CLEAN POWER FOR INDUSTRY: UNLOCKING FLEXIBLE, RENEWABLE ENERGY FOR INDUSTRIAL HEAT PROCESSES

Anna Johnson,
Andrew Hoffmeister,
Ed Rightor

August 2023
ACEEE Report

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Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

About the Authors

Anna Johnson is a senior researcher with the Industrial Program at ACEEE, working on a range of industrial decarbonization technology and policy projects. Prior to joining ACEEE, Anna worked at the Western Pennsylvania Conservancy, in the Pennsylvania Natural Heritage Program as a conservation planner and communication specialist. She earned a PhD in geography and environmental systems from University of Maryland, Baltimore County, and a bachelor of arts in Liberal Arts from St. John's College in Annapolis, MD.

Andrew Hoffmeister conducts research on industrial decarbonization for ACEEE's industrial team. His work focuses primarily on the analysis of emerging technologies, such as industrial heat pumps, and policy research at the state, federal, and international level. Andrew earned a bachelor of science degree in earth and environmental science from Vanderbilt University.

Edward Rightor is the principal at Rightor consulting, and the previous director of the Center for Clean Energy Innovation at the Information Technology and Innovation Foundation (ITIF). Prior to joining ITIF, he was the director of ACEEE's Industrial Program. Ed also held several leadership roles at Dow Chemical during his 31-year career there, and holds three patents. He earned a PhD in chemistry from Michigan State University and a bachelor of science in chemistry from Marietta College.

Acknowledgments

This report was made possible through the generous support of Breakthrough Energy Foundation. The authors gratefully acknowledge external reviewers, internal reviewers, colleagues, and sponsors who supported this report. External expert reviewers included Colin McMillan (National Renewable Energy Lab), Abigail Registky (Breakthrough Energy Foundation), and one anonymous reviewer. Internal reviewers included Nora Esram, Steve Nadel, and Edward Yim. The authors also gratefully acknowledge the expert advice of Ahmad Abbas (Oak Ridge National Laboratory), Ammi Amaranth (Electric Power Research Institute), Justin Baca (Solar Energy Industry Association), Ted Borer (Princeton University), Blaine Collison (Renewable Thermal Collaborative), Rick Kotze (Stonyfield), Eric Masanet (UC Santa Barbara), Paulomi Nandy (Oak Ridge National Laboratory), Shawn Rumery (Solar Energy Industry Association), Kris Spaulding (Brewers Association), Kiran Thirumaran (Oak Ridge National Laboratory), and Thomas Wenning (Oak Ridge National Laboratory). External review and support do not imply affiliation or endorsement. Last, we would like to thank Ethan Taylor for managing the editing process, Mariel Wolfson for developmental editing, Phoebe Spanier for copy editing, Roxanna Usher for proofreading, Kate Doughty for graphics design, and Mary Robert Carter and Ben Somberg for their help in launching this report.

Suggested Citation

Johnson, A., A. Hoffmeister, and E. Rightor. 2023. Clean Power for Industry: Unlocking Flexible, Renewable Energy for Industrial Heat Processes. Washington, DC: ACEEE. aceee.org/research-report/I2302.

Executive Summary

BACKGROUND

- Successful decarbonization of industrial manufacturing, including substantial reduction in the reliance on fossil fuels for industrial process heat, is necessary to meet economy-wide emissions reductions goals in the United States.
- Renewable energy generated from wind turbines and solar photovoltaic panels is rapidly increasing its portion of the power supply in the United States as the power sector transitions toward a net zero emissions grid.
- To accommodate and take advantage of the inherent variability of wind and solar energy and the more geographically distributed nature of renewable energy resources, industry will need to change the way it manages energy.
- Large industrial energy customers have the opportunity to play an important role in facilitating this transformation in how our economy uses and manages energy.

KEY FINDINGS

- For the near term (present day–2030), we have identified a set of commercially viable tools that can be deployed now and will have a substantial impact on the carbon intensity of industrial processes. These include energy efficiency, industrial electrification, demand flexibility enabled by smart manufacturing, energy storage, and other approaches that allow industry to operate more efficiently and also to participate profitably in energy markets.
- The optimal tools available to industry vary by geographic location, industry subsector, facility size, and energy market. We describe how industrial starting points toward decarbonization are dependent on these characteristics, and also how new federal investments in industrial decarbonization can be leveraged.
- We highlight the key roles that third-party stakeholders and solutions providers are playing in facilitating early-stage industrial decarbonization efforts.
- We conclude with three scenarios that support utilization of renewable power to meet industrial energy demand: efficient, beneficial electrification of industrial process heat; monetizing flexible industrial loads; and building networks of social and economic support to advance industrial decarbonization.

Decarbonization of the industrial sector—the reduction or elimination of carbon-emitting processes—is critical for transforming how our nation uses energy, as more than a quarter of GHG emissions in the United States come from industrial activities. Substantial progress toward industrial decarbonization is also a necessary step toward building a resilient and sustainable economy for future generations. The industrial sector is often characterized as hard to decarbonize, in large part due to the high proportion of energy that is consumed in the form of fossil fuels for process heating. Finding a path to rapidly transition industrial energy demand, including process heating needs, from fossil fuels to electricity while simultaneously increasing the supply of emissions-free, renewable energy can bring the United States close to meeting many of our more ambitious climate and carbon goals. Wind- and solar-powered energy sources, along with hydropower, are often referred to as "variable renewable energy" because the timing of energy availability, as well as the quantity produced, varies depending on weather conditions, season, and time of day. Wind and solar energy sources, in particular, are likely to make up a substantial portion of our power sector in the future.

This report sets out a suite of tools and strategies that can feasibly be assembled today to set the stage for successful electrification of industrial process heat while maximizing industrial utilization of low-carbon variable renewable energy sources. We discuss how the tools and strategies available to three main stakeholder groups—industrial facilities; grid operators, managers, and regulators; and third-party solutions providers—can complement one another. We also search for places where incentives align best across these stakeholder groups. In particular we focus on how third-party solutions providers can play a key role in the energy ecosystem by facilitating more coordination between industrial energy users and the broader power grid. Industrial stakeholders, by virtue of often being one of the largest power consumers within a grid operating area, can substantially impact broader grid function. Third-party solutions providers can support integration across both supply- and demand-side strategies for managing low-carbon electricity.

Industrial facilities can implement a variety of tools and strategies to advance decarbonization goals. In this report, we highlight a set of impactful first steps that can improve the functioning of current industrial systems via enhanced energy efficiency, cost savings, and expanded markets while also unlocking future decarbonization potential as variable renewable energy (VRE) sources become more dominant across the electrical grid. The approaches we identify include

- energy efficiency and smart manufacturing
- electrification via industrial heat pumps and electric boilers
- highly efficient new technologies to support industrial electrification
- industrial demand flexibility resources, including participation in new energy markets, energy storage technologies, fuel switching, and combined heat and power (CHP)
- shifts in industrial business strategy and energy management approaches

The structure and management of the power sector creates conditions that can incentivize and support adoption of new industrial energy technologies, or produce regulatory barriers and roadblocks as a result of insufficient infrastructure and energy resources. We discuss in this report how aspects of energy utility and distribution that influence low-carbon energy supply, reliability, and flexibility are essential to industrial decarbonization progress.

Finally, we highlight the key integrating role third-party stakeholders can play by connecting industrial players and the power sector. These key integrative roles include

- supporting industrial facilities in navigating the utility regulatory environment
- supporting participation in ancillary services or energy markets by industrial power users
- enabling information sharing between stakeholder groups and building data communications platforms
- building social support via peer-to-peer collaboration networks
- de-risking new industrial decarbonization technologies through policy and funding support

We conclude with three focal scenarios to support integration across energy supply and energy demand and build synergies between stakeholder groups. These approaches to "putting together the pieces" are

- efficient beneficial electrification of industrial process heat
- monetizing flexible industrial loads
- investing in social and economic support for industrial decarbonization strategy deployment

Large industrial energy consumers have the opportunity to demonstrate how new technologies and updated energy management strategies can support a reliable, resilient, efficient, affordable, and low-carbon electrical grid for all. Flexible, beneficial electrification of industrial process heat, and the associated increasing demand for low-carbon power, can support ongoing expansion of renewable energy supply. A rapid increase in large industrial customer demand for clean energy could potentially drive electricity costs down, allow for expansion of transmission and distribution infrastructure, and lead to nationwide adoption of utility policies that incentivize the most efficient utilization of low-carbon power.

Introduction

In an effort to mitigate the worst impacts of global climate change, ambitious greenhouse gas (GHG) emissions reductions commitments made by nations, regions, cities, and companies have led to a wide range of investments and strategies to reach a net zero GHG emitting global economy. In the United States, over a quarter of GHG emissions come from industrial activity, but limited progress has been made, to date, on cutting emissions from this sector at the scale needed to address the problem. However, successful industrial decarbonization—the reduction or elimination of carbon-emitting processes—is critical for transforming how our nation uses energy and for building a resilient and sustainable economy for future generations.

The industrial sector is often described as especially hard to decarbonize. Heavy manufacturing industries are energy intensive and frequently rely on fossil fuels to heat materials to extremely high temperatures; for example, cement manufacturing kilns need to heat materials to temperatures of up to 1,450°C, well beyond the limit of most electric heating technologies. Industrial process heat makes up the bulk of energy-related carbon emissions in industry (figure 1). Even with less extreme industrial process temperatures (e.g., breweries, paper mills, or dairy processing facilities), where commercially viable technologies exist to provide the necessary heat without fossil fuels, industry has not jumped to electrify process heating. The equipment, feedstocks, and infrastructure within industrial facilities are all integral to both the business and economics of industry. Companies are often slow to pursue new business models, even when there are clear advantages to new technologies and strategies. The direct linkages and deep integration between equipment, energy usage, production methods, operating practices, and profit margins are all barriers to rapid progress toward decarbonization at the scale necessary to meet urgent climate goals. Additionally, the variability of infrastructure and practices from industry to industry—or even between facilities within the same industry—makes it difficult to deploy a small number of drop-in solutions widely.

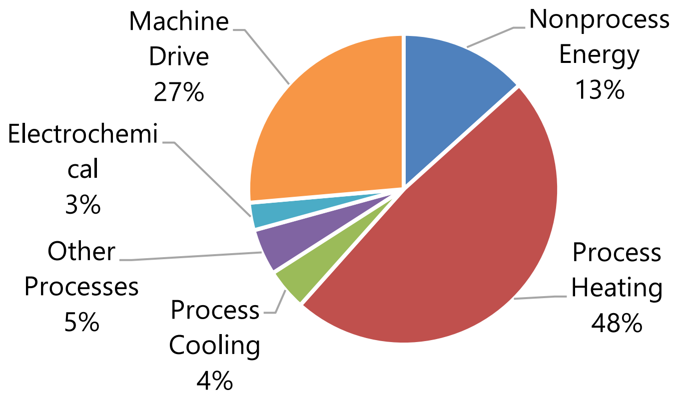

Figure 1. CO_2 emissions from manufacturing sources. Source: 2018 MECS.

While the energy-intensive, complex, and risk-averse nature of industry is often seen as a barrier to decarbonization, the industrial sector can also provide unique opportunities for reaching carbon emissions targets and transforming our energy economy. The majority of GHG emissions in industry (which constitutes 30% of the total emissions in the United States) are condensed into a relatively small number of facilities; successful interventions in a handful of these major emitters would lead to substantial, encouraging progress toward economy-wide decarbonization goals. High profile successes within industry subsectors can drive uptake of new technologies and demand for lower-carbon goods, building momentum rapidly for more sustainable manufacturing. Some industry players have also found ways to profitably participate in energy markets, expanding business practices to include not just manufactured products but also the energy consumed. Large, new demand for clean energy for industrial manufacturing can help to advance a net zero grid for all, encouraging investment in utility-scale renewable supply and the accompanying technologies to best manage this reimagined power sector. A thoughtful and integrative approach to developing supportive policy to kickstart near-term industrial emissions reductions can set the stage for the necessary decarbonization of the entire economy to occur by 2050, while simultaneously improving industrial competitiveness, resilience, and workforce capabilities.

Decarbonization of the industrial sector, however, requires that the electricity consumed by industrial processes be low carbon. Finding a path to rapidly transition industrial energy demand to electricity while simultaneously increasing the supply of emissions-free, renewable energy can bring the United States close to meeting many of our more ambitious climate and carbon goals. The U.S. electric power grid is the sector that has made the most progress to date toward decarbonization. Current federal targets aim for 100% carbon pollution–free electricity by 2035, an ambitious goal that is technically possible (Denholm et al. 2021), but for which no single clear path has yet been defined. As the power sector decarbonizes, the renewable share of the U.S. power supply is rapidly increasing, mostly driven by expansion of wind and solar photovoltaic (PV). Renewable generation has more than doubled since 2010, with even faster growth in some regions of the country, such as California and the Southwest Power Pool (SPP) region (Comstock 2022). Wind and solar-powered energy sources, along with hydropower, are often referred to as *variable renewable energy* because the timing of energy availability, as well as the quantity produced, varies diurnally, seasonally, and interannually, depending on weather conditions. Additionally, these variable power sources tend to be more geographically distributed across the landscape (e.g., solar panels on residential homes or wind turbines along ridgelines), compared to traditional electric grids that rely on a small number of large, central power plants. As both wind and solar power are likely to provide the bulk of low-carbon energy sources in U.S. grids in the future (Brinkman et al. 2021), policies, management strategies, and technologies are needed to ensure that a more distributed electric grid dominated by these variable power sources can still reliably meet our nation’s energy demands; industry must also design new systems that best take advantage of the inherent characteristics of these new power sources.

Substantial industrial electrification—primarily the shift from fossil-fuel driven process heating to electrically driven processes (e.g., industrial heat pumps)—combined with the power sector's steady movement toward lower-carbon sources between now and 2050 are both necessary and technically achievable steps toward decarbonization of the U.S. economy (Worrell and Boyd 2022; Kroposki 2017). But even as numerous roadmaps and models are developed to usher the various industrial sectors toward decarbonization, and new regulations and policies at the state and federal level are passed to create further incentives to decarbonize rapidly (e.g., Davenport and Friedman 2023), uncertainty remains over the current best practices and optimal first steps that stakeholders should take in the industrial decarbonization space, particularly regarding how industrial demand-side needs should interact with a variable renewable power–dominated grid. Moreover, as industrial heat process equipment is electrified, and industrial manufacturing sectors expand in the United States (e.g., electric vehicle and semiconductor manufacturing), industrial demand is only expected to increase for a consistent and reliable supply of clean electricity.

This report explores how the opportunities and challenges inherent in a low-carbon power sector dominated by variable renewable energy affect the near-term pathways to industrial decarbonization, especially through beneficial industrial electrification (Rightor, Whitlock, and Elliott 2020). Based on a literature review and expert interviews, we identify key tools and opportunities along the path to industrial decarbonization. As we describe strategies to achieve better integration of low-carbon energy supply and energy demand, we also highlight key stakeholders that are playing important roles in ensuring the shifting practices on both the energy supply and industrial energy demand side are complementary (figure 2).

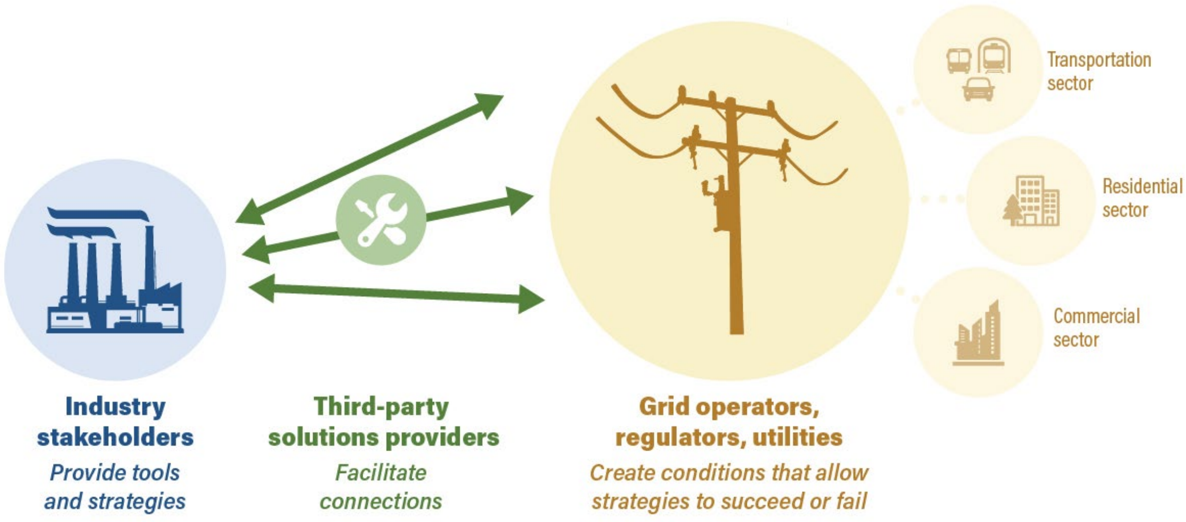

Figure 2. Third-party solutions providers play a key role in the energy ecosystem by facilitating connections between industrial stakeholders and the broader power grid. Industrial stakeholders, who are often one of the largest power consumers within a grid operating area, can have an outsized impact on broader grid function. Third-party solutions providers, by helping to integrate across low-carbon energy supply and demand, fill a key niche: They allow industrial facilities to address decarbonization goals while still maintaining needed

levels of production and economic viability, and avoiding negative impacts on broader grid reliability and access to energy by other economic sectors.

We gather a suite of tools and strategies that can feasibly be assembled today to set the stage for successful electrification of industrial process heat, while maximizing the utilization of low-carbon variable renewable energy sources, given current regulatory, economic, technical, or informational constraints. We discuss how the tools and strategies available to industrial facilities; grid operators, managers, and regulators; and third-party solutions providers can complement one another, and search for places where incentives align best across stakeholder groups.

Integrating Grid and Industrial Progress toward Decarbonization

Electrification of industrial process heat is maximally beneficial when industrial facilities consume electricity from low-carbon sources. Many industrial companies, especially larger and well-resourced ones, address this issue by signing power purchase agreements (PPAs) and purchasing the associated renewable energy credits (RECs) to cover their current electrical load. PPAs, however, are rapidly increasing in price (Penrod 2022), making it more difficult for smaller or less well-resourced companies to use this decarbonization tool to address Scope 2 emissions[1] from their consumption of delivered energy. For low-carbon power to be available more equitably, the power sector must more broadly transform how it generates, stores, distributes, prices, and regulates electricity, and work with industry to incentivize electrification of processes driven by onsite fossil fuel combustion.

The U.S. electrical grid was designed around large, central power generators, some of which are easily dispatchable (i.e., power is available on-demand), with power flowing in one direction over long distances via high voltage transmission lines, from utility-scale generators (mostly coal-fired) to consumers. Today, power generation in the electric grid is increasingly distributed, with many more, smaller, power sources that are more variable in timing and availability, such as solar panels on buildings. These distributed energy technologies require bidirectional flow of both information and electrons to be managed optimally (Henderson, Novosel, and Crow 2017; Zhou, Hurlbut, and Xu 2021). As the grid becomes more structurally complex, industry—especially energy-intensive industries—will have to be more intentional about how they consume power and interact with the grid.

In this report, we will focus on how grid operators can deliver reliable, low-carbon power to industrial consumers at the scale necessary to match their growing demand for clean

[1] Scope 2 emissions consist of the emissions caused indirectly by a company, as a result of the production of the energy they use or purchase.

electricity, while highlighting some of the strategies and technologies that support industry taking greater advantage of the characteristics of variable renewable power.

ENSURING ADEQUATE CLEAN ENERGY SUPPLY TO MATCH INDUSTRIAL ENERGY DEMAND

Carbon intensity, as well as overall carbon emissions from the power sector, have been consistently declining in the United States, with average annual emissions approximately 40% below 2005 levels in 2021 (EIA 2022). This has largely been driven by retirement of coal-fired power plants, with capacity replacement by more efficient natural gas–fired power plants[2] and variable renewable wind and solar farms (figure 3).

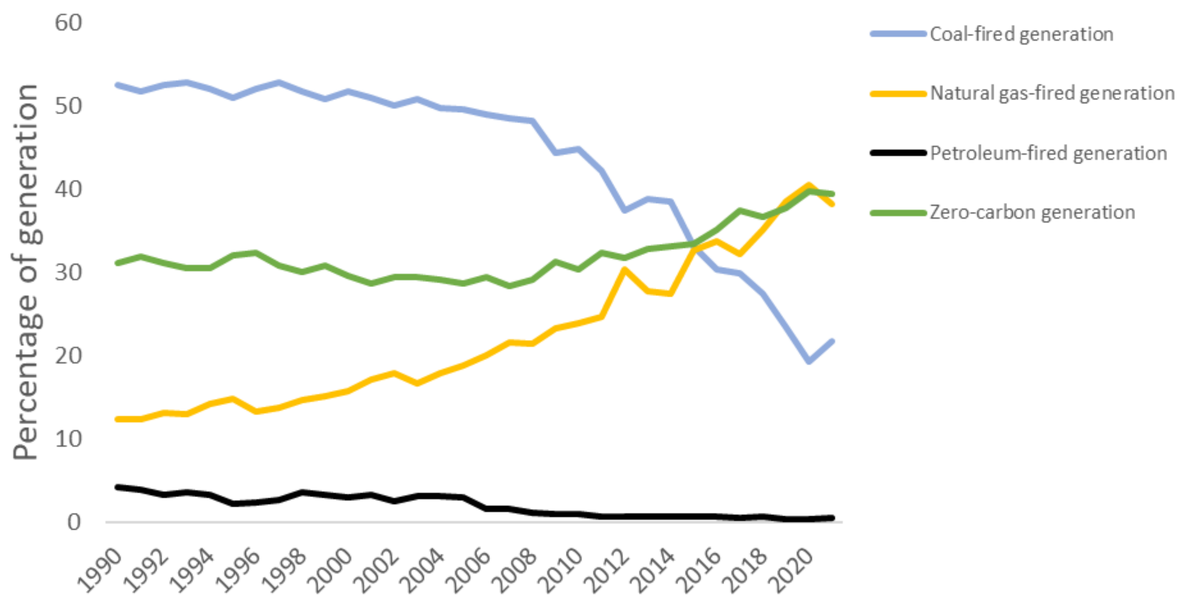

Figure 3. Percentage of electricity generation by source. In 2021, for the first time, zero-carbon generation (a category that includes nuclear, hydroelectric, wind, solar, and other renewables) was the largest single category of electricity generation in the U.S. Data source: U.S. Energy Information Administration (EIA).

This average trend in carbon intensity of grid power, however, is not predictive of the local availability of low-carbon electricity. Carbon intensity of the power supply varies dramatically across the United States (figure 4), as some states continue to source the vast majority of their power from carbon-intensive fossil fuels (coal-fired power plants still dominate the power sector in states such as Indiana, West Virginia, and Wyoming), while other states are

[2] When accounting more fully for methane released throughout natural gas production and transport, however, much of the apparent climate-change advantages of natural gas–fired power plants versus coal-fired power plants erodes (Alvarez et al. 2018).

already moving rapidly toward a variable renewable dominated power sector (wind-dominated South Dakota and Oklahoma, or solar-dominated California), or historically have relied on other low-carbon power sources (hydroelectric power in Idaho or Washington, nuclear power in New Hampshire and South Carolina).

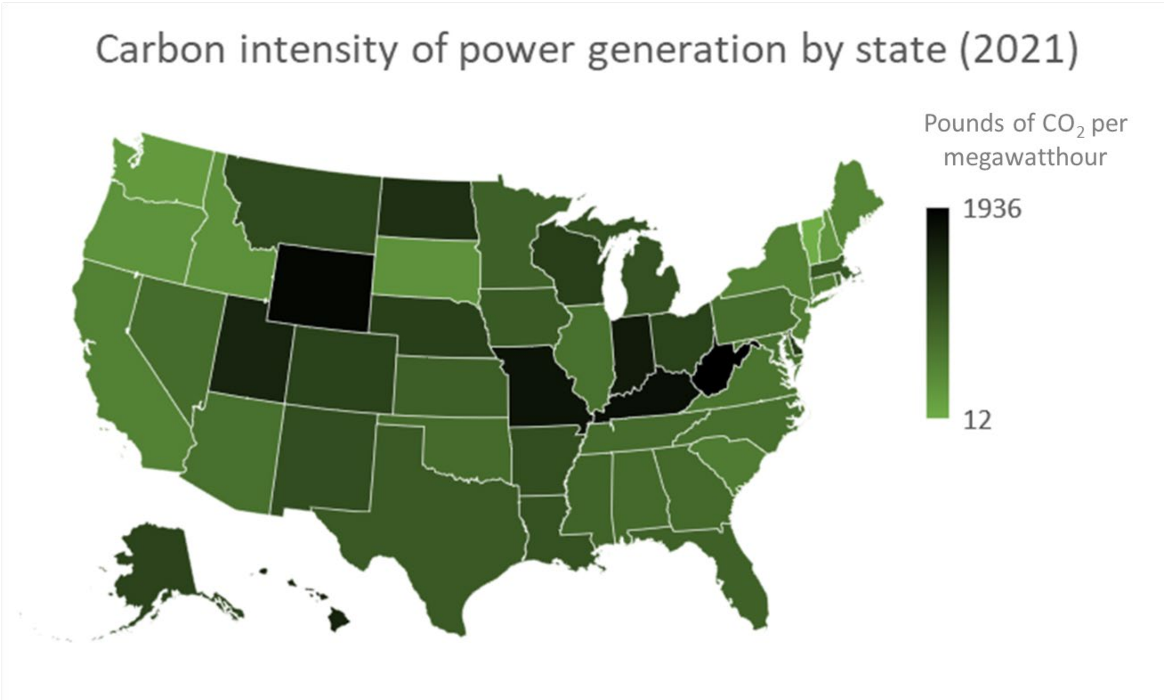

Figure 4. Map showing the high level of variability of power-sector carbon intensity across the country; on average, power generated in the most carbon-intensive states produces at least seven times the emissions per megawatthour as power generated in the least carbon-intensive states. Data source: EIA Electric Power Annual 2021.

LACK OF CLEAN ENERGY CAN BE A BARRIER TO INDUSTRIAL DECARBONIZATION PROGRESS

The current variability of power sector emissions across the country leads to geographic differences in the success of industrial decarbonization technologies. For example, electric boilers are a key industrial electrification technology for decarbonizing process heat. Boilers currently account for 17% of energy demand for U.S manufacturing, yet only 2.6% of energy supplied to conventional boilers across manufacturing sectors is electric (Zuberi, Hasanbeigi, and Morrow 2021). Recent analyses (Zuberi, Hasanbeigi, and Morrow 2021; Schoeneberger et al. 2022) have found that there are only a handful of regions in the United States today where widespread electrification of industrial boilers would lead to reduced carbon emissions due to increased electric demand from carbon-intensive grids. As grids across the country decarbonize, electric boilers' impact as an industrial decarbonization technology will increase. A recent study estimates the current technical potential energy savings by electrifying industrial boilers at 445 PJ per year of final energy use or 21% of the U.S. industrial boiler energy demand in 2018. If fully implemented, the study also estimates that electric boilers can reduce the boiler onsite energy demand by 16–29% in various industrial sectors (Zuberi, Hasanbeigi, and Morrow 2021) .

Despite the growing capacity for renewable power generation in the United States, adequate supply of low- or zero-carbon power remains a concern for many industrial companies, especially as they consider construction of new facilities intended to be fully powered by renewable sources. Additionally, given the variability of wind and solar, a greater relative generation capacity of these variable renewable sources must be installed to replace fossil-fuel powered plants (Bolson, Prieto, and Patzek 2022). For example, large utilities in Georgia are struggling to supply enough solar power to support clean energy demand from new commercial and industrial facilities (Lutz 2023). This is indicative of challenges ahead, as demand for clean power is expected to grow considerably in the coming years in the United States, driven by recent industrial policy investments that have led to an expansion of manufacturing, including by companies that have committed to near-term transitions to fully carbon neutral operations in both their manufacturing facilities and supply chains.

Other barriers to industry's ability to access an adequate clean power supply include the cost and time to upgrade transmission and distribution infrastructure, build new interregional transmission, and connect new renewable supply to the grid; a suite of permitting reforms and other strategies for expediting this process will be necessary in the coming years for renewable supply to match demand (Osaka 2022). Industry may also need to more directly engage with utility planning processes, to ensure that large, flexible, industrial consumer loads can be viewed as a system resource (Polymeneas, Tai, and Wagner 2018).

Energy efficiency strategies for supporting industrial electrification

Rather than wait for clean energy supply to increase before engaging in strategies to reduce carbon emissions, industry can leverage energy efficiency interventions as an essential tool for enabling quicker, cost-effective decarbonization progress; the industrial sector historically saves more energy per efficiency program dollar than other customer classes (Goldberg, Taylor, and Hedman 2014). By implementing new, more efficient technologies as well as engaging in strategic energy management practices, the industrial sector has substantial opportunities for reducing current industrial energy usage—in addition to generating non-energy benefits such as improved air quality, deferred grid infrastructure costs, and energy security.

Implementing energy efficiency strategies is also often a necessary prerequisite for more complex and capital-intensive decarbonization strategies. Efficiency can preemptively reduce carbon emissions by decreasing overall energy consumption and peak energy demand. Efficiency makes distributed energy resources (DERs), electric technologies, and other emissions reducing practices more cost effective and more technically feasible (York, Relf, and Waters 2019). While energy efficiency strategies have often supported fossil fuel–powered industrial processes (for example, combined heat and power (CHP) systems), future energy efficiency investments will need to better align with longer-term electrification goals in order to maximally support decarbonization of the industrial sector. Efficiency programs will need to expand their scope to include tools such as fuel switching, which may necessitate state and utility policy changes (Specian, Gold, and Mah 2022). Policymakers can also support the development and implementation of more efficient, systems-optimizing technologies through rebates, incentives, tax breaks, and others. Previous ACEEE research has found that accelerating the implementation of emerging industrial technologies can enable savings of up to 15% of energy use (ACEEE 2019).

Smart Manufacturing Technologies to Efficiently Decarbonize Industrial Operations

One of the most promising energy efficiency approaches for furthering decarbonization is smart manufacturing, an umbrella term encompassing automation, adaptability, monitoring, and other computing enabled optimization. Smart manufacturing is a systems-based approach to saving energy, enabled by information and communication technologies (ICT) and real-time information for users. In addition to accessing significant savings—ICT that promotes system efficiency can reduce energy use in relevant applications by around 20% (Rogers 2014)—ICT supports systemwide optimization, interconnectedness between otherwise isolated processes, and instantaneous demand response measures. ICT systems in industry can also reduce peak energy demand and shift loads while promoting the integration of renewables and electrified technologies into industrial processes.

One example of a smart manufacturing strategy is the installation and management of variable speed drives, devices that change the speed of motors by altering the voltage supply. Variable speed drives enable motor optimization to meet the requirements of variable loads, allowing for greater motor system control and decreasing electricity losses in applications including the use of conveyors, mixers, grinders, pumps, and fans. Variable speed drives can reduce motor energy consumption by approximately 50% in many use cases, in addition to allowing flexibility in manufacturing processes that can be optimized with the use of variable loads. Similar technologies and approaches to motor efficiency improvements exist across industrial subsectors.

Emerging federal legislative support for smart manufacturing will enable this transition. The State Manufacturing Leadership section of the 2021 Infrastructure Investment and Jobs Act (IIJA), for example, authorizes competitive financial assistance to states for establishing programs supporting smart manufacturing technology implementation. Another section of the IIJA expands the scope of DOE's Industrial Assessment Centers (IACs)[3] to include smart manufacturing improvements. The Industrial Emissions Reduction Technology Development Program introduced in the Energy Act of 2020, for another example, centers around research, development, demonstration, and deployment (RDD&D) of technologies that

[3] IACs are a DOE funded network of public engineering universities that perform energy use assessments and submit efficiency improvement recommendations for industrial customers using teams of students and faculty.

Energy Efficiency Enabled Savings in Food and Beverage Manufacturing and Connections to Variable Power

According to the 2022 DOE Industrial Decarbonization Roadmap, various energy efficiency pathways have the combined potential to reduce food and beverage emissions by up to nine million metric tons of CO2e emissions by 2050 (approximately 40% of needed reductions), compared to business as usual. ICT enabled energy efficiency, for example, can lead to a 7–13% reduction in food waste, which is responsible for approximately 11% of the sector's CO_2 emissions, while also supporting load optimization and integration of renewable assets.

Some examples of recent energy efficiency implementations within the food and beverage sector come from the ongoing Food Production Investment Program (FPIP) in California, funded through the California Climate Investments program.[1] FPIP has provided funding for advanced energy efficiency and renewable energy technology implementation within food processing industry facilities. The state of California has more food and beverage manufacturing facilities than any other state in the United States. Across the 43 projects funded from 2018–2021 for which data were available, energy efficiency implementation tended to lead to a greater reduction in carbon emissions at a lower cost than onsite renewable energy installations (figure 5).

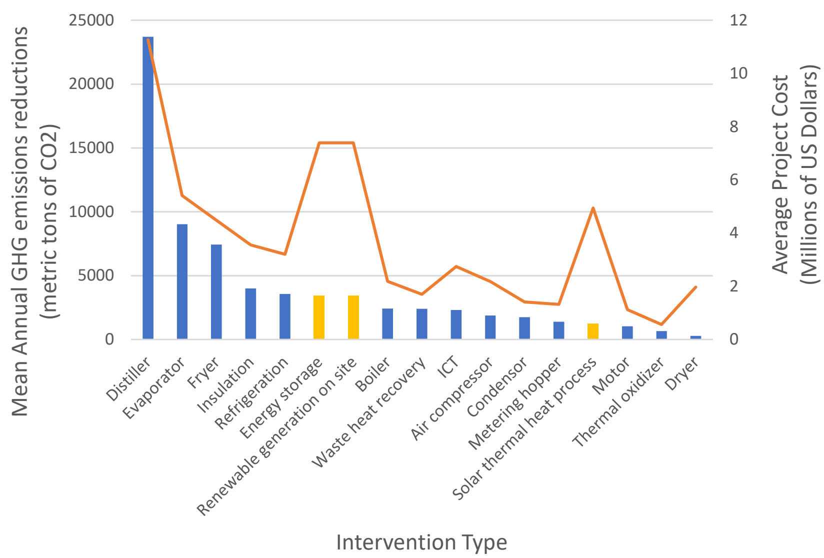

Figure 5. Energy efficiency (blue bars) or renewable energy implementations (yellow bars) annual GHG emissions reduction results, with average cost per project overlaid, for projects funded through the California Food Production Investment Program. Data source: California Energy Commission.

cost, and model, simulate, and optimize energy efficiency in manufacturing.

Thermal Storage as a Form of Energy Efficiency

Thermal storage can also be viewed as a form of efficiency because it can recycle waste heat from other processes and reduce the energy demand needed for process heat: Air that is already quite warm requires less energy to reach a high heat. Thermal storage in this manner has been employed for many years in industry, especially in sectors such as pulp and paper or wastewater treatment. District heating systems are also an example of an energy management strategy that incorporates thermal energy storage. Some district heating systems that rely on thermal energy storage, such as at Princeton University (Valenti 2021), were initially planned to reduce energy costs. With the advent of renewable energy technologies and price signals that indicate when low-carbon power is available on the grid, these systems now can also optimize their operations to reduce the carbon intensity of grid power that is consumed, in addition to reducing absolute facility energy demand.

ENSURING RELIABLE ENERGY FROM VARIABLE RENEWABLE SOURCES

Concerns over the reliability of a grid dominated by wind and solar are at the core of many of the arguments against moving toward a net zero power sector based on variable power. Critics argue that some form of firm generation—that is, generation that is dispatchable when needed and consistently available—will always be necessary to ensure reliability of electricity. There are already many regions of the world, however, that have grids with a high average penetration by variable renewable energy sources, as well as short periods in which the grid is almost entirely supplied by variable renewable power sources (Hoke et al. 2021). It appears increasingly technologically feasible for a power sector to rely almost fully on variable renewable power, including the provision of ancillary services (Alam et al. 2020; Denholm et al. 2021). Firm clean energy technologies continue to mature as well, expanding the solutions set for a fully emissions-free power sector. One such example, enhanced geothermal systems, is a current focal DOE research and development effort (https://www.energy.gov/eere/geothermal/enhanced-geothermal-shot).

Taking Advantage of Grid Reliability Strategies

Given the wide geographic variation in carbon intensity of the U.S. power sector and the concentration of renewable power in certain geographies (e.g., wind farms in the central plains), broader, more interconnected transmission and distribution networks are one key tool that can help to build resilience and reliability into a renewable-dominated power sector. Investing in transmission and coordinating across political boundaries substantially reduces the overall cost of the power system (DOE 2022; Tong et al. 2021). Additionally, greater interconnection supports temporal complementarity of generation sources, and helps to balance local over- and under-supply of renewable power, avoiding curtailment of generation or the necessity of demand reduction measures (Rinaldi et al. 2021). Increasing interconnection across the grid is considered a strategy for increasing reliability of power. For example, the Western Energy Imbalance Market (WEIM, https://www.westerneim.com) was established in 2014 to allow real-time trading of energy across a wider geographic area, making excess renewable energy available at low cost to all participating utilities. A system like this allows low-cost excess solar energy in California to be easily transmitted to areas outside of the state that would otherwise be meeting energy demand with more expensive and higher carbon power sources.

Building hybrid generation plants with both solar and wind generation capacity (Clark et al. 2022) or integrating battery storage into utility-scale renewable installations and throughout the transmission and distribution system (Bowen, Chernyakhovskiy, and Denholm 2019) are other potential strategies for ensuring more consistent renewable supply at a single location. The ability to store energy until it is needed within the grid enables greater flexibility in the timing of when and where power can be made available and supports higher proportions of VRE without sacrificing grid reliability. As the cost of batteries declines, many utility-scale VRE installations—especially solar farms—are now being built with integrated battery technology to store energy for 2–12 hours (Blair et al. 2022). Battery storage on the grid not only provides ancillary services like frequency regulation and voltage or reactive power support, general load management support, and reduced curtailment of solar and wind generation, but also supports new market opportunities, particularly in the form of price arbitrage (Kennedy 2022). Combining utility-scale renewable energy with onsite storage also allows battery storage installations to qualify for federal tax credits and helps owners to navigate congestion, transmission, and interconnection delay issues (Kessler 2022).

Long-duration storage technologies[4] are expected to substantially reduce overall system operating costs in a VRE-dominated power grid, in addition to increasing system reliability (Dowling et al. 2020). A wide variety of promising technologies are being developed to enable low-cost, long-duration energy storage on the grid. These include green hydrogen, thermal storage, pumped hydro, and other electrochemical or mechanical solutions (Golden 2021; Shan et al. 2022), though it remains uncertain when any of these tools can be economically deployed at scale.

Industrial behind-the-meter energy storage strategies to increase reliability of energy supply

Many industrial processes, especially in heavy manufacturing industries, run continuously and require uninterrupted power sources that are available 24/7. Some industrial facilities are installing battery storage systems behind the meter to allow facilities to reduce peak load demand without curtailing production while creating a more resilient facility to electrical interruptions. For example, a snack food processing facility in California received a grant to support installation of a solar-powered microgrid equipped with battery storage, allowing the facility to be *islanded* (become a self-contained electrical grid) in the event of a

[4] Long duration is defined by DOE as systems capable of powering the grid for at least 10 hours.

systemwide power disruption (CEC 2020). This type of investment in resilience and increased demand flexibility for industrial facilities is especially important in regions like California, where grid-wide disruptions due to extreme weather are becoming more common. Demand response by large utility customers is a key tool for combating broader system outages.

For large-scale battery backup system deployment across the United States, continued innovation and cost decline for lithium-ion batteries and other forms of thermal and electrochemical storage are likely necessary. DOE has announced a series of funding opportunities as part of their new Energy Storage Grand Challenge (https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge), which invests in the development and implementation of energy storage technologies to meet growing U.S. market demand.

Given the expected high demand for lithium-ion batteries from the transportation sector, industry should consider diversifying energy storage approaches, focusing some effort on chemical and, especially, thermal storage opportunities. Incorporating energy storage into the design of electrification strategies can allow facilities to install smaller capacity electrical process heating equipment, such as heat pumps or electric boilers, by reducing demand peaks. Modeling can be used to optimize the size of heat pumps or boilers in combination with thermal storage; modeling can also help to reduce the cost of running a system or decrease energy usage (e.g., Powell et al. 2016; Hannan et al. 2020).

ENHANCING FLEXIBILITY OF ENERGY SUPPLY AND DEMAND

More flexible management at the scale of the entire grid can smooth over the variability of wind and solar to provide reliable, carbon-free electricity[5] to all consumers, even if large industrial facilities increase their electricity demand. Additionally, a more flexible management approach would support a fuller utilization of current infrastructure; transmission and distribution systems, for example, have seen declining utilization rates, even as peak demand has increased (Shear 2014). Not maximizing the benefit per unit cost of infrastructure is an inefficient and expensive way to manage an energy system. To counteract these trends, grid operators and managers can deploy a suite of complementary technologies and behavioral strategies to achieve a more flexibly managed electric grid, leading to a better real-time match between consumer energy consumption and grid output.

[5] We are considering *carbon-free electricity* here as VRE backed by grid-scale storage or firm renewable energy, to provide adequate power to meet system peak demand. While carbon-free electricity is available during some time periods, all systems in the United States still rely on firm, primarily fossil-fuel based sources in addition to VRE to cover customer needs.

Balancing energy supply and demand

Large industrial customers frequently pay significant charges based on their individual peak energy demand, or for energy used during the system's peak demand hours, referred to as "coincident peak charges." Both pricing structures incentivize consumers, especially in energy-intensive industries, to invest in onsite energy storage or other tools that support energy load-shifting or demand peak shaving. Additionally, there is a growing role for large energy consumers to absorb excess renewable energy, preventing the need for curtailment of production. For example, some grids that have a very high penetration of wind or solar power already experience an excess of power generation during optimal production hours (O'Shaughnessy, Cruce, and Xu 2020). A combination of hardware (data communication platforms and sensors), as well as software and communications (dynamic energy pricing to share information about grid energy availability and carbon intensity) can support a better balance of supply and demand of energy as the grid decarbonizes. Industrial subsectors or individual plants that can take advantage of peak pricing information by adjusting their operating conditions may also find opportunities to optimize energy usage without necessarily affecting production volume; for example, they may be able to schedule batch processes when energy prices are lower. Manufacturers that embrace the transition to renewable energy by investing in enabling technologies and flexible energy management strategies can achieve greater operational sustainability, reduce energy losses, and maximize their consumption of low-carbon power.

One significant barrier to this transition is that existing electric grids were often built decades ago and struggle to rise to the evolving energy needs of the 21st century. That is why investment in bidirectional grids is urgently needed to enable this energy transition. Data communications infrastructure is required on both the supply and demand side, as well as rate-based incentives that lead to greater consumption of lower-carbon power.

Grid-powered electrolysis of hydrogen is one potentially large productive use for excess renewable power that might otherwise be curtailed. Hydrogen, especially so-called "green" hydrogen powered by renewable energy, is expected to play an important role in decarbonizing select industrial processes that require extremely high temperature process heat. This technology, however, is not yet economically advantaged (Bartlett and Krupnick 2020). Regions of the EU and the United States are anticipated to have sufficient grid power to enable electrolysis to produce hydrogen more effectively than steam methane reforming (SMR) in the coming decade, although power availability is likely to vary seasonally. Industrial production of hydrogen is an example of a shift in energy management strategy toward functioning as a *prosumer*: both a consumer and producer of power.

Flexible grid management

While industrial facilities will need to employ a new set of tools to change how they manage energy, grid operators also will require an updated suite of strategies. An integrated grid management approach will likely need to include a combination of demand response, energy efficiency strategies, distributed energy generation or storage, time-based rates, and strategic use of electric vehicle charging (Potter, Stuart, and Cappers 2018), complemented by supportive policies at the state and at the regional transmission level. Incorporating a variety of these approaches, or at least both energy efficiency and demand response tools, into a cohesive programmatic approach is currently quite rare among utilities and utility-regulating organizations. The cost of implementing demand response and demand flexibility programs, however, is generally less than the cost of building the additional generation resources that would be required in the absence of these programs, and the suite of benefits such programs provide is broader than simply consumer cost savings. Successful deployment of a set of these approaches is expected to maximize the use of renewable power sources, reduce the needed operating reserve capacity—often supplied by inefficient, carbon-intensive, but fast-ramping power generators—as well as reduce the need for physical upgrades or expansions of transmission and distribution infrastructure. Tools to increase flexibility of energy demand and avoid the need for these upgrades are often referred to as "non wires alternatives."

In many cases, utility rate structure and regulatory guidelines actually disincentivize the most efficient strategies for flexible grid management (Specian, Gold, and Mah 2022; Schwartz et al. 2022). For example, many current utility business models, or state public utility council regulatory strategies, prioritize increasing sales, which is often in direct conflict with efficiency or fuel switching strategies that would reduce carbon emissions from the power sector. Also, these demand flexibility strategies are generally not valued equally to supply-side resources (e.g., nameplate generating capacity of power plants). While utilities can earn a rate of return on capital expenditures such as new power lines or transformers, they can only recover costs for efficiency and demand response programs. This leads to a capital expenditure bias (e.g., Goldenberg et al. 2022), in which utilities are financially incentivized to invest more heavily in new infrastructure.

Dynamic real time pricing (RTP), time of use, or critical peak pricing of electricity for industrial clients is a valuable component of demand side management strategies, and can be used to incentivize more flexible use of power by industry, including load shifting and reductions in demand during peak hours (Nandy, Botts, and Wenning 2022). These time-shifting rates, especially for energy-intensive industries, can be a powerful tool for signaling when low-carbon and low-cost energy is available. A number of opt-in programs are currently being implemented with residential, commercial, and industrial clients. One of the largest examples of a serious effort to switch to a fully RTP market is taking place in California (Madduri et al. 2022), where the California Public Utility Commission is working to implement a universally accessible electricity price that signals the marginal cost of energy as well as current grid capacity. Pricing models that incentivize utility customers to increase the amount of load flexibility as they electrify buildings, transportation, or install onsite energy resources could also ensure sustained grid reliability, even as overall electrical load increases and variable renewable energy resources account for a greater proportion of overall supply. Grids that are currently engaging in these types of programs, at least in pilot phases, tend to be located in states, cities, or regions that have implemented GHG reduction policies compelling utilities to take actions to reduce their emissions (York, Relf, and Waters 2019).

The Role of Third-Party Entities in Enabling Variable Power Expansion

Many of the most viable opportunities for integrating variable renewable energy into industrial facilities lie at the intersection of industry and the broader energy grid. Grid characteristics, including regulatory frameworks, energy markets, carbon intensity of utility-scale power plants, and the availability of real-time pricing data, all vary dramatically across the country. Similarly, industrial facility energy management challenges and opportunities vary by industrial sector and even by individual plant. Especially at this current early stage of transition toward a net zero power sector and decarbonized industrial sector, third-party entities can play a critical role by enabling shifts in energy management in both the power and industrial sector, and by providing support for matching low-carbon energy supply to low-carbon energy demand. Given that solutions often are extremely localized, however, a major challenge for third-party solutions providers will be effectively scaling up decarbonization strategies beyond an individual facility while navigating municipal and state regulations and maintaining a viable business model. A complex and heterogenous regulatory environment will slow the deployment even of modular technologies.

A wide variety of energy stakeholders are finding innovative niches, fulfilling needs, and overcoming obstacles in ways that help to move industrial power systems toward decarbonization (figure 6). Often this consists of piecing together various clean energy solutions in novel ways to create synergy between stakeholders. For example, virtual power plant operators can combine electrification of industrial heat processes with participation in flexible energy demand markets. By increasing industrial consumption of low-carbon and price-advantaged electricity, this approach leads to economic and operational benefits for the companies as well as supporting stability and expansion of a variable renewable power–based grid (Fraunhofer Institute for Industrial Mathematics ITWM 2022). In the following section, we outline some of the integrative functions that third-party stakeholders are performing, helping to align energy supply- and demand-side needs.

Figure 6. Third-party solutions providers have found a wide variety of roles and niches, addressing different aspects of the obstacles and opportunities unfolding in the transition to a variable renewable power–dominated power sector and a decarbonized industrial sector.

NAVIGATING THE REGULATORY ENVIRONMENT

Current regulatory frameworks in most energy markets were initially designed around energy grids dominated by large, centrally located, and easily dispatchable generators. In these systems, energy flows in a single direction, and cost and overall energy supply are the dimensions to optimize. However, as energy resources become more distributed, power flow becomes bidirectional, and renewable portfolio requirements are expanded across energy markets, the tools and strategies needed to advance energy management are often at odds with current regulations.

The expanding array of behind the meter clean energy technologies; wide variety of leasing, purchasing, and crediting options; and the complexity of energy markets can be daunting for companies that are not used to managing the production of power as part of their business. Third-party companies, fitting roughly into a *sustainability as a service* niche, have arisen to provide a portfolio of renewable energy financing, system design and installation, power management, and maintenance. In addition, they provide expertise when engaging with power utility providers around rate design or interconnection permitting.

PARTICIPATING IN ANCILLARY SERVICES OR ENERGY MARKETS

Profitable participation in energy markets is a relatively recent extension of more traditional industrial demand response programs (Nandy, Botts, and Wenning 2022). Industrial facilities that either produce energy onsite, or store and use energy flexibly, have the potential to profitably participate in these markets by selling energy back to the grid when demand is high but supply is low. The complexity of utility program offerings and rate structures, however, often makes it difficult for industry to confidently navigate energy transactions themselves. Third-party companies are addressing this need by facilitating energy market participation for industry. To accommodate diurnal patterns of production and demand (i.e., high afternoon solar production paired with high evening power demand), markets with a greater overall penetration of variable renewable energy, particularly solar, tend to have a greater range of energy prices, which is necessary to make these markets more consistently profitable (Helman, Kaun, and Stekli 2020). For example, over 80% of battery storage that was added to the California Independent System Operator (CAISO) grid in 2021 was used for price arbitrage (McGrath and Comstock 2022).

There is also a growing demand for ancillary services, such as frequency regulation or balancing services, which are increasingly valued as the grid becomes more distributed in nature and central, synchronous generators are no longer able to provide these services consistently (EPRI 2019).

ENABLING COMMUNICATION AND BUILDING DATA PLATFORMS

For industrial facilities to take maximum advantage of wholesale energy markets by responding flexibly to energy price signals, data infrastructure is required to monitor and manage energy usage behind the meter, as well as to communicate with the broader grid. Many manufacturing facilities already employ paired hardware (meters and sensors) and software (advanced dashboard controls, data models, and analytics) to efficiently manage industrial processes. Few industrial facilities, however, communicate with the grid directly or allow information to flow bidirectionally, and utilities still lag in matching these investments with software and hardware that support more flexible supply-side management.

The bidirectional flow of energy information is, however, becoming more common in commercial and residential buildings, termed grid-interactive efficient buildings (GEBs). A recent roadmap for GEBs, published by DOE Building Technologies Office (BTO) (https://gebroadmap.lbl.gov/), found substantial carbon savings possible through a combination of energy efficiency and demand flexibility unlocked by GEBs platforms. Of particular note is that carbon emission reductions were expected to be more dramatic in regions of the country where the power sector is more carbon intensive, suggesting that efficiency paired with flexibility and the ability to match demand to real-time carbon intensity of the energy grid would make electrification of energy loads beneficial even before the power grid was fully decarbonized.

Translating this concept to industrial facilities, however, remains challenging. Due to concerns about sharing proprietary information, network security, disruption of essential industrial processes, and the complex and highly variable design of manufacturing facilities, data communication systems must be designed individually to meet user needs. Some industrial companies have begun to develop in-house expertise around data modeling and energy management: for example, Lineage Logistics, an industrial real estate investment trust (REIT) focused on cold-storage warehouses, includes a data science team that works on energy efficiency and rate structure optimization (DOE 2021). More often, however, third-party technology companies, such as Cisco, Siemens, and IBM have begun to provide data sensing and communication solutions services designed specifically for industrial needs.

PEER-TO-PEER COLLABORATION NETWORKS

Successful industrial decarbonization is a complex sociotechnical transition that in some cases requires building entirely new systems. Successful system-building requires alignment of developments across markets, technology readiness, supporting infrastructures, and resource mobilization; progress in only one aspect without concurrent movement in other related sectors is likely to stall progress overall. As a result, the same technology may be readily accepted in one country but struggle to gain market support in another. Decentralized, collaborative peer support communities, especially when run alongside robust government policy support, have been a key aspect of many successful, rapid national energy transitions (Sovacool and Martiskainen 2020). When diverse stakeholders convene around a central issue, the work of coalition building is likely to promote cooperation rather than competition and broaden the potential solutions space. Often this process is geographically specific and relies on localized interactions, although increasingly, virtual user support communities have arisen to support the acceleration of energy transitions by expanding markets beyond early adopters and enthusiasts (Meelen, Truffer, and Schwanen 2019; Hyysalo, Juntunen, and Martiskainen 2018).

In the United States, the development of well-known and trusted peer sharing networks around industrial renewable energy and decarbonization has been slow. One leading example is the Renewable Thermal Collaborative (https://www.renewablethermal.org/), established in 2017 to serve as a coalition for companies, institutions, and governments to work together on scaling up renewable heating and cooling solutions. Other government-facilitated peer cohorts include DOE's Better Plants program, as well as working groups and partnerships with manufacturers and government labs, including the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory.

DE-RISKING NEW TECHNOLOGIES

Incentivizing companies to experiment with new technologies can be challenging, especially when production margins are tight, as in many manufacturing industries, and lost production time when installing or repairing equipment comes with substantial profit loss on top of capital expenditures. There are several ways that third-party stakeholders have attempted to reduce the risk for new technologies.

DOE's establishment of an Office of Clean Energy Demonstrations (OCED) in 2021 is meant to directly address this purpose, by partnering with the private sector to help equitably and successfully scale up technologies, while building market support for the tools needed to transition to a decarbonized industrial sector. By using government funding to demonstrate a variety of clean energy technologies at scale, in regionally distributed centers around the country, DOE will attempt to de-risk some of these new technologies and increase uptake within private facilities.

Third-party companies, functioning in the role of energy, sustainability, or heat as a service companies, can also help de-risk new technologies. By managing the installation and in some cases operation of energy savings and management software and hardware, third-party companies may be particularly supportive to smaller and medium-sized industrial companies, who can thereby reduce or even eliminate capital expenditure costs and profit through energy and emissions savings from installed process upgrades. While energy as a service companies (ESCOs) have primarily focused on public and institutional clients (e.g., K–12 schools) (Stuart et al. 2021), heat or energy management as a service for industrial facilities is likely to be a growing niche.

GOVERNMENTAL POLICY AND FUNDING SUPPORT

The U.S. government has vastly expanded policy support to increase industrial resilience and drive decarbonization in recent years. At the federal level, this includes the Energy Act of 2020, the Infrastructure Investment and Jobs Act of 2021, and both the CHIPS/Science Act and Inflation Reduction Act of 2022. How this funding will be dispersed, however, is still uncertain. Much of the funding may flow to states, cities, and regional coalitions to run programs, build needed energy infrastructure, and otherwise incentivize growth of low-carbon manufacturing in concert with increased supply of low-carbon power. Other portions of funding may go directly to industrial facilities, in the form of grants or loans, and some funding may be used to build additional government support infrastructure for navigating market transformation and deploying new technologies. Some examples of federal and state funding support to address various industrial decarbonization opportunities and challenges are listed in table 1, below.

Table 1. Examples of federal and state-level funding programs to address key issues related to industrial decarbonization

Target issue	Funding level	Examples
Industrial heat pump supply chain issues	Federal	●2022 Defense Production Act prioritization of IHP manufacturing ●IRA Advanced Industrial Facilities Deployment Program ●Office of Clean Energy Demonstration (OCED) Grants ●Loan Program Office (LPO) clean energy loan guarantees ●48C manufacturing tax credits
Long duration energy storage	Federal	●2022 expansion of investment tax credit (ITC) to support stand-alone and integrated energy storage projects ●IRA Section 45X for battery manufacturing tax credits
Sustainable hydrogen production	Federal	●IIJA Section 813 Regional Clean Hydrogen Hubs ●IRA Section 13204: Clean Hydrogen
Workforce training	Federal	●IIJA and IACs ●National Institute of Standards and Technology's Manufacturing Extension Partnerships ●National Science Foundation (NSF) Community Colleges Initiative
Workforce training	State	●California Public Utilities Commission (CPUC), California Conservation Corps (CCC), and California Energy Commission (CEC) all support industrial energy efficiency by providing workforce training ●Certified Energy Manager training in CT, FL, IA, MA, VA, MT, NB and others ●PA Sustainable Energy Technology program ●NC Environmental Stewardship Initiative

Putting the Pieces Together

Despite the technical feasibility of rapid decarbonization of both the industrial and the power sectors, not enough progress has been made toward carbon emissions reductions to meet Paris agreement goals (Bearak and Popovich 2022). Prevailing business cases, risk aversion, and uncertainties surrounding new energy management practices have delayed movement on both sides. With increasing volatility of energy prices (including natural gas), pressure to establish new domestic manufacturing supply chains, and substantial federal investments in industrial decarbonization technologies and policies supportive of a clean energy economy, however, there are great opportunities to align industrial and grid business cases, and begin to implement the tools we have had available for some time. In this section, we summarize our findings by identifying three integrative scenarios that support synergistic interactions between energy supply and energy demand, potentially leading both to substantial progress toward industrial decarbonization alongside increased variable renewable power supply in the United States. Each of these scenarios encompasses both industrial facility actions and grid conditions, while relying on the support of third-party stakeholders to make connections and provide key enabling solutions components.

EFFICIENT BENEFICIAL ELECTRIFICATION OF INDUSTRIAL PROCESS HEAT

IHPs have unignorable technical potential to help decarbonize the industrial sector through the electrification of fossil-fuel generated process heat. However, IHPs have existed for decades, and little progress has been made so far in their use at scale in the U.S. industrial sector. As the circumstances of the climate crisis worsens, and IHP technology develops, it is important to leverage learnings and recognize the success of other countries where IHPs have occupied a more centralized niche in decarbonization strategy.

For example, in the EU, electrification of industrial process heat is supported by several policy mechanisms and enabling circumstances. The three billion euro EU innovation fund, one of the focuses of which is innovative electrification in industry and hydrogen; widespread district heating networks that operate as sinks for industrial waste heat; and a robust IHP and IHP component market have enabled IHP proliferation. Several EU nations have participated in IEA’s heat pump annexes, studies aimed at collecting energy and economic data on the status of heat pumps in industrial settings. These annexes include case studies of approximately 350 IHPs currently in use in medium to high process heat applications, and the economic, energy, and emissions savings that they enable.

The technology that creates those savings exists today and is commercially available domestically. While policy and funding mechanisms globally can and must be replicated, other barriers must be mitigated to promote uptake at scale in U.S. industry. Some of these barriers include workforce limitations (including energy and thermal engineering), code constraints for IHP components, informational barriers for implementation, lack of testing infrastructure, and lack of robust current domestic supply of IHP components. However, significant legislative and market momentum will help minimize and overcome these barriers, including

- Industrial electricity prices are projected to decline as natural gas prices increase.
- Currently existing manufacturing (especially HVAC) infrastructure can be leveraged to produce critical IHP components.

- The United States plans to increase international knowledge exchange opportunities, such as participating in the EIA IHP Annex 58, to learn from early adopters of mass electrification strategies.
- The Inflation Reduction Act’s expanded section 48C manufacturing tax credit is poised to provide $10 billion in tax credits for manufacturers to construct specified clean energy projects.
- DOE’s Industrial Heat Shot aims to develop industrial heat decarbonization technologies with at least 85% lower GHG emissions by 2035.
- DOE’s Loan Program Office (LPO) provides financial support for deployment of technologies in “the last mile of commercialization”: for example, virtual power plants (Shah 2022).

These efforts, along with the potential to pair IHPs with other decarbonization measures including electric boilers, thermal storage, smart manufacturing, and especially onsite generation of renewable electricity, mean that IHPs can immediately become a major component of industrial decarbonization.

MONETIZING FLEXIBLE INDUSTRIAL LOADS

Industry can bring together a combination of energy storage, smart manufacturing, and electrified process heat to increase both the quantity and the flexibility of electrical energy demand. This practice is made feasible by the availability of utility rate structures that incentivize purchase of low-carbon power and reduction of peak system demand. Key third-party stakeholders include virtual power plant (VPP) operators that support energy management and monetization strategies for industry as well as technology companies that support automated bidirectional communication between industry and the power grid, and within-facility optimizing for energy cost and carbon intensity during both system design and operational phases.

VPPs are only just beginning to operate widely in the United States, where they often come into conflict with grid regulatory structures, particularly in utility-run and regulated grids. Market and regulatory structures have been more welcoming to this business model in Germany, where a variety of VPP operators and industrial facilities have been participating successfully in energy markets for years (Xia-Bauer, Große-Kreul, and Thomas 2021). For example, an ongoing German collaboration between a research institute, software technology company, and an industrial facility focuses on optimizing the profitability of industrial participation in energy markets, using large flexible power loads made available through aluminum smelting (Fraunhofer ITWM 2022).

University campuses have also been able to leverage flexible energy loads to profitably participate in energy markets and support broader grid services. The combination of large campus district energy systems with a diverse mixture of heating and cooling needs (Valenti 2021), and opportunities for large-scale energy storage (for example, thermal storage in heated swimming pools or freezers in research facilities) are all important components of the success of demand flexibility programs that save energy costs while supporting university carbon goals.

EXPANDED SOCIAL AND ECONOMIC SUPPORT FOR INDUSTRIAL DECARBONIZATION DEPLOYMENT

Many of the industrial technologies and energy management strategies that are becoming more mainstream in other countries have yet to become widely accepted in the United States. Electrification with VRE will not be "plug and play" for industry; it requires a shift in operating strategies and mindset. Complex integration and upstream and downstream control and sensing (e.g., of when renewable energy is available and at what price) will need to be addressed before VRE can be reliably used by industry at greater scale.

These energy technology transitions take time and require substantial collaborative efforts to scale. For example, Finland successfully transitioned from approximately 1,500 heat pumps installed in total in 2000 to 34% of households having a heat pump in 2018. To accomplish this, a broad suite of government policies, incentives, and programs were put in place: a national heat pump association was established, online heat pump user forums were created, and many multi-stakeholder collaborations worked to support supply chains, certifications, training, and policy development (Sovacool and Martiskainen 2020). By contrast, in this same time period residential heat pumps struggled to gain acceptance in Denmark, where user communities and stakeholder advocacy groups did not develop in support of the spread of heat pumps (Nyborg and Røpke 2015).

Industry leaders in the United States can similarly form groups to boost the market signal of successful technologies and strategies (e.g., Clean Energy Buyers Association or the Renewable Thermal Collaborative). Industrial trade associations have also been able to serve these convening, networking, and peer-to-peer support functions in the United States. For example, the Craft Brewers Association has developed sustainability benchmarking tools to support members in tracking and managing energy more sustainability, to save money as well as reduce resource consumption and GHG emissions from their brewery operations. More direct engagement from industrial policymakers and local, state, and federal agencies implementing decarbonization efforts with these types of industrial associations will be necessary to encourage broader uptake of electrification and energy efficiency technologies, and to build the kind of lasting networks of support required to transform how energy is used in industrial manufacturing.

Conclusions

As large industrial customers work toward company environmental, social, and governance (ESG) and emissions reductions targets, they have the opportunity to model how consumer behavior and energy management strategies should support a reliable, resilient, efficient, affordable, and low-carbon electrical grid for all. Industry has the tools at hand to lead by example, switching much of their power supply from fossil fuels to electricity. Flexible, beneficial electrification of industrial process heat, and the associated increasing demand for low-carbon power, can support ongoing expansion of renewable energy supply. A rapid increase in industrial customer demand for clean energy could potentially drive electricity costs down, support expansion of transmission and distribution infrastructure, and lead the way to nationwide adoption of utility policies that incentivize the most efficient utilization of low-carbon power.

In this report, we have highlighted a set of tools that are currently available to industrial stakeholders and detailed the circumstances in which their application will be most effective in moving industry toward substantial decarbonization. These shifts in how energy is consumed will not only lead to substantial reduction in carbon emissions but also can simultaneously improve industrial competitiveness and resilience. Especially in the current transitional period, third-party solutions providers can play pivotal roles in meeting the growing need for low-carbon products and services by connecting industrial players and grid operators so they can take advantage of new business opportunities for managing clean energy supply and demand. Now is the time to implement clean industrial energy solutions at the scale needed to transform how we supply and use energy in the United States.

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