ENABLING INDUSTRIAL DEMAND FLEXIBILITY: ALIGNING INDUSTRIAL CONSUMER AND GRID BENEFITS

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Contents

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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.

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Abstract

Decarbonizing the power grid is an important step toward widespread decarbonization of the U.S. economy. Yet, power system planning processes are increasingly challenged to keep pace with a growing resource portfolio of weather-dependent renewable sources such as solar and wind, combined with growing electricity demand. Industrial customers have been central to utility demand-side management (DSM) for many years, especially for peak demand reduction. As the problem of balancing supply and demand becomes more complex and ongoing, however, the industrial sector is a strong candidate for shifting from discretely responding to events or reducing energy demands within set hours to a broader demand flexibility framework. Demand flexibility approaches enabled by information and communication technology (ICT) has great promise for providing the kind of advanced and bi-directional communications and controls that can respond effectively to more complex grid and energy user needs; to date, however, little of this potential has been realized, particularly in the industrial sector.

This white paper identifies alignments between power sector and industrial priorities during this transitional period for the energy system. We argue that utilities should more strongly prioritize the expansion of ICT-enabled demand flexibility capacity from large industrial customers over the coming years, especially as part of their long-range planning efforts. Doing so will ensure that price signals and program incentives lead to efficient industrial electrification to support decarbonization goals, while also resulting in beneficial outcomes for the broader grid. We identify steps that utility program managers and administrators can take to work more effectively with industrial energy consumers to balance energy supply and demand in a cost-effective way while enhancing grid decarbonization progress. We also highlight examples of current approaches to electric utility DSM that integrate ICT-enabled solutions and support industrial customers.

Introduction

Decarbonizing the power grid is an important step toward widespread decarbonization of the U.S. economy. Having reliable, abundant clean power is an essential enabler of beneficial electrification[1] across all sectors, including residential and commercial installation of heat pumps for heating and cooling; the rise of battery electric vehicles (EVs) for transportation; and the electrification of industrial processes, such as switching fossil-fuel-powered boilers to electric boilers and using heat pumps for thermal energy generation. Yet, power system planning processes will increasingly be challenged to keep pace with a growing resource portfolio comprised of weather-dependent renewable sources such as solar and wind, and growing electricity demand will require significant investment in transmission and distribution infrastructure. Adapting utility rate structures for industrial customers can be one tool to help meet the challenges of a changing grid, as these customers have been central to utility demand-side management (DSM) portfolios for years, especially for peak demand reduction.

In the past, the industrial sector has provided significant demand response (DR) capacity in many areas in response to constrained grid capacity or discrete grid stressors such as extreme heat or cold weather events that lead to increased HVAC use (Hiller 2022). Utility DR and DSM programs originated in the 1970s as a way to increase energy security and reduce dependence on foreign oil supplies. These programs later expanded as utility regulators incentivized least-cost and integrated resource planning processes (Eto 1996). DR contributes to capacity and resource adequacy markets, as well as to ancillary service markets. To support participation in these markets, rates such as interruptible tariffs and time-of-use pricing developed, especially for large energy consumers (Hurley, Peterson, and Whited 2013).

As the problem of balancing supply and demand becomes more complex and ongoing, however, the industrial sector is a strong candidate for shifting from discretely responding to events or responding in set peak demand hours to using a flexibility framework for planning and operations. This entails moving to a more temporally granular approach to balancing energy supply and demand (IRENA 2019) while allowing for two-way communication, two-way power flow, and more dynamic pricing signals (Honarmand et al. 2021). Demand flexibility is the capacity of energy consumers to change their energy consumption at various timescales; for example, shifting energy-intensive processes away from peak system demand times to other hours of the day when more energy is available, at a lower price. Demand

[1] Electrification can be considered beneficial when it results in increased utilization of low carbon energy for end users and an overall reduction in GHG emissions associated with energy consumption (Rightor, Whitlock, and Elliott 2020; Dennis 2015). If end-user electrification leads to an increase in the use of fossil-fuel-powered generation sources to meet grid demand, especially at peak times, then the outcomes may not be universally beneficial from the standpoint of reducing GHG emissions.

flexibility approaches enabled by information and communication technology (ICT) has great promise for providing the kind of advanced communications and controls that can yield increased demand flexibility (table 1). To date, however, little of this potential has been realized, particularly within the industrial sector.

Table 1. Information and communication technology (ICT) enables solutions that can alleviate grid challenges due to increased electrification and variable/distributed electricity generation sources (i.e., wind and solar)

ICT-enabled solutions	End-user benefits	Grid benefits
Aligning customer energy use with the grid's carbon intensity	Reduced value chain emissions	Reduced average marginal emissions
Dynamic pricing programs	Maximized return on investment of distributed energy resources (DERs), lower energy costs	Avoided curtailment and reduced peak demand
Grid balancing	Increased energy system reliability and resiliency	Increased energy system reliability and resiliency
Maximizing existing transmission and distribution infrastructure	Reduced electricity rates	Reduced capital investments and flattened investment curve
Operational efficiency	Lower operational costs	Reduced overall energy use
Improved grid monitoring	Reduced electricity rates	Reduced need for demand response (DR) events
Load shifting	Reduced electricity costs and potential to earn response payments	Avoided curtailment and reduced peak demand

We define ICT as all technologies that enable the collection, storage, and use of data to optimize complex systems; these technologies are becoming a necessary layer of infrastructure for the grid. ICT enables practices such as sharing dynamic price signals (Madduri et al. 2022), adjusting distribution patterns to balance the system (Dizdar 2022), and triggering energy charging and release from energy storage systems (Rissman and Gimon 2023). By using ICT, customers can dynamically optimize energy use across multiple parameters—including price, carbon-intensity, and submetered facility equipment—to maximize benefits for grid reliability, moving beyond more traditional interruptible tariff industrial DR programs. These energy controls can also unlock additional flexibility for the grid across various time scales, including at the second, minute, hour, and longer time horizons.

The strategy of using ICT to optimize energy or material systems is referred to as intelligent efficiency. Intelligent efficiency realizes its most immediate grid benefit when implemented by large industrial, commercial, and institutional customers who are in the position to offer significant aggregate demand flexibility. These large customers typically have the administrative infrastructure and operational scale to unlock substantial economic incentives and savings when acting as a grid resource.

In this white paper, we identify alignments between power sector and industrial needs during this transitional period for the U.S. energy system, consisting of accelerating electricity demand and expanding renewable generation. The United States has set a goal of reaching 100% carbon pollution-free electricity by 2035, and many states have set renewable or clean energy standards and goal as well, although these vary substantially; more ambitious states plan to meet at least 50% of electricity demand from renewable sources by 2030 (Barbose 2021). Industrial DR is already a large component of DSM portfolios,[2] and approximately half of retail potential demand peak savings come from industrial consumers (FERC 2022). We argue, however, that building demand flexibility capacity from large industrial customers to support improved balancing of energy supply and demand for a renewable-power-based grid should be prioritized more strongly by utilities over the coming years, especially as a part of their long-range planning efforts. We discuss strategies for utilities to increase large industrial customer participation in demand flexibility programs, using examples of current DSM programs integrating ICT-enabled solutions for industrial customers. We also highlight some of the remaining regulatory and program planning challenges that hinder the expansion of industrial demand flexibility capacity.

INDUSTRIAL ELECTRIFICATION IS LIKELY TO LEAD TO A MAJOR INCREASE IN ENERGY DEMAND

Electrification across major sectors of the economy, including the industrial sector, will be needed to meet decarbonization goals. While other sectors have made substantial progress toward electrification—in 2022, for example, electric heat pump sales exceeded gas furnace sales for homes and sales of EVs increased by 55% (Walton 2023a)—the industrial sector has lagged behind. Most large industrial energy demands that could be electrified are integral to manufacturing processes, and progress has been slowed by the cost of production downtime, the tight coupling between equipment within manufacturing systems, and the very high temperature of many heat processes (Rightor, Whitlock, and Elliott 2020). As table 2 shows, industrial electrification progress is likely to accelerate as new industrial

[2] Core demand-side management (DSM) approaches include energy efficiency programs, demand response (DR) programs, and distributed energy resources (DERs). A primary goal of DSM is to reduce the cost of energy acquisition by reducing peak loads in an effort to avoid/limit the use of high-cost generation resources and defer the need for building additional energy infrastructure.

electrification technologies mature, fossil fuel prices become more volatile, and federal incentives and corporate goals push industry to take steps to decarbonize their operations.

Industrial electricity demand growth projections range from relatively minimal changes by 2050 to additions of 6,000–10,000 terawatt-hours annually overall—potentially doubling today's current total national demand for electricity (Gimon 2023). The challenge of building and connecting sufficient clean electricity generation to meet this need, along with the load growth in other sectors, necessitates using strategies such as DSM that can shift load and mitigate demand based on available grid resources.

U.S. private sector manufacturing investments have doubled since the end of 2021 (Department of Treasury 2023). For example, the Inflation Reduction Act (IRA) was passed in August 2022; over its first year, more than $240 billion were invested in U.S. manufacturing facilities, mostly supporting clean energy and EV supply chain growth. The federal government received 411 concept paper applications in March 2023 for its Industrial Decarbonization and Emissions Reduction Demonstration-To-Deployment Funding Opportunity Announcement, with applicants requesting a total of $60 billion in support to match approximately $100 billion in private capital—or roughly 10 times the available federal funding pool—to decarbonize industrial facilities across a variety of high-emitting, energy-intensive sectors.

In particular, the glass, iron and steel, pulp and paper, and food and beverage sectors have industrial electrification technologies that range from early commercial stages to fully deployable (DOE 2023). Other industrial sectors, such as chemicals, are at only early pilot stages, but models predict that electrification technology strategies such as electric crackers (Gallucci 2023) and green hydrogen-based ammonia (Jones 2022) will be essential to decarbonization progress—and add large new loads to the electric grid. For example, a single industrial-scale electric ethylene cracker could add 350–400 megawatts (MW) (Gallucci 2023).

Table 2. Factors that will accelerate industrial electrification

Industrial electrification driver	Details	Examples
Emerging technologies	Efficient, new commercially available technologies or supply chains established in the United States for internationally proven tools	Thermal batteries, industrial heat pumps, electrified cement kilns, electric crackers
Market demand	Tier 1 companies pressuring supply chains to decarbonize; sustainable private sector financing groups	Major automakers demanding sustainable steel; green bank lending patterns

Industrial electrification driver	Details	Examples
Political will	State and regional carbon taxes; federal industrial policy legislative successes	RGGI; California cap-and-trade program; Inflation Reduction Act; the CHIPS and Science Act
Regulatory support	Enhanced clean air standards	EPA updated carbon pollution standards and PM2.5 standards
State and federal incentives	State support for clean energy economies; federal grants, loans, and tax credits for decarbonizing industry	Bipartisan Infrastructure Law (BIL) and IRA funded programs such as DOE's Industrial Demonstrations Program and the 48C Tax Credit
Shifting energy prices	More volatile natural gas prices; more expensive coal; lower cost renewables	Replacing coals plants with solar and wind is more affordable than continuing to run them

INDUSTRIAL DEMAND FLEXIBILITY IS INCREASINGLY VALUABLE

The major, ongoing shifts in how energy is produced and where and in what quantity it is demanded—especially by large energy consumers—are likely to increase demand flexibility's value in addressing some of the emerging operational challenges in the energy system. These challenges include 1) balancing energy supply and demand at every hour, 2) limiting increases in system demand peaks, and 3) enabling more cost-effective system planning.

Improving the Balance of Energy Supply and Demand

When energy demand is well balanced against energy supply, the grid's overall reliability increases by keeping grid frequency in the required range. Various extreme weather events in recent years have had tragic impacts resulting from extended electricity outages. One example was the 2021 Texas outage due to Winter Storm Uri; in addition to the loss of life and harm to community health and economies when key generation resources became unavailable, industrial factory shutdowns occurred across the state (Melaku, Fares, and Awal 2023). In other instances, DR and demand flexibility capacity of large energy users has been key to preventing catastrophic power outages, as when more than 2,000 MW of DR capacity was activated by residential, commercial, and industrial customers in California during a heat wave to avert system blackouts (St. John 2022). Additional research is needed to find better ways to assess the value of demand-side flexibility's contribution to increasing grid resilience to power outages (Hanif et al. 2022).

Industry can also play an important role in balancing supply and demand outside of extreme events. For example, compared to the residential and commercial sectors, industry has great potential for absorbing excess renewable energy at off-peak hours and reducing renewable curtailments (Langevin et al. 2021). Demand flexibility can ensure that when energy supply is highest (e.g., midday in the summer in solar-dominated grids) there is ample demand for that energy, and it is not curtailed or wasted.[3] New industrial electrical loads such as industrial short-haul freight and drayage vehicle fleets (Hoffmeister et al. 2023) or green hydrogen production are examples of new, energy-intensive demands that can respond to energy price signals to preferentially operate when low-cost renewable power is available.

Investment in demand flexibility programs becomes more affordable than maintaining fossil fuel generation capacity for reliability when electricity demand is high and renewables are dominant; this is especially the case for grids dominated by solar power (Satchwell et al. 2022). For example, a recent analysis of the interaction between growing renewables and transmission limits in the Electric Reliability Council of Texas (ERCOT) (EIA2023) found that by 2035, 53% of energy generation would be from solar and wind (compared to 31% in 2022) and that this rise in renewable penetration could lead to curtailment of a predicted 13% of wind generation and almost 20% of solar generation in 2035. This would at least double curtailment rates compared to today if strategies to mitigate curtailment and enhance demand flexibility—such as increased transmission lines, energy storage, and time-of-use pricing—were not instituted. ERCOT also found that 2035 congestion cost—that is, the cost of not having enough infrastructure to move energy resources from lower-cost grid regions to meet demand, and thus having to meet demand with higher-cost resources—could more than double compared to 2019 congestion costs, annually topping $2.8 billion if neither transmission nor demand flexibility capacity were expanded.

As figure 1 shows, in 2022, solar-dominated renewables met up to 45% of peak demand in the California Independent System Operator (ISO), where the difference between peak morning and evening net demand (i.e., demand minus wind and solar production) and mid-afternoon net demand has become more exaggerated every year as renewable penetration increases. This change has been characterized as a shift from a duck curve to a canyon curve (Patel 2023) and is already resulting in increased curtailment of renewable energy during midday generation peaks (Aniti 2021) and steeper evening ramping periods. California regulators recently voted to extend the lifespan of fossil-fuel-generating power plants to ensure that evening peak demand continues to be met and to avoid system blackouts (Roth

[3] Curtailing renewable resources means that they are operated below their potential capacity, an uneconomic strategy given that operational costs of renewable energy resources are very low but fixed costs (the money spent to build necessary infrastructure) are high. In addition to being uneconomic, curtailing zero carbon renewable energy sources might result in having to increase operation of higher carbon energy sources, such as natural gas plants, to meet peak demand at other times.

2023). Congestion due to a lack of transmission is likely driving much of the increase in curtailment (Aniti and Smith 2023).

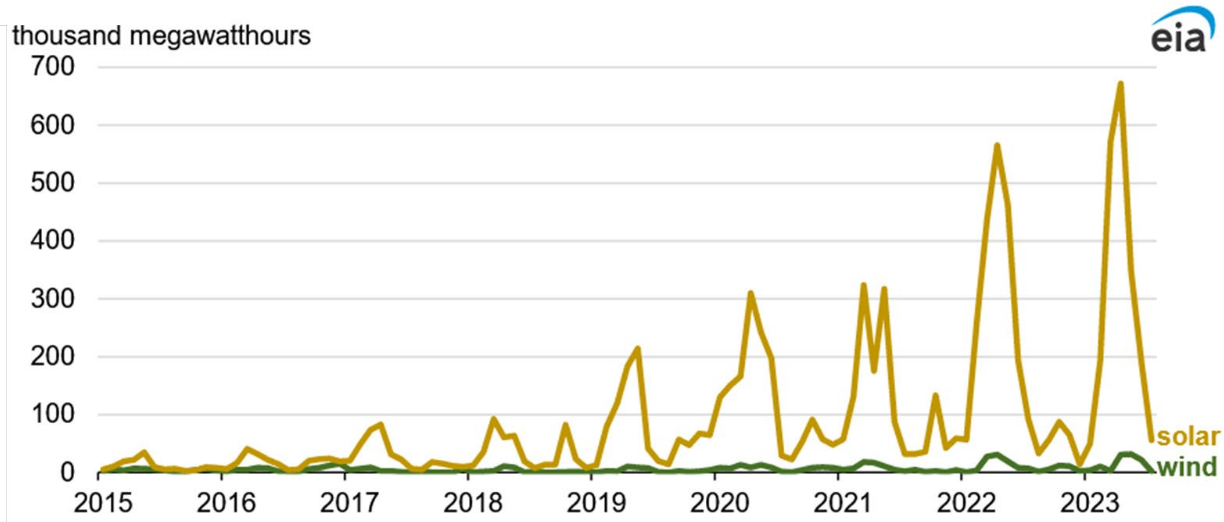

Figure 1. Monthly curtailment of renewable energy, especially solar, is increasing dramatically in the California ISO. Source: U.S. Energy Information Service.

Avoiding Negative Grid Impacts from Rapid Demand Growth

If new industrial electricity demand is not adequately planned for, growing industrial energy needs can lead to unintended negative consequences, including rate increases for other customers and prolonging the operation of fossil fuel power plants with associated grid emissions. Further, if additional industrial load raises peak demand hours, inefficient gas peaker plants can dramatically increase grid emissions and disproportionately emit pollution into lower-income communities and communities of color (Mullendore 2023).

A recent cautionary tale comes in the form of a new Panasonic EV battery factory in Kansas. Expected to be fully operational in 2026, the facility is expected to add 200–250 MW of additional demand on the system, and the system is not well prepared to meet this need with affordable, clean power. Evergy, the utility delivering power in the new factory's service area, estimates it will need to construct two new substations, upgrade three existing substations, and extend and rebuild 31 miles of transmission lines to meet this need and maintain system reliability. In addition to requiring Panasonic to pay for some of these upgrades, Evergy also filed a request to increase rates for all system customers and delay a transition plan for a coal plant until at least 2028 (Shorman and Bernard 2023). Over $90 billion in new U.S. battery manufacturing and supply chain investments have been announced during the last three years, most of it concentrated across the Midwest (Indiana, Michigan, Ohio) and southeast (Georgia, Kentucky, North Carolina, South Carolina, Tennessee) (Tracy and Novak 2023). If these regions where new energy demands are concentrated do not proactively address issues around grid upgrade needs and clean energy adequacy, similar negative impacts could be realized.

Enabling More Cost-Effective Planning

Utility and distribution planning efforts need to account for the potential scale and timing of increasing electricity demand, especially to support a future decarbonized industrial sector. Without proactively planning for changing electricity demands and weighing the costs and benefits of multiple pathways to meeting system needs, end-user electrification plans may stall, and the cost of upgrading energy systems may be unfairly passed on to consumers. A recent Brattle Group study found that 90% of transmission investments were justified based solely on reliability concerns and did not incorporate robust estimates of economics or strategies to reduce overall project costs (Pfeifenberger and DeLosa 2022).

Facing unexpected increases in electricity demand, some electric grids are already having to reformat plans and request approval for additional generation capacity. For example, Georgia Power is preparing a request to regulators to add new electricity resources by the end of the decade to meet higher-than-expected capacity needs—much of it stemming from several very large new industrial factories under construction (Kann 2023). To account for the expected load growth of 6,600 MW through 2030, Georgia Power is using a combination of expanded natural gas plants and approximately 10,000 MW of new renewable resources, complemented by up to 250 MW[4] of distributed energy resource (DER) and DR programs for large industrial and commercial customers (Georgia Power 2023). The cost of these additional system infrastructure upgrades may be passed on to other energy consumers, especially if the new energy demands substantially increase peak system demand and lead to additional capital-intensive transmission and distribution projects (Odom and Daniel 2022). In an attempt to avoid similar challenges, the Tennessee Valley Authority (TVA) Board of Directors recently approved $15 billion in investments over the next three years to build additional generation and upgrade existing systems to meet rapidly growing expected loads following many years of flat demand. TVA combined physical system upgrade plans with a strategy to offset more than 30% of the expected new load growth in the next 10 years through energy efficiency and DR programs, investing $1.5 billion toward DSM programs (Tennessee Valley Authority 2023).

Utility programs that incentivize investment in industrial demand-side technologies to support flexible energy use, such as ICT-based industrial process controls for batteries or customer microgrids (Elliott, Srinivasan, and Hoffmeister 2022), are likely to be a more cost-effective strategy than relying solely on expanded transmission, distribution, and energy supply to meet growing energy demands.

[4] compensating for less than 4% of expected load growth

Key ICT Enablers of Effective Industrial Demand Flexibility Programs

ICT enables effective demand flexibility programs by supporting monitoring, management, and coordination of energy both in and between the grid's demand and supply sides. To maximize system functioning, the grid should include 1) utility side ICT, 2) industrial facility ICT, and 3) advanced metering infrastructure (AMI) to enable information sharing between facilities and utilities.

Utility-Side ICT to Support Demand Flexibility

Utility-side ICT is part of the solution for enabling and operating automated flexible industrial demand. Grid control interface technologies, or DER management systems (DERMS), enable the communications, monitoring, analysis, and control required to manage DERs, including flexible loads in industrial customer facilities. As DERs continue to be brought online and developed, ICT is needed to fully integrate those resources, as the increases in global ICT investment and deployment in figure 2 show. DERMS are the critical hub between the utility and customer loads for demand flexibility, but they vary substantially in their use cases and functionalities, and can be integrated into advanced distribution management systems (Blair 2023).

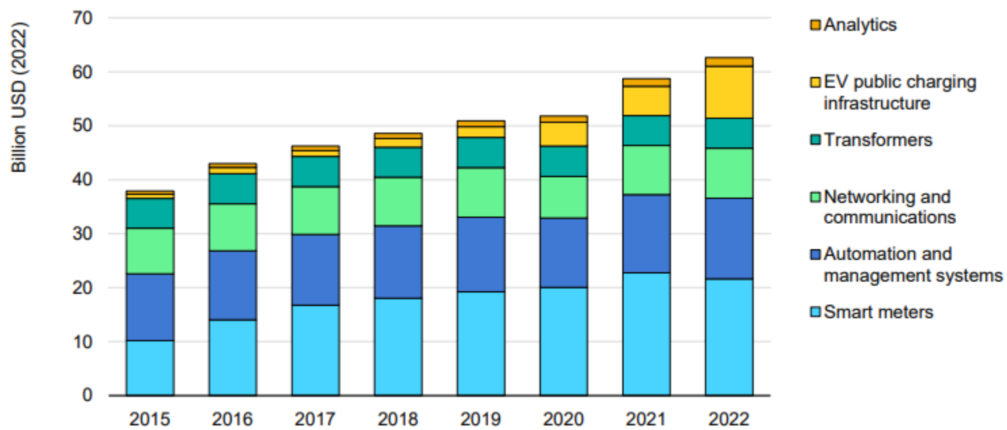

Figure 2. The increase in distributed energy resources (DERs) such as wind and solar has required a parallel increase in ICT investments to efficiently control grid operations. Source: IEA 2023.

Industrial Customer Demand-Side ICT to Support Demand Flexibility

Creating the capability to provide flexible demand to grid operators requires installation or enabling of various technologies on customer equipment and system controls. Devices and equipment require ICT to be able to respond to signals sent from the grid to reduce power demand by shutting down, cycling on/off, or otherwise shedding load by reduced operation. Such equipment includes motors, compressors, heat pumps, chillers, refrigeration units, and lighting. Industrial equipment is typically part of larger systems that have existing centralized, automated controls to manage and optimize the equipment operation. ICT adds a layer of controls that connect with and interact with grid data and signals so that industrial systems can be operated when they benefit the grid most, such as during periods of significant solar and wind generation. These kinds of plant-level energy management systems can also be used to alter plant energy demand profiles. For example, a paper-processing company used an ICT method to measure the energy usage patterns of individual equipment in its facility. Based on the data collected, it discovered the capacity to reduce its peak electricity demand by 10–15% by better optimizing processing schedules, reducing both the cost and carbon intensity of production (Guidewheel 2023).

ICT to Connect Energy Consumers and Grid Operators

AMI—also known as smart metering—is a foundational requirement for beneficial ICT deployment. AMI collects, communicates, and records electricity usage over short time intervals (e.g., in real-time, every 15-minutes, or hourly). It also has the potential to support two-way communication and even real-time data transmission—both of which are key enablers of smart energy management and grid-benefitting load flexibility (Gold, Waters, and York 2020). AMI penetration rates continue to rise across customer classes; as of 2020, approximately 58% of U.S. industrial customers have AMI installed (FERC 2022). Still, the minimum requirement for AMI remains hourly data, and not all currently deployed AMI can provide two-way communication or support real-time data. AMI is not well integrated into DSM programs, and it remains an underutilized resource for utilities in terms of driving energy savings for consumers and reducing system costs (Gold, Waters, and York 2020).

Some of the best potential AMI applications to facilitate flexible loads for commercial buildings and industrial facilities are grid-interactive efficiency buildings (GEBS).[5] A defining feature of GEBs is having integrated DERs to serve building loads, with corresponding control systems in place that are capable of two-way interactions with grid operators. While there is great promise and many demonstration projects planned or in place, no full GEB programs currently exist in the United States. Prior ACEEE research (Bastian and York 2019) reveals that the closest existing program models are those that target both DR and energy efficiency. For example, some commercial lighting programs support installation and operation of lighting and associated controls equipment that are both high efficiency and capable of adjusting loads in response to signals from grid operators. However, the willingness of commercial customers to consider these technologies has not translated to the industrial sector. Industrial operations—such as a car assembly line—cannot be adjusted remotely in the way that an office building's temperature can be shifted a few degrees with minimal impact on workers and production. However, as industrial electrification increases,

[5] According to the DOE, GEBs "are energy-efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way" (Satchwell et al. 2021). Four key GEB characteristics are (1) energy-efficient, (2) smart, (3) connected, and (4) flexible.

utilities should be ready to offer some targeted two-way control programs to industrial customers who may be persuaded to make some of their power use responsive to the grid given even larger electrical loads and the right financial incentives. Development of industrial flexible demand programs may draw on experience from monitoring-based commissioning programs, which can yield large energy and demand savings, as well as provide visibility into facility energy use patterns and end uses that may be suitable for demand flexibility (Nadel 2023).

Accelerating the Implementation of Industrial Demand Flexibility to Support Grid Operations

To support adoption of industrial demand flexibility programs, utilities and grid operators will need to clarify the business case for industrial customers and identify the industrial sectors best equipped to participate based on their operations. Unlike in the residential and commercial sectors, most industrial energy consumption is tied directly to productivity; thus, pausing operations or reducing energy use often requires a drop in production, unless energy needs are naturally intermittent in the facility or other strategies (e.g., thermal storage) are used to temporally decouple energy demand from energy use. Various studies have explored the challenges to industrial participation in DSM programs (e.g., (Golmohamadi 2022; Trabish 2021b; Shoreh et al. 2016); these challenges include energy market barriers (e.g., a lack of accessible data on energy pricing and system demand patterns); behavioral barriers (e.g., lack of industrial customer understanding or trust of new demand flexibility programs); technological barriers (e.g., lack of interruptible energy loads or lack of technical expertise in industrial facilities to manage changed operations); regulatory barriers (e.g., regulators preventing industrial demand flexibility pilots from expanding into full utility programs); and financial barriers (e.g., participation incentives do not compensate adequately for lost productivity).

In the following section, we focus on three approaches that utilities, utility program implementors, and grid planners and regulators could use to improve the uptake of industrial demand flexibility while maximizing grid benefits, primarily by overcoming or avoiding technological and behavioral barriers to industrial participation. The three approaches are as follows:

1) Integrating the goals and strategies of demand flexibility with well-established and trusted efficiency programs.
2) Targeting early efforts toward industrial facilities and subsectors that have greater capacity to participate in industrial demand flexibility programs through pre-existing technologies, staff expertise, or compatible manufacturing processes.
3) Focusing proactively on emerging energy-intensive industries and business cases to establish demand flexibility practices in early operational paradigms and reduce net additional demand on the grid.

BUILDING ON SUCCESSFUL INDUSTRIAL EFFICIENCY PROGRAMS TO EXPAND AND ENHANCE INDUSTRIAL DEMAND FLEXIBILITY CAPACITY

Industrial energy management is often conducted with the goal of reducing absolute energy consumption by increasing energy efficiency and managing energy costs. Commercial and industrial customers provide the majority of low-cost energy savings to utilities, as well as the majority of peak demand savings in most parts of the country (Frick et al. 2021). Energy efficiency is also a fast, affordable way to reduce emissions to support corporate sustainability goals. Operational efficiency strategies (through both capital investments and low-cost behavioral interventions) include certification and partnership programs such as U.S. Department of Energy (DOE) programs (e.g., ENERGY STAR, Better Plants, and Better Climate); Strategic Energy Management[6] (SEM) programs; and international standards such as ISO 50001.[7] Such efficiency investments, combined with technology development, have resulted in decades of consistent reductions in energy intensity per production unit across the industrial sector. What is currently missing from most energy efficiency programs, however, is the ability to not just reduce absolute energy use, but also to dynamically shift energy use to either optimize carbon emissions from purchased electricity or provide grid services such as more efficient utilization of existing transmission and distribution resources.

Timing efficiency interventions to save more energy during distribution peak load times increases the value of efficiency compared to interventions that primarily reduce energy demand during times of lower cost and lower carbon power availability (e.g., midday in the summer). The result of time-targeted efficiency strategies can be increased cost savings to customers and grid operators, as well as lower carbon emissions for the grid at large.

Utility DSM uses a range of tools and strategies, including energy efficiency, DR, customer-based energy resource incentives, interruptible tariffs, and time-based rates. Rarely are these strategies integrated into a single, comprehensive program that could support improved matching of customer demand to grid conditions. Such integrated DSM strategies remain rare given the remaining programmatic barriers; these programs are typically managed by various utility staff, funded based on different kinds of justifications, and even regulated and approved by different state or regional entities (Potter, Stuart, and Cappers 2018). One example of an integrated DSM program aimed at industrial customers is Con Edison's Real-

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[6] SEM is a set of practices and principles that creates the foundation for long-term, continuous energy performance improvement. It involves securing buy-in from top-level management, forming an energy team, setting energy-related targets, identifying opportunities for energy management and efficiency improvements (action plans), implementing action plans, continuously monitoring and reviewing progress, conducting measurement and verification of avoided energy consumption, and creating organizational change.

[7] ISO 50001 provides a practical way to improve energy use through the development of an energy management system for large commercial and industrial applications.

Time Energy Management (RTEM) pilot program, which offers incentives for commercial and industrial customers with 300 kW or greater peak based on electricity savings when using ICT to model facility energy use and automate operations. New York utilities also run "clean heat" programs, driven by statewide electrification goals. These programs provide incentives to customers, including industrial customers, for electrifying portions of their process heating with efficient heat pumps, which also can be used for DR.

In energy intensive industries, increased operational efficiency is a core component of industrial energy management because, in many cases—including primary metals, bulk chemicals, and wastewater treatment facilities—energy consumption is the largest operational cost that facilities face. Many of the efficiency interventions that industry already pursues to reduce energy costs could also contribute to increased operational flexibility, even if the interventions were not intentionally pursued with a flexibility framework in mind.

Industrial facilities that invest in sensors, submeters, and software solutions to monitor and manage energy usage can use this information to identify specific facility processes that trigger peak demand thresholds or individual machines that consume energy while idling. Having detailed, daily energy monitoring abilities lays the groundwork for facilities to recognize opportunities both for reducing energy demand with minimal impact on productivity and for recognizing which processes could have peak demand timing shifted without negatively impacting downstream productivity. While larger companies and facilities often have customized tools and systems, along with in-house energy management staff to conduct this work, small and medium-sized companies lacking in-house expertise can facilitate this data gathering using third-party technology companies with program models such as efficiency-as-a-service, which do not require large upfront expenditures or in-house expertise (U.S. Department of Energy 2023). Some utilities are already investing in programs that provide this kind of financial and technical support to industrial customers to install energy management information systems (EMIS) in their facilities. These ICT solutions are seen as a cross-cutting efficiency-enabling technology that can work with many kinds of industrial customers to lead to more strategic and deeper energy efficiency savings than approaches like lighting efficiency upgrades offer (LaBarge 2023). For industrial customers, the versatility of these ICT platforms can also lead to a more straightforward shift from an efficiency approach to a demand flexibility approach.

INDUSTRIAL END USES AND PROCESSES WITH THE GREATEST POTENTIAL FOR INDUSTRIAL DEMAND FLEXIBILITY

In the industrial sector, some operations are inherently suited for load-shifting without significant process retooling and should be considered as an economical option for utilities and grid planners to quickly expand grid capacity and resources. Instead of capital investments, businesses can adjust operational decisions to add flexibility to their electricity demand. Industrial facilities able to engage in demand flexibility programs today generally have a pre-existing flexible electrical load, as well as advanced operational controls that provide the ability to monitor the facility's energy usage across equipment. In interviews, industrial DR and flexibility program implementors noted that administrative capacity to set up the program's advanced controls was critical for the program's overall success. For industrial sites that lacked IT staff to carry out the initial setup, program implementors found that the full program benefits took longer to realize. Across all demand flexibility programs, customers require clear, easy-to-use data on electricity prices and carbon-intensity that will allow them to see where they can benefit in the program.

Industrial Process Heat and Cooling

Process heat refers to any heat used for an industrial process; such processes are traditionally powered by fossil fuels and are one of the largest sources of industrial emissions. Across industries, a wide range of temperatures can be required, from high-heat applications like concrete and steel to the lower temperatures used in the food and beverage sector. For process heat needs in the lower range, electrical options such as industrial heat pumps are becoming increasingly available. As these facilities electrify, utilities have an opportunity to work with the customers to enroll in demand flexibility programs that take advantage of newly electrified process heat operations. ICT upgrades in these facilities can unlock grid benefits by allowing proactive temperature shifts that preserve operational functions, while reducing electrical load during periods in which curtailment is needed. As demand flexibility's value proposition becomes clearer to customers, investments in thermal batteries and other energy storage solutions in industrial facilities could increase.

The opportunities for efficiency and grid benefits are also available for utility customers using refrigeration systems. The Electric Power Research Institute (EPRI) has been a leader in thermal energy storage,[8] documenting numerous cases in which refrigerated warehouses can take advantage of thermal energy to meet food cooling needs more efficiently (Reindl 2008). As industrial facilities look to decarbonize and replace fossil-fuel-powered heaters with technologies such as industrial heat pumps or thermal batteries, customers who would not have been strong candidates for demand flexibility programs could become valuable grid resources as their electricity usage increases when they switch to electric heat. Pilot programs to support industrial electrification are becoming more prevalent, especially in states that lack regulatory barriers to fuel switching policies (ACEEE 2022).

Heat batteries are another new technology that enable industrial electrification of process heat while innately supporting flexible energy use (Rissman and Gimon 2023). These batteries convert electricity—purchased at low-cost and low-carbon times—to heat, which can then be discharged to power industrial processes, much like an industrial combined heat and power system. For example, many of the early installations of Antora Energy's heat

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[8] Thermal energy storage refers to a variety of tools that allow energy to heat or cool a material and then release that energy when needed. Examples of approaches to storing thermal energy include refrigerators, water tanks, chemicals (e.g., molten salts), and technologies such as heat batteries.

battery technology occur in fuel ethanol plants located near large utility-scale wind farms (Kearns 2023). This company's business model merges energy storage technology with energy management software to simplify the timing of charging; this can maximize the purchase of low-cost renewable energy and allow variable renewable power to function as a dispatchable resource for industrial processes. Rondo Energy, another heat battery manufacturer, is piloting its heat battery technology to decarbonize process heating in a California biofuels plant, pulling power from the grid. Additional projects, however, will focus on linking heat battery installations to customer-sited renewable energy (Baker 2023). Utilities can support industrial customers' adoption of these heat batteries by offering rate structures with cheaper electricity during times when the heat batteries can most optimally charge from the grid's perspective.

Electrified Logistics

As industrial operations mitigate their carbon emissions, one of the first areas to consider is logistics. When transportation fleets, drayage operations, and smaller industrial vehicles (such as forklifts) are electrified, utilities should consider how they can leverage ICT to synchronize charging with grid need. Integrating demand flexibility program enrollment with the installation of charging infrastructure is one way to ensure that the grid can fully capture the co-benefits of behind the meter (BTM) storage such as EV batteries. Industrial customers can charge their batteries while electricity prices are low and, if needed, discharge that electricity back into the grid when prices are high. Some estimates indicate that there is significant revenue potential from these activities—that is, frequency regulation, DR, adding capacity, and selling electricity back to the grid—that could be worth as much as $10,000 annually per vehicle, depending on the region and the vehicle's battery size (Fröde, Noffsinger, and Sahdev 2023). Tapping into EV batteries as a storage solution can save significant capital expenses by avoiding new energy storage builds at the bulk grid level (Aydin and Aydin 2023). EV charging policy development is generally more advanced and could be more quickly repurposed to address industrial heavy vehicle fleet electrification; an example here is California's Vehicle-to-Grid Integration program to support statewide goals around zero-emission vehicle deployment (California Energy Commission 2023b).

Wastewater Operations

Treating and pumping wastewater is energy intensive and can be a significant expense for utility customers, particularly industrial customers in the food and beverage and pulp and paper sectors, as well as municipal governments responsible for a city's wastewater. In the case of municipal wastewater treatment, the system's electricity costs are as much as one-third of a city's total energy budget (U.S. Environmental Protection Agency 2013). Demand flexibility programs can provide substantial grid benefits and cost savings for these communities by shifting electricity use to off-peak times.

The DOE's Better Plants Program has done extensive work with wastewater treatment facilities across the country, showing that there are efficiency and cost-savings gains to be made using ICT upgrades in this sector. For example, wastewater treatment facilities with a flow equalization basin allows incoming water to be diverted to a holding area for later processing; such basins could be treated as pumped storage with the proper metering and controls, allowing for dispatchable loads to help meet grid needs (Swank et al. 2019).

Agricultural Irrigation Pumping

Another industry with inherently flexible loads is agriculture. Farms that rely on irrigation can time their pumping operations to maximize grid benefit. In California's Central Valley, where irrigated agriculture is the norm, utilities have established DR programs for farmers (Olsen, Aghajanzadeh, and McKane 2015). PG&E's Automated DR program, for example, installs advanced ICT on irrigation pumps to allow for automated participation during DR events, while also allowing participating customers to override pump shutoffs if needed and access advanced data to use water more efficiently (PG&E 2022). Controlled environment agriculture (CEA) also presents opportunities to align water usage, lighting, heating, and other production variables with the grid's energy needs (Garfunkel 2023).

EMERGING INDUSTRIAL BUSINESS CASES FOR DEMAND FLEXIBILITY

Decarbonizing industrial operations is expected to be a capital-intensive process, requiring a combination of retrofits of existing facilities as well as entirely new operational paradigms at newly built or expanded sites. Designing new industrial energy systems with efficiency and flexibility of operations in mind can lead to more economical outcomes for industry; it can also increase utilization of renewable energy supply for the grid and support grid resiliency through increased capacity to participate in DR programs.

Instead of focusing primarily on upgrading energy supply and distribution systems, utilities could proactively engage with expanding industries to focus on incentivizing energy flexibility strategies from the beginning. Examples here include incorporating energy storage into system design and ensuring that energy management systems that enable data collection and communication—and eventually, automation—are incorporated. The vast majority of energy projects awaiting interconnection today are renewables, and these projects face accelerating interconnection costs and long wait times (Interconnection Innovation e-Xchange 2023). If companies increase the amount of behind-the-meter generation or storage capacity, they can minimize upgraded interconnection requirements, vastly speeding development of new energy resources and effectively greening the grid by increasing the proportion of the power they consume that is sourced from renewables. New, renewably based industrial energy microgrids also provide the additional benefit of enhanced resiliency to power disruptions; utility programs can support the capital costs of installation as well as managing operation for large industrial and commercial consumers (Walton 2023b).

In West Virginia, for example, a new manufacturing ecosystem is emerging. In 2021, 91% of the state's energy was generated by coal-fired power plants, and the state utility commission has remained supportive of the coal industry, even with rising electricity rates (Maher 2022). Despite this unfavorable grid environment for energy-intensive industries, in the past year, more than $1.2 billion in investments have been announced to redevelop industrial sites in the state. New industry is strategically incorporating energy storage and renewable energy onsite, and the sector's growing demand can act as a strong pull for additional clean energy investments. For example, Precision Castparts (PCC) recently announced a new $500 million investment to build a titanium manufacturing facility. This new plant plans to partner with a rechargeable 10-hour battery manufacturer, as well as an on-site solar farm, to ensure that reliable, clean power supports its energy-intensive operations. As West Virginia competes for additional manufacturing investments from heavy industry, its clean energy installations are also expanding; while just 10 MW of solar were operational in the state in 2022, an additional 50 MW are under construction, with industrial demand cited as a major reason for the shift toward clean energy in the coal-dominated grid (FirstEnergy Corp 2023).

Green hydrogen production (hydrogen produced from renewable energy using electrolysis) may also be a major driver of industrial electricity consumption increases. As table 3 shows, for example, DOE's Industrial Decarbonization Roadmap (DOE 2022) predicts that reaching a net zero emissions scenario for the iron and steel sector in 2050 would increase its electricity consumption approximately 1.5 times business as usual as a result both of deploying green hydrogen as a fuel and reducing agent and of expanding electric arc furnace production in place of blast furnace–basic oxygen furnace (BF-BOF) pathways. For ammonia production—another energy-intensive industrial subsector[9]—to reach net zero emissions goals, a dramatic increase in the consumption of green hydrogen produced via electrolysis would lead to an astounding 16-times increase in electricity use in this subsector, with ammonia production rivaling the iron and steel sector for its overall electricity demand by 2050. It will be essential to proactively find ways to ensure that green hydrogen production facilities are not detrimental to grid reliability; do not increase the need to run fossil-fuel-powered generation plants during peak demand hours; and incorporate technologies that enhance the flexibility of energy demand, including onsite production of renewable energy, energy storage, and effective ICT-enabled energy management systems.

[9] Ammonia production currently accounts for 6.5% of all U.S. industrial natural gas consumption, and its production increased 46% between 2015 and 2020. Annual ammonia production emits the equivalent GHG of almost 8 million gasoline-powered cars driven for one year (EIA 2021).

Table 3. Calculations of predicted electricity consumption by select industrial subsectors for which scenario data were available. The table shows business as usual (BAU) scenarios in 2050 vs. a net zero (NZ) scenario with aggressive uptake of emissions reducing technologies and electrification.

Industrial sector	Expected production increase 2015–2050	Electricity consumption (GWh)			Electricity consumption increase NZ vs. BAU scenarios	Average additional hourly demand (GW)
		2015	2050 BAU	2050 NZ		
Iron and steel	12%	72,546	68,587	103,507	151%	3.53
Ammonia	39%	2,136	7,281	118,859	1633%	13.32

Source: DOE Industrial Decarbonization Roadmap.

Reaching the Potential for Flexible Industrial Loads: What Is Needed to Overcome Barriers

MAKING THE BUSINESS CASE FOR CUSTOMERS

For industrial customers to prioritize capital investments and change their operations to increase load flexibility requires a strong business case. Typically, such a case is based on the electricity cost savings that would result from taking these actions. These savings are largely a direct function of electricity rates, which vary in both structure and value. Industrial electricity rates typically have three components:

- *Fixed charges* are a flat fee that covers various utility fixed costs for providing service.
- *Demand charges* are a flat fee based on the peak customer power demand (in kilowatts) measured during a previous period (typically the past year). Demand charges are structured into tiers, with each tier covering a specific range of values. Each higher tier ratchets the value higher.
- *Consumption/use charges* (volumetric) are rates paid per unit of electricity consumed by customers (cents/kilowatt-hour).

From a customer standpoint, two principal strategies can help manage energy costs:

- Reduce peak demand to reach a lower tier with a lower demand charge
- Reduce overall energy consumption (kilowatt-hours)

DR programs focus mainly on reducing peak demand. Common approaches include paying incentives to customers to reduce or shift loads during periods of high system demand, or structuring rates that encourage customers to modify their energy use to avoid high use during times with high rates (time-of-use rates).

A related factor affecting the business case for customers is risk: What would the potential losses be if the ICT and related technologies fail to perform as intended? Clearly, industrial customers are strongly averse to any unexpected disruption to production processes. Given this, the most amenable energy end uses for flexible load options are often ancillary to core production processes. As we noted earlier, the technologies best suited for flexible load options might include refrigerated storage or lighting.

Programs and funding mechanisms that serve to financially "de-risk" early adopters in priority sectors for industrial demand flexibility could also be an important strategy for making a stronger business case for customers. Many current pilot programs are led by state energy agencies partnering with utilities, especially in states with more ambitious emissions reduction goals. Leading examples of industrial demand flexibility pilot programs taking this approach include the following:

- The California Energy Commission (CEC) is in the process of developing the new Industrial Decarbonization and Improvements to Grid Operations (INDIGO) grant program, which is expected to target energy efficiency, industrial electrification, and other advanced energy technologies that serve to both reduce industrial pollution and GHG emissions while also increasing industrial capacity to participate in DR and demand flexibility programs (California Energy Commission 2023a). This program is being established in response to legislative directives to decarbonize the California economy.
- Many New York utilities offer non-wires alternatives programs to help reach ambitious state-level decarbonization and clean energy goals that rely on increasing the role of privately owned DERs in the system (Trabish 2021a; NYSERDA 2024). Large industrial consumers are also incentivized to participate, including through technical assistance programs sponsored by New York State Energy Research and Development Authority. These programs provide planning and other financial de-risking services for industrial customers to implement efficient, clean energy technologies.
- Green Mountain Power, a utility in Vermont, runs a Flexible Load Management (FLM) 2.0 pilot program that enrolls commercial and industrial customers to reduce or increase their load during grid events multiple times a month. When distributed solar resources are abundant, the program asks customers to increase their load. The pilot also works to shape the participant cohort's aggregate load to match a predefined shape—such as flattening a demand peak or smoothing an evening ramp rate as solar resources go offline and electricity demand increases (Green Mountain Power 2021).

SUPPORTIVE REGULATION FOR FLEXIBLE DEMAND

Beyond the technological and behavioral barriers to industrial participation in demand flexibility programs, regulatory challenges also exist that many regions will need to overcome. Utility regulators at both the state and federal levels can strongly influence the amount of flexible demand on the grid through rate structures, planning requirements, and electricity market rules and operations. Simply providing energy monitoring tools such as AMI is generally not enough to achieve full customer participation in either efficiency or demand flexibility programs (Gold, Waters, and York 2020).

At the state level, public utility commissions can establish standards and create incentives for achieving the desired load flexibility outcomes. As we discussed above, rate structures play a large role in industrial customer responsiveness to DSM options. State commissions also wield strong influence over utility planning and approval of a wide range of utility investments, such as upgrades to transmission and distribution systems and new generation resources.

Recent federal decisions have created new opportunities for and increased emphasis on demand-side options, such as load flexibility, for utilities and grid operators. Federal Energy Regulatory Commission (FERC) Order 2222 issued in September 2020, sets new rules for wholesale electricity markets; these rules create and expand opportunities for all types of DERs—including energy efficiency, DR, customer-sited renewable generation, and battery systems—to participate in and contribute to meeting grid loads. Grid operators must propose and enact DERs rules and guidelines to allow them to compete and be selected as grid resources (Specian 2021). The large electrical loads of many industrial customers may be especially well suited to participate in wholesale markets, but compliance and implementation has been slow in many regions of the country (Macbeth and Bell 2021).

IMPROVED INDUSTRIAL LOAD FORECASTING AS PART OF INTEGRATED RESOURCE PLANNING PROCESSES

Incorporating flexible demand into scenario modeling in support of integrated resource planning (IRP) processes could improve long-range planning outcomes and help utilities to be more prepared to meet changing energy demands in an efficient and economic manner. Most utility planning groups model DERs as negative load, subtracting things such as customer-sited energy storage or solar PV panels from total system load for resource adequacy calculations (Carvallo et al. 2023). If these resources are deployed more flexibly at scale, it could substantially impact the economics of system operation in a way that this simplified modeling approach fails to capture, and planners may have to develop different or additional metrics to assess grid function with and without load flexibility.

Technical support for utilities that lack the in-house expertise or modeling sophistication required to identify the best available technology could help to ensure that IRPs across the country are all equipped with what they need to plan successfully for a renewable-dominated future. Additional research is also warranted to identify potential regulatory hurdles related to using demand-side resources for grid resource adequacy plans. Finally, technical support for regulatory commissions that evaluate and approve long-range plans could also support more consistently realized best practices across regions. Such support could ensure that regulators have the necessary tools to evaluate IRP models for how well they consider potential load increases and assess deployment of demand flexibility to alleviate grid stress.

Conclusion and Recommendations

The value of demand flexibility for industrial energy consumers is context dependent; it relies on having the right rate structures and incentives in place to make the case to these consumers that changing their approach to energy management is worth the effort involved in changing their business practices and giving already busy operations staff an additional activity. However, when large consumers such as industry have more flexible energy demand, it helps the grid provide needed capacity, reliability, and resiliency in a cost-effective manner. This is especially important as the power sector transitions to a more decentralized, temporally variable, and complex grid structure.

While some industries have existing business models that well prepare them for using energy more flexibly, the major opportunities to increase the industrial demand flexibility programs that we identify in this paper are in the expansion of new industrial business models and the early but growing progress of industrial electrification technologies. New industries such as EV battery manufacturing and green hydrogen production are electricity-intensive and will add large new demands to energy systems. Utilities and state energy offices can proactively work with these new industrial facilities to design technology pathways that will limit the additional of new energy demand to the grid. These pathways include incentivizing onsite renewable energy generation or energy storage, and developing rate structures that reduce the magnitude of peak load additions, which can help to make necessary grid infrastructure expansion more efficient and economic.

Many new electrification technologies—including heat batteries, onsite renewable energy installations, industrial heat pumps, and other forms of energy storage—enable energy flexibility and, when paired with ICT, they also give industry opportunities to participate in demand flexibility programs. As new industrial energy demands (especially for process heating) become electrified, federal, state, utility, and end-user investments in building the technological capacity to communicate and coordinate between energy supply and demand will be essential to maintaining a reliable, resilient, and efficient grid.

To be ready for the growing potential of industrial demand flexibility, utility program managers can work now to make a stronger business case to their customers. This includes improving rate structures for more flexible energy usage, but it also may require more experimental or innovative approaches, including helping to financially de-risk the installation of flexible, energy-efficient industrial equipment. Future efforts could model, for specific regions, the economic benefits of partnering with industry to increase flexible energy demand capacity and improve industrial demand flexibility's valuation, especially for system resilience.

Utility regulators can also improve regulatory practices to make them more supportive of industrial demand flexibility by examining system planning requirements and electricity market rules and operations. As more states adopt decarbonization targets, it will also be important to address the regulatory barriers to industrial electrification that exist in many states today, as these may hinder decarbonization progress and the economic expansion of future clean energy systems.

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