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Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization

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Abstract: The U.S. government aims to achieve net-zero greenhouse gas emissions by 2050 to reduce the severe impacts of climate change. The U.S. industrial sector will become a focal point for decarbonization since it accounts for 33% of the nation's primary energy use and 30% of its energy-related CO_2 emissions. Industrial emissions are also expected to increase by 15% through 2050, making the industrial sector a logical target for decarbonization efforts. Energy efficiency technology pathways provide low-cost, foundational routes to decarbonization that can be implemented immediately. Energy efficiency technology pathways, such as strategic energy management, system efficiency, smart manufacturing, material efficiency, and combined heat and power, are well established and would immediately reduce energy use and emissions. However, their role in the aggressive net-zero decarbonization pathway for the industrial sector is still unclear. This study aims to address energy efficiency pathways for decarbonization, and reviews studies related to these technologies for industrial decarbonization through 2050. This study identifies different strategies for the industrial sector in general and that are specific to six energy-intensive industries: iron and steel; chemical; food and beverage; petroleum refining; pulp and paper; and cement. Finally, a path toward the successful implementation of energy efficiency technologies is outlined.

Keywords: decarbonization; energy intensive industries; smart manufacturing; material efficiency; strategic energy management; industrial energy savings

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1. Introduction

Around the world, efforts are increasing to drastically reduce greenhouse gas (GHG) emissions by 2050, with the Paris Agreement on Climate Change calling for critical and transformative actions [1]. The Paris Agreement calls to keep the global average temperature rise below 2 °C compared to pre-industrial levels, specifically aiming to limit it to 1.5 °C. As of 2017, the global average temperature rise reached approximately 1 °C and is expected to hit the 1.5 °C mark by 2040 if the same trend continues. Limiting the temperature to 2 °C will require reaching net zero emissions in the latter half of the 21st century, whereas for limiting it to 1.5 °C, GHG emissions must reach a near-zero value by 2050 [2]. Decarbonization can be achieved through pathways deployed across various economic sectors. However, the industrial sector has been at the forefront regarding energy-related GHG emissions. In the United States, the industrial sector accounted for 33% of overall primary energy use in 2020 and was responsible for 30% of the nation's total energy related GHG emissions, as shown in Figure 1 [3]. Reducing the sizeable portion of the emissions from the industrial sector will play a key role in meeting the Paris Agreement goals.

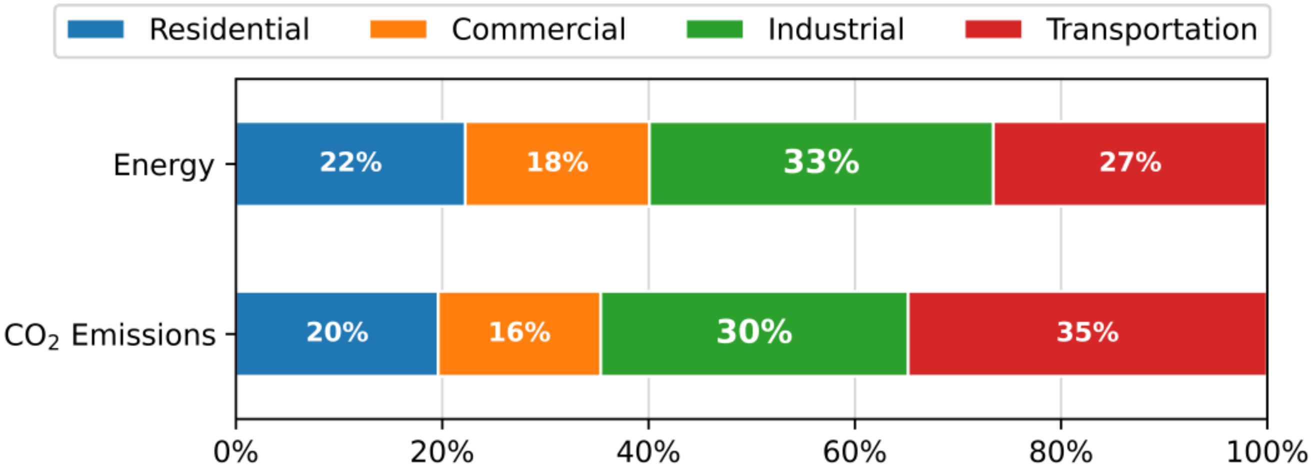

Figure 1. Carbon emissions and primary energy use by sector in 2020 based on data from [3].

The focus of industrial decarbonization is on the energy-related CO_2 emissions from fossil fuel combustion and specific processes as they constitute the most considerable portion of industrial GHG emissions. While other GHGs, such as CH_4 and N_2O, have higher global warming potentials and should be reduced as well, they are comparatively lesser in amount, making CO_2 emission reduction a key focal point in industrial decarbonization. As of 2021, manufacturing alone was responsible for almost three-quarters of all industrial GHG emissions in the United States [4]. The bulk of the manufacturing energy-related CO_2 emissions comes from a few industries, such as iron and steel, chemical, food and beverage, petroleum refining, pulp and paper, and cement, as shown in Figure 2. Decarbonization efforts must focus on these industries because together they can lower a substantial share of the CO_2 emissions from the industrial sector.

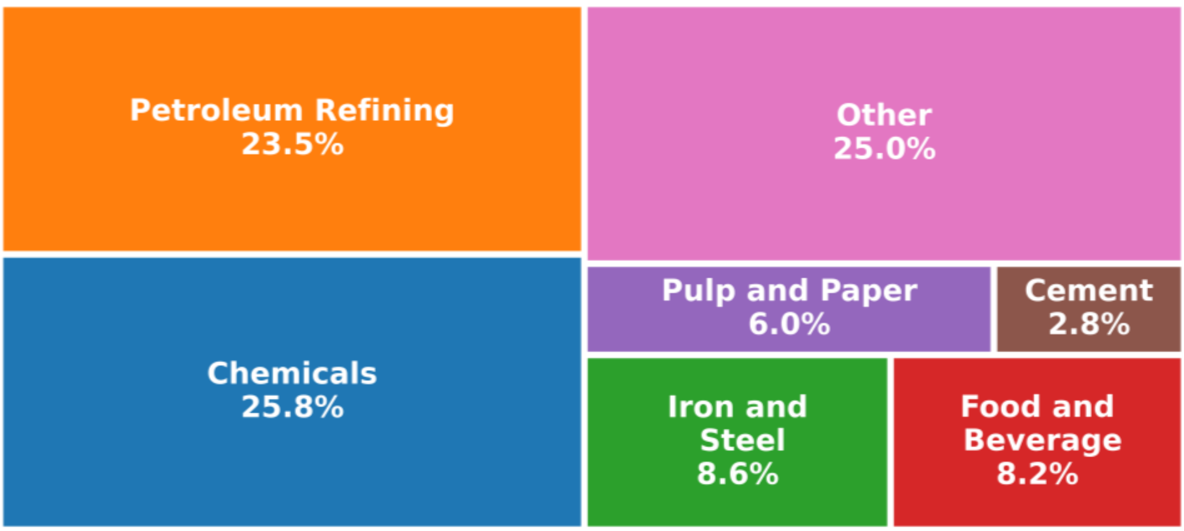

Figure 2. Percentage of energy-related CO_2 emissions from manufacturing sectors based on data from [4].

Over the past several years, various strategies (e.g., less carbon-intensive processes, fuel switching from coal to gas and renewables, and increased efficiency) have been adopted by industries to reduce energy intensity and the related emissions. Studies have identified various decarbonization pillars as viable options for industries to reduce emissions [5,6]. The U.S. Department of Energy's (DOE's) Industrial Decarbonization Roadmap identified four pillars: energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS), as shown in Figure 3 [7]. The energy efficiency pillar focuses on lowering energy demand, and therefore the CO_2 emissions from fossil fuel combustion. The industrial electrification pillar focuses on using electricity as an energy source to replace the direct combustion of fossil fuels, which can leverage the lowering carbon intensities of both grid and on-site electricity generation sources. The LCFFES pillar can further lower emissions associated with fossil fuel combustion by substituting fossil fuels, feedstocks, and energy sources with low- and no-carbon alternatives. The final pillar, CCUS, is aimed at capturing the difficult-to-abate CO_2 emissions at the source or directly from the atmosphere. The captured CO_2 emissions can either be utilized or stored for longer periods to prevent it entering the atmosphere [7].

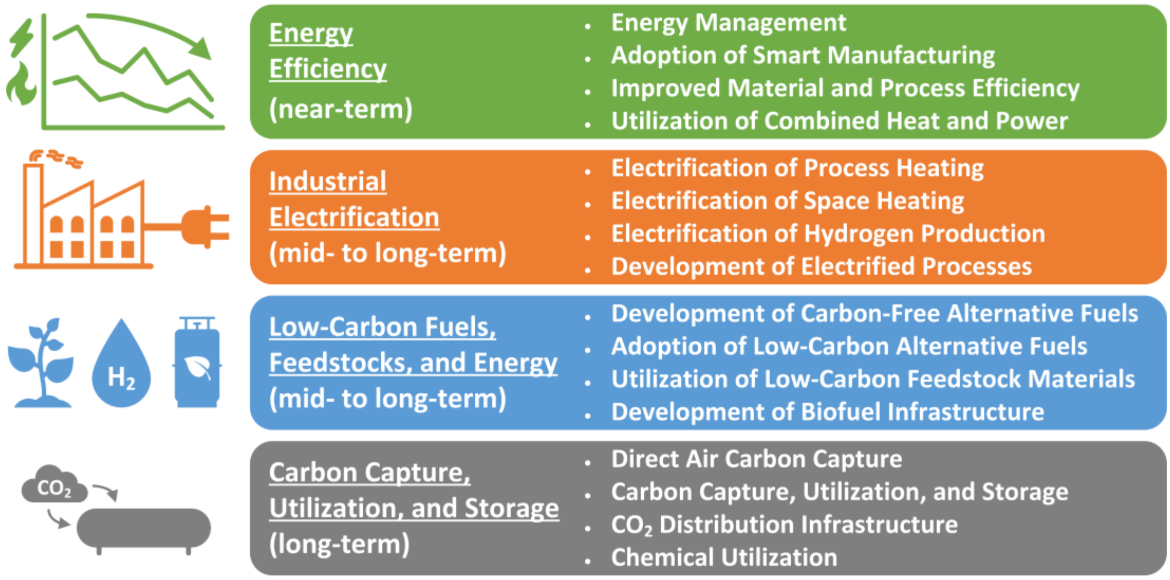

Figure 3. Four pillars of industrial decarbonization along with example approaches under them.

To achieve net-zero emissions by 2050, the U.S. industrial sector needs to decarbonize by adopting emerging and transformative technologies (electro-technologies, LCFFES, and CCUS) and keeping a near-term focus on increasing energy efficiency efforts. Although almost half of the emissions reductions in 2050 are expected to come from transformative technologies of low technology readiness levels, most emission reductions through 2030 would come from the energy efficiency technologies that are already proven to be effective and available in the market today. In total, 66% of overall on-site manufacturing sector's CO_2 emissions are from process energy use, and are mostly attributable to process heating, steam, and motor-driven systems [8]. Energy efficiency remains the most cost-effective option to reduce these GHG emissions. With the emergence and growing discussions on other decarbonization strategies such as electrification, LCFFES and CCUS, energy efficiency is taking a back seat for many manufacturers especially in the energy-intensive sectors. Along with this, the surplus oil and gas supplies in the U.S. coupled with low natural gas pricing is making energy efficiency a lower priority. However, energy efficiency is the foundational pillar on which decarbonization can be achieved, as it reduces the overall energy and material demands. To strengthen and bolster the role of energy efficiency in decarbonization, different energy efficiency approaches that industries can implement must be understood, along with their potential to save energy and reduce carbon emissions. The objective of the study is to address this knowledge gap and detail the different energy efficiency approaches for the industrial sector in general and those specific to six energy-intensive industries: iron and steel; chemical; food and beverage; petroleum refining; pulp and paper; and cement. A thorough literature review of various studies across the globe on energy efficiency's potential to reduce carbon emissions is presented with quantified measures. The industrial sector would be able to use this review to down-select specific energy efficiency technologies that are relevant to the sector, while also considering the challenges presented here to make informed decisions. In addition, sustainable manufacturing is not only about decarbonization, as noted by the 17 Sustainable Development Goals (SDGs) from the United Nations Development Program (United Nations Development Program, 2023). While this study is aimed at SDG No. 13 (Climate Action), it also touches upon other SDGs, such as No. 7 (Affordable and Clean Energy), No. 9 (Industry, Innovation, and Infrastructure), and No. 12 (Responsible Consumption and Production), due to the multiple benefits arising from energy efficiency technologies.

2. Energy Efficiency for Industrial Decarbonization

Energy efficiency improvement is a foundational, feasible, low-cost approach towards decarbonization. In most cases, it does not require any major change to the industrial processes and can bring immediate reductions in emissions. Since 2010, through the Better Plants program, DOE has worked with more than 270 manufacturers and water and wastewater utilities representing every U.S. state and territory to accelerate the adoption of more energy efficient practices, highlight new and innovative technologies, and spur change at an organizational level. The objective of the Better Plants program is to help industrial organizations set and meet ambitious energy, water, waste, and carbon emission reduction targets. By partnering with industry, the Better Plants program aims to help leading manufacturers boost efficiency, increase resilience, strengthen economic competitiveness, and reduce their carbon footprint through improvements in energy efficiency. Through the program, DOE supports 3600 facilities, corresponding to 14% of the U.S. manufacturing footprint. Collectively, these partners have reported savings of 2.2 QBtu (2.3 exajoule (EJ)) of energy and USD 10.6 billion [9]. This is equivalent to 131 MMT of CO_2 emissions reductions. Figure 4 shows the average energy intensity improvement in terms of the number of plants and the program's energy footprint for selected sectors since 2010. According to Nadel and Ungar, current energy efficiency measures in the U.S. industrial sector can potentially save 6.25 quads (6.6 EJ) of energy (6.5% of baseline energy use in 2050) and reduce CO_2 emissions by 244 MMT (5.6% of baseline energy CO_2 emissions in 2050) through 2050 [10].

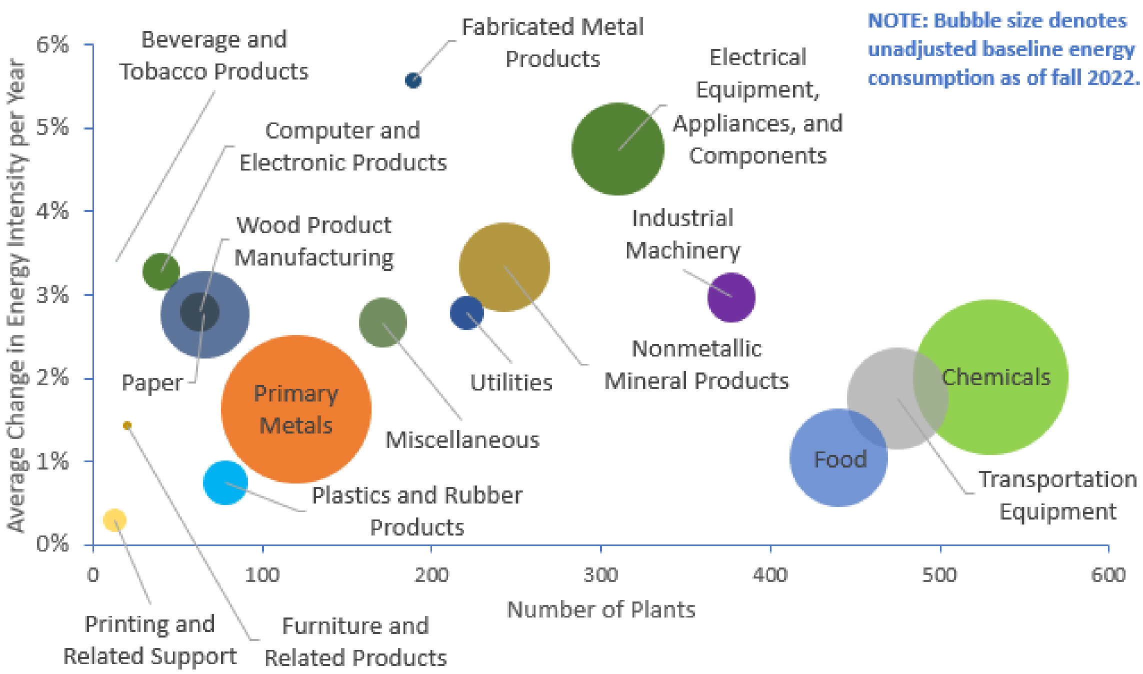

Figure 4. Average energy intensity improvement in terms of number of plants and program energy footprint for selected sectors. Source: U.S. DOE Better Plants Program, 2022 [9].

Decarbonization is not only a priority in the United States; similar studies have been conducted in different countries around the world, developing roadmaps to reduce carbon footprints. The UK government, for instance, released a series of reports that assessed the potential for a low-carbon future and developed decarbonization roadmaps for eight of the most heat-intensive industrial sectors in the United Kingdom [11]. Per the comprehensive study, combined max tech pathways which include CCUS, electrification, material efficiency, energy efficiency, and others can bring down emissions from 81 MMT CO_2 in 2012 to 22 MMT CO_2 in 2050. Energy efficiency combined with heat recovery alone potentially contributes to a reduction in total emissions of 8 MMT CO_2 (13% of the overall reduction) in 2050. The main contributors to emission reductions are the refining industry (43%) and the pulp and paper industry (41%), followed by the food and beverage industry (36%) [11].

Similarly, industrial energy consumption in the European Union is projected to drop by 25% in 2050 compared to that in 2015 through energy efficiency improvements, with waste heat recovery applications being the primary driver. The energy efficiency improvements are also expected to reduce the energy-related CO_2 emissions by 22% in iron and steel sectors, 22% in chemical sectors, 35% in the nonmetallic minerals (e.g., cement, lime) sector, 15% in the nonferrous metals (e.g., aluminum, copper, and lead) sector, and 32% in refineries in 2050 compared with the baseline scenario, which reflects the EU decarbonization trajectory from 2015 to 2050 based on existing and agreed energy and climate policies [12]. In Australia, energy efficiency in the manufacturing sector could cause a 40% reduction in energy intensity by 2050 compared to 2010 levels [13]. Multiple studies on such subjects were examined, a select few of which are compiled with their saving potentials and timelines in Table 1.

There are multiple pathways for the energy efficiency pillar. Implementation will differ based on the sector, leading to diverse solutions being deployed across the industrial sector. This study aims to aggregate these different pathways in the upcoming sections to provide strategies that can be generalized across sectors. Specific solutions have also been detailed. The different pathways to the energy efficiency pillar are discussed in the following sections and also shown in Table 2. The table provides energy efficiency strategies for six major energy-intensive sectors: iron and steel; chemical; food and beverage; petroleum refining; pulp and paper; and cement.

Table 1. Summary table of select studies on the industrial decarbonization through energy efficiency with their savings potential and time frames.

Source	Origin	Baseline Year	Target Year	Energy Savings	Emissions Reduction by Energy Efficiency Pillar	Savings Type	Sector	Pillars/Pathways Addressed
Nadel and Ungar, 2019 [10]	United States	2019	2050	6.25 quads (6.6 EJ)	244 MMT	Energy use/ CO_2 emissions	Industrial	Energy efficiency
WSP et al., 2015 [11]	United Kingdom	2012	2050	—	23–59 MMT	CO_2 emissions	Industrial (energy-intensive)	Multiple pillars; energy efficiency contributing 12.8–23% reduction
ClimateWorks Australia, 2014 [13]	Australia	2010	2050	40%	—	Energy intensity	Industrial	Energy efficiency
European Commission, 2018 [12]	Europe	2015	2050	25%	259 MMT CO_2e (53% from baseline)	Energy use/ CO_2 emissions	Industrial	Energy efficiency
Hasanbeigi et al., 2019 [14]	United States	2040 Business as usual	2040 advanced technology deployment	—	0.54 MMT CO_2 per year (5% from baseline)	CO_2 emissions	Cement	WHR to power and other emerging technologies and measures
McKane and Hasan-beigi, 2010, 2011 [15,16]	United States, Canada, European Union, Thailand, Vietnam, and Brazil	2008	—	173–234 TWh/year (28% to 38%)	—	Energy use	Industrial	Motor systems (pumping, compressed air, and fans)
Whitlock et al., 2020 [17]	United States		2050	—	15% from baseline	CO_2 emissions	Industrial	Multiple pillars considered
de Pee et al., 2018 [18]	Global	2014	2050	—	15–20% from baseline	CO_2 emissions	Industrial	Multiple pillars considered

Table 2. Specific strategies under each energy efficiency pathway for the six energy-intensive industries considered in this study.

Energy Efficiency Pillar	Iron and Steel	Chemical	Food and Beverage	Petroleum Refining	Pulp and Paper	Cement
Strategic energy management	Commitment, identification, and implementation of energy efficiency projects, tracking energy and carbon efficiency performance, ISO 50001, and energy management information systems					
System efficiency	Process heating, compressed air, pumps, and fans	Steam, process heating and cooling, compressed air, pumps, and fans	Steam, process heating and cooling, compressed air, pumps, fans, non-thermal drying, and dewatering	Steam, process heating and cooling, compressed air, pumps, and fans	Steam, process heating and cooling, compressed air, pumps, fans, efficient dispersers, refiners, and grinders	Process heating, compressed air, pumps, and fans; efficient grinding technologies (e.g., high-pressure grinding rolls, and vertical roller mills in place of ball mills
Materials and life cycle efficiency	Top pressure recovery turbine, coke dry quenching, basic oxygen furnace gas recovery, improving semi-manufacturing yields, and scrap reduction of end-use goods by improved manufacturing techniques (e.g., AM)	Energy, system, and material efficiency (e.g., recycling and waste minimization)	Food waste reduction	Desulfurization using clean hydrogen; efficient use of low-carbon energy sources	Innovative drying techniques, increased use of recycled pulp, biogas production from effluent, and black liquor gasification	High-efficiency clinker cooling and grinding; innovative chemistry (blended cement and low-carbon binders), and clinker substitutes (fly ash, ground granulated blast furnace slag, limestone, and calcined clay) wastes (oils and solvents) as alternative fuels in kilns
Smart manufacturing	Shortened smelting time and enhanced smelting efficiency using automated detection of molten steel components, blowing controls, and component analysis; digital twin	Smart manufacturing using data mining and modeling to develop dynamic target values for energy consumption; digital twin	Automation and smart manufacturing (soft or virtual software sensors to augment physical data points and enable control of nonstandard process variables), and precise measurement and control of steam energy; digital twin	Digital twin	Automation and smart manufacturing, such as cleaner automation; digital twin	Upgraded cement process controls to lower firing temperatures and times; digital twin
Combined heat and power	Waste heat management (reduce, recover, and recycle)	Combined heat and power; waste heat to power	Waste heat recovery	Waste heat recovery	Waste heat recovery; combined heat and power	

2.1. Strategic Energy Management

Strategic energy management (SEM) is a systematic approach that empowers an organization with continual energy management practices. It supports energy and emission reductions by providing the tools necessary to integrate energy management into a facility's daily operation. There are three vital elements to SEM: the organization's commitment, the identification and implementation of energy efficiency projects, and the tracking and reporting of performance [19]. SEM also includes using energy management information systems (EMISs) and adopting energy management standards and protocols, such as ISO 50001. DOE has developed 50001 Ready Navigator for manufacturers, which is an online application that provides step-by-step guidance for implementing and maintaining an energy management system in conformance with the ISO 50001 Energy Management System Standard [20].

2.1.1. EMISs

EMISs help organizations manage their energy use more effectively by empowering them with needed information. EMISs combine hardware and software systems to simplify data gathering and analysis. However, unlike a building automation system, they do not control facility equipment [21]. EMISs can only be used to monitor and display vital operating parameters or may have additional advanced capabilities to perform algorithm-based data analytics. The results are then displayed in an easy-to-understand format for industrial operators that aids their decision-making. EMIS technologies have been shown to enable energy savings ranging from 3% to 9% in buildings with annual cost savings of ~USD 3 million [22].

2.1.2. Energy Management Standards

ISO 50001 is a global standard for energy management systems that provides a continual improvement framework to help organizations better manage their energy use and sustain achieved savings. The standard helps an organization to develop and implement an energy policy, identify significant areas of energy consumption, and commit to a continual improvement in the energy performance [23]. DOE requires the adoption of ISO 50001 for the Superior Energy Performance 50001 energy management certification program, which is a comprehensive approach to energy management and sustained savings. The potential global energy and CO_2 emissions savings associated with the ISO 50001 uptake in the industrial and service sectors can be estimated using tools such as ISO 50001 Impacts Estimator Tool [24]. Implementing ISO 50001 across the global industrial and service sector can potentially result in cumulative primary energy savings of approximately 99,500 TBtu (105 EJ) and prevent CO_2 emissions of approximately 6500 MMT between 2011 and 2030 [24]. For any facility that is interested in reducing GHG emissions, 50001 Ready Navigator provides guidance on managing and lowering energy-related GHG emissions through the energy management system. Specifically, 50001 Ready Navigator provides guidance for facilities and organizations to develop or improve a data collection, analysis, and reporting process for energy-related GHG emissions and establish a systematic approach to managing and reducing energy-related GHG emissions [25].

2.2. System Efficiency

The energy efficiency of industrial systems can be improved by evaluating the performance of energy end uses (i.e., process heating, process cooling, steam, compressed air, pumps, fans, and other systems) and taking actions to reduce their energy consumption. Some of the most considerable industrial energy requirements come from a few systems. Process heating (fuel-based, steam-based, and electricity-based) and machine drives play a dominant role and are responsible for more than 77% of total energy use and 60% of total emissions in the US manufacturing sector (Figure 5).

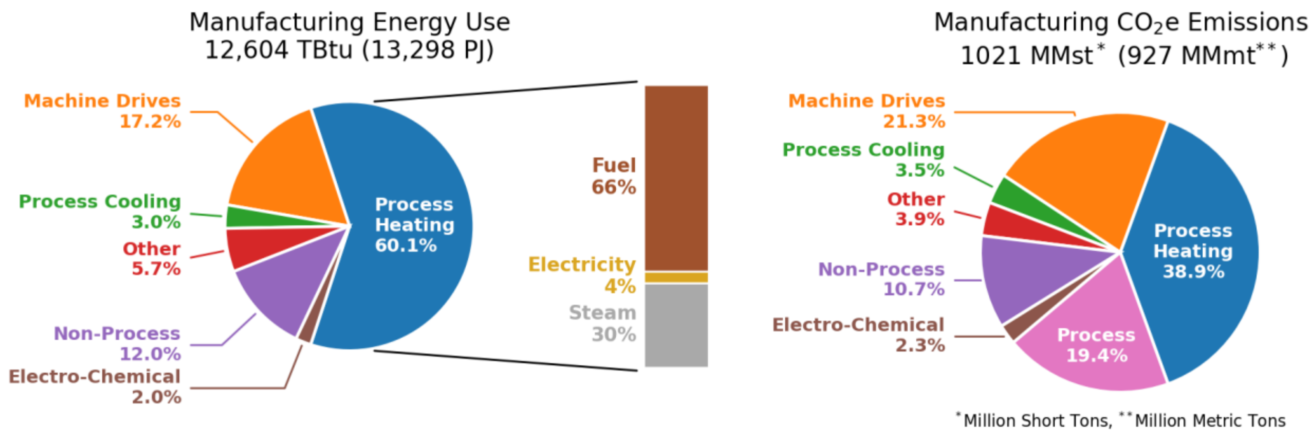

Figure 5. Total energy and emissions in the manufacturing section by end use in 2018 based on data from [8].

Process heating operations, such as heating, melting, curing, heat treating, drying, and smelting, are essential for manufacturing various industrial and consumer products. Different process heating equipment, such as furnaces, ovens, dryers, kilns, and incinerators, operate under the same principle of transferring the thermal energy from fuel combustion directly or indirectly to the load or the material. Using high-efficiency systems can provide significant savings in energy and CO_2 emissions, an example being high-efficiency boilers that can deliver 350 TBtu (369 petajoule (PJ)) of energy savings and a 20 MMT CO_2 reduction annually in the United States [26]. In 2018, process heating systems used 7576 TBtu (7993 PJ) of primary energy, contributing to about 360.4 MMT of CO_2-equivalent (CO_2e) GHG emissions (Figure 5) in the U.S. manufacturing sector [27]. The process heating energy is mainly from fuel (63.8% of total) and steam (31.3%), and a relatively small percentage is from electricity (4.9%) [28]. Most of the energy-saving opportunities in process heating are reducing, recycling, and recovering waste heat losses. DOE estimated that waste heat management systems can achieve 260 TBtu (274 PJ) of energy savings and 25 MMT of avoided CO_2 emissions annually [26]. Waste heat from manufacturing plants is discharged in a broad temperature range. Low-temperature waste heat that is at temperatures of <450 °F (<232 °C) alone can account for a large percentage (50% to 60%) of the total energy used in manufacturing. Thekdi et al. quantified the potential of recovering the low-grade waste heat from manufacturing facilities and the technologies available to recover this waste heat [29]. Waste heat recovery has also shown promise for industrial decarbonization, as illustrated in a California-based study that estimates the decarbonization potential of energy efficiency approaches for the cement industry [14].

In 2006, DOE initiated Save Energy Now assessments to evaluate the energy efficiency of industrial steam and process heating systems in energy-intensive U.S. facilities [30]. The results from the assessments conducted between 2006 to 2011 at different facilities indicated that process heating and steam systems combined could, on average, save approximately 480,000 MMBtu/plant per year (506 terajoule/plant per year), which equates to a CO_2 reduction potential of about 31,000 metric tons/plant per year with most of the savings coming from the recovery and reuse of waste heat.

Motors and machine drives, such as pumps, fans, and compressors, are the backbone of the industrial sector and are used in almost every step of the manufacturing process. They are used in various applications, such as fluid handling, material handling, processing, and HVAC systems. Industrial motors and machine drives accounted for about 17% of total energy use and 21% of carbon emissions in the U.S. manufacturing sector (Figure 5). Inappropriate equipment sizing and poor system design result in inefficiency, increased maintenance, reduced control, and decreased energy performance [31]. These inefficiencies can be countered by using high-efficiency or premium-efficiency motors, installing adjustable speed drives, power conditioning, developing better system designs, and properly sizing equipment [32]. In addition, operating drive systems, such as pumps, fans, and compressors, to match end use requirements will ensure reduced energy usage. The implementation of energy efficiency technologies for industrial motor drives in six countries showed an average potential of 28–38% energy savings compared to the 2008 electricity use of these systems; the potential electricity savings were found to be 25–35% in the United States [15]. Optimizing performance, regular system maintenance, continuous monitoring, and upgrading can ensure a highly efficient system and lower energy consumption and carbon emissions.

2.3. Material and Life Cycle Efficiency

The principle behind material and life cycle efficiency is using less material to produce the same set of products, extend the life of a product, and increase product utilization rates without compromising the end use benefits of the product. Material efficiency, additive manufacturing (AM), material substitution, and a circular economy are crucial to reducing material waste, energy demand, and GHG emissions in the manufacturing sector. Heavy industries, such as iron and steel (7–8%) and cement (6%), are leading contributors to global energy system combustion and industrial process CO_2 emissions in the industrial sector and can benefit significantly from material efficiency, especially since demand is expected to increase by 12–23% for cement and 40% for steel by 2050 [33,34]. Material efficiency can help achieve significant CO_2 emissions reduction by 2060, potentially reducing the total emissions by approximately 20% for steel, 70% for cement, and 30% for aluminum [35].

The manufacturing process, by itself, can impact material efficiency, a case in point being AM. AM technologies are progressing from rapid prototyping to manufacturing various products [36]. AM offers several advantages over conventional manufacturing methods, which involve building objects by cutting or machining blocks of materials into the desired shape or through molding and stamping techniques. The benefits of AM include enabling novel geometries that improve component performance, low-energy consumption during production, and reduced lead time and waste material, which aid in material and life cycle efficiency. Many business sectors could benefit from AM technologies; however, the adoption of AM has been fading with the development and growth of other disruptive technologies that prove to be more valuable for energy savings and emission reduction. Only specific sectors that require small-scale production of complex components are expected to continue taking advantage of AM, such as the aerospace sector. Huang et al. estimated that in the United States, if there is rapid adoption of AM in the aircraft industry, the total annual primary energy saving potential can reach 66–164 TBtu (70–173 PJ) with cumulative primary energy savings of 1137–2654 TBtu (1200–2800 PJ) from 2019 through 2050. The corresponding carbon emission reduction would be an annual CO_2 equivalent of 5.4–13.3 MMT and a cumulative CO_2 equivalent of 92.1–215 MMT from 2019 through 2050 [37].

Material and life cycle efficiency can also be improved by replacing the traditional linear economy with a circular economy. In a circular economy, a material's end of life is extended by reuse, remanufacturing, repair, or refurbishment, followed by recycling and clean disposal when the material can no longer be circulated across its life cycle. These circular economy strategies can be used as tools to enable decarbonization, increase resource productivity, ensure sustained access to scarce resources, and extend the economic value of materials and products. The Ellen MacArthur Foundation estimated that a circular economy approach can reduce global CO_2 emissions from critical industries such as those for cement, steel, plastics, and aluminum by 40% (3700 MMT CO_2) annually by 2050. While the waste elimination accounts for 24% of the emission reduction (0.9 Gt), extending the lifetime by reusing and recirculating the material accounts for 30% (1100 MMT) and 50% (1700 MMT) of emission reduction, respectively [38]. In Europe, the circular economy model is expected to reduce emissions by 56% (300 MMT CO_2) annually until 2050 in energy-intensive sectors [39].

2.4. Smart Manufacturing

Implementing smart manufacturing (SM) technologies can create energy savings through improved process control, reduced waste, a shorter downtime, and improved performance and productivity. SM involves using advanced sensors, monitoring and control systems, and optimization technologies to gather and process data and provide actionable insights to manufacturing personnel while improving decision making across facilities and supply chains. SM is a culmination of several revolutionary inventions in the information and communication technology world that have enabled interconnection between devices and people. Big data, the Industrial Internet of Things (IIoT), and machine-to-machine communication are all driving forces for SM [40]. The benefits of SM include a reduced cost, production flexibility, a shorter product to market time, greater energy efficiency, reduced environmental impact, and increased productivity [41].

SM can help the manufacturing sector unlock energy saving potential, which would otherwise be difficult to identify through practices such as industrial automation. SM builds on automation to provide additional actionable information that manufacturers need to run their facilities more efficiently. Multiple levels of SM technologies can be adopted in a facility. Level 0 adds automatic controls to the manufacturing processes or systems, Level 1 adds a communication system, and Level 2 adds advanced features to automatic controls for performance enhancement along with communication systems. An example of Level 2 systems includes advanced mass flow combustion controls with actuators that can change the mass–fuel ratio automatically to compensate for changes that affect combustion performance, and the ratio information is communicated to plant operators. Level 3 builds on Level 2 by adding additional sensors or controls to aid decision making [42,43]. Level 3 systems use non-local information in decision-making; with the same example, mass flow control systems can also integrate feedback from oxygen sensors to enhance safety and ensure that the equipment does not operate below the stoichiometric ratio. The DOE Industrial Assessment Centers Database shows that Level 0 to 1 SM implementation for energy support systems across the different manufacturing sectors from 2000 to 2016 has resulted in average energy savings of 1.5% of total plant source energy. Implementing higher levels of SM technologies can potentially achieve higher energy savings and/or make energy savings more sustainable [42]. Gallaher et al. estimated that SM can result in a 3.2% reduction in the shop floor cost of production with the greatest potential for cost savings in labor (12%) and energy (13%) [44]. A study conducted by The Royal Society estimated that artificial intelligence could reduce GHG emissions by 4% by 2030 [45]. Overall, the U.S. Department of Energy estimates average energy savings of more than 20% across all industries based on a review of several sets of studies [46].

The feasibility of SM technologies depends on several factors, such as energy use, capital, O&M costs, increased revenue from increased productivity, education and training, cybersecurity, and energy savings. SM feasibility for energy productivity can be determined using the cost of a conserving energy framework, which balances some of these factors against changes in energy use. The framework has been used to evaluate the energy and productivity benefits of SM projects in the craft brewing industry [41,47]. Rogers estimated that with existing technologies, SM can reduce energy intensity in the US manufacturing sector by 20%, resulting in energy cost savings of close to USD 15 billion by 2035 [48]. Additionally, while the IoT and SM can support other EE and decarbonization projects, such as using peak shaving, increasing renewable energy sources and microgrids, using EV and subsequent charging, using advanced metering systems, and so on, additional challenges arise with optimization needs and big data processing. Studies have shown that deep learning-based algorithms, such as the probabilistic delayed double deep Q-learning (P3DQL) algorithm, can be used to forecast and optimize the demand response from the customer and reduce peak energy loads by 27% in residential applications [49]. Such algorithms can also be used in the microgrids in manufacturing facilities, lowering the peak energy load, which can result in smaller microgrid component capacities.

2.5. Combined Heat and Power

Combined heat and power (CHP; i.e., cogeneration) is an energy-efficient pathway that generates electricity or mechanical power and captures the heat that would have otherwise been wasted to provide valuable thermal energy [50]. CHP is a type of distributed generation located at or near the point of use. CHP improves efficiency and reduces GHG emissions by reducing or replacing the purchase of electricity from the grid and thermal energy produced by boilers, typically fueled by natural gas. In addition, electricity generated by CHP does not have any transmission and distribution losses, unlike conventional electricity generation.

CHP systems have been used to generate electricity for decades and continue to be relevant as industries seek to reduce their impact on the environment while maintaining a reliable energy supply with high efficiency and low emissions. Industrial CHP systems, through both topping and bottoming cycles, can provide needed energy services for some sectors with overall energy efficiencies of 65–85% compared to the separate production of heat and power, which collectively average to 45–55% system efficiency [50,51]. As reported in 2012, the existing 82 GW of CHP capacity in the U.S. at that time reduced GHG emissions by approximately 240 MMT per year [52,53]. A 1 MW CHP system, running 24/7, has been shown to potentially reduce carbon emissions by 1000 lb (454 kg) for each megawatt hour of displaced grid electricity in 2020, and by 450 lb (204 kg) for each megawatt hour of displaced electricity in 2050 [54]. The impact of CHP might not be as strong in the future as it is now because of the expected shift toward more efficient power plants and low-carbon alternatives. However, it could still provide emission reduction. For instance, the same 1 MW system installed in 2020 could still avoid about 78,000 MT of emissions by 2050 compared to the average U.S. marginal grid. CHP has historically relied on fossil fuels, typically natural gas; however, current CHP technologies have the flexibility to use low-carbon fuels, such as biogas, renewable natural gas or biomethane, and hydrogen, which can further reduce GHG emissions. Renewable natural gas and hydrogen CHP systems can be a long-term path to decarbonizing industrial thermal processes that are resistant to electrification because of technology or cost barriers, and for critical operations where dispatchable on-site power is needed for resilience and reliability.

3. Decarbonizing Energy-Intensive Industries through Energy Efficiency

The majority of industrial emissions (~75% of the total manufacturing sector CO_2 emissions, see Figure 2) come from very few sectors, such as those for iron and steel, chemical, food and beverage, petroleum refining, pulp and paper, and cement; hence, focusing decarbonization efforts in these sectors would substantially reduce CO_2 emissions in the industrial sector. The remaining portion of this paper summarizes energy efficiency technology pathways and strategies for the aforementioned six manufacturing sectors.

The potential reduction in primary energy intensity for energy-intensive sectors globally through implementing the best available technologies has been previously studied [55]. Similarly, DOE's Advanced Manufacturing Office conducted energy bandwidth studies to analyze energy use and potential energy savings for selected manufacturing sectors [56]. The studies estimated energy savings by setting the energy consumption of selected manufacturing sectors in 2010 as a baseline (current typical) and assessing the energy consumption reduction that may be possible through the adoption of existing best practices and technologies (that are state-of-the-art) and the deployment of the applied R&D technologies under development (practical minimum). The results from the energy bandwidth study for the energy-intensive manufacturing sectors are shown in Figure 6 [57–61]. This shows that the energy efficiency technology pillar can achieve a significant reduction in energy consumption and corresponding energy-related CO_2 emissions by reducing current typical energy intensities to state-of-the-art energy intensities.

As identified in a French report on this subject [62], energy-intensive industries have traditionally been difficult to decarbonize (due to the difficult-to-abate, fossil fuel-driven, large, and expensive process heating infrastructure) and have been reluctant to join government program offerings to decarbonize the industrial sector. Energy-intensive industries consume a large amount of energy and use carbon-intensive fuels. A brief review of programs around the world for decarbonizing the industrial sector was conducted [63–72]. Figure 7 presents these results, showing the uptake of the select programs by companies or projects from energy-intensive industries. The uptake of these programs was dominated by the food and beverage industry, such that it led to the Australian government launching a separate program focused on this sector. Canadian programs have seen petroleum refining industries participate more frequently than in other parts of the world, which can be attributed to Canada's unique sector-specific characteristics. Iron and steel industries had relatively less participation. These results can be leveraged further to identify the reasons behind the reluctance in participation and develop programs catered toward specific sectors. Additional details of these programs are given in Table A2.

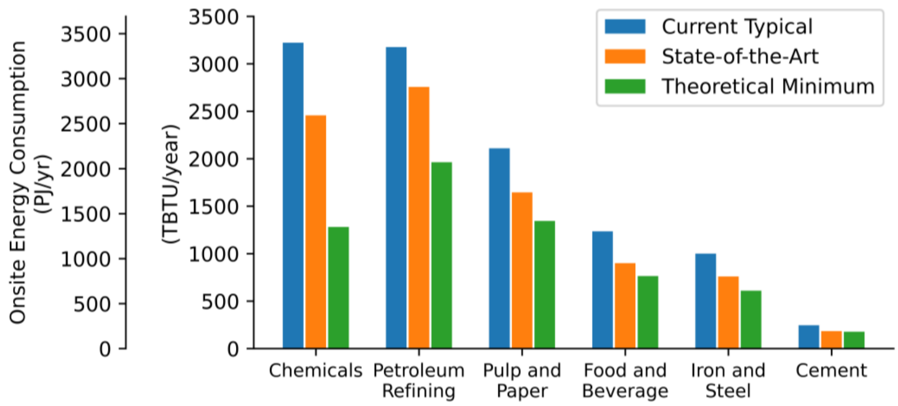

Figure 6. Energy use of select energy- and carbon-intensive industries in the United States based on data from [57–61].

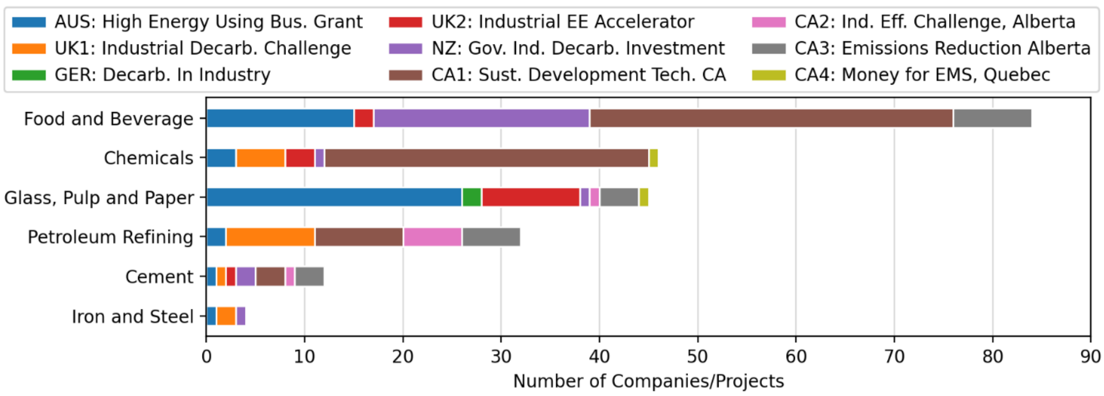

Figure 7. Selected programs from around the world for decarbonizing the industrial sector and their uptake by companies or projects from energy-intensive industries.

Government-backed programs are focused not only on funding, but also on providing technical assistance and different types of assessments. In fact, compared with the larger investments in electrification, switching to low-carbon fuels, and CCUS, energy-intensive industries seem to be enthusiastic about implementing energy efficiency projects. For instance, the Save Energy Now assessments from DOE also provided powerful insights into the potential of energy efficiency to decarbonize the industrial sector [30,73]. The assessments were conducted between 2006 and 2011, and the recommendations that were identified can still be beneficial for the industry at large. To this end, the top ten recommended strategies identified in the program for the whole industrial sector, as well as the top six energy-intensive industries discussed in this paper, are listed in Table A1. The following sections go beyond these specific recommendations and identify other easily achievable energy efficiency strategies from the broader literature that have been targeted toward energy-intensive industries.

3.1. Iron and Steel Industry

The iron and steel industry accounted for 9.1% (90 MMT) of total energy-related CO_2 emissions from the U.S. industrial manufacturing sector in 2020 [3]. The potential to reduce the energy intensity for steel making using the best available energy efficiency technologies varies from 9% to 30% [55]. As identified in previous studies, specific energy efficiency strategies to decarbonize this sector include leveraging relatively low-capital solutions through energy efficiency and SEM. However, energy efficiency decarbonization strategies also depend on the type of operation, facility age, and size, which vary significantly across facilities [74,75]. Waste heat recovery strategies in the iron and steel industry can be targeted to specific processes, such as recirculation during sintering and using a flat heat pipe during rolling [76]. One successful implementation of waste heat recovery practices used a cupola furnace and air to oil exchanger at Waupaca Foundry in the United States [77]. Several other energy efficiency technologies have also been investigated, such as industrial reheating furnaces, top pressure recovery turbines, coke dry quenching, and different temperature and pressure control technologies. These technologies promise decarbonization and several other non-energy benefits [76,78,79]. Decarbonization can also be achieved by probing routes to improve material efficiency and the flexibility of reusing, recycling, and refurbishment; an example is material and energy recovery from slag [68,76]. SM and IoT will be very important to iron and steel producers as they look to reduce GHG emissions and remain profitable. Additionally, advancing modular technologies to a greater scale and market proportion can be relevant.

3.2. Chemical Industry

The chemical industry accounted for 27.6% (274 MMT) of total energy-related CO_2 emissions from the U.S. industrial manufacturing sector in 2020 [3]. In 2016, 96% of all U.S. goods were produced from chemical industry products [80]; hence, decarbonizing the chemical industry can affect other manufacturing industries.

Low-capital solutions, such as energy efficiency, alternative separation methods, SM, and electrification, can drive decarbonization in the chemical industry [81]. Smart technology combined with energy efficiency has been seen to reduce energy use, costs, and carbon emissions [82]. In contrast, boiler efficiency upgrades, such as those implemented in an Eastman Chemical facility, can reduce steam and electricity consumption [83]. Similar benefits can be obtained by pursuing process heat opportunities with lower temperatures and expanding mid-temperature capabilities. Material efficiency can be leveraged by using recycled content and biomass to provide low-carbon, low-embodied-energy feedstocks for different processes. However, misconceptions regarding what constitutes a low-carbon fuel or feedstock, and which alternatives are viable for a certain application can hinder the switching of conventional fuels and feedstocks with low-carbon ones [84]. Therefore, a need exists for research strategies to ensure that these transitions can be integrated seamlessly.

3.3. Food and Beverage Industry

The food and beverage industry accounted for 7.9% (78 MMT) of total energy-related CO_2 emissions from the U.S. industrial manufacturing sector in 2020 [3]. This industry has a unique food waste challenge that contributes to carbon emissions [85]. Life cycle assessment studies and collaboration with manufacturers have identified methods to reduce food waste through supply chains via the beneficial reuse of the waste stream, source reduction, supply chain visibility, and processing and packaging improvements for increasing shelf life and stability [86,87]. The beneficial reuse of waste streams can be further extended to include waste heat, which will require advancing R&D with the development of methods to better share and store low-grade waste heat for food manufacturers. Carbon emissions can also be reduced by investing in SM and IoT strategies, such as system optimization, the integration of thermal systems, and refrigeration optimization. Overall, a need exists to increase R&D in automation and modularization and deepen our understanding of what is needed to rapidly scale transformative technologies to help decarbonize this industry [88].

3.4. Petroleum Refining Industry

Petroleum refining is highly carbon-intensive; it accounted for 23.7% (235 MMT) of total energy-related CO_2 emissions from the U.S. industrial manufacturing sector in 2020 [3]. The low-capital solutions for distillation and separation innovations can be used to enhance the impact of decarbonization. Another solution for decarbonization is efficient waste gas recycling. The lowest-cost opportunities have been identified as the optimization of utilities, heat exchangers, and fired heaters; however, the relevant energy efficiency opportunity would depend on each unique refinery and their processes. Introducing energy management programs has been lauded as the most successful and cost-effective method of improving the energy efficiency of this industry [89]. Additionally, specific interventions with different focuses (e.g., motors, compressed air, and process-specific focuses) have been identified, including the proper design and replacement of equipment, lighting controls, and optimized flaring [90].

3.5. Pulp and Paper Industry

The pulp and paper industry accounted for 4.8% (48 MMT) of total energy-related CO_2 emissions from the U.S. industrial manufacturing sector in 2020 [3]. The pulp and paper industry can benefit significantly from incorporating energy efficiency strategies. A recent Canadian study found that energy efficiency could be the highest contributing pillar to the industry's decarbonization by reducing carbon emissions by 66% relative to business as usual by 2050 [91]. Upgrades and modifications of different equipment, such as refiners and digesters, along with waste heat recovery have been identified as opportunities to reduce energy consumption [92]. Material efficiency and circularity can also play a significant role in decarbonizing this industry, with increasing recycled content in pulp and paper products [93]. Monitoring the production processes through SM technologies such as supervisory control and data acquisition, manufacturing execution systems, and enterprise resource planning can help facilitate operations and maintenance, leading to lower energy consumption [94]. CHP technology has played and will continue to play a key role in reducing the industry's natural resource consumption, with wide adoption across the pulp and paper sector [95].

3.6. Cement Industry

The cement industry accounted for 2.2% (22 MMT) of total energy-related CO_2 emissions from the U.S. industrial manufacturing sector in 2020 [3]. The potential to reduce the energy intensity of cement using energy efficiency approaches varies from 20% to 25% [55]. Relatively low-capital solutions, such as energy efficiency and SEM, and waste reduction/recovery solutions (focusing on waste heat to power) must be leveraged. Material efficiency and flexibility can decrease carbon emissions; probing routes toward a circular economy with innovative chemistry and blended cement can be highly effective. Decarbonizing the cement industry can be supported by advancing approaches to reduce waste and using the circular approach for the construction of concrete, low-carbon binding materials, and supplementary cementing materials. Because energy (fuel) costs are a significant portion of the cost of cement production, lowering firing temperatures and times will reduce cost and environmental impacts, making this industry more viable through its adoption of SM technologies and processes (specifically in data acquisition for high-temperature manufacturing, contextualization, and control) [96].

4. Path Forward

Multiple energy efficiency pathways and strategies could be implemented to decarbonize different energy-intensive industrial sectors. Implementing multiple strategies simultaneously can lead to more greatly reduced carbon emissions while improving processes and reducing operational costs. Multiple roadmaps have been developed focusing on different countries and industries. Depending on the type of industry, size of a facility, type of processes, and other such factors, the implementation of energy efficiency can look very different, and the benefits will also differ. However, proper design and implementation will lead to long-term energy savings and reduced carbon emissions.

Although different research, development, and deployment needs were identified at a high level for successfully employing energy efficiency strategies for industrial decarbonization, a concentrated effort is needed to conduct extensive energy efficiency studies on individual industrial sectors. A major opportunity exists for the wider implementation of existing energy efficiency technologies and practices. Furthermore, there is also an urgency to address the needs identified to accelerate the benefits of energy efficiency strategies outlined in this study. For instance, process heating, steam, and motor systems are the largest energy end users in the industrial sector and are therefore key targets for efficiency improvements. Material efficiency and circularity can lead to long-term CO_2 emission reductions. This area also needs extensive work to identify specific material efficiency and circular economy strategies from industrial sector and quantify decarbonization potential.

Similarly, SM and IoT can create energy efficiency opportunities at every level of system integration: equipment, facility, and supply chain. Emerging SM and industrial IoT technologies could enable significant opportunities for optimizing manufacturing processes and reducing energy use and GHG emissions. Combining strategies for thermal process intensification and industrial decarbonization with SM and industrial IoT can create and enhance existing opportunities for saving time and energy via approaches such as tighter control of temperature zones, better adjustment of thermal systems for variations in production levels and feedstock properties, and increased process throughput [97]. Additionally, integrating SEM, EMIS, and SM and IoT can promote more carbon reductions in multiple industrial sectors, including energy-intensive industries. To facilitate this integration, several steps need to be taken. Demonstrations of plant automation systems can provide real-time energy performance data. Multiple standards relevant to SM can aid in the proper implementation of SM at various levels of system integration. However, improved consistency and clarity among the standards are needed. Additionally, the development of open-source SM technologies can further encourage SM uptake by industries [98]. Data integration can facilitate utility efficiency programs that can then reward manufacturers for energy saved rather than equipment installed. However, research is also needed to address the big data challenges that arise with SM related to data quality, storage, and computing; advanced analytical tools are needed to process the data and improve cybersecurity [99].

Research can also aid in achieving closer-to-practical minimum energy consumption, as identified in different energy bandwidth studies [100]. Technology demonstration and deployment are also key in this effort and are required for commercializing lower technology readiness levels. Multiple global programs provide financial support for deploying energy-efficient technologies; however, risks are present in adopting emerging technology. Programs, such as DOE's Industrial Technology Validation pilot that are aimed at evaluating the energy, carbon, and water savings potential of emerging technologies, can help reduce the risk of adopting these technologies [101].

5. Conclusions

The pursuit of rapid decarbonization has emerged as a priority globally to deal with climate change. The industrial sector plays a crucial role in the U.S. economy and decarbonizing it can lead to significant reductions in emissions, even in other economic sectors. Hence, for the U.S. to achieve its long-term climate goals, immediate actions need to be taken to decarbonize manufacturing. In the U.S., the industrial sector alone is responsible for 30% of the nation's overall energy-related GHG emissions of which a majority comes from energy intensive industries. The U.S. DOE's Industrial Decarbonization Roadmap identified the four pillars for decarbonization as energy efficiency; industrial electrification;

low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS). Energy efficiency has been a well-established and foundational strategy that can bring about an immediate reduction in carbon emissions. However, with the emergence of other strategies, energy efficiency is becoming a lower priority. While there has been research focusing on the importance and benefits of energy efficiency, there has not been a comprehensive study quantifying the benefits of energy efficiency pathways and their potential to reduce carbon emissions through 2050.

This study serves as a primer to understand the potential of the energy efficiency technology pillar and its pathways for decarbonizing the industrial sector with special attention on energy-intensive industries. From the study, energy efficiency strategies implemented at the system and process level can bring both short-term and long-term reductions in carbon emissions. Short-term emission reductions in energy intensive industries can be realized through the strategic adoption of various energy efficiency pathways, as discussed. The deployment of existing energy efficiency technologies with a continuing drive to implement SEM and emerging technologies, especially digitalized solutions, can unlock the next generation of energy saving potential and further decarbonize the industrial sector. This study also highlights that the government can play a significant role in scaling the market for next-gen solutions through policies and incentives. The global efficiency and decarbonization programs investigated in this study show that investments made through these programs have increased the adoption of best practices and energy efficiency improvements especially in energy-intensive industries. The U.S. DOE's Better Plants program highlights the energy efficiency progress made by its more than 270 manufacturing partners in its 2022 Better Plants Annual Progress Update report [9]. These organizations, which make up roughly 14% of the US manufacturing energy footprint, have cumulatively saved USD 10.6 billion and 2.2 QBtu (2.3 EJ) of energy with an associated CO_2 emission reduction of 131 MMT and an average energy intensity improvement rate of 1.8% since the start of the program. To realize maximum carbon reductions through energy efficiency, we must also continue to invest in research, development, and demonstration (RD&D) activities to achieve an efficiency closer to the theoretical minimums as highlighted by the different energy bandwidth studies.

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Appendix A

Table A1. Top ten recommendations from DOE's Save Energy Now assessments from 2006 to 2011 based on data from [30,73].

No.	All	Iron and Steel	Chemical	Food and Beverage	Petroleum Refining	Pulp and Paper	Cement
1.	Recover heat from the stack	Use an alternative fuel	Use an alternative fuel	Add or modify operation of condensing steam turbine (from high-pressure to condensing)	Add or modify operation of a condensing steam turbine (from high-pressure to condensing)	Reduce steam demand by changing the process steam requirements	Use an alternative fuel or energy source
2.	Use an alternative fuel or energy source	Recover heat from the stack	Add or modify operation of condensing steam turbine (from high-pressure to condensing)	Use an alternative fuel	Modify the medium-pressure condensate flash system	Change boiler efficiency	Use waste heat for water or air cooling, steam generation, or absorption cooling
3.	Recover heat	Add or modify operation of condensing steam turbine (from high-pressure to condensing)	Use feedwater heat recovery (general)	Install new appropriately sized fan	Reduce steam demand by changing the process steam requirements	Change operating parameters	Recover heat from exhaust air
4.	Add or modify operation of condensing steam turbine (from high-pressure to condensing)	Rearrange ductwork at fan inlet or discharge	Reduce steam demand by changing the process steam requirements	Control (reduce) makeup air for ovens to meet process safety requirements	Change the boiler blowdown rate	Improve insulation	Use oxygen for combustion
5.	Develop a water system balance	Recover heat from hot products or other heat sources (i.e., walls) from a furnace oven	Use an alternative fuel or energy source	Use proper heating methods; replace inefficient and uneconomical methods with economical and efficient systems	Add or modify operation of a backpressure steam turbine	Reduce excessive valve friction loss	Reduce oxygen content of flue (exhaust) gases
6.	Use an alternative fuel	Eliminate excess unburned hydrocarbons (CO, H_2, CH_4, and soot in the exhaust gases)	Add or modify operation of a backpressure steam turbine	Heat recovery from hot products or other heat sources (i.e., walls) from a furnace oven	Change boiler efficiency	Add or modify operation of a backpressure steam turbine	Recover heat from hot products or other heat sources (i.e., walls) from a furnace oven
7.	Recover heat from exhaust air	Use proper heating methods; replace inefficient and uneconomical methods with economical and efficient systems	Recover heat from hot products or other heat sources (i.e., walls) from a furnace oven	Reduce steam demand by changing the process steam requirements	Use flue or exhaust gas heat for combustion air preheating	Change condensate recovery rates	Heat cascading: use flue or exhaust gas heat from the higher-temperature process of supplying heat to lower-temperature processes

Table A1. *Cont.*

No.	All	Iron and Steel	Chemical	Food and Beverage	Petroleum Refining	Pulp and Paper	Cement
8.	Use waste heat for water or air cooling, steam generation, or absorption cooling	Use flue or exhaust gas heat for combustion air preheating	Heat cascading: use flue or exhaust gas heat from the higher-temperature process of supplying heat to lower-temperature processes	Load or charge preheating using heat from flue or exhaust gas, or other sources of waste heat	Implement a steam trap maintenance program	Implement a steam trap maintenance program	Perform furnace scheduling, loading, shut down to avoid delays, waits, cooling between operations, and so on
9.	Use oxygen for combustion	Change boiler efficiency	Change condensate recovery rates	Use diaphragm pumps	Perform boiler optimizations	Reduce or recover vented steam	Control (reduce) makeup air for ovens to meet process safety requirements
10.	Use proper heating methods; replace inefficient and uneconomical methods with economical and efficient systems	Heat cascading: use of flue or exhaust gas heat from the higher-temperature process of supplying heat to lower-temperature processes	Use deaerator heat recovery (general)	Perform boiler optimizations	Reduce or recover vented steam	Install more energy-efficient equipment	Load or charge preheating using heat from flue or exhaust gas, or another source of waste heat

Table A2. Details of the select programs around the world for decarbonizing the industrial sector as shown in Figure 7.

Program Name	High Energy Using Business Grant	Industrial Decarb. Challenge	Decarb. in Industry	Industrial E.E. Accelerator	Govt. Ind. Decarb. Investment	Sust. Development Tech. Canada	Ind. Efficiency Challenge, Alberta	Emissions Reduction Alberta	Money for EMS, Quebec
Country	Australia	United Kingdom	Germany	United Kingdom	New Zealand	Canada	Canada	Canada	Canada
Time frame	2020–2022	2019–2024	2020–2024	2017–2020	2021–present	2001–present	2018–present	2009–present	2018–2020
Investment (USD)	~10.5 million	~212.7 million	~3.2 billion	~16.2 million	~38.4 million	More than ~0.9 billion	~55.4 million	~648 million	—
Percentage financed	50%	39%	100%	40–60%, avg. 52% in phases 1 and 2	40%	Up to 40% (avg. 33%)	—	12%	50%
Typical grant size	AUD 10,000–25,000	Project-specific	Project-specific	GBP 150,000–1 million	—	Project-specific	—	—	CAD 2000–50,000
Potential benefits	—	—	60–90% GHG emission reduction	Potential savings = 12% of UK's 2019 elec. demand	6.6 MMT of GHG emission reduction	Annual reduction of 22.4 MMT in GHG emissions	>5.3 MMT of GHG emission reduction by 2030	42.3 MMT of GHG emission reduction	—

References

1. United Nations Framework Convention on Climate Change. The Paris Agreement. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 15 May 2023).
2. Rissman, J.; Bataille, C.; Masanet, E.; Aden, N.; Morrow, W.R.; Zhou, N.; Elliott, N.; Dell, R.; Heeren, N.; Huckestein, B.; et al. Technologies and Policies to Decarbonize Global Industry: Review and Assessment of Mitigation Drivers through 2070. *Appl. Energy* **2020**, *266*, 114848. [CrossRef]
3. U.S. Energy Information Administration. Annual Energy Outlook 2021. Available online: https://www.eia.gov/outlooks/aeo/tables_side.php (accessed on 15 May 2023).
4. U.S. Energy Information Administration. Table 19. Energy-Related Carbon Dioxide Emissions by End Use (AEO2022 Reference Case). In Annual Energy Outlook 2022. 2022. Available online: https://www.eia.gov/outlooks/archive/aeo22/ (accessed on 15 May 2023).
5. National Academies of Sciences, Engineering, and Medicine. *Deployment of Deep Decarbonization Technologies: Proceedings of a Workshop*; Martin, A., Ed.; The National Academies Press: Washington, DC, USA, 2019; ISBN 978-0-309-67063-0.
6. De Pee, A.; Pinner, D.; Roelofsen, O.; Somers, K.; Speelman, E.; Witteveen, M. How Industry Can Move toward a Low-Carbon Future. Available online: https://www.mckinsey.com/capabilities/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future (accessed on 15 May 2023).
7. Cresko, J.; Rightor, E.; Carpenter, A.; Peretti, K.; Elliott, N.; Nimbalkar, S.U.; Morrow, W.R.; Hasanbeigi, A.; Hedman, B.; Supekar, S.; et al. *Industrial Decarbonization Roadmap*; DOE/EE-2635; United States Department of Energy: Washington, DC, USA, 2022.
8. Industrial Efficiency & Decarbonization Office. Manufacturing Energy and Carbon Footprints (2018 MECS). 2018. Available online: https://www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs (accessed on 15 May 2023).
9. U.S. DOE Better Plants Program. Better Plants 2022 Progress Update: Working with Industrial Partners to Advance Energy Efficiency & Decarbonization. 2022. Available online: https://betterbuildingssolutioncenter.energy.gov/resources/2022-better-plants-progress-update (accessed on 15 May 2023).
10. Nadel, S.; Ungar, L. Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050. 2019. Available online: https://www.aceee.org/research-report/u1907 (accessed on 15 May 2023).
11. WSP; Parsons Brinckerhoff; DNV-GL. Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Cross-Sector Summary; U.K. Department of Energy and Climate Change and Department for Business, Innovation and Skills. 2015. Available online: https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050 (accessed on 15 May 2023).
12. European Commission. A Clean Planet for All: A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy. In *Depth Analysis in Support of the Commission*; COM 773 2018; European Commission: Brussels, Belgium, 2018.
13. ClimateWorks Australia. Pathways to Deep Decarbonisation in 2050. 2014. Available online: https://www.climateworkscentre.org/resource/pathways-to-deep-decarbonisation-in-2050-how-australia-can-prosper-in-a-low-carbon-world/ (accessed on 15 May 2023).
14. Hasanbeigi, A.; Springer, C.; Global, E. *Deep Decarbonization Roadmap for the Cement and Concrete Industries in California*; Global Efficiency Intelligence: San Francisco, CA, USA, 2019.
15. McKane, A.; Hasanbeigi, A. Motor Systems Energy Efficiency Supply Curves: A Methodology for Assessing the Energy Efficiency Potential of Industrial Motor Systems. *Energy Policy* **2011**, *39*, 6595–6607. [CrossRef]
16. McKane, A.; Hasanbeigi, A. *Motor Systems Efficiency Supply Curves*; United Nations Industrial Development Organization: Vienna, Austria, 2010.
17. Whitlock, A.; Elliott, N.; Rightor, E. Transforming Industry: Paths to Industrial Decarbonization in the United States: Cross-Sector Summary 2020. 2020. Available online: https://www.aceee.org/research-report/IE2001 (accessed on 15 May 2023).
18. De Pee, A.; Pinner, D.; Roelofsen, O.; Somers, K.; Speelman, E.; Witteveen, M. Decarbonization of Industrial Sectors: The Next Frontier. 2018. Available online: https://www.mckinsey.com/industries/oil-and-gas/our-insights/decarbonization-of-industrial-sectors-the-next-frontier (accessed on 15 May 2023).
19. Rogers, E.; Whitlock, A.; Rohrer, K. Features and Performance of Energy Management Programs. 2019. Available online: https://www.aceee.org/sites/default/files/publications/researchreports/ie1901.pdf (accessed on 15 May 2023).
20. U.S. Department of Energy. Lawrence Berkeley Laboratory about 50001 Ready Navigator. Available online: https://navigator.lbl.gov/about (accessed on 15 May 2023).
21. Crowe, L.N.; Leritz, C.N.; Alliance, N.E.E. Industrial Energy Management and Information Systems for Strategic Energy Management (SEM) Application. 2015 ACEEE Summer Study on Energy Efficiency in Industry. 2015. Available online: https://www.aceee.org/files/proceedings/2015/data/papers/1-146.pdf (accessed on 15 May 2023).
22. Kramer, H.; Lin, G.; Curtin, C.; Crowe, E.; Granderson, J. Proving the Business Case for Analytics: Results from Scaled Implementation of Energy Management and Information Systems, as Documented by the Smart Energy Analytics Campaign. 2020. Available online: https://smartenergyanalytics.org/assets/EMIS%20Report.pdf (accessed on 15 May 2023).
23. Gopalakrishnan, B.; Ramamoorthy, K.; Crowe, E.; Chaudhari, S.; Latif, H. A Structured Approach for Facilitating the Implementation of ISO 50001 Standard in the Manufacturing Sector. *Sustain. Energy Technol. Assess.* **2014**, *7*, 154–165. [CrossRef]

24. McKane, A.; Therkelsen, P.; Scodel, A.; Rao, P.; Aghajanzadeh, A.; Hirzel, S.; Zhang, R.; Prem, R.; Fossa, A.; Lazarevska, A.M.; et al. Predicting the Quantifiable Impacts of ISO 50001 on Climate Change Mitigation. *Energy Policy* **2017**, *107*, 278–288. [CrossRef]
25. U.S. Department of Energy. Lawrence Berkeley Laboratory 50001 Ready Decarbonization Management Guidance. Available online: https://navigator.lbl.gov/decarbonization (accessed on 15 May 2023).
26. U.S. Department of Energy. Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. In *Quadrennial Technology Review 2015*; U.S. Department of Energy: Washington, DC, USA, 2015.
27. U.S. Department of Energy. All Manufacturing (NAICS 31-33) Energy Consumption and Loss (TBtu). 2018. Available online: https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf (accessed on 15 May 2023).
28. U.S. Department of Energy. Energy Efficiency & Renewable Energy Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy. 2022. Available online: https://www.energy.gov/eere/amo/articles/thermal-process-intensification-transforming-way-industry-uses-thermal-process (accessed on 15 May 2023).
29. Thekdi, A.; Nimbalkar, S.U.; Sundaramoorthy, S.; Armstrong, K.; Taylor, A.; Gritton, J.; Wenning, T.; Cresko, J. *Technology Assessment on Low-Temperature Waste Heat Recovery in Industry*; Oak Ridge National Lab. (ORNL): Oak Ridge, TN, USA, 2021; ISBN 1800553684.
30. Wright, A.; Martin, M.; Nimbalkar, S.U.; Quinn, J.; Glatt, S.; Orthwein, B. *Results from the US DOE 2008 Save Energy Now Assessment Initiative*; Carbon Dioxide Emissions: Oak Ridge, TN, USA, 2010.
31. O'Rielly, K.; Jeswiet, J. Strategies to Improve Industrial Energy Efficiency. *Procedia Cirp* **2014**, *15*, 325–330. [CrossRef]
32. U.S. Congress Office of Technology Assessment. *Industrial Energy Efficiency*; OTA-E-560; U.S. Government Printing Office: Washington, DC, USA, 1993; ISBN 0520030133.
33. International Energy Agency (IEA). Technology Roadmap—Low-Carbon Transition in the Cement Industry. 2018. Available online: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry (accessed on 15 May 2023).
34. International Energy Agency (IEA). Iron and Steel Technology Roadmap. OECD. 2020. Available online: https://www.iea.org/reports/iron-and-steel-technology-roadmap (accessed on 15 May 2023).
35. International Energy Agency (IEA). Material Efficiency in Clean Energy Transitions. 2019. Available online: https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions (accessed on 15 May 2023).
36. ASTM Standard Terminology for Additive Manufacturing Technologies. 2012. Available online: https://www.astm.org/f2792-12.html (accessed on 15 May 2023).
37. Huang, R.; Riddle, M.; Graziano, D.; Warren, J.; Das, S.; Nimbalkar, S.U.; Cresko, J.; Masanet, E. Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components. *J. Clean. Prod.* **2016**, *135*, 1559–1570. [CrossRef]
38. Ellen MacArthur Foundation. Completing the Picture How the Circular Economy Tackles Climate Change. 2019. Available online: https://ellenmacarthurfoundation.org/completing-the-picture (accessed on 15 May 2023).
39. Enkvist, P.A.; Klevnäs, P.; Teiwik, A.; Jönsson, C.; Klingvall, S.; Hellberg, U. *Industrial Transformation 2050 Industrial Transformation 2050—Executive Summary*; University of Cambridge Institute of Sustainability Leadership: Cambridge, UK, 2019.
40. Meng, Y.; Yang, Y.; Chung, H.; Lee, P.-H.; Shao, C. Enhancing Sustainability and Energy Efficiency in Smart Factories: A Review. *Sustainability* **2018**, *10*, 4779. [CrossRef]
41. Supekar, S.D.; Graziano, D.J.; Riddle, M.E.; Nimbalkar, S.U.; Das, S.; Shehabi, A.; Cresko, J. A Framework for Quantifying Energy and Productivity Benefits of Smart Manufacturing Technologies. *Procedia Cirp.* **2019**, *80*, 699–704. [CrossRef]
42. Nimbalkar, S.U.; Guo, W.; Petri, C.; Cresko, J.; Graziano, D.J.; Morrow III, W.R.; Wenning, T. Smart Manufacturing Technologies and Data Analytics for Improving Energy Efficiency in Industrial Energy Systems. In Proceedings of the American Council for Energy Efficient Economy, Denver, CO, USA, 15–18 August 2017.
43. Muller, M. *Smart Manufacturing and Industrial Analytics: U.S. Department of Energy IAC Centers Training Materials*; U.S. Department of Energy: Washington, DC, USA, 2016.
44. Gallaher, M.P.; Oliver, Z.T.; Rieth, K.T.; O'Connor, A.C. *Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing: Smart Manufacturing*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2016.
45. The Royal Society. *Digital Technology and the Planet: Harnessing Computing to Achieve Net Zero*; The Royal Society: London, UK, 2020; ISBN 9781782525011.
46. U.S. Department of Energy Industrial Efficiency and Decarbonization Office. *The Implications of Advanced Manufacturing in a Connected Economy: Moving towards a Smart, Sustainable, and Productive Economy*; U.S. Department of Energy Industrial Efficiency and Decarbonization Office: Washington, DC, USA, 2023; Chapter 3: Smart Manufacturing.
47. Nimbalkar, S.U.; Supekar, S.D.; Meadows, W.; Wenning, T.; Guo, W.; Cresko, J. Enhancing Operational Performance and Productivity Benefits in Breweries through Smart Manufacturing Technologies. *J. Adv. Manuf. Process.* **2020**, *2*, e10064. [CrossRef]
48. Rogers, E.A. *The Energy Savings Potential of Smart Manufacturing*; American Council for an Energy-Efficient Economy: Washington, DC, USA, 2014.
49. Rouzbahani, H.M.; Karimipour, H.; Lei, L. Optimizing Scheduling Policy in Smart Grids Using Probabilistic Delayed Double Deep Q-Learning (P3DQL) Algorithm. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102712. [CrossRef]
50. U.S. Environmental Protection Agency. What Is CHP? Available online: https://www.epa.gov/chp/what-chp (accessed on 15 May 2023).

51. U.S. Department of Energy. Combined Heat and Power Technology Fact Sheet Series. DOE/EE-1692. 2017. Available online: https://www.energy.gov/eere/amo/articles/combined-heat-and-power-technology-fact-sheet-series-thermal-energy-storage (accessed on 15 May 2023).
52. U.S. Department of Energy. Combined Heat & Power and Microgrid Installation Databases. Available online: https://doe.icfwebservices.com/chp (accessed on 15 May 2023).
53. U.S. Department of Energy; U.S. Environmental Protection Agency. *Combined Heat and Power: A Clean Energy Solution*; U.S. Department of Energy: Washington, DC, USA, 2012.
54. lCF. Combined Heat and Power Potential for Carbon Emission Reductions: National Assessment 2020–2050. 2020. Available online: https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf (accessed on 15 May 2023).
55. Gutowski, T.G.; Allwood, J.M.; Herrmann, C.; Sahni, S. A Global Assessment of Manufacturing: Economic Development, Energy Use, Carbon Emissions, and the Potential for Energy Efficiency and Materials Recycling. *Annu. Rev. Environ. Resour.* **2013**, *38*, 81–106. [CrossRef]
56. U.S. Department of Energy. Energy Efficiency & Renewable Energy Energy Analysis, Data and Reports: Advanced Manufacturing. Available online: https://www.energy.gov/eere/amo/energy-analysis-data-and-reports (accessed on 15 May 2023).
57. Brueske, S.; Kramer, C.; Fisher, A. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing. 2015. Available online: https://www.energy.gov/sites/prod/files/2015/08/f26/chemical_bandwidth_report.pdf (accessed on 15 May 2023).
58. Brueske, S.; Kramer, C.; Fisher, A. Bandwidth Study on Energy Ese and Potential Energy Saving Opportunities in U.S. Petroleum Refining. 2015. Available online: https://www.energy.gov/sites/prod/files/2015/08/f26/petroleum_refining_bandwidth_report.pdf (accessed on 15 May 2023).
59. Dollinger, C.; Cresko, J.; Brueske, S.; Carpenter, A. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in Manufacturing Food and Beverages. 2017. Available online: https://www.energy.gov/sites/prod/files/2017/12/f46/Food_and_beverage_bandwidth_study_2017.pdf (accessed on 15 May 2023).
60. Jamison, K.; Kramer, C.; Brueske, S.; Aaron, F. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Iron and Steel Manufacturing. 2015. Available online: https://www.energy.gov/sites/prod/files/2015/08/f26/iron_and_steel_bandwidth_report_0.pdf (accessed on 15 May 2023).
61. Cresko, J.; Carpenter, A.; Schwartz, H.; Ward, N.; Levie, B.; Chadwell, B.; Brueske, S.; Lu, H.; McIntyre, D.; Garboczi, E.; et al. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing. 2017. Available online: https://www.energy.gov/sites/prod/files/2017/12/f46/Cement_bandwidth_study_2017.pdf (accessed on 15 May 2023).
62. Bornstein, A.; Faquet, R. *Decarbonising Industry in France*; Ministère de l'Économie, des Finances, et de la Relance: Paris, France, 2021; Volume 291. Available online: https://www.tresor.economie.gouv.fr/Articles/2021/10/07/decarbonising-industry-in-france (accessed on 15 May 2023).
63. Australian Government. Funding for High Energy Using Businesses to Improve Efficiency, Reduce Costs and Lower Energy Consumption. Available online: https://business.gov.au/grants-and-programs/energy-efficient-communities-program-high-energy-using-businesses (accessed on 15 October 2022).
64. Her Majesty's Government. Industrial Decarbonization Strategy. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/970229/Industrial_Decarbonisation_Strategy_March_2021.pdf (accessed on 15 October 2022).
65. German Federal Ministry for Economic Affairs and Climate Action. Funding Programme 'Decarbonisation of Industry'. Available online: https://www.klimaschutz-industrie.de/en/funding/ (accessed on 15 October 2022).
66. U.K. Department for Business Energy & Industrial Strategy. Industrial Energy Efficiency Accelerator (Energy Innovation Programme). Available online: https://programmes.carbontrust.com/ieea/ (accessed on 15 October 2022).
67. New Zealand Energy Efficiency and Conservation Authority. Government Industrial Decarbonisation Investment (GIDI) Funding. Available online: https://www.eeca.govt.nz/co-funding/industry-decarbonisation/ (accessed on 15 October 2022).
68. Sustainable Development Technology Canada. Sustainable Development Technology Canada Funding. Available online: https://www.sdtc.ca/en/building-partnerships-that-strengthen-canadas-climate-tech-ecosystem/ (accessed on 15 October 2022).
69. Emissions Reduction Alberta. Industrial Efficiency Challenge (Alberta). Available online: https://eralberta.ca/funding-technology/era-industrial-efficiency-challenge/ (accessed on 15 October 2022).
70. Emissions Reduction Alberta. Emissions Reduction Alberta Funding. Available online: https://www.eralberta.ca/apply-for-funding/ (accessed on 15 October 2022).
71. HydroQuebec. Money for Energy Management Systems in Quebec (Electricity Management Systems Program). Available online: https://www.hydroquebec.com/business/programs-tools/electricity-management-systems-program.html (accessed on 15 October 2022).
72. German Federal Ministry for Economic Affairs and Climate Action. Federal Funding for Energy and Resource Efficiency in Business. Available online: https://www.wettbewerb-energieeffizienz.de/WENEFF/Redaktion/DE/Artikel/auf-einen-blick-WEnEff.html (accessed on 15 October 2022).
73. Nimbalkar, S.U. *Presentation on US DOE's Energy Saving Assessment Management System (ESAMS Database)*; Oak Ridge National Lab. (ORNL): Oak Ridge, TN, USA, 2013.

74. Worrell, E.; Blinde, P.; Neelis, M.; Blomen, E.; Masanet, E. *Energy Efficiency Improvement and Cost Saving Opportunities: An ENERGY STAR® Guide for Energy and Plant Managers*; Lawrence Berkeley National Lab.: Berkeley, CA, USA, 2010.
75. Pardo, N.; Moya, J.A. Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the European Iron & Steel Industry. *Energy* **2013**, *54*, 113–128. [CrossRef]
76. Wang, R.Q.; Jiang, L.; Wang, Y.D.; Roskilly, A.P. Energy Saving Technologies and Mass-Thermal Network Optimization for Decarbonized Iron and Steel Industry: A Review. *J. Clean. Prod.* **2020**, *274*, 122997. [CrossRef]
77. U.S. Department of Energy. Waupaca Foundry: Cupola Waste Heat Recovery Upgrade Drives Deeper Energy Savings. 2020. Available online: https://betterbuildingssolutioncenter.energy.gov/showcase-projects/waupaca-foundry-cupola-waste-heat-recovery-upgrade-drives-deeper-energy-savings (accessed on 15 May 2023).
78. Zhang, H.; Wang, H.; Zhu, X.; Qiu, Y.J.; Li, K.; Chen, R.; Liao, Q. A Review of Waste Heat Recovery Technologies towards Molten Slag in Steel Industry. *Appl. Energy* **2013**, *112*, 956–966. [CrossRef]
79. Zhao, J.; Ma, L.; Zayed, M.E.; Elsheikh, A.H.; Li, W.; Yan, Q.; Wang, J. Industrial Reheating Furnaces: A Review of Energy Efficiency Assessments, Waste Heat Recovery Potentials, Heating Process Characteristics and Perspectives for Steel Industry. *Process Saf. Environ. Prot.* **2021**, *147*, 1209–1228. [CrossRef]
80. U.S. Department of Homeland Security. Chemical Sector Profile 2019. Available online: https://www.cisa.gov/resources-tools/resources/chemical-sector-profile (accessed on 15 May 2023).
81. Cucciniello, R.; Cespi, D. Recycling within the Chemical Industry: The Circular Economy Era. *Recycling* **2018**, *3*, 22. [CrossRef]
82. U.S. Department of Energy. Saint-Gobain Corporation: Roxboro Gypsum Wallboard Plant. Available online: https://betterbuildingssolutioncenter.energy.gov/showcase-projects/saint-gobain-corporation-roxboro-gypsum-wallboard-plant (accessed on 15 May 2023).
83. U.S. Department of Energy. Eastman Chemical: Boiler Efficiency Study and Upgrades Yield Big Savings. Available online: https://betterbuildingssolutioncenter.energy.gov/showcase-projects/eastman-chemical-boiler-efficiency-study-and-upgrades-yield-big-savings (accessed on 15 May 2023).
84. Lee, R.P. Alternative Carbon Feedstock for the Chemical Industry?—Assessing the Challenges Posed by the Human Dimension in the Carbon Transition. *J. Clean. Prod.* **2019**, *219*, 786–796. [CrossRef]
85. Dong, W.; Armstrong, K.; Jin, M.; Nimbalkar, S.U.; Guo, W.; Zhuang, J.; Cresko, J. A Framework to Quantify Mass Flow and Assess Food Loss and Waste in the US Food Supply Chain. *Commun. Earth Environ.* **2022**, *3*, 83. [CrossRef]
86. Zhang, B.Y.; Tong, Y.; Singh, S.; Cai, H.; Huang, J.Y. Assessment of Carbon Footprint of Nano-Packaging Considering Potential Food Waste Reduction Due to Shelf Life Extension. *Resour. Conserv. Recycl.* **2019**, *149*, 322–331. [CrossRef]
87. Hu, G.; Mu, X.; Xu, M.; Miller, S.A. Potentials of GHG Emission Reductions from Cold Chain Systems: Case Studies of China and the United States. *J. Clean. Prod.* **2019**, *239*, 118053. [CrossRef]
88. Chen, X.; Voigt, T. Implementation of the Manufacturing Execution System in the Food and Beverage Industry. *J. Food Eng.* **2020**, *278*, 109932. [CrossRef]
89. Worrell, E.; Galitsky, C. Energy Efficiency Improvement in the Petroleum Refining Industry. In *Proceedings of the 2005 ACEEE Summer Study on Energy Efficiency in Industry*; ACEEE: West Point, NY, USA; Available online: https://escholarship.org/uc/item/15w780mf (accessed on 15 May 2023).
90. Griffiths, S.; Sovacool, B.K.; Kim, J.; Bazilian, M.; Uratani, J.M. Decarbonizing the Oil Refining Industry: A Systematic Review of Sociotechnical Systems, Technological Innovations, and Policy Options. *Energy Res. Soc. Sci.* **2022**, *89*, 102542. [CrossRef]
91. Owttrim, C.G.; Davis, M.; Shafique, H.U.; Kumar, A. Energy Efficiency as a Critical Resource to Achieve Carbon Neutrality in the Pulp and Paper Sector. *J. Clean. Prod.* **2022**, *360*, 132084. [CrossRef]
92. Martin, N.; Anglani, N.; Einstein, D.; Khurshch, M.; Worrell, E.; Price, L.K. Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the U.S. Pulp and Paper Industry. 2000. Available online: https://escholarship.org/content/qt31b2f7bd/qt31b2f7bd.pdf (accessed on 15 May 2023).
93. Mobarakeh, M.R.; Silva, M.S.; Kienberger, T. Pulp and Paper Industry, Case Study. *Energies* **2021**, *14*, 1161.
94. Inderwildi, O.; Zhang, C.; Wang, X.; Kraft, M. The Impact of Intelligent Cyber-Physical Systems on the Decarbonization of Energy. *Energy Environ. Sci.* **2020**, *13*, 744–771. [CrossRef]
95. Furszyfer Del Rio, D.D.; Sovacool, B.K.; Griffiths, S.; Bazilian, M.; Kim, J.; Foley, A.M.; Rooney, D. Decarbonizing the Pulp and Paper Industry: A Critical and Systematic Review of Sociotechnical Developments and Policy Options. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112706. [CrossRef]
96. CESMII—The Smart Manufacturing Institute. Smart Manufacturing of Cement. Available online: https://www.cesmii.org/smart-manufacturing-of-cement/ (accessed on 15 May 2023).
97. Price, C.R.; Nimbalkar, S.U.; Thirumaran, K.; Cresko, J. Smart Manufacturing Pathways for Industrial Decarbonization and Thermal Process Intensification. *Smart Sustain. Manuf. Syst.* **2023**, *7*, 41–53. [CrossRef]
98. Lu, Y.; Xu, X.; Wang, L. Smart Manufacturing Process and System Automation—A Critical Review of the Standards and Envisioned Scenarios. *J. Manuf. Syst.* **2020**, *56*, 312–325. [CrossRef]
99. Kusiak, A. Smart Manufacturing Must Embrace Big Data. *Nature* **2017**, *544*, 23–25. [CrossRef] [PubMed]

100. U.S. Department of Energy. Manufacturing Energy Bandwidth Studies. Available online: https://www.energy.gov/eere/iedo/manufacturing-energy-bandwidth-studies (accessed on 15 May 2023).
101. U.S. Department of Energy. Industrial Technology Validation Pilot. Available online: https://betterbuildingssolutioncenter.energy.gov/better-plants/industrial-technology-validation-pilot (accessed on 15 May 2023).