


RAPID®
Transforming Process Industries

Beyond Heating: Process Electrification Priorities to Decarbonize the Process Industries

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RAPID – Who are we?

RAPID® Transforming Process Industries

AIChE The Global Home of Chemical Engineers

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

RAPID Impact

- *Build Community*
- *Drive Thought Leadership*
- *Educate students and professionals*
- *Fund and manage R&D projects*

RAPID is part of Manufacturing USA®

- *Public-private partnership model to drive U.S. advanced manufacturing competitiveness*
- *Brings $1B (federal) and over $2B (private) to R&D, tech demonstration, and education*
- *Innovating new ways to manufacture in the U.S.*
- *Developing the next generation workforce*

Electronics
- AIM Photonics – Integrated Photonics – *Albany, NY / Rochester, NY*
- NextFlex – Flexible Hybrid Electronics – *San Jose, CA*
- PowerAmerica – Wide Bandgap Semiconductors – *Raleigh, NC*

Digital / Automation
- America Makes – Additive Manufacturing – *Youngstown, OH*
- MxD – Digital Manufacturing – *Chicago, IL*
- ARM Institute – Advanced Robotics – *Pittsburgh, PA*
- CyManII – Cybersecurity in Manufacturing – *San Antonio, TX*
- CESMII – Smart Manufacturing – *Los Angeles, CA*

Energy / Environment
- RAPID – Modular Chemical Process Intensification – *New York, NY*
- REMADE Institute – Sustainable Manufacturing – *Rochester, NY*

Materials
- LIFT – Lightweight Materials – *Detroit, MI*
- IACMI – Advanced Composites – *Knoxville, TN*
- AFFOA – Advanced Fibers and Textiles – *Cambridge, MA*

Bio Manufacturing
- NIIMBL – Bio-pharmaceutical Manufacturing – *Newark, DE*
- BioFabUSA – Regenerative Manufacturing – *Manchester, NH*
- BioMADE – Bioindustrial Manufacturing – *Minneapolis, MN*

Institutes are funded in part by the Departments of Commerce, Defense, or Energy

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2023 RAPID Member Community

Premier

- University of Pittsburgh
- ExxonMobil
- Dow
- Georgia Tech
- Siemens
- Lubrizol
- Auburn University
- SRNL Savannah River National Laboratory (Operated by Savannah River Nuclear Solutions)
- Oregon State University
- University of Delaware
- SoCalGas

Choice

- NC State University
- Linde
- Shell
- Texas A&M
- Minnesota
- 3M Science. Applied to Life.™
- Owens Corning
- Texas, The University of Texas at Austin
- JM
- University of South Carolina
- The University of Alabama
- Texas Tech
- West Virginia University

Industrial Enabling

- FS Induction Food Systems
- Raytheon Technologies
- Koch Modular Process Systems — Engineered Smarter. Built Modular.
- DuPont
- Chemstations™
- MDavis
- Shepherd Since 1916
- Compact Membrane Systems
- Avadain™ — Unleashing the Graphene Revolution
- U.S. Clean Water Technology
- gti
- Zaiput
- Optimation
- Ascend Performance Materials
- HTRI
- Sironix Renewables
- aspentech
- Nalas Engineering Services, Inc.
- Gore
- AVEVA

Academic Enabling

- Stony Brook University
- Illinois, University of Illinois at Urbana-Champaign
- Washington State University
- Rensselaer
- University of Arkansas
- University of Michigan
- UH
- Carnegie Mellon University
- Arizona
- CESI Cornell Energy Systems Institute
- Rutgers, The State University of New Jersey
- WPI
- KU The University of Kansas

Non-Profit & National Lab Enabling

- CISTAR NSF Engineering Research Center — Center for Innovative and Strategic Transformation of Alkane Resources
- SwRI Southwest Research Institute
- Argonne National Laboratory
- NREL National Renewable Energy Laboratory
- MATRIC
- NETL National Energy Technology Laboratory
- Pacific Northwest National Laboratory
- INL
- RTI International

Affiliate

- appti
- Artisan Industries Inc.
- M2X
- Captis Aire
- Lydian Labs
- Starfire Energy
- Modern Electron
- microflowcvo
- Zeton
- Tecnológico de Monterrey
- Ageias Engineered Systems LT
- Enetor
- Flowid

RAPID's Mission & Metrics

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AIChE The Global Home of Chemical Engineers

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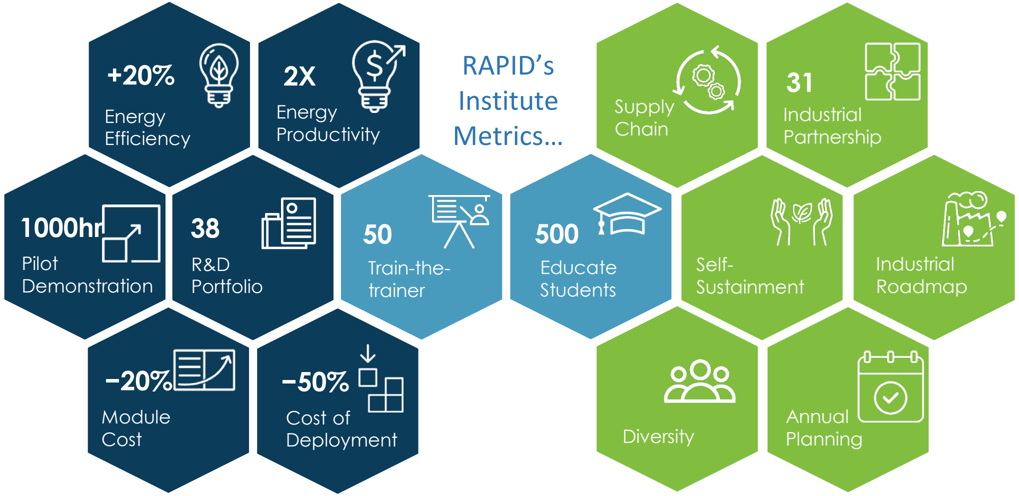
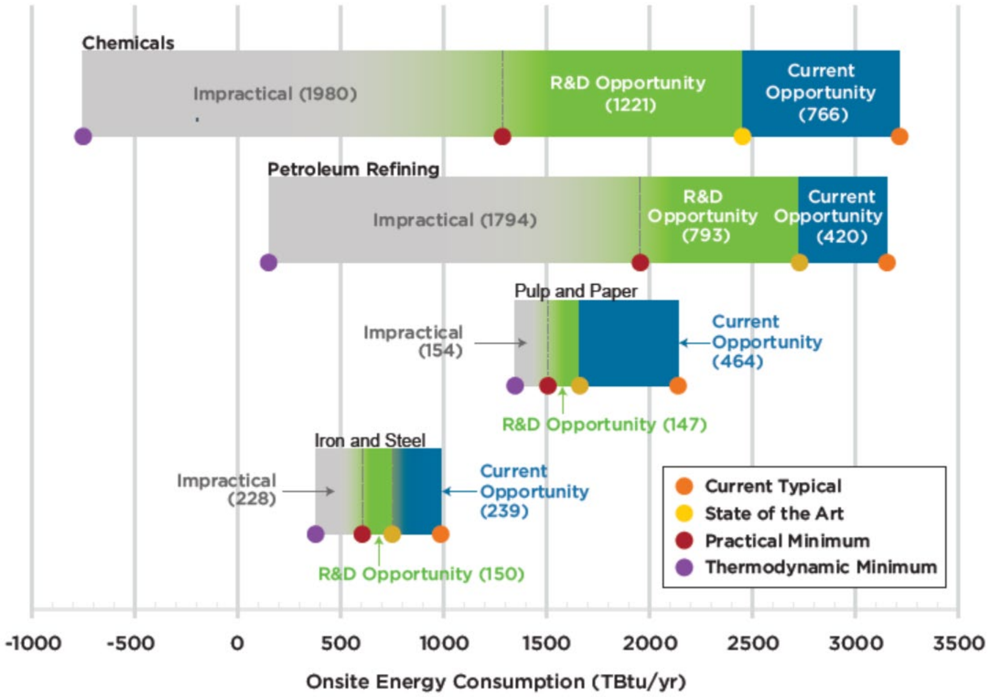
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Build a self-sustaining member consortium that convenes public and private organizations to research, develop, and deploy process intensification (PI) and modular process technologies to enable more resilient, lower cost, and reduced energy footprint manufacturing in the process industries.



Energy & the Chemical Process Industries

- Manufacturing sector accounts for a quarter of the total US energy use
- Process industries are the largest consumers in the sector
- AMO recognized potential for MCPI
- Process industries lacked the MCPI tools, knowledge, experience, leadership, and convening body needed to transform the industry



–DOE AMO Energy Bandwidth Studies
https://www.energy.gov/eere/amo/energy-analysis-data-and-reports

Carbon Emissions & the Chemical Process Industries

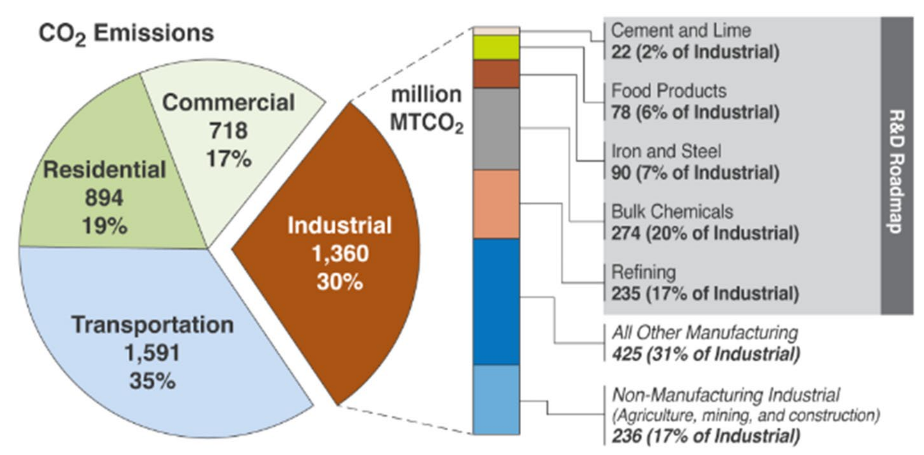


FIGURE 3. U.S. PRIMARY ENERGY-RELATED CO_2 EMISSIONS BY END USE SECTOR (LEFT PIE CHART) AND A BREAKOUT BY INDUSTRIAL SUBSECTOR (RIGHT STACKED CHART) IN 2020.

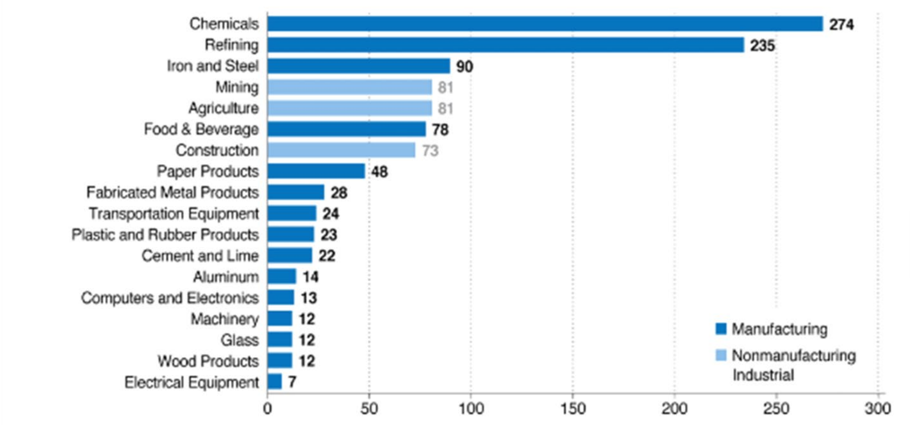


FIGURE 1. ENERGY-RELATED CO_2 EMISSIONS BREAKDOWN BY INDUSTRIAL SUBSECTOR IN 2020, MILLION MT CO_2.

2022 DOE Industrial Decarbonization Roadmap
https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

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2022 DOE Industrial Decarbonization Roadmap

Major Decarbonization Approaches for 5 Key Subsectors

Industrial Subsector	Important Context	Major Decarbonization Strategies
Iron and Steel	2/3 U.S. steel already electrified (secondary: recycled scrap)	• Address primary iron/steel emissions through low-carbon, iron ore reductants; Electrolytic RD&D • Transition heating operations to low carbon solutions • Improved heat management and waste recovery
Cement	CO_2 Emissions sources: 60% process; 40% energy	• CCUS to capture both emissions sources • Alternative heating/fuel switching; new processes/cement materials
Food and Beverage	Wide geographic diversity; grain/oilseed milling and meat largest emitters	• Electrify process heating, drying, dewatering to extent possible • Transition remaining heating operations to low carbon solutions • Reduce food waste and energy losses throughout the supply chain
Chemicals	Largest GHG footprint; diverse – 70K chemicals	• Electrification or low carbon fuel process heat • Low carbon feedstocks (bio, H_2, etc.); CO_2 utilization • Advanced catalysts, process intensification, biological processes
Petroleum Refining	Evolution of end-use fuel demand and impact on refinery product slate	• Electrification, low carbon fuels and clean hydrogen production • Advanced catalysts, process intensification, biological processes • CCUS

https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

Opportunities to Decarbonize the Process Industries

1. Electrification of Process Heat
2. "Clean" Hydrogen
3. "Everything else"
    - *Feedstocks*: waste carbon (plastic, biomass, CO_2)
    - *Products*: commodity chemicals (only?)
    - *Processing Technologies* (driving forces, costs, scale-up)

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DEPLOY Conference Series

- Invited conference and workshop series
- Focus on MCPI applications needs for key areas
- Prompt summary report

Waste Carbon Feedstock Modular CCU

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Feedstock Preprocessing

- Need feedstock quality standards
- TEA/LCA to properly value wastes, processes, and products
- Regulatory and policy frameworks

Conversion

- Having industrially *reliable, robust,* and *flexible processes* capable of attracting capital to accelerate their implementation.

Upgrading

- Co-feeding waste-derived intermediates can provide process flexibility.
- Co-products (e.g., fuels and chemicals) to improve process economics.

CO_2 Capture

- Product and utilization processes to determine options
- Capture should be integrated into existing infrastructure

CO_2 Utilization

- Conversion to C1 and mineralization are the highest TRL options.
- Conversion to C2+ need substantial technology development and piloting

Process Integration

- Modular approaches are key to minimizing engineering costs.
- Standardization and numbering up of modular CCU platforms.

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Process Electrification

Driving sustainability and industrial decarbonization by electrifying processes to replace or supplement fossil-driven technologies.

- ***Process Heating*** – use of electromagnetic (e.g., induction, microwave, plasma), heat pump, and other electrified technologies in place of traditional fossil-fuel-fired heating
- ***Electrochemical*** – use of electrochemical reactive and separation technologies in place of or alongside traditional thermochemical or biochemical production methods
  - *Alternative Chemical Pathways* for more selective routes to produce certain chemicals with lower (or no) greenhouse gas emissions
  - *Direct Conversion of CO2* via electrochemical reduction C1 or C2 compounds
  - *Novel Separations Processes* that use redox chemistry to effect difficult separations.
- ***Energy Storage*** – use or integration of electricity storage technologies at manufacturing sites to optimize grid integration and/or manage renewable asset intermittency

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Advanced Energetic Reactors

Reactions driven by new forms & sources of energy, often from electricity, rather than from conventional thermal energy from fossil fuel combustion. Decarbonization benefits are derived from efficient energy delivery of decarbonized energy (renewable electricity).

- *Electromagnetic Energy Reactors* use electromagnetic energy (RF induction & microwave) energy to drive reactions.
- *Sonic Energy Reactors* use ultrasound, or other forms of sonic energy, to drive and/or enhance reactivity.
- *Plasma Reactors* use plasmas, of different types and power levels, to drive and enhance reactivity.
- *Electrified Reactors* include other ways to delivery electrical energy (e.g. resistive) to drive reactions.

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Electrification Options for the Chemical Process Industry

Industry Sponsored Project

Renewable Electricity Sources & Technologies	Electrified Utilities / Process Heating
Energy Storage	
Heat / Steam Generation - Novel Electrified Technologies	
Cooling - Novel Electrified Technologies	
Electrified Process Heating	
Electrochemical Reaction Technologies	Unit Operations
Electrochemical Separations Technologies	
CO2 (and other novel feedstock) Utilization - via Electrochemistry	Alternative Feedstocks
Process Digitization - (i.e. artificial Intelligence for optimization)	Efficiency Improvements
Energy Efficiency - Lighting, Buildings	
Energy Efficiency - Advanced Motors and Drives (Switched Reluctance, Axial Flux, etc.)	

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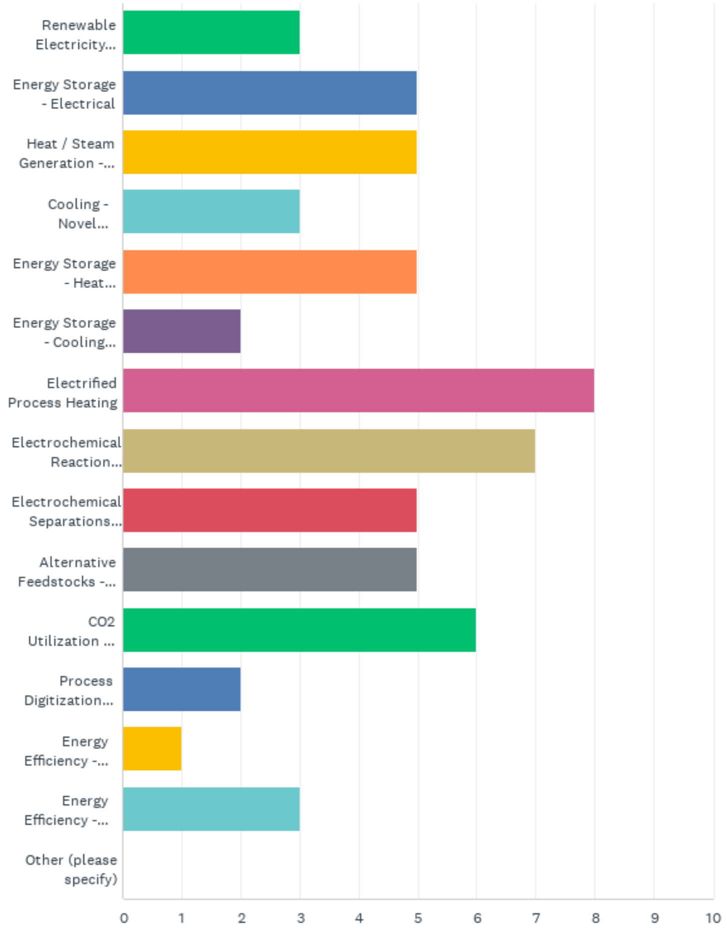
Electrification Focus Areas of most interest to 4 surveyed companies

Top 5:

- Electrified Process Heating
- Electrochemical Reactions
- CO2 Utilization (electrochemical)
- Electrified Utilities (Energy Storage, Electrified Heat/Steam)
- Electrochemical Separations



Process electrification technology options

Renewable Electrcity: Solar - PV	Electrified Utilities
Renewable Electrcity: Wind	
Renewable Electrcity: Geothermal	
Combined Heat & Power - Renewable Fuel / Biomass	
Combined Heat & Power - Natural Gas	
Energy Storage - Electric - Li Battery	
Energy Storage - Electric - Alt. Chemistry	
Energy Storage - Electric - Flow Battery	
Energy Storage - Chemical (ammonia, LOHC, etc.)	
Electricity Usage Strategies - Peak Shifting	
Electricity Usage Strategies - Demand Response	
Energy Storage - Thermal - Heat (Enabling)	
Energy Storage - Thermal - Cool (Enabling)	
Thermal - Electrified Utilities (furnaces, boilers, steam, etc.)	
Thermal - Industrial Heat Pump / Novel Electric Cooling	
Microwave Process Heating	Electrified Process Heating
Induction Process Heating	
Radio Wave Process Heating	
UV Process Heating	
Infrared Process Heating	
Resistive Process Heating	
Electrified Steam Cracking	Electrified Unit Operations – Reactions
Electrochemical CO2 Reduction (CO2 to X)	
Electrochemical Organic Functionalization	
Electrochemical Organic Coupling	
Inorganic Electrosynthesis (Ammonia, Chlor-Alk, etc.)	
Separations - Electrodialysis	Electrified Unit Operations – Separations
Separations - Electrodeionization	
Separations - Capacitive Deionization	
Artifical Intelligence - Process monitoring and optimization	Efficiency Improvements
Artifical Intelligence - Predictive Maintenance	
Artificial Intelligence - Advanced Control Strategies	
Digitization / Artificial Intelligence - Other	
Novel / Electrified Air Separation	
Advanced Motors & Drives	
Energy Efficiency Improvements (Lighting, Building envelope, HVAC, etc.)	

RAPID Process Electrification Database focus and status

Process Electrification	
Microwave Process Heating	
Induction Process Heating	
Thermal - Electrified Utilities (furnaces, boilers, steam, etc.)	
Resistive Process Heating	
Infrared Process Heating	
UV Process Heating	
Electrochemical CO2 Reduction (CO2 to X)	
Energy Storage - Electric - Flow Battery	
Energy Storage - Chemical (ammonia, LOHC, etc.)	
Energy Storage - Thermal - Heat (Enabling)	
Electrified Steam Cracking	
Electrochemical Organic Functionalization	
Energy Storage - Electric - Li Battery	
Radio Wave Process Heating	
Electrochemical Organic Coupling	
Advanced Motors & Drives	
Combined Heat & Power - Renewable Fuel / Biomass	
Energy Storage - Electric - Alt. Chemistry	
Electricity Usage Strategies - Demand Response	
Energy Storage - Thermal - Cool (Enabling)	
Thermal - Industrial Heat Pump / Novel Electric Cooling	
Separations - Electrodialysis	

Identified Electrification Technology Options (Quick Review)

- Process Heating
  - 55 Technologies
  - 13 priority for chemical process industry
  - Induction, microwave primarily
- Electrochemical CO2 conversion
  - 16 technologies
  - 8 priority
  - Variety of products from CO to alcohols to formic acid to ethylene
- Electrified Utilities
  - 12 technologies
  - Electrified industrial steam boilers
  - Industrial heat pumps
- Novel Energy Storage (i.e. flow battery)
  - Enabling technology
  - Many options
- Electrified or Low T Ethane Cracking
  - 8 technologies
  - Various stages of development

RAPID Renewal
Four Key Priorities

- Decarbonizing the process industries
- Advancing U.S. manufacturing competitiveness
- Promoting diversity, equity, inclusion, and accessibility across Institute operations
- Delivering institute sustainment

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RAPID Renewal Technical Focus

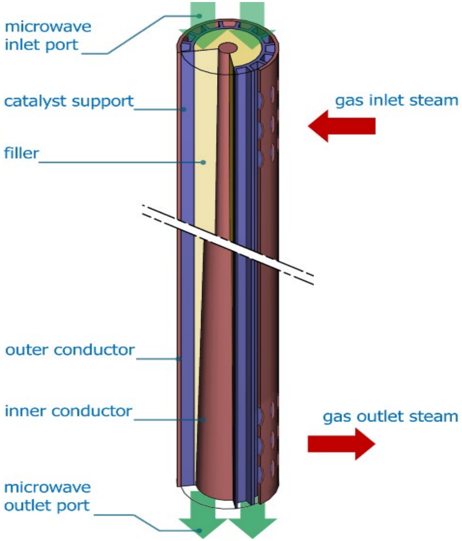
- Development, scale-up, and demonstration of process technologies
- Enable decarbonization of the process industries

		INDUSTRIAL APPLICATIONS			
		Specialty Chemicals	Carbon Reuse	Low C Fuels (incl. H_2)	Food & Bioproducts
TECHNOLOGY THRUSTS	Modular Approaches				
	Batch-To-Continuous				
	Microchannel				
	Novel Energetics				
	Enhanced Fluidics				
	Modeling and Data				

Microwave-Enhanced Reactions

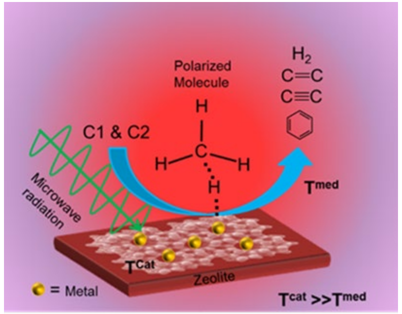
Intensified Microwave Reactor Technology

Develop a suite of tools that enable broad deployment of traveling wave microwave reactors

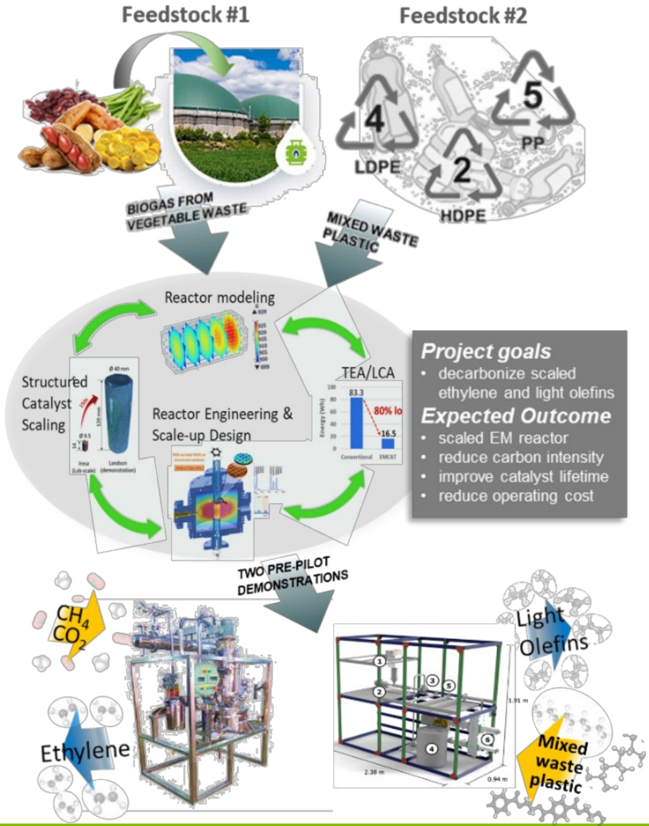


Alternative Energetics for Hydrocarbons Upgrading

A viable, modular system for direct conversion of lower alkanes to aromatics using microwave heating.



DECARBONIZING LIGHT OLEFIN PRODUCTION USING ADVANCED ELECTROMAGNETIC REACTORS



Scaling EM Technology

- High performance EM absorbing dehydrogenation catalysts with increased catalyst lifetime (50%) over commercial catalysts.
- Develop MW and RF induction reactors for C waste feedstock conversion into light olefins.
- Pilot scale EM/RF hybrid reactor optimized for producing ethylene and light olefins from RNG (100 CFM) and waste plastic (100 kg/day) feedstocks.
- ≥70% reductions in carbon intensity and energy consumption per unit of olefin produced, and ≥25% reduction in operating costs

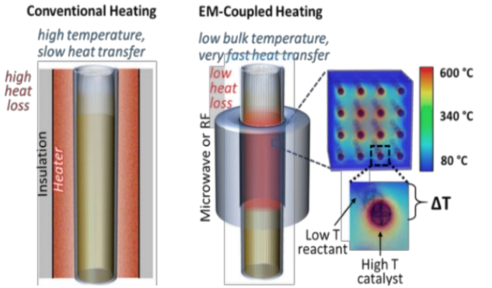


Figure 1. Conventional heating is energy intensive with high heat loss. Using EM heating allows for direct, intense heating of enhanced EM absorbing catalyst particles resulting in greater energy and reaction efficiencies.

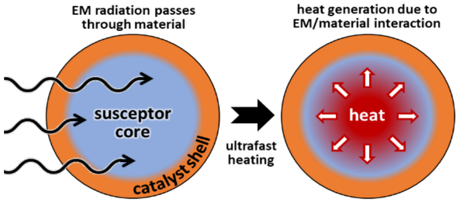


Figure 4. *Volumetric heat generated by e.g., RF interaction between susceptor and catalyst.*

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CO_2 Upgrading via Electrochemistry

- CO_2 hydrogenation in electrochemical membrane reactor based on high-performance protonic ceramic electrochemical cells (PCECs)
- H_2O oxidation occurs concurrently to produce hydrogen needed for conversion of CO_2
- Leverages efficient, iron-based catalysts
- Electrical potential enables moderate temperature operation (350 °C, compared to 800 °C for electrolysis in oxygen-ion conducting cells or < 100 ° C for aqueous electrochemical CO_2 reduction)
- Currently TRL 3 →→ RAPID 2.0 project to advance to TRL 5/6

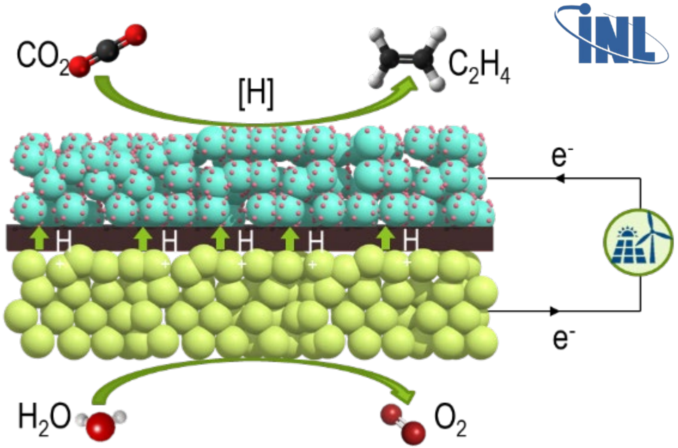
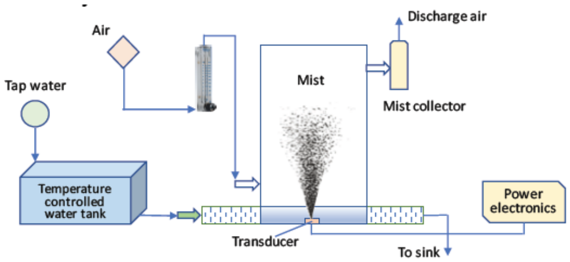


Image from RAPID Project 5.10 Final Technical Report by Dong Ding and Lucun Wang of Idaho National Laboratory

Electrically Enhanced Separations for Bioprocesses

Power Ultrasound for Nonthermal, Non-equilibrium Separation of Ethanol/Water

Low energy ethanol separation from aqueous solution using power ultrasound avoiding azeotrope limitations.



Physical Property Data and Models for Bioprocessing Separation Technologies

Provide data and models for faster and more cost-effective bioseparations scale-up. Expand to electrochemically-driven separations.

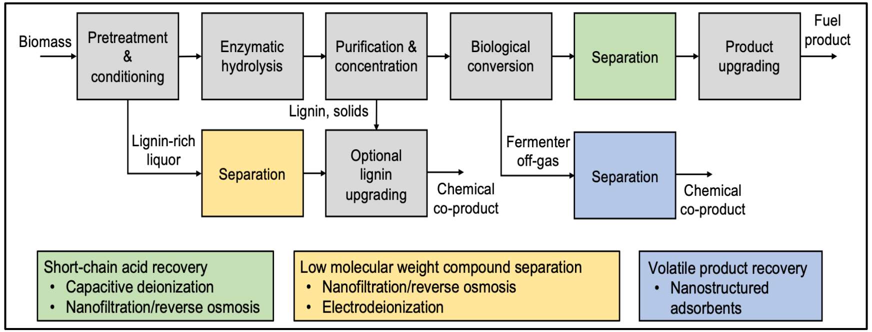


Diagram A: Separations targeted by the Separations Consortium in a biochemical conversion pathway

Summary

- RAPID to refocus effort from energy efficiency improvements to decarbonization of process industries
- Electrification of process technologies is key to enable industrial decarbonization
- Electrification of process heating is "low hanging fruit" (*not necessarily that low!*)
- Beyond heating:
  - Novel energetics reactions/separations:
    - Microwave/RF reactors
    - Electrochemical upgrading of waste C
    - Electrochemically-driven separations

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EXTRA SLIDES

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Institute Timeline

Original DOE Agreement

$160M Total Funding ($125M over 38 R&D projects)

Projects funded under DOE AMO cooperative agreement

New Potential DOE Agreement

$60M (Fed+CS)

New DOE award (5 years)

Other Projects:

- Over 11 projects (2019-2022)
- RAPID lead on 4 projects
- $14.4M through late 2022
- Several pending proposals

Other Federal Funding

Projects from DOE (AMO, BETO), DoD (DARPA, ONR), DOC (NIST)

RAPID and members collaborate on different federal funding opportunities

2022 Projects (6 company sponsorships):

- Process Electrification
- Transition Tech.

Industry-Sponsored Project Funding

Members pool funding for selected projects

DOE cooperative agreement

Diversified phase

2017 | 2019 | 2021 | 2023 | 2025 | Beyond

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Modular Chemical Process Intensification (MCPI)

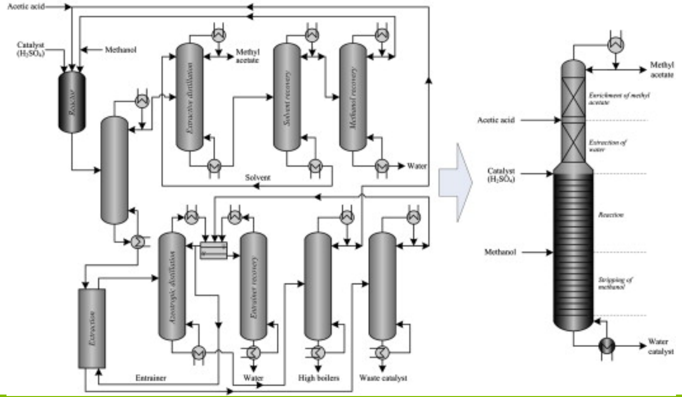
Modular Processing

- Rethinking systems to enable flexible, **distributed manufacturing**
- Shift from **bigger is better** paradigm to **small, modular** paradigm
- Transition from volume scaling to **numbering up**

Process Intensification

- Rethinking processes to dramatically **improve performance**
- Shift from **unit operations** paradigm to **integrative** paradigm
- Transition from **batch to continuous**

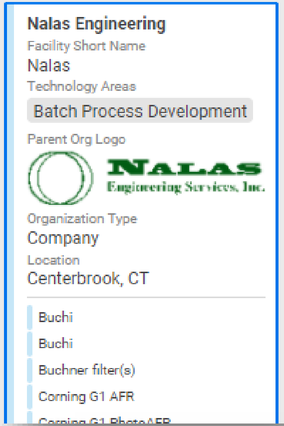


RAPID® Member Engagement Opportunities

Transforming Process Industries

- **Connect** with the RAPID Community
- **Attend** RAPID Events
- **Access** Technical Tools & Resources
- **Educate** the Current and Future Workforce
- **Collaborate** on Technical Projects



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