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Office of Energy Efficiency & Renewable Energy
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585
RE: DE-FOA-0002687: Request for Information on Industrial Decarbonization Priorities

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INTRODUCTION

Thank you for the opportunity to provide insight into emerging technologies that can decarbonize key industrial sectors, specifically the chemical and plastics, iron and steel, and food and beverage sectors. The Information Technology and Innovation Foundation (ITIF) is a non-profit, non-partisan research and educational institute—a think tank. Its mission is to formulate, evaluate, and promote policy solutions that accelerate innovation and boost productivity to spur growth, opportunity, and progress. Clean energy, climate innovation, and industrial policies are some of ITIF's primary issue areas.

Advanced industry and technology strategies of the sort discussed in this submission complement policies that impact the entire economy and have climate benefits. The former's success depends on the latter's success, such as workforce education and training, basic research funding, and infrastructure policies. The United States is on the verge of adopting advanced industry and technology strategies, but it is not yet prepared to carry them out. The federal government lacks the detailed information and specialized analytical capabilities to make such strategies effective.[1] This RFI is a useful first step in the right direction.

The RFI correctly notes that there is no silver bullet to industrial sector decarbonization due to the incredibly diverse array of fossil energy and industrial feedstocks used in each sub-sector. The approaches taken to reduce and eliminate emissions will have to be multipronged, relying on industrial energy efficiency gains, electrification of low-heat industrial processes, substitution with low-carbon fuels, carbon capture and storage, and other ideas that are not yet commercialized. Only 28 years remain until mid-century, the target date for emission reduction levels established by the Paris Agreement and elsewhere.[2] In the industrial sectors, with long-lived capital assets, 2050 is only one or two reinvestment cycles away. However, U.S. industry does do not yet have all the necessary technology to decarbonize while maintaining its competitive edge in manufacturing. Only with continued federal and private investment in low-carbon RD&D will the United States be able to achieve the twin goals of supporting a robust manufacturing sector while reducing and ultimately eliminating emissions.

CATEGORY 1: CHEMICAL INDUSTRY DECARBONIZATION

Eliminating GHG emissions from the production of chemicals and plastics poses a unique set of challenges. These industries are highly diverse and entangled with the production of transportation fuels and are heavily reliant on fossil fuel feedstocks, especially natural gas.[3] Major reductions are possible, however. Below, we have ordered the technology categories from those most likely to have a significant decarbonization impact in the near term to those technologies that are likely to be longer-term options to decarbonize the plastics sector. These include:

- Carbon capture and storage
- Direct use of low-carbon hydrogen and electrification of crackers and industrial processes
- Bio-based production, including ethanol-based plastics
- Non-conventional chemical feedstocks

Carbon Capture and Storage for Chemical and Plastics Production

The most straightforward way to decarbonize the chemicals and plastic industries is through industrial carbon capture and storage (CCS). Carbon capture has the advantage of preserving most existing production assets and using well-proven technologies. The relatively high densities of CO_2 in many waste streams from these systems reduce overall capture, transportation, and storage costs. CCS can be either retrofitted onto existing plants or built onto new plants. In addition, CCS applied to hydrogen production creates a valuable low-carbon feedstock that can be utilized in various chemical and plastic production. While there are few CCS plants on chemical and plastics manufacturing plants in the U.S., marketing, infrastructure, and regulatory hurdles are larger barriers than technological issues. However. DOE's AMO should continue to tackle the specific technical challenges of CCS in this sector, including reducing the costs of retrofitting plants, improving modularity of systems, improving chemical sorbent CO_2 uptake, and reducing system energy costs. In sum, CCS will be a critical tool between now and mid-century that allows costly existing chemical and plastic facilities to remain in operation while nearly eliminating CO_2 emissions from their production.

Direct Use of Low-Carbon Hydrogen and Electrification of Crackers

Beyond CCS, the plastics and chemical industry might be decarbonized through electrification of industrial processes, particularly crackers. As the U.S. electric grid decarbonizes, opportunities to electrify formerly fossil-fuel-intensive operations will expand. For many plastics, production processes can be achieved using relatively low temperatures of around 100°C. Such processes can be met with electric resistance heating or newly emerging high-temperature heat pumps that can cut electricity use by factors of 3 or more.[4] However, ethane cracking, a precursor process to many plastics value chains, requires temperatures of 800-900°C. These levels are not yet cheaply and easily met by electric technologies.[5] New electric technologies are, however, being actively explored. German firms BASF SE and Linde are partnering with the Saudi Arabian firm SABIC on one such prototype.[6] Dow and Shell are working on a competing process called the "e-cracker."[7] And Japan's Toyo Engineering recently announced plans to study the feasibility of electrifying an ethylene cracker in Thailand, with an expected start date of 2029.[8]

Direct use of low-carbon hydrogen as a fuel may also provide a viable pathway to provide process heat for high-temperature processes with appropriate modifications in combustion technology. Hydrogen may be produced sustainably through electrolysis using net-zero electricity from renewables or nuclear power or by the "pre-combustion" methods cited earlier that use fossil fuels and sequester the CO_2.[9]

Systems using electricity or hydrogen to provide heat offer a clear path to low-carbon manufacturing. They may provide additional benefits over carbon capture technologies. For instance, since they are not as large physically as post-combustion carbon capture systems, they may be easier to incorporate into existing plants. Challenges, however, remain:

- While commercial systems for using hydrogen to provide industrial heat are becoming available and electric crackers are under development, they are not yet widely available, nor are they cost-competitive with existing large fossil fuel-fired crackers.[10]
- Total process costs are largely unknown, though if DOE were to meet its ambitious $1/kg hydrogen goal, that would help make low-carbon processes far more competitive.
- Electricity and hydrogen can eliminate emissions from the production process, but they do not eliminate the carbon embodied in petrochemicals themselves.

Together, electrification and low-carbon hydrogen provide opportunities to move away from fossil fuel feedstocks and reliance on fossil fuel heat and energy inputs. However, producing consistent and cheap low-carbon energy, alongside cheap low-carbon hydrogen, will be determining factors.

Bio-Feedstock Substitutes

Bio-based materials, particularly ethanol, are the focus of ongoing efforts to transition away from fossil-fuel feedstocks entirely. Recent advances make it possible to manufacture chemical products using biotechnological techniques rather than relying on natural gas inputs. However, these processes are currently more expensive than traditional processes and are not yet widely adopted. In addition, they face technical, infrastructure, and deployment challenges given the competitive market structure of the U.S. plastics and chemical industry.

The largest bio-based chemical product is ethanol, which is currently primarily used as a blend in gasoline in the United States. U.S. ethanol is made almost entirely from corn, consuming roughly 40 percent of the nation's crop. Ethylene production from corn-based ethanol feedstock is attractive because it relies on proven technology and may provide a reliable market for corn producers if electric vehicles reduce demand for gasoline and blended ethanol. The use of ethanol also eliminates the expensive and energy-intensive requirement to crack ethane and may reduce the total energy inputs required for chemical production.

The CO_2 released using corn-based ethanol as a feedstock in chemical production can be significantly lower than emissions associated with fossil-based processes. The CO_2 embodied in corn itself was extracted from the atmosphere, releasing it is carbon-neutral. Corn-based ethylene production, however, faces significant challenges:

- Ethanol production, alongside precursor production processes such as growing, fertilizing, transporting, drying, and fermenting corn, may have significant emissions impacts.
- The cost of ethylene from corn or sugarcane could be 35-65 percent more expensive than conventional ethylene (in the absence of a carbon tax or equivalent).[11]
- There may be growing demand for biomass fuels in other sectors, such as aviation, which will likely pay a premium above plastics producers.

A significant shift to bio-based chemical production would require other feedstocks and corn, such as sugar cane, sugar beets, switchgrasses, and even woody inputs. Biological feedstocks may also be distributed more widely across the United States than fossil fuels. Some industry research suggests that a shift to such feedstocks would be feasible without competing with food production. In contrast, other research suggests that moderate food and bio-plastics consumption levels may put increased stress on land use and increase competition with food production.[12]

A combination of acid treatments, enzymes, and other processes for producing ethanol from these lignocellulosic materials are close to commercial operation.[13] However, commercial implementation of such processes has been slow in part because processing can be slow, and it can be difficult to recycle catalysts.[14] The use of waste and other biological materials to produce ethylene shares most of the advantages and challenges of corn-based production, but the supply of this feedstock might be much greater -- large enough to supply the entire chemical manufacturing industry.

Ongoing challenges to consider include:

- Many approaches are still far from maturity, requiring continued public RD&D funding until they become commercially viable.
- Costs are uncertain and may be significantly higher than conventional fossil fuel processes.[15]
- Mitigating ongoing land and water use competition concerns will be critical to the wider-scale adoption of bio-based feedstock substitutes.

Non-Conventional Chemical and Plastic Feedstocks

Recent advances in biotechnology have made it possible to engineer organisms that can produce virtually any chemical by fermentation. NREL, for instance, has engineered a bacteria that can convert CO_2 to ethylene from photosynthetically fixed carbon or biomass-based sugars.[16] There is growing industrial interest in these systems. Occidental Petroleum, for example, is partnering with the startup Chemvita to develop an engineered organism that can produce chemicals from atmospheric CO_2 and water.[17] In addition, Brazil-based Braskem Company produces 180,000 metric tons annually of polyethylene from sugarcane.[18] In the United States, companies like LanzaTech use captured CO_2 alongside microbes to produce ethanol through fermentation, which is then used to produce ethylene and subsequent polymers for commercial plastic use.

Going one step further, lab and pilot stage studies using advanced membranes to treat captured industrial CO_2 and low-carbon hydrogen have been able to turn these inputs into useful chemicals in a single step.[19] New simulation and artificial intelligence techniques prove useful in accelerating the development of needed catalysts. A related approach aims to develop devices that can imitate photosynthesis using sunlight, atmospheric CO_2, and water to produce complex chemicals.[20]

CATEGORY 2: IRON AND STEEL INDUSTRY DECARBONIZATION

The United States metal manufacturing sector is already less carbon-intensive than many global industrial peers, such as Japan, South Korea, China, and Europe for some industries and countries. This advantage is largely due to U.S. reliance on electricity as a fuel source in secondary steel production in electric arc furnaces and the use of low carbon electricity in aluminum production. However, there are emerging technological areas where international competitors are outpacing or can outpace advances in domestic metal manufacturing. These areas include using clean hydrogen as a reductant in the direct reduced iron (DRI) process. The United States cannot afford to fall behind international competitors in developing and deploying these low-carbon metal manufacturing processes.

Take hydrogen-DRI processes. While the technology deployment is currently in its infancy in Europe, there is no effort in the United States to bring together major steel producers, purchasers, academia, or technology startups or providers to develop a comparable clean steel industry based on low-carbon hydrogen and DRI.[21] Clean, cheap, and available hydrogen is the linchpin to low-carbon DRI steel. Europe, Australia, and Japan have already announced DRI-H2 steel plants capable of producing hundreds of thousands of tons of virtually zero-carbon steel. The United States must be at the forefront of this critical industrial technology innovation, which will likely play a large role in any global effort to decarbonize the iron and steel industry.

CATEGORY 3: FOOD AND BEVERAGE INDUSTRY DECARBONIZATION

Decarbonization opportunities in the food and beverage industry are plentiful due to the low overall temperature requirements for processing compared to other sectors. Low-temperature heat is used throughout the industry, from washing and pasteurization to drying and distillation. The International Energy Agency (IEA) projects that heat below 200°C will account for approximately two-thirds of the projected increase in energy used by industry for process heat by 2040. Table 1 lists some of the most common industrial processes to which innovative electricity-powered heating, cooling, and drying technologies might be applied.[22] Therefore, the most likely emissions solutions for many locations will be devices powered by zero-carbon electricity, such as heat pumps.

Table 1: Common industrial low- and medium- temperature processes

Process	Temperatures (°C)
Washing	40-90
Cooking	60-100
Pasteurization	60-80
Sterilization	60-90
Distillation	140-150
Drying	60-100
Sanitary Hot Water	40-80

Even though heat pump deployment, particularly for residential space heating, has grown rapidly, the technology needs to improve much further to achieve large-scale penetration and cost competitiveness in the industrial sector. The remaining key challenges to electric heat pump deployment include:

- initial costs well above competing units that run on natural gas;
- lower heating efficiency in cold climates;
- potential winter electric grid peaking concerns;
- refrigerants that present environmental hazards or safety concerns; and
- inability to reach temperatures above 100°C required in some industrial processes.

Continued DOE RD&D investment would help overcome the remaining technical hurdles to commercial heat pumps for the food and beverage sector. Some of the most promising innovations that could resolve these challenges and unlock new markets include:

- Novel refrigerants: Alternative refrigerants (including supercritical CO_2, water, hydrogen, and other materials) may provide heat pump options for industrial processes. These refrigerants are inexpensive and nontoxic. One already-commercialized product can heat air to 120°C while simultaneously cooling water to 25°C, and prototypes have pushed temperatures up another 20 to 30°C. Novel approaches that compress hydrogen using membrane technologies similar to those used in fuel cells also look promising.[23]

- Cascading systems: Cascading systems use a series of heat pumps optimized for different temperatures. The first lifts the working fluid from ambient temperature to an intermediate temperature for which the next heat pump is optimized, and so on. Although the heat exchange between systems incurs an energy penalty, this architecture can reach higher temperatures more efficiently than a single-stage heat pump can. Hybrid systems that combine heat pumps with electric resistance heating may provide very precise process control that is attractive to industrial producers.

- Non-Vapor-Compression Cycles: Vapor compression has been the main mechanism for heat transfer in heat pumps for over a century, but alternative approaches are proliferating. These include using electrons and holes, magnetic and electric dipoles, and smart metal alloys that take advantage of magnetocaloric, electrocaloric, thermoelectric, and electrocaloric properties. While none of these approaches yet meet commercial cost and performance requirements, they promise environmentally benign, safe, efficient heat pumps capable of serving a wide range of building and industrial markets.[24]

- Geothermal systems: The temperature two to three meters below the surface of the Earth(and large bodies of water) is usually significantly warmer than the ambient air in winter and cooler in summer. Heat pumps that take advantage of this differential can be more efficient and have a smaller architectural footprint than heat pumps exchanging heat with ambient air. To date, however, these "geothermal" systems have been too expensive to be competitive—particularly in retrofits—since trenching or drilling is typically required to install the pipes needed for the heat exchange.[25]

Beyond advanced heat pumps, various innovative technologies offer the potential for much higher efficiency. The options include mechanical systems (e.g., ultrasound), infrared, shock electrodialysis, electrostatics, and dielectrics. Heat is also used in separations that divide mixtures into components. The optimal drying technology will depend on the specific application; removing water from clothing is very different from removing it from a food product.[26] Drying technologies may also be integrated in hybrid systems that include pre-drying. Hybrid systems may improve system control and efficiency without compromising product quality. Alternatives to heat pumps for removing water from the air could also improve energy performance. [27] For instance, the use of membranes that selectively pass water vapor and not dry air could raise the efficiency of these processes. Nonthermal separation technologies could help prevent complex heat-sensitive molecules from undergoing side reactions.[28] Yet, despite the enormous potential benefits, research in this area has been virtually nonexistent.

Heat exchangers are often the most expensive and the bulkiest components of heating, cooling, and drying systems. Despite continuous improvements over the last several decades, many opportunities to further their performance remain. New materials and designs, as well as advanced manufacturing techniques, are enabling important optimization opportunities. In particular, large improvements in the air side of liquid-to-gas heat exchangers that do not appreciably increase costs or the rate of fouling could significantly enhance the effectiveness of these devices. Innovative industrial systems (including those that use advanced heat pumps to reach higher temperatures than today's units provide) must fit well into the broader production processes. They are just one important part. Advanced simulation and analysis tools and improved sensors and controls will be critical for designing and operating these systems

While DOE has supported heat pump and dehumidification technologies for decades, given their importance for meeting climate goals and expanding U.S. manufacturing, much greater investment is needed. Detailed roadmap and investment plans should focus on developing high-efficiency, low-cost, highly reliable heating, cooling, and drying systems for buildings and industry. It may be useful to establish ambitious, specific goals for heat pump cost and performance, such as a residential heat pump with a seasonal COP of at least 4.5 in all major U.S. climate zones with an installed cost of $1,000 per ton (or $1,500 per ton if the house lacks ductwork).

CATEGORY 6: CROSSCUTTING INDUSTRIAL DECARBONIZATION OPPORTUNITIES

Carbon capture and storage will be an essential crosscutting technology necessary to reduce and eliminate carbon emissions from a number of important industrial sectors, including those detailed above. Today, all operational CCS plants in the United States are on industrial applications. In particular, the use of CCS on ethanol plants, which have a much higher CO_2 concentration in their waste streams and thus a lower cost of capture, provides the opportunity to reduce or nearly eliminate emissions. CCS on iron and steel processes is also a critical area of RD&D due to the greater technical burdens of capturing CO_2 from a number of diffuse sources along the production process. Finally, CCS on cement production offers an opportunity to capture a relatively high concentration waste stream while reducing process emissions that are otherwise difficult to impossible to eliminate.

Limiting factors to widely developing CCS are numerous, including lack of adequate pipeline transportation, few developed onshore sequestration sites, developed commercial markets for captured CO_2, and remaining technical hurdles for retrofitting and installing CCS facilities onto industrial sites with space constraints. DOE has dramatically ramped up its efforts due to the Infrastructure Investment and Jobs Act of 2021 to spur a domestic CCS industry. In particular, a continued focus on industrial applications with small-scale pilots and continued RD&D efforts to improve capture from diverse points in the industrial production process will be key.

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