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CONTENTS

Introduction ........................................................................................................................................................................6

COAL TO CARBON PRODUCTS ..............................................................................................................................................7
Battelle Memorial Institute: A Novel Process for Converting Coal to High-Value Polyurethane Products .........................9
C-Crete Technologies, LLC: Light, High Performance and Scalable Coal-Derived Composites for Construction: Precast and Cast-In-Place Applications .....................................................................................................................10
C-Crete Technologies, LLC: Low Cost Conversion of Coal to Graphene: Bench-Scale Testing, Modeling and Techno-Economical Analysis .................................................................................................................................11
C-Crete Technologies, LLC: Low Cost, Rapid and Scalable Microwave Carbon Ore Melt-Casting for Modular Carbon-Based Buildings ............................................................................................................................12
CFOAM, LLC: Continuous Processing of Carbon Foam Products Made from Coal at Atmospheric Pressure ...............13
George Washington University: Conversion of Coal to Li-Ion Battery Grade (Potato) Graphite ......................................14
H Quest Vanguard, Inc.: Efficient Ultra-Rapid Microwave Plasma Process for Generation of High Value Industrial Carbons and 3D Printable Composites from Domestic Coal ...........................................................15
Massachusetts Institute of Technology: Carbon Foam House ..................................................................................................16
Microbeam Technologies, Inc.: Development of Novel Sintered Carbon-Ore Building Materials ..................................17
Minus 100, LLC: U.S. Coal to Conductive Inks ..........................................................................................................................18
Oak Ridge National Laboratory: C4WARD: Coal Conversion for Carbon Fibers and Composites ................................19
Oak Ridge National Laboratory (ORNL): Scale Up Production of Graphite and Carbon Fibers from Carbon Ore and Coal Refuse .......................................................................................................................20
Ohio University: Direct Utilization of U.S. Coal as Feedstock for the Manufacture of High-Value Coal Plastic Composites ............................................................................................................................................21
Ohio University: Coal-Derived Alternatives to Fiber-Cementitious Building Materials ......................................................22
Ohio University: Coal Plastic Composite Piping Infrastructure Components ...............................................................23
Ohio University: Utilization of Carbon Supply Chain Wastes and Byproducts to Manufacture Graphite for Energy Storage Applications ...........................................................................................................24
Pennsylvania State University: Coal-Based Bricks & Blocks (CBBS): Process Development to Prototype Fabrication Coupled with Techno-Economic Analysis and Market Survey .................................25
Physical Sciences, Inc.: Efficient Process for the Production of High Conductivity, Carbon-Rich Materials from Coal ................................................................. 26

Ramaco Carbon, LLC: Coal to Carbon Fiber Novel Supercritical Carbon Dioxide (sCO₂) Solvated Process .......... 27

Ramaco Carbon, LLC: Experimental Validation and Continuous Testing of an On-Purpose High-Yield Pitch Synthesis Process for Producing Carbon Fiber from US Domestic Coal ................................. 28

Semplastics EHC LLC: Coal as Value Added for Lithium Battery Anodes ................................................................. 29

Semplastics EHC LLC: Coal Core Composites for Low Cost, Light Weight, Fire Resistant Panels and Roofing Materials .................................................................................. 30

Semplastics EHC, LLC: High-Performance Coal-Based Commercial Facade Panels and Architectural Components .................................................................................................................. 31

Semplastics EHC, LLC: Low Weight, High Strength Coal-Based Building Materials for Infrastructure Products ........ 32

Semplastics EHC, LLC: Coal-Waste-Enhanced Filaments for Additive Manufacturing of High-Temperature Plastics and Ceramic Composites ........................................................................ 33

Universal Matter Ltd: Developing a Facile Technology for Converting Domestic United States Coal into High-Value Graphene ................................................................. 34

University of Delaware: Lab-Scale Production of Particle Bonded Filaments with High-Loading Coal-Derived Carbon ........................................................................................................ 35

University of Illinois: Production of Carbon Nanomaterials and Sorbents from Domestic U.S. Coal ................. 36

University of Kentucky: Coal to Carbon Fiber (C2CF) Continuous Processing for High Value Composites ........... 37

University of North Dakota Energy and Environmental Research Center (UNDEERC): Laboratory-Scale Coal-Derived Graphene Process ................................................................. 39

University of North Dakota Energy and Environmental Research Center (UNDEERC): Lignite-Derived Carbon Materials for Lithium-Ion Battery Anodes ...................................................... 40

University of Tennessee: Utilizing Coal-Derived Solid Carbon Materials Towards Next-Generation Smart and Multifunction Pavements ................................................................. 41

University of Utah: Sub-Pilot-Scale Production of High-Value Products from U.S. Coals ........................................ 42

University of Wyoming: Eco-Friendly High-Performance Building Material Development from Coal .................. 43

University of Wyoming: Environmentally Friendly Production of High-Quality and Multifunctional Carbon Quantum Dots from Coal ................................................................. 44

X-MAT CCC, LLC: Modular, Manufactured Homes from Coal-Based Building Materials ......................................... 45
COAL TO CARBON PRODUCTS & COAL PROPERTIES DATABASE ................................................................. 46
National Energy Technology Laboratory (NETL): Carbon Materials Manufacturing .......................... 47

FEEDSTOCK UPGRADED ........................................................................................................................................ 48
Carbon Fuels LLC: The Novel Charfuel Coal Refining Process 18 Tpd Pilot Plant Project for Co-Producing an Upgraded Coal Product and Commercially Valuable Co-Products ......................................................... 49

Abbreviations ....................................................................................................................................................... 51
Contacts ............................................................................................................................................................... 52
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 its 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 sustains jobs within a critical sector of the US 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 nano-materials 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

<table>
<thead>
<tr>
<th>Organization</th>
<th>Project Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battelle Memorial Institute</td>
<td>A Novel Process for Converting Coal to High-Value Polyurethane Products</td>
<td>9</td>
</tr>
<tr>
<td>C-Crete Technologies, LLC</td>
<td>Light, High Performance and Scalable Coal-Derived Composites for Construction: Precast and Cast-In-Place Applications</td>
<td>10</td>
</tr>
<tr>
<td>C-Crete Technologies, LLC</td>
<td>Low Cost Conversion of Coal to Graphene: Bench-Scale Testing, Modeling and Techno-Economical Analysis</td>
<td>11</td>
</tr>
<tr>
<td>C-Crete Technologies, LLC</td>
<td>Low Cost, Rapid and Scalable Microwave Carbon Ore Melt-Casting for Modular Carbon-Based Buildings</td>
<td>12</td>
</tr>
<tr>
<td>CFOAM, LLC</td>
<td>Continuous Processing of Carbon Foam Products Made from Coal at Atmospheric Pressure</td>
<td>13</td>
</tr>
<tr>
<td>George Washington University</td>
<td>Conversion of Coal to Li-Ion Battery Grade (Potato) Graphite</td>
<td>14</td>
</tr>
<tr>
<td>H Quest Vanguard, Inc.</td>
<td>Efficient Ultra-Rapid Microwave Plasma Process for Generation of High Value Industrial Carbons and 3D Printable Composites from Domestic Coal</td>
<td>15</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>Carbon Foam House</td>
<td>16</td>
</tr>
<tr>
<td>Microbeam Technologies, Inc.</td>
<td>Development of Novel Sintered Carbon-Ore Building Materials</td>
<td>17</td>
</tr>
<tr>
<td>Minus 100, LLC</td>
<td>U.S. Coal to Conductive Inks</td>
<td>18</td>
</tr>
<tr>
<td>Oak Ridge National Laboratory</td>
<td>C4WARD: Coal Conversion for Carbon Fibers and Composites</td>
<td>19</td>
</tr>
<tr>
<td>Oak Ridge National Laboratory (ORNL)</td>
<td>Scale Up Production of Graphite and Carbon Fibers from Carbon Ore and Coal Refuse</td>
<td>20</td>
</tr>
<tr>
<td>Ohio University</td>
<td>Direct Utilization of U.S. Coal as Feedstock for the Manufacture of High-Value Coal Plastic Composites</td>
<td>21</td>
</tr>
<tr>
<td>Ohio University</td>
<td>Coal-Derived Alternatives to Fiber-Cementitious Building Materials</td>
<td>22</td>
</tr>
<tr>
<td>Ohio University</td>
<td>Coal Plastic Composite Piping Infrastructure Components</td>
<td>23</td>
</tr>
<tr>
<td>Ohio University</td>
<td>Utilization of Carbon Supply Chain Wastes and Byproducts to Manufacture Graphite for Energy Storage Applications</td>
<td>24</td>
</tr>
<tr>
<td>Pennsylvania State University</td>
<td>Coal-Based Bricks &amp; Blocks (CBBS): Process Development to Prototype Fabrication Coupled with Techno-Economic Analysis and Market Survey</td>
<td>25</td>
</tr>
<tr>
<td>Physical Sciences, Inc.</td>
<td>Efficient Process for the Production of High Conductivity, Carbon-Rich Materials from Coal</td>
<td>26</td>
</tr>
</tbody>
</table>
Ramaco Carbon, LLC:
Coal to Carbon Fiber Novel Supercritical Carbon Dioxide (sCO\textsubscript{2}) Solvated Process ................................................................. 27

Ramaco Carbon, LLC:
Experimental Validation and Continuous Testing of an On-Purpose High-Yield Pitch Synthesis Process for Producing Carbon Fiber from US Domestic Coal................................................................................................. 28

Semplastics EHC LLC:
Coal Core Composites for Low Cost, Light Weight, Fire Resistant Panels and Roofing Materials .......................................................... 30

Semplastics EHC LLC:
Coal-Waste-Enhanced Filaments for Additive Manufacturing of High-Temperature Plastics and Ceramic Composites.............. 33

Universal Matter Ltd:
Developing a Facile Technology for Converting Domestic United States Coal into High-Value Graphene................................. 34

University of Delaware:
Lab-Scale Production of Particle Bonded Filaments with High-Loading Coal-Derived Carbon ............................................................. 35

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Production of Carbon Nanomaterials and Sorbents from Domestic U.S. Coal ...................................................................................... 36

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Coal to Carbon Fiber (C2CF) Continuous Processing for High Value Composites ........................................................................... 37

University of North Dakota Energy and Environmental Research Center (UNDEERC):
Laboratory-Scale Coal-Derived Graphene Process .............................................................................................................................. 39

University of North Dakota Energy and Environmental Research Center (UNDEERC):
Lignite-Derived Carbon Materials for Lithium-Ion Battery Anodes ................................................................................................. 40

University of Tennessee:
Utilizing Coal-Derived Solid Carbon Materials Towards Next-Generation Smart and Multifunction Pavements.......................... 41

University of Utah:
Sub-Pilot-Scale Production of High-Value Products from U.S. Coals .................................................................................................. 42

University of Wyoming:
Eco-Friendly High-Performance Building Material Development from Coal ......................................................................................... 43

University of Wyoming:
Environmentally Friendly Production of High-Quality and Multifunctional Carbon Quantum Dots from Coal.............................. 44

X-MAT CCC, LLC:
Modular, Manufactured Homes from Coal-Based Building Materials................................................................................................. 45
A Novel Process for Converting Coal to High-Value Polyurethane Products

<table>
<thead>
<tr>
<th>Performer</th>
<th>Battelle Memorial Institute</th>
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<tr>
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The goal is to advance Battelle’s breakthrough technology for making high-value polyurethane (PU) foam from coal, which involves three subsystems: preparing liquefied coal via direct liquefaction, converting liquefied coal to polyols via ozonation, and converting coal-derived polyols to PU foam. The objectives are to (1) demonstrate the proposed novel coal-to-PU foam process at bench scale and establish a straightforward path to near-term commercial production, (2) confirm a high rate of return compared to petroleum-based, solid PU foam products, (3) determine the PU foam properties to establish a market value for these high-value solid products, and (4) develop a process scale-up and commercialization plan.

Potential benefits include a breakthrough in innovative utilization of U.S. coals without the need for advanced preparation of coal. Target products, which could be up to $81 billion/year, could lead to coatings and adhesives manufacturing. The process developed could also help reduce petroleum imports and improve the economics of PU foam production.

Liquefied Coal \(\rightarrow\) Distillation (optional) \(\rightarrow\) Fuel Oil (optional)

\textit{SUBSYSTEM 1}

\textit{Ozonation}

\(O_3\) \(\rightarrow\) \(H_2SO_4\) \(\rightarrow\) Hexanol

\textit{SUBSYSTEM 2}

\textit{Transesterification}

Glycerol \(\rightarrow\) Polyol

\textit{Polyol to PU Foam}

MDI/HMDI \(\rightarrow\) PU Foam

\textit{SUBSYSTEM 3}

Coal to polyurethane foam process.
Light, High Performance and Scalable Coal-Derived Composites for Construction: Precast and Cast-In-Place Applications

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<tr>
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<th>C-Crete Technologies, LLC</th>
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<tr>
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Carbon materials and carbon composites have mechanical, thermal, and electrical properties that can produce new types of building materials or superior versions of existing building materials. The market value of these products exceeds the fuel value of coal, representing an opportunity to produce products that have superior properties, and in some cases lower cost, offering value to both manufacturers and consumers of coal-derived building materials. This project may provide key technical information needed to optimize coal-derived construction materials with near-term implications for precast applications.

C-Crete Technologies’ overall objective is to produce coal-based construction material that has up to ~95 percent by weight coal with physical, chemical, and thermal properties exceeding ordinary Portland cement (OPC)-based construction material. The first goal is to minimize external binders by implementing novel mixing techniques while exceeding the performance/cost ratio of OPC. The second is to demonstrate a semi-continuous production process of precast products through design and fabrication of a bench-scale semi-continuous process.

C-Crete Technologies will couple a combination of advanced synthesis, fabrication, characterization, and engineering to create novel coal-based construction materials. The strategy is to apply and further develop current data on binders, activators, and modular industrial design through a bottom-up approach.

A set of systems-scale analyses will be performed to understand the technoeconomics and determine the economic viability of the proposed technology and the market penetration possibilities. Candidates from a wide (coarse) Taguchi design of experiments on different recipes will be shortlisted using performance/cost ratio index (figure of merit) as the downselection criterion. The top candidates will be optimized by fine tuning the composition and curing parameters (a second refined Taguchi design) to achieve properties that exceed those of OPC. Refined recipes that surpass a comprehensive performance/cost index of OPC will be demonstrated, leading to the design and fabrication of a small bench-scale semi-continuous process.

Images represent coal-driven composites with more than 80% coal in the mix and strength of more than 4000 psi.
Low Cost Conversion of Coal to Graphene: Bench-Scale Testing, Modeling and Techno-Economical Analysis

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The overall objective of this project is 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) is bench-scale testing of flash Joule heating (FJH) and parametric study of FJH processes on various coal ranks. The second objective (Task 4-5) is 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) is 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/moisture.

This project could provide 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. This technology is scalable and could convert all coal ranks to graphene for <$40/ton in FJH cost, with a high yield of >90% and purity of >99%.

Manufacturing concrete composites reinforced with graphene.
Low Cost, Rapid and Scalable Microwave Carbon Ore Melt-Casting for Modular Carbon-Based Buildings

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 bench-scale fabrication protocols, 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 analysis to demonstrate feasibility for use in modular, precast buildings.

This project will provide key technical information to optimize coal-derived building components, perform various structural/environmental bench-scale testing for modular, interlocking precast building materials, and conduct key conceptual design, TEA, LCA modeling to demonstrate the feasibility of coal-based building prototypes. The technology can turn various coals to key components for modular buildings. Technical results will enable detailed assessment for commercial feasibility for large-scale coal feed manufacturing facilities to make carbon-based buildings. 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. The high-value building materials will significantly drive demand for domestic coals, raising their value across the whole coal industry.

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Bricks.
Continuous Processing of Carbon Foam Products Made from Coal at Atmospheric Pressure

The objective is to develop methods for continuous production of carbon foam panels and lightweight aggregates from coal at atmospheric pressure. Coal-derived carbon foams are currently produced commercially via a batch process at elevated pressure, primarily for use in composite tooling applications for the aerospace industry. This method of production limits carbon foam to high-value, small-volume markets. The goal of this project is to reduce the cost of carbon foam manufacture by over 90% to open up much larger market opportunities in the construction, infrastructure, and other industries, creating meaningful demand for U.S. coal. Several markets have been identified that could collectively result in the use of hundreds of millions of tons of coal and tens of billions of dollars of revenue generation per year, creating substantial coal demand with much greater value uplift and reduced emissions versus current combustion uses of coal.
Conversion of Coal to Li-Ion Battery Grade (Potato) Graphite

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<tr>
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<td>$ 949,030</td>
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The main objective 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 production from lignite.

Graphite from small (left) and large (right) grain sawdust.
Efficient Ultra-Rapid Microwave Plasma Process for Generation of High Value Industrial Carbons and 3D Printable Composites from Domestic Coal

The objective of this project is to establish the technical and economic feasibility of using coals from the major domestic coal basins—Powder River, North Appalachia, and Central Appalachia, which together account for 68% of the current U.S. coal production—as feedstocks for production of value-added solid products. Technical feasibility will be established through demonstration of rapid, efficient, high-yield conversion of commercially sourced domestic coals using a low-temperature microwave plasma coal pyrolysis technology (Wave Liquefaction™; WL), with subsequent conversion of liquid intermediaries into solid products. Economic feasibility will be established through a techno-economic assessment leveraging the experimental process data and targeted market studies for the solid products.

The two high-value solid product targeted categories are carbon and graphitic materials for industrial electrode applications and advanced 3D-printable carbon polymer composites. The first category represents an established industrial use case with a large and growing market, while the second represents an advanced manufacturing use case with potential for wide industrial adoption in a rapidly growing market. To address conversion by-products, solid char will be transformed into activated carbon feedstock, while the purity and composition of the aromatic compounds (BTEX—benzene, toluene, ethylbenzene and xylenes; naphthalene; and anthracene oil) will be evaluated for their potential use as feedstocks for the petrochemical industry.

Expected project outcomes include (1) advancing the understanding of low-temperature microwave plasma as a means of converting domestic coal into high-performance carbon materials such as polymer composites, graphitic materials, and activated carbon, and (2) integration of coal into the value chain of the advanced composites and 3D printing industries, neither of which have used coal in their typical manufacturing processes. Notably, high-performance advanced polymer composites are used in many industries, including aerospace and defense, where both strength and weight are of critical importance.

Direct microwave heating and plasma discharges drive rapid pyrolysis reactions within the hydrogen-rich media, affording control over liquid compositional profile (e.g., aromatic vs. naphthenic) and physical properties and low gas yields.
Carbon Foam House

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<td>Collaborators</td>
<td>Composite Design Studio, Ltd.; Huntsman Advanced Materials Americas, LLC; NanoComp Technologies, Inc.; Touchstone Research Laboratory, Ltd.</td>
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This project looks to deploy carbon foams derived from coal as core materials for all-composite buildings, with a prime focus on housing. The team is focusing primarily on carbon foam as a potential core substrate for carbon nanotube composite panels. Carbon foam offers non-combustible, acoustically absorptive, compression-carrying properties that seem well-suited to building use. Additionally, the project will look at using the electro-thermal capacity of carbon foam to permit heating and cooling in place of separate systems. Fire, structural, thermal, acoustic, and other properties will be tested per building code requirements. The main goals are to more fully characterize carbon foam as a composite substrate for building use. An all-carbon house will be designed using the poly-functional attributes of carbon foam (and carbon nanotube), and life cycle analysis and techno-economic analysis will be performed on this design pilot.

Carbon foam offers a core material for carbon-composite buildings as a vital aspect of the drive to supplement hydrogen production as the cheapest gas/energy. Mastering these novel forms of carbon via prototyping and testing through to pilot buildings aims to demonstrate efficient, cost-effective, high-quality building production. The beneficiaries will be those who own and process U.S. hydrocarbon assets and those who license cloud-delivered software to international markets to permit simple execution of all-composite buildings. Taking the difficulty out of composite design, engineering, and fabrication by embedding MIT and other expertise into simple-to-use software offers the United States the ability to repurpose its excess carbon ore and liberalize the production of buildings that could lead to a great reduction in costs, increasing affordability and sustainability throughout building markets.
Development of Novel Sintered Carbon-Ore Building Materials

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<tr>
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<td>Project Duration</td>
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The objective of this project is 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 wt.% carbon with more than 51 wt.% carbon from coal. The project team will identify feedstock materials, optimize material development and performance, develop process flow diagrams, perform life cycle analysis for the flexible process, and complete a technical and economic assessment (TEA) of the product. Following these tasks, the team will perform additional materials testing to demonstrate compliance with all relevant building codes under relevant methodologies and update 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.
U.S. Coal to Conductive Inks

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<td>Project Duration</td>
<td>07/02/2018 – 08/26/2023</td>
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<tr>
<td>Total Project Value</td>
<td>$ 1,774,489</td>
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This project will develop new or improved methods of manufacturing conductive ink pigments using coal as a primary feedstock. The conductive inks to be developed will use calcined coal pigments obtained from proprietary thermal treatment processes and combinations of the coal-derived conductive pigments with other conductive materials such as graphite/graphene platelets and carbon black. The commercial manufacturing of graphene is in its infancy and currently top-down (subtractive) scalable manufacturing processes use graphite as a precursor material for graphene production. Minus 100 will collaborate with existing graphite and ink manufacturers to convert domestic coal sources to conductive pigments that can be used to produce highly conductive inks. Process flow diagrams will be developed for individual process steps that are intended to lead to practical scale-up to commercial- or demonstration-scale operations. A bottom-up cost analysis will be performed to validate the economics of the new and improved conductive pigment manufacturing process using coal as the primary feedstock.

A significant portion of the current conductive inks use elemental silver or silver compounds to achieve high levels of conductivity. This expensive base material will be replaced where appropriate with electrically conducting coal-based materials that are significantly lower in cost. It is estimated that the unit cost of these coal-based materials will be at least 50 percent less than silver-based conductive inks.

Coal-based ink sheet resistivity (ohm/sq/mil) vs pigment #.
C4WARD: Coal Conversion for Carbon Fibers and Composites

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<th>Performer</th>
<th>Oak Ridge National Laboratory</th>
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<tr>
<td>Award Number</td>
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<tr>
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<tr>
<td>Collaborator</td>
<td>University of Kentucky Center for Applied Energy Research (UK-CAER)</td>
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The purpose of the ORNL C4WARD Field Work Proposal is to 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 will mitigate the risk associated with potential disruptions in the availability of coal tar pitch in the United States. Another key element of this project will be 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

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<th>Performer</th>
<th>Oak Ridge National Laboratory (ORNL)</th>
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<tr>
<td>Award Number</td>
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<td>Collaborator</td>
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</table>

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
Direct Utilization of U.S. Coal as Feedstock for the Manufacture of High-Value Coal Plastic Composites

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<tr>
<th>Performer</th>
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<tr>
<td>Award Number</td>
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<tr>
<td>Collaborators</td>
<td>Clear Skies Consulting; CONSOL Energy; Engineered Profiles; Pacific Northwest National Laboratory</td>
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The objective of this project is to develop coal plastic composite (CPC) decking boards which possess lower manufacturing costs than current commercial wood plastic composite (WPC) decking boards and meet all applicable ASTM and International Building Code (IBC) performance specifications. Bench-scale screening trials will be completed to assess coal/polymer interface chemistry and impacts of formulation additives on composite properties. Commercial continuous-manufacturing equipment will be used to produce CPC decking boards, which will undergo ASTM testing to determine important application properties and be installed in outdoor applications. Process simulations will be developed and validated using continuous-manufacturing information to support techno-economic studies. Further, CPC marketing studies will be completed along with the identification of additional promising applications for CPC materials.

The project will contribute to achieving the goal of new or existing coal processing plants that can increase the domestic and international marketability of U.S. coals through new products and create or maintain coal industry jobs in the United States. In addition, the carbon products developed could create new industries that will increase the value of U.S. coal resources.

Utilizing coal to produce carbon materials will create new business opportunities by integrating coal into the value chain of industries that typically do not use coal in their manufacturing processes. 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 building automotive and aerospace applications.

a) CPC formulation extrusion results and (b) scaled composite profile manufactured using industrial extruder.
## Coal-Derived Alternatives to Fiber-Cementitious Building Materials

The objective of this project is to develop coal-based siding materials used for cladding of residential and commercial buildings. The coal-based alternatives will consist of at least 70% carbon (by weight), and at least 51% of the carbon (by weight) must be coal derived and offer performance, cost, and environmental benefits in comparison to commercially available fiber-cementitious (FC) siding materials. The project team will assess the ability to design a continuous thermal process to directly convert coal into siding material to supplant and meet all applicable ASTM performance specifications for fiber-cementitious building materials. Bench-scale manufacturing trials will be conducted to assess coal-derived material properties and technical feasibility for siding and related applications. In addition, molecular dynamic simulations will be experimentally validated and utilized to predict properties of coal siding materials. Techno-economic and technology gap analyses will be conducted to assess coal siding manufacturing costs and identify best suited initial market applications and resources necessary to scale and commercialize the product.

Coal siding potentially offers consumers and the construction industry significant advantages over fiber-cementitious siding materials including lower cost, better manufacturing life cycle, and minimal silica content. The global fiber cementitious siding market is undergoing tremendous growth and is expected to reach $20.3 billion by the end of 2025. If proven successful, coal siding manufacturing would establish a new high-value market and increase market demand for U.S. coal by 0.5-1.0 million tons annually, along with creating new manufacturing jobs.

### Performer
Ohio University

### Award Number
FE0031981

### Project Duration
01/01/2021 – 09/30/2022

### Total Project Value
$ 625,000

### Collaborators
CFOAM LLC; CONSOL Energy Inc.

Cross-sectional views of (left) commercial FC siding and (right) prototype coal siding product.
Coal Plastic Composite Piping Infrastructure Components

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<th>Performer</th>
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<tr>
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<tr>
<td>Collaborators</td>
<td>CONSOL Energy; Engineered Profiles; Clear Skies, LLC</td>
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The objective of this project is to develop coal plastic composite (CPC) formulation(s) containing at least 70 wt.% carbon and 51 wt.% coal that offer cost, performance, and environmental benefits in comparison to existing plastic pipe infrastructure materials. Phase I objectives include conducting bench-scale formulation and pipe manufacturing trials to generate data to validate CPC pipe technical feasibility, identifying and analyzing existing market applications for CPC piping, and conducting techno-economic and technology gap analyses to identify required selling prices and resources necessary to scale-up and commercialize CPC-based piping materials. If successful, a Phase II program will be proposed with the objective of conducting commercial-scale manufacturing trials to generate sufficient CPC piping to undergo testing and use in field applications to demonstrate the materials comply with ASTM plastic piping specifications and assess CPC formulations for plastic pipe fitting applications.

CPC piping offers significant advantages including minimal coal processing yielding low capital/operating costs, nearly zero carbon emissions, utilizes existing commercial manufacturing equipment, and a CPC piping product with lower manufacturing costs and equivalent or superior properties than existing plastic piping. The global plastic piping market is undergoing tremendous growth and is expected to reach $106.5 billion by 2022, therefore CPC piping could increase the domestic coal value-chain establishing a new demand for U.S. coal. If successful, CPC manufacturing could generate new U.S. coal demand of over 3 million tons annually along with new manufacturing jobs.

(a) Engineered Profiles Electrical Discharge Machining DM system and (b) semi-continuous CPC extrusion manufacturing line.
Utilization of Carbon Supply Chain Wastes and Byproducts to Manufacture Graphite for Energy Storage Applications

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<th>Performer</th>
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<tr>
<td>Award Number</td>
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<td>Project Duration</td>
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<tr>
<td>Total Project Value</td>
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The objective of this project is to develop coal-derived graphite materials for transportation and grid-scale energy storage applications utilizing continuous engineered foaming processes. The graphite products will possess a carbon content which is greater than 51% coal-derived. Coal wastes will be given preference as the process feedstock. If successful, the coal-derived graphite manufacturing 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-Based Bricks & Blocks (CBBS): Process Development to Prototype Fabrication Coupled with Techno-Economic Analysis and Market Survey

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<tr>
<th>Performer</th>
<th>Pennsylvania State University</th>
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<tr>
<td>Award Number</td>
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<td>Project Duration</td>
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<tr>
<td>Collaborators</td>
<td>ADI Analytics, LLC; Schobert International, LLC</td>
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Potentially advancing new markets for coal could enhance the United States’ national security, energy and mineral security, environmental objectives and contribute to America’s economic prosperity. Moreover, the economic growth potential of coal-to-products may provide social benefits in the form of new mining and local manufacturing job creation. With assistance from Schobert International, LLC and ADI Analytics, LLC, Pennsylvania State University, will evaluate the ability of coal-based bricks and blocks (CBBs) to compete on price and quality, identifying competitive strengths and limitations. Market attractiveness will be assessed based on market size, market growth rate, required attributes, and competitive strengths of the CBBs. The research plan will gather data via testing for an assessment of the technical feasibility of the concept, provide an analysis of the target market for the coal-derived products and all by-products created from the process, including a discussion of the required selling price, and complete a technology gap analysis showing what additional research and development is necessary to scale-up or commercialize the technology. To assess the readiness of the proposed technology a techno-economic analyses will be conducted at the end of the project.

This project transforms coal into bricks and blocks for construction and residential markets while creating new markets for coal-based products and associated manufacturing jobs.
Efficient Process for the Production of High Conductivity, Carbon-Rich Materials from Coal

**Performer**  
Physical Sciences, Inc.

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<th>Award Number</th>
<th>SC0018837</th>
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<tr>
<td>Project Duration</td>
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The overall goal of this project is to demonstrate the feasibility and economic viability of producing high-value carbon-based products from coal feedstocks for the manufacturing of high-conductivity materials for electrochemical applications. The proposed technology builds upon pre-existing structures in coal to create high-conductivity features under mild conditions. The innovation is a two-step process that generates carbonaceous materials with key structural attributes for high conductivity.

Under this grant, the research team will (a) screen and select coal sources suitable as feedstocks; (b) demonstrate scalable processes to produce the high-conductivity material; (c) demonstrate performance in battery electrode formulations and one potential electrochemical application; and (d) perform techno-economic analysis to outline pathways for scale-up and further development and optimization.

This process could provide for minimal reagent usage, characterized by efficient recycling (greater than 90 percent), and produce a carbon product for electrochemical applications with 20 to 30 times higher value than coal used as fuel. Additionally, the process also could generate valuable byproducts such as critical minerals and low-emission gaseous fuels.

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![PSI process produces a high conductivity carbon product for electrochemical applications with 20-30X higher value than that of the coal used as fuel](image)

PSI’s innovative process.
Coal to Carbon Fiber Novel Supercritical Carbon Dioxide (sCO₂) Solvated Process

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<th>Performer</th>
<th>Ramaco Carbon, LLC</th>
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<tr>
<td>Award Number</td>
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<tr>
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The objective of this project is to assess the technical feasibility for generation of quality carbon fiber precursor materials using a supercritical carbon dioxide (sCO₂) solvation process. This includes the generation and recovery of coal tar pitches from Powder River Basin (PRB) coal, removal of low-molecular-weight (MW) compounds from pyrolysis coal tar, evaluation of the efficacy of sCO₂ systems for increasing coal tar average MW, and carbon fiber creation from high-MW coal tar pitch fractions. PRB coal-derived pitch needed for sCO₂ solvation testing will be generated using an sCO₂ pyrolysis test loop. Pyrolysis tar will be tested with sCO₂ and co-solvents to solvate light-MW compounds and increase the average MW of the resulting pitch. Methods used will determine the rate of solvation and condition severity (temperature and pressure) for optimum recovery of high-MW pitch fractions. High-MW coal tar will be heat treated within an sCO₂ solvated system (neat CO₂ and solvent solutions) to build MW, and heat-treated samples will be analyzed to determine if aromatic condensation occurs. The conversion of the high-MW coal pitch to carbon fiber will be tested. Techno-economic evaluation of sCO₂ solvation and the carbon fiber forming process will be performed based on experimental results and analysis.

Coal-based carbon fiber and carbon fiber reinforced polymers offer opportunities for producing new forms of lightweight structural materials and composites which will be beneficially used in both automotive and aerospace applications. Using coal as the basis for carbon nanomaterials such as graphene and carbon quantum dots can bring down the costs of these materials for use in electronic display screens, pigments/dyes/coatings, enhanced textiles, and structural composites. Inexpensive carbon nanomaterials can also be used in 3D printing fluids/plastics to enhance the electrical/thermal/optical properties of the final printed material. Also, coal-based coke, pitch, and carbon nanomaterials can be used to produce electrode materials for aluminum production, batteries and related energy storage, and supercapacitors.

Supercritical CO₂ test loop for generating coal pyrolysis tar.
Experimental Validation and Continuous Testing of an On-Purpose High-Yield Pitch Synthesis Process for Producing Carbon Fiber from US Domestic Coal

The objective of the project is the development of a high-quality carbon fiber precursor material from U.S. domestic coal, accomplished through pilot-scale processing and characterization to develop a scheme that can be evaluated for technical and economic feasibility prior to future scale-up. To achieve this goal, the project aims to: (1) Investigate the effectiveness of using a low-severity direct coal liquefaction (LSDCL) technique as a continuous process to synthesize coal-tar-derived pitch, (2) qualitatively evaluate the use of this mesophase pitch to produce carbon fibers, (3) determine any modifications to the coal-to-tar processes that aid in the production of mesophase pitch optimized for carbon fiber production and further reduce the overall cost of such, and (4) assess the engineering and economic impact of using LSDCL techniques and associated processes to produce carbon fibers from coal.

The techniques used by Ramaco can dramatically increase coal tar pitch yields, especially from low-cost western U.S. coals, which have not historically yielded high amounts of suitable coal tar pitch by conventional means such as high- or low-temperature pyrolysis. Carbon fiber and carbon fiber reinforced polymers offer weight and performance benefits that are driving demand. Market expectations are for increasing demand for these products across several market sectors (wind energy, aerospace, automotive, and pressure vessel) by more than 10 percent per year.
Coal as Value Added for Lithium Battery Anodes

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<th>Performer</th>
<th>Semplastics EHC LLC</th>
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<td>Award Number</td>
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<tr>
<td>Total Project Value</td>
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Semplastics will complete development and begin commercialization of a novel composite material specifically targeted for use in lithium-ion (Li-ion) battery anodes. The goal is to find the best formulation for technical performance and economic viability, thereby preparing this material for insertion into the coal value chain. Specifically, this project will (1) produce several new battery anode materials comprised of filled, conductive silicon oxide carbide or silicon oxycarbide (SiOC) ceramics based on Semplastics’ X-MAT technology, targeting a specific capacity at least three times that of current graphite anodes as well as improved specific power; (2) provide the best six formulations (highest specific capacity and/or highest specific power) to a commercial Li-ion battery manufacturer as fine powders or of the form they request; and (3) fund the battery manufacturer to produce prototype single-cell industrial batteries and test the batteries under standard test conditions.

At the end of the project, the X-MAT anode material will be ready for implementation into existing battery manufacturing processes and will have a significant impact on the utilization of coal, with positive effects for the mining sector and the mitigation of carbon dioxide emissions.

Li-ion battery operating mechanism.
Coal Core Composites for Low Cost, Light Weight, Fire Resistant Panels and Roofing Materials

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<th>Performer</th>
<th>Semplastics EHC LLC</th>
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<tr>
<td>Total Project Value</td>
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In this project, prototypes of a coal-core composite- (CCC-based) roofing tile will be produced. This work will include optimization of the blending process to ensure scalability and to position the product for commercial production. The prototypes will be subjected to testing in laboratory facilities near Semplastics in Florida to characterize the material properties, as well as testing by commercial laboratories to show compliance with roofing industry standards. Successful commercialization of and market penetration by these roofing tiles will positively impact the coal industry ecosystem, contribute to diversification in the use of coal through value-added products across the United States, and produce domestic manufacturing jobs. The CCC-based roofing tiles will offer a viable high-volume, high-growth end market for mined coal.

Cut samples of the tile materials tested.
High-Performance Coal-Based Commercial Facade Panels and Architectural Components

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<th>Performer</th>
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<td>Award Number</td>
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<tr>
<td>Collaborators</td>
<td>Center for Applied Research and Technology; University of North Dakota Energy and Environmental Research Center</td>
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Semplastics will develop, test, and prove the viability for commercialization of a new class of composite architectural panel materials that use coal as the primary constituent. Semplastics will produce sample panels using these novel materials that comprise 55% coal by mass (71% carbon by mass) and are comparable in dimensions to commercially available materials, but that display far superior mechanical strength (three to five times stronger), significant weight savings (30% to 50% lower density), and better insulating ability at a competitive cost.

These new materials require less energy to produce than comparable commercial products and could be manufactured on existing conventional plastic resin processing equipment in commercial quantities. The coal particles are completely encapsulated in ceramic from a polymer-derived ceramic (PDC) precursor, then bonded together by another inorganic resin. 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. Phase I will move this coal-based composite materials technology from a current Technology Readiness Level of 3 to 5.

The proposed work could result in a secure and consistent channel for the use of significant amounts of coal in building materials across North America. Because the X-MAT Panels will be fire-resistant, lightweight, and less bulky, a major impact can be made on the building materials industry. Benefits include:

1. Higher percentage of non-toxic fire-resistant materials in residential and commercial homes
2. Faster installation time because of lighter materials
3. Greater design flexibility because of thinner panels with paintable surfaces
4. Lower total cost and schedule because panels can fill both interior and exterior needs

Expected beneficiaries of this work include owners of coal-based power plants, who will be able to leverage a new use for their product, and the construction industry, who will have access to new high-strength, lightweight alternative material.
Low Weight, High Strength Coal-Based Building Materials for Infrastructure Products

This project will develop and demonstrate the viability of a new class of composite infrastructure components that use coal as the primary component. Coal particles are completely encapsulated and bonded using a specially formulated polymer-derived ceramic (PDC) that is cured to form an aggregate of coal and PDC resin. This aggregate can be further processed and pressed to produce a brick. The project team aims to produce brick and block components, called X-BRIX and X-BLOX, with dimensions comparable to commercially available bricks and concrete blocks, but with superior mechanical strength, lower weight, greater hardness, improved toughness, greater abrasion resistance, and greater chemical resistance than concrete. Sufficient quantities of full-size X-BLOX and X-BRIX will be fabricated to demonstrate the technology and to support the development of mortar or joining techniques. The work could result in a secure and consistent channel for the use of coal in infrastructure and commercial building materials. X-BRIX and X-BLOX are lightweight for low-cost transportation and easy assembly, have high design flexibility because of their high strength to weight ratio, and have a low total cost. Expected beneficiaries of this work include owners of mines, coal processors, coal-based power plants, and the infrastructure and construction industries.

Performer | Semplastics EHC, LLC
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Award Number | FE0031991
Project Duration | 01/01/2021 – 09/30/2022
Total Project Value | $ 623,688
Collaborators | The Center for Applied Research and Technology; University of North Dakota Energy and Environmental Research Center

Sample of full-size X-BRIX - Coal-derived building block of the future.
Coal-Waste-Enhanced Filaments for Additive Manufacturing of High-Temperature Plastics and Ceramic Composites

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<td>Collaborators</td>
<td>Clemson University; University of North Dakota Energy and Environmental Research Center (UNDEERC); Virginia Polytechnic Institute and State University</td>
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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.

3D Printed Parts Utilizing Coal Fines: (a) part made from Semiplastics’ UV-curable resin, (b) cured (plastic) part, (c) fired (ceramic) part.
Developing a Facile Technology for Converting Domestic United States Coal into High-Value Graphene

Universal Matter Ltd., in partnership with the University of Missouri, will scale up and attempt to commercialize a breakthrough process, flash Joule heating (FJH), to transform different coal grades into high-quality graphene. The main objective of this project is to optimize the process by using artificial intelligence techniques (AI) and to validate the technical and economic benefits of producing graphene by using different grades of coal as the feedstock for the FJH process. The graphene products developed from different feedstocks will be analyzed for application development in different strategic markets to further validate the cost and performance advantages and the environmental benefits that can be realized by the incorporation of graphene-based modifiers into different end-use applications.

Utilizing FJH technology, graphene is produced using a high-voltage electric discharge that brings the carbon source to temperatures higher than 3,000 K in less than 10 milliseconds. The short burst of electricity breaks all chemical bonds and reorders the carbon atoms into thin layers of a special type of graphene.

This project plans to advance the FJH technology from its current technology readiness level (TRL) of 4 to TRL 5. To achieve this goal, Universal Matter Ltd will focus on the application of AI methods to develop the process-structure-property relationship required for process optimization and quality control of graphene produced in a controlled industrial environment using the FJH process.

Information garnered from the FJH process can be utilized to set a guideline for application development of coal-derived graphene in different strategic markets. The exceedingly high quality of flash graphene (FG), with yields of 70–90% and conversion cost of $100 per metric ton, presents an opportunity for the U.S. coal industry as well as the electronics, steel, aluminum, concrete, and plastics industries to become potential bulk users of the high-quality and cost-effective FG product to enhance their respective product lines. Once scaled up, it is anticipated that this process will convert large quantities of different grades of coal into high-quality graphene in a highly economical and environmentally friendly manner. The 1–5 layers thick, high-quality graphene (with less than 0.05% defects and purity greater than 99%) will have potential utility across several market segments including energy storage, sensors, hyperlubricants, reinforced plastics, and building materials such as concrete.
Lab-Scale Production of Particle Bonded Filaments with High-Loading Coal-Derived Carbon

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

<table>
<thead>
<tr>
<th>Performer</th>
<th>University of Illinois</th>
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<td>Award Number</td>
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The main goal of this project is to produce high-value carbon nanomaterials and carbon sorbents from domestic coal resources in a cost-effective manner. Specific objectives of this project include (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 will be processed using the proposed process to produce GO, RGO, and AC products. Materials developed will be extensively characterized, and the impact of the coal feedstock type on the yield and quality of each product will be 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 will be performed. The feasibility of producing coal-based graphene materials at a cost 10–50 times lower than the current cost of graphene will be 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.

Characterization by Raman spectroscopy of a graphene oxide sample produced from PRB coal and comparison with the literature 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

<table>
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<tr>
<th>Performer</th>
<th>University of Kentucky</th>
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<tr>
<td>Award Number</td>
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<td>$ 1,847,971</td>
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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 will efficiently 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 unique green fiber weaving and subsequent thermal processing for high-volume efficient throughput of coal-derived carbon-fiber woven 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

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.

**Performer**
University of North Dakota

**Award Number**
FE0032139

**Project Duration**
04/07/2022 – 04/06/2025

**Total Project Value**
$ 1,542,469
Laboratory-Scale Coal-Derived Graphene Process

<table>
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<tr>
<th>Performer</th>
<th>University of North Dakota Energy and Environmental Research Center (UNDEERC)</th>
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University of North Dakota Energy and Environmental Research Center (UNDEERC) will demonstrate a laboratory-scale coal-derived graphene process to produce graphene oxide, reduced graphene oxide, and graphene quantum dots starting from domestic U.S. coals. The steps to meet the proposed objective include (1) coal pretreatment with EERC-developed methods, (2) graphitization of treated coal products, (3) exfoliation of graphite to graphene, (4) an economic feasibility analysis, and (5) analysis of product target markets and technology gaps. These processes will be applied to anthracite, bituminous, subbituminous, and lignite coals to advance the current state of technology as well as maximize the coal value chain. EERC-developed techniques will be employed to pretreat the coal, which will then be further improved via chemical hydrogenation and reduction reactions. The resultant residue will be carbonized at 1000 °C and graphitized at 2800 °C. The modified Hummer’s method will be used to exfoliate graphite to graphene oxide, which will then be chemically reduced to graphene derivatives.

Potential benefits include economic growth stemming from an increased use of coal in nonenergy sectors as well as in potential new industries and markets. In addition, the results of the economic feasibility analysis will be useful for evaluating the commercialization prospects of this technology.

Structural models of graphene products.
Lignite-Derived Carbon Materials for Lithium-Ion Battery Anodes

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.

<table>
<thead>
<tr>
<th>Performer</th>
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<td>Clean Republic LLC; The North American Coal Corporation</td>
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Simplified schematic of the proposed technology for producing LIB anodes from lignite. The process in the green dashed frame was completed by NAC through its proprietary technology.
Utilizing Coal-Derived Solid Carbon Materials Towards Next-Generation Smart and Multifunction Pavements

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<tr>
<th>Performer</th>
<th>University of Tennessee</th>
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<td>Award Number</td>
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This project plans to develop and demonstrate a field deployable, multifunctional smart pavement system made from domestic coal-derived solid carbon materials. This research will demonstrate 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. Specifically, this project will (1) carry out multiscale experimental and numerical studies to establish processing-structure-property relationships, (2) develop a novel coal char-bearing multifunctional pavement system and gather experimental data to evaluate its performance and assess the feasibility for scale up, (3) test a prototype pavement section to evaluate its intended functionalities, and (4) perform a comprehensive technoeconomic analysis to identify the potential market size and key technology gaps to field implementation.

The coal-based multifunctional pavement system to be 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

The University of Utah will (1) provide 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) investigate the production of a high-value β-SiC byproduct using residual coal char from the tar production process, and (3) develop 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 will be used to pyrolyze coals to produce tars suitable for upgrading to coal-tar pitch. The same reactor technology will be 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 will be 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 will be performed on the new coals included in this study to provide this information. The product pitch will be spun into carbon fiber to assess fiber quality arising from different coals and from different processing conditions. The solid char byproduct from coal pyrolysis will be used to produce a high-value β-SiC byproduct. A novel database, coupled with detailed economic models and analysis tools, will be 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.
Eco-Friendly High-Performance Building Material Development from Coal

University of Wyoming researchers will develop coal-derived carbon building materials from Wyoming Powder River Basin (PRB) coal pyrolysis products. Two building components containing more than 70% carbon, most of which is derived from coal itself, are proposed: char-based concrete bricks (CCB) and carbon-based structural units (CSU). These construction products have the potential to be transformational from a cost-benefit perspective and it is anticipated that they will be amendable to manufacture at scale, with intended application in residential and commercial buildings.

In this project, the as-mined coal will be converted to functional carbon elements through an integrated solvent extraction and pyrolysis process invented by the University of Wyoming. This process includes treatment of coal at elevated temperatures in an inert atmosphere to generate pyrolyzed char (PC) and coal deposits, extracts, and residuals (CDER). The CCB will be developed for building wall applications by adding surface functionality to the PC, providing the modified material with engineered properties to ensure a high degree of interaction/reactivity and bonding with a cement binder. The purity of the PC and CDER intermediates has been shown to comply with the strictest health and environmental requirements for building materials.

Specific goals for the development of the CCB and CSU coal-carbon based building components include: CCB with thermal conductivity greater than 0.40 W/mK, mechanical strength of 14 MPa (compression), and light weight (1.0-1.5 g/cm³); and CSU with mechanical strength greater than 30 MPa (compression) and light weight (1.0-1.3 g/cm³) with minimal water retention, long-term corrosion resistance, and durability.

Additionally, it is anticipated CCB and CSU will result in value-added consumption of domestic coals, and that these materials can be produced with a minimal carbon footprint. Other advantages include low manufacturing cost, excellent thermal insulation characteristics, and robust mechanical properties.
Environmentally Friendly Production of High-Quality and Multifunctional Carbon Quantum Dots from Coal

The objective of the project is to develop an innovative, facile, low-temperature, cost-effective, and environmentally friendly technology for producing high-value coal-based carbon quantum dots (CQDs), which have not been a commodity product yet. The coal-based CQD production is based on a proprietary technology developed at UW. A green solvent is used for directly extracting carbon out of coal with the help of coal itself. 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 from coal. Since CQD have novel optical properties, efficiencies of photoelectric conversion and photocatalysis of the synthesized CQDs will be carried out in order to determine suitability towards each application. Additionally, a techno-economic analysis of the novel coal-to-CQDs technology will be 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.
Modular, Manufactured Homes from Coal-Based Building Materials

X-MAT CCC will establish the utility of coal-derived building materials (CDBM) licensed from their partner, Semplastics. CDBM components contain at least 55% coal by weight; including the binders within the resin, and at least 71% carbon by weight. The project will result in a market-worthy design for a CDBM dwelling structure and achieve the performance requirements to meet insurance standards (seismic, fire, wind resistance) and those of the International Building Code.

The scope of work for this project will be (1) to develop a conceptual design of dwelling structure composed of CDBM (with at least two walls, a partial roof, and a partial foundation) to test the assembly of the prototype building under stress conditions, (2) to establish the fastening methodology of CDBM and traditional building materials components, (3) to perform a techno-economic analysis to determine economic viability and the market penetration possibilities, (4) to perform a gap analysis and describe the additional work needed to meet building code requirements for CDBM to achieve market adoption, (5) to perform a life cycle analysis of CDBM dwelling structures against those composed of traditional materials, and (6) to develop a financial model with theoretical production costs to verify the commercial viability of the business model.

If successful, the project could result in a secure and consistent channel for the use of significant amounts of coal in building materials across North America. Because CDBM are fire-resistant, lightweight, and less bulky, a major impact can be made on the building materials industry.

Benefits include:
1. Higher percentage of non-toxic fire-resistant materials in residential and commercial homes
2. Faster installation time because of lighter materials
3. Greater design flexibility
4. Lower total cost and schedule because CDBM can fill both interior and exterior needs

Expected beneficiaries of this work include owners of coal-based power plants, who will be able to leverage a new use for their product, and the construction industry, who will have access to new high-strength, lightweight alternative materials.

X-MAT CDBC Concept Elevation.
COAL TO CARBON PRODUCTS &
COAL PROPERTIES DATABASE

National Energy Technology Laboratory (NETL):
Carbon Materials Manufacturing ................................................................. 47
Carbon Materials Manufacturing

<table>
<thead>
<tr>
<th>Performer</th>
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The United States (U.S.) Department of Energy’s (DOE) Office of Fossil Energy and Carbon Management (FECM) Carbon Ore Processing Program is developing new approaches for using low-value, carbon-containing, waste streams to manufacture high-tech, high-value carbon products. Research in this Program focuses on using carbon-containing waste from mining and manufacturing operations, along with other domestically sourced carbons, to create new manufacturing approaches for making high-tech materials and products. These manufacturing technologies divert carbon waste from landfills and impoundments (which is a costly, long-term management challenge) back into the manufacturing supply chain, where it is used to create saleable products that generate revenue, jobs, and new manufacturing industries.

The Carbon Materials Manufacturing Field Work Proposal (CaMM FWP) supports the Carbon Ore Processing Program by: (1) creating new chemical, thermal, and mechanical processing technologies that convert low-value carbons into more beneficial materials; (2) characterizing the performance and costs of new carbon material manufacturing technologies; (3) conducting life cycle analyses (LCA) to evaluate the environmental footprint associated with deploying these technologies; and (4) analyzing the impact new technologies will have on the markets associated with carbon products.

Areas of research include (1) development of nanostructured carbon materials for use in memristors, field effect transistors, and other novel microelectronic devices, (2) development of activated carbons with well-controlled pore sizes and distributions tailored specifically to improve the performance and costs of electrochemical energy storage devices, (3) the development of ligand-free, graphene-based, solid carbon membranes capable of filtering organic and inorganic impurities from water sources (4) development of nanostructured graphene materials tailored specifically for use as cement and concrete additives that improve the mechanical strength and increase the service life of the material.
FEEDSTOCK UPGRADING

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

Minerals Refining Company, LLC:
Pilot-Scale Testing of the Hydrophobic-Hydrophilic Separation Process to Produce Value-Added Products from Waste Coals
The Novel Charfuel Coal Refining Process 18 Tpd Pilot Plant Project for Co-Producing an Upgraded Coal Product and Commercially Valuable Co-Products

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<th>Performer</th>
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<td>Collaborator</td>
<td>Hazen Research</td>
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Carbon Fuels, LLC will operate the integrated 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

![Illinois #6 Coal Composition](chart.png)
In a typical coal preparation process, coal particles are separated from earthen matter using mechanical separation techniques. These techniques are only economically capable of separating coal particles greater than 40 microns in size. As a result, the particles less than 40 microns are not efficiently recovered and are subsequently lost to impoundment ponds. The hydrophobic-hydrophilic separation (HHS) novel process is a physicochemical process that was developed to capture coal particles of less than 40 microns; its technical feasibility has been successfully demonstrated using bituminous coal in batch laboratory experiments, in a small proof-of-concept process, and most recently in a larger pilot-scale process with a coal recovery rate of 500 to 750 pounds per hour. To be economically viable, the process equipment, energy consumption, and chemical consumption must be optimized. The objectives of this project are to utilize the one-skid HHS process to demonstrate that (1) the HHS process is an economical method for recovering fine coal particles for use in coal-fired power plants, (2) the HHS process is an economical method for recovering high-purity coal particles containing less than 1.5 percent ash for high-value specialty market applications, and (3) the HHS process can be used to recover fine coal particles from an anthracite rank of coal, and to evaluate several process improvements to reduce the capital investment and operating costs associated with the HHS process.

Completed market penetration analysis will define the demand/price structure for the proposed sales of the coal and carbon products generated by the pilot-scale HHS facility and will include potential customers’ evaluation of the super-clean and ultra-clean coal for use in new market applications.

Effect of contact angle on the recovery of fine particles during two-liquid flotation.
<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>°C</td>
<td>degrees Celsius</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional</td>
</tr>
<tr>
<td>AC</td>
<td>activated carbon</td>
</tr>
<tr>
<td>β-SiC</td>
<td>beta form of silicon carbide</td>
</tr>
<tr>
<td>BTEX</td>
<td>benzene, toluene, ethylbenzene, and xylene</td>
</tr>
<tr>
<td>C2CF</td>
<td>coal to carbon fiber</td>
</tr>
<tr>
<td>CBBs</td>
<td>coal-based bricks and blocks</td>
</tr>
<tr>
<td>CCB</td>
<td>char-based concrete brick</td>
</tr>
<tr>
<td>CCC</td>
<td>coal-core composite</td>
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<tr>
<td>CDBM</td>
<td>Coal-derived building materials</td>
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<tr>
<td>CDER</td>
<td>coal deposits, extracts, and residuals tar</td>
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<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
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<td>COP</td>
<td>Carbon Ore Processing</td>
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<tr>
<td>CPC</td>
<td>coal plastic composite</td>
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<tr>
<td>CQD(s)</td>
<td>coal-derived quantum dot(s)</td>
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<td>CSU</td>
<td>carbon-based structural unit</td>
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<td>CTP</td>
<td>coal-tar pitch</td>
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<td>DOE</td>
<td>Department of Energy (U.S.)</td>
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<tr>
<td>EERC</td>
<td>Energy and Environmental Research Center (University of North Dakota)</td>
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<tr>
<td>FC</td>
<td>fiber-cementitious</td>
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<td>FECM</td>
<td>Office of Fossil Energy and Carbon Management (DOE)</td>
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<tr>
<td>FJH</td>
<td>flash joule heating</td>
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<tr>
<td>FG</td>
<td>flash graphene</td>
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<td>FWP</td>
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<td>GO</td>
<td>graphene oxide</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>hydrogen peroxide</td>
</tr>
<tr>
<td>HCCM</td>
<td>high conductivity carbon material</td>
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<tr>
<td>HHS</td>
<td>hydrophobic-hydrophilic separation</td>
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<tr>
<td>IBC</td>
<td>International Building Code</td>
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<tr>
<td>kt/yr</td>
<td>kilotons per year</td>
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<tr>
<td>LIB</td>
<td>lithium-ion battery</td>
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<tr>
<td>Li-ion</td>
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<tr>
<td>LSDCL</td>
<td>low-severity direct coal liquefaction</td>
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<td>ML</td>
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<td>OPC</td>
<td>ordinary Portland cement</td>
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<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
</tr>
<tr>
<td>PC</td>
<td>pyrolyzed char</td>
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<tr>
<td>PCM</td>
<td>phase-change material</td>
</tr>
<tr>
<td>PDC</td>
<td>polymer-derived ceramic</td>
</tr>
<tr>
<td>PU</td>
<td>polyurethane</td>
</tr>
<tr>
<td>PRB</td>
<td>Powder River Basin</td>
</tr>
<tr>
<td>QI</td>
<td>quinoline insoluble</td>
</tr>
<tr>
<td>RGO</td>
<td>reduced graphene oxide</td>
</tr>
<tr>
<td>sCO₂</td>
<td>supercritical carbon dioxide</td>
</tr>
<tr>
<td>SG</td>
<td>synthetic graphite</td>
</tr>
<tr>
<td>SiC</td>
<td>silicon carbide</td>
</tr>
<tr>
<td>TEA</td>
<td>technical and economic assessment</td>
</tr>
<tr>
<td>TPD</td>
<td>tons per day</td>
</tr>
<tr>
<td>TRL</td>
<td>technology readiness level</td>
</tr>
<tr>
<td>UK</td>
<td>University of Kentucky</td>
</tr>
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<td>UND</td>
<td>University of North Dakota</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States</td>
</tr>
<tr>
<td>WL</td>
<td>Wave Liquefaction™</td>
</tr>
<tr>
<td>WPC</td>
<td>wood plastic composite</td>
</tr>
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