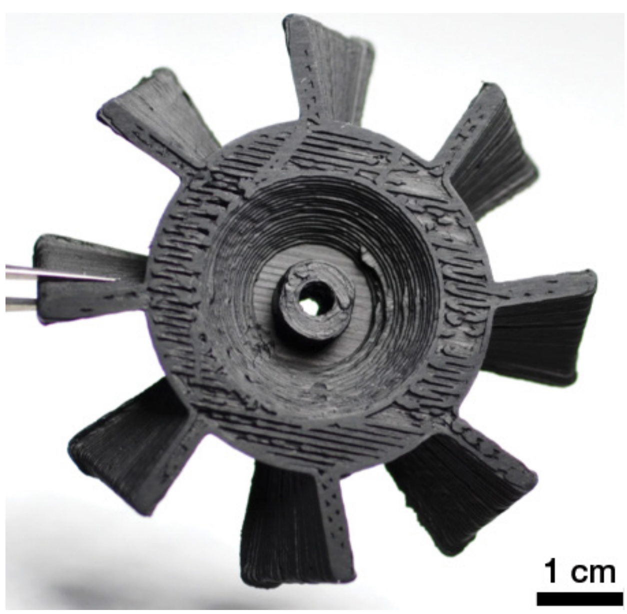
Graphene formed into shape of heat sink.

Lab-Scale Production of Particle Bonded Filaments with High-Loading Coal-Derived Carbon

Performer	University of Delaware
Award Number	FE0032147
Project Duration	02/01/2022 – 01/31/2025
Total Project Value	$ 1,250,000

The main objective is to develop a lab-scale manufacturing process to fabricate filaments with high carbon content for fused deposition modeling (FDM) 3D printing use. Graphene particles derived from domestic U.S. coal wastes will be used as feedstock for filament development. The specific objectives are to (1) develop a coal-enhanced filament production technology to fabricate filament containing high loading of coal-derived graphene, (2) develop debinding and sintering post-processing to fabricate a fully carbon preform structure, (3) develop a composite material based on the carbon preform structure and explorationally evaluate composite properties as a potential alternative to carbon fiber composite, and (4) perform a full techno-economic analysis to assess the coal-enhanced filament potential for the fast-growing and high-value additive manufacturing and composite market.

Using carbon nanomaterials derived from plentiful domestic U.S. coals and their wastes provides abundant and low-cost feedstock resources for 3D printing, offering a great upgrading opportunity to develop high-value carbon-filled filament for the carbon economy. The proposed multiscale reinforced composite concept based on 3D printing-enabled coal-derived carbon will address DOE's goal of extracting the full economic value from coal-derived materials. Using the low-cost and abundant coal-derived carbon feedstock to develop multiscale carbon preform through 3D printing and sintering can significantly enhance the composite multiscale reinforcing effect and become a promising alternative to carbon fiber in the fast-growing and high-value aerospace, defense, and vehicle lightweight composite markets.



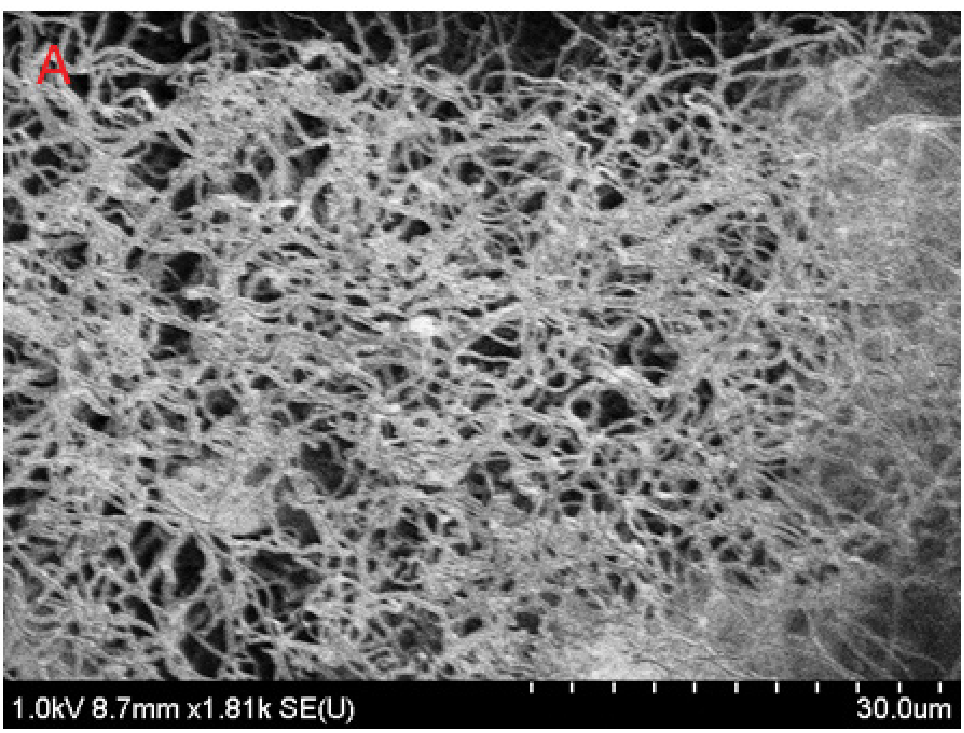
3D Printed carbon/carbon composite compressor for engine.

Development of Coal-based Supercapacitor Materials for Energy Storage

Performer	University of Illinois
Award Number	FE0032283
Project Duration	08/01/2023 – 07/31/2025
Total Project Value	$ 1,257,427

This project will develop high-value supercapacitor (SC) materials (i.e., carbon nanotubes (CNT) or carbon nanofibers (CNF) and functionalized porous carbon) from domestic coal in a cost-effective manner. This includes converting coal samples to high-performance SC materials at a laboratory scale and quantifying the performance of the developed materials in comparison with a baseline commercial material and performing a technoeconomic analysis and technology gap assessment for the proposed technology. The developed materials will be extensively characterized, and the impact of the coal feedstock type and synthesis methods on the yield and quality of each product will be determined. The feasibility of producing coal-based SC materials with performance similar to commercial SC materials but at less than half the current cost of commercial materials will be evaluated.

Conversion of coal and coal wastes (the carbonaceous solid portion of waste resulting from the cleaning of coal) into value-added products that are outside of traditional thermal and metallurgical markets can provide great societal benefits. These products can contribute to the U.S. gross domestic product while providing a stable and sizable market for U.S. coal and a path for utilizing coal wastes.



Coal-based CNT/CNF sample.

Production of Carbon Nanomaterials and Sorbents from Domestic U.S. Coal

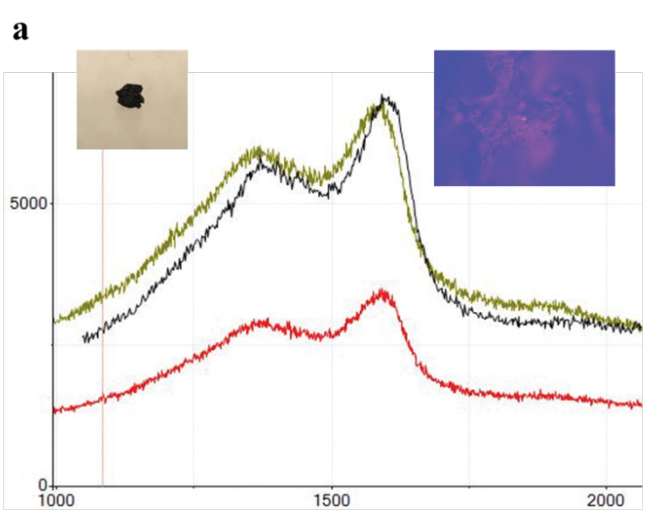
Performer	University of Illinois
Award Number	FE0031798
Project Duration	11/01/2019 – 10/31/2023
Total Project Value	$ 988,431
Collaborator	Trimeric Corporation

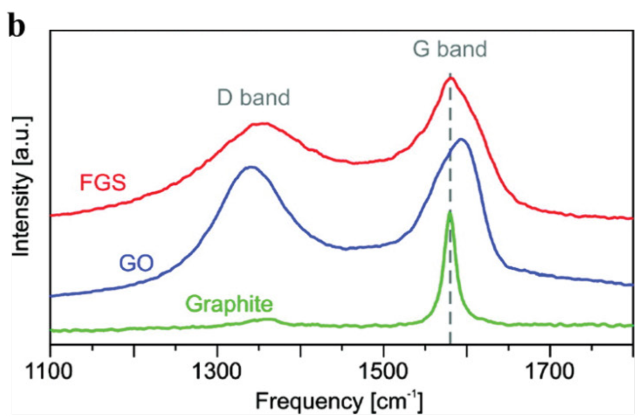
The main goal of this project was to produce high-value carbon nanomaterials and carbon sorbents from domestic coal resources in a cost-effective manner. Specific objectives of this project included (1) converting domestic coal samples to graphene oxide (GO), reduced graphene oxide (rGO), and activated carbon (AC) products at a laboratory scale by using an integrated approach with oxidation, reduction, and activation stages; and (2) performing a technoeconomic analysis, market evaluation, and technology gap assessment for the proposed technology.

Different domestic coal samples were processed using the proposed process to produce GO, rGO, and AC products. Materials developed were extensively characterized, and the impact of the coal feedstock type on the yield and quality of each product was determined.

A technoeconomic analysis for process simulation and conceptual cost estimation for a production facility, a market evaluation for graphene materials, and a technology gap analysis were performed. The feasibility of producing coal-based graphene materials at a cost 10–50 times lower than the current cost of graphene was evaluated.

With further development, the proposed technology could provide low-cost graphene materials for numerous applications such as composites, functional coatings, and electronics that could lead to a new market for domestic coal.





Raman spectra of FGS (functionalized graphene sheets), GO (graphene oxide), and graphite. G band is indicated with a dashed line (Source: K.N Kudin et al., *Nano Lett.*, 2008, 36-41).

Characterization by Raman spectroscopy of a graphene oxide sample produced from Powder River Basin (PRB) coal and comparison with theliterature data. (a) Replicate analyses of a laboratory-prepared sample from PRB coal, along with a sample photograph. (b) Raman spectra of graphene oxide materials or graphite from the literature.

Coal to Carbon Fiber (C2CF) Continuous Processing for High Value Composites

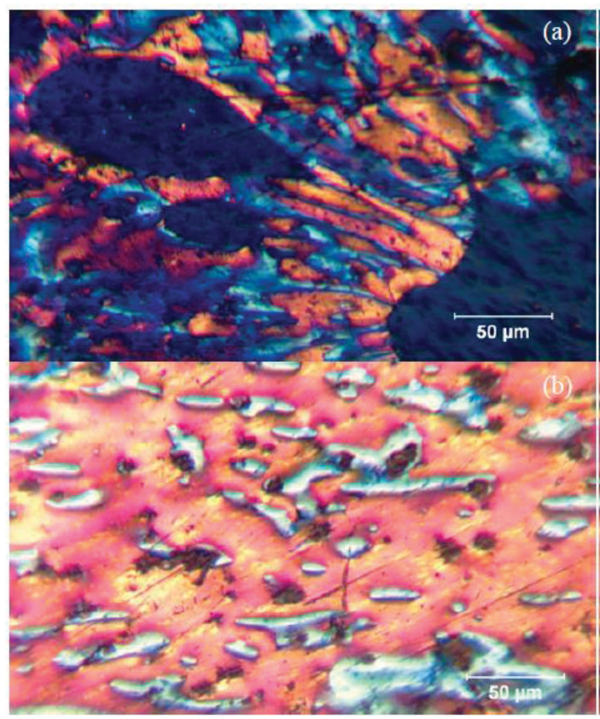
Performer	University of Kentucky
Award Number	FE0031796
Project Duration	10/01/2019 – 09/29/2024
Total Project Value	$ 1,847,971

The University of Kentucky (UK) Center for Applied Energy Research will develop and demonstrate the technologies, from precursor to continuous spinning and processing, to produce carbon fiber with an estimated value-add of up to 55 times the value of the coal-tar pitch (CTP) from which it is derived.

UK will partner with Koppers Inc., which buys tens of kilotons per year (kt/yr) of recovered domestic coal tar, to generate isotropic CTP that has ultra-low levels of quinoline insolubles (QI) and a high softening point for carbon fiber precursor. Koppers and UK will convert the CTP to mesophase pitch. UK will develop the processing of continuous multifilament fiber to generate high-quality carbon fiber from this new mesophase precursor. Collaborating with Materials Sciences LLC, UK will develop subsequent thermal processing for high-volume efficient throughput of coal-derived carbon-fiber preforms. In the end, the project aims to develop novel low-QI CTP and subsequent mesophase pitch in a process easily scaled to tens of kt/ yr, ready for scale-up, and to demonstrate end composites that will lead to new markets.

The project is expected to increase domestic and international marketability of U.S. coals through new products, creating new or maintaining existing U.S. coal industry jobs. The carbon products developed could lead to the creation of new complementary industries that will increase the value of U.S. coal resources.

Utilizing coal for carbon materials production creates new business opportunities by integrating coal into industries that typically do not use it in their manufacturing processes to add value. Coal-based carbon fiber and carbon-fiber reinforced polymers offer opportunities for producing new forms of lightweight structural materials and composites which have utility in automotive and aerospace applications.



Polarized reflected light microscopy imaging of the Koppers coal tar mesophase. (a) Sample C2CF-20-0002, 72-76% mesophase. (b) Sample C2CF-20-0012, 96 – 100% mesophase.

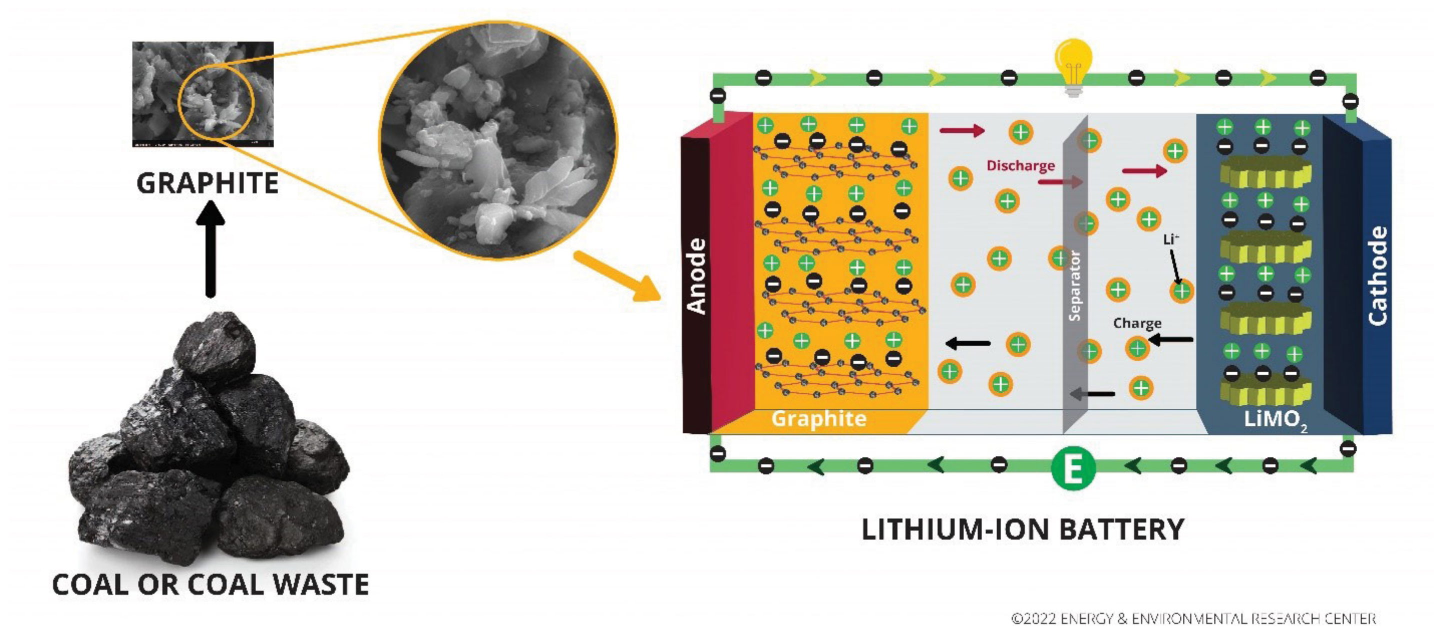
Advanced Processing of Coal and Waste Coal to Produce Graphite for Fast-Charging Lithium-Ion Battery Anode

Performer	**University of North Dakota**
Award Number	FE0032139
Project Duration	04/07/2022 – 04/06/2025
Total Project Value	$ 1,542,469

The proposed project will validate an approach to make high-grade graphite from North Dakota lignite coal and lignite coal waste and to fabricate and test a fast-chargeable (FC) lithium-ion battery (LIB) anode prototype made from the produced graphite. Two pathways for coal-derived graphite will be pursued for comparative purposes:

(1) lignite coal waste-to-graphite method and (2) lignite coal tar pitch-to-graphite method. The graphite made from each process will be further functionalized and utilized to fabricate and test a FC LIB anode prototype.

Anticipated project impacts include providing an economic boost to coal and power plant communities in North Dakota by producing a high-value product from lignite and lignite coal wastes, creating a FC LIB anode material to meet the demands of a fast-growing LIB market, and creating opportunities for U.S. independence from foreign sources of synthetic graphite.

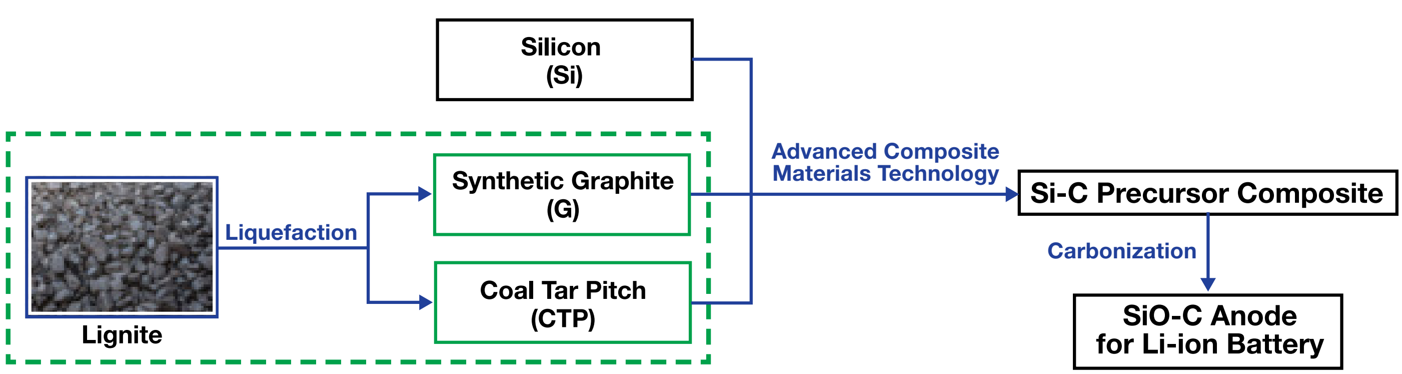


Lignite-Derived Carbon Materials for Lithium-Ion Battery Anodes

Performer	**University of North Dakota**
Award Number	FE0031984
Project Duration	01/20/2021 – 06/30/2024
Total Project Value	$ 667,465
Collaborators	Clean Republic LLC; The North American Coal Corporation

The overall goal of this project is to develop advanced anode materials for lithium-ion batteries (LIB) from lignite-derived carbon feedstock. Specific objectives include (1) prepare silicon carbon (Si-C) composite anode materials for LIBs using lignite-derived pitch and synthetic graphite (SG) as the main feedstock; (2) identify the optimal pitch and SG for LIB anode applications from a variety of sources produced by a co-sponsor; (3) develop a low-cost and scalable process to make porous and spherical Si-C composite anode materials; (4) evaluate the battery performance of the new Si-C composite anodes and compare with a similar commercial anode as the benchmark; (5) investigate the feasibility of making the Si-C composite anodes at pilot scale; and (6) evaluate the economic and commercial potential of the technology.

The anticipated benefits of this project are (1) the unique high-quality lignite-derived pitch and synthetic graphite will be suitable feedstocks for high-value carbon-based LIB anode materials such as Si-C composite anodes; (2) the current technology of preparing Si-C anode materials will be advanced toward a low-cost and high-performance product; (3) the project will accelerate the commercialization of production of high-quality lignite-derived pitch and SG through opening a high-value LIB market; and (4) the domestic and international marketability of U.S. coals and of domestic production of LIBs will be increased.



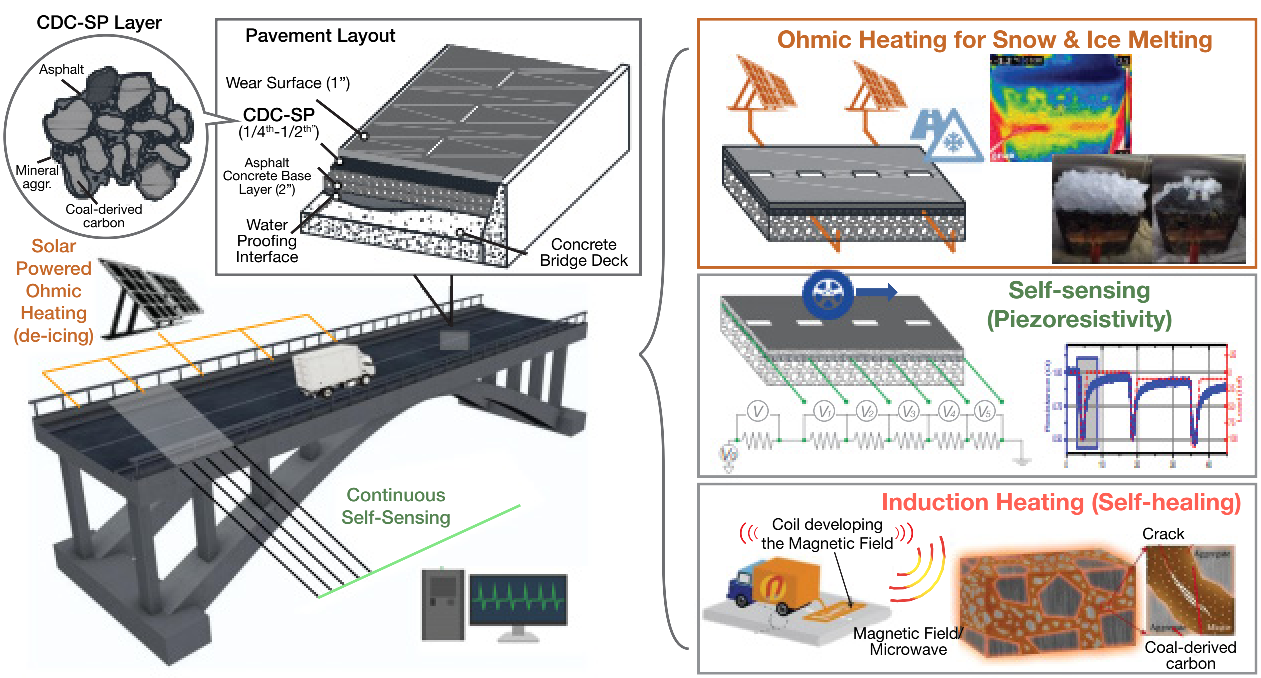
Simplified schematic for producing lithium ion battery anodes from North Dakota lignite.

Utilizing Coal-Derived Solid Carbon Materials Towards Next-Generation Smart and Multifunction Pavements

Performer	**University of Tennessee**
Award Number	FE0031983
Project Duration	01/05/2021 – 03/31/2024
Total Project Value	$ 537,500

This project planned to develop and demonstrate a field deployable, multifunctional smart pavement system made from domestic coal-derived solid carbon materials. Research demonstrated the use of coke-like coal char, a key byproduct of the coal pyrolysis process, in the design and construction of a prototype multifunctional pavement system that could provide roadways with the capability for self-sensing, self-heating (deicing), and self-healing. This project (1) carried out multiscale experimental and numerical studies to establish processing-structure- property relationships, (2) developed a novel coal char-bearing multifunctional pavement system and gathered experimental data to evaluate its performance and assess the feasibility for scale up, (3) tested a prototype pavement section to evaluate its intended functionalities, and (4) performed a comprehensive technoeconomic analysis to identify the potential market size and key technology gaps to field implementation.

The coal-based multifunctional pavement system developed in this project could provide a promising pathway to convert U.S. domestic coal resources to a high-value solid carbon product by promoting the integration of domestic coal resources in bridge and roadway construction. Compared to current roadways, potential performance benefits of the multifunctional pavement system include reduced maintenance costs, extended service life, and reduced travel delay costs imposed by deicing.



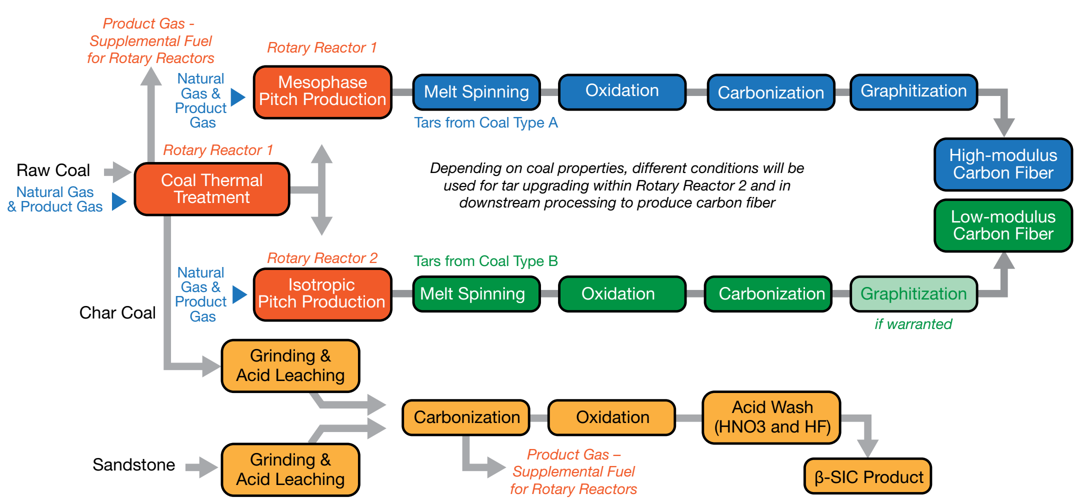
The proposed multifunctional pavement made from coal-derived solid carbon (e.g., coal-char, coke).

Sub-Pilot-Scale Production of High-Value Products from U.S. Coals

Performer	**University of Utah**
Award Number	FE0031880
Project Duration	06/01/2020 – 11/30/2023
Total Project Value	$ 1,932,495
Collaborators	University of Wyoming; Marshall University

The University of Utah's project objectives (1) provided sub-pilot-scale verification of lab-scale developments on the production of isotropic and mesophase coal-tar pitch for carbon fiber production, using coals from five U.S. coal-producing regions (Utah, Wyoming, West Virginia, Alaska, and Illinois), (2) investigated the production of a high-value beta silicon carbide (β-SiC) byproduct using residual coal char from the tar production process, and (3) developed an extensive database and suite of tools for data analysis and economic modeling to relate process conditions to product quality and assess the economic viability of coals from different regions for producing specific high-value products. An existing 0.5 ton per day rotary reactor was used to pyrolyze coals to produce tars suitable for upgrading to coal-tar pitch. The same reactor technology was used in a second stage to perform the tar upgrading to either mesophase or isotropic pitch, depending on the properties of the original coal. The operating parameters used for this effort were based on scaling up previous lab-scale R&D that identified conditions for primary and secondary pyrolysis reactions leading to desired chemical properties for the tar intermediates. Additional lab-scale testing was performed on the new coals included in this study to provide this information. The product pitch was spun into carbon fiber to assess fiber quality arising from different coals and from different processing conditions. The solid char byproduct from coal pyrolysis was used to produce a high-value β-SiC byproduct. A novel database, coupled with detailed economic models and analysis tools, was created to provide a means for understanding correlations between coal properties, process conditions, and product quality to allow for the assessment of the potential economic viability of coals from different regions for producing specific high-value products. Access to some of these computational tools will become available to the public through a web-based community portal.

This effort is a major step toward providing a low-cost carbon fiber product from coal for potential use in automotive and other important markets. It is expected to lead to new opportunities for economic development in communities with coal-based economies.

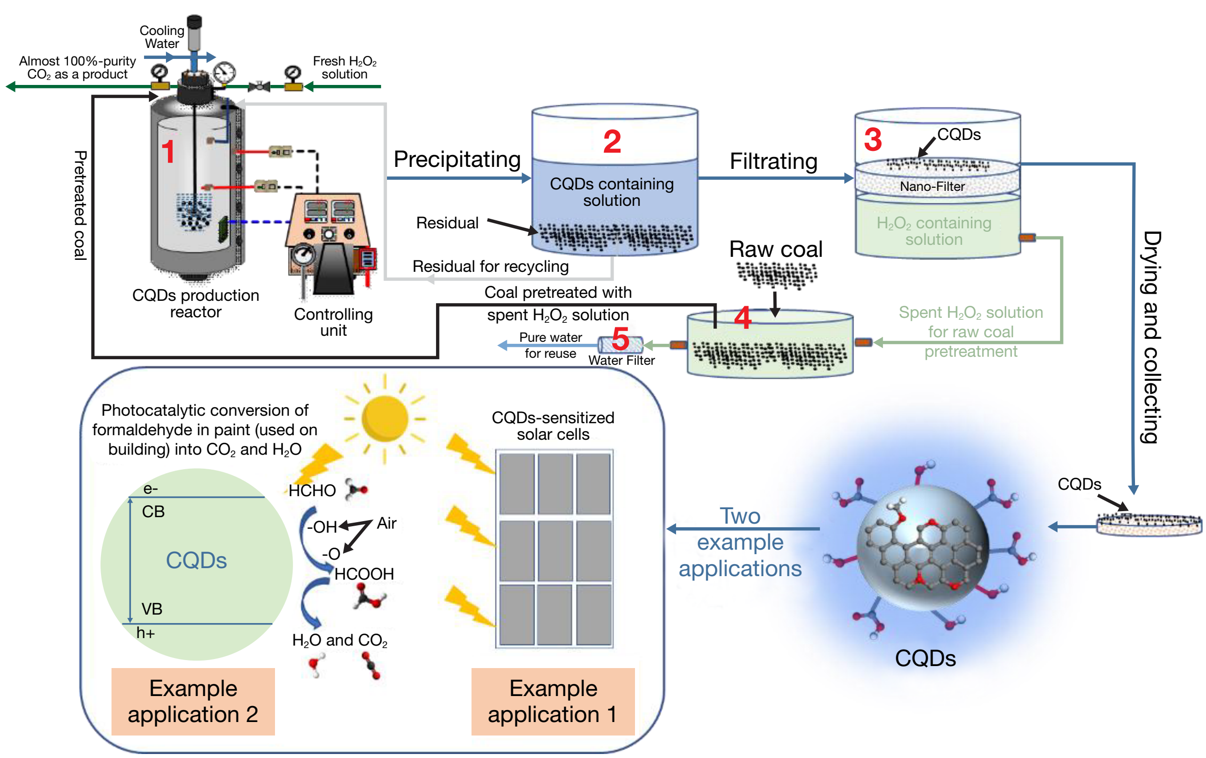


Process for the production of coal-tar pitch products, carbon fiber products and β-SiC byproduct from raw coal.

Environmentally Friendly Production of High-Quality and Multifunctional Carbon Quantum Dots from Coal

Performer	**University of Wyoming**
Award Number	FE0031997
Project Duration	01/01/2021 – 12/31/2023
Total Project Value	$ 554,765
Collaborator	University of Utah

The objective of the project was to develop an innovative, facile, low-temperature, cost-effective, and environmentally friendly technology for producing high-value coal-based carbon quantum dots (CQDs), which are not yet a commodity product. The coal based CQD production is based on a proprietary technology developed at the University of Wyoming (UW). A green solvent is used to directly extracting carbon out of coal. Optimal extraction conditions will be obtained via a study of the effects of different factors on the quantity and qualities (size, bandgap, and purity) of the solid carbon obtained from coal. Since CQDs have novel optical properties, efficiencies of photoelectric conversion and photocatalysis of the synthesized CQDs were carried out in order to determine suitability towards each application. Additionally, a techno-economic analysis of the novel coal- to-CQDs technology was performed to evaluate the proposed CDQ production technology. The market value of these products exceeds the fuel value of coal, representing an opportunity to offer value to both manufacturers and consumers of coal-derived carbon products.



Schematic drawing of the proposed CQD technology.

Environmentally Friendly Use of Carbon Ore for Advanced Building Materials for Homes and Commercial Buildings

Performer	X-MAT CCC, LLC
Award Number	FE0031985
Project Duration	01/01/2021 – 05/31/2024
Total Project Value	$ 3,572,286
Collaborators	Center for Applied Research and Technology, Inc. (CART); Industrial Commission of North Dakota - Lignite Energy Council; Semplastics EHC, LLC; University of North Dakota Energy and Environmental Research Center (UNDEERC)

X-MAT CCC, LLC will work with production partner the Center for Applied Research and Technology, Inc. (CART) to establish the utility of coal-derived building materials (CDBM). The project will result in a market-worthy design for a CDBM structure and achieve the performance requirements to meet insurance standards (seismic, fire, wind resistance) and those of the International Building Code (IBC). CDBM components contain at least 55% coal by weight. Including the binders within the resin, the components contain at least 71% carbon by weight. In this Phase I effort, X-MAT CCC will perform the development and testing needed to improve the maturity of the technology.

X-MAT CDBM concept elevation.

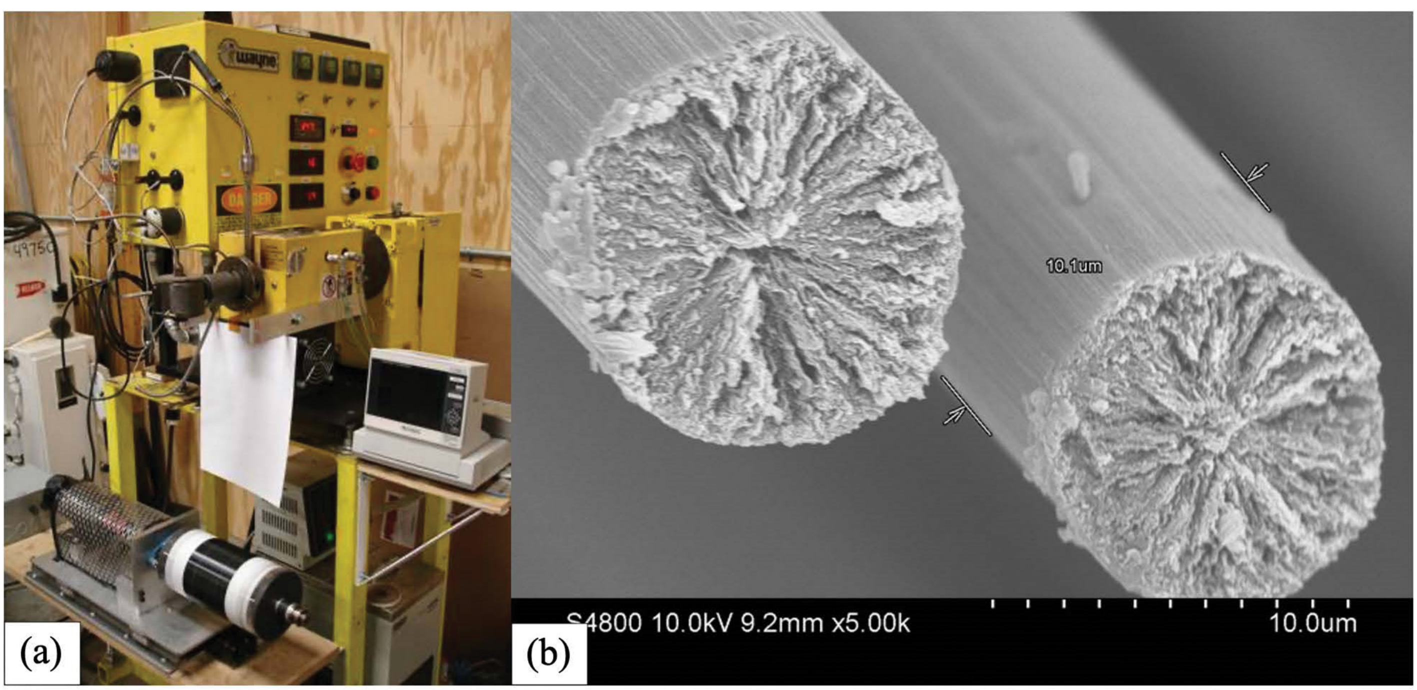
The project will examine the feasibility of utilizing CDBM for manufactured building components for lower-cost public housing and for higher-performance modular construction. The outcome of the project will not only reduce the cost of building construction for the targeted markets, but also maintain employment in the existing coal supply value chain including mining and preparation, and additionally provide employment opportunity in the CDBM industry.

C4Ward@Scale: Scaled-Up Coal Conversion for Carbon Fibers and Graphite

Performer	**University of Kentucky Center for Applied Energy Research**
Award Number	FE0032313
Project Duration	01/02/2024 – 01/01/2027
Total Project Value	$ 5,919,907

The purpose of this work is to develop the scientific understanding and processing technologies to enable safe, efficient conversion of domestic carbon ores and waste coals to high-value products including graphitic carbon fibers for composites, and anode-grade graphite powders for energy storage. Building on prior work in collaboration with ORNL, this project will scale up processing to the semi-production scale, which will allow for production of sufficient quantities of materials to investigate relevant industrial processing including multifilament melt spinning of fibers and anode powder classification for batteries.

This work will enable scale-up and improve the capability to generate carbon pitch from carbon ore domestically, assisting in the production of carbon fiber and synthetic graphite.



(a) Single screw extruder system for the melt spinning of pitch fiber. (b) SEM images of mesophase pitch derived carbon fiber.

FEEDSTOCK UPGRADING

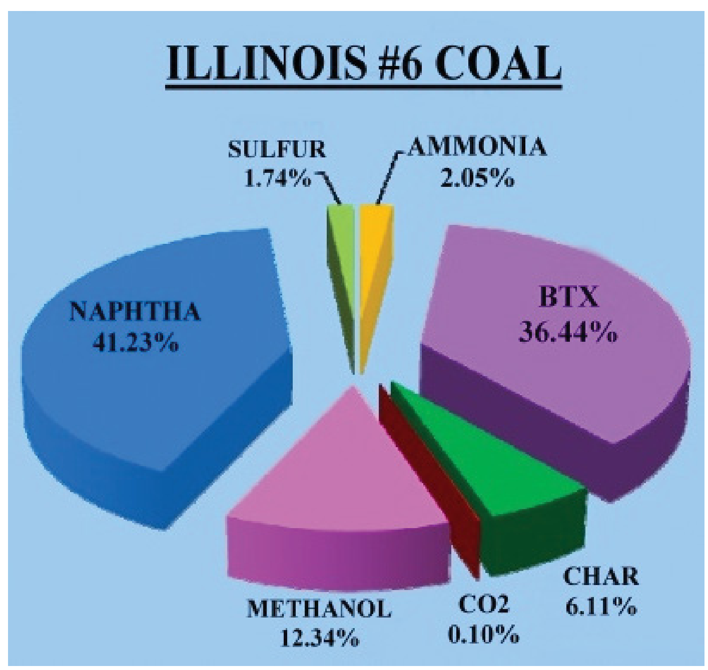
The Novel Charfuel Coal Refining Process 18 Tpd Pilot Plant Project for Co-Producing an Upgraded Coal Product and Commercially Valuable Co-Products

Performer	**Carbon Fuels LLC**
Award Number	FE0031708
Project Duration	02/01/2019 – 01/31/2024
Total Project Value	$ 4,334,144
Collaborators	Hazen Research, Inc.; University of Illinois; University of Wyoming

Carbon Fuels, LLC will operate and integrate an 18 ton-per-day pilot plant using two coal ranks demonstrating process flexibility by producing different products (gas, liquid, and char), as well as determining operating parameters for identifying scale-up criteria for the two coal ranks; Other objectives of this work include generating engineering and design information for use in designing a commercial-scale plant; determining the environmental issues surrounding the process and the products by analysis of effluent streams; producing sufficient quantities of product to allow reliable commercial economic evaluation of both the refined coal product and the co-products; and assessing longer-term reliability of unit operations.

To achieve these objectives, Carbon Fuels will reconfigure the current process to accommodate a large amount of coal and corresponding product storage in order to meet the technical and economic performance targets required to commercialize the technology: perform computer analysis of the critical process parameters against produced products to optimize a particular slate of products produced from a specific rank of coal, analyze the data generated from the pilot plant for each rank of coal to assess economic feasibility and viability, conduct a market penetration analysis of the upgraded coal product and all coproducts for each coal rank, and conduct a complete environmental assessment of a commercial facility for each rank of coal, including pollutants reporting to the upgraded coal product, as well as external process water consumption and the environmental emissions impact of the process associated with each coal rank.

Project benefits include improved quality of coal as a fuel and production of high-value products from coal. Data obtained from the project could subsequently be used to increase the capacity of the process to commercial-scale modules that could potentially be integrated with existing power plants to supplement current revenue.



Main products produced from the Charfuel® process for Illinois #6 coal.

ABBREVIATIONS

3D .... three-dimensional
AC .... activated carbon
AM .... additive manufacturing
β-SiC .... beta form of silicon carbide
BSE .... backscattered electron
C2CF .... coal to carbon fiber
CART ..... Center for Applied Research and Technology, Inc.
CDBM .... Coal-Derived Building Materials
CDC-SP ...... coal-derived carbon enabled smart pavement
CGM .... coal-derived graphite manufacturing
CMC .... carbon metal composites
CNF .... carbon nanofibers
CNT .... carbon nanotubes
CQD .... carbon quantum dots
CTP .... coal-tar pitch
DOE .... Department of Energy (U.S.)
FC .... fast-charging
FDM .... fused deposition modeling
FJH .... flash Joule heating
FWP .... Field Work Proposal (DOE)
G .... synthetic graphite
GO .... graphene oxide
HHS .... hydrophobic-hydrophilic separation
IBC .... International Building Code
kt/yr .... kilotons per year
LCA .... life cycle analysis
LIB .... lithium-ion batteries
Li-ion .... lithium-ion
LLC .... Limited Liability Company
NETL .... National Energy Technology Laboratory (DOE)
ORNL .... Oak Ridge National Laboratory
PEEK .... polyether ether ketone
PRB .... Powder River Basin
QI .... quinoline insoluble
R&D .... research and development
rGO .... reduced graphene oxide
SC .... supercapacitor
SEM .... scanning electron microscope
Si .... silicon
Si-C .... silicon carbide
SiO-C .... silicon oxide/carbide
SG .... synthetic graphite
TEA .... technical and economic assessment
Tpd .... ton-per-day
TSU .... Tennessee State University
TTU .... Tennessee Technological University
UK .... University of Kentucky
UND .... University of North Dakota
UNDEERC .... University of North Dakota Energy and Environmental Research Center
U.S. .... United States
UV .... ultra-violet
VARTM .... vacuum assisted resin transfer molding
wt% .... weight percent

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https://netl.doe.gov/resource-sustainability/carbon-ore-processing

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U.S. DEPARTMENT OF ENERGY

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