Southeast Regional Challenges and Opportunities for Carbon Reduction and Removal Technologies

Michelle K. Kidder, Ph.D
Senior Research and Development Staff

USEA-DOE-FECM
Grant Workshop
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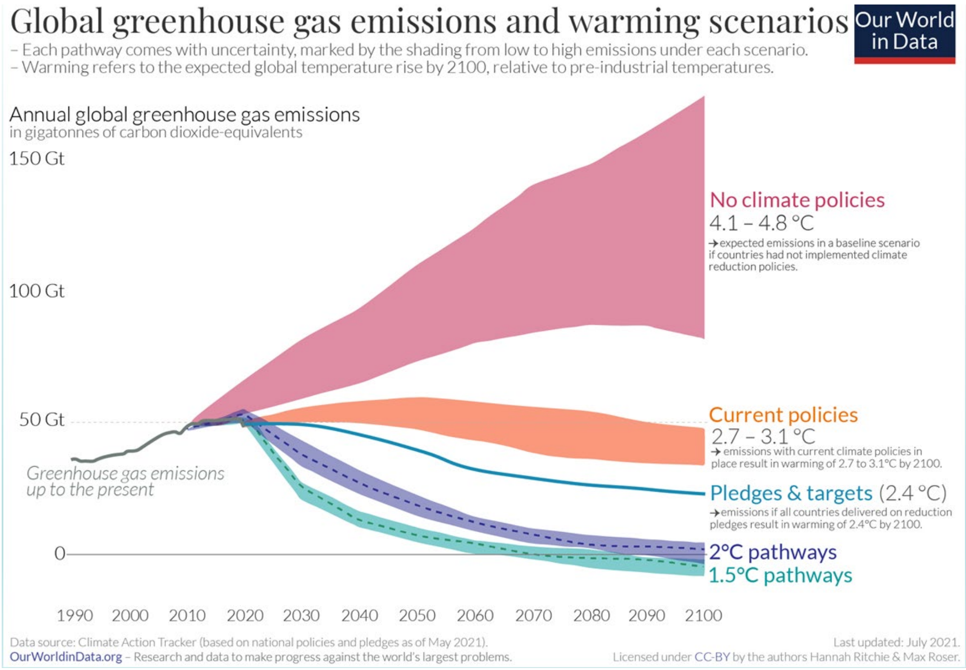
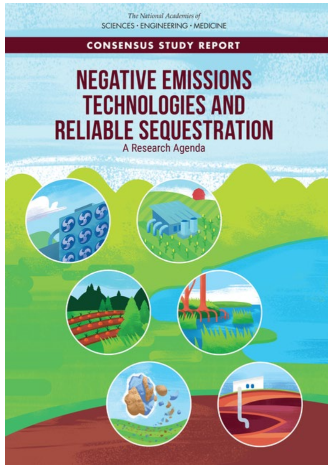
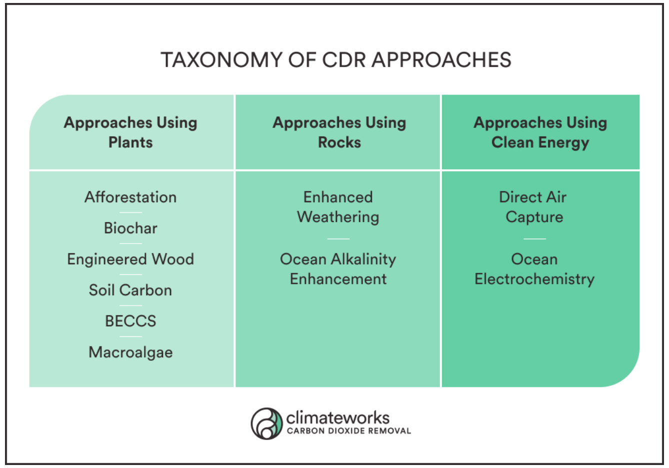
Approved for public release

Problem

- 40 GT CO_2 emitted per year globally. To achieve 1.5 - 2℃, need reduced emissions and remove ca. 10 $GtCO_2$/yr by 2050
  - *National Acad. Of Sci,* 2019 "To meet targets of climate goals, need negative emission tech. to remove CO_2 from the air"
- CO_2 (and GHG) is a global issue; Biden Administration Climate Goals
  - By 2035 – 100% emission-free electricity
  - By 2050 – achieve net-zero emissions
- Direct Air Capture (DAC) needs to meet the target of <\$100/ton CO_2
  - suffers from scalable, economical (energy and life cycle emissions), system integration technologies







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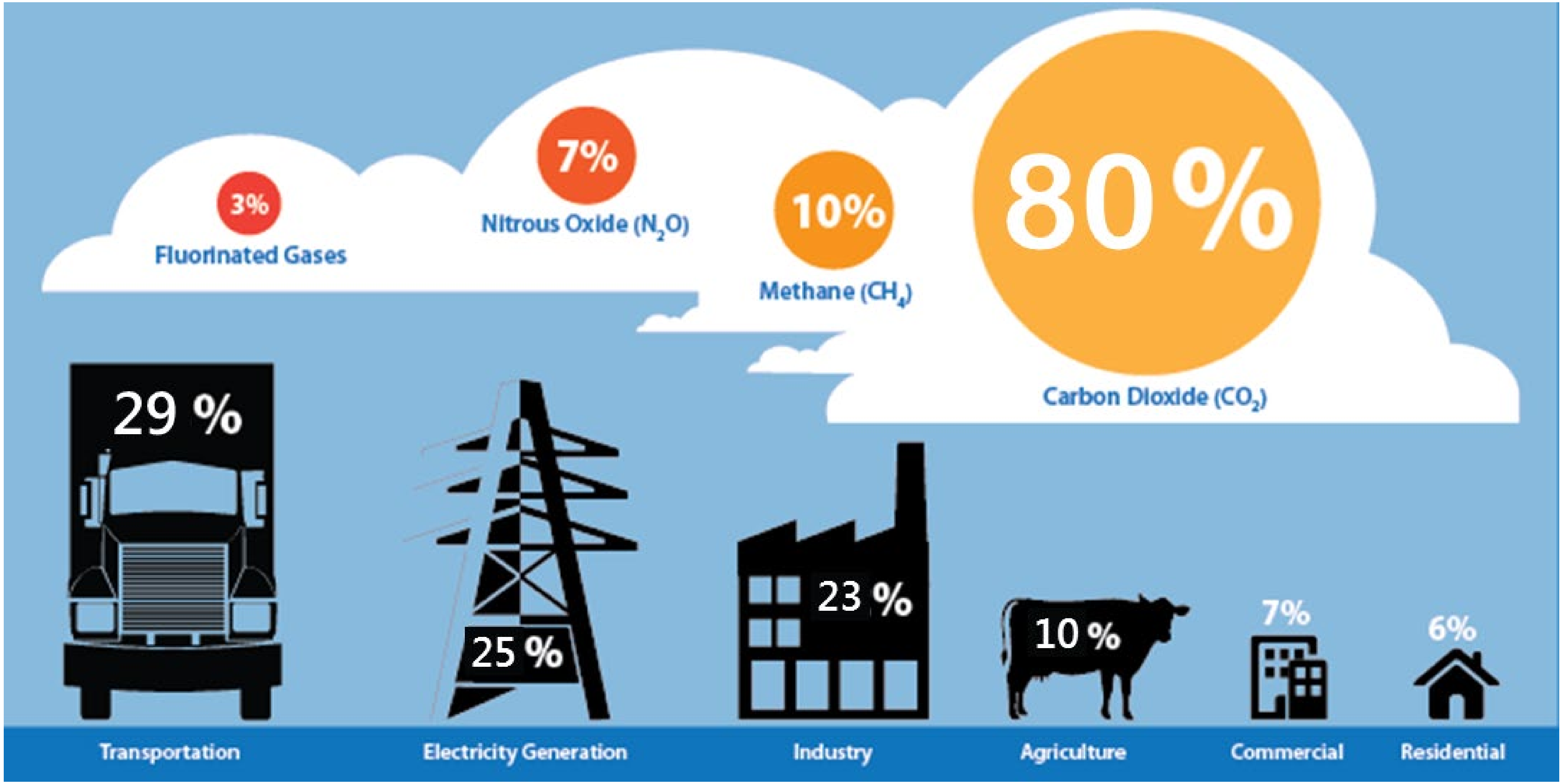
Open slide master to edit

Overall Picture of Emissions and the Source



https://theconversation.com/us

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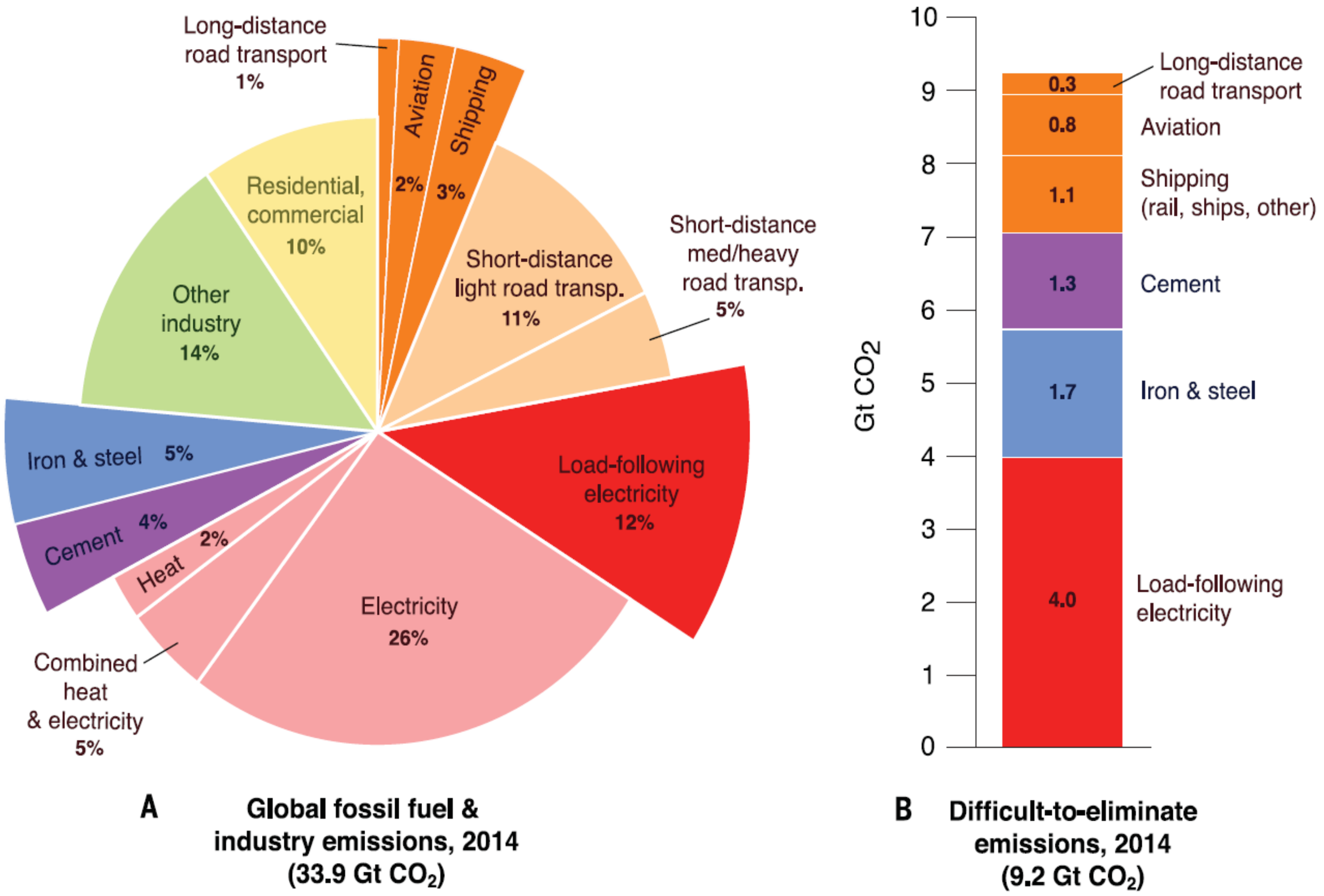
Sectors that are difficult to convert or abate emissions

Reaching net-zero emissions goals will require society-wide changes to the economy



Difficulty of decarbonization varies from "relatively straightforward" to "difficult to eliminate"

"Straightforward" = electrify all processes and generate electricity from CO_2-free source

Growth in renewable energy generation in US from 2000-2020 was ~5 quads
Estimate for "straightforward" sectors in chart for US is ~70 quads

CO_2-negative technologies will be needed at gigaton scales to reach net zero

Davis et al., Science 360 (2018) 1419

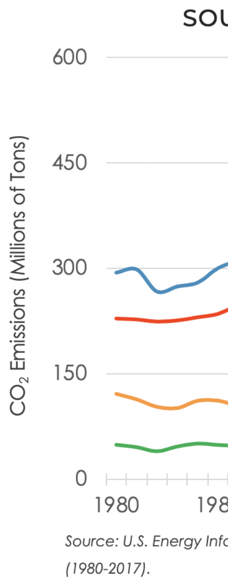
Regional Emissions

EMISSIONS FORECAST FOR UTILITIES

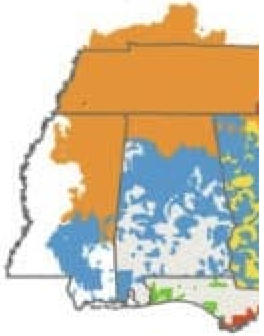
ACTUAL

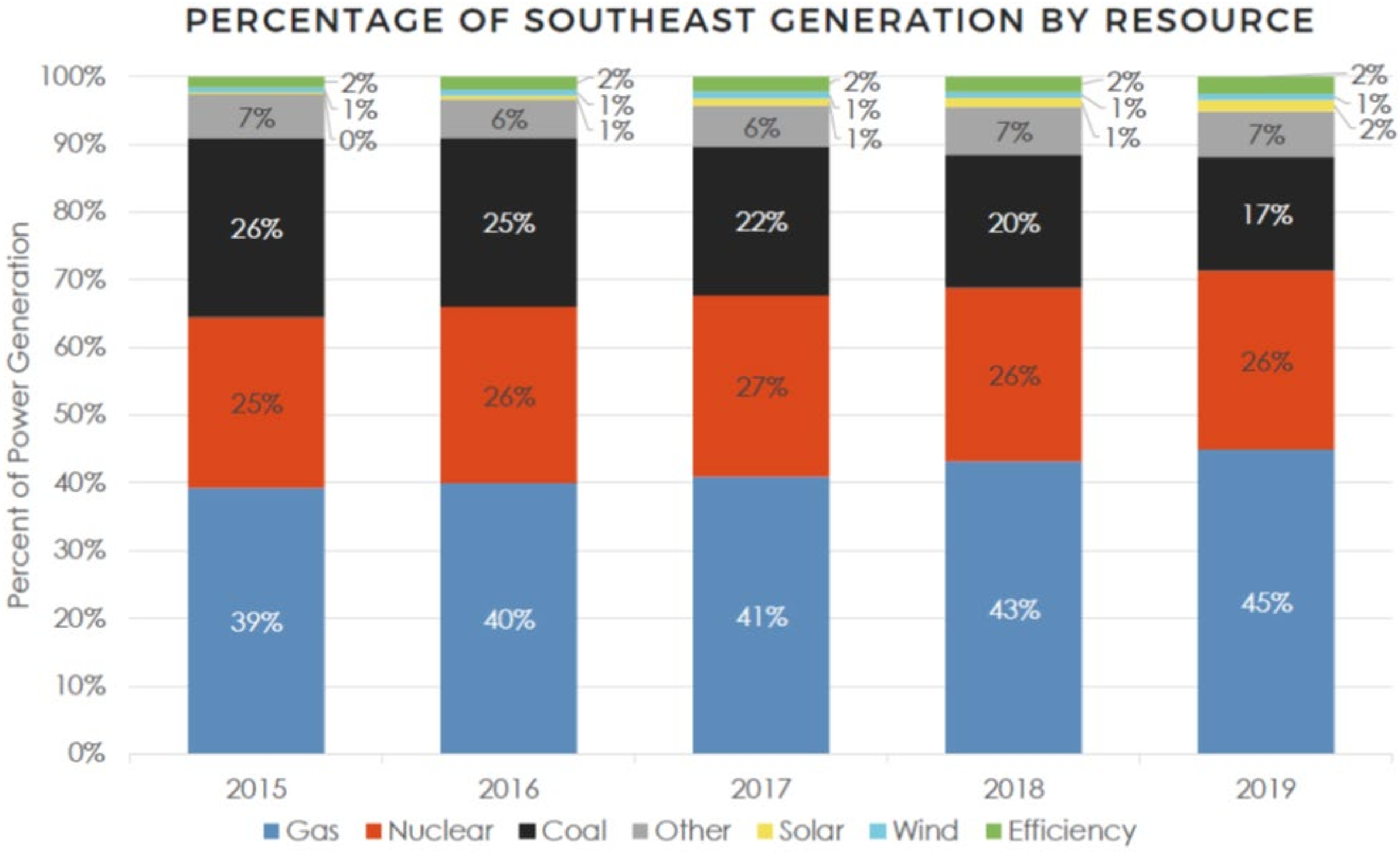
PLANNED

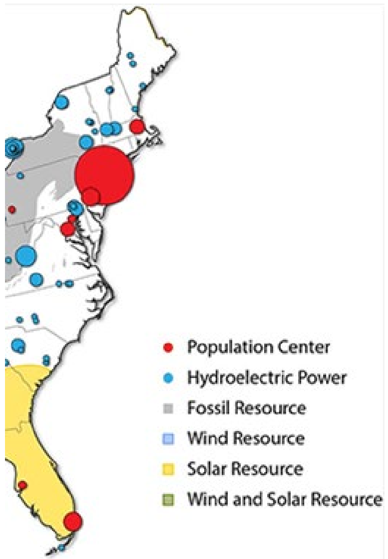
CO_2 EMISSIONS (million tons)	2019	2030
ıtheast Utilities Total	*360*	*296*
Other Utilities	109	88
minion Energy	11	7
xtEra	47	36
ınessee Valley Authority	47	41
ıthern Company	79	64
ке Energy	66	60



Source: U.S. Energy Info
(1980-2017).







12:00 PM | 1:00 PM | 2:00 PM | Eastern 3:00 PM

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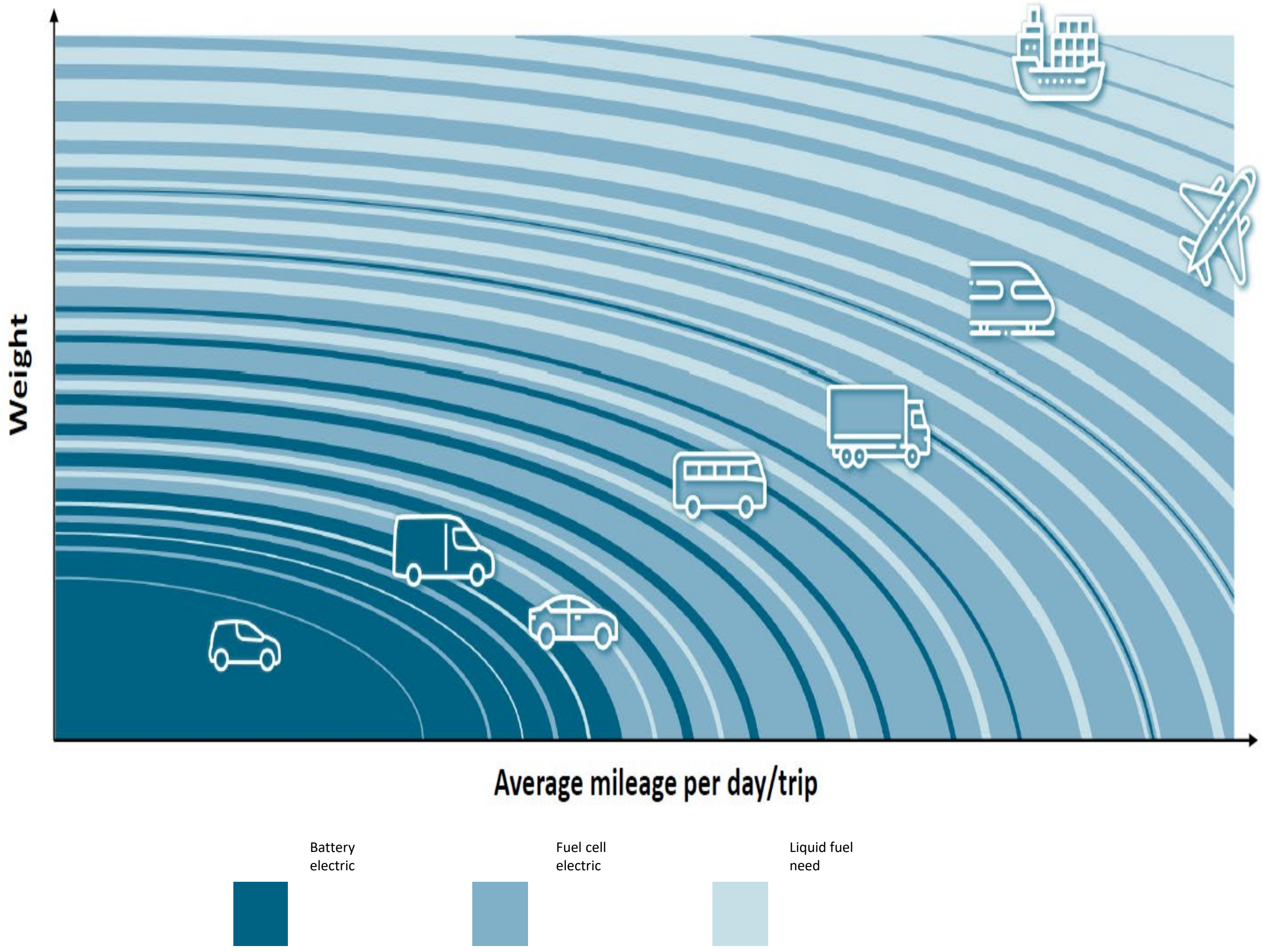
Southern Alliance for Clean Energy@ Cleanenergy.org

Principles of Transportation

- Economy of Scale
- Economy of Distance
  - Both determine the need for battery electric, fuel cell or liquid fuels
- Vehicle lifetime and transitioning
- Lack of alternative fuels during a time of disruption to the fossil fuel supply, the market can be very volatile and difficult to predict.
  - Overhaul transportation energy resources in the US and increase resiliency and energy security with diversification of fuels, storage and renewable resources



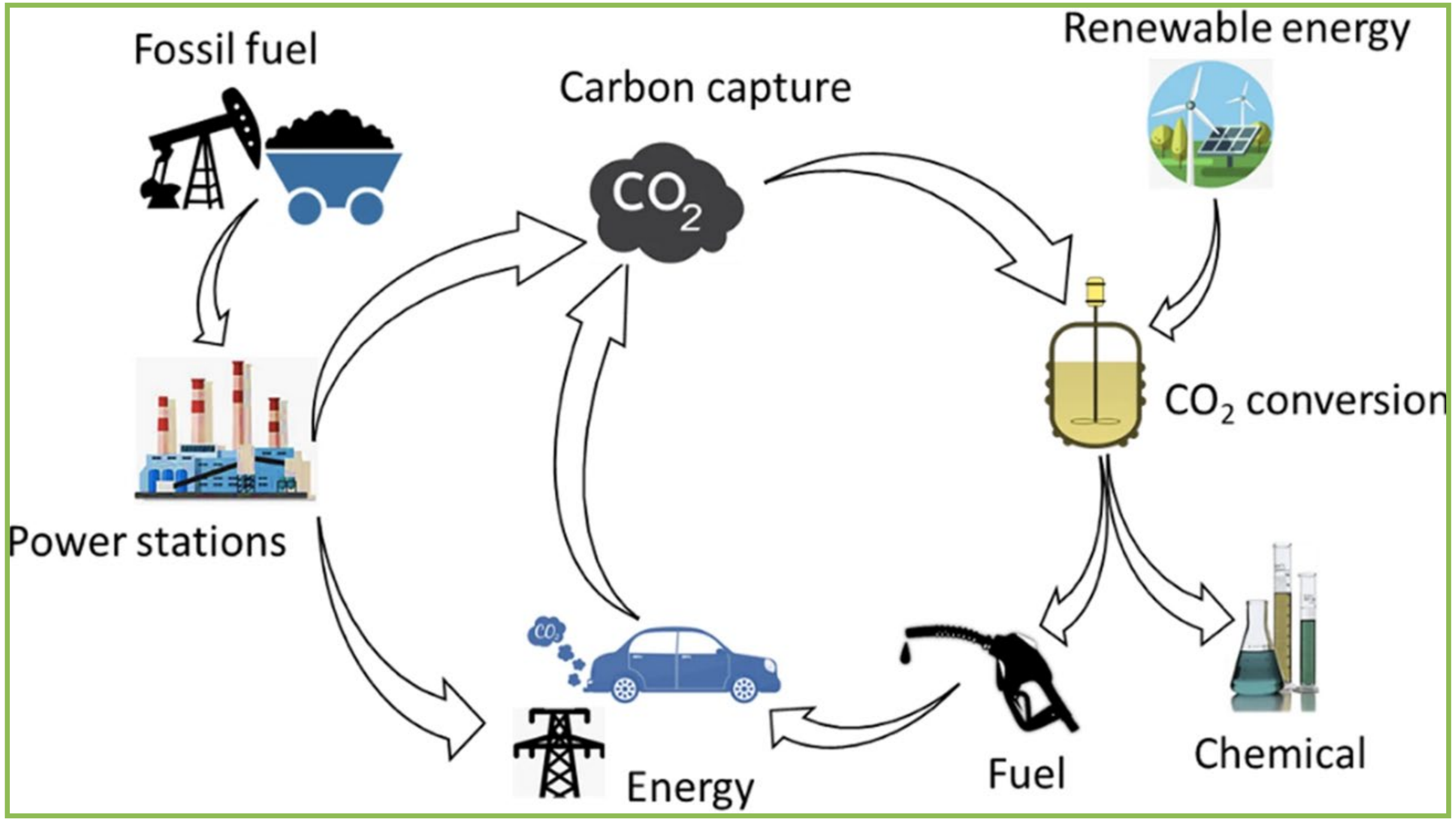
Fuel opportunity by weight and trip length. Source: IEA ETP; IHS; A Portfolio of Powertrains for Europe (2010)

Alternative Fuel Options for Transportation

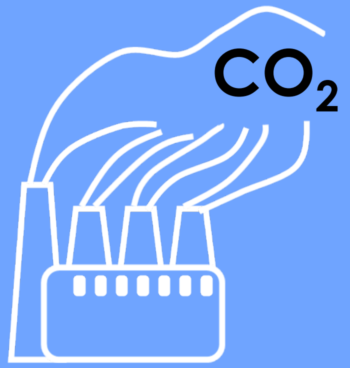
- Hydrogen: low gravimetric and volumetric density; storage at high pressure/low temps: storage mass of diesel energy eq = 6x H_2 storage
  - Possible hydrogen fuel cells or H-battery
- Ammonia: can oxidize to NOx, low grav. density than diesel
- Biofuels: only 4% biofuels used in transport (worldwide); challenge life-cycle carbon emissions, cost and scalability
- Synthetic hydrocarbons: hydrogenation of feedstock; potential for carbon-neutral (green hydrogen+emission free electricity + CO_2 (DAC?))
  - Electrolysis ($$$); DAC($$$)

Capture and Conversion Considerations

- Development of materials and processes are key to mitigate the ongoing challenges
  - Optimizing
  - Scaling
  - Cost
  - Life Cycle
  - Energy intensity
  - Stability
  - Regenerability



CO_2 Conversion



Convert by

Thermal Catalysis

Electrocatalysis

Photocatalysis

Plasma Catalysis

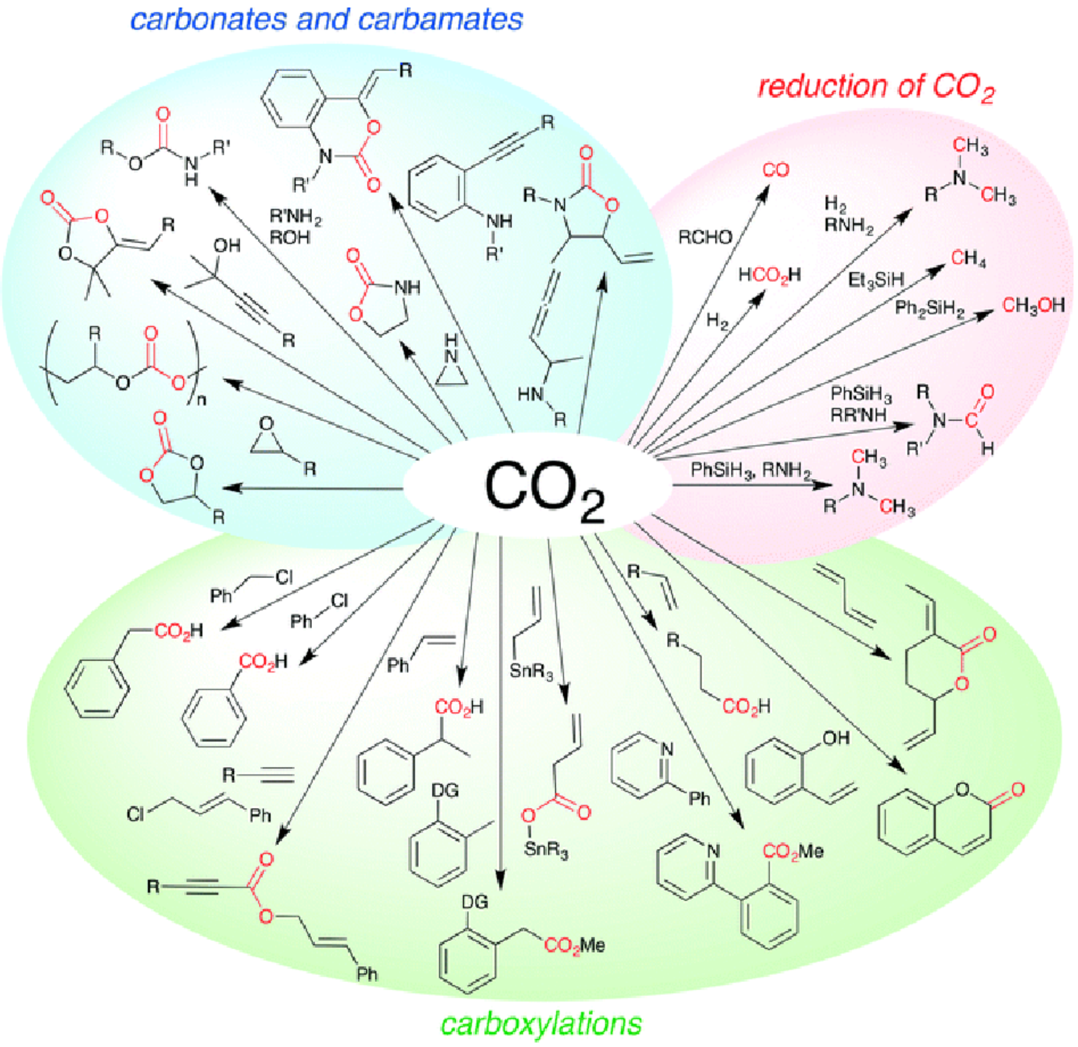
Enzymatic

Homogeneous

Heterogeneous

Value added fuel or chemicals

Chemical Targets from CO_2



O=C=O

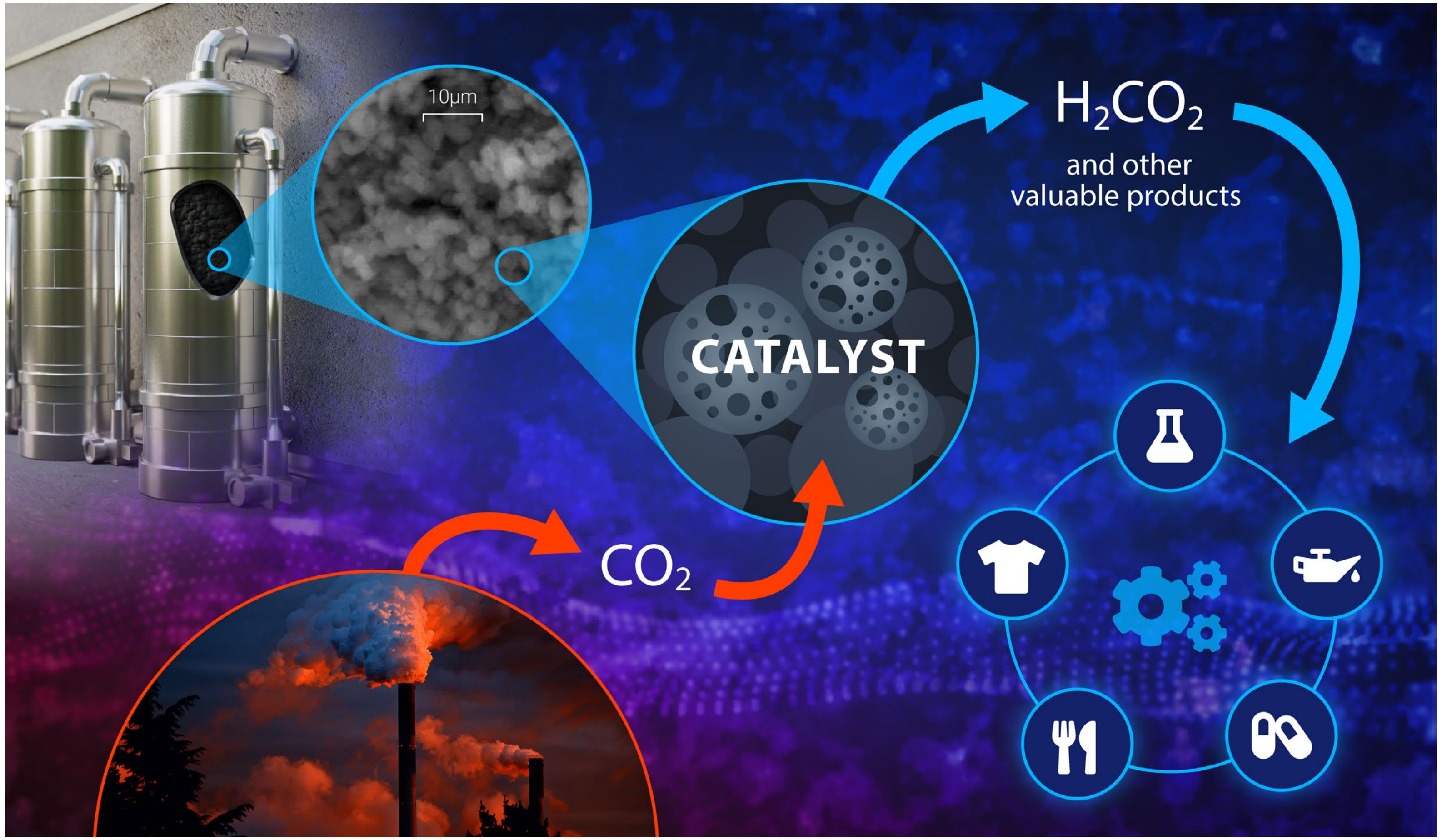
- Numerous products can be made from CO_2, but reactive pathways are limited, and efficiencies can be plagued by separations.
- All chemical reactions of CO_2 proceed via nucleophilic attack on the central carbon or electrophilic coordination to the oxygens.
- Majority of thermochemical or catalytic conversions are done in organic solvents.
- Understanding the market to implement design of reactions (begs for TEA/LCA)

Catal. Sci. Technol., 2014, **4**, 1482-1497

Dual functional catalytic polymer for simultaneous capture and conversion of CO_2 (Michelle K. Kidder)

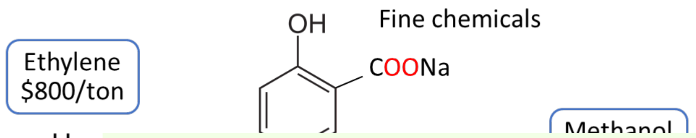
A holistic approach

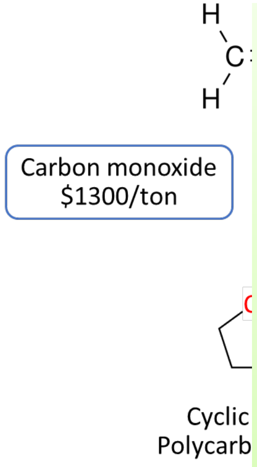
- Catalytic polymer designed capture CO_2 and convert to valuable products, e.g. formic acid
- The technology decreases the need for expensive separations
- Currently scaling from TRL 2 to TRL 4
- Optimization process through incorporation of reactor and kinetic modeling
- TEA/LCA to guide and facilitate economic evaluations and feasibility

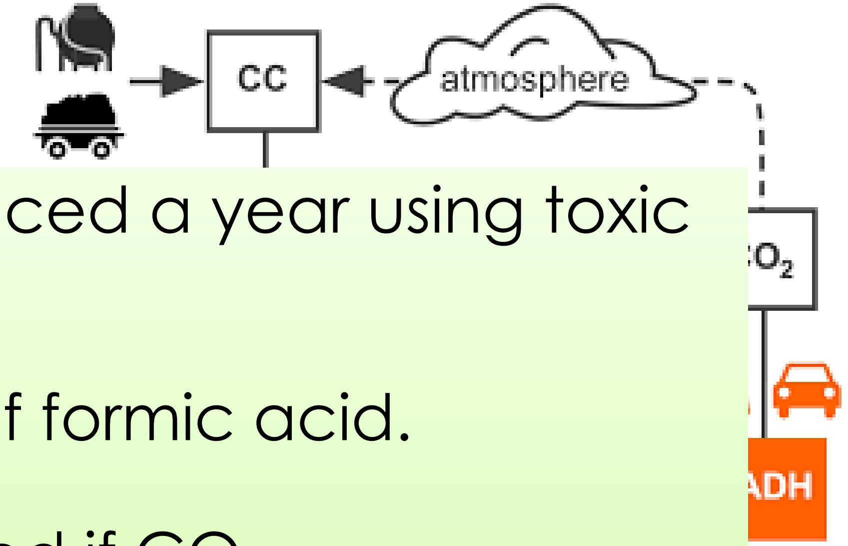


Pathway to Products: Chemical Targets

Potential to upgrade value of CO_2 by over 60 times ($20 to $1300/ton) into a zero-carbon chemical/fuel at an estimated 30% lower cost than existing fossil base synthesis routes.



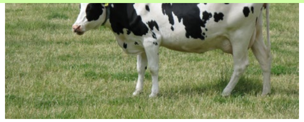




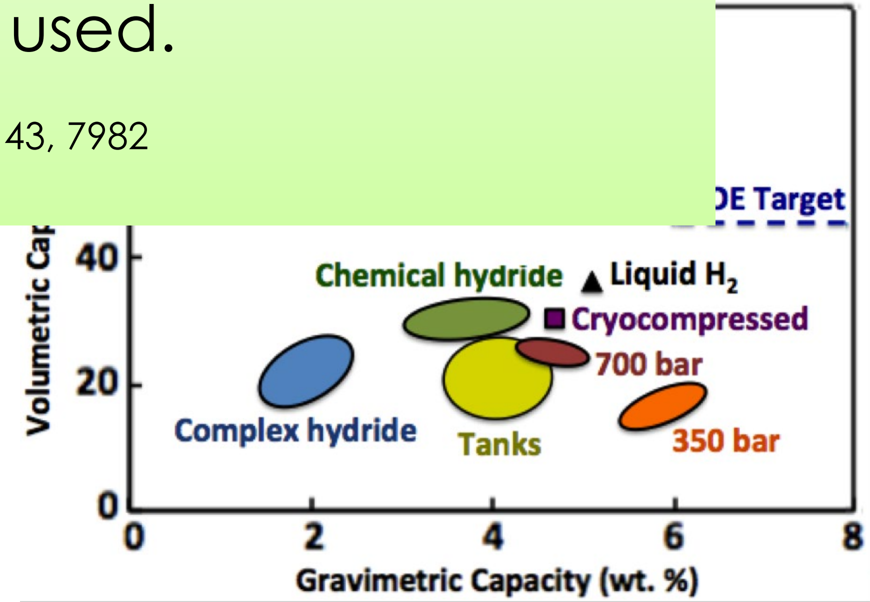
- 800,000 T of formic acid produced a year using toxic CO and methanol.
  - Emits 3076 kg CO_2 per 1 T of formic acid.
  - Whereas 100 kg CO_2 emitted if CO_2 hydrogenation process was used.

Nat. Commun, **2014**, 5, 4017 and *Chem. Soc. Rev.*, **2014**, 43, 7982

Formic acid use

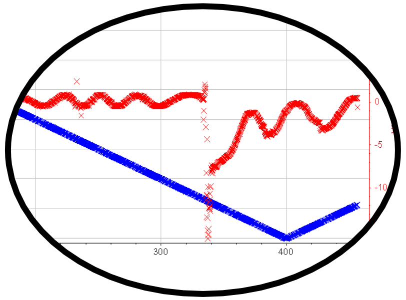


De-ice

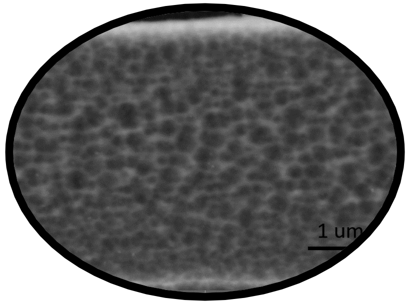


Efficient, Scalable, Reactors Using Supercritical CO_2 (Gabriel Veith)

Reverse normal paradigm for electrochemistry by using $scCO_2$ as the solvent and reactant with dilute water as a proton source

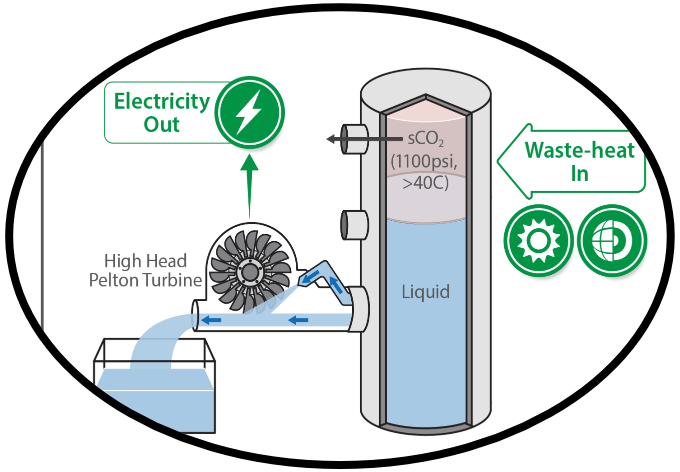


Electrochemical conversion

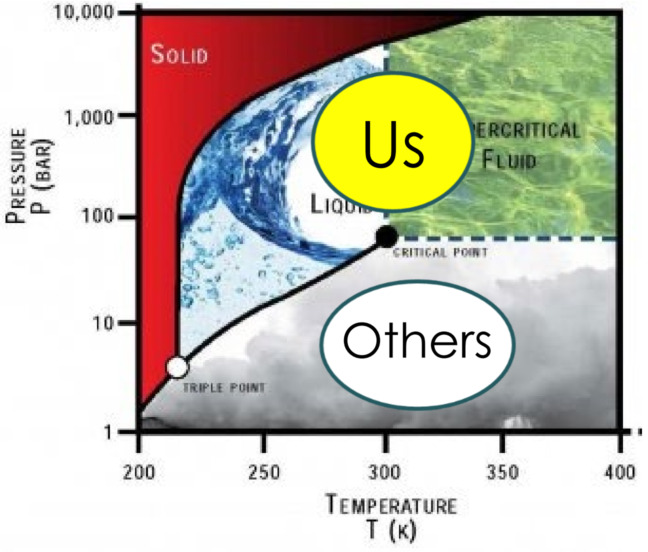


Robust carbon fiber catalysts support

Testing



Scaleup, integration, demonstration, deployment



$scCO_2$ requires only slightly higher pressure than pipeline CO_2

<u>Reaction products – Current Market</u>

Ethanol – 0.2 Gt/year ($90B)

Methanol – 0.1 Gt/year ($30B)

Formic Acid – 0.6 Bt/year ($0.75B)

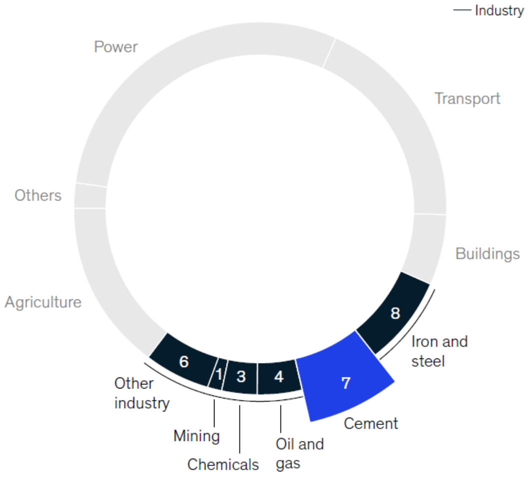
Advantages Compared To Aqueous Phase Chemistry

1. Reduce or eliminate hydrogen generation
2. Cost effective scaleup
3. Integration with CO_2 point sources
4. Ease of separations for products
5. Supercritical CO_2 already industrially accepted

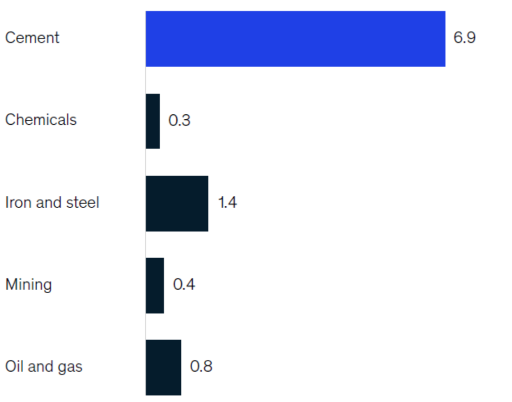
Cement

Cement production is a major source of global CO_2 emissions and also generates the most emissions per revenue dollar.

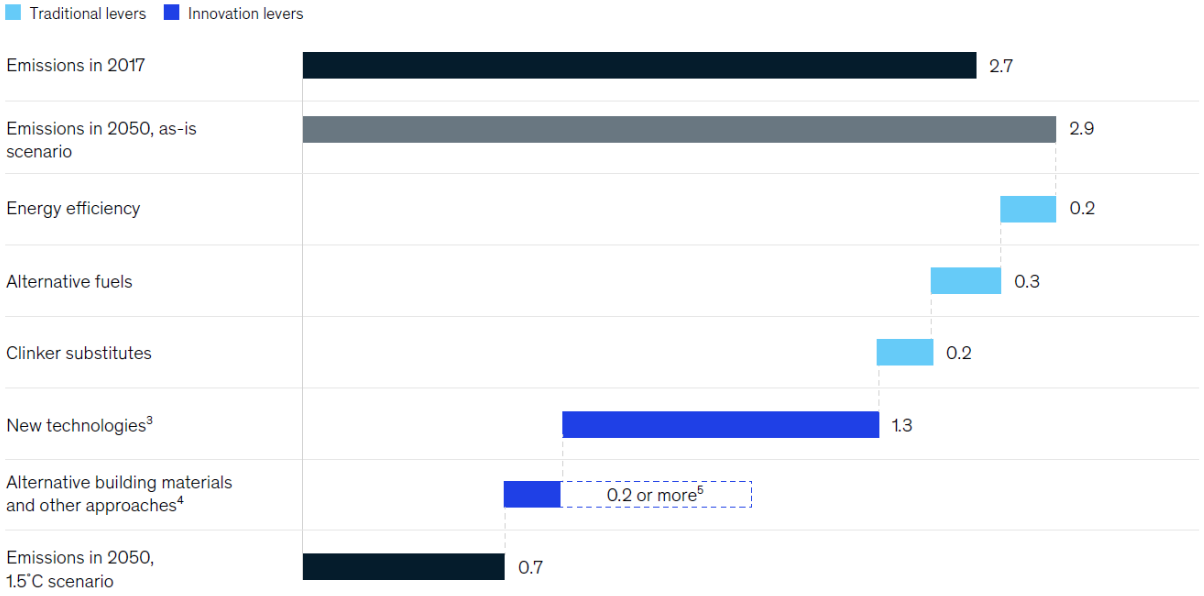
Share of global CO_2 emissions, % in 2017



kg of CO_2 per $



Potential CO_2 emissions and reductions,[2] $GtCO_2$ anually

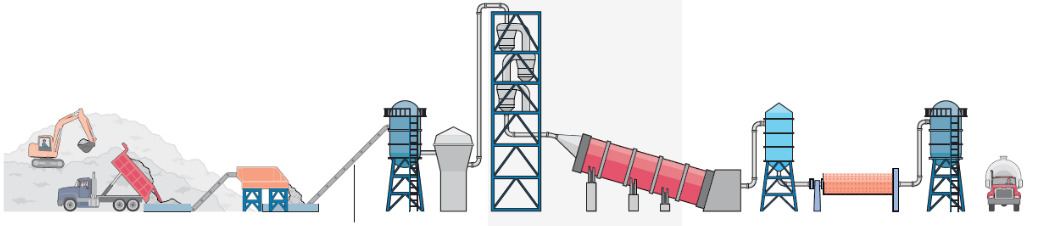


[1]Figures are global estimates for emissions potential, taking all potential levers into consideration.
[2]Effect might be smaller or larger depending on speed of shift.
[3]For example, carbon capture, use, and storage; carbon-cured concrete; 3-D printing.
[4]For example, cross-laminated timber, lean design, prefabricated/modular construction, building information modeling.
[5]Alternative building materials and other approaches will likely play an important role in decarbonizing the cement industry, but a great deal of uncertainty remains as to how much they will reduce emissions.

Source: "Getting the numbers right," Global Cement and Concrete Association, 2017, gccassociation.org; *Global Cement*, fifth edition, Freedonia Group, May 2019, freedoniagroup.com; *The Global Cement Report*, 13th edition, CemNet, cemnet.com; Umweltbundesamt (German Environment Agency); McKinsey 1.5-degree-pathway model; McKinsey Cement Demand Forecast Model

Cement manufacturing is a highly complex process.

Raw materials, energy, and resources | **Clinker and cement manufacturing**



	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]	Cooler[3]	Cement mill	Logistics[4]	Total
Energy, megajoule/ton	40	5	40	100	3,150	160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process; 319 Fossil fuels	28	49	22	925

[1]Assumed with 1kWh/t/100m.
[2]Assumed global average, data from the Global Cement and Concrete Association, Getting the Numbers Right 2017.
[3]Assumed reciprocating grate cooler with 5kWh/t clinker.
[4]Assumed lorry transportation for average 200km.

Carbon Mineralization for Concrete Alternatives (Paula Bran Anleu)

Goal

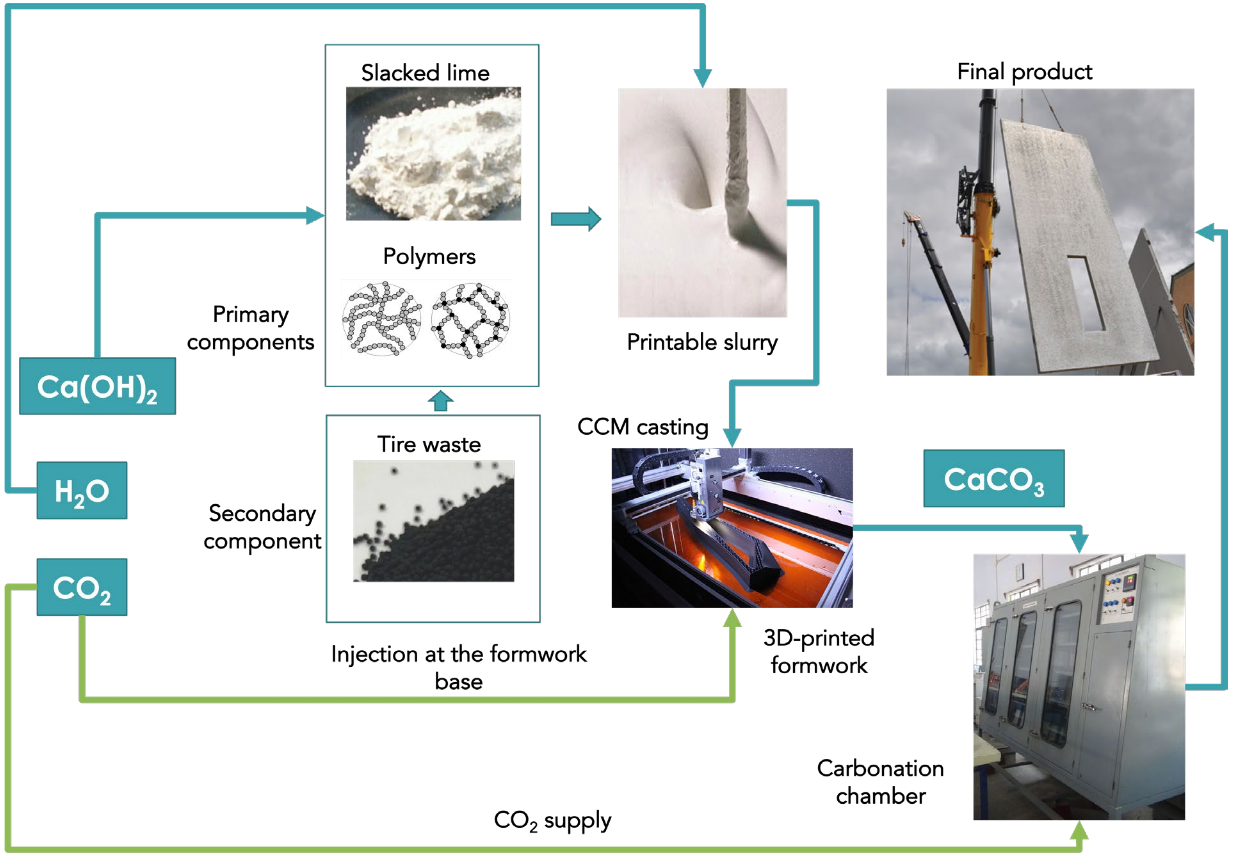
- Develop an **alternative concrete** that captures CO_2 for its strength gain

Objectives

- Complete material characterization
- Improve carbonation to > 70%
- Fabricate a CO_2-injecting formwork for precast panels
- Scale up material development
- Fabrication of a thin precast wall panel

Impacts

- Potential to replace a significant share of Portland cement production
- Proof of concept already achieved carbonation of ~57%



Potential to reduce CO_2 emissions from ~800 kg/ton-cement to ~460 kg/ton-cement

National Carbon Capture Center (NCCC)

- Managed and operated by Southern Co; collaborative agreement with FECM and NETL

NATIONAL CARBON CAPTURE CENTER

About Research News Contact

National Carbon Capture Center supports successful commercialization of CarbonBuilt low-carbon concrete technology

Bolstered by successful testing at the National Carbon Capture Center, CarbonBuilt and Blair Block have reached an agreement to utilize CarbonBuilt's revolutionary low-carbon concrete technology...

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Technologies tested at National Carbon Capture Center selected for large-scale pilot demonstration

Two carbon capture technologies developed through testing at the National Carbon Capture Center have been selected by the U.S. Department of Energy to advance to...

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National Carbon Capture Center achieves major milestone with first fire of natural gas testing system

Operation of new infrastructure a major step in expanding the facility's work to advance carbon capture for natural gas power plants.

Read More ›

CO_2 Utilization in the Southeast

CarbonBuilt technology produces very low- or no-carbon concrete blocks by using diluted CO_2 to cure them, thus chemically transforming and permanently sequestering CO_2.

Blocks manufactured using this system were recently used to construct a single-story Habitat for Humanity home in Alabama.

The Concrete Center (2022)

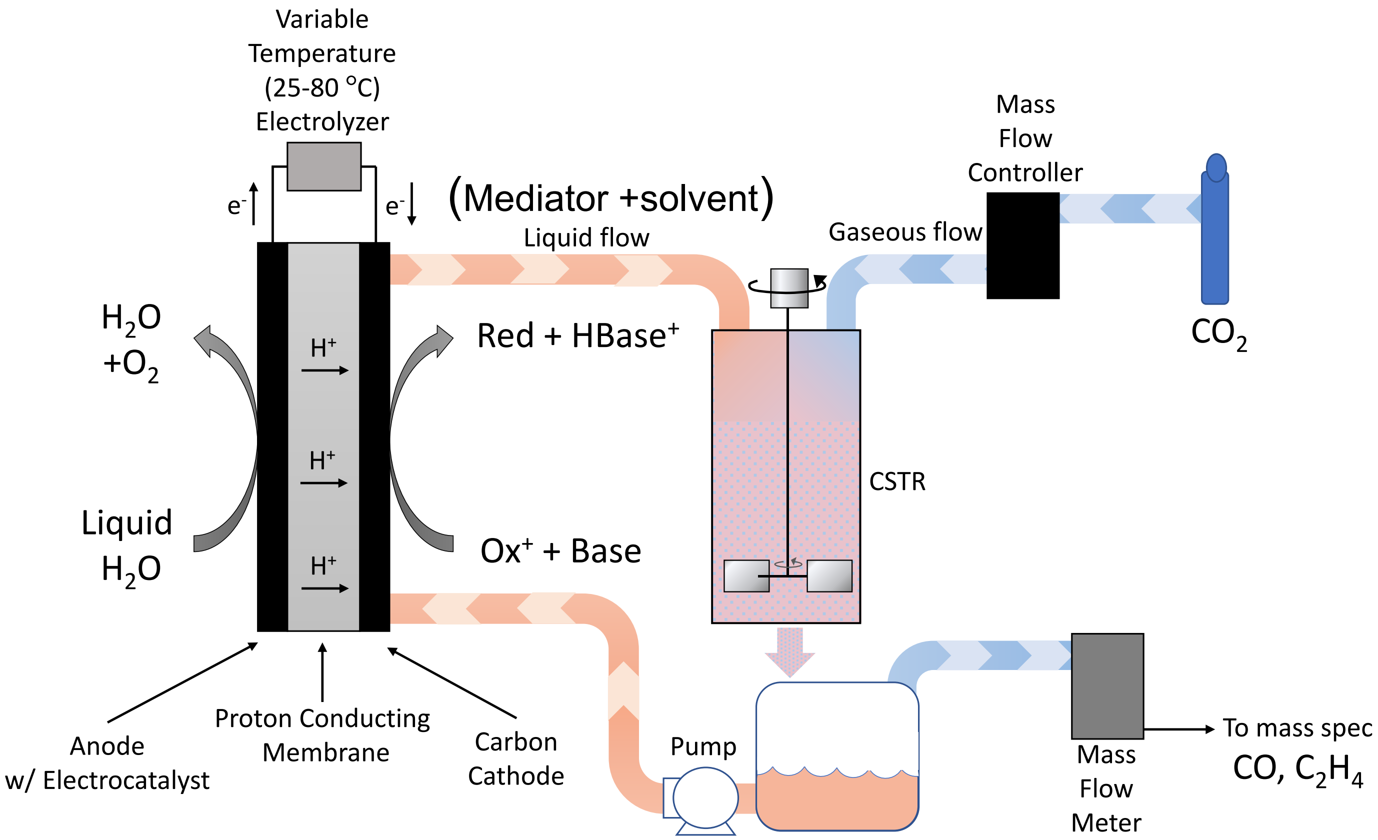
Testing of CarbonBuilt's "Reversa" process was completed at the NCCC in 2021 by injecting CO_2 from flue-gas streams into more than 5,000 concrete blocks. Southern Company manages and operates the NCCC for DOE.

The Reversa process is based on technology developed at UCLA that received the prestigious 2021 Carbon XPRIZE.

Eastman Low-Carbon Feedstock Strategy

Non-aqueous Electrochemical CO_2 Reduction with Electron-Proton Mediators (Jagjit Nanda)

This project will develop a non-aqueous electron-proton mediated (EPM) flow cell for scalable reduction of CO_2 to high value products like ethylene



Net reaction $CO_2 + nH^+ + ne^- \leftrightarrow C_2H_4$

Combining redox mediators and electrocatalysis significantly reduces the overpotential to improve energy efficiency

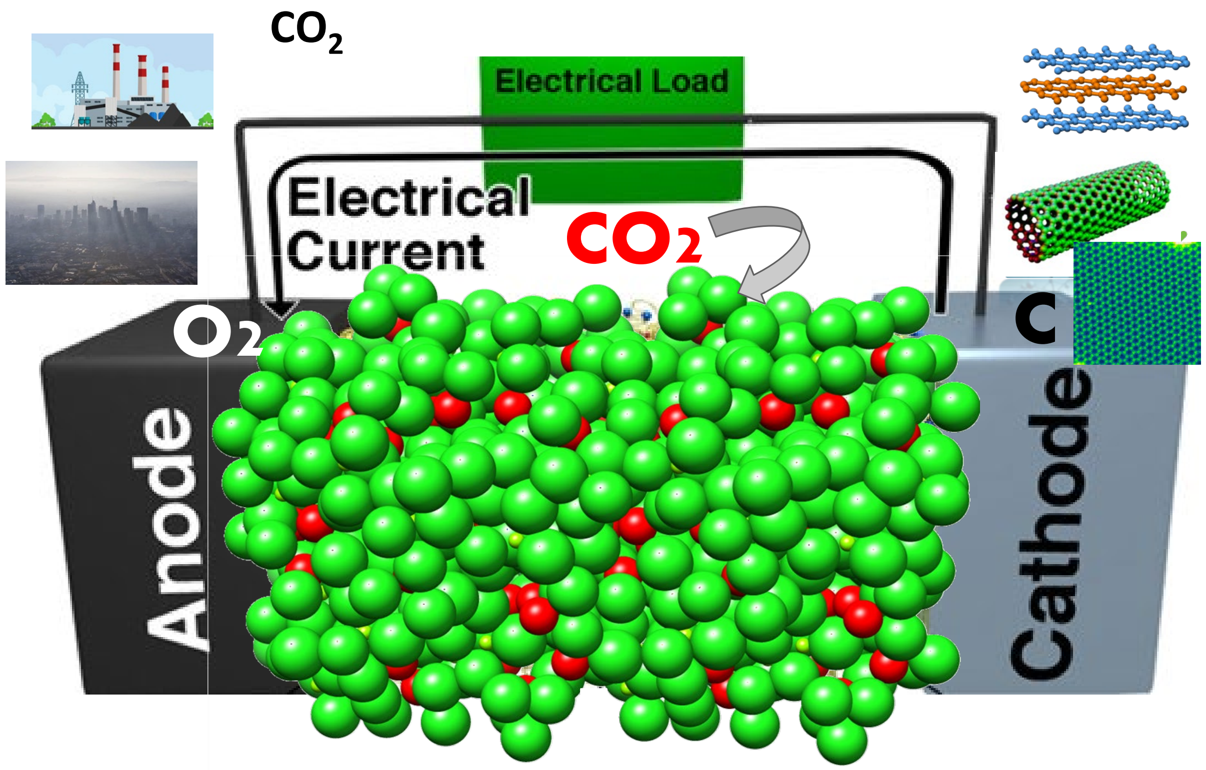
Electrolysis cell and continuous stir reactor (CSTR) are both scalable

$$Energy\ Efficiency = \frac{E^\circ}{E^\circ + \eta} \times \varepsilon_{Faradaic}$$

An example of a mediator & solvent that will be used is cobaltocene $[Co(C_5H_5)_2]$ & DMF

Molten Salt CO_2 Capture and Conversion to Carbon Nanomaterials (Shannon Mahurin)

- **Goal**: Develop molten salts (e.g. Li_2CO_3) to electrochemically convert CO_2 to high-value solid carbon products
- **Task 1**: Develop low-melting-point salts with high CO_2 absorption and efficient conversion
  - Target 400 °C melting point salts
  - Use AI/ML to reduce salt parameter space
- **Task 2**: understand and control mechanisms at the interface
- Target product will be graphite, a critical material lacking a domestic supply chain
- Process does not require pure CO_2 as input, allowing for a broad envelope of feed streams



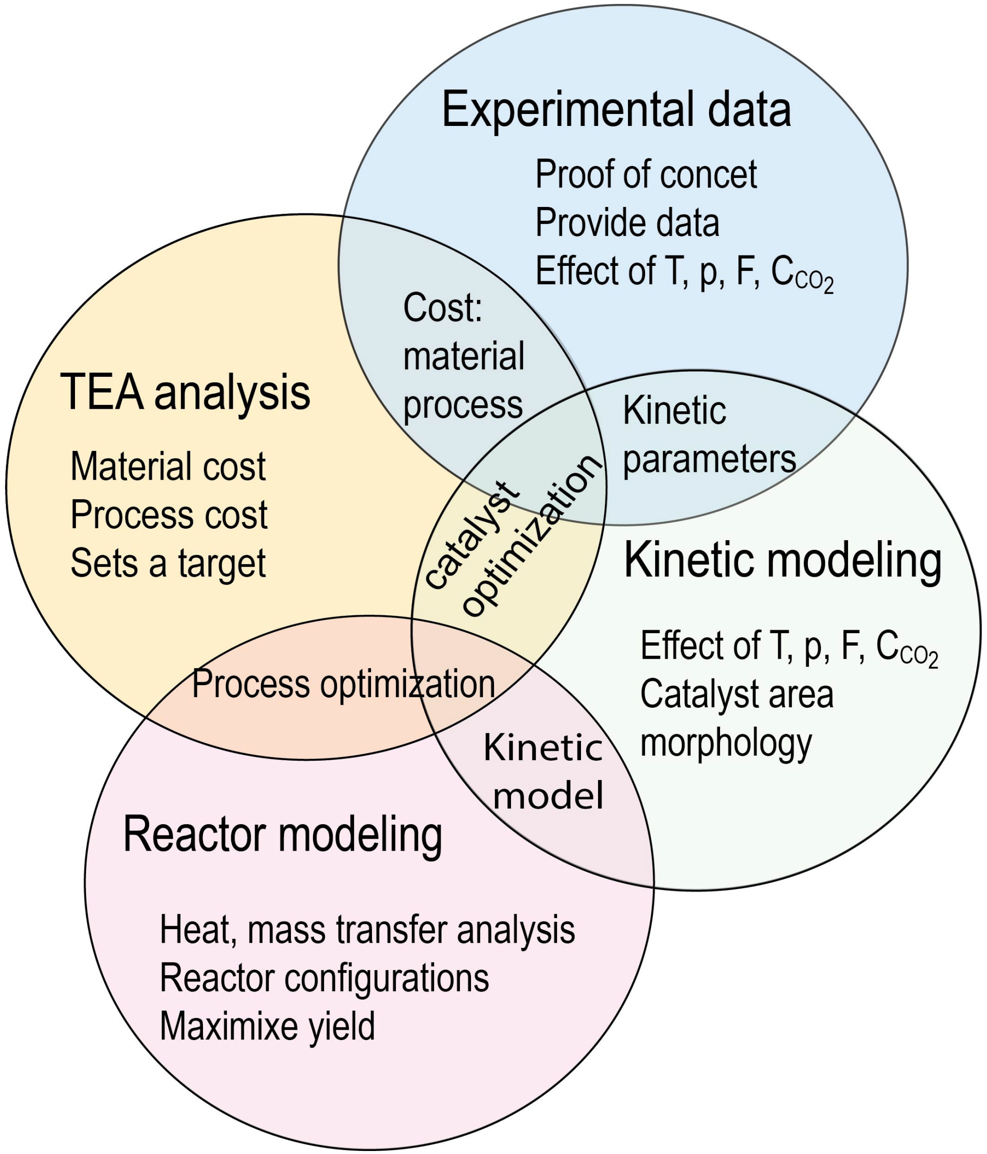
Molten Salt

<u>Expected outcomes</u>

- Significant lowering of temperature needed for molten salts
- High value solid carbon products

Outcomes Expected from Process Intensification Approach

- **Versatile toolset** for understanding the behavior and characterizing the performance of energy conversion processes
- **Accelerate reactor development and reduce cost** by using multiphase flow reactor modeling and simulation tools
- **Optimizes performance** for equipment and unit operations, enabling more throughput and less process downtime
- **Reduces design risks** when validated by predictive science-based calculations, lowering risk in obtaining return on investment



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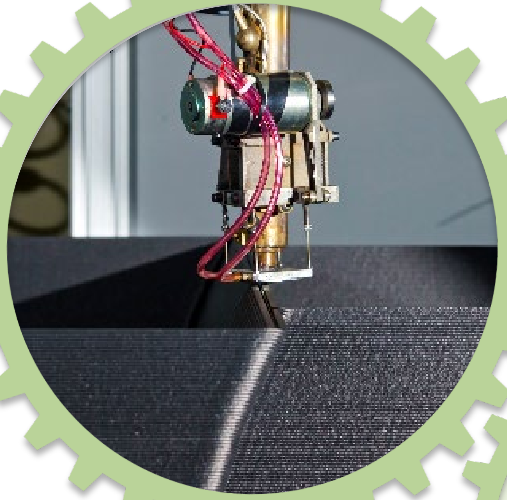
ORNL committed to strengthening the regional innovation ecosystem



Making our resources available to industry partners

- Technology licenses
- Small business vouchers
- Strategic Partnership Projects
- Cooperative R&D agreements

Deploying an industry cluster strategy to build regional competitive advantage

- Carbon fiber
- Automotive
- Additive manufacturing

Contributing to state and local economic development initiatives

- SkyNano LLC

What Constitutes CapEx?

- Business case in general
  - Physical assets: buildings, equipment, machinery, vehicles
- Chemical Industry impacted by
  - Replacement: Lifetime may be shortened due to "breakdown"
  - Supply needs and regulations
  - Many refineries are built and can run 100+ years, expensive to rebuild
- What will convince industry to invest in chemicals from CO_2?
  - Repurposing some of existing infrastructure
  - Location; supply of CO_2, H_2, etc. and distribution of product
  - Efficiency of processes, incentive, etc.
    - Energy needs, storage, waste management, implementation of renewables, purifications/separations

Summary

- Multiple pathways from CO_2 to products
- Need to identify cost effective, energy efficient pathways
  - Scalable
  - Feedstock challenge: purity, cost, source, modular/adaptable
  - Separations (upstream and downstream)
  - Repurposing of current infrastructure and location
- Teaming; industrial engagement to help identify challenges
  - Market drivers and incentives
  - Transport of products, infrastructure/repurpose?
  - Emission reduction potential overall
    - TEA/LCA
  - Data management; regulatory controls and digital transformation
- Social, economic and environmental justice

Thank you!

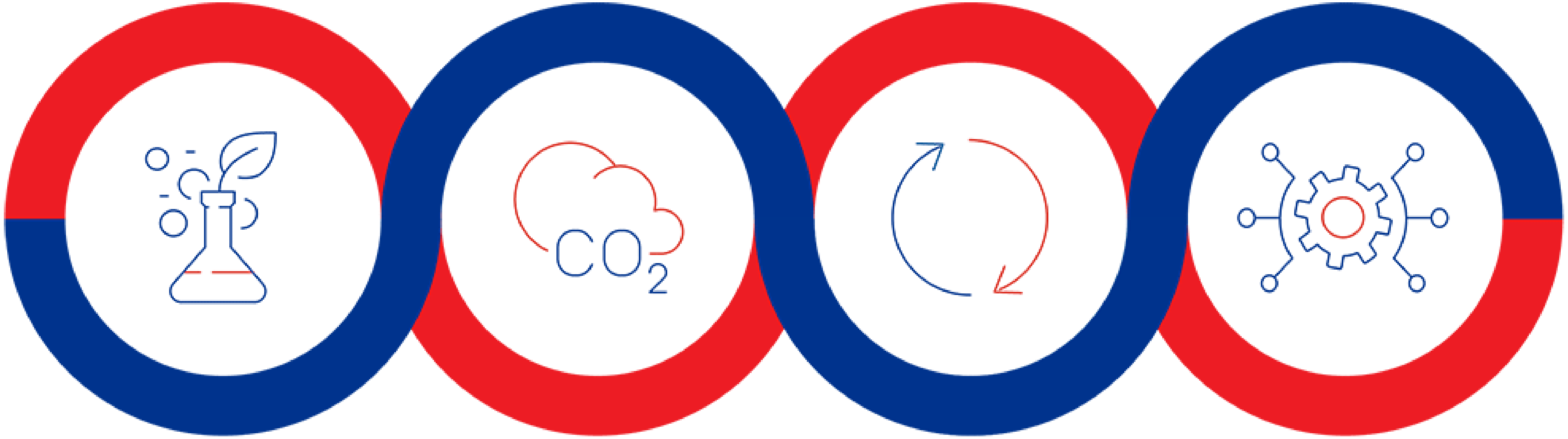
U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

kidderm@ornl.gov

Additional insights

- Out of challenges come opportunities:
  - Job creation
  - Education
  - Teaming: *We are ALL in this together*
- Needs
  - Greening the grid; and reducing energy input for capture and conversion
  - Affordability: CO_2 (goal of DAC <$100/ton <10y), H_2, electricity, for end products (chemicals and fuels)
    - Process, material (from atomic to molecular scale i.e., catalysts to pipelines), etc.
  - Infrastructure
  - Sustainability
  - Data management
  - AI/ML for rapid screening; modeling at different length scales and use of autonomous systems
- Awareness
  - Environmental and Social Justice
  - Economics: start with TEA/LCA to identify gaps and advantages

Summary



Alternative feedstocks

- Synthetic feedstock from captured carbon
- On-purpose biomass feedstock
- Feedstock from municipal, industrial or biomass waste
- Blue or green hydrogen

Process decarbonization

- Generating and/or sourcing renewable electricity and fuels
- Microgrids and energy storage
- Energy efficiency and electrification
- Carbon capture, use and storage
- Regulatory and social license requirements

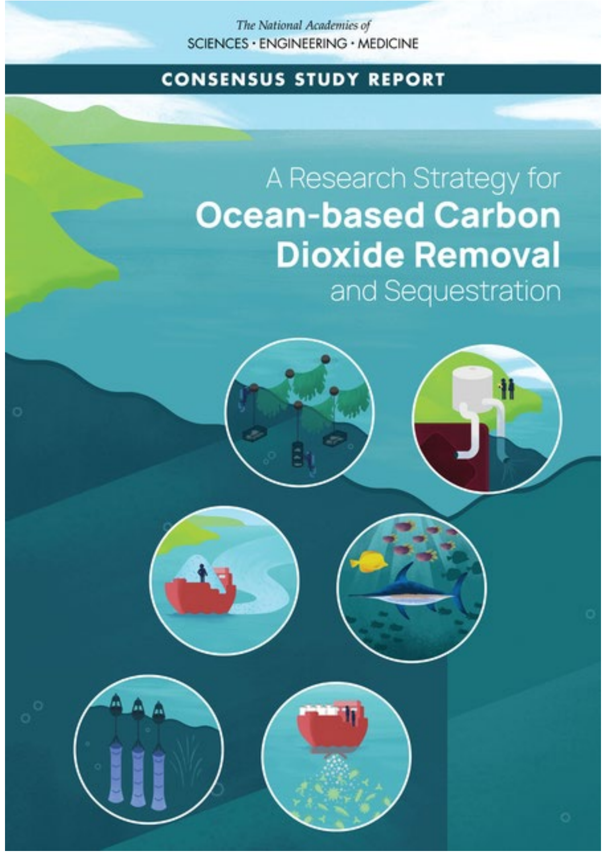
Resource stewardship

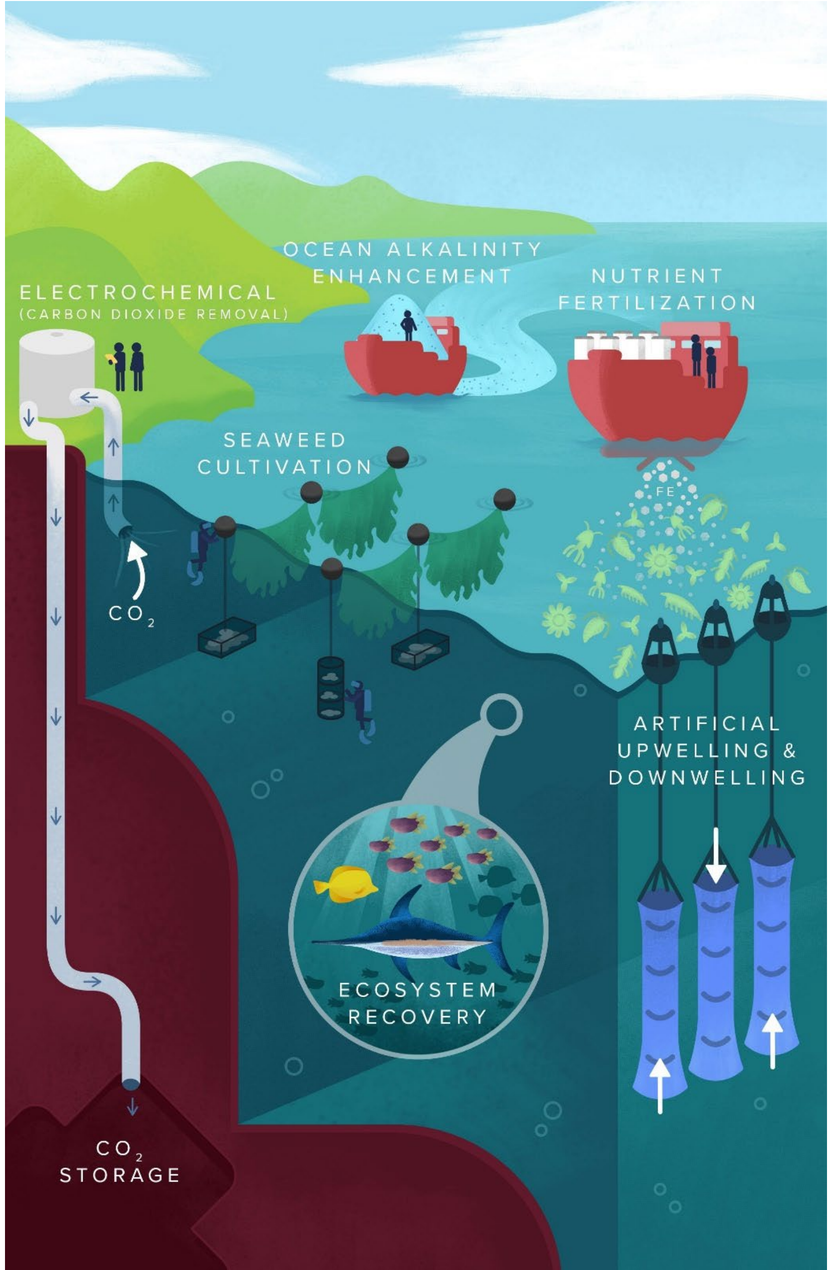
- Product recycling
- Circular recovery to new feedstocks
- Product recovery to alternative uses (e.g. fuels)
- Product waste-to-energy
- Water reduction and re-use

Digital transformation

- Digital twin for asset management
- Process simulation and optimization
- Operational monitoring and analytics
- Carbon accounting and compliance
- Information and regulatory control
- Data collaboration best practices

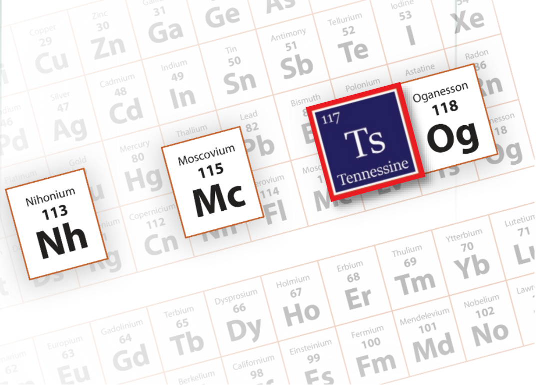
Ocean carbon removal





ORNL has a distinguished history of making groundbreaking discoveries and meeting national needs

Development, production, and distribution of radioisotopes and stable isotopes	Science and engineering of the nuclear fuel cycle Reactor technology Materials and fuels Separations chemistry	Development of neutron scattering, neutron activation analysis, and other innovative research tools	Development and application of high-performance computing resources	Delivering advances in physical and life sciences



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ORNL facts and figures

$2.3B
annual expenditures

5,720
employees

$750M
modernization investment

Nation's most diverse energy portfolio

3,200
research guests annually

Nation's largest materials research portfolio

Forefront scientific computing facilities

World's most intense neutron source

World-class research reactor

2,032
journal articles published in FY20

Managing major DOE projects: US ITER, exascale computing

236
invention disclosures in FY20

70
patents issued in FY20

State of the art facilities

Carbon Dioxide Removal approaches (CDR)

CDR Primer Ch. 2 (cdrprimer.org): Editors Jennifer Wilcox, Ben Kolosz, Jeremy Freeman

1. *Direct Air Capture (DAC)*
2. *Bioenergy with CCS (BECCS)*
3. *Biomass Storage*
4. *Soil Carbon Sequestration*
5. *Ocean Alkalinity Adjustment*
6. *Mineralization*
7. *Hybrid Concepts*

Also in CDR Primer: Forest management, coastal blue carbon

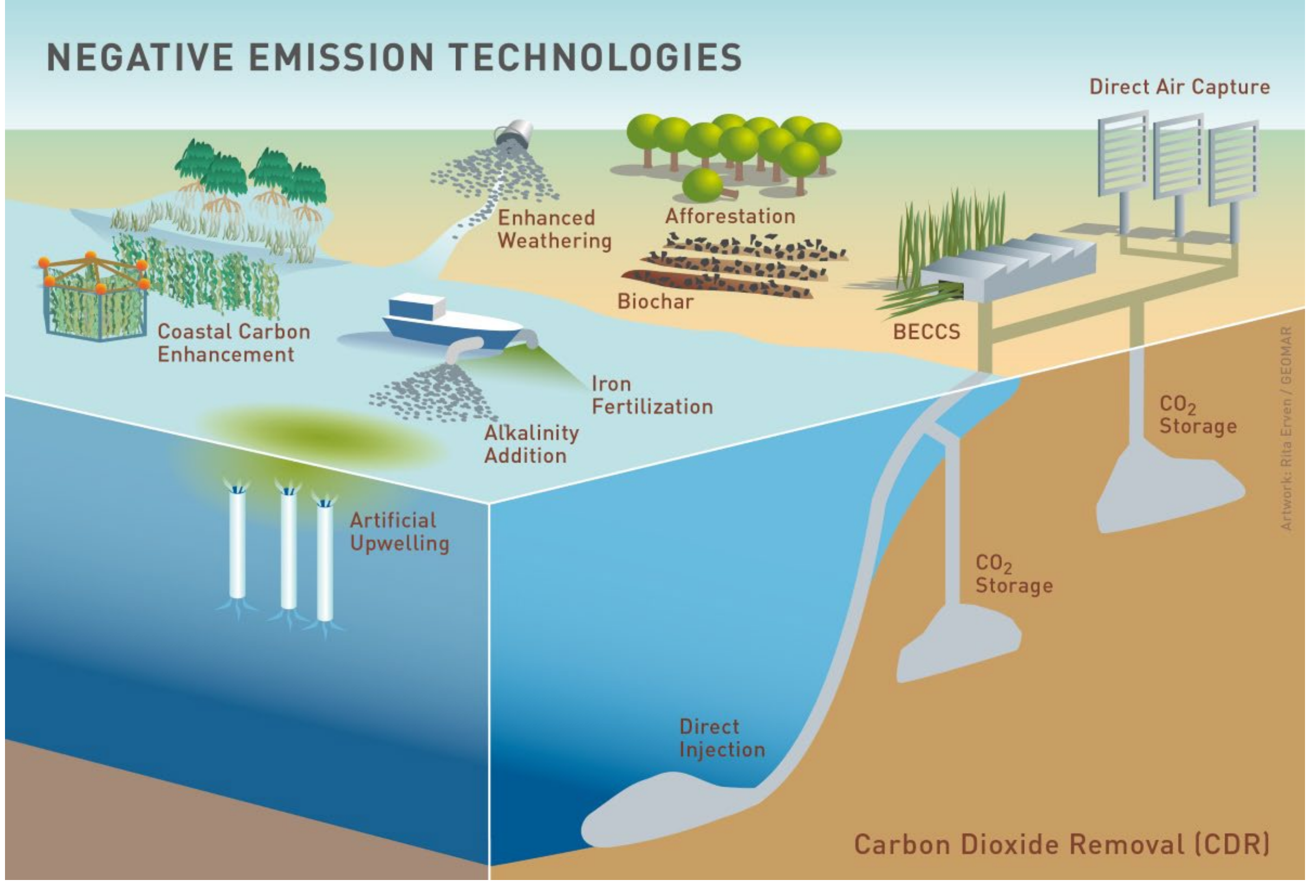
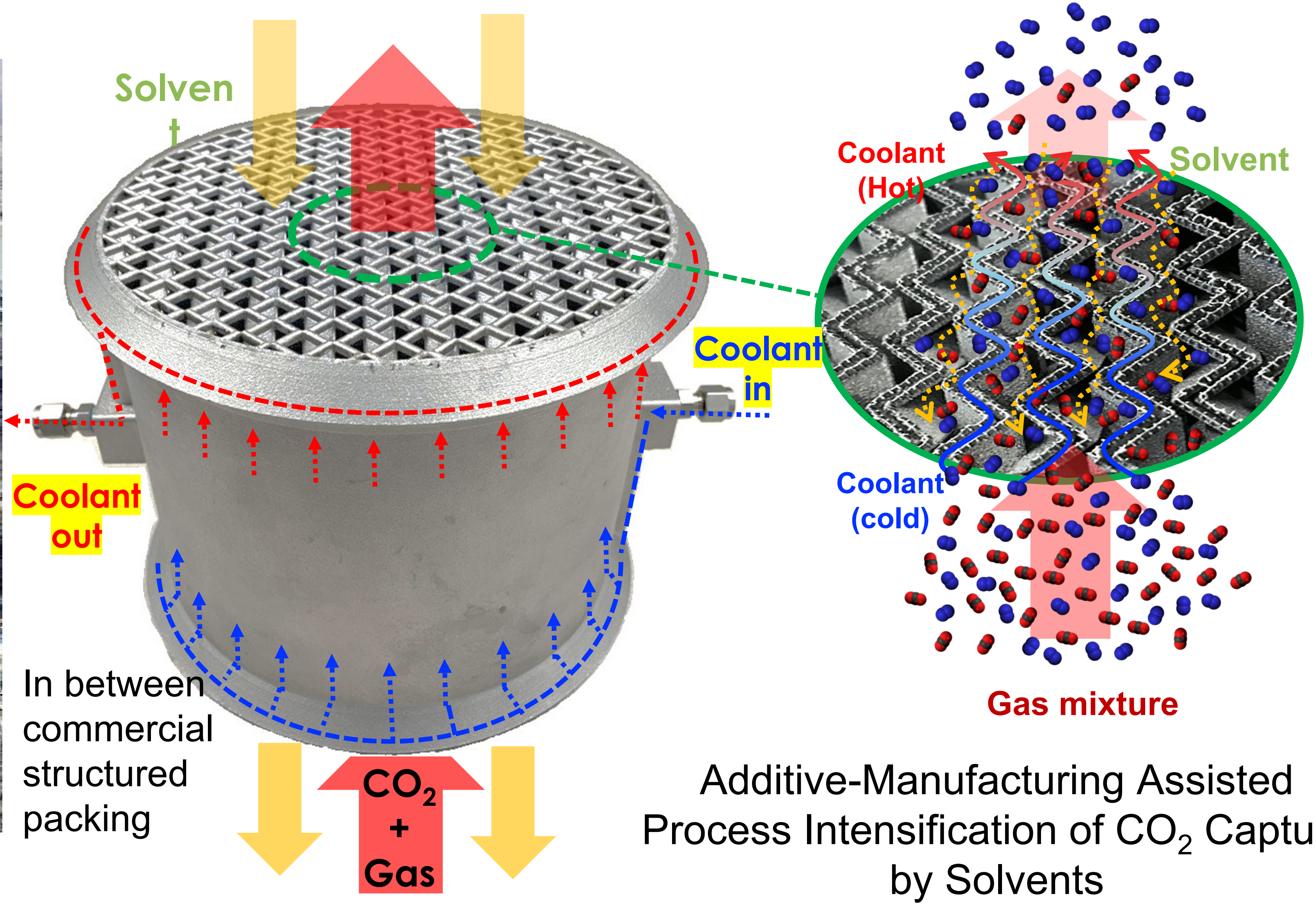


Image: Physics World

In every case, cost when deployed at gigaton scale will determine impact

Large pilot testing for flue gas (2021-2024)



Additive-Manufacturing Assisted Process Intensification of CO_2 Capture by Solvents

Process intensified absorber to reduce capital expense from flue gas capture

Oak Ridge National Laboratory

Summary

- Polymer-Hybrid materials can impact the efficiency and potential cost in capture and conversion
  - DAC
    - Enhance capacity and kinetics for DAC of NOHMs
    - Reduce water sorption to decrease energy penalty
    - Decrease diffusion limitations
    - Allow for physical and practical use (woven materials, membranes, etc) in system integration
  - Simultaneous Capture and Conversion
    - Allow for catalytically robust materials
    - Decrease the need for separation or compression of CO_2
    - Synthetic use of CO_2 for non-toxic synthetic pathways of chemicals

How ORNL is funded and collaborates

- DOE sponsors (some not all)
  - Basic research: DOE Office of Science
  - Applied research: DOE EERE (AMO, VTO, HFC,and BETO), FECM

  User facilities: SNS, HFIR, CNMS, NTRC, Computing

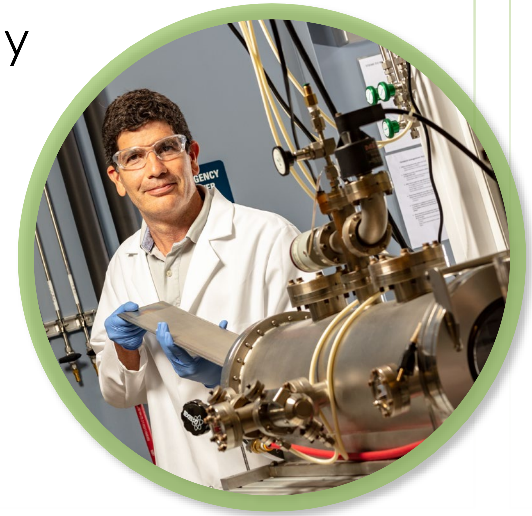
  Collaborations: SPP or one of the DOE FOA's

  Watch for or get on a mailing list for DOE –RFI's
  -DOE especially values input from industry

Partnerships are vital to accelerating technology transition and engaging with industry and universities

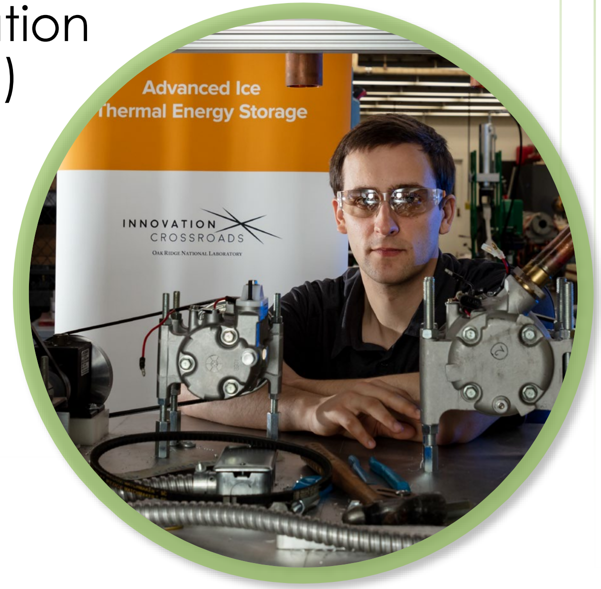
Technology transfer

- Cooperative R&D agreements (CRADAs)
- Strategic partnership projects
- Technology licensing



Industry and economic development partnerships

- Regional industry recruiting and cluster development
- State and local economic development partnerships
- Institute for Advanced Composite Materials Innovation (IACMI)



Education and university partnerships

- Research and educational experiences
  – UT-ORNL Bredesen Center
  – GEM fellowship program
  – Graduate Opportunities (GO!) program
  – Science education and workforce development programs (through ORISE)
- Postdoctoral program
- Ambassador program

Interacting with the private sector

Technology licensing

Moving intellectual property developed at ORNL to the commercial marketplace

Sponsored research

Bringing ORNL expertise and facilities to bear on problems that can only be solved using these resources, with full cost recovery

Industrial partnerships

Engaging in collaborative R&D for shared benefit

Providing technical assistance to solve complex problems

Economic development

Supporting the creation of new jobs, new companies, and increased competitiveness for the region, the state, and the nation

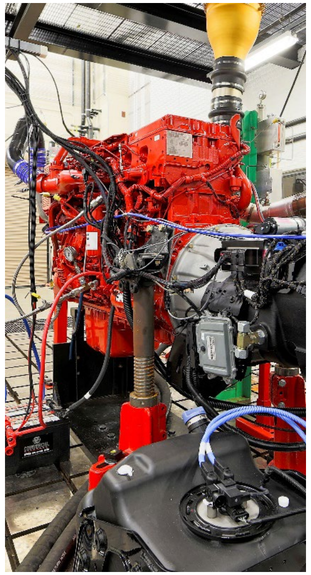
Sub-contracting

Purchasing a wide variety of goods and services, with a special emphasis on small businesses

Flexible Research Platforms at DOE's ORNL User Facilities

National Transportation Research Center (NTRC)

Fossil Energy CO_2 Capture Column for Process Intensified Packing Element R&D



Combustion Research Platforms

Building Technologies Research and Integration Center (BTRIC)

Fossil Energy Direct Air Capture (CO_2) with Building Air HVAC System

Ground-Level Integrated Diverse Energy Storage (GLIDES)

Manufacturing Demonstration Facility (MDF)

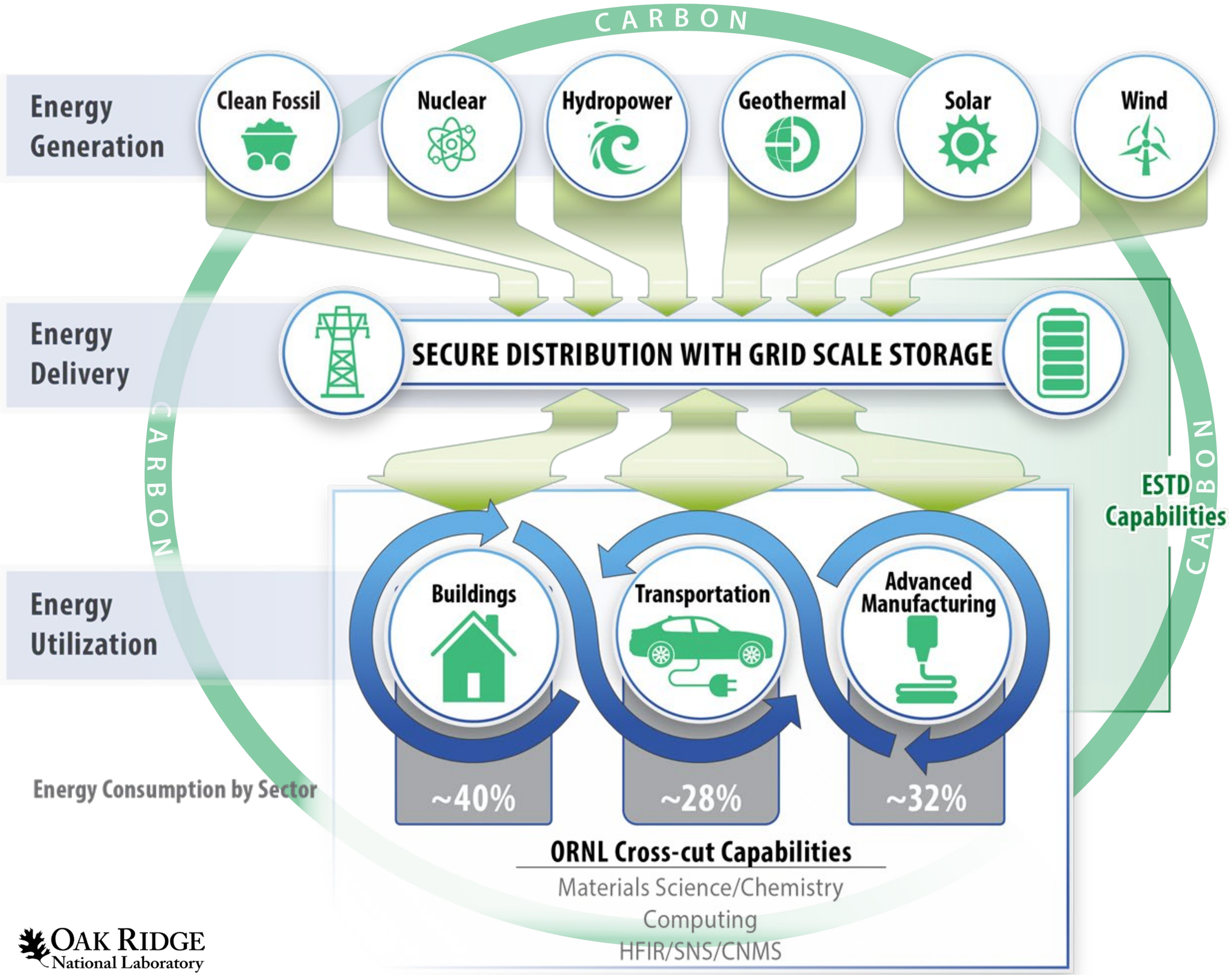
Possibilities for Fossil Energy CO2 Utilization: Research Platform for CO2 to Intermediates for Chemical Manufacturing???

Also (not shown)…

Carbon Fiber Technology Facility (CFTF)

Grid Research Integration and Deployment Center (GRID-C)

ESTD Strategy for Decarbonization
– An *Integrated* Systems Approach



Span of ORNL capabilities in energy generation, distribution, and end use

- Bi-directional electron flow:
  - Transactive energy controls
  - At-scale energy storage
  - Light duty vehicle electrification
- Net-zero carbon flow:
  - Large scale CO_2 capture
  - Direct air capture
  - Low-cost carbon-free H_2
  - CO_2 conversion to useful chemicals/materials/feedstocks
  - Synthetic carbon-neutral fuels for hard to electrify sectors
- Bi-directional heat flow:
  - Waste heat recovery/upgrade
  - Heat integration/optimization

OAK RIDGE National Laboratory

ORNL is managed by UT-Battelle, LLC

THE UNIVERSITY of TENNESSEE

UT-BATTELLE

BATTELLE
It can be done

Serving Tennesseans through education, research, and outreach

ORNL partner since 1946

State-funded Science Alliance, started in 1982, builds programs with ORNL

ORNL is the property of the US Department of Energy

DOE contracts with UT-Battelle to manage ORNL

OAK RIDGE National Laboratory

Develops and deploys technology worldwide

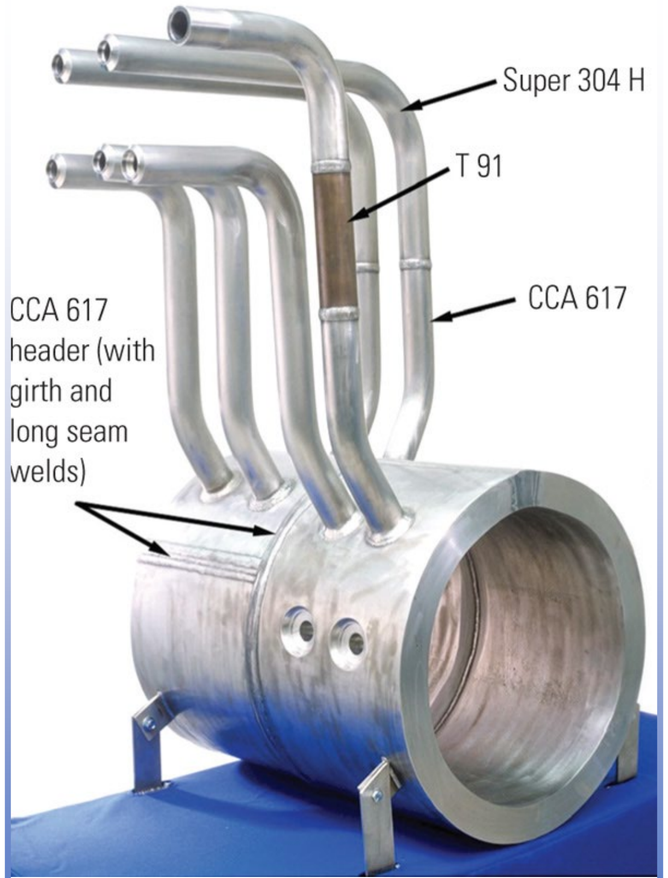
75-year relationship with DOE

Manages or co-manages 7 DOE national labs

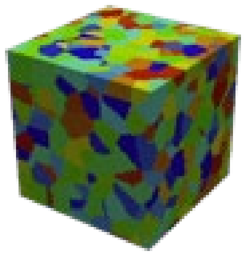
Core university partners

- Duke
- Virginia Tech
- ORAU
- Vanderbilt
- North Carolina State
- Virginia
- Florida State
- Georgia Tech

ORNL's exceptional capabilities for designing, characterizing and certifying structural materials, are enabling the development of more efficient fossil fuel energy systems

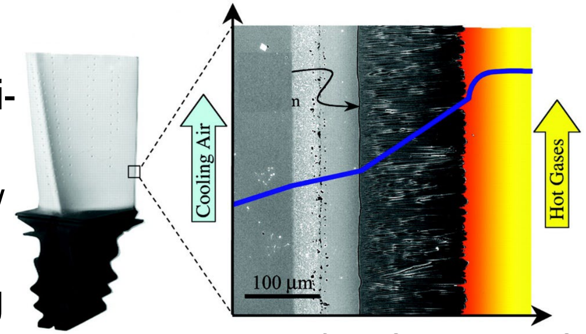


Evaluation and ASME Codification of Materials, Weldments and Components for **A-USC** Boilers and Turbines.



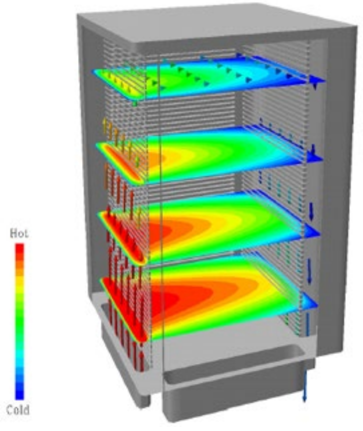
Alloy Design **Materials for Extreme Environments**

Design and Fabrication of Ni-based Turbine Components by **Additive Manufacturing**

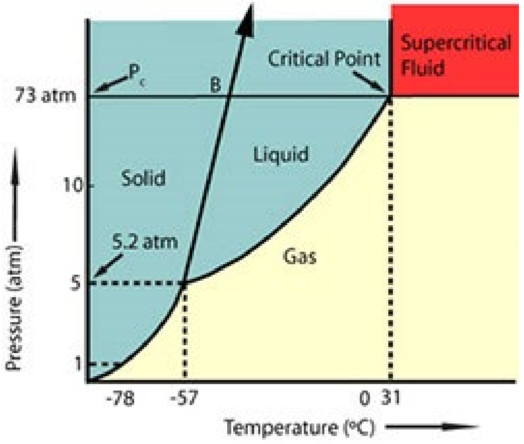


Evaluation of **TBCs** and **EBCs**

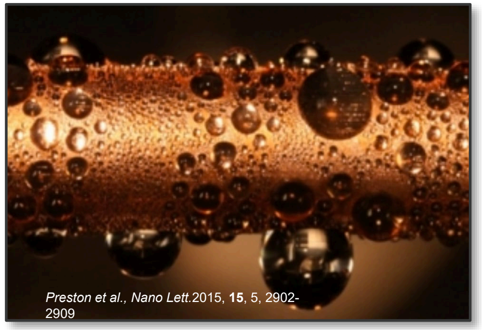
Corrosion S&T



Durability and Reliability of Materials and Components for **SOFCs**



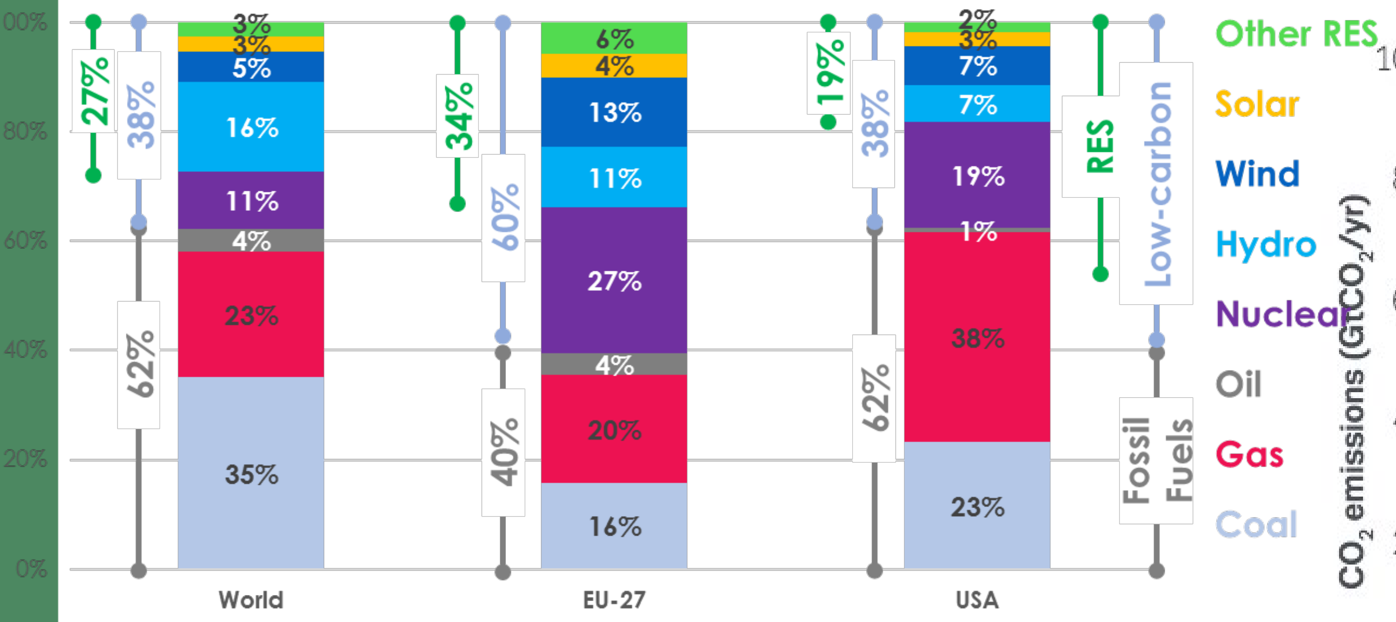
Selection and Evaluation of Materials for **sCO_2 Power Cycles**

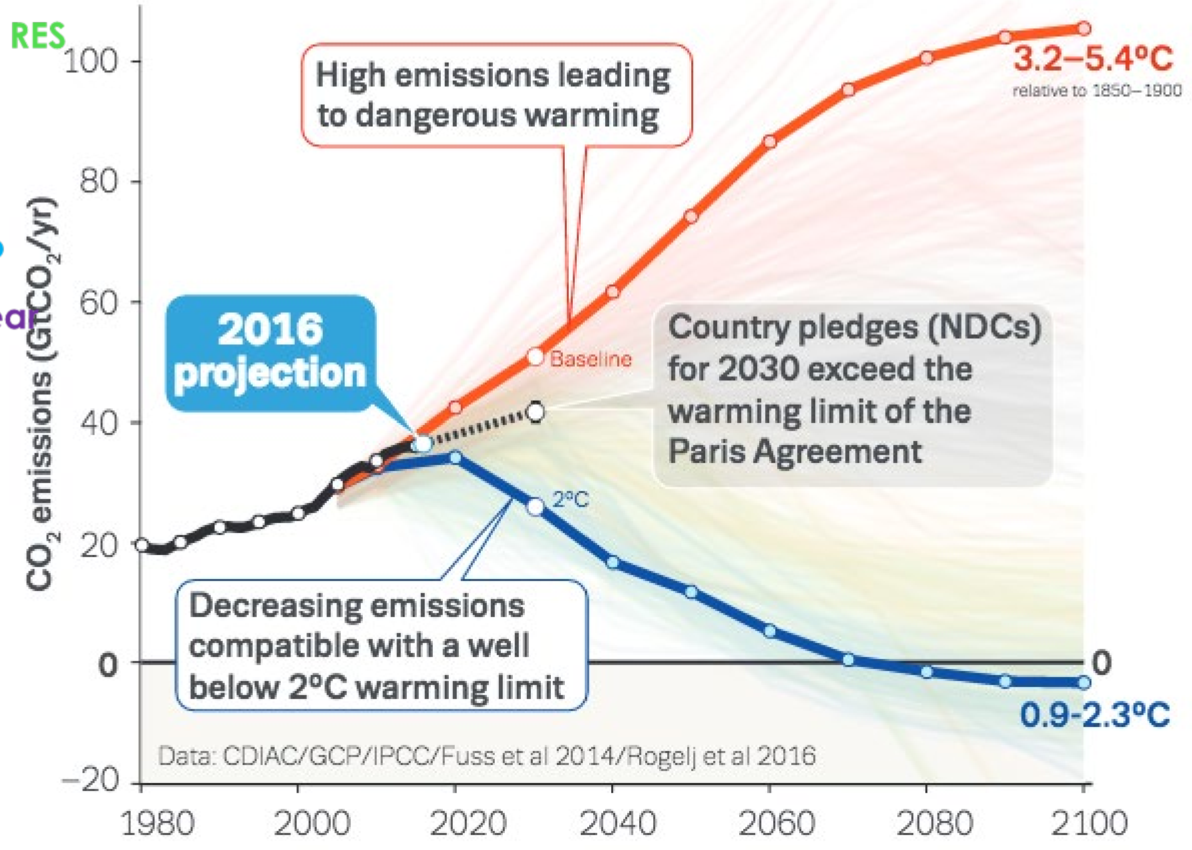


Surface Modifications to improve **Steam Condensers**

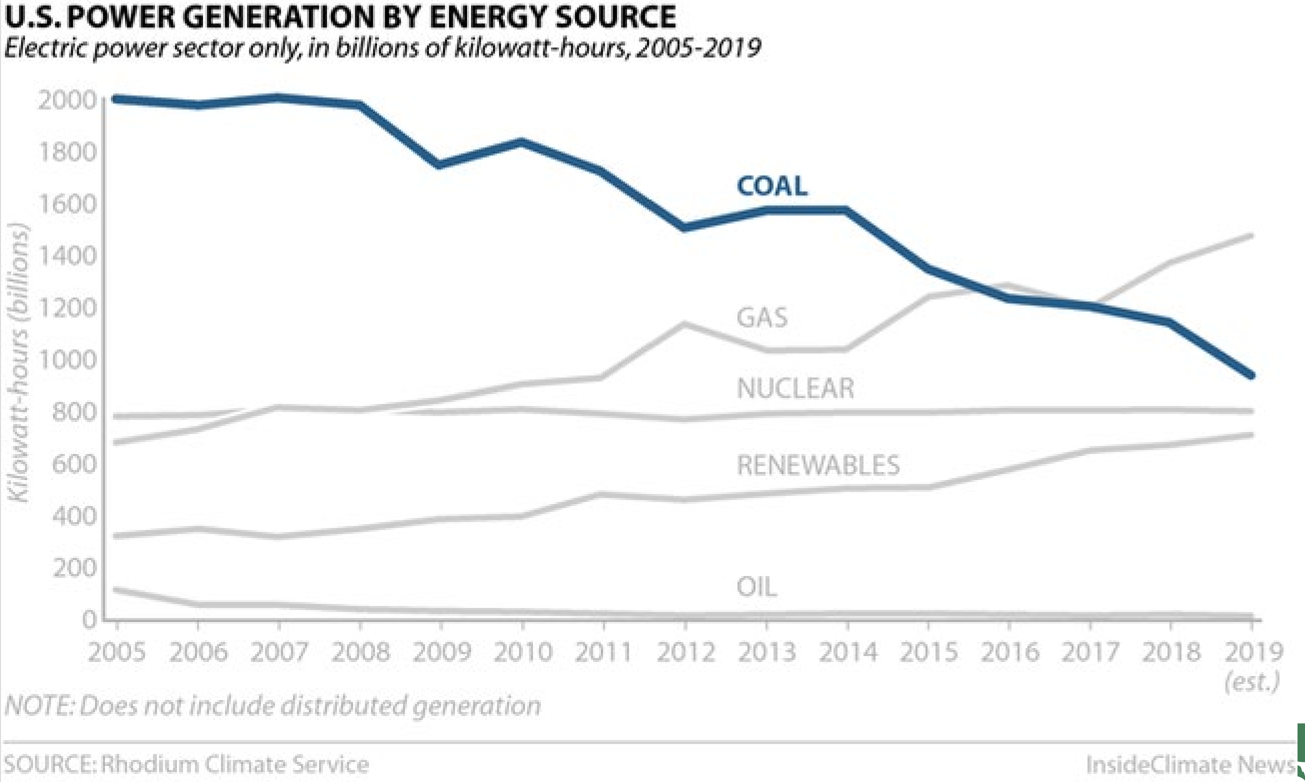
OAK RIDGE National Laboratory · GE · EPRI ELECTRIC POWER RESEARCH INSTITUTE · SIEMENS · CES Combustion Engineering Solutions

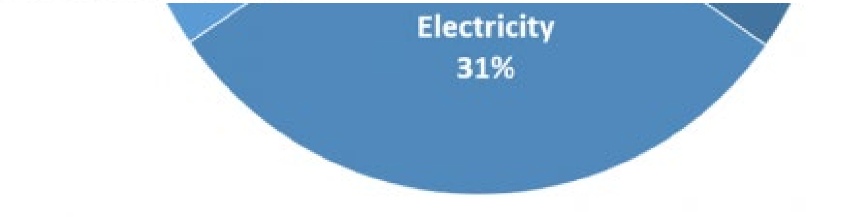
Regional Emissions

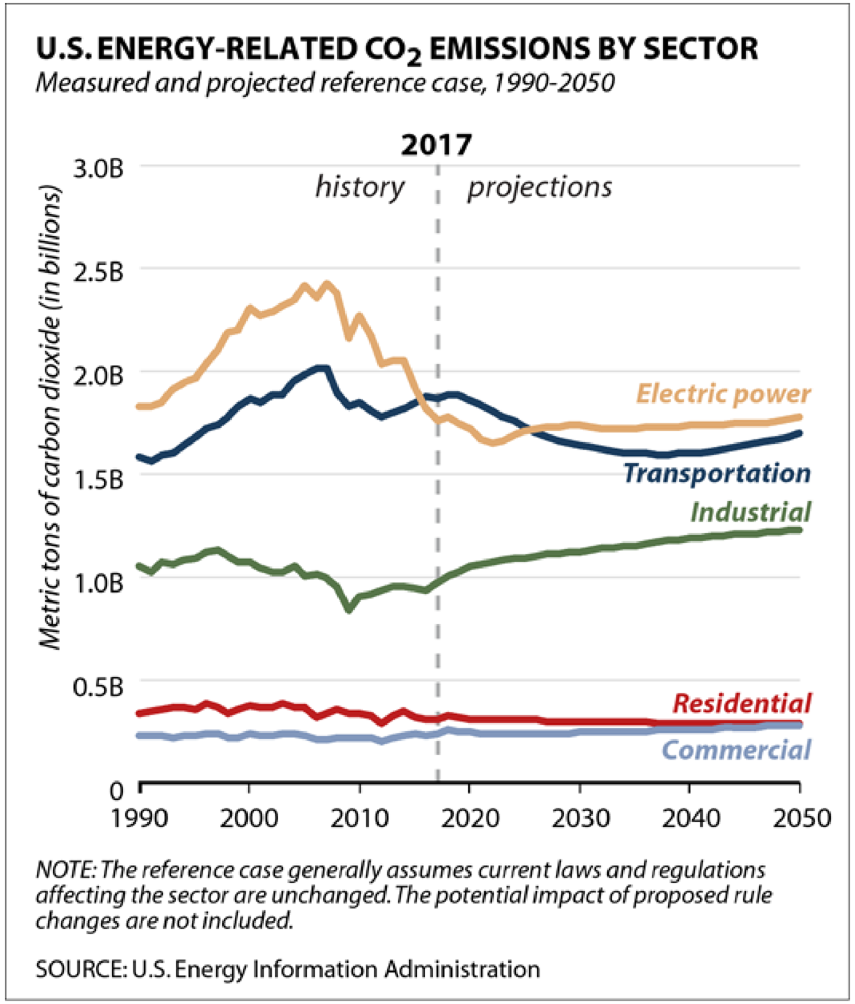




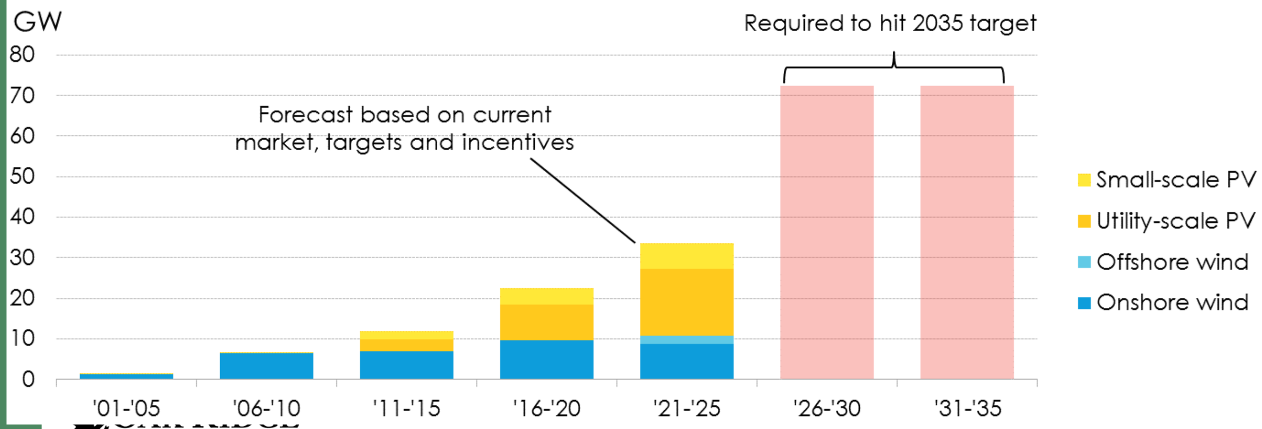
CO_2 US Emissions

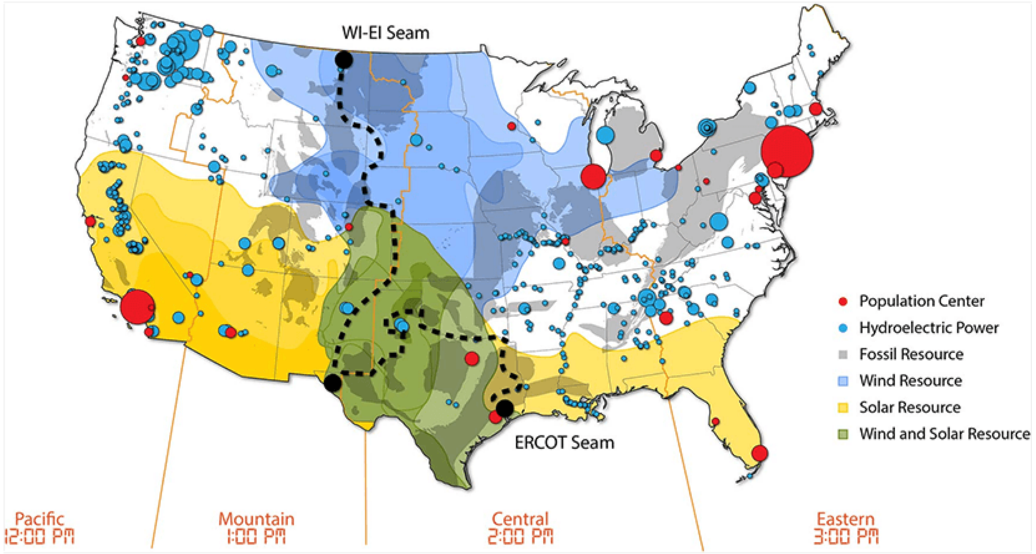






PAUL HORN / InsideClimate News

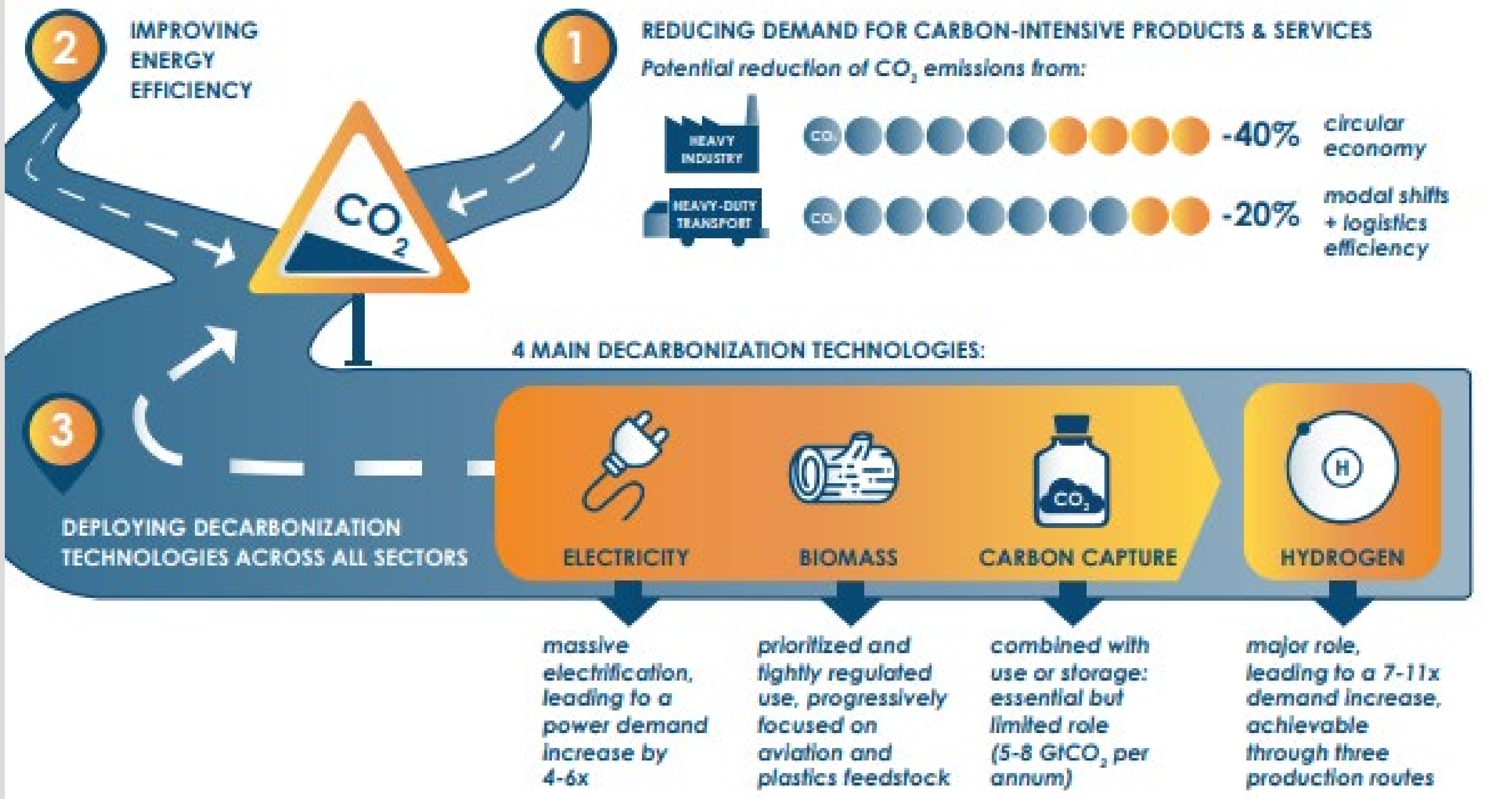




National Laboratory

Cleaning the Grid

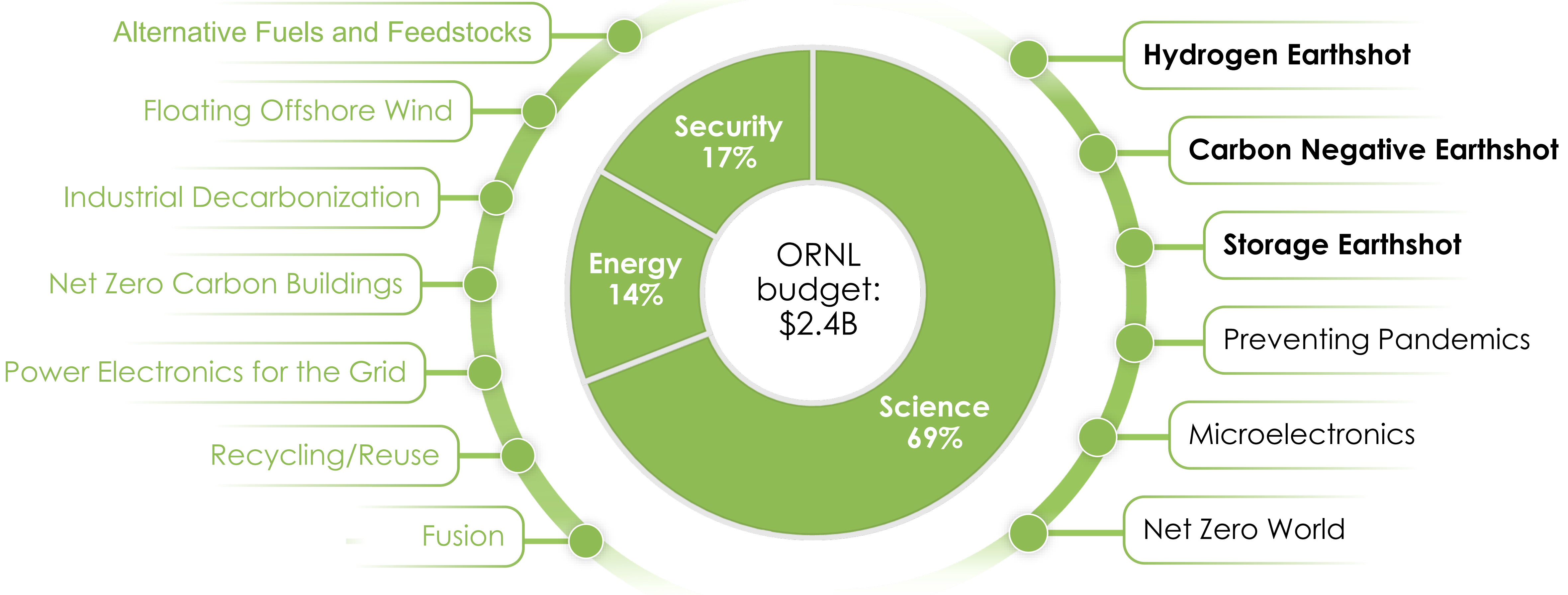
- Utilities setting targets from decarbonization
  - Decarb. fuel sources
  - Electric vehicles will impact the grid
  - Southern Alliance for Clean Energy (SACE)



DOE investments at ORNL enable solutions to the most compelling challenges of our time

DOE Ideation sessions (April/May)

ENERGY earthshots U.S. DEPARTMENT OF ENERGY

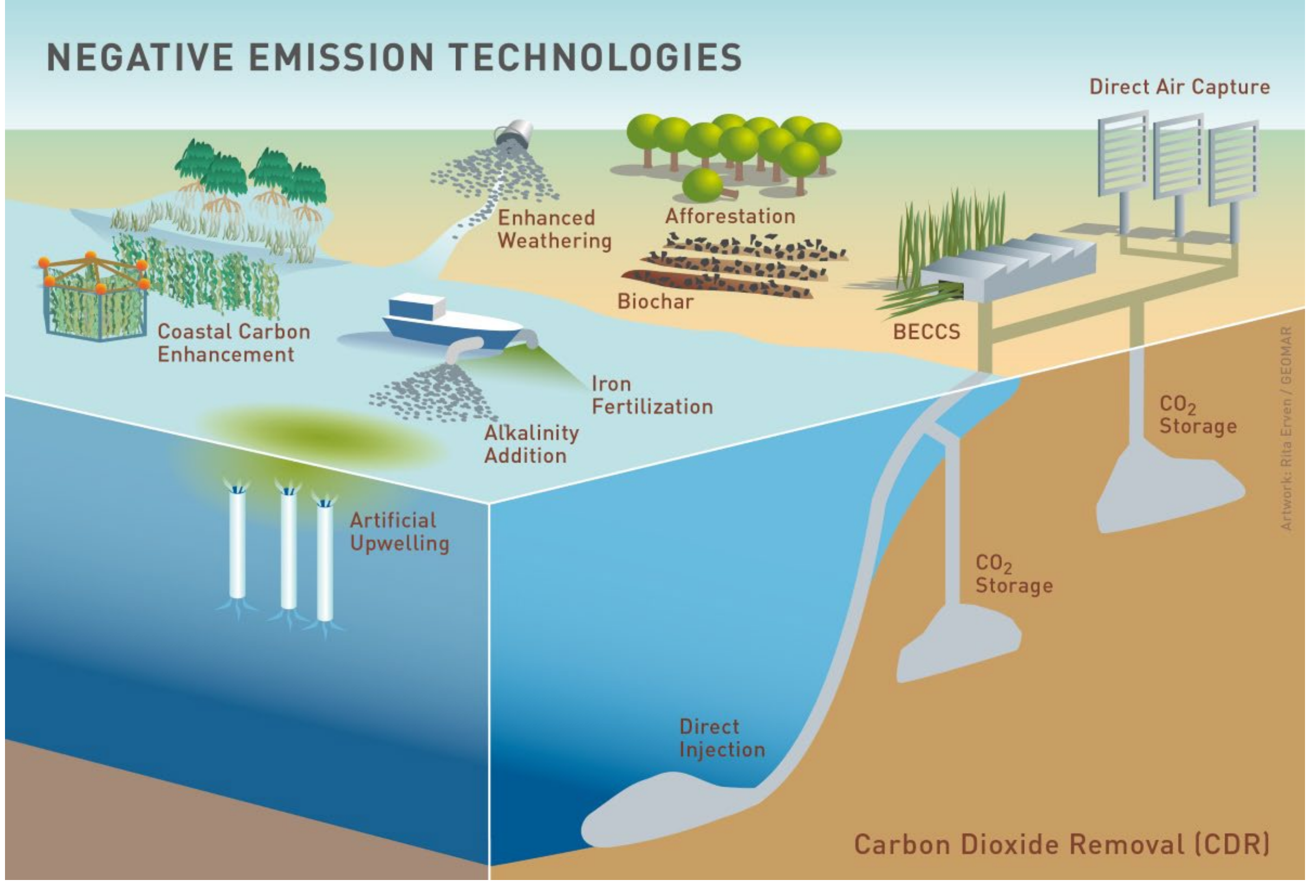


Carbon Dioxide Removal approaches (CDR)

CDR Primer Ch. 2 (cdrprimer.org): Editors Jennifer Wilcox, Ben Kolosz, Jeremy Freeman

1. *Direct Air Capture (DAC)*
2. *Bioenergy with CCS (BECCS)*
3. *Biomass Storage*
4. *Soil Carbon Sequestration*
5. *Ocean Alkalinity Adjustment*
6. *Mineralization*
7. *Hybrid Concepts*

Also in CDR Primer: Forest management, coastal blue carbon



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