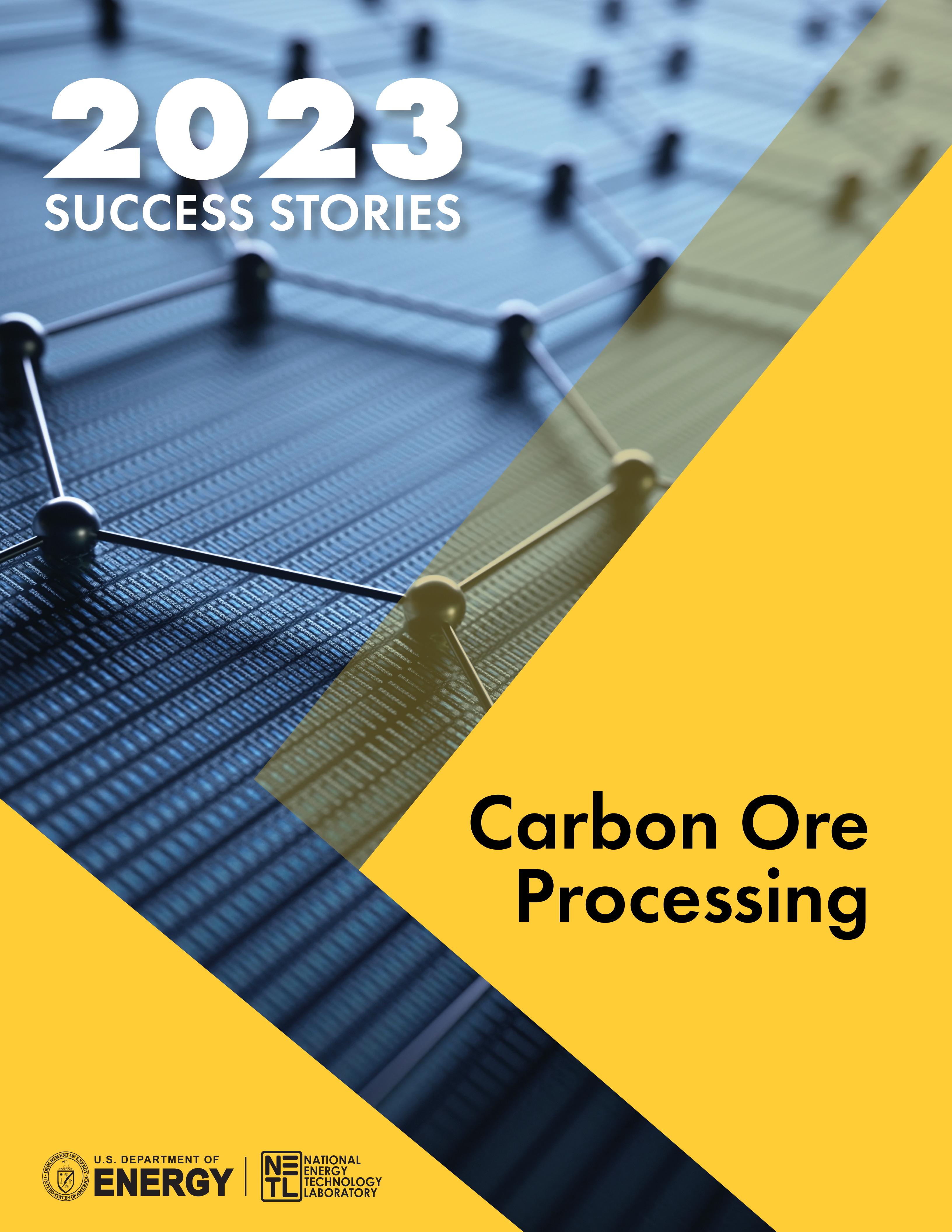


2023
SUCCESS STORIES

Carbon Ore Processing

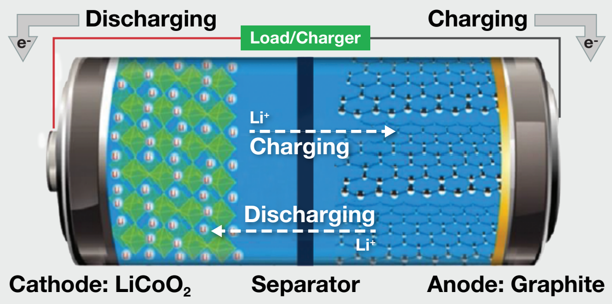
U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Award No. FE0031879

Producing Anodes for Lithium-Ion Batteries from Domestic Coal Waste

- Coal anodes offer a viable pathway to support the battery anodes supply chain – addressing a critical lack of supply for battery grade graphite.

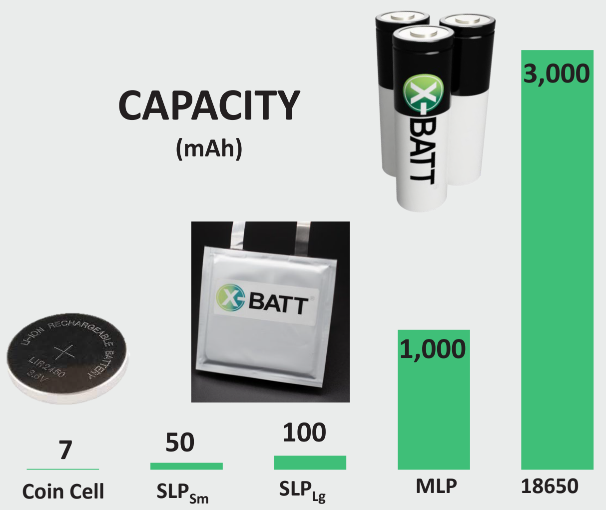
Anodes from Coal Waste can Significantly Improve Anode Capacity when Compared to Graphite



In 2020, Semplastics was awarded a three-year, $1 million NETL Cooperative Agreement to research ways to utilize coal as an anode material in lithium-ion batteries. Results to date have found that coal, a low-cost, abundant resource, when mixed with the proprietary Semplastics resin system can significantly improve anode capacity when compared to graphite.

The Semplastics technology is cost competitive with traditional battery grade graphite.

Commercialization is Underway



Semplastics

- Semplastics has produced several new battery anode materials comprised of filled, conductive silicon oxide carbide or silicon oxycarbide (SiOC) ceramics.
- The company is targeting a specific discharge capacity at least three times that of current graphite anodes. Specific discharge capacity is the maximum amount of energy that the battery can deliver under certain specified conditions.
- As part of the commercialization process, Semplastics is providing formulations to commercial lithium-ion battery manufacturers.

Initial testing in half and full coin cells allowed for high-throughput, iterative testing of materials. Single-Layer (SLP) and Multi-Layer (MLP) Pouch Cells validated performance of materials in a larger format system. Building and testing in an 18650 single cell has required materials to be processed in an automatic or semiautomatic process that replicates what would be done at scale.

In 2022, a battery manufacturer working with Semplastics produced prototype single-cell industrial batteries and is testing the batteries under standard test conditions.

Semplastics Awarded Battery Innovation Center Voltage Award

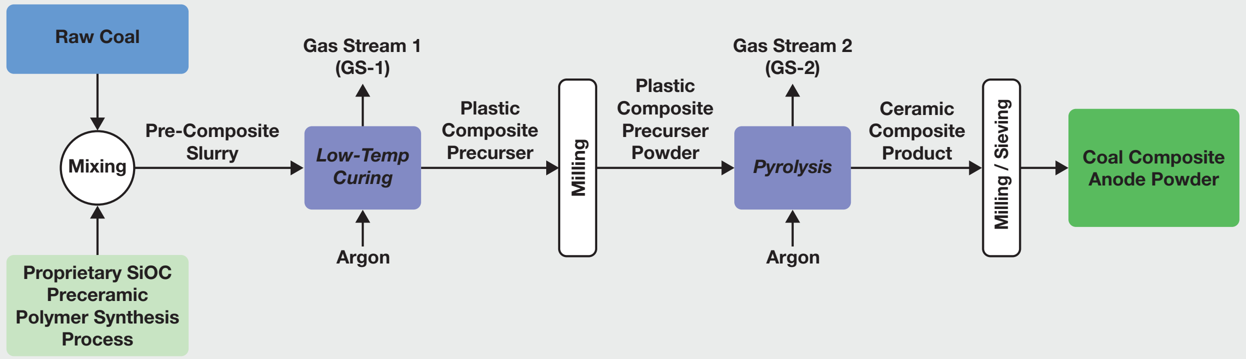
The Voltage Award recognizes an emerging company and/or technology with the highest potential to make a difference in batteries and electrification.

The Battery Innovation Center is an independent, highly regarded collaborative initiative designed to incorporate leadership from renowned universities, government agencies, and commercial enterprises.

Polymer-Derived Ceramic (PDC) Technology

Ceramic SiOC are called Polymer-Derived Ceramic (PDC). Adding coal to PDC anodes offers the following benefits:

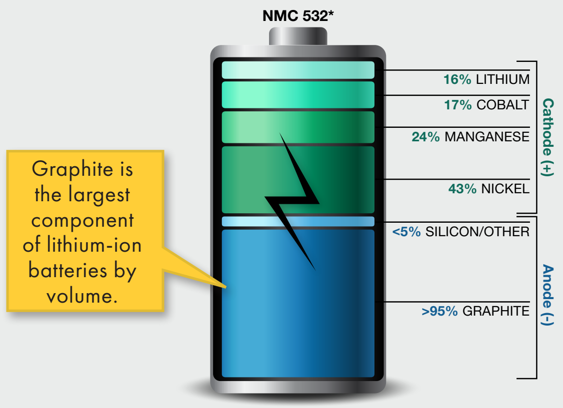
- The ceramic forming polymers can be integrated with impure carbon materials like coal.
- Higher specific discharge capacities using PDC (500-800 mAh/g) exceed the theoretical capacity of graphite (372 mAh/g).
- Improves charge and discharge behavior, decreases nominal voltage and increases first-cycle efficiency (FCE), exhibits low-volume expansion compared to other silicon-based anode materials (20-30% vs 200-300%) and provides greater cycling performance than other silicon-based anode materials.
- Technology is low-cost and scalable compared to alternative approaches.



Low-cost, simple, scalable process.

Anodes from Coal Waste Solve an Impending Critical Graphite Shortage

There are about 150 lbs of graphite per electric vehicle and, by 2035, it has been estimated that a combination of 150 graphite mines or synthetic graphite plants would be required to meet projected demand.*
(Source: Benchmark Mineral Intelligence)



Graphite is the largest component of lithium-ion batteries by volume.

Data compiled March 30, 2022.
*NMC 532=nickel-maganese-cobalt lithium-ion battery. Percentages listed are approximate.
Assumes average size of graphite mines of 56,000 tonnes/yr (which compares to an average U.S. coal mine that produces 1 MM tonnes/yr).
Graphic credit: Cat Weeks
Sources: S&P Global Market Intelligence; Pallinghurst-Traxys; Nouveau Monde Graphite

All Semplastics anode raw materials are domestically sourced.

PARTNERSHIP WITH:

Semplastics

SCAN FOR MORE INFORMATION:

Award No. FE0031809

Coal-Plastic Composite (CPC) Materials for Decking Applications

CPC Decking Shows Significant Price and Performance Advantages Over Existing Composite Decking

The objective of this project was to develop a CPC decking product that possesses lower manufacturing costs than current commercial wood-plastic composite (WPC) decking and meets all applicable ASTM and International Building Code (IBC) performance specifications. The project was a resounding success as the CPC product:

- Meets or exceeds ASTM and IBC requirements
- Exhibits equivalent or greater strength
- Shows greater resistance to oxidation
- Lowers flammability
- Improves the price point
- Reduces embodied energy and emissions

Manufacturer	Product	End User Pricing ($/linear ft)
DE-FE0031809	CPC	1.29
Trex	WPC	1.75-5.78
Choicedek	WPC	3.67
TimberTech	WPC	4.48-6.68

Property	Test Method	Status
Board Strength	ASTM D1609	Exceeds IBC[1] Specification
Board Deflection	ASTM D1609	Exceeds IBC Specification
Water Absorption	ASTM D570	Water absorption significantly lower than WPC[2]
Oxidation	ASTM D3895	Greater oxidation resistance than most WPCs
Flash Ignition Temperature	ASTM D1299	Higher than WPCs
Self Ignition Temperature	ASTM D1299	Higher than WPCs
Rate of burning	ASTM D635	Slower than WPCs
Smoke/Heat Release	ASTM E1354	Lower total heat/smoke release than WPCs
Surface Burning	ASTM E84	Passes, Class B rating
Leaching	SPLP/TCLP	Passes, BDT[3] or well below RCRA limit
Respirable Dust	NIOSH 600	Pass
Hail	Ice Cannon	Pass
Screw Fastening	ASTM D7032	Pass

CPC boards were provided to externally certified organizations to conduct testing according to ASTM D7032 specifications for composite decking applications.

[1] IBC: International Building Code
[2] WPC: Wood-Plastic Composite
[3] BDT: Below Detection Limit

CPC Meets or exceeds ASTM and IBC requirements with a lower price point.

Growing Demand and Markets for WPCs Provides an Ideal Opportunity for CPCs

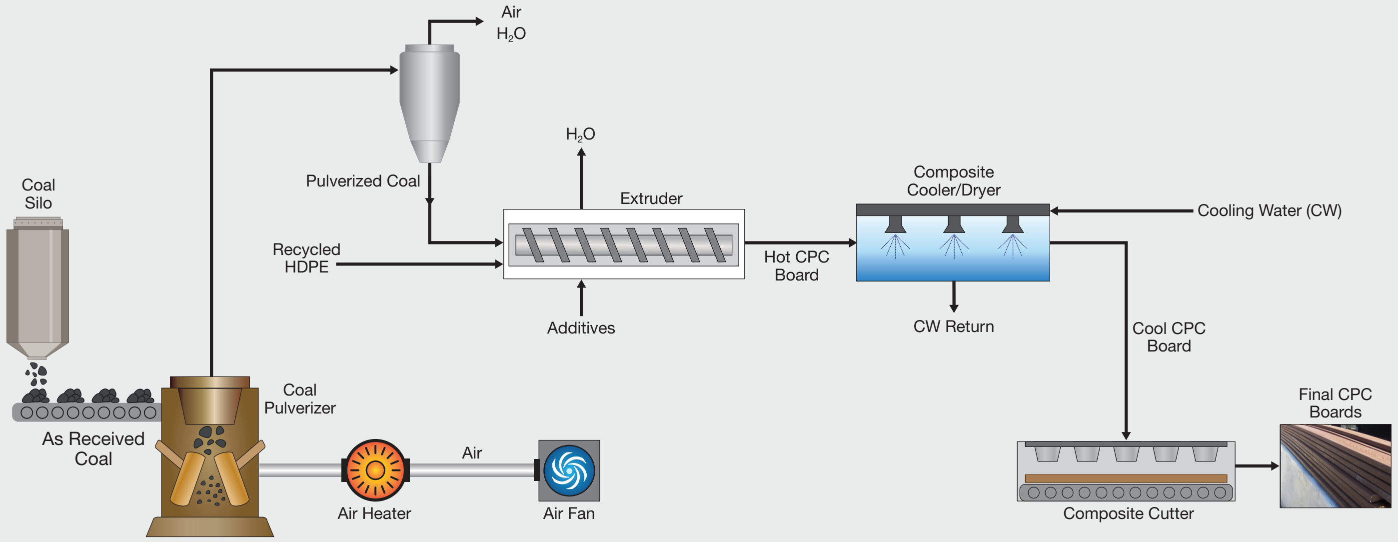
The WPC market is significant, with a global value of $6.42 billion in 2021. The largest WPC market segments include building and construction (65%), automotive (18%), and electrical (8%), with the remainder associated with miscellaneous applications. Tremendous growth in global WPC materials production is expected, with an 11.5% compound annual growth rate (CAGR) through 2030. The growing demand and markets for WPCs provides an ideal opportunity for CPCs to enter and expand into this market without having to initially displace existing WPC production.

Other potential uses include fencing, molding, railing, doors, and siding.

CPC Technology

The CPC manufacturing process consists of intimately mixing fine coal with high density polyethylene (HDPE) or other thermoplastic resins plus additional additives to enhance processing and product properties.

- Coal waste is pulverized and then fed along with HDPE and additives into a continuous extrusion process.
- This mixture is extruded into a substrate (or other profiles) along with a capstock to form the board product.
- The final product is cooled before being cut to various lengths (8 to 20 ft) and bundled for sale.



CPC manufacturing process flow diagram with mass balances.

Commercial WPC extrusion equipment is used to manufacture CPC decking boards.

CPC Decking Boards are Ready for Commercialization

Deck constructed with CPC boards.

CPC boards manufactured at Engineered Profiles – an industry leader in custom plastic extrusion solutions based in Ohio – were provided to a home building product testing organization to obtain feedback from deck builders on the handling and installation of the CPC product.

Five teams of two experienced deck builders were recruited to build a 10-ft by 20-ft deck. Key advantages noted by the builders were that the CPC material was easier to carry and install in comparison to existing decking materials.

Results from the constructability study indicate CPC decking is a viable commercial product and demonstrates maturation of the technology to Technology Readiness Level (TRL) 8.

CPC decks have been installed by four independent contractors.

PARTNERSHIP WITH:

OHIO UNIVERSITY

SCAN FOR MORE INFORMATION:

Award No. FEAA157

Coal Conversion for Carbon Fibers and Composites

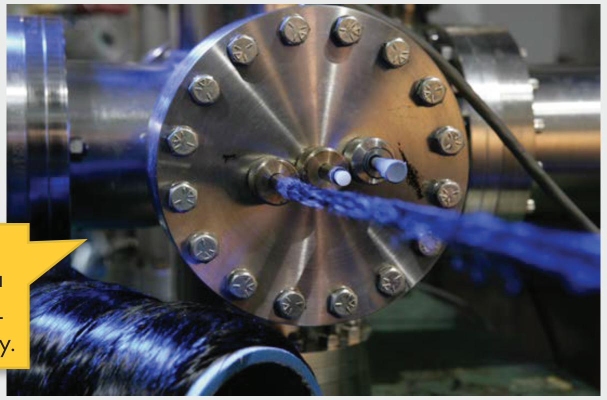
Developing Energy-Efficient and Cost-Effective Processes for Manufacturing Carbon Fibers from Coal Waste

Oak Ridge National Laboratory (ORNL) and the University of Kentucky are collaborating to use domestic coal-based pitch to make carbon fiber technologies for a wide range of potential applications.

This field work is developing and demonstrating processes for scaling up the production of carbon fibers from carbon ore, coal refuse, and waste streams associated with previous coal mining activities. The work includes establishing processing-structure-properties relationships for carbon fibers derived from carbon ore.

Together, ORNL and the University of Kentucky capabilities include expertise in:

- Coal processing
- Separation science and technology
- Carbon science and technology
- Computational chemistry and high-performance computing
- Advanced characterization
- Advanced manufacturing



Fully carbonized fiber exiting the microwave-assisted plasma carbonization unit at the ORNL Carbon Fiber Technology Facility.

ORNL and the University of Kentucky bring complementary and unparalleled capabilities in fundamental science and translational research and development expertise.

High-Performance Carbon Fibers from Coal and Coal Wastes

Potential benefits from the waste-based carbon fibers include:

- **Lower costs** – High carbon content, lower cost of coal tar pitch enable lower cost production.
- **A range of fibers** – Extends from short chopped fibers for low-cost applications to graphitizable fibers for demanding aerospace applications.
- **Varying elastic modulus, strength, and conductivity** – Can be tailored depending on pitch precursor, fiber processing, and heat treatment.

This R&D is a major step toward providing a low-cost carbon fiber product from coal waste for potential use in automotive and other important markets.

ORNL's Carbon Fiber Technology Facility (CFTF)

As the nation's leader in low-cost carbon fiber research and development, ORNL's Carbon Fiber Technology Facility (CFTF) offers a 42,000 sq. ft. innovative technology facility with a highly flexible, highly instrumented carbon fiber line for demonstrating advanced technology scalability and producing market-development volumes of prototypical carbon fibers and serves as the last step before commercial production scale.

The facility, with its 390-foot-long processing line, is capable of custom unit operation configuration and has a capacity of up to 25 tons per year, allowing industry to validate conversion of their alternative carbon fiber precursors at semi-production scale.

The facility houses a thermal (conventional) conversion line and a melt-spinning precursor fiber production line and includes space for a future advanced conversion line.

ORNL has successfully scaled up coal waste-based carbon fiber manufacturing to semi-production scale.

There is a Clear Path for Competitive Industrialization of Coal-Derived Carbon Fibers and Composites for a Wide Range of Applications

By developing the underlying and translational science required to establish processing-structure-properties relationships for coal-derived fibers, this research is enabling the development of energy-efficient and cost-effective processes for manufacturing carbon fibers with tunable properties.

The feasibility of tailoring the physical and mechanical properties of carbon fibers on demand could open up opportunities for carbon fibers in new high-volume applications, such as thermal insulation for buildings and materials for construction and infrastructure.

Additionally, by processing carbon fiber precursors directly from coal waste, this research has mitigated the risk associated with potential disruptions in the availability of coal tar pitch in the United States.

ORNLs Carbon Fiber Technology Facility.

Deployment of these new technologies will lead to coal waste remediation and economic development opportunities in distressed communities.

PARTNERSHIP WITH:

Oak Ridge National Laboratory

University of Kentucky

SCAN FOR MORE INFORMATION:

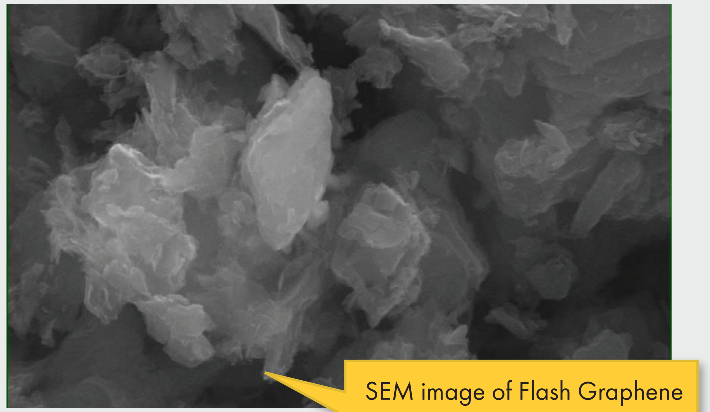
Award No. FE0031988

Flash Joule Heating for Producing High-Value Graphene Materials

Breakthrough Process Can Transform Carbonaceous Material Feedstocks Such as Waste Coal into High-Quality Graphene

Flash Joule Heating (FJH) can transform different carbon-based materials into high-quality graphene. "Flash Graphene" (FG) is produced using a high-voltage electric discharge that brings the carbon source to temperatures higher than 3,000 K in milliseconds. FJH can produce 1-5 layer-thick high-quality graphene (with defects of <0.05% and purity of >99%).

The innovative process is a green, practical, and cost-effective alternative to high-cost conventional chemically or mechanically intensive top-down methods or slow bottom-up methods for graphene synthesis.

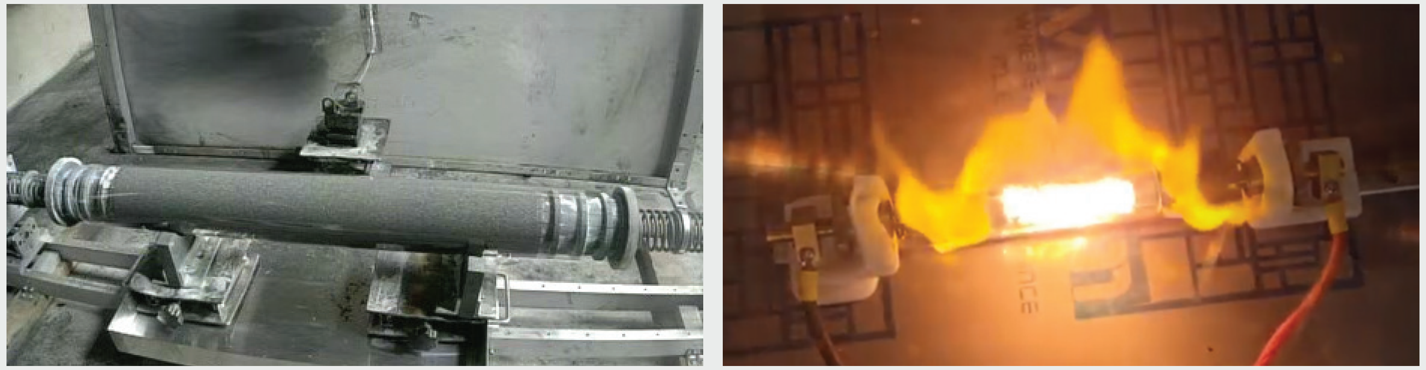


SEM image of Flash Graphene derived from metallurgical coke.

FJH is a lower-cost alternative to conventional methods for producing graphene.

Demonstration Plant Under Construction

After converting coal to graphene at ~1 kg scale, the FJH process was scaled up to a 20-kg batch reactor that produced 15 kg of graphene. The coal-derived graphene produced by these FJH operations has been successfully demonstrated in epoxy, asphalt, and concrete applications. A demonstration plant is now under construction that will commence operation with the capability for 1 ton/day throughput.

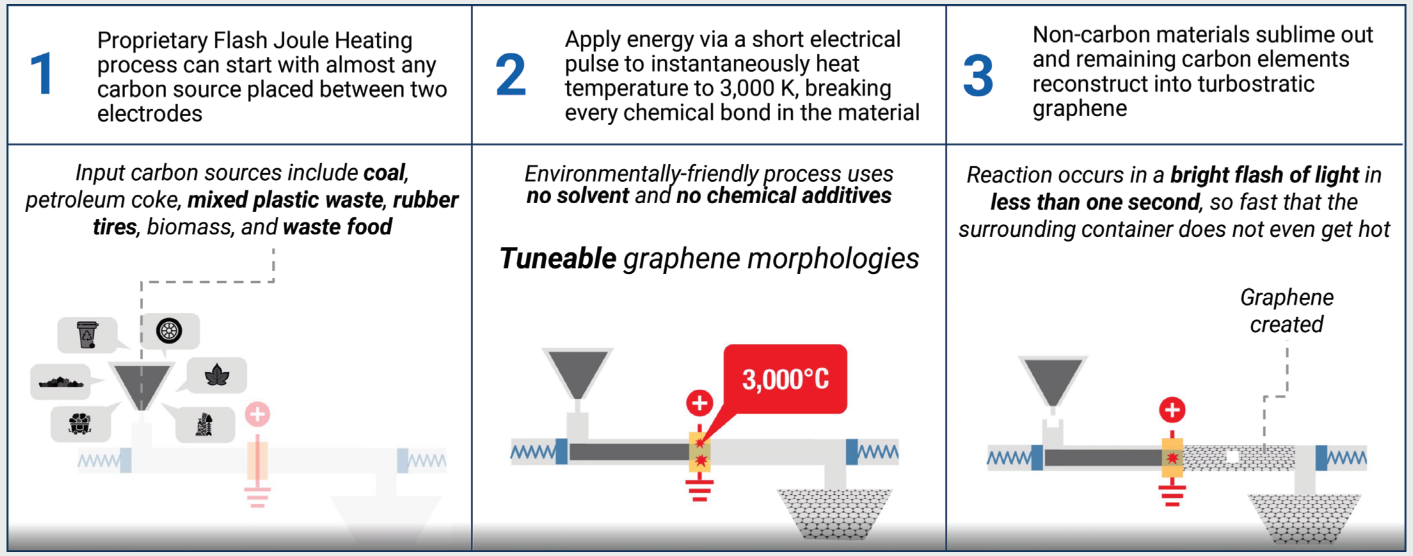


Flash Joule Heating reactor.

Demonstration plant will commence operation with capability of 1 ton/day throughput.

Making Graphene by Flash Joule Heating

The FJH technology can convert any carbon source into graphene. Transforming coal to multilayer graphene at 70% yield is a notable accomplishment because unprocessed coal presents unique challenges due to its undesirable constituents.



1 Proprietary Flash Joule Heating process can start with almost any carbon source placed between two electrodes

Input carbon sources include ***coal****, petroleum coke,* ***mixed plastic waste****,* ***rubber tires****, biomass, and* ***waste food***

2 Apply energy via a short electrical pulse to instantaneously heat temperature to 3,000 K, breaking every chemical bond in the material

Environmentally-friendly process uses ***no solvent*** *and* ***no chemical additives***

Tuneable *graphene morphologies*

3 Non-carbon materials sublime out and remaining carbon elements reconstruct into turbostratic graphene

Reaction occurs in a ***bright flash of light*** *in* ***less than one second****, so fast that the surrounding container does not even get hot*

Transforming coal waste to multilayer graphene at 70% yield is a notable accomplishment because unprocessed coal presents unique challenges due to its undesirable constituents.

FG has Many Valuable Applications

The high quality and low costs of FG could enable the electronics, steel, aluminum, concrete, and plastics industries – among many others – to become potential bulk users of the FG product to enhance their respective products. The many possibilities include:

- **Reinforcement of concrete** — Test results show an improvement of approximately 9% in compressive strength with FG.
- **Additive to asphalt binder to improve aging performance** — FG improves deformation characteristics of asphalt binder, especially after being aged.
- **Epoxy coatings** — Three types of FG (medium to high surface area, and chemical milled FG) incorporated into epoxy resins were found to significantly improve the adhesion strength of coatings, compared to epoxy coatings, which contained no graphene compound.
- **Additive in an epoxy composite for mechanical enhancements** — Exfoliated FG at 0.5% concentration shows a 3.1% improvement in flexural modulus, a 14.5% improvement in flexural strength, and a 25.0% improvement in flexural strain compared to a control sample with no additives or graphene. For both flexural strength and strain, exfoliated FG achieved the highest level of performance among 17 total graphene samples tested in collaboration with the Graphene Council.

FJH process can convert diverse carbon sources into graphene with tunable characteristics for an almost unlimited number of applications.

PARTNERSHIP WITH:

UNIVERSAL MATTER
ADVANCED MATERIALS

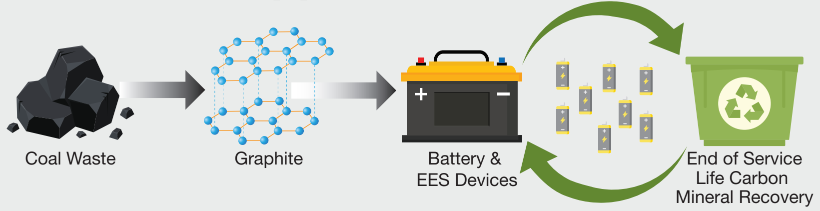
University of Missouri

SCAN FOR MORE INFORMATION:

Award No. FWP-FEAA157

Production of Graphite from Carbon Ore and Coal Refuse

Research at NETL and ORNL Shows Coal Waste Can be a Viable Feedstock for Making High-Quality Graphite Materials Suitable for Battery and Other High-Performance Applications



Innovative technologies under development for graphite synthesis use electrochemical or catalytic methods to reduce process temperatures and times in graphite production.

These technologies can use inexpensive and domestically sourced coal waste, lowering graphite production costs, encouraging remediation of legacy mining wastes, and eliminating potential supply chain disruptions.

These novel processes could lead to an improved environmental footprint for graphite production compared to current methods of making synthetic graphite.

Carbon waste to value-added products.

Electrochemical Approach to Graphite Manufacturing

A new process developed at ORNL uses a molten salt assisted low-temperature electro-catalytic graphitization method to synthesize graphite directly from coal char.

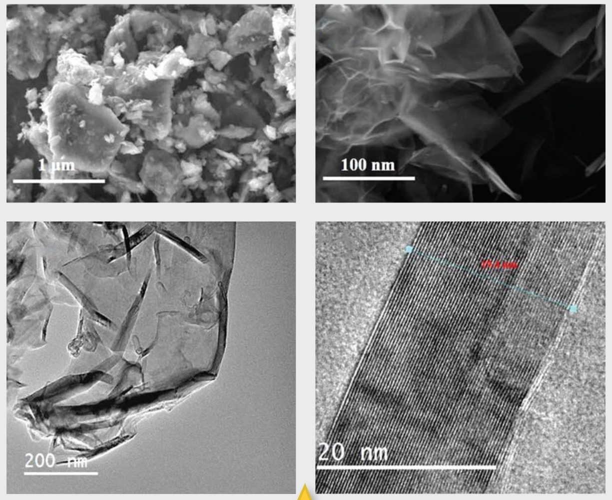
Conventional methods for synthetic graphite synthesis involve graphitizing non-graphitic carbon by chemical vapor deposition from hydrocarbons, decomposition of certain carbides, or crystallizing from metal melts supersaturated with carbon, all of these methods requiring extremely high process temperatures (>2,800°C). The high temperatures demand expensive reactor vessels and high energy consumption.

In contrast, the electrochemical reactor in development significantly reduces process temperatures and time associated with current synthetic graphite manufacturing.

The electrochemical reactor utilizes cathodic polarization of amorphous carbon (e.g., coal char) in molten salts such as $MgCl_2$ or $CaCl_2$ at moderate temperatures of ~850°C. The char is transformed into graphite in suspension in the molten salt under these conditions.

The graphite produced from this process has been tested as a battery anode and produces results in promising performance with a stable long cycle and improved rate performance compared to commercial graphite.

This is an early encouraging result that could lead to the possible economic, industrial graphite manufacturing using inexpensive coal-derived materials.



Graphitized coal char at increasing levels of magnification.

OAK RIDGE
National Laboratory

The ORNL process is unique because it allows carbon typically considered "non-graphitizable" to be converted directly into high-value graphite materials.

Award No. FWP-1022432

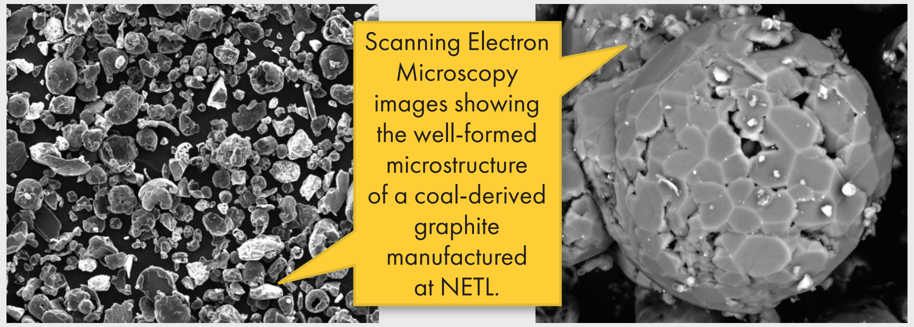
Manufacturing Graphite from Coal Waste

Using Earth-Abundant Catalysts to Improve Graphite Manufacturing

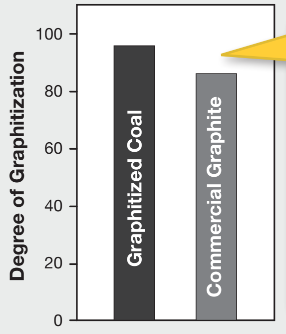
A novel process developed by researchers at NETL focuses on using earth-abundant catalyst materials, such as iron, to facilitate the production of highly crystalline graphite.

Coal of different ranks, coal waste, coal char, and plastic waste have been demonstrated to work as feedstocks with this process.

The catalyst is responsible for dropping process temperatures from 3,000°C down to 1,500°C and reducing process times from several weeks to just a few hours. Additionally, research demonstrates the catalyst can be recovered, recycled, and reused indefinitely, which improves the overall economics and environmental footprint of graphite production.



Scanning Electron Microscopy images showing the well-formed microstructure of a coal-derived graphite manufactured at NETL.



Data illustrating that the graphitization degree of coal-derived graphite manufactured at NETL is better than commercially available samples.

Battery anodes using graphite produced with this catalytic process outperforms anodes made with commercial graphite.

New Graphite Sources and Manufacturing Methods are Critically Needed in the US

Graphite is classified as a critical mineral in the United States because of its use in essential manufacturing combined with the limitations caused by its offshore supply chain. Graphite has a central role for renewable and low-carbon energy technologies, where it is used in anodes for lithium-ion batteries, high-strength composites for wind and wave turbines, and high-strength composites for fly wheel energy storage.

Roughly ⅓ of the global market is supplied using natural graphite, with the remaining two-thirds being supplied by synthetic graphite. Global production of both natural graphite and synthetic graphite is concentrated in China. China currently produces over two-thirds of the world's natural graphite (71% of world production in 2019) and more than half of the world's synthetic graphite (2.07 MMt of synthetic graphite was produced in 2019, with China producing ~58% of that). Natural graphite has not been mined in the United States since 1990, while synthetic graphite production continues to grow.

Low-temperature synthesis of graphite from inexpensive carbon ore/coal waste could lead to a new cost-effective domestic industrial manufacturing base for this critical material, boosting the sustainable energy sector and preserving the environment for future generations.

NATIONAL
ENERGY
TECHNOLOGY
LABORATORY

SCAN FOR MORE INFORMATION:

Award No. FE0031797

Conversion of Coal to Li-Ion Battery-Grade Graphite

Low-Value Lignite Coal is Converted to High-Value Graphite

Domestic low-cost lignite coal has been successfully transformed in very high yield (greater than 95% of carbon present graphitized) into highly crystalline, high-purity graphite (greater than 99%), with properties that are nearly identical to that of high-grade Li-ion battery (LIB) graphite.

This work represents remarkable success in converting lignite coal to graphite as lignite is traditionally regarded as a "non-graphitizable carbon" (carbonaceous material that does not graphitize even when heated to 3,000°C).

The novel technology uses a laser to irradiate coal mixed with a simple earth-abundant, non-toxic, and potentially recyclable iron (Fe) catalyst.

The laser method achieves temperatures of approaching 1,500°C, which are adequate to transform lignite to graphite in this configuration. Notably, this innovation presents a potential alternative to the traditional energy-intensive graphite production process from petroleum coke, which requires temperatures of approximately 3,000°C.

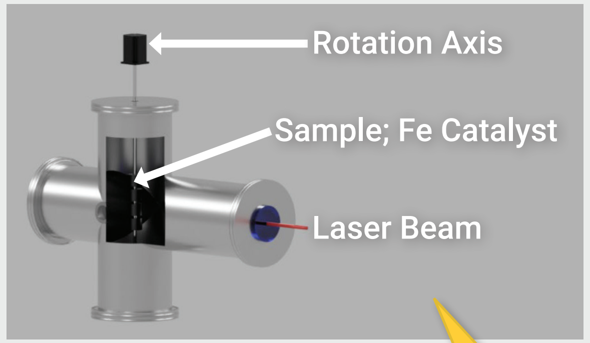


Illustration of the batch process: a pressed sample pellet of lignite char mixed with iron catalyst is irradiated by laser beam, transforming the char to graphite in a low-energy process.

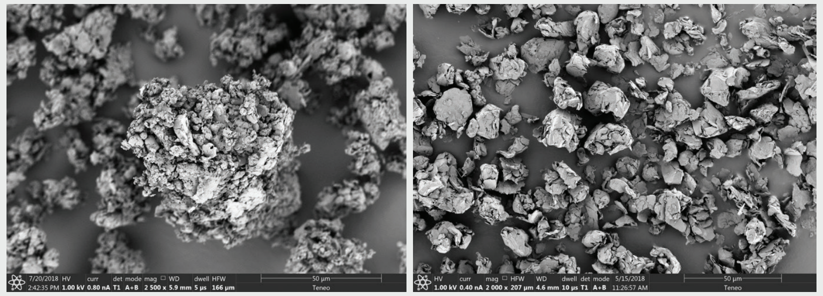
Innovative, scalable method produces 1,000-fold increase in value from lignite to graphite.

Low-Cost Lignite Coal Yields Graphite with Comparable Properties to Commercial Graphite

Research findings have clarified the mechanism of the graphitization of lignite by examining the reaction intermediates and products and determining the factors that govern the size, quality, and yield of the lignite-derived graphite.

Notwithstanding the high-impurity/mineral content of lignites (17-27% dry ash for North Dakota and Mississippi lignites, respectively), a tailored purification method of the converted material yields graphite with properties similar to commercial graphite.

The most significant advantage of this novel method is that shaped graphite is produced in a one-step, low-energy, laser-powered conversion process with minimal material loss, whereas conventional/commercial methods must transform natural flake graphite (or synthetic graphite) into the desired shape through intensive processing, thereby incurring process losses of significant amounts of graphite.



Shaped graphite synthesized from lignite (left) is similar in form and properties to commercial standard Hitachi MagE3 graphite (right) used in lithium-ion battery manufacture.

Shaped graphite is produced in a one-step, energy-efficient, laser-powered conversion process with minimal material loss.

A Continuous Process is Under Development

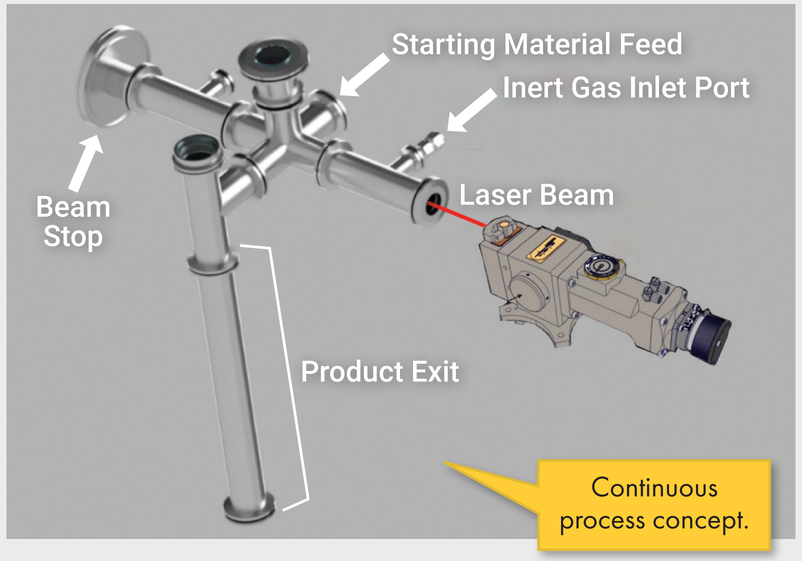
Efforts are underway to transition this technology from batch processing (gram scale) to continuous processing (kilogram scale), which will be essential to the development of a commercially viable, cost-effective processing capability.

Commercialization of this new technology will entail optimizing:

- Composition and processing (mixing, forming, composition, and lignite charring).
- Sample residence time.
- Laser power and wavelength.
- Size of the graphite being produced.

In addition, the continuous production of LIB-grade graphite at optimal yield and a long cycle life with optimized graphite must be demonstrated.

A system with significantly increased efficiency already has been developed that can operate continuously at approximately 0.6 kg/h graphite synthesis at 1 kW. It is anticipated that minimal process modifications would be required to adapt this technology to a 12-kW fiber laser system capable of producing more than 60 tons per year, which would nearly match 2022 domestic consumption.



Continuous process concept.

Projected cost is currently estimated to be significantly below current graphite costs, offering the possibility of the establishment of an entirely domestic supply chain for LIB-grade graphite.

Novel Technology Could Support a Domestic Graphite Supply Chain While Simultaneously Reducing Cost

Graphite is a critical mineral utilized in LIB anodes. Importantly, LIBs are used to power a wide range of battery electric vehicles and enable energy storage applications. Significant shortfalls in graphite supply are anticipated to exist over the coming decades.

If this technology matures to a large-scale continuous process, it could directly address near-term future shortages of LIB-grade graphite, which are predicted due to the expected high demand associated with the rapid expansion of the battery market.

The United States has no graphite mines, so production from natural graphite is not feasible. Production from other carbon sources (in this case coal) may offer a near-term domestic supply chain option, especially as lignite mines are currently operating at scale in the United States with decades of proven reserves available.

The conversion of lignite to graphite can confer supply chain security, lower costs and environmental footprint, and create economic opportunities for mining and manufacturing communities in the United States.

PARTNERSHIP WITH:

THE GEORGE
WASHINGTON
UNIVERSITY
WASHINGTON, DC

SCAN FOR MORE INFORMATION:

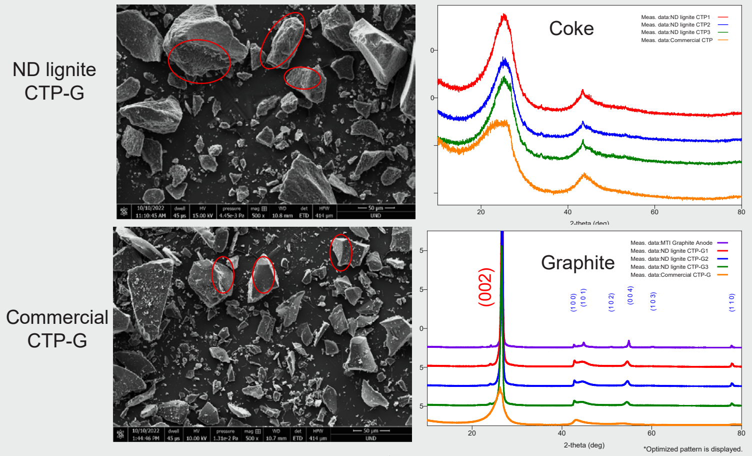
Award No. FE0031984

Lignite-Derived Carbon Materials for Lithium-Ion Battery Anodes

Low-Cost Domestic Lignite is Used to Synthesize High-Value Advanced Anode Materials

A novel approach has been devised to efficiently convert abundant domestic low-rank coal such as North Dakota lignite into unique high-quality, lignite-derived pitch. This pitch is a high-performance, low-cost, and readily available feedstock for synthetic graphite (SG) manufacture.

Additionally, advanced technologies have been devised to manufacture composites for high-value, carbon-based lithium-ion battery (LIB) silicon/carbon (Si/C) anodes using the lignite-derived SG.



Comparison of Coal Tar Pitch Graphite (CTP-G) from North Dakota lignite (top) and commercial CTP-G (bottom).

These advances will accelerate the commercialization of production of high-quality, lignite-derived pitch and SG into the rapidly expanding, high-value LIB market in the United States.

A Low-Cost and Scalable Process to Make Porous and Spherical Si-C Composite Anode Materials

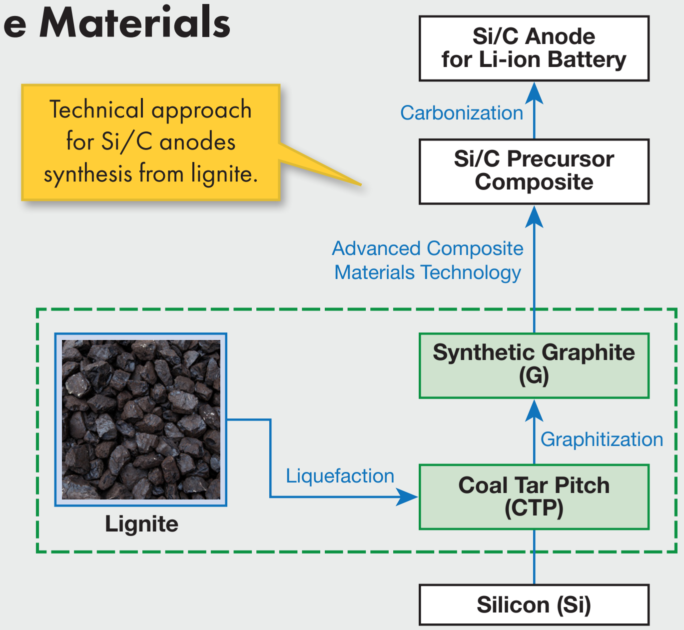
The Si-C composite anode materials being produced in this project incorporate domestically sourced lignite-derived pitch and SG as the main feedstocks.

In addition to producing the lignite-derived carbon feedstock, developing a low-cost and scalable process to make porous and spherical Si-C composite anode materials with excellent properties for high-performing anodes for LIBs is a key aspect of this technological advancement.

The quality of the anodes has been verified by evaluating the performance of the new Si-C composite anodes as compared with a commercial anodes.

Process improvements have aimed at identifying the optimal pitch and SG for LIB anode applications from a variety of sources.

Technical approach for Si/C anodes synthesis from lignite.



Si/C Anode for Li-ion Battery

Carbonization

Si/C Precursor Composite

Advanced Composite Materials Technology

Synthetic Graphite (G)

Graphitization

Coal Tar Pitch (CTP)

Liquefaction

Lignite

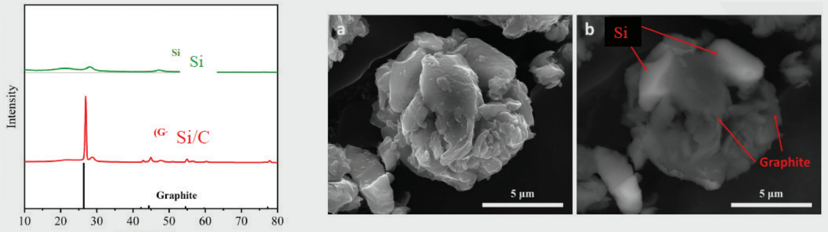
Silicon (Si)

Process advantages in scalability and cost.

A Novel Production Process

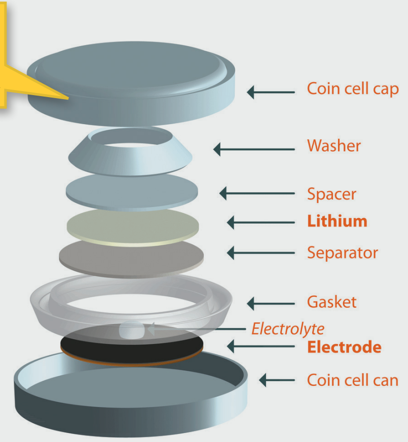
A highlight of this research and development (R&D) effort is a novel production process that forms composite/bonded Si/C particles in the optimal shape for incorporation in advanced, high-performing anodes for application in lithium-ion batteries.

Success of the process in meeting targeted performance requirements has been achieved in battery electrochemical parameters, including specific capacity, initial Coulombic efficiency (ICE), and cycling life. And significantly, preliminary techno-economic analysis (TEA) projects an estimated Si-C production cost of only $5/kg based on an 8,000 ton/year production capacity.



X-ray diffraction and scanning electron microscopy (SEM) imaging demonstrates successful formation of bonded spherical Si/C particles

Coin-cell Li-ion battery configuration.



Coin-cell battery performance results have exceeded targets and exceed commercial performance references. Extension of the technology to the production of 18,650 cells is currently underway.

Advantages of Composite Anodes

Silicon anodes in LIBs have very high capacities (the total amount of electricity generated due to electrochemical reactions in the battery), but they are beset with problems that result in poor cycle life and conductivity and performance losses.

Graphite anodes, on the other hand, are more stable and cheaper than silicon anodes, but the capacity of graphite anodes is much lower than silicon anodes.

The composite anode being developed in this R&D effort uses both graphite and silicon materials and has the potential advantages of high performance with reversible capacity, high Columbic efficiency, excellent cycling life, and lower overall costs.

Another advantage to composite anodes is the ability to source the graphite and silicon from domestically available sources such as low-rank coal, and decreasing the amount of graphite in an anode requiring less extraction of material.

	Graphite	Si
Capacity	372 mAh/g	3600-4200 mAh/g
Cycle Life (80% Retention)	>1000	<300
Mechanism	Li = 6C = LiC_6	15Li + 4Si = $Li_{15}Si_4$ 22Li + 5Si = $Li_{22}Si_5$
Cost	$10-15/kg	≥$65/kg
Other Key Issues	Poor low-T performance & rate capability	Low conductivity & low ICE, >300% volume change

Tradeoffs of LIB anode types.

Coin-cell tester.

Composite anodes confer performance improvements and domestic sourcing opportunities.

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