A New Carbon Economy on the Horizon

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

The Carbon Based Economy

A carbon based economy is an opportunity. Engineering systems to use renewable carbon consistently and efficiently can enable an economy that functions as a tool to manage carbon on an industrial scale.

Carbon sources

- Fossil
  - Coal, oil, natural gas, tar sands
- Biomass
  - Agricultural and forest residues
  - Dedicated energy crops
  - Algae
- Waste
  - Industrial/utility waste gases
    - CO, CO_2
  - Biogas
    - Landfills
    - Digesters
  - Biosolids
  - Sorted MSW
    - Construction and demolition waste
    - Yard waste
    - Plastic
- Atmospheric CO_2

Utilizing Carbon sources

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USDA United States Department of Agriculture

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United States Environmental Protection Agency

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BETO and Carbon Management

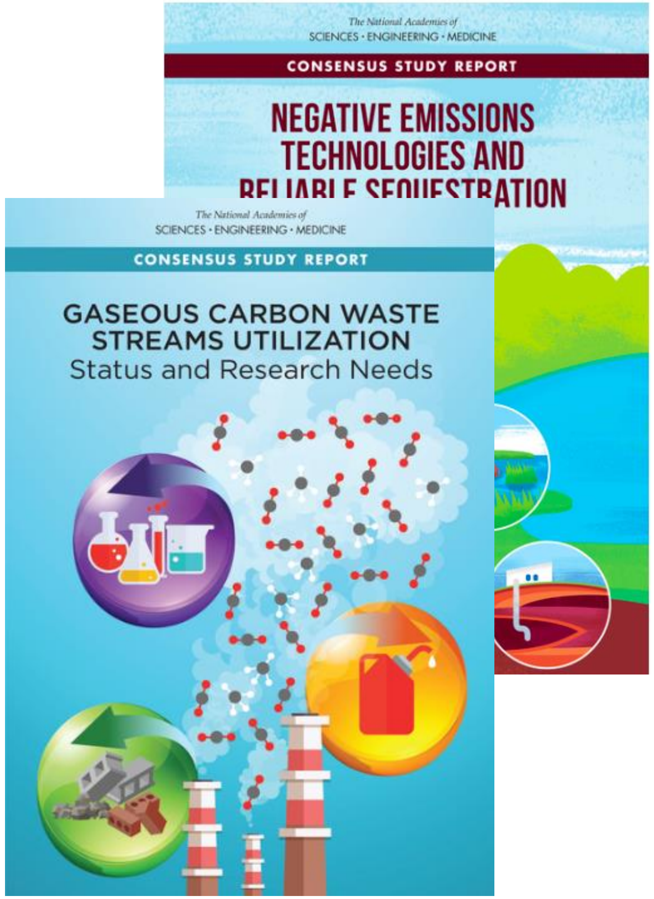
- BETO's current efforts in carbon management fall into two categories
  - Maximizing efficient use of renewable carbon resources
    - Energy security
    - Economic development
    - Environmental service
  - Identifying more domestic carbon resources and further closing the carbon cycle
    - Opportunity feedstocks (wet and dry wastes, plastics, etc.)
    - Engineer new systems that directly remove GHGs from the air

Objective

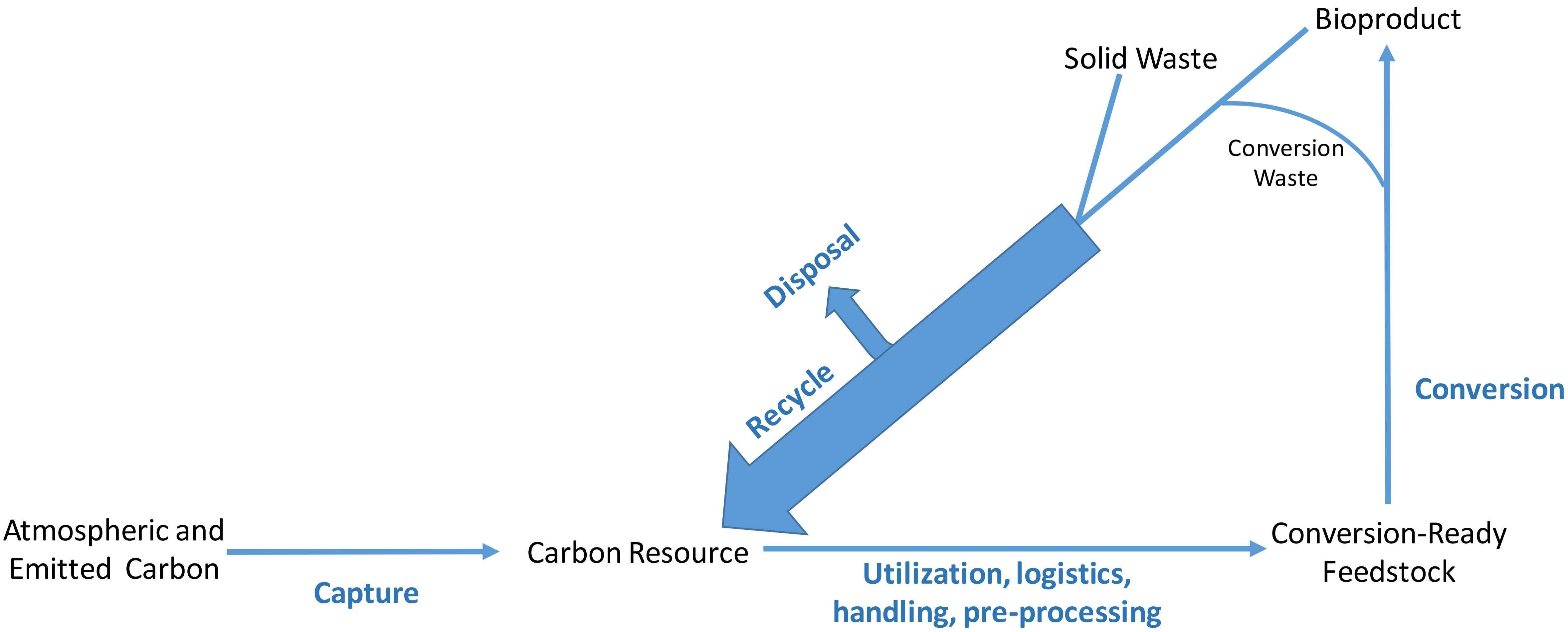
- The objective of BETO's carbon management efforts are to optimize the use, re-use, and recycle of carbon sources to add value to the bioeconomy, minimize wasted emissions of carbon to the atmosphere, and maximize the utilization of renewable carbon in biofuels and bioproducts.

Why is BETO Expanding our scope?

- Part of our continual efforts to maximize environmental, economic and social benefits of the technologies we develop
  - Resource-sparing (land, water, fertilizer)
  - Environmental service (e.g. wet and plastic waste)
  - Productive use of waste gases
- Leverage expertise in carbon manipulation and deconstruction of complex polymers
- Maximize utilization of existing core capabilities, and strategically add new capabilities
- Broadening our view of potential carbon sources
- Expanding U.S. regions that can contribute to the bioeconomy
- Help meet the advanced biofuel standards in RFS and LCFS



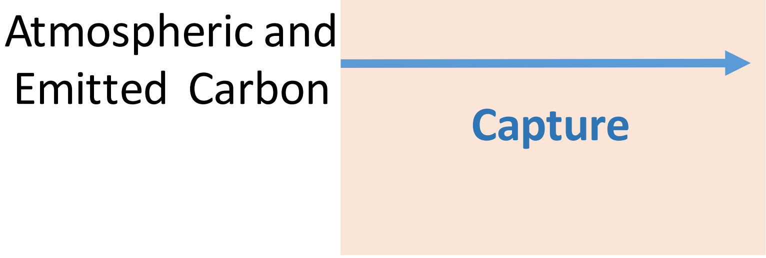
Carbon Life Cycle

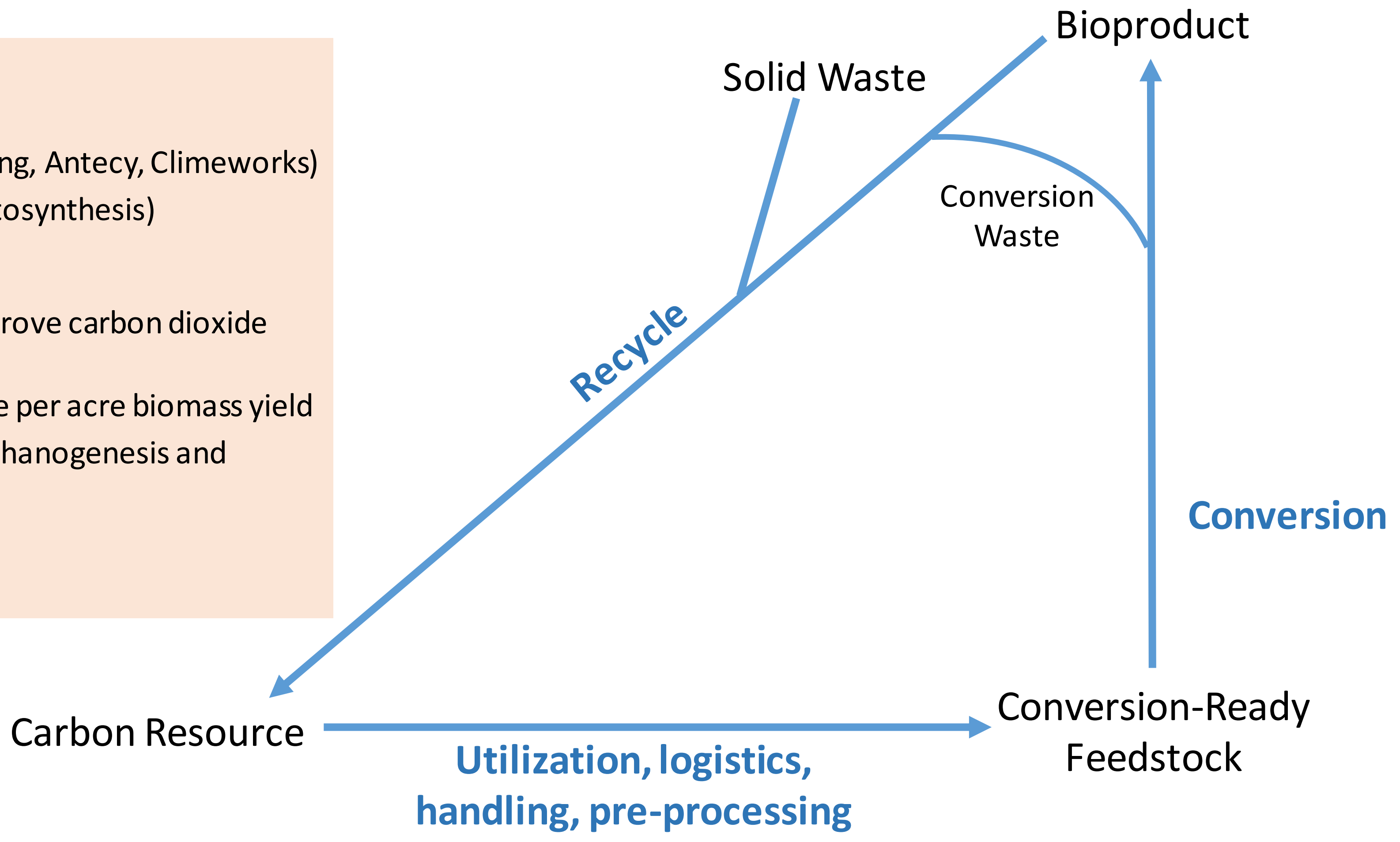


BETO activities along the carbon life cycle

Carbon Life Cycle – Capturing or avoiding CO2 or GHG emissions

- Types of capture
  - Point source capture (e.g. smoke-stack)
  - Direct Air Capture (e.g. Carbon Engineering, Antecy, Climeworks)
  - Capture by Primary Production (e.g. photosynthesis)
- BETO approaches
  - Increasing paddlewheel efficiency to improve carbon dioxide circulation in ponds
  - Landscape design approaches to increase per acre biomass yield
  - Metabolic engineering (e.g. arrested methanogenesis and enzyme capture)
  - Low-energy (enzyme) carbon capture
  - Analysis – BECCS, C storage in products

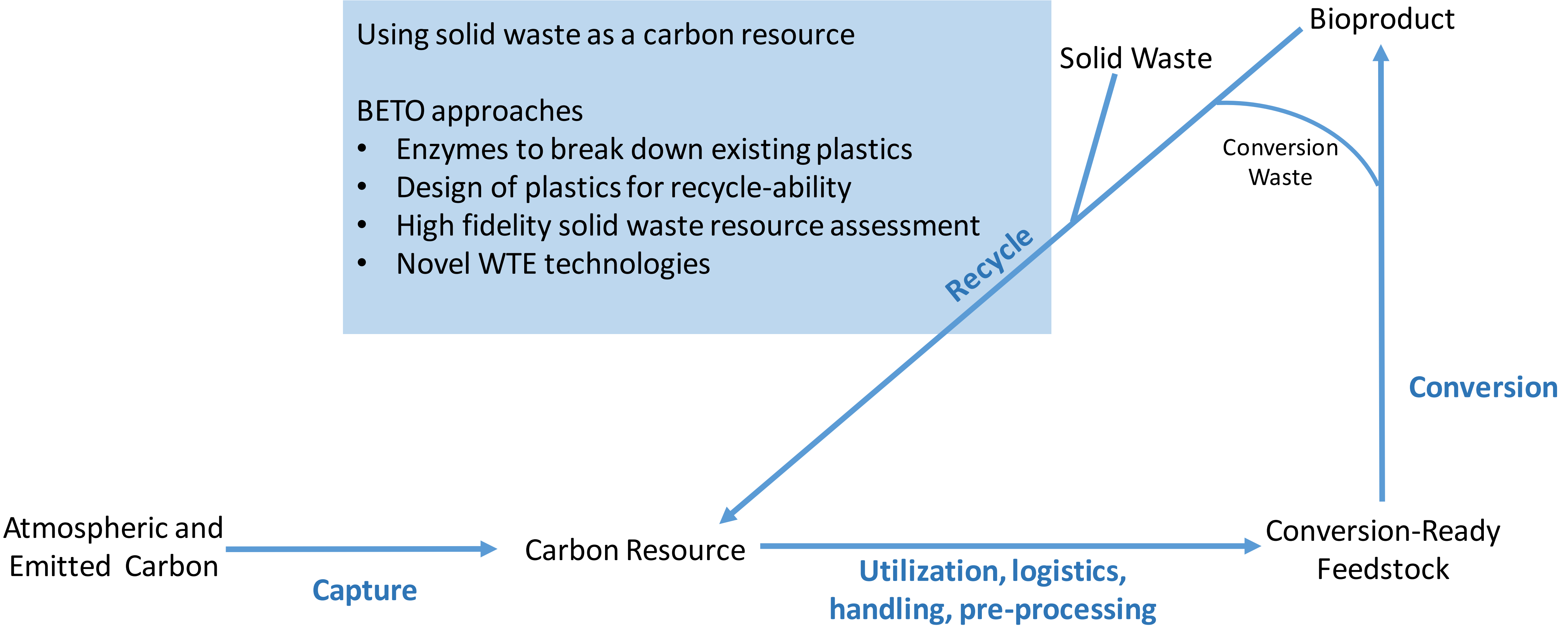




Carbon Life Cycle – Enhancing Carbon Re-Use

Using solid waste as a carbon resource

BETO approaches
- Enzymes to break down existing plastics
- Design of plastics for recycle-ability
- High fidelity solid waste resource assessment
- Novel WTE technologies

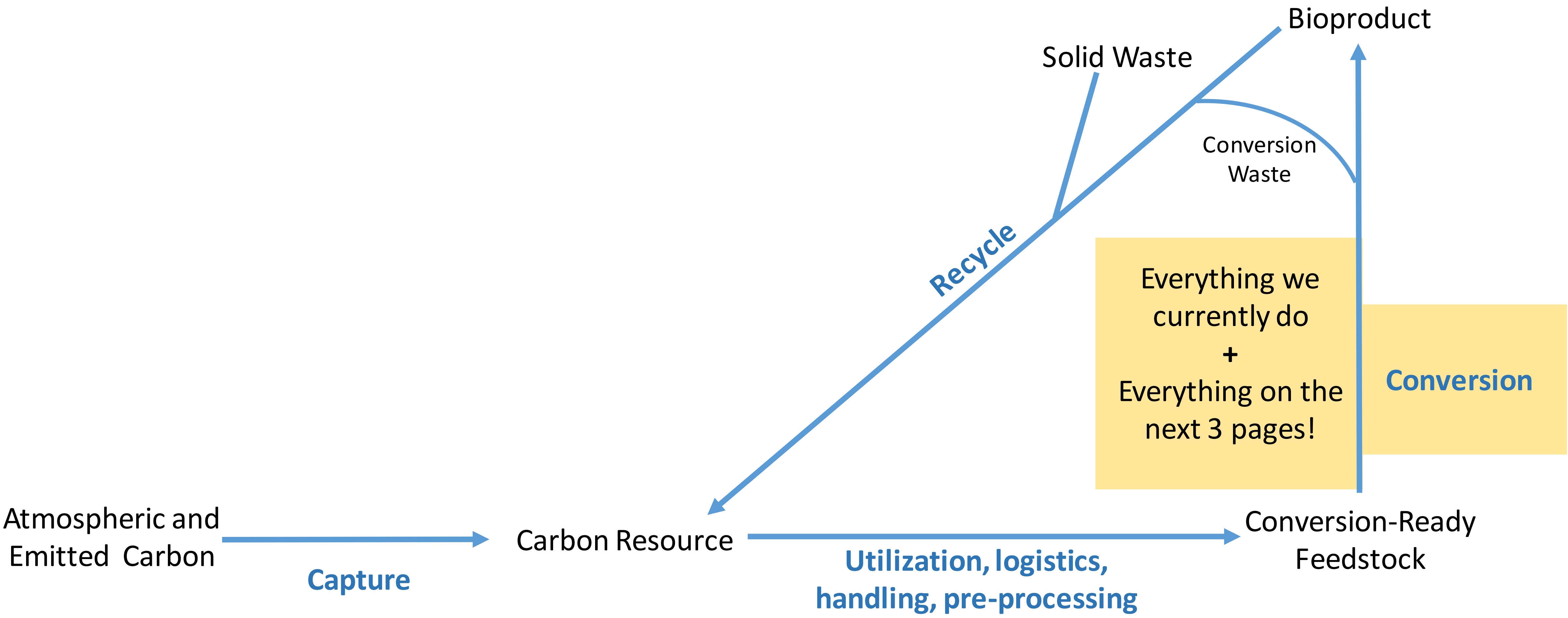


Processing carbon resources into more conversion-ready feedstock

- Physical, chemical, and biological approaches to make carbon sources more conversion-ready
  - Harvesting, handling, collection, storage, transport, pre-processing (separation, fractionation, etc.)
- BETO approaches
  - Improving storage technologies to reduce losses
  - Densification technologies to reduce energy inputs to transport and process
  - New pre-processing approaches to improve uniformity and quality of feedstock entering conversion process
  - CO_2 Activation (CO, formate, etc.)

Bioproduct
Solid Waste
Conversion Waste
Recycle
Conversion
Atmospheric and Emitted Carbon
Capture
Carbon Resource
Utilization, logistics, handling, pre-processing
Conversion-Ready Feedstock

Carbon Life Cycle



BETO Efforts in CO_2 utilization

Non-biological CO_2 activation

Enabling Studies:

2.1.0.304 Feasibility Study of Utilizing Electricity to Produce Intermediates from CO_2 – TEA and LCA overview of the various technologies available to convert CO_2 to intermediates

2.3.1.316 CO_2 Utilization: Thermo- and Electro-catalytic routes to fuels and chemicals – determining the best practices for baselining CO_2 catalysis and determining design strategies for commercial membrane electrode assemblies.

Electrocatalysis and thermocatalysis:

SBIR Phase II - Utilization of Waste CO_2 to Make Renewable Chemicals and Fuels (Opus12)
SBIR Phase I - Excess Electric Power-Driven Conversion of Carbon Dioxide to Chemicals (Precision Combustion)
SBIR Phase II - Renewables-Driven Production of Organic Acids from Industrial CO_2 Waste Streams (Skyre)
- FY17 and FY18 SBIR awards for CO_2 catalysis

2.3.1.317 Electrocatalytic upgrading of CO_2 to fuels and C2+ chemicals – CO_2 conversion to ethanol using Cu catalyst on carbon nanospikes

2.5.4.707 Catalyst Development for Selective Electrochemical Reduction of CO_2 to High-value Chemical Precursors w/Opus-12 – CRADA leveraging CCB to help catalyst development for CO_2 conversion to CO

BETO Efforts in CO_2 utilization

Engineering of microorganisms to upgrade CO_2 or intermediates derived from CO_2

2.3.2.106 <u>CO2 valorization via rewiring of the carbon metabolic network</u> – Engineering C. ljungdahli to biologically convert CO_2 and H_2 to 3HB

BRDi <u>Engineered reversal of the β-oxidation cycle in clostridia for the synthesis of fuels and chemicals</u>
Agile Biofoundry CRADA <u>Progress towards a new model chemolithoautotrophic host</u>
Agile Biofoundry CRADA <u>Data Integration and Deep Learning for Continuous Gas Fermentation Process Optimization</u>
- 3 projects improving metabolic engineering capabilities for CO conversion

2.3.2.111 <u>Improving formate upgrading by Cupriavidus necator</u>
2.3.2.112 <u>Enhancing Acetogen Formate Utilization to Value-Added Products</u>
2.3.2.113 <u>Synthetic C1 Condensation Cycle for Formate-Mediated ElectroSynthesis</u>
- 3 projects improving metabolic engineering for formate/methanol conversion

CO_2 conversion to pipeline-grade methane:

5.1.3.102 <u>Biomethanation to Upgrade Biogas to Pipeline Grade Methane</u>
5.1.3.104 <u>Modular Microbial Electromethanogenesis Flow Reactor for Biogas Upgrading</u>
2.3.2.700 <u>Integrating electrolysis and biomethanation for long-term energy storage</u>
- 3 collaborations w/labs (NREL/LLNL) and SoCal Gas for energy storage

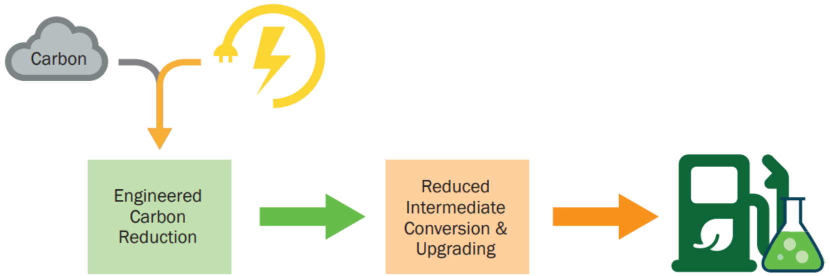
BETO Efforts in CO_2 utilization

Integrated processes for CO2 reduction followed by biological intermediate upgrading

BEEPS FOA Integrating Chemical Catalysis and Biological Conversion of Carbon Intermediates for Deriving Value Added Products from Carbon Dioxide – Johns Hopkins University
BEEPS FOA Development of a scalable, robust electrocatalytic technology for conversion of CO_2 to formic acid via microstructured materials – Montana State University
BEEPS FOA Production of bioproducts from electrochemically-generated C1 intermediates – Lanzatech
- 3 awards for generating C1 intermediates and biologically upgrading to fuels and products

SBIR Award Phase I CO_2 to Chemicals: A Hybrid Process for Bioproduct Synthesis From CO_2
SBIR Award Phase I Electrochemical conversion of CO_2 to CO for use as a fermentation feedstock
- FY18 SBIR awards for generating C1 intermediates and biologically upgrading to fuels and products

5.1.3.101 Integration of Flue Gas CO_2 Electrolysis with Microbial Syngas Fermentation
- Biopower lab call award for upgrading lower concentration dirty CO_2



Carbon Management Highlights at Peer Review

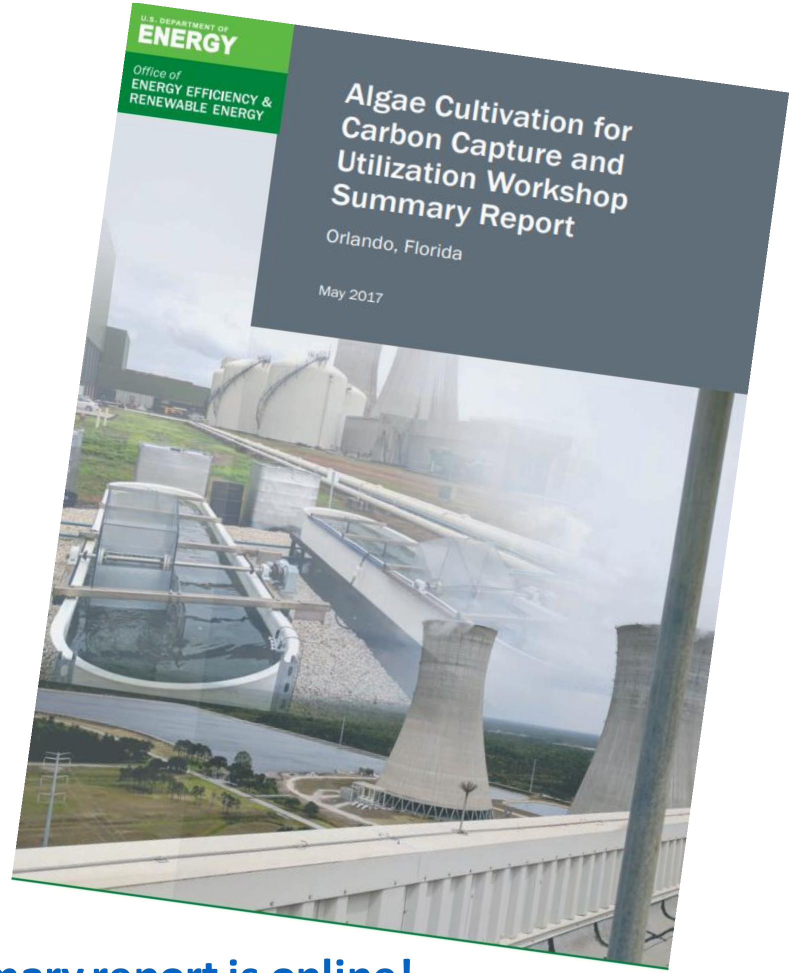
- FY14/15 Targeted Algal Biofuels and Bioproducts FOA included projects to improve carbon dioxide utilization efficiency; Global Algae Innovations and Arizona State University presenting in the Algae session starting at 1 PM on Thursday.
  - ASU's "Atmospheric CO2 Capture and Membrane Delivery" @ 1:00p
    - Working on atmospheric CO_2 capture, enrichment, and delivery via integration of moisture-swing sorption and membrane carbonation to increase biomass productivity.
  - GAI's "Algae Production CO_2 Absorber with Immobilized Carbonic Anhydrase" @ 1:30p
    - Working to increase algal biomass yield by deploying an innovative system to absorb CO_2 from flue gas using immobilized carbonic anhydrase. The project site is in Kauai, HI, at a 33-acre algae facility adjacent to a power plant.
  - Both of these project teams have won FY18 FOA awards to continue their research in these topics.
- FY18 Efficient Carbon Utilization in Algae Systems FOA recipients had posters at Tuesday evening session.

Algal Cultivation for Carbon Capture and Utilization Workshop

Hosted the **Algal Cultivation for Carbon Capture and Utilization Workshop** May 23-24, 2017 in Orlando, FL

Over 80 attendees:

- Discussed **innovative technologies** and **business strategies** for growing algae on CO_2 emissions
- **Toured** an algae research project at a coal-fired power plant
- Proposed a framework to support federally funded algal biofuels research **in real-world relevant** carbon capture and utilization conditions.
- **Engineering** and **biological** solutions are needed to increase the efficiencies of **CO_2 delivery** and **uptake** by the algae, and it is important to show that algae can **thrive** on these emissions while **reducing costs** of production.



[Summary report is online!]

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THANK YOU