CLEAN AND COMPETITIVE:
OPPORTUNITIES FOR U.S. MANUFACTURING LEADERSHIP IN THE GLOBAL LOW-CARBON ECONOMY

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The United States needs an integrated national strategy to address the twin challenges of bolstering its manufacturing sector and averting climate change. Timely federal RD&D and deployment policies targeted to specific manufacturing industries could create comparative advantage, expanding domestic investment and employment.

KEY TAKEAWAYS

- Sincere efforts to fulfill national pledges to achieve net-zero emissions will drive a nearly complete retooling of global manufacturing.
- This retooling gives the United States a chance to rebuild domestic manufacturing while converting to clean production. To seize it, the federal government must act strategically and forcefully to leverage the nation's strength in innovation.
- Clean hydrogen production will become a core sector of the global low-carbon economy. Focused policies could enable significant domestic investment and job creation, both in the industry itself and in hydrogen-using industries like steelmaking.
- Next-generation heat pumps, novel drying technologies, and related innovations will be in high demand worldwide to cut emissions from buildings and low-temperature industrial processes. Smart, targeted policies could bring their production onshore.
- Clean chemical manufacturing will require innovations in recycling and bio-based production. A well-funded and coordinated national program could convert U.S. strengths in this industry into durable advantages and large rural investments.
- Biotechnology-based proteins could displace emissions from agriculture. The United States is a global leader in this emerging industry, and a robust federal policy could help secure that position.

INTRODUCTION

Majorities of Democrats and Republicans—in Washington, DC, and around the country—agree on the goal of rebuilding the nation's manufacturing sector. This sector has historically been a key job creator, with spillovers rippling across broad regions of the country and helping to lift many workers without a college education into the middle class. A strong manufacturing base creates a more resilient and equitable economy, accelerates innovation, strengthens international competitiveness, and improves national security.[1]

At the same time, a growing majority of Americans (along with the vast majority of scientists) are alarmed or concerned about climate change and perceive it to be an important priority for the federal government, although public opinion is less unified on this issue than on manufacturing.[2] If the world is to meet the targets set by the Paris Agreement, the United States, along with other major world economies, will have to reduce its greenhouse gas (GHG) emissions dramatically over the next three decades. The quest for net-zero emissions will touch every sector of the global economy.[3]

Until very recently, these two national challenges have been treated largely within their own policy silos. Policies that sought to address the decline in U.S. manufacturing were not motivated by or centered on the need to transition to a net-zero economy. Climate policies focused primarily on the electricity system, even though that sector accounts for only about 25 percent of total U.S. emissions, and devoted little energy to addressing manufacturing, which may soon become the largest emissions sector.[4]

Manufacturing must play a central role in any successful climate policy.

This division between manufacturing and climate policy is counterproductive for both, and it overlooks a crucial opportunity to create an integrated national strategy. From the standpoint of manufacturing, a net-zero commitment constitutes a requirement that many products and processes be upgraded or replaced with unprecedented speed. If managed effectively, this shift in demand could bolster U.S. manufacturing and disrupt global markets for end products, from electric cars to packaged goods, and for intermediate goods, such as construction materials and agricultural technologies. With such rapid capital turnover, lagging domestic industries may have a chance to retool and improve their competitive standing, and leading industries may be able to push further out in front. Climate policies could also open new markets for new products, several of which are explored in this report.

Symmetrically, manufacturing must play a central role in any successful climate policy. Ideally, domestic producers, with appropriate policy support, will find innovative ways to drive down the costs of new and reformulated products rapidly. If they fall short of this ideal, the nation may face difficult trade-offs, either lagging behind competitors that are able to shift to cleaner, cheaper production more quickly or bearing higher costs. These risks and costs could ultimately put at risk public support for policies driving the low-carbon transition. That, in turn, would impose on the world the very consequences that climate policy seeks to avoid.

While there is a clear basis for integrating U.S. climate and manufacturing policies, developing specific joint strategies that are effective and achievable requires much additional work. First, analysts must identify the broad panoply of low-carbon technologies needed for net-zero emissions and the pathways they are likely to follow in each market. Second, because no country will be self-sufficient in a low-carbon global economy, policymakers must identify industries that present the best opportunities to become successful domestic and global suppliers. Finally, all stakeholders, including the affected industries, must work together to develop policies that leverage entrepreneurship, public and private capital, and the U.S. ecosystem of universities, national labs, and firms of all sizes, to catalyze innovation.

This report seeks to take a first step toward creating an integrated manufacturing and climate strategy. Through a series of workshops and interviews as well as documentary research, we examined a broad swath of technologies in order to identify sectors in which the United States might find opportunities for domestic manufacturing with a high potential for economic growth and emissions reductions. While much more work must be done to fully develop an integrated strategy, the report illustrates the potential of pursuing this approach and the nature of the more detailed work that lies ahead.

The next section of the report discusses the nexus of manufacturing, climate, and trade policies in greater depth to flesh out the motivation for an integrated strategy that includes a focus on specific industries. It also briefly reviews the state of U.S. manufacturing as the global transition to a low-carbon economy gets underway in earnest.

The bulk of the report describes four industries that exemplify potential opportunities for U.S. competitive advantage in clean manufacturing and recommends policies that could realize that potential. These industries—hydrogen production; heating, cooling, and drying equipment; chemicals production and recycling; and protein alternatives to meat and dairy products—have received less attention from the policy community than many others. The report explains why each industry matters, sets out potential pathways to net-zero emissions, examines the comparative position of U.S. manufacturers, assesses opportunities and gaps, and lists policy recommendations.

This report is by no means the last word on this vast and complex subject. The opportunities it identifies are not the only ones out there. Better evidence may reveal flaws in its assessment of them. But if it accelerates the conversation that the United States must have at the intersection of climate and manufacturing policies, it will have succeeded in its task.

AN INTEGRATED CLIMATE-MANUFACTURING STRATEGY: SETTING THE STAGE

The Paris Agreement calls for the signatory nations to raise their ambitions for emissions reductions over time. Increasingly dire observations and forecasts, notably the Intergovernmental Panel on Climate Change's (IPCC) *1.5 Degree* report, have reinforced this imperative. As a new round of negotiations in the fall of 2021 in Glasgow approaches, 131 countries, covering 73 percent of global GHG emissions, have adopted or are considering net-zero targets. President Joe Biden has proposed that the United States join the nations of the European Union, Japan, South Korea, and others targeting net zero by 2050, while China has pledged to hit that target by 2060.[5]

Fulfilling such pledges will require significant progress across the entire landscape of emissions, including industrial emissions, which account for more than 30 percent of the U.S. and global totals. Major industries for which there are currently few feasible solutions and even fewer cost-effective ones, such as steel and chemicals, must be targeted for innovation, scale-up, and deployment in the coming three decades. Indeed, the drive to reduce industrial emissions will be so pervasive that it will amount to a nearly complete retooling of global manufacturing.

Opportunities to create new manufacturing industries that reduce or offset emissions in other sectors, including industry and agriculture as well as transportation and electricity, are also emerging. As we detail, biotechnologies have the potential to displace emissions from livestock, a major source of agricultural emissions that is set to grow rapidly as increasingly affluent societies consume more meat and dairy products. Heat pumps and related equipment must be manufactured to enable building and industrial electrification. In addition, to offset those slices of the emissions pie that prove to be intractable, negative emissions technologies such as direct air capture will need to be manufactured and deployed at scale.

U.S. Manufacturing at a Crossroads

The looming transformation of global manufacturing comes at a challenging moment for the United States. China's emergence as the world's factory, along with determined efforts by manufacturing powers such as Japan and Germany to sustain their industries, shrank the U.S. share of global manufacturing activity from 28 percent in 2002 to 18 percent in 2016. Real manufacturing value added fell by 20 percent as a share of the U.S. economy between 2007 and 2019 (from 12.1 percent to 9.7 percent), once the statistical overstatement of output growth in the computer industry is corrected. U.S. manufacturing employment fell off a cliff during the 2000s and recovered more slowly than the rest of the economy in the ensuing years; it now accounts for just 8.5 percent of the workforce.[6]

To remain strong economically, the United States needs to rebuild its manufacturing sector. The sector's small share of the workforce is deceptive. Each manufacturing job generates about five to seven others in the supply chain and through spillovers, far more than a comparable job in the service sector.[7] Manufacturing is intimately connected with innovation as well. Manufacturing firms account for the vast majority of private research and development (R&D) spending and patents in the United States.[8] And manufacturing is crucial to the U.S. position in the global economy. Goods far exceed services in international trade, and the United States' weakness in manufacturing contributes greatly to its chronic trade deficits.[9]

Seizing the Opportunity

U.S. policymakers must therefore fashion an integrated response to both the climate imperative and the manufacturing challenge. A manufacturing policy that fails to trigger radical emissions reductions could lead to the United States' increasing economic isolation and worsening competitiveness if the rest of the world shifts toward clean production. Worse, such a policy could undermine global progress toward net-zero emissions, while leaving the United States far short of that goal.

This moment of challenge is also a moment of opportunity. History teaches that transformations in the core technologies and business models of major industries can radically alter the international competitive positions of companies, regions, and nations. The rise of the German chemical industry in the late Nineteenth century, which fused science and engineering for the first time, foreshadowed the decline of British economic hegemony. In the 1970s, Japanese auto firms challenged Detroit's "Big 3" and became symbols of "Japan as #1" by implementing new production methods and winning over new markets opened by the oil crisis. China today recognizes that the replacement of internal combustion vehicles with electric vehicles could shake up the global auto industry once again.[10]

The United States should seize the opportunity to alter the trajectory of its manufacturing sector while converting it to clean production. To do so, it must leverage the nation's most valuable asset: its strength in science and technology. Although other nations, including China, lead the world in specific domains, including important areas of manufacturing, the United States remains at the core of the global innovation system, with the broadest array of strengths. The United States invests more in R&D than any other nation in absolute terms and remains the preferred destination for many of the world's brightest scientists, engineers, and technology managers.[11]

Acting Strategically

U.S. leadership in these input indicators for discovery and innovation, however, does not always translate into meaningful outputs, such as emissions reductions or domestic manufacturing jobs. Scaling up an innovation to commercial production can cost hundreds or thousands of times more than proving it at the laboratory bench. Many promising ideas expire in the "commercialization valley of death" because they are unable to secure scale-up financing from investors who prefer to put their money in safer, more "bankable" deals.[12]

Many other U.S.-devised innovations are scaled up elsewhere in the world, where investors are more patient and governments underwrite some of the risk. Complex, capital-intensive hardware technologies, including manufacturing systems, are particularly prone to this "innovate here, produce there" pattern, as William B. Bonvillian has labeled it. Mercantilist policies, especially those of China, including state-sponsored industrial espionage and forced technology transfer, have amplified the pattern, while further deterring U.S. investors. Meanwhile, the U.S. economy has emphasized financialization over investment in productive capacity.[13]

Policymakers will need to carefully target federal investment toward industries and technologies wherein domestic producers are most likely to succeed against international competitors.

To make the most of the clean manufacturing opportunity, the federal government will have to act more strategically and forcefully than it has in the recent past (outside the realm of national defense, which even today accounts for about half of federal R&D funding). It must adopt policies that have comparatively long time horizons and pursue them consistently. Federal policymakers must implement methods to ferry innovations across the valley of death, by providing timely public support for technology demonstration and early deployment, in collaboration with private sector partners.

Crucially, policymakers will need to carefully target federal investment, concentrating resources on industries and technologies wherein domestic producers are most likely to succeed against international competitors. "Advanced industry and technology strategies," as the Information Technology and Innovation Foundation's (ITIF) Robert D. Atkinson calls this approach, are not monolithic central plans.[14] They engage industry, labor, the states, and communities around the country to play important roles with significant autonomy, and they mobilize the awesome power of markets to inspire innovators and rapidly scale up innovations.

An Evolving Climate of Opinion

Atkinson points out that the United States has implemented advanced industry and technology strategies in one form or another since the 1st Congress established federally owned munitions factories in 1799. Since the Korean War, such strategies have been justified primarily on national security grounds and funded through the Department of Defense (DOD).[15]

But mainstream opinion within both political parties is evolving. Biden administration economic advisor Brian Deese has alluded to both climate change and Chinese competition in touting his new “openness to … targeted efforts to try to build domestic industrial strength.”[16] On the other side of the aisle, while not endorsing the climate justification, Republican Senator Marco Rubio of Florida has stated that “existing characterizations of ‘industrial policy’ do not apply cleanly in the 21st century” and has called for revising U.S. policy to support high-wage manufacturing in response to state-subsidized competition from China.[17] And, as David Adler chronicled, Operation Warp Speed, the crash program that led to the development of vaccines for COVID-19, is a very recent example of a highly successful drive led by the federal government not only to create new products but rapidly bring them to scale.[18]

Complementary Economy-Wide Policies and New Capacities

It is important to note that advanced industry and technology strategies complement smart policies that have an impact across the entire economy. The success of the former depends on the success of the latter, such as education and training and infrastructure policies.

Advanced industry and technology strategies can be fully compatible as well with a rules-based global economy. International trade (along with international cooperation in many areas of R&D) is vital to improve efficiency and foster innovation. National strategies must be constrained by global rules to avert unfair competition from state-subsidized firms. (Ironically, China’s failure to abide by the rules since its accession to the World Trade Organization helped precipitate the changing political mood in the United States.)

Economy-wide climate policies such as carbon pricing and border adjustment mechanisms bear a similar relationship to clean manufacturing strategies that the “framework” policies previously described do to advanced industry and technology strategies in general. These policies are necessary to ensure that innovation in clean manufacturing accelerates to meet global competition and sustain domestic jobs, but are far from sufficient.[19]

The United States appears to be moving toward adopting advanced industry and technology strategies, but it is far from being prepared to carry them out. The federal government lacks the detailed information and specialized analytical capabilities it will take to make such strategies effective. Yet, neither the climate nor international competition will wait. We have to do the best we can to finish building the plane while we taxi down the runway and prepare for takeoff.

PRELIMINARY SCREENING OF HIGH-OPPORTUNITY SECTORS

Atkinson’s framework for devising national advanced industry and technology strategies sets out four criteria for selecting industries to support. One is intrinsic to this project: the industry must contribute to the achievement of key national goals, in this case averting climate change while securing U.S. manufacturing. We have relied primarily on another of Atkinson’s criteria to identify prospects: whether the United States has some potential for success because of its existing assets and strengths. Our research sought expert opinion to gain insights into these assets and strengths and to shed light on Atkinson's final two criteria: whether active government policy support would dramatically strengthen the industry's performance, and whether the industry wants such support and is willing to share the costs of the effort.

We gathered this information through three major activities. First, we carried out an extensive review of the academic and trade literature. Second, we conducted over 40 interviews with experts in industry, government laboratories, and academia to learn about emerging technologies, stakeholder efforts, and existing and potential policies.

Third, we organized a series of four expert workshops, which brought together scientists, engineers, industry leaders, and representatives of nongovernmental organizations that are working on new industrial processes with high emissions-reduction potential. (Appendix A lists the speakers and participants at the workshops.) Each workshop was built around a technological challenge common to several industries:

- High-temperature heat: A wide variety of chemical and metallurgical processes require large quantities of heat above 150 degrees Celsius.
- Low-temperature heat: Heating and cooling buildings, agricultural and food processing, and papermaking are among the sectors that use heat below 150°C.
- Bio-manufacturing: Food, chemicals, and fuels might be made through biotechnology-based processes with much lower emissions than current production methods.
- Alternative material solutions: Engineered materials with dramatically improved functionality made using low-emission, low-cost methods may substitute for traditional materials.

The next four sections, which highlight specific industries worthy of serious consideration in a U.S. advanced industry and technology strategy, reflect our synthesis of insights from these workshops, along with gleanings from the literature and interviews. They do not represent a consensus among the workshop participants, and we fully recognize that deeper empirical analysis and stakeholder engagement, which we plan to carry out in the next phase of our project, will be required in order to assess them more fully.

OPPORTUNITY: HYDROGEN PRODUCTION

Hydrogen, the lightest element, is a versatile energy carrier with the potential to perform many functions in a low-carbon economy. It is already in wide use as an input to the chemical and refining industries. This use could be extended into combustion for heat or electricity generation as well as making synthetic fuels. Hydrogen can be used as well in fuel cells that produce electricity through chemical processes to power vehicles or other equipment. And it can function as a stable energy storage medium, residing indefinitely in a tank or cavern until its energy is needed.[20]

Hydrogen's versatility leads many energy and climate experts to expect that its production, transport, storage, and use will become core economic sectors in the not-too-distant future. Right now, though, hydrogen production is very carbon-intensive, emitting on a global basis as much as the United Kingdom and Indonesia combined (equivalent to about 830 million metric tons of carbon dioxide (MMT CO_2-e) per year).[21] Hydrogen production must therefore be decarbonized regardless of whether the element's emerging end uses scale the way experts foresee. Its potential to decarbonize other sectors will only be realized if hydrogen production itself is cleaned up. Combustion of hydrogen, especially when blended with natural gas, may raise local air pollution concerns that must be addressed as well.[22]

Why This Industry Matters

The United States currently produces about 15 percent of the world's hydrogen (about 10 MMT per year). The primary domestic end uses are oil refining and fertilizer and biofuel production.[23] A majority of U.S. production is "captive;" in other words, it is produced by the user at the site of use, such as a fertilizer plant or oil refinery. "Merchant" hydrogen is made at a central facility and delivered to customers by pipeline, tanker, or truck. The U.S. market for merchant hydrogen exceeds $4 billion annually and is growing about 7 percent per year.[24]

This market could grow dramatically if hydrogen becomes a major input for hard-to-decarbonize sectors. A recent National Renewable Energy Laboratory (NREL) report estimates that the technical potential for hydrogen use in the United States is an order of magnitude larger than today's, about 106 MMT per year, across a range of industrial, transportation, and storage applications.[25] An "ambitious" scenario in an industry roadmap finds that hydrogen demand in the United States could grow to 17 MMT per year by 2030 and 63 MMT per year by 2050, results that are consistent with several scenarios in Princeton University's Net-Zero America Project.[26]

An expansion of this magnitude would provide a significant opportunity for the United States. The industry roadmap estimates that it would generate $140 billion annually across the value chain in 2030. Like many other capital-intensive energy infrastructure sectors, hydrogen production on this scale would create many high-skill, high-wage jobs. However, like other climate solutions, the expansion of hydrogen use may also displace existing jobs, including some in the domestic natural gas industry, which employs over 600,000 people.[27]

Pathways to Clean Hydrogen Production

Two major pathways to clean hydrogen production emerge as the most promising from the modeling literature. The first, sometimes called "blue" hydrogen, applies carbon capture and sequestration (CCS) technology to methane reforming, the dominant production process today. The second, labeled "green" hydrogen, uses electrolysis to split water, drawing on electricity generated from low-carbon resources. (A third pathway, bio-based production, has been developed, but studies such as NREL's H2@Scale find that it will likely play a negligible role in any future net-zero system, so we do not treat it here.[28])

Each pathway combines a hydrogen feedstock (methane or water) and a conversion technology (reforming or electrolysis). This section focuses on the potential for innovation in conversion technologies. However, the viability of either production method will also hinge on the cost and availability of the feedstock as well as the price of energy used in conversion, which are beyond the scope of this report.

Methane reforming uses natural gas as its main feedstock. There are two types. One, steam methane reforming (SMR) uses steam to provide the heat and pressure needed to extract hydrogen from methane. The other, autothermal reforming (ATR), relies on carbon monoxide to react with the methane to release hydrogen as well as heat. Both types of methane reforming emit large volumes of carbon dioxide, which may be captured with chemical or physical techniques. If the captured carbon dioxide is permanently sequestered, GHG emissions from hydrogen production would be dramatically reduced, although methane emissions may persist due to leakage in natural gas production, transmission, and processing. Although SMR is cheaper than ATR without CCS, ATR is cheaper than SMR with CCS, because it produces a more concentrated stream of carbon dioxide. Most models of net-zero pathways therefore prefer this method for blue hydrogen production.

Electrolysis splits water molecules into their elemental constituents: hydrogen and oxygen. The use of electricity from a source such as a nuclear or renewable power plant makes it "green." There are three main types of electrolyzers: alkaline, proton exchange membrane (PEM), and solid oxide electrolysis cells (SOECs).[29] Alkaline electrolyzers are the most mature of the three, with relatively long lifetimes and low capital costs, but opportunities for further cost reduction and performance improvement along this pathway appear limited. Alkaline electrolyzers also require more space than the other types. PEM electrolyzers, by contrast, currently have higher capital costs and shorter lifetimes than alkaline electrolyzers, but they are more compact and easier to integrate with variable power sources such as renewables. Experts generally agree that PEM electrolyzers have the potential to improve rapidly.[30] SOECs are an emerging technology that require further R&D to become commercially viable.[31]

Figure 1: Hydrogen production costs by method[32]

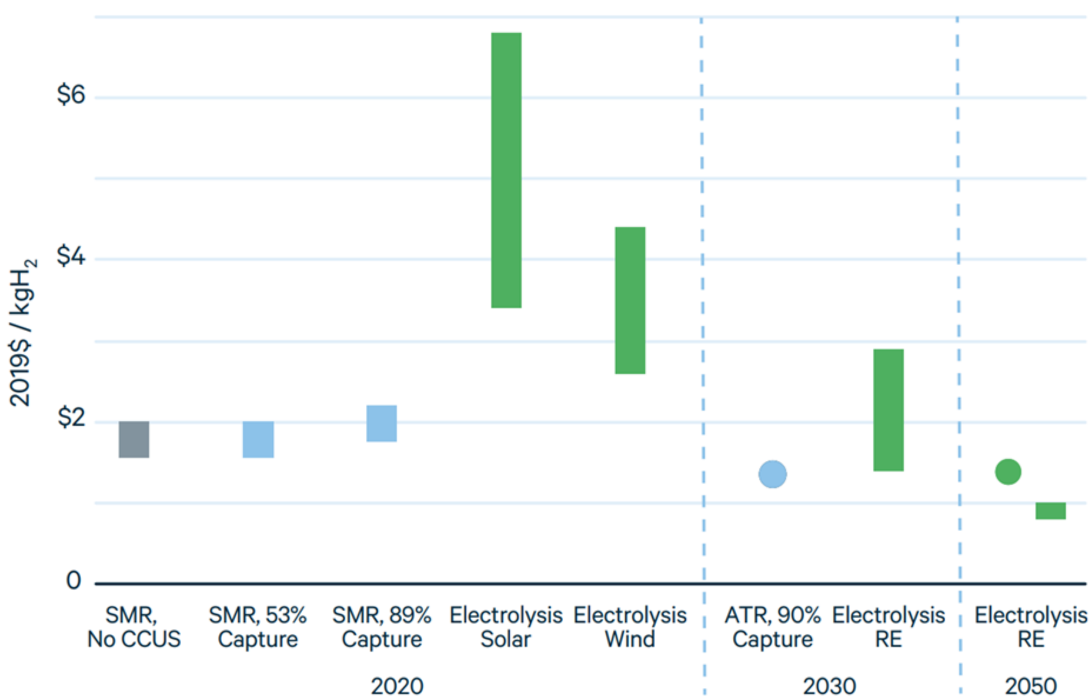


Figure 1 (drawn from work by Resources for the Future) compares the unit costs of hydrogen production in the United States (not including the social costs imposed by pollution) using various methods now and in the future. Blue hydrogen (SMR with 89 percent carbon capture) cost about $2 per kilogram in 2020. Green hydrogen, whether relying on solar or wind power, is far more expensive today. But, according to this model, the gap is expected to close considerably by 2030 and disappear by 2050.

It is worth noting that hydrogen can be efficiently transported as ammonia (a molecule composed of nitrogen and hydrogen). Ammonia is an important industrial feedstock in its own right, especially for fertilizer production, and it may be used as a fuel. Adding ammonia to the hydrogen value chain involves another layer of conversion technology, with its own technical, environmental, and cost challenges—but also the potential to further expand domestic manufacturing opportunities.

U.S. Positioning and Capabilities

The United States has historically been a world leader in the development and deployment of hydrogen production technologies. Over the past 20 years, the Department of Energy (DOE) has invested more than $4 billion in hydrogen production, delivery, storage, and conversion technologies, including fuel cells and turbines. This investment has resulted in over 330 U.S. patent applications for hydrogen production and delivery technologies alone, aiding cost declines in electrolyzer technologies.[33]

The DOE office that has funded most of this work, the Hydrogen and Fuel Cells Technologies Office, is a unit within the department's Vehicle Technologies Office, and its work has focused heavily on transportation end uses. Although some forms of heavy-duty transportation may ultimately shift to hydrogen fuel cell propulsion, battery electric vehicles seem likely to dominate the light-duty market (cars, SUVs, and pickups) in the coming years. End uses that are more likely to grow have received relatively less attention from DOE in the past, as has hydrogen production.

Partly as a result of this focus, U.S. hydrogen policy has lagged behind just as demand for clean hydrogen is beginning to ramp up dramatically. Many high-income countries have adopted national hydrogen strategies and are coupling production targets with investments and incentives to catalyze near-term deployment and scale-up. The European Union, for example, plans to deploy 6 gigawatts (GW) of green hydrogen electrolyzers by 2024, rising to 40 GW by 2030. Australia, which is moving to utilize its vast renewable resources and strategic position relative to Asian customers to become a major hydrogen exporter by 2030, is another case in point.[34]

Blue Hydrogen: World Leadership, For Now

Although it lacks a national target, the United States is a world leader in blue hydrogen production. Four U.S. facilities that make hydrogen via methane reforming and capture the resulting carbon dioxide emissions are in operation. They include a refinery in Texas and fertilizer plants in Kansas, Louisiana, and Oklahoma. The Great Plains Institute has identified 34 hydrogen production facilities and 3 ammonia facilities—which together emit over 15 MMT of carbon dioxide per year—as potential near-term candidates for carbon capture retrofits. Congress has incentivized blue hydrogen production with the 45Q tax incentive, which provides a credit of $35 or more for each ton of carbon dioxide a facility permanently sequesters.[35]

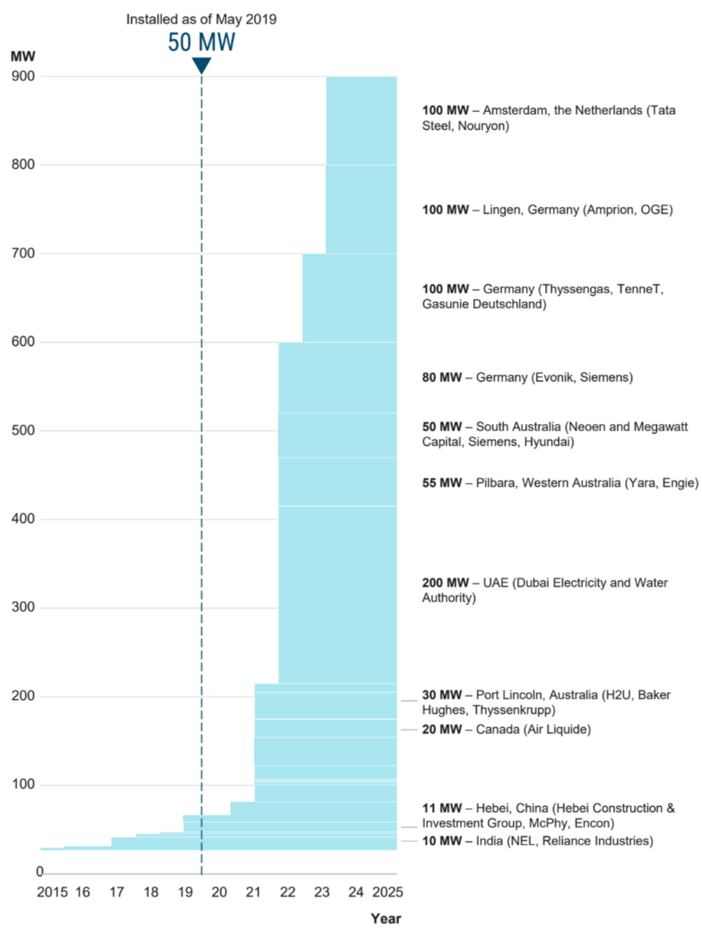
With an abundance of near-term opportunities for carbon capture, cheap natural gas, large reservoirs for underground sequestration, and a relatively mature policy framework, the United States has many of the ingredients needed to maintain its lead. Nonetheless, key barriers remain. Captive hydrogen producers have no incentive to retrofit their facilities with carbon capture in the absence of a policy that fully addresses the high cost of cleaner production. Merchant producers face the same cost differential and also lack a mechanism to distinguish clean from dirty hydrogen in sales. All producers face infrastructure barriers, particularly access to pipelines that will carry captured carbon dioxide to sequestration sites. The existing hydrogen pipeline system is modest and concentrated in a few regions, such as the Gulf Coast. Fugitive emissions could offset reductions if the natural gas and carbon dioxide pipeline systems are not well maintained and operated. Given these barriers, the U.S. Fuel Cell and Hydrogen Energy Association (FCHEA) finds that the 45Q tax incentive alone may stimulate only a few projects.[36]

Green Hydrogen: Back in the Pack

The United States is less well positioned for green hydrogen production than it is for blue, although it is home to several leading electrolyzer and hydrogen component and system manufacturers as well as large multinational hydrogen producers. The largest announced domestic project for green hydrogen is a partnership between Nel (a Norwegian hydrogen company) and Nikola (a U.S. designer of zero-emissions trucks) that will supply 1 GW of electrolyzers to 30 hydrogen fueling stations across the country.[37]

Developments abroad, particularly in Europe, account for the majority of electrolytic hydrogen capacity planned by 2025, as figure 2 shows. These plans aim to support the scale-up of electrolyzer manufacturing and de-risk investment in the supply chain. John Parnell of *Greentech Media* noted in February 2021 that, spurred on by targets set by the EU and its member states, “major [European] utilities like RWE and Iberdrola have joined oil majors Shell, BP and Total in developing substantial early-stage green hydrogen projects.”[38]

Figure 2: Global installed/expected capacity of electrolyzers[39]



Opportunities and Gaps

Although blue hydrogen production technology has not been widely deployed, the low cost of natural gas and the availability of existing hydrogen production facilities for retrofit make this technology an attractive near-term opportunity in the United States. As figure 1 suggests, green hydrogen may overtake it on a cost basis over the longer run. Market analysts, including Bloomberg New Energy Finance, IHS Markit, and Wood Mackenzie, find that the unit costs of blue and green hydrogen will be roughly comparable by 2030. Declining capital costs of electrolyzers, improvements in conversion efficiency, and cheap electricity generated by renewables are likely to give green hydrogen the edge in the ensuing decades.[40] Demand for hydrogen is also rising rapidly, as governments and businesses increasingly turn to it to cut emissions. Taken together, falling costs and rising demand for clean hydrogen should spur greater deployment and investment in hydrogen production technology and its supporting supply chain.

How much of this investment occurs in the United States will depend on bridging gaps in support for technology scale-up and integration. The federal government has supported R&D with grants on the order of $1 million–$2.5 million per project, but this scale is too small to demonstrate and validate low-cost, high-volume production. Other countries are already investing large sums in commercial-scale demonstration projects, which are intended to attract even greater private sector investment. For example, the state of South Australia has put the equivalent of US$26 million (out of a total project cost of $173 million) into the world's largest green ammonia plant, including a 75 MW electrolyzer.[41] Similarly, the EU and many of its member states are making major investments in the electrolyzer supply chain as well as in prototype and demonstration production plants.[42]

Policy Recommendations for Spurring Clean Hydrogen Production

A federal policy agenda for clean hydrogen production should set ambitious cost reduction targets and prioritize research, development, and demonstration projects aimed at realizing these targets. The federal government should also support deployment by encouraging its own agencies to become early adopters of clean hydrogen and enacting policies that bridge, narrow, and ultimately eliminate the cost differential between dirty and clean hydrogen. Key steps include:

Research and Development

- Shifting the focus of DOE's Hydrogen and Fuel Cells Technology Office away from light-duty vehicles and toward hydrogen production and end-use applications in hard-to-abate sectors, such as industry, energy storage, and heavy-duty transportation. The office's authorization should be expanded to include these applications.[43]
- Increasing appropriations for R&D funded by DOE's Hydrogen and Fuel Cells Technology Office by 150 percent over five years. This investment should be embedded in a broader effort to build strong linkages across DOE's hydrogen innovation pipeline from basic research supported by the Office of Science on one end to commercially oriented demonstration projects managed elsewhere in DOE or by other federal agencies on the other.[44]

- Working with industry and state and local governments to establish a new Manufacturing USA innovation institute to carry out cost-shared R&D on PEM electrolyzer manufacturing and systems integration. Such an institute could support problem-solving projects of broad interest across the hydrogen value chain, provide shared infrastructure, and develop programs to train skilled workers and support small and medium manufacturers.

Demonstration

- Authorizing and providing public funding for a portfolio of pilot- and commercial-scale demonstration projects or clean hydrogen "hubs" that are cost-shared with private investors and operated by commercial firms. These projects could encompass both blue and green hydrogen production in a range of configurations as well as diverse end uses, informed by a strategic analysis of the competitive advantage of U.S. locations.[45]
- Authorizing and encouraging federal agencies to become early adopters of clean hydrogen by executing long-term contracts to buy the output of demonstration projects. DOD and the General Services Administration (GSA), for instance, manage large fleets of buildings and heavy-duty vehicles that might be converted to hydrogen technologies in the coming decades.
- Trialing a contract-for-differences model to support demonstration projects. This model would create a bidding process to establish the lowest price that clean hydrogen producers are willing to offer and then fund the difference between that price and the market price for high-emissions hydrogen.

Deployment and Market Expansion

- Adopting a "Moon Shot" production cost target for clean hydrogen of $1 per kilogram, with additional specific cost targets for storage and distribution. That level is 50 percent lower than the current DOE target and the current price of dirty hydrogen and in line with market-based projections of green hydrogen production costs in 2050 (see figure 1).[46] (Just as this report went to press, DOE announced a target of $1 per kilogram for clean hydrogen by 2030.[47])
- Establishing production tax incentives (beyond the existing credit for hydrogen fuel cells) that are authorized through at least 2035, are eligible for some form of direct payment, are received by producers based in part on the amount of hydrogen produced, and have maximum life-cycle carbon-intensity limits for eligibility, with greater incentives for cleaner production methods.[48]
- Expanding the range of hydrogen production, infrastructure, and end-use technologies that are explicitly eligible for assistance from the DOE Loan Programs Office. Loans, loan guarantees, and other federal assistance can help worthy borrowers that are not able to secure full financing from risk-averse private lenders to establish the "bankability" of clean hydrogen production.[49]

Innovation Ecosystem and Technical Assistance

- Expanding initiatives to evaluate the potential of the existing natural gas infrastructure to transport hydrogen, while controlling local air pollution as well as GHG emissions. Blending modest amounts of hydrogen with natural gas could allow the existing infrastructure to serve as a bridge to a dedicated hydrogen infrastructure as volumes rise over the longer term.[50]
- Ensuring that federal safety standards for hydrogen pipeline and distribution systems are adequate, and developing standards and guidance for the safe integration of hydrogen, ammonia, and other hydrogen carriers with industrial, heating, transportation, and other end-use infrastructure. Hydrogen is corrosive as well as inflammable, and any dramatic expansion in its production, transportation, and use will entail risks that must be managed.[51]
- Updating measurement and improving modeling of the hydrogen value chain across production pathways, including both merchant and captive producers. Significant gaps mar the current understanding of job and value creation in this rapidly changing industry.[52]

OPPORTUNITY: HEATING, COOLING, AND DRYING EQUIPMENT

Heating, cooling, and dehumidifying buildings, and the provision of low-temperature heat to industrial processes for drying, separations, and other purposes, are responsible for significant GHG emissions. The firms that make the equipment that provides these services are major employers. The installation and maintenance of these systems also support jobs throughout the country. Climate policy may lead to rapid growth in demand for their products and services.

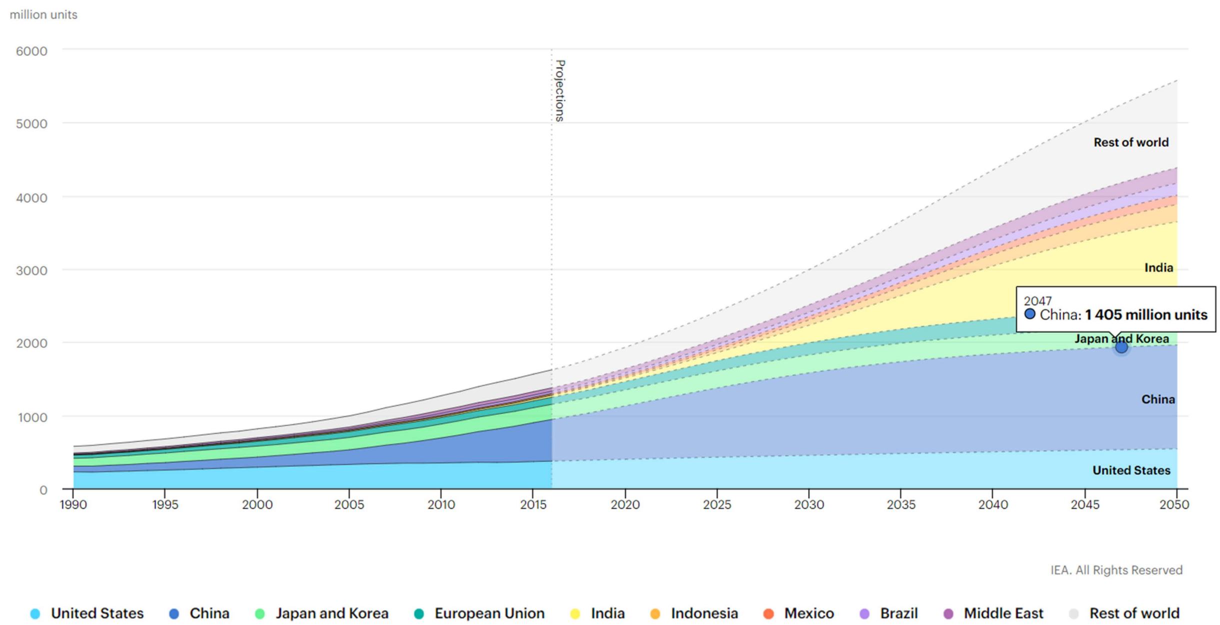
Why This Industry Matters

Heating, clothes drying, and water heating consume about 12 percent of all U.S. energy, and about 3 percent more is used to dehumidify air in the process of cooling residential and commercial buildings.[53] Another 4 percent is used in the chemicals, refining, paper, and food industries in processes that use heat at temperatures below 150°C. A rough estimate suggests that about 16 percent of U.S. emissions arise from systems that require temperatures that could be provided by heat pump technologies.[54]

At the global level, income growth, climate change, and climate policies are likely to sharply increase demand for heating, cooling, and dehumidification in buildings in the coming decades. It is abundantly clear that people desire these services. Air conditioning, for instance, is one of the first purchases households make when their incomes rise enough to afford it. While 90 percent of U.S. and Japanese households have air conditioning, only 18 percent do in Mexico and Brazil, and just 5 percent in India.[55]

Moreover, climate change is raising average temperatures and humidity in the most populated parts of the world, which will accelerate demand (see figure 3). According to the International Energy Agency (IEA), “Cooling is the fastest growing use of energy in buildings.... Without action to address energy efficiency, energy demand for space cooling will more than triple by 2050—consuming as much electricity as all of China and India today.”[56]

Figure 3: Projected demand for cooling[57]



Like the global demand for cooling, energy use in industrial processes that use low-temperature heat is growing rapidly. 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.[58] Figure 4 lists some of the most common industrial processes to which innovative electricity-powered heating, cooling, and drying technologies might be applied.

Figure 4: Common industrial low- and medium-temperature processes[59]

Process	Temperatures (°C)	Subsectors
Washing	40–90	Food and beverage, agro-industry, textiles
Cooking	60–100	Food and beverage, paper
Pasteurisation	60–80	Food and beverage
Sterilisation	60–90 100–120	Food and beverage Agro-industry
Distillation	140–150	Food and beverage, plastics, pharmaceuticals
Drying	60–100 100–130 120–200	Wood, paper Textiles Agro-industry, plastics
Bleaching	60–100 130–150	Textiles Paper
Sanitary hot water	40–80	Food and beverage, pharmaceuticals, mining
Boiler feed water	60–90	Agro-industry, paper, textiles, chemicals

The 2020 Princeton Net-Zero America study estimates that spending for new heating, cooling, and drying equipment could increase by $160 billion–$180 billion over the next decade.[60] Firms manufacturing residential and commercial heating, refrigeration, and air conditioning equipment employ about 128,000 workers today at a mean wage of $46,690.[61] Installation and maintenance of this equipment employs another 344,020 workers at a mean annual wage of $53,410.[62] (These figures do not include indirect or induced jobs.)

Pathways to Net Zero

It is unlikely that on-site emissions associated with distributed heating and cooling can be captured and sequestered at a competitive cost for any but the largest facilities. The most likely emissions solutions for many locations will therefore be devices powered by zero-carbon electricity, such as heat pumps.[63] These devices will probably predominate for residential and commercial space heating and cooling and hot water equipment, and may also play a significant role in providing heat to and removing water from low-temperature industrial processes. (However, some of these applications may prove to be better-suited to combustion equipment powered by zero-carbon fuels.)

Heat Pumps

Heat pumps are among the most versatile devices for heating, cooling, and drying (see box "What Is a Heat Pump?"). Although their basic principles were introduced in 1803, heat pumps have progressed rapidly in the past decade. Recent innovations have improved their performance in cold weather and incorporated variable-speed motors that provide high performance across a wide temperature range.[64] Researchers have identified new refrigerants that promise to boost efficiency further in small units.[65]

What Is a Heat Pump?

A heat pump is a device that removes thermal energy from a cooler material (such as the air in a room) and transfers ("pumps") it to a warmer material (such as the air outside of a building). An air conditioner is a heat pump that pumps heat from a cooler indoor space to a warmer outdoor space. During the heating season, a heat pump system can be reversed to remove heat from outdoor air and pump it indoors. Heat pumps require energy to transfer heat, and most today use electricity to power a compressor that moves refrigerant between the warmer and cooler spaces. Refrigerants typically change from a liquid to a gas in the process. The refrigerant releases heat when it condenses from a gas to a liquid and absorbs heat when it evaporates from a liquid to a gas. Innovative heat pump systems under development use alternatives to refrigerants to move heat, such as materials that absorb and release heat when magnetic or electric fields are applied or released or when the material is flexed. The efficiency of a heat pump is measured by the ratio of the heat energy moved to the electric energy consumed; typical commercial refrigerant-based heat pumps transfer approximately three units of energy for each unit of electricity consumed, which is about a third of their theoretical maximum efficiency.

If the federal government adopted policies that all space heating in U.S. residences were to be provided by heat pumps by 2050, heat pump sales would increase by a factor of six. Heat pump water heater sales would need to increase by even larger factors since they represent only about

1 percent of current water heater sales.[66] More than 110 million water heaters and 104 million home heating systems would be impacted by such a policy. (These devices would replace air conditioners in most homes as well.) Additional market growth would come from commercial buildings wherein heat pumps currently heat only about 15 percent of all floor space (90 percent of commercial floor space is air conditioned).[67]

Even though heat pump deployment, particularly for residential space heating, is growing rapidly, the technology will need to improve much further in order to achieve these projected penetration levels over the long run. Key challenges include:

- initial costs that are well above competing units that run on natural gas,
- locations with high electric rates and low natural gas rates make operating costs for heat pumps higher than gas systems,
- 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.[68]

Some of the most promising innovations on the horizon that could resolve these challenges and unlock new markets include:

- Novel refrigerants: Alternative refrigerants (which may include supercritical carbon dioxide, 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 degrees. Novel approaches that compress hydrogen using membrane technologies similar to those used in fuel cells look promising as well.[69]
- 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 is capable of reaching higher temperatures more efficiently than a single-stage heat pump can. Hybrid systems that combine heat pumps with electric resistance heating may be able to 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 elastocaloric properties. While none of these approaches yet meet commercial cost and performance requirements, they promise environmentally benign, safe, efficient heat pumps that are capable of serving a wide range of building and industrial markets.[70]

- 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. Community systems that share a heat source such as a lake or a shared underground pipe loop may help reduce costs in some sites.[71]

Industrial Drying and Separations

The removal of water from industrial materials, mostly by heating, accounts for 10 percent of the process energy consumed in U.S. manufacturing. Drying is particularly significant in papermaking and food processing. While advanced heat pumps may be applied in some of these processes, a variety of innovative technologies offer the potential for much higher efficiency. The options include mechanical systems (e.g., by using ultrasound), infrared, shock electrodialysis, electrostatics, and dielectrics. Heat is also used in separations that divide mixtures into components. Separating ethanol from fermented mash is an ancient example.[72] (A shift to bio-based chemicals production, described in the next section, would further expand demand for low-temperature separations.)

The optimal drying technology will depend on the specific application; removing water from clothing is very different from removing it from a food product, for instance. 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 air could improve energy performance as well. For instance, the use of membranes that selectively pass water vapor and not dry air could raise the efficiency of these processes.[73] Nonthermal separation technologies could help prevent complex heat-sensitive molecules from undergoing side reactions.[74] Yet, in spite of the enormous potential benefits, research in this area has been virtually nonexistent.

System Components and Integration

Heat exchangers are often the most expensive, and certainly 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 cost or the rate of fouling could significantly enhance the effectiveness of these devices.[75]

The integration of components into systems will require careful assessment of the application. In buildings, heating, cooling, and drying systems will be installed as a part of systems that include advanced controls, windows with controllable optics, and other innovations. 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 of which they are just one important part.[76] Advanced simulation and analysis tools and improved sensors and controls will be critical for designing and operating these systems.

In many cases, system efficiency may be improved by using lower-temperature heat in applications in which, historically, higher temperatures were used simply because fossil fuels were available and not because they were needed to meet manufacturing requirements. This approach should expand the market for heat pumps, although other factors will also play a role in technology choice, including potential control problems arising from greater size and complexity. System redesigns must also include evaluations of productivity, safety, and waste reduction as well as potential reductions in GHG and other emissions.

U.S. Positioning and Capabilities

Global markets for heat pumps are highly competitive. Top heat pump manufacturers spanning both domestic and international firms include Carrier, UTC, and Trane, as well as Mitsubishi Electric, Fujitsu, Daikin, and Panasonic (Japan) and LG (South Korea).

U.S. manufacturers are not yet well positioned to capture the rapidly growing domestic and international markets for heat pumps and other advanced electric heating and drying equipment. U.S. demand for these products is weak, in large part because low U.S. natural gas prices have maintained strong markets for conventional equipment. In 2015, only about 10 percent of U.S. households used heat pumps for heating (although this figure was up from 2 percent in 2001).[77] Corporate investment in heat pump innovation may also have been limited by the fact that the United States has been much slower than most of the rest of the developed world to phase out refrigerants that contribute to climate change. Innovations leading to inexpensive heat pumps with high performance, however, could give U.S. producers a significant advantage in both domestic and international markets.

The European Union and its member states have made advanced heat pumps and related technologies a priority both to meet their own needs and to capture international markets. This effort focuses on both building and industrial applications. A recent roadmap for the industry outlines a goal of building 36 heat pump megafactories (each with a capacity of approximately 150,000 units per year) by 2030. Sites are already under consideration in Northern Italy and Poland. The European Heat Pump Association has been very active in innovation, with 12 major R&D and demonstration projects involving a variety of European industries.[78] Japan is home to world-leading manufacturers of heat pumps as well and undertakes appreciable applied R&D in heating, cooling, and drying technologies.

Opportunities and Gaps

A program to accelerate adoption of high-efficiency electric heating systems in the United States can build on recent trends. Energy efficiency programs operated by states, cities, and electric utilities have promoted heat pumps. Utilities in the United States provide close to $110 million in energy efficiency funding for heat pump installations, targeting roughly 80,000 participants. These programs, coupled with improved technology, have accelerated market adoption. Heat pump sales exceeded sales of natural gas furnaces in 2020, with sales up 10 percent year on year.[79] In 2020, a third of U.S. air conditioning sales were for units that also provide heat pump heating.[80]

Electric water heaters (though not necessarily heat pump water heaters) are also increasing in popularity among residential and commercial building owners. Sales of electric water heaters for commercial buildings were 75 percent higher than sales of natural gas units in 2020. In residential markets, electric and gas water heater sales were nearly equal in 2020.[81]

Policy Recommendations

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).

R&D

Key focus areas include:

- new refrigerants and highly innovative alternate cycle technologies such as electrocaloric and elastocaloric systems for heat pumps;
- next-generation heat exchangers exploring new materials, new designs, new fabrication techniques, and new design and simulation software;
- innovations that could cut the cost of drilling and piping for geothermal heat pump systems;
- novel electric drying systems such as those that use mechanical methods and design software needed to achieve system efficiencies;
- redesigning and reengineering low-temperature industrial processes to take advantage of the characteristics of heat pumps;
- innovative separation technologies with a focus on membranes; and
- new sensors, simulation, and modeling tools for designing and operating zero-emission production systems in specific industries, such as food processing and paper manufacturing, including redesigning processes to incorporate heat pumps and novel drying techniques.

Demonstration

- In conjunction with industry, the federal government should fund pilots and first-of-a-kind demonstrations of zero-emission industrial processes that use innovative heating, cooling, and drying equipment.
- Federal loans and other financial assistance should be provided for manufacturing advanced heat pumps domestically.

Deployment and Market Expansion

- Appliance standards should be expanded to include a wider range of commercial and industrial equipment and consideration of system efficiency, such as the costs of grid integration and efficient dehumidification.

- Highly efficient electric heating and cooling equipment should be mandated for all new buildings constructed in the United States and become an integral part of any building efficiency retrofit program.
- Congress should provide incentives for retrofits that assist with the installation cost of high-efficiency and low-emissions systems, while minimizing replacement of conventional units that have not reached their design lifetimes. Where appropriate, Congress could provide incentives for local geothermal piping loops.
- All federal buildings, including those owned by DOD as well as civilian agencies, should replace fuel-fired space and water heating water systems with efficient electric systems.

OPPORTUNITY: CHEMICAL PRODUCTION AND RECYCLING

Worldwide demand for chemicals made from oil and gas is growing rapidly, driven in part by increases in demand for plastics.[82] Chemical manufacturing, (which in addition to plastics includes fertilizers, synthetic fabrics, paints, and many other products) is responsible for about 18 percent of global carbon dioxide emissions from industry and about 2 percent of all GHG emissions.[83] It remains a major U.S. industry, employing nearly 10 percent of the domestic manufacturing workforce.[84]

GHG emissions from chemical production result from two distinct types of sources. About half of the coal, oil, and gas used in this sector is combusted during the production process.[85] The other half is used as feedstocks, and their derivatives are embodied in the final products, such as the polymers in plastics.[86] A portion of these products is recycled, but much of it is not, meaning embodied GHGs are eventually released to the environment, particularly if they are incinerated as a means of waste disposal—though more work is needed to understand these flows.

Why This Industry Matters

While growth in demand for chemical products is strong worldwide, plastic demand has grown exceptionally fast: three times as fast as the economy as a whole since 1970. Plastics are cheap, versatile, and durable. They perform a wide and growing variety of functions, ranging from packaging to insulation to lightweight, corrosion-resistant structural components of products such as automobiles and airplanes. The emissions and water use associated with plastics manufacturing is significantly lower than many of the materials they have replaced, such as aluminum and steel.[87]

Climate policies could accelerate growth by driving demand for lightweight vehicles and renewable energy equipment made in part from plastic, such as wind turbines. Some projections find that petrochemicals will be responsible for more than a third of the growth in petroleum demand by 2030, and nearly half by 2050.[88] (The United States is an exception because low U.S. natural gas prices mean most domestically produced plastic is made from gas.) As is the case for most materials, global demand is growing much faster than domestic demand. U.S. chemical sales stagnated between 2000 and 2019, while growth worldwide averaged 3.9 percent per year. Growth in China was nearly three times that rate.[89]

Of course, the oil and gas industry is itself under pressure. If some or all of the roughly two-thirds of oil and gas that is converted into fuel for transportation or power systems today is displaced in order to reduce GHG emissions, feedstock for the production of chemicals will become an even larger part of the industry's future. Fatih Birol, executive director of IEA, called petrochemicals "one of the key blind spots in the global energy debate … they will have a greater influence on the future of oil demand than cars, trucks and aviation."[90]

Pathways to Net Zero

Eliminating GHG emissions from the production of chemicals poses a unique set of challenges. The industry is highly diverse, entangled with the production of transportation fuels, and reliant on fossil fuel feedstocks. Major reductions are, however, clearly possible. A recent European study concludes that by 2050 creative policies could cut GHG emissions from chemical production by 76 percent.[91]

Such cuts will require greater efficiency in the end uses of chemicals (using them only when, and as much as, needed) as well as replacing traditional fossil fuel inputs, which we focus on here, exploring three potential replacements:

- Recycled materials, including materials designed for recycling
- Materials produced from biological resources
- Materials produced through artificial photosynthesis

The share of global markets captured by using these innovations will depend on whether they can compete with systems that capture and permanently sequester carbon dioxide from the combustion of fossil fuels. CCS systems cannot eliminate emissions that arise from carbon embedded in chemical products that eventually find their way into the atmosphere. (Emissions from chemical production can also be lowered by designing products with longer lifetimes and better performance per unit of material to reduce net demand, reducing losses in production processes, and replacing chemicals in end uses with lower-carbon materials such as engineered wood.)

Innovations in Recycling

Only about 10 percent of plastics in the United States are made from recycled materials, compared with nearly 70 percent of steel. Most other chemical products (such as paints, textiles, and lubricants) are difficult to recycle with current processes. Although plastics' end uses are more dispersed than those of steel, which is used mainly in automobiles and other big-ticket items, a recent European study suggests that up to 60 percent of plastics now made from raw materials could be replaced if recycling improves.[92]

Technologies that cut the cost of recycling and increase the quality of the resulting products would help capture this potential. Five classes of polymers comprise 91 percent of recycled plastic and should be targeted.[93] Promising approaches would:

- develop plastics and other products that are easily disassembled for recycling, as many existing plastics lose desirable properties after being recycled several times;[94]
- improve processing systems for disassembling chemicals into components that can be remade without loss of performance and at lower cost than production from virgin materials, using tools such as selective catalysts and nonselective gasification technologies;[95]

- use synthetic biology to accelerate the evolution of microbes to produce both new, easily recyclable chemicals and facilitate the recycling process itself, as plastics have not been in the environment long enough for microbes to evolve to recycle them;[96] and
- develop systems that combine conventional mechanical recycling (sorting, washing, chopping) with advanced chemical recycling methods.

Innovations in Bio-Production

For generations, people have been using microorganisms to make chemicals. Recent advances now make it possible to manufacture virtually any chemical product using biotechnological techniques.[97] It is also possible to manufacture chemicals from air and water with artificial photosynthetic processes that are more efficient than natural photosynthesis. However, before these approaches can become climate solutions at scale, additional progress must be made on feedstocks, fermentation processes, and artificial photosynthesis.[98]

Feedstocks

Feedstocks are the raw materials that biological systems such as engineered bacteria convert into chemicals. Bio-feedstocks may actually sequester carbon dioxide, since the plants from which they derive remove it from the air, or they may be carbon-neutral if the carbon dioxide is ultimately released at the end of a product's life. However, such calculations omit emissions caused by growing or processing them.[99] There are limits to the availability of bio-feedstocks, and chemical production could compete with other uses for biological resources, including biofuels for transportation and electricity generation and serving as "offsets" that draw down atmospheric carbon dioxide.[100]

The largest bio-based chemical product is ethanol, which is blended into gasoline in the United States and elsewhere. U.S. ethanol is made almost entirely from corn, consuming roughly 40 percent of the nation's corn crop.[101] A growing portion of this resource would become available for other purposes if electric vehicles gain market share, displacing gasoline. Even so, the bio-resources used for ethanol production represent only about 10 percent of the energy the United States uses to produce all chemicals.[102] A significant shift to bio-based chemical production would require other feedstocks, such as waste materials or crops grown on land not suitable for conventional agriculture. Research suggests that such a shift would be feasible in the United States without competing with food production.[103]

Such feedstocks will generally be inedible plant material such as corn stalks and woody materials.[104] While organisms exist in nature that can break down such materials into precursors for chemical production, replicating this ability at a reasonable cost has frustrated inventors for decades.[105] Computational systems biology and other biodesign tools as well as new gasification methods may well overcome these barriers, given adequate investment.[106]

Fermentation

Fermentation is the process by which microorganisms transform feedstocks into chemicals under controlled conditions. Advances in biotechnology have made it possible to engineer organisms that can produce virtually any chemical by fermentation.[107] This production method allows for efficient production facilities to be built on a much smaller scale than do current methods. Biological feedstocks may also be more widely distributed than fossil fuel feedstocks, motivating further decentralization. Ultimately, bio-based chemical plants may get on a learning curve such as that for ethanol plants between 1981 and 2006, when unit capital costs fell by a factor of four.[108]

A number of commercially promising bio-based chemicals have already been introduced (box lists examples recognized by the European Union). However, only high-value specialty and pharmaceutical products have gained substantial market share. The massive markets for commodity chemicals, which are the largest emissions sources in this industry, have not yet been touched due to the relatively high cost of bio-based alternatives.

Examples from the European Union's "Top 20 Innovative Bio-based Products"[109]

- Guayule rubber
- Microfibrillated cellulose
- Thermoplastic biopolymers reinforced with plant fibers
- Self-binding composite nonwoven plant (alternative to glass or carbon)
- Biolubricants
- Biodegradable plastics/technical plastics
- Lignin-based nanofibers (alternative to PAN-based carbon fibers and composites)
- Lignin-based resins
- Aromatic hydrocarbons and PHAs (chemical feedstock)
- Bio-based polyurethanes, polyamides, polycarbonates
- Bacterial biosurfactants (medical, personal care)

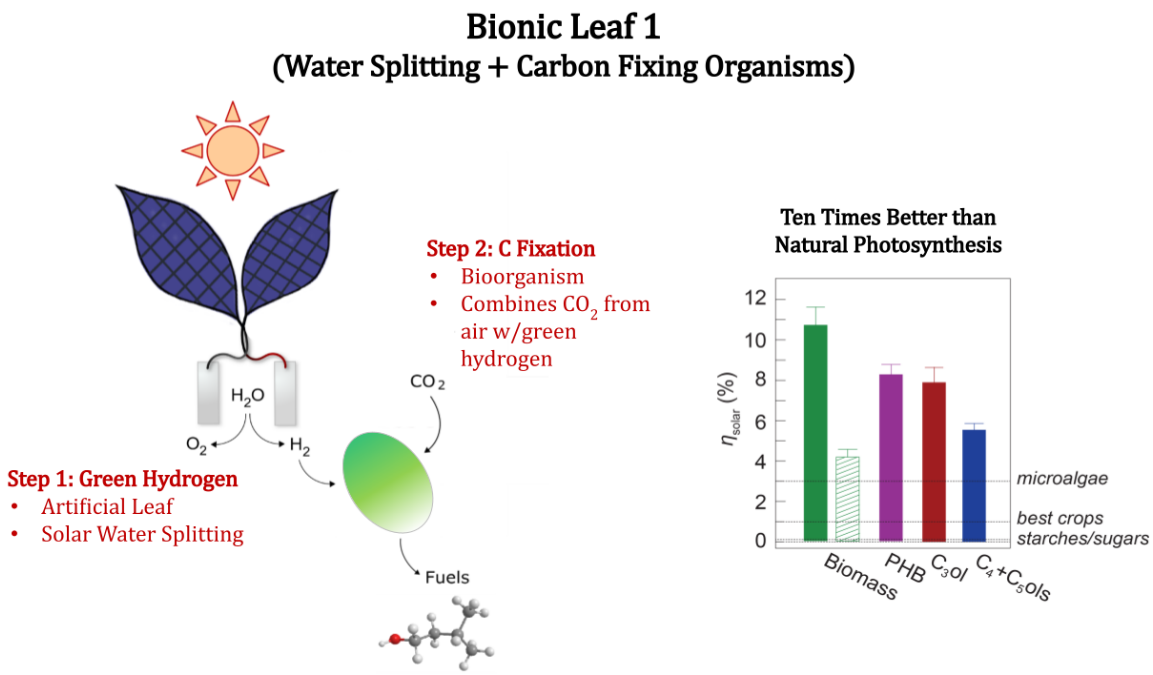
The skills required to design, build, and operate high-volume, low-cost commercial production facilities are quite different from the scientific skills needed to develop organisms in a laboratory setting. Commercial production also faces a number of vexing process development problems including breaking cells into broth and removing spent cells, concentrating products by removing water, and purifying products through crystallization.[110]

Artificial Photosynthesis

The use of solar power to provide electricity for large-scale fermentation is clearly one way sunlight can be used as the major energy input into bio-based chemical production. But plants themselves are living proof that sunlight, air, water, and nutrients drawn from the environment can be converted into complex chemicals. Photosynthesis is the source of all biomass, and the ultimate source of fossil fuels as well. Although the theoretical efficiency of photosynthesis is about 16 percent, natural photosynthesis in crops operates with an efficiency of only about 1 percent.[111] If this gap could be closed, improved crops grown as feedstocks could make bio-based chemical production much more cost effective.

One possibility is to use the tools of synthetic biology to remove some of the inefficiencies of natural photosynthetic processes. (The evolution of plant chemistry was not driven entirely by the efficiency imperative.) A competing approach uses catalysts in an "artificial" or "bionic" leaf (see figure 5) to produce hydrogen from water, which is then fed to a microorganism that combines it with carbon dioxide from the air to make a feedstock. Such systems have been demonstrated that are 10 times as efficient at converting solar energy into chemical energy as typical crops are. Several other approaches also look promising.[112]

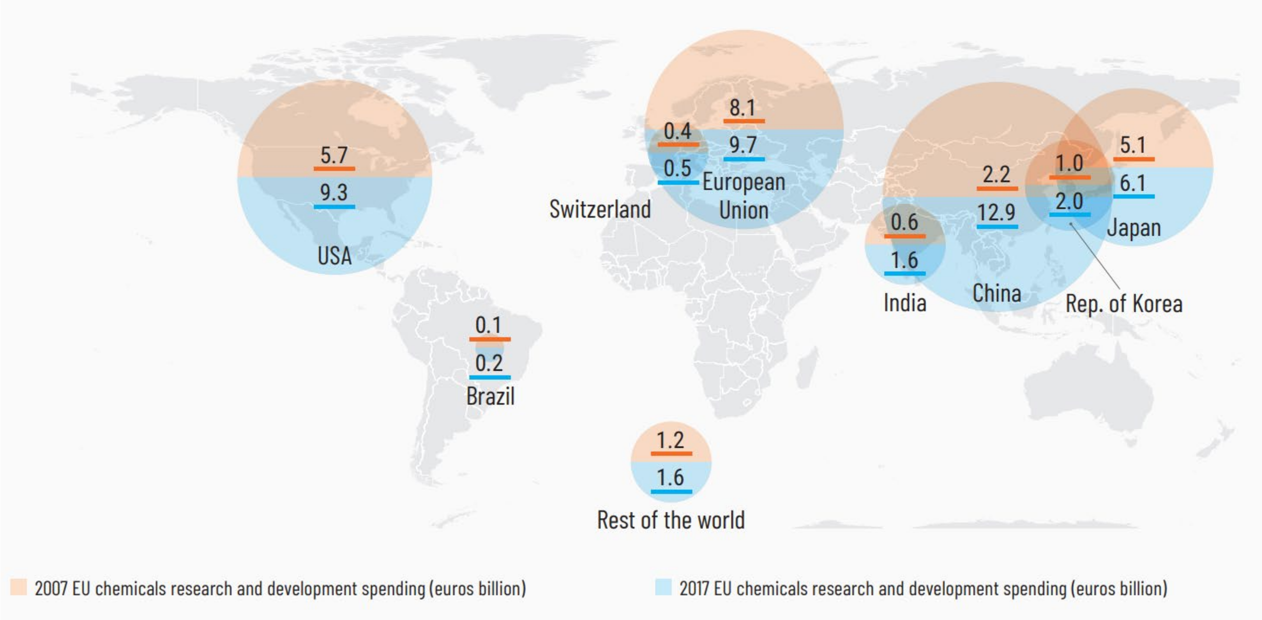
Figure 5: The Bionic Leaf[113]



U.S. Positioning and Capabilities

The United States enjoys enormous strengths in chemical manufacturing. With capabilities spread across universities, national laboratories, and chemical industry research centers, the United States probably leads the world in the skills and know-how that are most relevant for this aspect of the low-carbon transition. The U.S. chemical industry also has decades of production experience and excellent access to material inputs, including bio-feedstocks. But this leadership position is in jeopardy. In 2007, for instance, U.S. chemical companies invested twice as much in research as did their Chinese counterparts. Today, Chinese firms spend 36 percent more (see figure 6).

Figure 6: Corporate research and development spending globally, 2007 and 2017 (EUR billion)[114]



The United States has also lagged behind in exploring innovation pathways that could lead to replacements for fossil fuel-based chemical production.[115] In both Europe and Asia, government and industry have taken an intense interest in this topic, developing detailed roadmaps for recycling and investigating bio-based production.[116] A recent German strategy document concludes that "successfully shaping climate protection in Germany offers opportunities to build up sustainable technology and innovation leadership in future technologies, which can help stabilize the growth of international market shares for German exporters and importers and help position them in growth markets."[117] Agri-science and synthetic biology are two of the United Kingdom's "Eight Great Technologies" for the future, and that nation has established a Synthetic Biology Leadership Council with representatives from government, academia, and industry.[118]

Opportunities and Gaps

At present, there is no cohesive U.S. strategy in the federal government or in key industries for managing a transition that will affect at least 10 percent of U.S. manufacturing jobs over the next three decades. U.S. producers will need to make significant investments in order to preserve domestic markets in a low-carbon world and to win markets abroad in countries with ambitious climate policies. Some international oil majors with significant U.S. chemical production footprints are beginning to take action. Shell, for example, has set a goal of reducing its "carbon intensity by 45 percent by 2035 and by 100 percent by 2050."[119] But the overall rate of change to date seems far short of what will be required.

Creative climate policies could lead to growing domestic employment and production in a reinvented chemical industry. U.S. ethanol policy, while hardly a model from the perspective of either economic or environmental policy, shows how quickly an industry can be born when political will and capital are put behind the effort. The United States is the world's largest producer of ethanol, with an output of about 16 billion gallons in 2019, up more than 140 percent since 2007.[120]

Policy Recommendations

A successful strategy for domestic bio-based chemical production would include R&D, demonstration, and deployment programs. It should pursue a portfolio of technologies because the advantages of each approach are only beginning to be understood and the pace of innovation has been so rapid. It would be accelerated by the development of a comprehensive national roadmap that builds on existing roadmaps; involves several federal agencies, notably DOE, the U.S. Department of Agriculture (USDA), DOD, and U.S. National Science Foundation (NSF); and covers the full innovation lifecycle.[121]

R&D

A national roadmap would include a coordinated and well-funded program of basic and applied research. Applied research on chemical production at DOE has traditionally focused on transportation fuels (primarily ethanol) as well as carbon sequestration and conventional petrochemical production. DOE's Office of Science has financed innovative work in synthetic biology, artificial photosynthesis, and other advanced topics. These priorities and strategies to manage them should be revised to include additional priorities:

- Plastics and other chemical products designed to be disassembled and recycled without sacrificing performance
- Improved methods for disassembling chemical products (and mixed wastes) and rebuilding the components into useful materials without loss of performance, including selective catalysts, nonselective gasification, and possibly biological systems
- Development of crops designed to produce feedstocks for bio-based chemical manufacturing
- Organisms engineered to make commodity chemicals on a large scale using inexpensive feedstocks that do not compete with food production
- Production systems that use electricity and hydrogen as major inputs, perhaps combining synthetic and biological resources
- Hybrid systems that combine abiotic production of hydrogen gas or carbon monoxide with biological processes for chemical production
- Post-processing technologies for separations and purification of bio-products
- Computational tools for designing biological systems, novel materials, and next-generation production facilities that use artificial intelligence and other new tools to tackle genetic selection, process inhibitors, and other challenges involved in scale-up.[122]

Demonstration

Moving novel processes for chemical production to the 100,000-liter (or larger) scale can cost $100 million or more and take six to eight years.[123] This risk and cost profile make it very difficult to attract private investors to such projects. Federal policy should seek to de-risk them by supporting public-private partnerships to build and operate large-scale test facilities aligned with the R&D program previously outlined.

Deployment and Market Expansion

Potential investors in innovative chemical production technologies will be looking toward the growth of markets in both the United States and globally.[124] The European Union has adopted an aggressive growth strategy in its Circular Economy Action Plan. It includes an array of incentives and regulations to create markets for durable, repairable products such as improved labeling, "green public procurement," and recycling strategies for specific end-use products like electronics and textiles.[125]

New directions for the United States could include:

- Improve public infrastructure for recycling plastics and other products of chemical manufacturing, as proposed by the BOTTLE Consortium, among others.[126] The effort would be enhanced if there were ways to combine the collection of recycled materials with chemical reprocessing facilities.
- Expand and make more effective use of USDA programs, such as BioPreferred, which includes requirements for federal procurement, sample purchasing contracts, training, and voluntary labeling programs for industry program across a wide range of products including "cleaners, carpet, lubricants, [and] paints." Three thousand private companies are already participating.[127]
- Ensure that products labeled as "biodegradable" actually lead to environmental benefits. Many products currently labeled as such do not degrade rapidly, particularly in marine environments.[128]
- Create product labeling systems that reflect climate impacts, including a detailed environmental impact analysis covering water and land-use impacts wherever possible. As in Europe, these systems could include national product databases and embedded materials (e.g., unique taggants) that verify a product's origins.
- Establish public procurement ("buy clean") programs for low-emission, bio-based chemicals. Federal procurement could accelerate the growth of markets for these products.
- Tighten emission standards and enforcement at conventional chemical production facilities.

Innovation Ecosystem and Technical Assistance

The chemical industry is concentrated in specific geographical regions in the United States. Federal policy should explore ways of helping these communities transition to next-generation chemical production. Biomanufacturing opens particularly interesting opportunities for investment when chemical production located near biological resources provides an economic advantage. This rural economic development initiative should partner with states and localities to build on their investments, such as those in Louisiana and North Dakota, and take better advantage of existing USDA resources such as the Agricultural Research Cooperative Extension Services as well as loan grants that could support the development of bio-based chemical production.[129]

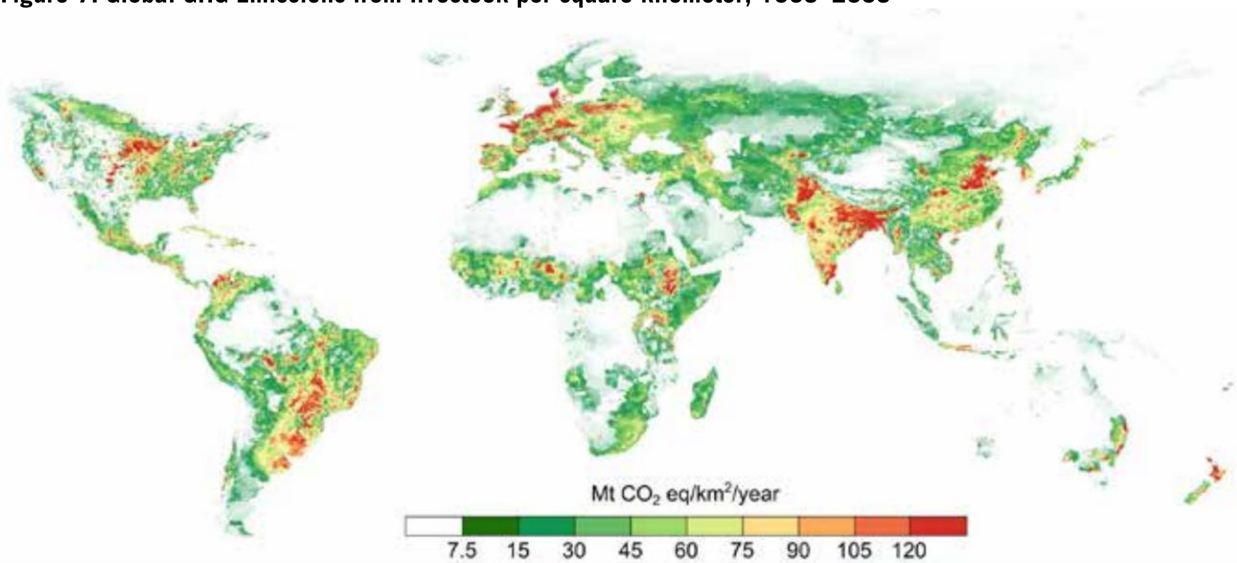
OPPORTUNITY: BIOTECH-BASED ALTERNATIVES TO MEAT AND DAIRY PRODUCTS

Innovations in industrial biotechnology have the potential to displace emissions from agriculture, in addition to displacing emissions from chemical production (as discussed in the previous section). In particular, proteins made by microbes in fermenters and animal cells cultivated in bioreactors could substitute for many meat and dairy products. Any large-scale shift from farm and ranch to tank and vat, even if it only limited the growth in demand for high-emissions foods, would have profound implications for the environment as well as society and the economy.

Why This Industry Matters

Livestock and manure are directly responsible for about 6 percent of global GHG emissions. That figure roughly doubles when emissions from land-use changes and other inputs are included in the calculation (see Figure 7). As incomes rise globally, demand for meat and dairy products will rise as well, driving emissions up by a projected 1 to 5 percent per year.[130] Beyond contributing to climate change, animal agriculture causes a range of other environmental harms, including deforestation and water pollution.

Figure 7: Global GHG Emissions from livestock per square kilometer, 1995–2005[131]



Substitution of proteins made through biotechnological methods for conventional meat and dairy products could reduce GHG emissions substantially. (The term "alternative proteins" also embraces products made without biotechnology by combining agriculturally grown ingredients.) A study of Quorn, the alternative protein industry's oldest firm, by the Carbon Trust found that its substitute (made from fermented mycoprotein, originally derived from a fungus) had a carbon footprint at least 89 percent smaller than that of beef raised in the United Kingdom and Europe.[132] A recent lifecycle assessment by the Dutch firm CE Delft for the Good Foods Institute found that cultivated beef (animal cells grown in a bioreactor) would reduce the typical climate impact per unit consumed by 85 to 92 percent by 2030, when that emerging technology will be mature.[133] For less GHG-intensive meats such as pork and chicken, the reduction would be a third or more.[134]

These estimates have large uncertainties, and the studies behind them have been funded mostly by industry sources. Moreover, the environmental impact of conventional agriculture, according to a recent study, can vary by as much as 50-fold across producers of the same product.[135] Assumptions about both the baseline climate impacts of agriculture as well as alternatives thus greatly affect the comparison of the two. While more research from neutral sources may help reduce the uncertainty, new technologies for protein production undoubtedly create the potential for dramatic emissions reductions.

The meat and dairy industry in the United States, which might be partly displaced if consumers turn to alternative proteins, is large. Meat and poultry processing employs about a half-million workers today, and dairy products manufacturing employs another 150,000. Many other workers are employed upstream and downstream in these value chains.[136] Employment estimates for alternative protein production are necessarily speculative. The Breakthrough Institute found that the industry could generate nearly 200,000 direct jobs in the United States if it continues to grow globally at its recent pace, 20 percent of that growth occurs in the United States, and the industry continues to generate jobs at the same rate for each new increment of market growth.[137]

Pathways to Net Zero

Alternative proteins can be made with a variety of biotechnological techniques. Molecular biology provides the basic tool kit for many of these techniques, allowing the genes of microorganisms to be reprogrammed so they produce proteins or create other ingredients that can be used as inputs to downstream production processes. These modified strains are then grown under controlled conditions in fermentation vessels, and their protein products are separated afterward. Impossible Foods' beef substitute, for instance, combines plant products with heme, a basic component of blood, that is made by fermentation of genetically engineered yeast.[138]

Cultivated meat begins with stem cells, which have the potential to turn into more specialized cells under the appropriate stimuli. Producers manage these stimuli in cultures such that the stems cells differentiate as they reproduce on a large scale in a bioreactor. The ultimate goal of these processes is "actual animal meat grown outside an animal," including muscle, fat, and other cell types.[139]

Making unique proteins or cell cultures in a laboratory, while impressive scientific feats, are far cries from displacing gigatons of GHG emissions. To scale up these processes, each stage of production must be optimized as part of a system to reduce cost and improve quality as well as limit GHG emissions. In fermentation, the feedstock, microbial strain, fermenter operations, and post-extraction processing all contribute to cost and performance, and there are opportunities for improvement in each stage. The same general point applies to cell cultures, which depend on growth media that are expensive today. Complicating the issue further, most food products are not single proteins but complex mixes of ingredients that must be combined without degrading textures and flavors that appeal to consumers. New supply chains may need to be created to provide ingredients that are currently uncommon in large quantities.[140]

Biotechnology-based alternative proteins are not generally cost competitive with conventional products. The rapid advance of the biological sciences, along with further progress in fermentation, cell culture, and other biotechnologies, should bring this goal within reach in the near future for alternatives to processed meats such as hamburger and milk products such as whey. Seafood, egg, and poultry substitutes may be the next potential markets, approaching price parity with conventional products in the early 2030s, according to Boston Consulting Group. Even quite complex products are visible on the horizon; Israeli-based Aleph Farms announced to much fanfare that it had cultivated a rib-eye steak in February 2021.[141]

In addition to achieving cost competitiveness, the success of the alternative protein industry will depend on surmounting societal challenges. The production and consumption of meat and dairy products are deeply embedded in cultures and economies around the world. Objections to alternative proteins may emerge because livelihoods and identities are threatened by innovation. In addition, consumers who are willing to try biotechnology-based alternative proteins must be assured that they are safe. Regulators in the United States have already begun to develop protocols for bio-based ingredients, manufacturing processes, and product labeling.[142]

U.S. Positioning and Capabilities

The United States has led the biotechnology revolution since scientists at Stanford and the University of California learned how to splice DNA in the 1970s. The U.S. government invests a larger fraction of its research funding in the life sciences than do its international peers.[143] Although the vast bulk of this investment is intended to support the public health mission (with very modest investments that directly advance biotechnology-based alternative proteins), some of the fundamental knowledge it creates spills over to food production.[144]

Building on federal funding for basic biological research, plentiful private venture capital (VC) has positioned the United States to take an early lead in the emerging alternative protein industry. According to the Good Food Institute (GFI), almost half of the 44 fermentation companies focused on alternative proteins that had formed around the globe by mid-2020 were United States-based. Nineteen of the 34 cultivated meat companies tracked by GFI were also in the United States. Big companies, including JBS, the world's largest meat company, are jumping into the alternative protein sector as well. VC investment in the sector and product introductions are growing exponentially, more than doubling annually in recent years.[145]

Acceptance of biotechnology-based alternative protein products by U.S. consumers, which might give domestic producers a lead market in which to scale rapidly, is uncertain. GFI reported that "fermented and cultured foods have recently achieved something of a health halo and a premium status within 'foodie' circles."[146] Data collected by Nielsen for *Food Dive* indicate that consumption of meat alternatives grew by 129 percent from 2019 to 2020. Climate concerns may help accelerate mainstream acceptance. On the other hand, it's likely most U.S. consumers are unfamiliar with these products, and their views are probably malleable.[147]

The United States' main challenge may lie between product development and consumption. With the exception of ethanol, which benefits from federal mandates and subsidies, the United States is not as well positioned in large-scale biotechnological production as in basic research and start-ups. The "innovate here, produce there" pattern noted by Bonvillian could recur in this sector unless policymakers take steps to avert this outcome. VC investors typically balk at providing the large sums required to scale up capital-intensive physical production processes without relatively clear signals that they will receive large returns. The alternative-protein VC boom could peter out as start-ups hit this capital wall. Alternatively, successful start-ups may find patient investors with deep pockets abroad. Israel and Singapore have set out aggressive strategies for this industry, and other nations have begun to take an interest as well.[148]

Opportunities and Gaps

The opportunity for U.S. leadership in biotechnology-based alternative protein production remains significant. The industry is in its infancy, and although consumer demand is growing rapidly, it would have to continue to grow exponentially for many years to reduce emissions from meat and dairy production on a gigaton scale by 2050. Yet, even if it only slows emissions growth in this sector, that would be an important contribution to meeting the climate challenge—one that would likely grow substantially in the second half of the century.

Intermediate-scale production facilities represent a key gap in the U.S. alternative protein innovation system. Production beyond the lab but short of full commercial scale is crucial for most food industry start-ups to establish their credibility and prove out their processes. While simulation technology can greatly facilitate scale-up, investors and customers typically want hard evidence that young companies have mastered engineering as well as the science and are able to meet specifications. [149]

DOE provides 300-liter tanks for industrial process development at the Advanced Biofuels and Bioproducts Process Development Unit of Lawrence Berkeley National Laboratory, but these are orders of magnitude smaller than the 100,000-liter (or larger) units that are typical for commercial-scale fermentation. In late 2020, DOD created the BIOMADE manufacturing innovation institute, which plans to build pilot facilities geared to utilizing local feedstocks in particular regions, but it is not necessarily going to serve the food industry.[150]

Although DOE and DOD both work with biotechnology-based alternative protein companies, this sector is a tiny element of their main missions. By contrast, alternative proteins lie squarely within the mission of USDA, but it has made very limited investments to support the emerging industry. USDA R&D programs are focused on well-established segments of the food supply chain and operate primarily through formula-based grants to institutions. As one scientist told *Nature* in 2020, funding for applied research on cultivated meat "falls into this funding no-man's land between biomedical research and agricultural research."[151]

In addition to public support for R&D and demonstration, the societal dimensions of shifting protein consumption will require a significant amount of research and smart communication. With some justification, farmers and ranchers may fear displacement caused by alternative proteins. Consumer acceptance may also prove challenging, especially in export markets with rising middle classes that perceive meat and dairy products to be desirable luxuries.[152]

Policy Recommendations

A robust federal policy to accelerate biotechnology-based alternative protein innovation in order to secure U.S. global leadership and enable large-scale emissions reductions might include:

R&D

- Expand support through existing USDA programs for applied research on all aspects of the alternative protein supply chain. Opportunities abound to improve feedstocks, develop new ingredients and processing methods, and create production systems that are well adapted to seasonal variations in the availability of biomass inputs.[153]

- Create targeted R&D programs to tackle specific barriers within the Agriculture Advanced Research and Development Authority (AGARDA), an authorized but as-yet unfunded office modeled on the Defense Advanced Research Projects Agency (DARPA). Such entities seek to fill high-impact "white spaces" that have been neglected in their parent agency's technology portfolio.[154]

Demonstration

- Provide public funding to cover the capital gap that prevents testbed facilities from being built in the United States. These facilities should be funded in conjunction with and operated by companies or industry organizations, and facility users should be required to cover operating costs.
- Work with states, localities, and groups of firms to develop a new Manufacturing USA innovation institute to accelerate innovation in alternative protein production technology. Such an institute could house shared facilities, support research into industry-defined problems, invest in workforce development, and assist small and medium-sized companies to join emerging supply chains.[155]

Deployment and Market Expansion

- Focus regulatory attention on potential risks posed by products, rather than singling out products made with biotechnological methods for particular scrutiny. In particular, the Food and Drug Administration (FDA), which will have oversight of important aspects of cultivated meat production, has taken an excessively risk-averse approach to biotechnology-based products in the past, ignoring an evidence-based, bipartisan consensus for a more balanced approach.[156]
- Level the playing field by cutting back federal subsidies for meat and dairy products and ensuring fair labeling of all products. The milk industry, for instance, which already receives a substantial portion of its income from the government, has petitioned the FDA to forbid plant-based substitutes such as soy milk from using the word "milk" in their marketing. Biotechnology-based innovations will surely face similar opposition.[157]
- Put alternative proteins on an equal footing with conventional products in federal food procurement and nutrition support programs. Every day, federal agencies subsidize meals for millions of people, from soldiers to students to the needy, and they could use this buying power to advance climate-friendly alternative protein innovations, emulating innovation policies employed in many other fields of technology.[158]

Innovation Ecosystem and Technical Assistance

- Assist farmers, ranchers, and rural communities that depend on the livestock industry directly or indirectly to join alternative protein supply chains or shift to other industries. Those who take land out of production may provide soil carbon sequestration services, while others may be able to shift from growing grain to sell to feedlots to raising plants that serve as inputs used in fermentation or cell culture.[159]

CONCLUSION

The United States faces the twin issues of rebuilding a vibrant, inclusive economy that includes a strong manufacturing sector while simultaneously accelerating progress toward net-zero GHG emissions across all sectors, including industry. We argue that the United States should respond to these challenges by adopting an integrated strategy that features policies that target specific industries that have a high potential for both emissions reduction and high-quality job growth. Such policies would build on a long U.S. tradition of using public investment in strategically important industries and infrastructure to catalyze private investment—and they can coexist alongside a strong, rules-based international system of trade.

The United States will not be alone in seeking to develop such industries, assuming the world's major economies take their obligations under the Paris Agreement seriously. The United States' historic and continuing advantage in this competition is its capacity for innovation. This advantage is not as dominant as it was immediately after World War II. Nor is it static in areas where U.S. producers have a lead at any moment—fast followers abound. But sophisticated strategies, built around specific, important opportunities for manufacturing innovation, we believe, can secure and sustain advantages that expand U.S. employment and encourage international trade, even as they contribute to the planetary quest to limit concentrations of GHGs to tolerable levels.

While far from exhausting the potential opportunities, our research identifies four industries that merit additional investigation and policy development. The hydrogen production industry (along both "green" and "blue" technological pathways) is nearly certain to become a very large new global industry that includes manufacturing across an extensive value chain as well as infrastructure construction and operation. Allies and rivals of the United States are already investing heavily in hydrogen production, but the domestic market is substantial, and U.S. producers have several competitive strengths.

Heating, cooling, and drying equipment also represent an important manufacturing and climate abatement opportunity. This industry employs over 125,000 manufacturing workers in the United States today, and its market is likely to grow steadily through the next several decades as climate policies around the world emphasize decarbonizing low-temperature heat in buildings and industry. Promising pathways for cost-reducing, performance-enhancing innovation through the use of new refrigerants, cycles, fuel sources, and other design changes beckon. Future leaders in these markets must continue to invest in innovation and scale-up.

The third industrial opportunity we have identified is chemicals production and recycling. Plastics, fertilizers, and other petrochemicals account for almost 10 percent of U.S. manufacturing jobs. Innovations leading to clean production in this industry could also expand the U.S. share of growing global markets. In particular, advances in synthetic biology raise the likelihood that bio-based chemicals can be manufactured at scale from a wide variety of new feedstocks with very low emissions. In pursuing these opportunities, the United States can draw on a number of strategic advantages, including a strong academic and industrial research base and the experience of rapidly scaling up corn ethanol production.

Finally, alternative protein production could become a significant source of new manufacturing jobs, while addressing one of the most difficult-to-abate sources of GHG emissions: meat and dairy production. The United States already leads the world in this nascent industry, drawing on a thriving ecosystem of researchers, start-up companies, VC, and federal support from unusual sources, such as DOD. Nonetheless, the nation lacks facilities to assist companies with process scale-up, and unknowns abound with respect to the market's potential and the prospect of transitioning U.S. farms and ranches away from traditional production while preserving rural economies and employment opportunities.

Success is not guaranteed in any of these four manufacturing industries. To become major sources of domestic jobs and economic activity, they will need support in the form of public-private roadmapping, increased R&D and demonstration funding, and scale-up policies that maximize subsequent private investment and stimulate demand. With an advanced industry and technology strategy that include these elements, tailored to the opportunities and barriers each industry faces, the United States has an excellent chance to provide global leadership on climate that strengthens its manufacturing sector and economy as well. Without such a strategy, the nation is likely to fall further behind others that are already positioning themselves to gain the markets and jobs of the future, while deepening the peril facing the planet.

APPENDIX: WIDENING THE LENS WORKSHOP SERIES

The Boston University Institute for Sustainable Energy, Fraunhofer Center for Manufacturing Innovation at Boston University, and ITIF convened a four-part workshop series in January and February 2021. The workshops included lightning talks by invited experts (denoted with an asterisk below) and focused discussions on technical challenges and policy options among all participants. We drew on these presentations and discussions in preparing this report, but are solely responsible for the contents. We are very grateful to the presenters and participants for devoting their time, thoughts, and energy to the workshops. Links to videos of the presentations, which may be viewed by the public, are found in the endnote for each workshop.

Greening High-Temperature Manufacturing: Toward an RD&D Agenda[160]

January 27, 2021

Addison Stark, Bipartisan Policy Center

Alan Weimer, University of Colorado Boulder

Ali Hasanbeigi, Global Efficiency Intelligence*

Arvind Thekdi, E3M Inc.

Cecilia Springer, Boston University

Charles Hernick, CRES

Charles Weiss, Army Engineering Research and Development Center

Chendril Periasamy, Air Liquide

Colin McMillan, National Renewable Energy Laboratory

Dorothy Robyn, Boston University

Doug Vine, C2ES

Emanuela Del Gado, Georgetown University

Eric Masanet, Northwestern University

Everett Anderson, Nel Hydrogen*

Greg Thiel, ARPA-E

Guarav Sant, UCLA

Jeffrey Rissman, Energy Innovation

Joe Cresko, DOE

Joe King, ARPA-E

John Thompson, Clean Air Task Force

Karthish Manthiram, MIT*

Kathy Ayers, Nel Hydrogen

Madhav Acharya, ARPA-E

Maria Juenger, University of Texas, Austin*

Mark Johnson, Clemson University*

Mark Ruth, NREL*

Marlene Arens, Fraunhofer ISI*

Mike Fowler, Clean Air Task Force

Nicole Ryan, U.S. Congress

Sharon Nolen, Eastman

Spencer Nelson, Clear Path

Stacy Smedley, Skanska

Zack Pritchard, U.S. Congress

Low-Temperature Industrial Processes[161]

February 3, 2021

Alan Pears, University of Melbourne

Alyssa Gunter, UC Davis

Ayyoub Momen, Ultrasonic Technology Solutions*

Bill Goetzler, Guidehouse

Bo Shen, Oak Ridge National Laboratory

Craig Blue, Oak Ridge National Laboratory

Dani Alexander, RACE for Business

David Claridge, Texas A&M*

David Sholl, Georgia Institute of Technology

Detlef Westphalen, Guidehouse

Gregor Schumm, Piller

Ignacio Bonel, Heat X

Jamal Yagoobi, Center for Advanced Research in Drying*

Joe Hagerman, Oak Ridge National Laboratory*

Kashif Nawaz, Oak Ridge National Laboratory*

Lena Schnabel, Fraunhofer ISE*

Mark Lippi, Center for Advanced Research in Drying

Matthew Gurwin, Heat X Tech*

Neal Elliott, ACEEE

Paul Scheihing, 50001 Strategies*

Pega Hrnjak, University of Illinois

Reinhard Radermacher, University of Maryland

Takenobu Kaida, Central Research Institute of Electric Power Industry

Tony Bouza, DOE*

Xavier Moya, University of Cambridge

Xiaobo Yin, University of Colorado Boulder

Bio-Manufacturing: Opportunities to Contribute to Climate Change Mitigation[162]

February 10, 2021

Aindrila Mukhopadhyay, JBEI, LBNL*

Anna Fokina, DCVC Bio

Brian Sylvester, Covington*

Charles DeLisi, Boston University*

Daniel Drell, DOE (retired)

Daniel Nocera, Harvard*

Deepti Tanjore, Lawrence Berkeley National Laboratory

Doug Friedman, EBRC and BioMade Institute

Ed Perkins

Jay Fitzgerald, DOE

Jeff Lievense, Lievense Bioengineering LLC

Karim Cassimjee, Enginzyme*

Liz Specht, Good Food Institute*

Mark Warner, Warner Associates

Paul Dauenhauer, University of Minnesota

Rich Roberts, New England BioLabs

Sarah Glaven, U.S. Naval Research Laboratory

Susan Singer, Rollins College

Tim Gardner, Riffyn*

Alternative Materials[163]

February 17, 2021

Alan Luo, The Ohio State University

Alper Kiziltas, Ford

Daniel Cooper, University of Michigan

Eduardo Saiz, Imperial College London

Elsa Olivetti, MIT

Eric Kreiger, US Army Corps of Engineers*

Greg Olson, MIT*

Gregg Beckham, NREL

Iddo Wernick, Rockefeller University

Jill Martin, Dow*

Jonathan Cullen, University of Cambridge

Julie Christodoulou, Office of Naval Research*

Linda Sapochak, NSF

Mark Asta, UC Berkeley

Meghan Lewis, Carbon Leadership Forum*

Narayanan Neithalath, Arizona State

Patrick Rose, ONRG*

Per Klevnas, Materials Economics*

Robert Moser, Army Corps of Engineers*

Stefano Curtarolo. Duke University

Tresa Pollock, UC Santa Barbara

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About ITIF

The Information Technology and Innovation Foundation (ITIF) is an independent, nonprofit, nonpartisan research and educational institute focusing on the intersection of technological innovation and public policy. Recognized by its peers in the think tank community as the global center of excellence for science and technology policy, ITIF's mission is to formulate and promote policy solutions that accelerate innovation and boost productivity to spur growth, opportunity, and progress. For more information, visit www.itif.org.

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As part of Fraunhofer Gesellschaft, Europe's largest nonprofit R&D organization, CMI bridges the gap between academic research and industrial needs. In collaboration with Boston University, CMI conducts applied research and development leading to the deployment of technological solutions that enhance the productivity and competitive position of its customers, while educating engineering students in the process. Its objective is to help companies and universities translate academic research into marketable technologies in an efficient manner. For more information, please visit www.cmi.fraunhofer.org.

ENDNOTES

1. Deloitte, "2017 US Perception of the Manufacturing Industry," https://www2.deloitte.com/us/en/pages/manufacturing/articles/public-perception-of-the-manufacturing-industry.html.
2. Anthony Leiserowitz et al., "Climate activism: A Six-Americas analysis," Yale University Program on Climate Change Communication, December 2020, https://www.climatechangecommunication.org/wp-content/uploads/2021/03/climate-activism-six-americas-december-2020.pdf; Anthony Leiserowitz et al., "Politics & Global Warming," Yale University Program on Climate Change Communication, March 2021, https://www.climatechangecommunication.org/wp-content/uploads/2021/06/politics-global-warming-march-2021b.pdf.
3. IEA, "Net Zero by 2050, A Roadmap for the Global Energy Sector" (IEA, May 2021), https://iea.blob.core.windows.net/assets/ad0d4830-bd7e-47b6-838c-40d115733c13/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf.
4. Rhodium Group, "Clean Product Standards: A New Approach to Industrial Decarbonization," December 2020, https://rhg.com/research/clean-products-standard-industrial-decarbonization/.
5. Intergovernmental Panel on Climate Change (IPCC), *Special Report on Global Warming of 1.5 Degrees Celsius*, 2018, https://www.ipcc.ch/sr15/; Climate Action Tracker, "Global Update: Climate Summit Momentum," accessed May 5, 2021, https://climateactiontracker.org/publications/global-update-climate-summit-momentum/.
6. Robert D. Atkinson et al., "Worse Than the Great Depression: What the Experts Are Missing About American Manufacturing Decline," ITIF, March 19, 2012, https://itif.org/publications/2012/03/19/worse-great-depression-what-experts-are-missing-about-american-manufacturing; Adams Nager, "Trade vs. Productivity: What Caused U.S. Manufacturing's Decline and How to Revive It," ITIF, February 2017, http://www2.itif.org/2017-trade-vs-productivity.pdf; Stephen Ezell, "Policy Recommendations to Stimulate U.S. Manufacturing Innovation," ITIF, May 18, 2020, http://www2.itif.org/2020-policy-recommendations-us-manufacturing.pdf; National Association of Manufacturers, 2019 United States Manufacturing Facts, accessed May 9, 2021, https://www.nam.org/state-manufacturing-data/2019-united-states-manufacturing-facts/.
7. Josh Bivens, "Updated Employment Multipliers for the U.S. Economy," Economic Policy Institute, January 23, 2019, https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/.
8. U.S. National Science Foundation (NSF), "Key Characteristics of Domestic Business R&D Performance," January 2020, https://ncses.nsf.gov/pubs/nsb20203/u-s-business-r-d#key-characteristics-of-domestic-business-r-d-performance.
9. Statista, "Total Value of U.S. Trade in Goods Worldwide from 2004 50 2020," accessed May 8, 2021, https://www.statista.com/statistics/218255/total-value-of-us-trade-in-goods-worldwide-since-2004/.
10. See, for instance, David C. Mowery and Richard R. Nelson, eds. *Sources of Industrial Leadership* (Cambridge University Press, 1999).
11. NSF, "Cross-National Comparisons of R&D Performance," January 2020, https://ncses.nsf.gov/pubs/nsb20203/cross-national-comparisons-of-r-d-performance; Dennis Normile, "China Again Boosts R&D Spending by More than 10%," *Science*, August 28, 2020, https://www.sciencemag.org/news/2020/08/china-again-boosts-rd-spending-more-10.
12. Jetta Wong and David M. Hart, "Mind the Gap: A Design for a New Energy Technology Commercialization Foundation," ITIF, May 11, 2020, https://itif.org/publications/2020/05/11/mind-gap-design-new-energy-technology-commercialization-foundation.

13. William B. Bonvillian and Peter Singer, *Advanced Manufacturing - The New American Innovation Policies* (MIT Press, 2018); Nigel Cory and Robert D. Atkinson, "Why and How to Mount a Strong, Trilateral Response to China's Innovation Mercantilism," ITIF, January 13, 2020, https://itif.org/publications/2020/01/13/why-and-how-mount-strong-trilateral-response-chinas-innovation-mercantilism.
14. Robert D. Atkinson, "The Case for Legislation to Out-Compete China," ITIF, March 29, 2021, https://itif.org/publications/2021/03/29/case-legislation-out-compete-china.
15. Atkinson, "The Case for Legislation;" David M. Hart, *Forged Consensus: Science, Technology, and Economic Policy in the United States, 1921-1953* (Princeton University Press, 1998).
16. The Ezra Klein Show, "The Best Explanation of Biden's Thinking I've Heard," *The New York Times* April 9, 2021, https://www.nytimes.com/2021/04/09/opinion/ezra-klein-podcast-brian-deese.html.
17. Marco Rubio, *Made in China 2025 and the Future of American Industry*, Project on Strong Labor Markets and National Development, U.S. Senate Committee on Small Business and Entrepreneurship, 2020, https://www.rubio.senate.gov/public/_cache/files/d1c6db46-1a68-481a-b96e-356c8100f1b7/3EDECA923DB439A8E884C6229A4C6003.02.12.19-final-sbc-project-mic2025-report.pdf.
18. David Adler, "Inside Operation Warp Speed: A New Model for Industrial Policy," *American Affairs* 5(2), Summer 2021, https://americanaffairsjournal.org/2021/05/inside-operation-warp-speed-a-new-model-for-industrial-policy/.
19. David M. Hart, "Two Tools for Two Jobs: The Difference Between Carbon Taxes and Energy Technology Incentives," ITIF, July 3, 2019, https://itif.org/publications/2019/07/03/two-tools-two-jobs-difference-between-carbon-taxes-and-energy-technology.
20. International Energy Agency (IEA), "The Future of Hydrogen" (website) accessed May 27, 2021, https://www.iea.org/reports/the-future-of-hydrogen.
21. IEA, *The Future of Hydrogen* (IEA, 2020), 17, available at https://www.iea.org/reports/the-future-of-hydrogen.
22. Lew Milford et al., "Hydrogen Hype in the Air," Clean Energy Group, December 14, 2020, https://www.cleanegroup.org/hydrogen-hype-in-the-air/; Mark Menzies, "Hydrogen: The Burning Question," *The Chemical Engineer*, September 23, 2019, https://www.thechemicalengineer.com/features/hydrogen-the-burning-question/.
23. Mark F. Ruth et al., "The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States," National Renewable Energy Laboratory, NREL/TP-6A20-77610, 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf.
24. Fred Joseck et al., "Current U.S. Hydrogen Production" (U.S. Department of Energy, 2016), https://www.hydrogen.energy.gov/pdfs/16015_current_us_h2_production.pdf; Roger H. Bezdek, "The Hydrogen Economy and Jobs of the Future," *Renewable Energy and Environmental Sustainability* 4, 1 (2019), https://doi.org/10.1051/rees/2018005. These two sources differ considerably in their estimates of the market split between captive and merchant production in the United States.
25. Ruth et al., "Technical and Economic Potential."
26. Fuel Cell & Hydrogen Energy Association (FCHEA), *Road Map to a U.S. Hydrogen Economy* (FCHEA, 2021), https://www.fchea.org/us-hydrogen-study; Princeton Net-Zero America, "Interim Report," December 2020, 222, https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.
27. FCHEA, Road Map, 7; National Association of State Energy Offices and Energy Futures Initiative, *2020 U.S. Energy and Employment Report*, https://www.usenergyjobs.org/ xvi.
28. Ruth et al., "Technical and Economic Potential," xi.

29. Jay Bartlett and Alan Krupnick, “Decarbonized Hydrogen in the U.S. Power and Industrial Sectors” (Resources for the Future, 2020), https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/.
30. Everett Anderson, presentation at “Widening the Lens” workshop, January 27, 2021, http://www.bu.edu/ise/research/widening-the-lens-on-innovation-for-clean-manufacturing/high-temperature-manufacturing/.
31. Bartlett and Krupnick “Decarbonized Hydrogen.”
32. Ibid, 18.
33. U.S. Department of Energy (DOE), Hydrogen Program Plan (2020), https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.
34. Wood Mackenzie, “2050: The Hydrogen Possibility: Executive summary and report brochure” (Wood Mackenzie, 2021); “EU Hydrogen Strategy,” https://ec.europa.eu/commission/presscorner/detail/en/fs_20_1296; “Australia’s National Hydrogen Strategy,” https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy.
35. Global CCS Institute, “Core Facilities Database,” accessed May 7, 2021, https://co2re.co/FacilityData; Elizabeth Abramson, Dane McFarlane, and Jeff Brown, “Transport Infrastructure for Carbon Capture and Storage,” Great Plains Institute, June 2020, https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf; Carbon Capture Coalition, “45Q Tax Credit,” accessed May 27, 2021, https://carboncapturecoalition.org/45q-legislation/.
36. FCHEA, “Road Map,” 59.
37. As of June 2020, Nikola had ordered 85 MW of electrolyzers from NEL. Whether the full 1 GW project will be realized, and in what timeframe, is uncertain. Nel Hydrogen, “Nel ASA: Awarded Multi-billion NOK Electrolyzer and Fueling Station Contract by Nikola,” June 28, 2018, https://nelhydrogen.com/press-release/nel-asa-awarded-multi-billion-nok-electrolyzer-and-fueling-station-contract-by-nikola/.
38. John Parnell, “WoodMac on Green Hydrogen: It’s Going to Happen Faster Than Anyone Expects,” *Greentech Media*, February 5, 2021, https://www.greentechmedia.com/articles/read/woodmac-on-green-hydrogen-its-going-to-happen-faster-than-anyone-expects.
39. FCHEA, “Road Map,” 72.
40. Bloomberg New Energy Finance (BNEF), “`Hydrogen Economy’ Offers Promising Path to Decarbonization,” March 30, 2020, https://about.bnef.com/blog/hydrogen-economy-offers-promising-path-to-decarbonization/; IHS Markit, “Investment in Green Hydrogen Production Set to Exceed $1billion USD by 2023, According to IHS Markit,” December 3, 2020, https://news.ihsmarkit.com/prviewer/release_only/slug/2020-12-03-investment-in-green-hydrogen-production-set-to-exceed-1-billion-usd-by-2023; Wood Mackenzie, “2050: The Hydrogen Possibility.”
41. F+L Daily, “World’s Largest Green Ammonia Plant in South Australia Gets Boost,” November 6, 2020, https://www.fuelsandlubes.com/worlds-largest-green-ammonia-plant-in-south-australia-gets-boost/.
42. European Commission, “First Innovation Fund Call for Large-Scale Projects: 311 Applications,” May 11, 2020, https://ec.europa.eu/clima/news/first-innovation-fund-call-large-scale-projects-311-applications-eur-1-billion-eu-funding-clean_en; “Germany To Invest Around $10 Bln in Hydrogen Projects,” *Reuters*, May 28, 2021, https://www.reuters.com/world/europe/germany-invest-around-10-bln-hydrogen-projects-2021-05-28/.
43. Varun Sivaram et al., *Energizing America: A Roadmap to Launch a National Energy Innovation Mission* (ITIF and Columbia University SIPA Center on Global Energy Policy, 2020),

https://itif.org/publications/2020/09/15/energizing-america-roadmap-launch-national-energyinnovation-mission.

44. Colin Cunliff and Linh Nguyen, "Federal Energy RD&D: Hydrogen & Fuel Cells," ITIF, May 2021, https://itif.org/publications/2021/05/17/energizing-innovation-raising-ambition-federal-energy-rdd-fiscal-year-2022.
45. Robert Rozansky and David M. Hart, "More and Better: Building and Managing a Federal Energy Demonstration Project Portfolio," ITIF, May 2020, https://itif.org/publications/2020/05/18/more-and-better-building-and-managing-federal-energy-demonstration-project.
46. DOE, "FY 2021 Congressional Budget Justification," Volume 3 Part 1, 67–84 (DOE Chief Financial Officer DOE/CF-0163, February 2020), https://www.energy.gov/sites/prod/files/2020/02/f72/doefy2021-budget-volume-3-part-1_1.pdf.
47. DOE, "Secretary Granholm Launches Energy Earthshots Initiative to Accelerate Breakthroughs Toward a Net-Zero Economy," June 7, 2021, https://www.energy.gov/articles/secretary-granholm-launches-energy-earthshots-initiative-accelerate-breakthroughs-toward.
48. Carbon Free Technology Initiative (CFTI), "Zero-Carbon Fuels Recommendations," accessed May 6, 2021, https://www.carbonfreetech.org/Documents/CFTI%20Zero-Carbon%20Fuels%20--%20Summary%20Paper.pdf; Senator Carper Introduces Clean Hydrogen Tax Legislation, May 25, 2021, https://www.epw.senate.gov/public/_cache/files/4/0/406f71d6-9ed1-4a97-84aa-57f459b9077b/C65FA890588DA56E7876CDFB892EDB96.clean-h2-production-act-5-25-2021-introduced-gai21583.pdf.
49. H.R.1788, 117th Congress, available at https://www.congress.gov/bill/117th-congress/house-bill/1788; Varun Sivaram, "The American Recovery and Reinvestment Act and the Rise of Utility-Scale Solar Photovoltaics," American Energy Innovation Council, June 2020, http://americanenergyinnovation.org/wp-content/uploads/2020/06/The-Successful-Demonstration-of-Utility-Scale-PV.pdf.
50. Jeff St. John, "Green Hydrogen in Natural Gas Pipelines: Decarbonization Solution or Pipe Dream?" *Greentech Media*, November 30, 2020, https://www.greentechmedia.com/articles/read/green-hydrogen-in-natural-gas-pipelines-decarbonization-solution-or-pipe-dream.
51. U.S. Department of Transportation, Pipeline & Hazardous Materials Safety Administration, "Hydrogen," accessed May 28, 2021, https://primis.phmsa.dot.gov/comm/hydrogen.htm.
52. Argonne National Laboratory (ANL), "JOBS H2 and JOBS NG Model," accessed May 6, 2021, https://jobsmodels.es.anl.gov/index.php?content=h2.
53. Energy Information Administration (EIA), "Annual Energy Outlook 2021" (February 3, 2021), https://www.eia.gov/outlooks/aeo/tables_ref.php; James Cummings, "Sensible and Latent Cooling Load Control Using Centrally-Ducted, Variable-Capacity Space Conditioning Systems in Low Sensible Load Environments" (July 2021), https://www.energy.gov/sites/prod/files/2013/12/f5/issue7_sensible_loadcontrol.pdf. These figures do not include HVAC and refrigeration in industry.
54. EIA, "Annual Energy Outlook 2021" (February 3, 2021), https://www.eia.gov/outlooks/aeo/. This source attributes approximately 20 percent of U.S. carbon dioxide emissions to devices that could be replaced by heat pumps in residential and commercial buildings and to food processing and paper production. Carbon dioxide accounts for about 80 percent of all U.S. GHGs.
55. IEA, "The Future of Cooling: Opportunities for energy-efficient air conditioning—Technology Report" (May 2018), https://www.iea.org/reports/the-future-of-cooling.
56. Ibid.
57. Ibid.
58. Ibid.

59. Ibid.

60. Eric Larson et al., “Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report” (Princeton University, Princeton, NJ, December 15, 2020), https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.

61. U.S Bureau of Labor Statistic (BLS), Occupational Employment and Wage Statistics, https://www.bls.gov/oes/2016/may/naics4_333400.htm.

62. BLS, Occupational Employment and Wage Statistics—Occupational Employment and Wages, May 2020, https://www.bls.gov/oes/current/oes499021.htm#ind.

63. John Fialka, “Heat Pumps Gain Steam As Renewables Rise,” *E&E News,* April 17, 2019, https://www.eenews.net/climatewire/2019/04/17/stories/1060171793.

64. U.S. Department of Energy, Cold Climate Heat Pumps Help Consumers Stay Comfortable and Save Money, Office of Energy Efficiency & Renewable Energy, November 13, 2017, https://www.energy.gov/eere/articles/cold-climate-heat-pumps-help-consumers-stay-comfortable-and-save-money.

65. California Air Resources Board, “Choosing a New System?” accessed June 3, 2021, https://ww2.arb.ca.gov/resources/documents/choosing-new-system. The new refrigerants present fire safety hazards that may preclude their use in large units.

66. U.S. Environmental Protection Agency (EPA), “ENERGY STAR® Unit Shipment and Market Penetration Report Calendar Year 2019 Summary” (2019), https://www.energystar.gov/sites/default/files/asset/document/2019%20USD%20Summary%20Report.pdf.

67. EIA, “Residential Energy Consumption Survey (RECS)” (February 2021), https://www.eia.gov/consumption/residential/; EIA, “Residential Demand Module,” https://www.eia.gov/outlooks/aeo/assumptions/pdf/residential.pdf; EIA, “Commercial Buildings Energy Consumption Survey (CBECS),” https://www.eia.gov/consumption/commercial/data/2012/#b38-b46. To the extent possible, a retrofit program should be designed so that replacements only take place at the end of the useful life of the equipment; about 60 percent of all heating and cooling equipment installed today is less than nine years old.

68. Paul Scheinhing, Presentation at Widening the Lens workshop, February 3, 2021, http://www.bu.edu/ise/files/2021/02/Paul-Scheihing-Heat-Pumps.pdf.

69. Antonio M. Bouza, Presentation at Widening the Lens workshop, February 3, 2021, http://www.bu.edu/ise/files/2021/02/Tony-Bouza-Heat-Pumps.pdf; Mayekawa Mycom, “Eco Sirocco (CO_2 Heat Pump Air Heater),” accessed June 7, 2021, https://www.mayekawa.com.au/products/heat-pumps/eco-sirocco/,; HyET Hydrogen, “Cost Effective Electrochemical Hydrogen Processing,” accessed June 7, 2021, https://hyethydrogen.com/.

70. Xavier Moya and Neil Mathur, “Caloric Materials for Cooling and Heating,” *Science* 370, no. 6518 (2020): 797–803, https://doi.org/10.1126/science.abb0973; HeatX, Presentation at Widening the Lens workshop, February 3, 2021, http://www.bu.edu/ise/files/2021/02/Matthew-Gurwin-Heat-X.pdf; American Institute of Physics, “Squeeze To Remove Heat: Elastocaloric Materials Enable More Efficient, ‘Green’ Cooling,” March 25, 2015, https://phys.org/news/2015-03-elastocaloric-materials-enable-efficient-green.html.

71. Geothermal District Heating, “What Is Geothermal District Heating?” accessed June 3, 2021, http://geodh.eu/about-geothermal-district-heating/; Home Energy Efficiency Team (HEET), “Convening the System to Build Utility-Scale Geothermal Networks, Technical Workshop—2019,” October 29, 2019, https://heet.org/geomicrodistrict-workshop/.

72. Scheihing, Presentation at Widening the Lens workshop, February 3, 2021; Jamal Yagoobi, Presentation at Widening the Lens workshop, February 3, 2021, Electric Power Research Institute

(EPRI), "Radio Frequency Grain/Biomass Drying," February 5, 2019, https://www.epri.com/research/products/000000003002015214.

73. David Claridge, Presentation at Widening the Lens workshop, February 3, 2021, http://www.bu.edu/ise/files/2021/02/David-Claridge-Membrane-Dehumidification.pdf.
74. Stephen K. Ritter, "Putting Distillation Out Of Business in the Chemical Industry," *Chemical & Engineering News,* June 19, 2017, https://cen.acs.org/articles/95/i25/Putting-distillation-business-chemical-industry.html.
75. Oak Ridge National Laboratory (ORNL), "Multifunctional Equipment Integration Group," accessed June 3, 2021, https://www.ornl.gov/group/multifunctional-equipment-integration.
76. Paul Scheinhing, Presentation at Widening the Lens workshop, February 3, 2021, http://www.bu.edu/ise/files/2021/02/Paul-Scheihing-Heat-Pumps.pdf.
77. EIA, "Residential Energy Consumption Survey (RECS)" (February 2017),https://www.eia.gov/consumption/residential/data/2015/hc/php/hc6.1.php.
78. "Heat Pumping Technologies, Annex 35—Application of Industrial Heat Pumps," https://heatpumpingtechnologies.org/annex35/; Capgemini Invent, "Fit For Net-Zero: 55 Tech Quests To Accelerate Europe's Recovery and Pave the Way to Climate Neutrality," October 2020, https://www.capgemini.com/wp-content/uploads/2020/10/Net-zero-main-report-2020.pdf; CORDIS, "Next-Generation Heat Pump Offers More Affordable Heating and Cooling," June 21, 2018, https://phys.org/news/2018-06-next-generation-cooling.html; European Heat Pump Association, "Large Scale Heat Pumps In Europe," Vol 2 (2018), https://www.ehpa.org/fileadmin/red/03._Media/Publications/Large_heat_pumps_in_Europe_Vol_2_FINAL.pdf.
79. Air-Conditioning, Heating, & Refrigeration Institute (AHRI), "AHRI Releases December 2020 U.S. Heating and Cooling Equipment Shipment Data," February 12, 2021, https://www.ahrinet.org/App_Content/ahri/files/Statistics/Monthly%20Shipments/2020/December_2020.pdf.
80. AHRI, "Central Air Conditioners and Air-Source Heat Pumps," https://www.ahrinet.org/resources/statistics/historical-data/central-air-conditioners-and-air-source-heat-pumps.
81. AHRI, "Residential Automatic Storage Water Heaters Historical Data," n.d., https://www.ahrinet.org/resources/statistics/historical-data/residential-storage-water-heaters-historical-data.
82. IEA, "Chemicals," https://www.iea.org/reports/chemicals.
83. IEA*, The Future of Petrochemicals*. (OECD/IEA, 2018), 12, https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf.
84. Bureau of Labor Statistics, Employment Projections Data (Employment by major industry sector), accessed June 3, 2021, https://www.bls.gov/emp/tables/employment-by-major-industry-sector.htm.
85. Scott R. Nicholson et al., "Manufacturing Energy and Greenhouse Gas Emissions Associated with Plastics Consumption," *Joule* 5 (March 17,2021), 1–14, https://doi.org/10.1016/j.joule.2020.12.027.
86. IEA, "Future of Petrochemicals."
87. Mike Biddle, "Connecting the Dots: The Intersection of Plastics, Energy, and Planetary Health" (2019), NREL workshop presentation, https://www.energy.gov/sites/prod/files/2019/12/f70/beto-00-plastics-wkshp-dec-2019-biddle.pdf.
88. IEA, "Future of Petrochemicals."

89. United Nations Environmental Program (UNEP), “Global Chemicals Outlook II” (April 29, 2019), 26, https://www.unep.org/resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions.

90. IEA, “Petrochemicals Set To Be The Largest Driver Of World Oil Demand, Latest IEA Analysis Finds,” news release, October 5, 2018, https://www.iea.org/news/petrochemicals-set-to-be-the-largest-driver-of-world-oil-demand-latest-iea-analysis-finds.

91. Material Economics, “Industrial Transformation 2050” (University of Cambridge Institute for Sustainability Leadership, 2019), 46, https://materialeconomics.com/publications/industrial-transformation-2050; Jeffrey Rissman et al., “Technologies and Policies To Decarbonize Global Industry: Review and Assessment of Mitigation Drivers Through 2070,” *Applied Energy 266*, 11, https://doi.org/10.1016/j.apenergy.2020.114848.

92. Material Economics, “The Circular Economy, A Powerful Force for Climate Mitigation” (June 2018), https://materialeconomics.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1.

93. DOE, “Genome Engineering for Materials Synthesis Report,” June 2019, https://genomicscience.energy.gov/biosystemsdesign/gems/index.shtml.

94. Peter R. Christensen et al., “Closed-loop Recycling of Plastics Enabled by Dynamic Covalent Diketoenamine Bonds,” *Nature Chemistry 11* (April 22, 2019), 442–448, https://www.nature.com/articles/s41557-019-0249-2.pdf.

95. Christensen, “Closed-loop Recycling;” Alice Havill, “Composite Recycling for Manufacturing Feedstock Applications,” webinar presentation, March 2019, https://iacmi.org/wp-content/uploads/2019/04/Vartega_IACMI_Webinar__032619.pdf.

96. Matthew P. Nelsen et al., “Delayed Fungal Evolution Did Not Cause the Paleozoic Peak in Coal Production,” *Proceedings of the National Academy of Sciences*, 2016, https://www.pnas.org/content/113/9/2442#ref-9.

97. Aindrila Mukhopadhyay, Presentation at Widening the Lens workshop, February 10, 2021, http://www.bu.edu/ise/files/2021/02/Aindrila-Mukhopadhyay-Biofuels-and-Bioproducts.pdf.

98. National Academics of Sciences, Engineering, Medicine, “Industrialization of Biology, A Roadmap to Accelerate the Advanced Manufacturing of Chemicals” (National Academies Press, 2015), https://doi.org/10.17226/19001; Chong Liu et al., “Water Splitting—Biosynthetic System with CO_2 Reduction Efficiencies Exceeding Photosynthesis,” *Science 03* (AAAS, June 2016), https://science.sciencemag.org/content/352/6290/1210.

99. Melissa J. Scully et al., “Carbon Intensity of Corn Ethanol in the United States: State of the Science,” *Environmental Research Letters* 16 (March 10, 2021), https://iopscience.iop.org/article/10.1088/1748-9326/abde08/meta.

100. IEA, “Net Zero by 2050”.

101. Carson Vaughan, “Ethanol Market Is Disturbing to American Farmers. And Now There’s COVID-19,” *Successful Farming*, March 30, 2020, https://www.agriculture.com/news/business/ethanol-market-is-disturbing-as-hell-to-american-farmers-and-now-there-s-covid-19.

102. Energy Information Administration (EIA), “Monthly Energy Review.” May 2021, https://www.eia.gov/totalenergy/data/monthly/.

103. DOE, “2016 Billion-Ton Report, Advancing Domestic Resources for a Thriving Bioeconomy.” July 2016, https://www.energy.gov/eere/bioenergy/2016-billion-ton-report.

104. Katharine Sanderson, “Lignocellulose: A Chewy Problem” *Nature 474* (2011), S12–S14, https://www.nature.com/articles/474S012a.

105. David Biello, “Whatever Happened to Advanced Biofuels?” *Scientific American*, May 26, 2016, https://www.scientificamerican.com/article/whatever-happened-to-advanced-biofuels/.

106. Biotechnology Industry Organization, "Current Uses of Synthetic Biology for Renewable Chemicals, Pharmaceuticals, and Biofuels" (2013), https://archive.bio.org/articles/current-uses-synthetic-biology, https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf; NASEM, "Industrialization of Biology, A Roadmap to Accelerate the Advanced Manufacturing of Chemicals" (National Academies Press, 2015), https://doi.org/10.17226/19001.

107. Engineering Biology Research Consortium, "Engineering Biology & Materials Science: A Research Roadmap for Interdisciplinary Innovation" (2021), https://roadmap.ebrc.org/2021-roadmap-materials/.

108. James M. Clomburg, Anna M. Crumbley, and Ramon Gonzalez, "Industrial Biomanufacturing: The Future Of Chemical Production," *Science 06* (AAAS, January 2017), https://science.sciencemag.org/content/355/6320/aag0804/tab-pdf.

109. Directorate-General for Research And Innovation (European Commission), Fraunhofer ISI, University of Bologna, "Top 20 Innovative Bio-Based Products" (December 2018), https://op.europa.eu/en/publication-detail/-/publication/15135e98-81c2-11e9-9f05-01aa75ed71a1/language-en/format-PDF/source-98741617.

110. Maren Wehrs et al., "Engineering Robust Production Microbes for Large-Scale Cultivation," *Trends in Microbiology* (2019), 524–537, https://www.sciencedirect.com/science/article/pii/S0966842X19300198; Mark Warner, "Industrial Biotechnology Commercialization Handbook" (August 2019), https://drive.google.com/drive/u/0/folders/1Rg5LNp9Iw_B24vGo7tznYWIQymoby8Dq.

111. Robert E. Blankenship et al., "Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential For Improvement," *Science 13* (AAAS, May 2011), 805–809, https://science.sciencemag.org/content/332/6031/805.abstract.

112. Blankenship, "Comparing Photosynthetic;" Liu, "Water Splitting;" Mark Schwartz, "Scientists Discover a Novel Way To Make Ethanol Without Corn or Other Plants," news release, April 9, 2014, https://energy.stanford.edu/news/scientists-discover-novel-way-make-ethanol-without-corn-or-other-plants https://aip.scitation.org/doi/pdf/10.1063/1.5109785.

113. Daniel G. Nocera, Presentation at Widening the Lens workshop, February 10, 2021 https://docs.google.com/presentation/d/1qHMtJxj6Ma1WtoE83oYTeW06-OzCNCKz/edit#slide=id.p1.

114. UNEP, "Global Chemicals Outlook II" (April 29, 2019), 26, https://www.unep.org/resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions.

115. Capgemini Invent, "Fit for Net-Zero."

116. European Commission, "Circular Economy Action Plan" (March 2020), https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf; Federal Ministry of Education and Research, "Bioeconomy in Germany: Opportunities for a Bio-based and Sustainable Future" (November 2015), https://www.bmbf.de/upload_filestore/pub/Biooekonomie_in_Deutschland_Eng.pdf.

117. Philipp Gerbert et al., "Climate Paths for Germany" (Boston Consulting Group, January 2018), https://www.bcg.com/publications/2018/climate-paths-for-germany-english.

118. Science and Technology Facilities Council, "The Eight Great Technologies," last updated August 4, 2016, accessed June 3, 2021, https://stfc.ukri.org/research/engineering-and-enabling-technologies/the-eight-great-technologies/; NASEM, "Industrialization of Biology."

119. Shell, "Our Climate Target: Frequently Asked Questions," accessed June 3, 2021, https://www.shell.com/energy-and-innovation/the-energy-future/what-is-shells-net-carbon-footprint-ambition/faq.html.

120. "Global Ethanol Production," Renewable Fuels Association, accessed June 3, 2021, https://afdc.energy.gov/data/10331.

121. NASEM, "Industrialization of Biology;" DOE, "Genome Engineering for Materials Synthesis Report" (June 2019), https://genomicscience.energy.gov/biosystemsdesign/gems/index.shtml; DOE, "Plastics Innovation Challenge Draft Roadmap" (DOE, January 2021), https://www.energy.gov/sites/prod/files/2021/01/f82/Plastics Innovation Challenge Draft Roadmap.pdf; Engineering Biology Research Consortium, "Engineering Biology & Materials Science" Benjamin Wolfson, "DARPA and the Future Of Synthetic Biology," O'Reilly, December 6, 2017, https://www.oreilly.com/content/darpa-and-the-future-of-synthetic-biology/.

122. Patrick P. Rose, Presentation at Widening the Lens workshop, February 17, 2021, http://www.bu.edu/ise/files/2021/02/Patrick-Rose-Bioindustrial-Manufacturing.pdf; Greg B. Olson, "Computational Materials Design: Affordable Change," Presentation at Widening the Lens workshop, February 17, 2021, http://www.bu.edu/ise/files/2021/02/Greg-Olson-Computational-Materials.pdf.

123. NASEM, "Industrialization of Biology."

124. Meghan Lewis, Presentation at Widening the Lens workshop, February 17, 2021, http://www.bu.edu/ise/files/2021/02/Meghan-Lewis-Embodied-Carbon.pdf; Duane Dickson, David Yankovitz, and Aijaz Hussain, "Building Resilience in Petrochemicals" (Deloitte, October 2020), https://www2.deloitte.com/us/en/insights/industry/oil-and-gas/building-resilience-petrochemical-market.html; "Welcome to Tharaldson Ethanol," accessed June 3, 2021, http://www.tharaldsonethanol.com/.

125. The European Commission, "Circular Economy Action Plan" (2020), https://ec.europa.eu/environment/pdf/circular-economy/new_circular_economy_action_plan.pdf.

126. Greg T. Beckham, "Introduction to the Bottle Consortium," presentation at the DOE AMO/BTO Plastics for a Circular Economy Workshop (NREL, 2019), https://www.energy.gov/sites/prod/files/2019/12/f70/beto-05-plastics-wkshp-dec-2019-beckham_0.pdf.

127. USDA, "About the BioPreferred Program," and "BioPreferred Product Categories," accessed June 3, 2021, https://www.biopreferred.gov/BioPreferred/faces/pages/AboutBioPreferred.xhtml.

128. Matt Terwillegar, "Monomers and Polymers Derived from Biological Sources: Opportunities and Challenges," presentation at the DOE AMO/BTO Plastics for a Circular Economy Workshop (Danimer Scientific, January 2020), https://www.energy.gov/sites/prod/files/2020/01/f70/beto-01-plastics-wkshp-dec-2019-terwillegar.pdf.

129. Sue Retka Schill, "Agrebon to Install Biogas-To-Nitrogen Technology at Ethanol Plant," *Biomass Magazine*, April 8, 2013, http://biomassmagazine.com/articles/8852/agrebon-to-install-biogas-to-nitrogen-technology-at-ethanol-plant ; USDA, "Grants and Loans," accessed June 3, 2021, https://www.biopreferred.gov/BioPreferred/faces/pages/USDALoansAndGrants.xhtml.

130. Mario Herrero et al., "Greenhouse Gas Mitigation Potentials in the Livestock Sector," *Nature Climate Change* 6 (2016), 453, https://www-nature-com.mutex.gmu.edu/articles/nclimate2925.pdf.

131. Intergovernmental Panel on Climate Change (IPCC), *Special Report on Climate Change and Land* (IPCC, 2019), 477, https://www.ipcc.ch/site/assets/uploads/sites/4/2021/02/08_Chapter-5_3.pdf.

132. Carbon Trust, "Quorn Footprint Comparison Report" (March 2018), 17, https://www.quorn.co.uk/assets/files/content/Carbon-Trust-Comparison-Report-2018.pdf.

133. Ingrid Odegard, "LCA of Cultivated Meat. Future Projections for Different Scenarios," CE Delft, February 2021, https://www.cedelft.eu/en/publications/2610/lca-of-cultivated-meat-future-projections-for-different-scenarios This estimate assumes renewable electricity is used. If conventional electricity, the beef gain is 22–55% while pork and chicken are negative.

134. Breakthrough Energy, "Alternate Proteins," accessed May 9, 2021, https://www.breakthroughenergy.org/us-policy-overview/agriculture/alternate-proteins. Additional comparisons can be found in Natalie R. Rubio, Ning Xiang, and David L. Kaplan, "Plant-based and cell-based approaches to meat production," *Nature Communications* 11:6276 (2020), December 8,

https://doi.org/10.1038/s41467-020-20061-y; and Raychel E. Santo et al., "Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective," *Frontiers in Sustainable Food Systems*, August 31, 2020, https://doi.org/10.3389/fsufs.2020.00134.

135. J. Poore and T. Nemecek, "Reducing Food's Environmental Impacts Through Producers and Consumers," *Science* 360:987-992 (2018), 10.1126/science.aaq0216.
136. Bureau of Labor Statistics estimates for NAICS 311500 and 311600 in May 2020, accessed via bls.gov "Data Finder," May 29, 2021.
137. Saloni Shah and Dan Blaustein-Rejto, "Federal Support for Alternative Protein for Economic Recovery and Climate Mitigation," Breakthrough Institute, May 2020, https://thebreakthrough.org/articles/federal-support-for-alt-protein.
138. Impossible Foods, "Heme," accessed May 9, 2021, https://impossiblefoods.com/heme.
139. Good Food Institute (GFI), "2019 State of the Industry Report: Cultivated Meat," 2019, 4
140. Aindrila Mukhopadhyay, Presentation at Widening the Lens workshop, February 10, 2021; Brian H. Davison and Jefferson C. Lievense, "Technology Challenges and Opportunities," *CEP Magazine* (AIChE), June 2016, 35–42; Rubio, "Plant-Based and Cell-Based Approaches;" Bjorne Witte et al, "Food for Thought: The Protein Transformation," Boston Consulting Group, March 2021, https://www.bcg.com/en-us/publications/2021/the-benefits-of-plant-based-meats; Elie Dolgin, "Will Cell-Based Meat Ever Be a Dinner Staple?" *Nature* 588, December 9, 2020, S64–S67, https://doi.org/10.1038/d41586-020-03448-1.
141. Witte, "Food for Thought;" Rubio, "Plant-Based and Cell-Based Approaches;" Laura Reiley, "Raising the Steaks: First 3-D-Printed Rib-Eye Is Unveiled," *Washington Post*, February 9, 2021, https://www.washingtonpost.com/business/2021/02/09/3d-printed-ribeye-steak-usda-fda/.
142. Andrew Freedman, "New Culture War: The Meat You Eat," *Axios*, May 4, 2021, https://www.axios.com/food-climate-culture-wars-214118ef-6cc3-487a-9a21-ef5648ca8a81.html; Brian Sylvester presentation at "Widening the Lens" workshop 3, February 10, 2021.
143. NSF, "Cross-National Comparisons of Government R&D Priorities," January 2020, figure 4-11, https://ncses.nsf.gov/pubs/nsb20203/recent-trends-in-federal-support-for-u-s-r-d#cross-national-comparisons-of-government-r-d-priorities.
144. Dolgin, "Will Cell-Based Meat."
145. Liz Specht Presentation at Widening the Lens workshop, February 10, 2021; GFI, "Cultivated Meat," 4; GFI, "2019 State of the Industry Report: Fermentation," 2019, 40; Megan Poinski, "$3.1 Billion Invested in Alternative Proteins in 2020, Report Says," *Food Dive*, March 19, 2021, https://www.fooddive.com/news/31b-invested-in-alternative-proteins-in-2020-report-says/596993/.
146. GFI, "Fermentation," 66.
147. Lilliana Byington, "The Winners and Losers for Category Sales during the First 7 Months of the Pandemic," *Food Dive*, October 28, 2020, https://www.fooddive.com/news/the-winners-and-losers-for-category-sales-during-the-first-7-months-of-the/587793/; Jessi Devenyns, "Only 3 in 10 U.S. Consumers Would Buy Cultured Meat, Study Finds," November 28, 2018, https://www.fooddive.com/news/only-3-in-10-us-consumers-would-buy-cultured-meat-study-finds/543011/.
148. Bonvillian and Singer, *Advanced Manufacturing*; Ovais Subhani, "Temasek in Food-Tech Innovation Ventures with A*Star," *Straits Times*, November 20, 2020, https://www.straitstimes.com/business/economy/temasek-in-food-tech-innovation-venture-with-astar.
149. Specht presentation, February 10, 2021; Open discussion, "Widening the Lens" workshop 3, February 10, 2021.

150. Katy Christiansen, "ABPDU Celebrates Successes and its 50th Industry Partner," May 4, 2020, https://www.energy.gov/eere/bioenergy/articles/abpdu-celebrates-successes-and-its-50th-industry-partner; Mukhopadhyay presentation, February 10, 2021; University of Minnesota, "U.S. Department of Defense Awards $87.5 Million to Create a New Manufacturing Innovation Institute Sited at the University of Minnesota," October 20, 2020, https://twin-cities.umn.edu/news-events/us-department-defense-awards-875-million-create-new-manufacturing-innovation-institute.

151. Dolgin, "Will Cell-Based Meat."

152. Bryant, Christopher et al., "A Survey of Consumer Perceptions of Plant-Based and Clean Meat in the USA, India, and China," *Frontiers in Sustainable Food Systems,* February 27, 2019, https://doi.org/10.3389/fsufs.2019.00011.

153. Specht presentation, February 10, 2021.

154. Alex Smith, Saloni Shah, and Dan Blaustein-Rejto, "The Case for Public Investment in Alternative Proteins," Breakthrough Institute, March 30, 2021, https://thebreakthrough.org/issues/food/case-for-public-investment-in-alt-proteins. President Biden's fiscal year 2022 budget proposal includes $5 million to support AGARDA and $95 million within the USDA to support a new ARPA-C, which could also fund such research.

155. Specht presentation, February 10, 2021.

156. Val Giddings, "How the Biden Administration Can Accelerate Prosperity by Fixing Agricultural-Biotech Regulations," ITIF, March 31, 2021, https://itif.org/publications/2021/03/31/how-biden-administration-can-accelerate-prosperity-fixing-agricultural.

157. Gene Baur, "The Best Way To Help Dairy Farmers Is To Get Them Out of Dairy Farming," *Washington Post*, June 12, 2019, https://www.washingtonpost.com/opinions/2019/06/12/best-way-help-dairy-farmers-is-get-them-out-dairy-farming/; "Dairy Alternative Labeling Debate Continues," *National Law Review*, March 26, 2021, https://www.natlawreview.com/article/dairy-alternative-labeling-debate-continues.

158. Breakthrough Energy, "U.S. Federal Policy Playbook: Alternative Protein Procurement," https://www.breakthroughenergy.org/api/playbookbuilder/downloadplaybook?playbookId=f908e712-12a5-4b60-a5ee-b653db33b95b.

159. Emma Newberger, "Biden's Climate Change Strategy Looks to Pay Farmers to Curb Carbon Footprint," February 12, 2021, https://www.cnbc.com/2021/02/12/bidens-climate-change-plan-pay-farmers-to-cut-carbon-footprint.html.

160. "Widening the Lens on Innovation for Clean Manufacturing: Greening High-Temperature Manufacturing: Toward an RD&D Agenda," workshop presentations, January 27, 2021, https://itif.org/events/2021/01/27/widening-lens-innovation-clean-manufacturing-greening-high-temperature.

161. "Widening the Lens on Innovation for Clean Manufacturing: Low-Temperature Manufacturing," workshop presentations, February 3, 2021, https://itif.org/events/2021/02/03/widening-lens-innovation-clean-manufacturing-low-temperature-manufacturing.

162. "Widening the Lens on Innovation for Clean Manufacturing: Bio-Manufacturing," workshop presentations, February 10, 2021, https://itif.org/events/2021/02/10/widening-lens-innovation-clean-manufacturing-bio-manufacturing.

163. "Widening the Lens on Innovation for Clean Manufacturing: Alternative Materials Manufacturing," workshop presentations, February 17, 2021, https://itif.org/events/2021/02/17/widening-lens-innovation-clean-manufacturing-alternative-materials-manufacturing.