ACEEE
American Council for an Energy-Efficient Economy

POLICY BRIEF

"First Three": Providing Critical Support to New Low-Carbon Industrial Process Technologies

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The Need

Decarbonizing the industrial sector will require implementation of innovative process technologies to transform the way many products are produced. These technologies include new, lower-emission approaches to producing carbon-intensive materials in heavy industries such as steel, aluminum, chemicals, glass, cement, pulp and paper, and food manufacturing. The new process technologies would yield not only greenhouse gas (GHG) emissions reductions within industrial facilities but also enable production of new, lower-embodied-carbon products for society's use.

For example, in steel production a major source of carbon emissions is the production of iron from iron ore, which requires high temperatures and a reducing agent such as carbon. "Green" hydrogen (made using renewable electricity) can be used in place of coal or natural gas in direct reduction iron production, dramatically reducing GHG emissions and enabling primary steel production with electric-arc furnaces powered by renewable electricity.[1]

Direct use of electricity to produce cement offers a route where concentrated streams of carbon dioxide (CO_2) can be readily separated and sequestered or reused, and the hydrogen and oxygen generated could be used for beneficial purposes.[2] Alternative approaches to

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[1] J. Rissman et al. "Technologies and Policies to Decarbonize Global Industry: Review and Assessment of Mitigation Drivers through 2070," *Applied Energy* 266 (2020) www.sciencedirect.com/science/article/pii/S0306261920303603 and personal communications to N. Elliott by Cleveland Cliffs corporate executives, January 2021. Direct reduction iron production is discussed later in this paper. Primary steel production is a set of processes in which basic steel ingots (a basic steel product used to make final products such as pipes and beams) are produced from iron ore. Electric-arc furnaces are used to melt scrap and other steel, producing molten steel that can be used to form various steel products.

[2] L.D. Ellis, A.F. Badel, M.L. Chiang, R.J.Y. Park, and Y.M. Chiang, *Toward Electrochemical Synthesis of Cement—An Electrolyzer-Based Process for Decarbonating CaCO3 while Producing Useful Gas Streams* (2019). www.pnas.org/content/117/23/12584.

making concrete, such as the use of supplementary cement-like materials, are also attracting attention globally.[3]

The Energy Act of 2020

In December 2020, Congress passed the Energy Act of 2020, which among other provisions, in section 6003, includes an "Industrial Emissions Reduction Technology Deployment Program." This provision makes an early start in establishing a research, development, and demonstration (RD&D) program to increase the technological and economic competitiveness of U.S. technologies and manufacturing and to also achieve industrial sector emissions reductions. The provision lists many promising focus areas and authorizes a budget of $20 million in FY 2021, growing to $150 million in FY 2025. Given the immense scale of the challenge, far more support is needed to catalyze the development of transformative process technologies and most importantly to drive their demonstration at commercial scale.

To briefly summarize, the focus areas of the Energy Act of 2020 include support for

- Development of low-carbon technologies to be used in heavy industries
- Opportunities for GHG reduction for process heat
- Incorporation of approaches that apply to many industries, such as smart and sustainable manufacturing practices, sustainable chemistry, and energy efficiency
- Development and use of alternative, lower-carbon emitting materials
- Application of additional GHG reducing technologies, such as carbon capture, utilization, and storage (CCUS)

Additional information about industrial opportunities covered in the Energy Act of 2020 can be found in the appendix to this brief.

The Energy Act supports research, development, and demonstration projects in these areas, but does not support commercial-scale deployment. Therefore, a gap remains between pilot-scale demonstration projects and full-scale implementation of innovative industrial technologies. The U.S. Department of Energy (DOE) has worked extensively with industry for decades on research and development of new technologies and products, with an emphasis on reducing energy use and improving energy productivity. These efforts will increasingly shift their focus to decarbonization, aided by the Energy Act of 2020 provision noted above.

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[3] J. Lehne and F. Preston, *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete* (London: Chatham House, 2018) www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf.

However, once new technologies are developed, they are often considered too high risk for investment by potential adopting firms, making it challenging to convince companies to invest in initial, commercial-scale applications of these technologies, investments that can be $1 billion dollars or more for a single project. Assisting even one such project would require more funding than is authorized in the Energy Act of 2020, and ultimately many such projects will be needed to reach the government's decarbonization goals.

Proposed "First Three" Program

To fill this gap and aid this transition, we propose federal grants, loan guarantees, and/or tax credits for the first three installations at production scale of new technologies selected for their ability to decarbonize industrial processes. If a grant program, it would be run by DOE's Advanced Manufacturing Office (AMO). If loan guarantees, it would be a joint effort of AMO and DOE's Loan Program Office (LPO). If a tax credit, the Treasury Department would be the lead, but they would need substantial assistance from AMO. While each of these routes is possible, grants are preferable in our view because DOE staff would be able to monitor projects and could also make payments as project milestones are reached. For any of these routes we suggest the following elements:

Eligibility. The program would be open to new technologies for an industrial process that have been demonstrated as technically viable at pilot scale to reduce energy use or GHG emissions at least 20% relative to current technologies. Technologies with even greater reductions should receive preference, all other factors being equal. Assisted technologies should have the potential to reduce annual industrial consumption by at least 250 trillion Btu or reduce industrial sector GHG annual emissions by at least 15 million metric tons of CO_2 equivalent when fully deployed (these are about 1% of U.S. industrial sector annual energy use and GHG emissions). We suggest these 20% and 1% thresholds in order to focus on technologies that will have large impacts relative to current technologies (the 20% minimum) and to focus on sectors and subsectors that account for substantial energy use and emissions (the 1% minimum). Proposed projects would need to be at commercial scale, with details to be determined by DOE.

Screening. We suggest that individual companies or consortiums propose projects to DOE for consideration. Even if this is a tax credit, we still need technical experts to determine eligibility and the Treasury Department will need to work closely with DOE on technical issues. Proposals should be accepted once or twice a year and be screened by DOE with the aid of outside technical and market experts with knowledge of the sectors being targeted. DOE will have a fixed budget and will need to select projects that they determine have the best probability of achieving large GHG reductions by 2050. If there are several providers of a new technology, each would be eligible to apply. While up to three applications of a new technology would be eligible for assistance, each single project would need to apply and complete separately. Just because a first application of a project receives funding, there would be no guarantee that second and third projects would receive funding. These subsequent projects would need to compete on their own merits. Partners in second and third projects would likely be different to some extent from the first project as different sites would be involved.

Budget. We suggest an annual budget of at least $500 million per year and preferably $1.5 billion per year. The $1.5 billion per year figure is based on the fact that some of these commercial-scale plants can cost in the billions of dollars. Therefore, $1.5 billion, after considering industry cost shares, might allow two of these large projects to move forward each year. Appropriated funds should be available until expended. We recommend this program run for 10 years. Projects will often be large ($100 million and up) and be implemented over several years. If a grant program, project payments would generally be spread over several years. If tax incentives, the incentive would be earned upon project completion (or perhaps upon reaching significant project milestones); thus, the costs would be low the first few years but after several years would gradually use the early years' unspent budgets as projects are built.

Incentive Amount. We suggest that the amount of federal incentive be negotiated by DOE and capped at 60% of project cost for the first commercial installation of a new technology, including capital, construction, engineering and permitting costs.[4] This incentive could be grants and/or loan guarantees, with the value of the guarantee (and not the loan amount) charged against the 60% cap. Second and third installations of a technology should also be allowed to apply, with the maximum incentive capped at 45% of project cost for the second installation and 30% for the third installation from the same technology provider. These are maximum incentive levels, with DOE evaluating how much each project needs and often providing less than the maximum.

Importance of Learning. Part of the reason for federal support for new technologies will be so lessons learned from each project can be disseminated. Public dissemination of project results and lessons learned should be part of each project, with details negotiated on a project-specific basis in order to protect proprietary and competitive information of both the

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[4] A recent review found that for industrial demonstration projects, the global average public share was 64%. G. Nemet, V. Zipperer, and M. Kraus, "The Valley of Death, the Technology Pork Barrel, and Public Support for Large Demonstration Projects," *Energy Policy 119*, (2018): 154–167. www.sciencedirect.com/science/article/abs/pii/S0301421518302258.

technology provider and technology implementer while still providing the markets the knowledge required to advance other projects.

Illustrative Examples of Potential Projects

To achieve deep decarbonization of the industrial sector will require the deployment of transformative process technologies, in addition to expanded use of energy efficiency and renewable energy resources. Some of these technologies will have broad applications, such as the production and use at scale of low-GHG hydrogen in industrial processes, but many will be targeted at specific carbon-intensive industrial processes, such as the production of steel from iron ore, the manufacture of cement for use in concrete, and the production of aluminum using inert anode reduction.

LOW-GHG HYDROGEN

Hydrogen is an important feedstock in petroleum refining and ammonia production, along with smaller amounts used in industries such as metals production, methanol production, food processing, and electronics, with about 10 million metric tonnes produced annually.[5] Currently hydrogen is primarily produced from the reforming[6] of natural gas, which emits significant CO_2. In regional clusters, such as along the Gulf Coast, pipelines already exist for the transportation of hydrogen among plants.[7] ExxonMobil has announced its support for a Houston Hydrogen Hub.[8] In addition, hydrogen can be used in the future directly in other processes, such as iron reduction replacing natural gas or coal, and as a fuel to replace natural gas in boilers, engines, and furnaces, as well as for drayage applications such as forklifts.

Two paths are currently being developed for large-scale, low-GHG hydrogen production: electrolysis of water using low-carbon electricity, and steam reforming and autothermal reforming with CCUS.[9] Both technologies are capital intensive and not yet deployed at scale, facing challenges to integrate into existing hydrogen and fossil fuel infrastructure such as

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[5] DOE (Department of Energy), *Current Hydrogen Market Size: Domestic and Global* (2019). www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf.

[6] "Reforming" is the predominant current production process for hydrogen, in which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas.

[7] J. Vickers, D. Peterson, and K. Randolph, *Cost of Electrolytic Hydrogen Production with Existing Technology* (2020). www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

[8] G. Heynes, "Houston's Potential to Be a Key Hydrogen Hub Explored," Hydrogen Forward, July 1, 2021. www.hydrogenfwd.org/houstons-potential-to-be-a-key-hydrogen-hub-explored/.

[9] Vickers, Peterson, and Randolph 2020.

pipelines and storage. Significant expansion of the use of low-carbon hydrogen in production processes will require adaptation and integration with existing processes and means to store hydrogen. Therefore, this proposal would allow support for these initiatives to drive application of this low-carbon resource at commercial scale. Addressing these challenges may also require additional investments in dedicated infrastructure such as expanded pipelines and renewable generation to achieve reduction goals.[10]

LOW-GHG IRON PRODUCTION

Steel is pervasive throughout our economy—used in everything from packaging to vehicles to buildings to infrastructure. The U.S. is a global low-carbon steel producer in part because 70% of U.S. production is from electric-arc furnaces (EAFs) that largely make use of scrap, avoiding the need to produce iron from ore, which has been the most carbon-intensive aspect of steel production. While scrap is desirable as a feedstock, its use is limited by availability and the fact that some high-grade steel requires iron without the contaminants that are in scrap. Thus, it is important to shift from the blast and basic-oxygen furnaces, the traditional ways of producing iron, to new production methods that emit far less CO_2. Currently, two paths are being explored to produce low-carbon iron from ore: direct reduction and electrolysis.[11,12]

Direction reduction iron (DRI) uses a reactant such as natural gas or hydrogen to reduce the iron oxide to elemental iron, enabling carbon emissions reductions of 60% with natural gas and above 90% using primarily hydrogen.[13] Several DRI facilities are operating in the United States on natural gas, with a recently commissioned facility in Toledo built by Cleveland Cliffs designed to transition to hydrogen as it becomes commercially available at scale. This facility cost over $1 billion, with the transition to hydrogen requiring a large additional investment.[14]

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[10] J. Bartlett and A. Krupnick, *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions* (Washington, DC: Resources for the Future, 2020). media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf.

[11] C. Bataille, “Low and Zero Emissions in the Steel and Cement Industries: Barriers, Technologies, and Policies” OECD Green Growth and Sustainable Development Forum (2019). www.oecd.org/greengrowth/GGSD2019_Steel%20and%20Cemement_Final.pdf.

[12] A. Carpenter, *CO_2 Abatement in the Iron and Steel Industry* (IEA Clean Coal Centre, 2012). www.usea.org/sites/default/files/012012_CO2%20abatement%20in%20the%20iron%20and%20steel%20industry_ccc193.pdf .

[13] Bataille 2019; Bartlett and Krupnick 2020.

[14] Cleveland Cliffs. 2021. Toledo–Direct Reduction Plant (accessed July 2021). www.clevelandcliffs.com/operations/steelmaking/toledo-dr-plant.

Direct electrolysis of iron ore can be done either using a molten oxide at high temperatures (1,600°C) or in an aqueous bath at a low temperature (110°C). These processes, which are currently still at the RD&D stage, offer the potential to use less electricity than electrolytic production of hydrogen required for DRI.[15]

The iron produced by either process can then be used as a feedstock either alone or mixed with scrap for an EAF, which would have low carbon emissions if it operated on low-carbon electricity, as well as meeting the high standards required for some steel applications.

GHG REDUCTIONS IN PORTLAND CEMENT PRODUCTION

As with steel, concrete is ubiquitous throughout the economy—critical to buildings and infrastructure. A primary component in traditional concrete mixes is Portland cement, which binds the other components together, making the final product useful as a construction material. Unfortunately, the production of Portland cement emits large amounts of CO_2 due to fossil fuel combustion (to provide heat) and the release of CO_2 from the limestone in the calcination process.[16] Because this process emits so much carbon, carbon capture will be a key pathway to decarbonization of cement production.

While carbon capture technologies are advancing thanks to RD&D efforts, largely in the power sector, their application in industrial processes such as cement production faces several challenges, including the fact that many cement facilities are often co-located with limestone mining that are far away from CO_2 transportation and sequestration locations, as well as the unique configurations of individual plants that will require specialized designs. One of the most promising approaches is to use oxyfuel combustion to avoid diluting the exhaust gases containing the combustion and process-related CO_2 with air, resulting in a higher purity CO_2 stream, which improves collection efficiency. The shift to oxyfuel combustion, however, increases the installation and operating costs due to the need for onsite oxygen production; the need for a shift from coal to an alternative fuel such as natural gas, biogas or hydrogen; and the need for enhanced electric service to operate these

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[15] G.M. Cola, "Replacing Hot Stamped, Boron, and DP1000 with "Room Temperature Formable" Flash Bainite Advanced High Strength Steel." Proceedings of the 28th ASM Heat Treating Society Conference, p. 21-28, October 20-25, 2015; K. Thirumaran, S.U. Nimbalkar, A. Thekdi, and J. Cresko, *Energy Implications of Electro-Technologies in Industrial Process Heating Systems* (Oak Ridge National Laboratory, 2019). www.osti.gov/servlets/purl/1564150.

[16] A. Hasanbeigi and C. Springer, *Deep Decarbonization Roadmap for the Cement and Concrete Industries in California* (San Francisco: Global Efficiency Intelligence, LLC, 2019). www.climateworks.org/wp-content/uploads/2019/09/Decarbonization-Roadmap-CA-Cement-Final.pdf.

ancillary systems. Thus, these first applications will come with significant planning, engineering, and infrastructure requirements that increase the risks of these projects.

INERT ANODE ALUMINUM REDUCTION

Globally, aluminum production is a major contributor to GHG emissions. Fortunately, there are several proven steps to decarbonization through recycling and shifting to low-carbon electricity, since aluminum production is already dependent on electricity for its energy needs. However, even after these steps, a major source of CO_2 is still the process that reduces alumina to a pure metal required to produce some high-grade alloys and to meet the growing need for aluminum throughout the economy.[17]

The current aluminum reduction process uses sacrificial carbon anodes in the reduction process. These anodes emit CO_2 and also result in significant emissions in the production of the anodes themselves. A potential solution that has been identified for decades is transitioning to an inert anode that releases oxygen from the process rather than CO_2 and has an operating life that can be 30 times longer than the carbon anode.[18] While we have a technical solution, the scaling of production of these anodes and their integration into the reduction cells have proven technically challenging and costly. A joint venture between Alcoa and Rio Tinto has patented a new electrolytic smelting process called ELYSIS, which replaces the carbon anode with an inert anode that they are commercializing. ELYSIS has leveraged multiple funders, including Apple, Rio Tinto, Alcoa, and the governments of Canada and Québec, which are investing hundreds of millions of dollars to bring this technology, now poised for commercial deployment, to commercial scale.[19] These first deployments, mostly as retrofits of existing smelters, will require large investments in equipment, infrastructure, and integration to bring true commercial zero-carbon aluminum to the market.

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[17] Metal Bulletin, "Low-Carbon Aluminium Leads the Way to Product Sustainability" (2021). www.metalbulletin.com/Green-Aluminium-Center-Articles/Low-carbon-aluminium-leads-the-way-to-product-sustainability.html?Type=Channel&PageId=208371.

[18] Climate Technology Centre & Network, "Inert Anode Technology for Aluminium Smelters, Accessed July 28, 2021. www.ctc-n.org/technologies/inert-anode-technology-aluminium-smelters.

[19] ELYSIS, "Start of Construction of Commercial-Scale Inert Anode Cells" June 29, 2021. www.elysis.com/en/start-of-construction-of-commercial-scale-inert-anode-cells.

Appendix: Specific Industrial Technologies Covered in the Energy Act of 2020

- Industrial production processes, including technologies and processes that
    - Achieve emissions reductions in high-emissions industrial materials production processes, including production processes for iron, steel, steel mill products, aluminum, cement, concrete, glass, pulp, paper, and industrial ceramics
    - Achieve emissions reductions in medium- and high-temperature heat generation, including (1) through electrification of heating processes, (2) through renewable heat generation technology, (3) through combined heat and power, and (4) by switching to alternative fuels, including hydrogen and nuclear energy
    - Achieve emissions reductions in chemical production processes, including by incorporating, if appropriate and practicable, principles, practices, and methodologies of sustainable chemistry and engineering
    - Leverage smart manufacturing technologies and principles, digital manufacturing technologies, and advanced data analytics to develop advanced technologies and practices in information, automation, monitoring, computation, sensing, modeling, and networking, in order to (1) model and simulate manufacturing production lines, (2) monitor and communicate production line status, (3) manage and optimize energy productivity and cost throughout production, and (4) model, simulate, and optimize the energy efficiency of manufacturing processes,
    - Leverage the principles of sustainable manufacturing to minimize the potential negative environmental impacts of manufacturing while conserving energy and resources, including (1) by designing products that enable reuse, refurbishment, remanufacturing, and recycling, (2) by minimizing waste from industrial processes, including through the reuse of waste as other resources in other industrial processes for mutual benefit, and (3) by increasing resource efficiency
    - Increase the energy efficiency of industrial processes
- Alternative materials that produce fewer emissions during production and result in fewer emissions during use, including
    - High-performance lightweight materials
    - Substitutions for critical materials and minerals
- Development of net-zero emissions liquid and gaseous fuels
- Emissions reduction in shipping, aviation, and long-distance transportation
- Carbon capture technologies for industrial processes
- Other technologies that achieve net-zero emissions in nonpower industrial sectors

- High-performance computing to develop advanced materials and manufacturing processes, contributing to the focus areas described in the above provisions
- Incorporation of sustainable chemistry and engineering principles, practices, and methodologies