Carbon Ore Processing Program

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U.S. DEPARTMENT OF ENERGY

NETL's Carbon Ore Processing Program

Program Initiated 2018

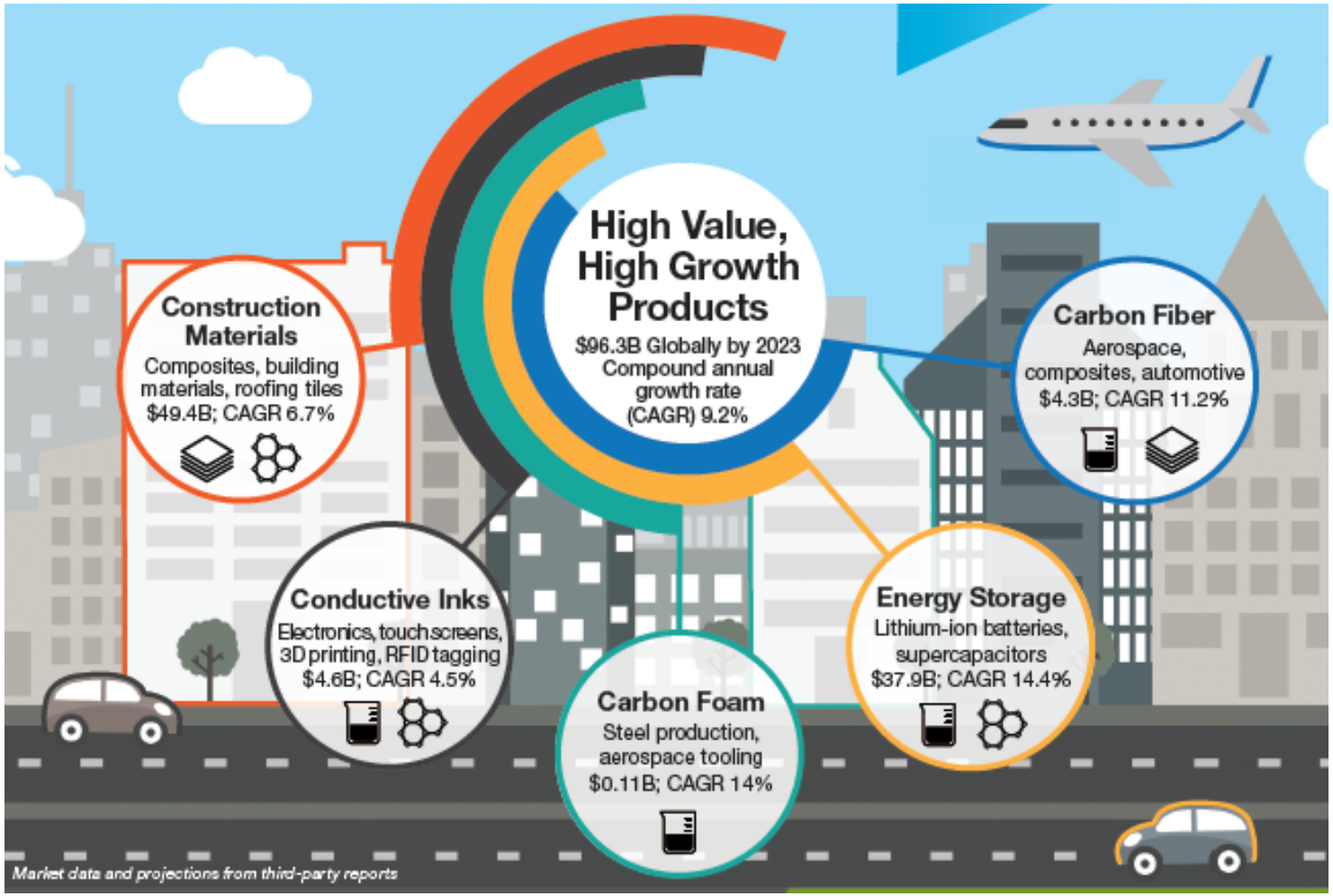
Program Goals

- Expand beyond traditional thermal and metallurgical applications
  - Covers high-volume through high-value
- Products from domestic coal and coal wastes
  - Remediation of legacy wastes is a benefit
- Advance laboratory and pilot-scale technologies
  - Must test processes at relevant scale
  - Must test product at relevant scale
  - "Prototypes are easy, production is hard"

Product and Application Market Potential

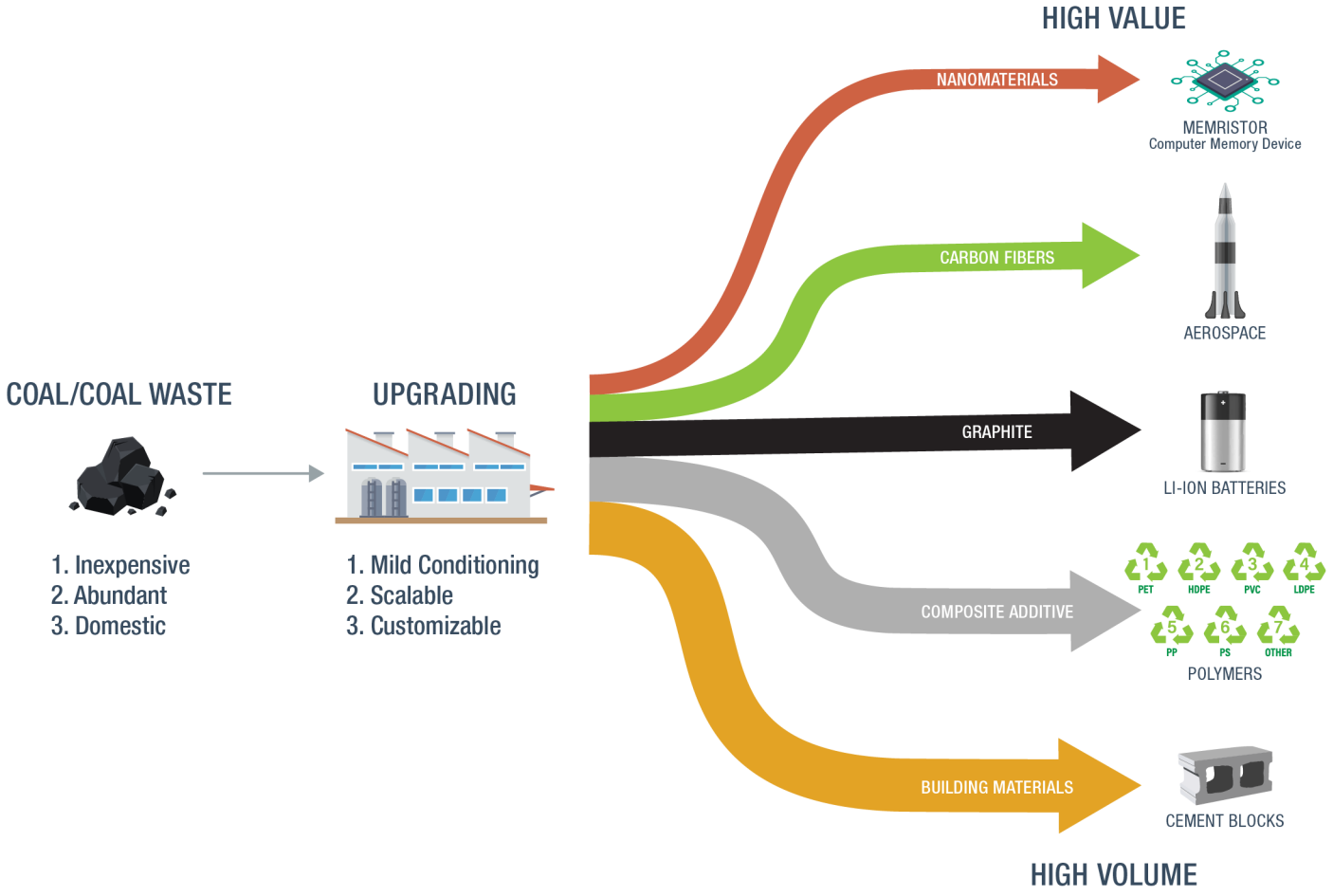
Carbon Ore Processing Program

- Program is focusing on high-value and high-growth products
- Current products and applications
  - $96.3B global market value by 2023
  - CAGR of 9.2%
- Tremendous potential for coal waste remediation



Expanding the Coal Value Chain

NETL's Carbon Ore Processing Program



- Expand use of coal wastes
- Advantages over other carbon-based feedstocks
  - Abundant and low cost
  - High-carbon density
  - Enables low cost, high-volume production of carbon materials
- Challenges
  - Optimizing product and process performance
  - Coal contains the periodic table

Coal Ore Processing Budget History

Funding Opportunity History

Funding Opportunity	Issue Date
FOA-0002185: Coal-derived materials for building, infrastructure, and other applications	4/10/2020
FOA-0002438: Design, R&D, Validation, and Fabrication of a Prototype Carbon-Based Building	12/11/2020
FOA-0002405: Advanced Coal Waste Processing: Production of Coal-Enhanced Filaments or Resins for Advanced Manufacturing and Research and Development of Coal-Derived Graphite	4/16/2021
FOA-0002620: Carbon Ore Processing	07/29/2022

FOA 2405: Selected Projects

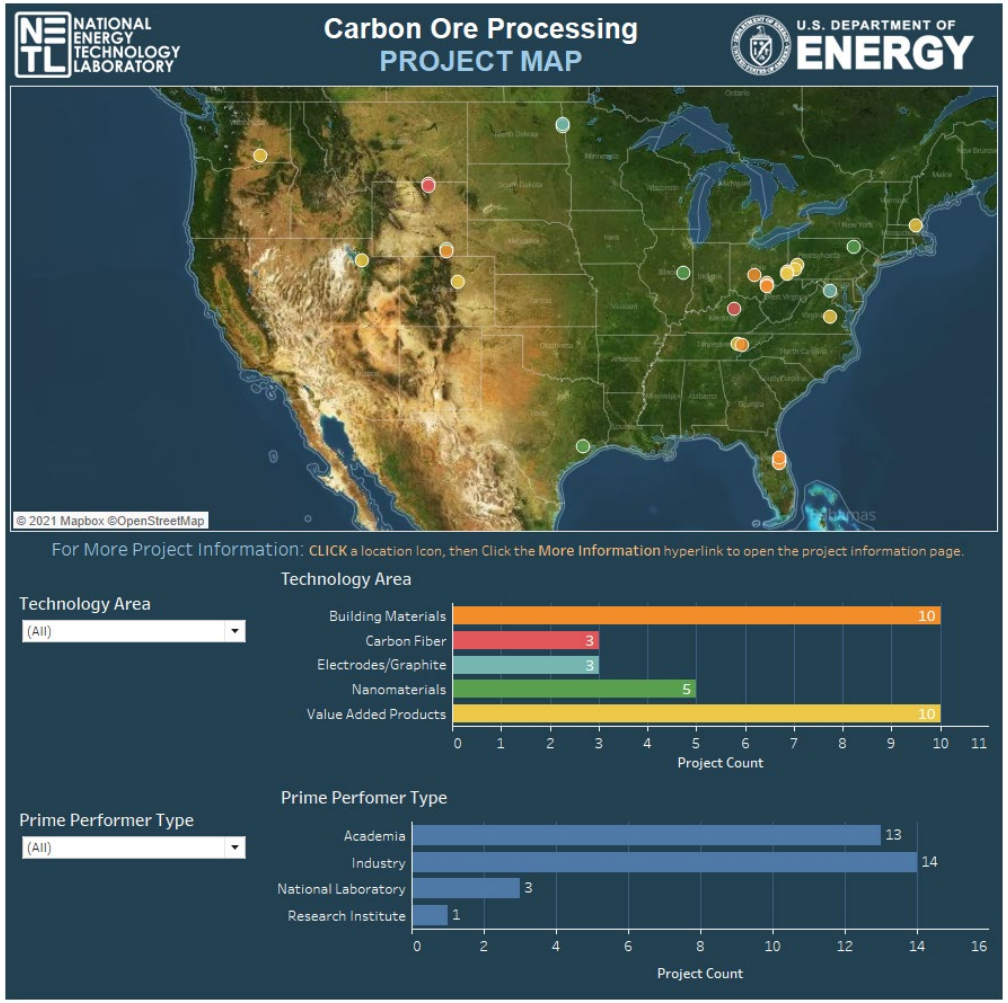
Advanced Coal Waste Processing: Production of Coal-Enhanced Filaments or Resins for Advanced Manufacturing and Research and Development of Coal-Derived Graphite

- AOI 1: Coal-Enhanced Filaments/Resins for Additive Manufacturing
  - *Ohio University*
  - *Baker Hughes Technology*
  - *Semplastics*
  - *University of Delaware*
- AOI 2: Supporting R&D of Coal-Derived Graphite
  - *University of North Dakota*
  - *Ohio University*
  - *Touchstone Research Laboratory*

Current R&D Portfolio

Active Projects

- Program has ~40 active projects
- Carbon Products Include:
  - High Value
    - Graphene, quantum dots, conductive inks, battery anodes, synthetic graphite, and supercapacitor materials, carbon fibers
  - High Volume
    - Building materials, carbon foam, composites, roofing materials.



Inflation Reduction Act EV Tax Credit

- To qualify for a tax credit of $3,750, the IRA requires that the "percentage of the value" of the applicable battery critical minerals extracted or processed in the US or a US free-trade partner or recycled in North America, be more than 40% prior to 2024 (rises to 80% by 2027).
- An additional tax credit of $3,750 is available if at least 50 percent of the battery's components are manufactured or assembled in North America prior to 2024 (increasing to 100 percent by 2029).
- Beginning in 2025 a vehicle will not qualify for a tax credit if it contains any critical minerals that were "extracted, processed, or recycled by a foreign entity of concern"
- Beginning in 2024, a vehicle will not qualify for a tax credit if any "components" contained in its battery are "manufactured or assembled by a foreign entity of concern".

DOE to issue proposed guidance by 12/31/22

EV-Battery Components By Mass

Mineral	Component	Amount in Battery (kg)	% of Total
Graphite	**Anode**	**52**	**28.1%**
Aluminum	Cathode, Casing, Current Collectors	35	18.9%
Nickel	Cathode	29	15.7%
Copper	Current Collectors	20	10.8%
Steel	Casing	20	10.8%
Manganese	Cathode	10	5.4%
Cobalt	Cathode	8	4.3%
Lithium	Cathode	6	3.2%
Iron	Cathode	5	2.8%
Total	**n/a**	**185**	**100.0%**

https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/

Low-temperature Catalytic Graphitization

Improved Graphite Manufacturing from Waste Carbons and their Blends

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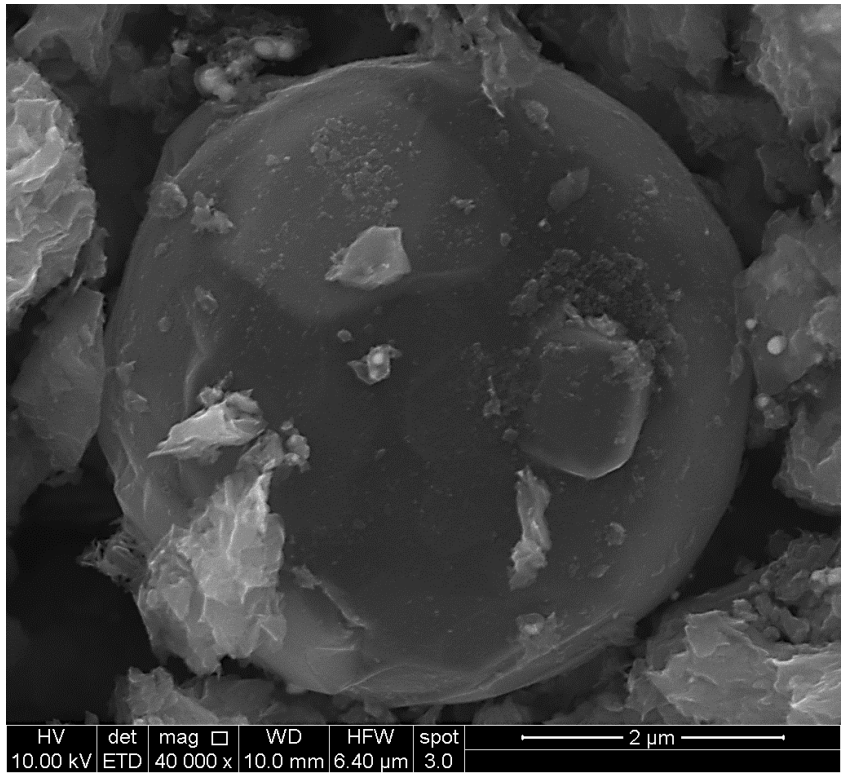
Key Benefits

- **Reduces Environmental Impacts -** Catalytic and microwave processes reduce manufacturing temperatures and process time
- **Lowers Manufacturing Costs -** Polygeneration of graphite and other carbon products uses low-cost feedstocks
- **Expands Domestic Graphite Supply Chains -** Converts low-cost, domestically-sourced waste coal, waste plastic, & biomass to graphite
- **Produces Battery Grade Graphite**

Low Process Intensity:
- Temperature ~ 1500 C
- Time ~ 3 hours

Degree of Graphitization > 90%

NETL's Low Temperature Graphitization Process



Coal-Derived Graphite

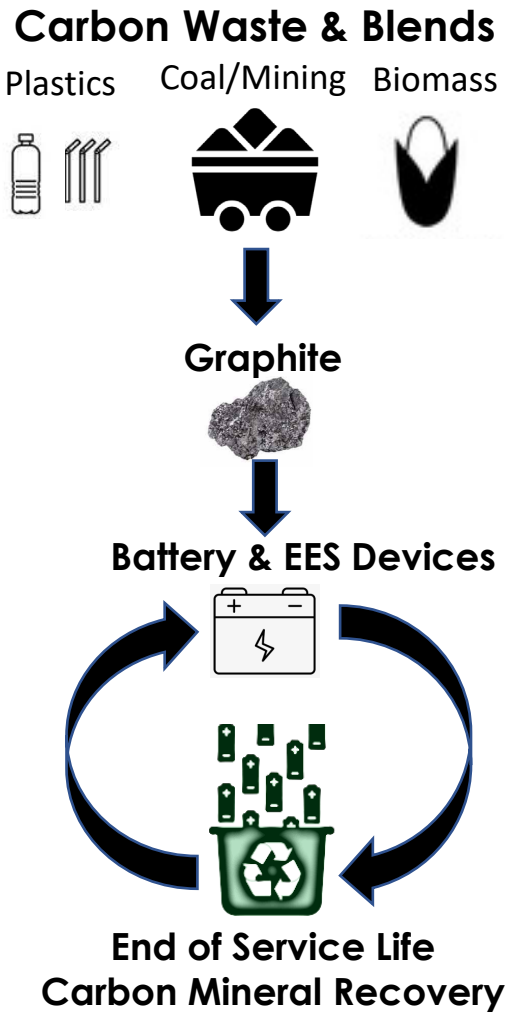
Game-Changing Source of Graphite for Lithium-Ion Batteries

Key Benefits

- **Reduces U.S. dependence on foreign sources** –Virtually all battery-grade graphite currently used in U.S. electric vehicle production is imported
- **Provides superior properties and/or economics** – Current research indicates coal-derived graphite can result in higher quality synthetic graphite using lower cost resources
- **Remediates legacy wastes** – Using coal wastes provides economic and environmental justice benefits
- **Creates prevailing wage jobs** – Utilizing coal wastes provides jobs typically located in economically distressed mining communities

Annual demand for graphite in lithium-ion batteries for domestically-produced electric vehicles could exceed 325,000 tons in 2030*

*Current U.S. EV production uses about 39,000 tons of graphite per year



Coal-Derived Graphite

Anodes for Lithium-ion Batteries from Domestic Coal Waste

- Viable SiOC - coal composite anodes
- Half coin cell (vs Li, 0.005-3V) specific reversible capacities of >700 mAh/g.
- Single Layer Pouch Cells(vs NMC 532, 2.5-4.2V) surpassed 500 cycles above relative capacity of 80%.

Currently testing in 50 mAh Pouch

Scaling up to 3-5Ah 18650 Cells by End of Project

Coal-Derived Building Materials

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High-performance, energy-efficient, low-cost, sustainable building materials

Key Benefits

- **Increase product performance** - Coal-derived materials in blocks and bricks improve structural and thermal insulating properties
- **Increase building energy efficiency** - Coal-derived insulating foams reduce building energy consumption
- **Reduce product cost** - Coal/plastic composite decking boards reduce manufacturing costs
- **Provide high-volume use for coal wastes** –Markets include carbon foam, roofing tiles, siding, decking, insulation, joists/studs, sheathing, tiles and carpet, and architectural block

Global demand for building materials can't be met with traditional biomass resources alone. Estimated needs could exceed 1100 gigatonnes over the next two decades.*

*Current demand is about 1,100 gigatonnes, about equal to living biomass

Coal-Derived Building Materials

Success with CPC Materials for Decking Applications

- Meets or exceeds ASTM and IBC requirements
- Equivalent or greater strength
- Greater resistance to oxidation
- Lower flammability
- Better price point
- Lower embodied energy and emissions

In the past 3 years, Ohio University and industrial partners have successfully matured technology from TRL4 to TRL8

Deck Constructed with CPC Boards

CPC Pricing with Commercial Products

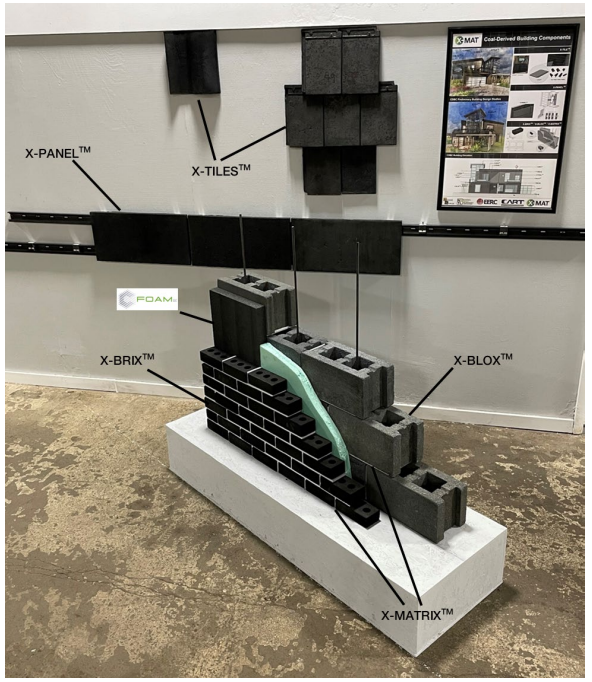
Manufacturer	Product	End User Pricing ($/linear ft)
DE-FE0031809	CPC	1.29
Trex	WPC	1.75-5.78
Choicedek	WPC	3.67
TimberTech	WPC	4.48-6.68

Coal-Derived Building Materials

XMAT Coal Derived Building Materials

Coal Derived Building Materials (CDBM) including X-BLOX, X-BRIX, X-PANEL, X-MATRIX, and X-TILES exhibit exciting high-performance characteristics:

- Five times the flexure strength of the best commercial brick
- Over twice the compressive strength of construction-grade concrete block
- Lower density than comparable material,
- Improved mechanical durability and abrasion resistance,
- Very high temperature stability, and
- Resistance to chemicals, acids, salts, and water.



Coal-Derived Nano-Materials

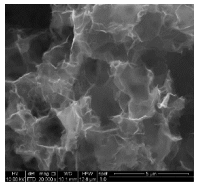
Additive Manufacturing and Carbon-Metal Composites are Focus Areas

Key Benefits

- **Leverage high carbon content of coal** – Coal wastes can produce a variety of carbon materials
- **Lower production costs** – Coal-derived nano-materials can have lower raw material costs
- **Provide materials for additive manufacturing** – Utilizes coal-enhanced filaments or resins for 3D printing
- **Provide superior properties and/or economics** –Atomically thin carbon dielectric film improves performance, facilitates miniaturization and outperforms metal oxides used in commercial devices
- **Allows multi-material printing** - Filaments or resins based on unique aspects of coal chemistry enable multi-material printing

3-inch prototype memristor computer memory devices are routinely manufactured and are scalable for large industrial production runs

Novel Carbon Materials

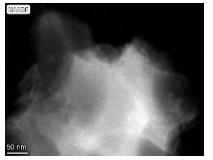


3D & Few-layer Graphene

Graphene Oxide

Graphite

Graphene Nanoflakes



Porous Carbons

Carbon Quantum Dots

Coal to Carbon Fibers

Producing High-Performance Materials from Coal

Key Benefits

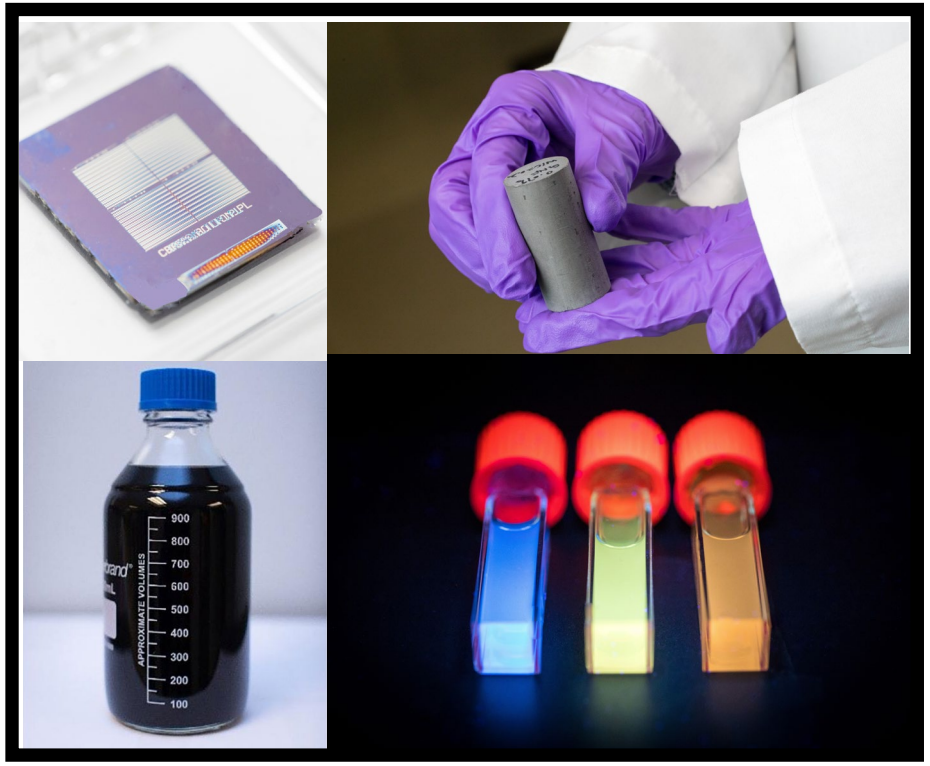
- **Lowers production costs** – High carbon content, lower cost of coal tar pitch enable lower cost production
- **Produces a range of fibers** – Extends from short chopped fibers for low-cost applications to graphitizable fibers for demanding aerospace applications
- **Offers varying elastic modulus, strength, and conductivity** - can be tailored depending on fiber processing and heat treatment conditions

R&D is improving manufacturing processes to address variability of source coal, pitch composition, and precise process control requirements

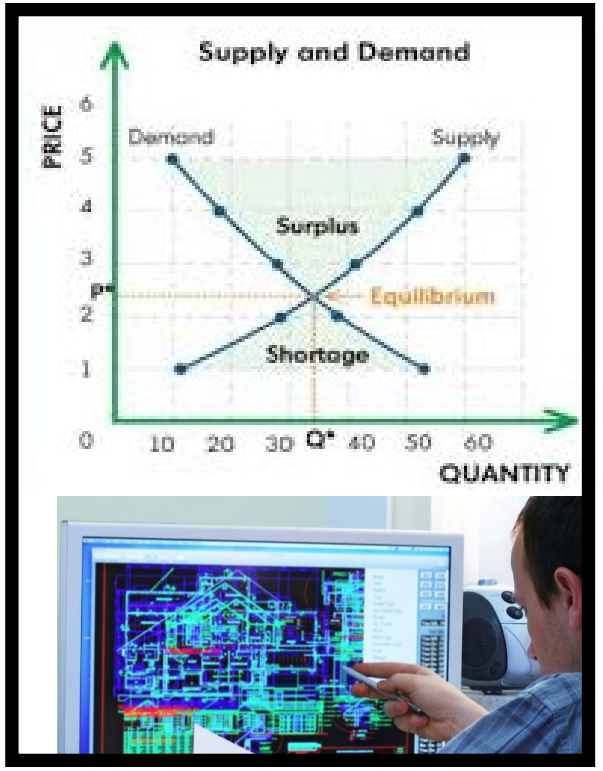
NETL-RIC's Coal to Products Research

NETL's Research Innovation Center

Materials Discovery & Design



Market, Process, & Environmental Analysis

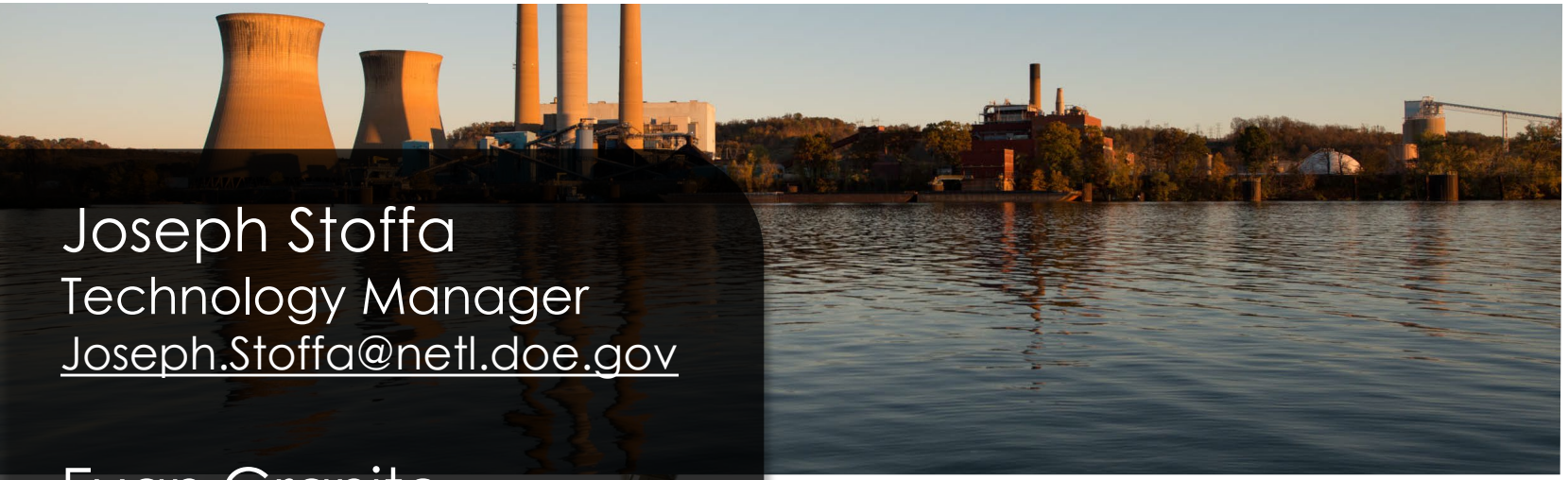


Takeaways

- Exciting opportunities exist to create jobs and support R&D of coal-derived products that could address legacy coal wastes
- Supports R&D of both high volume and high value applications
  - Coal based building materials may beat BAU in terms of carbon emissions
    - We don't have enough biomass for future construction
  - Coal-derived materials can offer unique properties at a competitive price point
- Lab scale through bench-scale development
- Most funding supports R&D of coal-derived products
  - Outside of traditional thermal and metallurgical markets
  - Mostly avoids support for R&D to produce commodities

Contacts

https://netl.doe.gov/Advanced_Coal_Processing



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