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U.S. Industrial and Commercial Motor System Market Assessment Report

Volume 3: Energy Saving Opportunity

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July 2022

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Prepared for the
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Preface

In the late 1990s, the U.S. Department of Energy (DOE) conducted two seminal studies to better understand the installed stock and energy savings opportunities of industrial and commercial motor systems: *The United States Industrial Electric Motor Systems Market Opportunities Assessment* (industrial sector) and *Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Electric Motors* (commercial sector). In the more than 20 years since the publication of these reports, the U.S. industrial and commercial sectors have undergone changes, including facility and/or motor system stock turnover, offshoring and onshoring of manufacturing, passage of motor efficiency standards, cost reductions in motor driven systems, and more. To gain a more current understanding of motor systems in the U.S. industrial and commercial sectors, DOE initiated an update to these two studies. Launched in 2016 and led by Lawrence Berkeley National Laboratory (LBNL), the Motor System Market Assessment (MSMA) provides an updated, more comprehensive assessment of the installed stock of motor systems in both the industrial and commercial sectors, a review of the supply chains supporting motor and drives in the U.S., and the performance improvement opportunity available from using best available technologies and maintenance and operation practices. The outcomes of the MSMA are documented in three *U.S. Industrial and Commercial Motor System Market Assessment* reports, with this one being the last listed:

1. *Volume 1: Characteristics of the Installed Base* documents the findings on the installed base of motor systems in the U.S. industrial and commercial sectors. Quantification of energy savings potential is not documented in the Volume 1 report but is done so in Volume 3. A searchable website with the underlying information contained in Volume 1 report is available at https://motors.lbl.gov/inventory. This website has been established to serve as a complement to the Volume 1 report and allows readers to create their own crosscuts and conduct their own analysis using the results from the Motor System Market Assessment.
2. *Volume 2: Advanced Motors and Drives Supply Chain Review* reviews the state of supply chains for motors and drives installed in U.S. industrial and commercial facilities, focusing on advanced motor and drive technologies and their constituent materials.
3. *Volume 3: Energy Savings Opportunity* (this report) analyzes the energy performance improvement opportunity for the installed base of U.S. industrial and commercial motor systems.

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List of Acronyms and Abbreviations

AC	alternating current
B	billion
CBECS	Commercial Building Energy Consumption Survey
CNT	carbon nanotube
CO_2	carbon dioxide
CR	copper rotor
DC	direct current
DOE	U.S. Department of Energy
EASA	Electrical Apparatus Service Association
EEI	Edison Electric Institute
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FIDVR	fault-induced delayed voltage recovery
GWh	gigawatt-hour
hp	horsepower
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LF	load factor
MECS	Manufacturing Energy Consumption Survey
MEPS	minimum energy performance standards
GaN	gallium nitride
HTS	high temperature superconducting
M	million
MANC	metal amorphous nanocomposite material
MMT	million metric tons
MSMA	motor system market assessment
NEMA	National Electrical Manufacturers Association
PBP	payback period
PM	permanent magnet
PM SynRM	permanent magnet synchronous reluctance
psig	pounds per square inch gauge
psia	pounds per square inch absolute
SiC	silicon carbide
SR	switched reluctance
SynRM	synchronous reluctance
TWh	terawatt-hours
UTC	unable to collect
VFD	variable frequency drive
WBG	wide bandgap

Executive Summary

At both the national and regional levels, aggressive decarbonization targets are being adopted in response to the urgent need to address climate change. Similarly, corporations are also setting ambitious carbon dioxide (CO_2) reduction targets as part of their sustainability efforts. Achieving these targets will require a staged approach that is initiated with deep energy efficiency improvements progressing to electrification, widespread adoption of renewable and clean energy generation, and deployment of emerging technologies/processes such as carbon capture, sequestration, and utilization. Often lost in this progression is the role of motor systems. Since they are already electrically driven, the common thinking is that decarbonizing motor system energy consumption will follow the decarbonization of the electric grid, with no further intervention necessary. However, this notion overlooks the various important roles motor systems play in decarbonizing the economy:

- Increasing the energy efficiency and power management of existing motor systems will substantially reduce the costs associated with the expansion of renewable electricity generation capacity, given the magnitude of the grid electricity used for motor systems.
- Many electrification plans involve adoption of a motor-based technology, such as a heat pump and replacement of fossil-fuel powered machine loads.
- Efficient electric load flexibility, which is needed to balance intermittent renewable electricity generation, is enabled by drives on motor systems.

This report seeks to inform the potential for motor systems to support decarbonization by estimating their potential energy, electricity cost, and CO_2 emissions reduction potential from adoption of proven energy efficiency actions and advanced technologies. This is the third and final report in a series of reports disseminating the findings of the U.S. Department of Energy's (DOE's) Motor System Market Assessment (MSMA). The MSMA and this report focus on polyphase motor systems greater than or equal to 1 horsepower (hp) in the industrial and commercial sectors. In the *U.S. Industrial and Commercial Motor System Market Assessment Report Volume 1: Characteristics of the Installed Base* (Volume 1 report), it was determined that these motor systems consume more than 1,000 terawatt-hours (TWh) annually. This equates to 29% of the U.S. electric grid load and results in 765 million metric tons (MMT) of CO_2 emissions and $166 billion in electricity costs. This report finds that substantial reductions to these energy, cost, and emissions impacts are possible, with three areas of significant opportunity being (1) improved load matching, (2) replacing older inefficient motors with more efficient motors, and (3) improving the condition of fluid (e.g., air, water, compressed air) distribution systems. A summary of the savings potential from these three opportunities placed within the context of the overall consumption for motor systems is illustrated in Figure ES 1 (industrial) and Figure ES 2 (commercial).

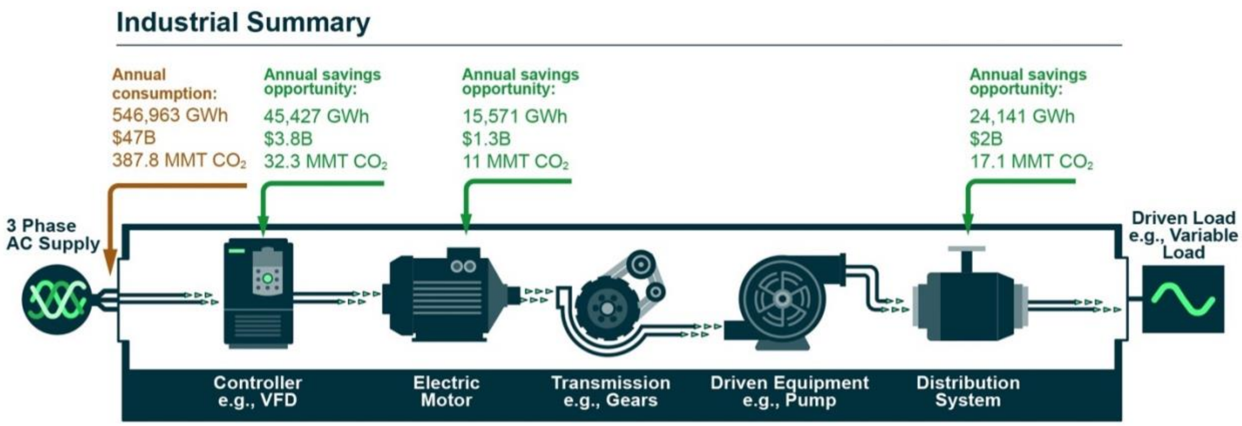

Figure ES 1: Summary of energy consumption, cost expenditures, and CO_2 emissions for industrial motor systems and reduction potential from the most significant opportunities

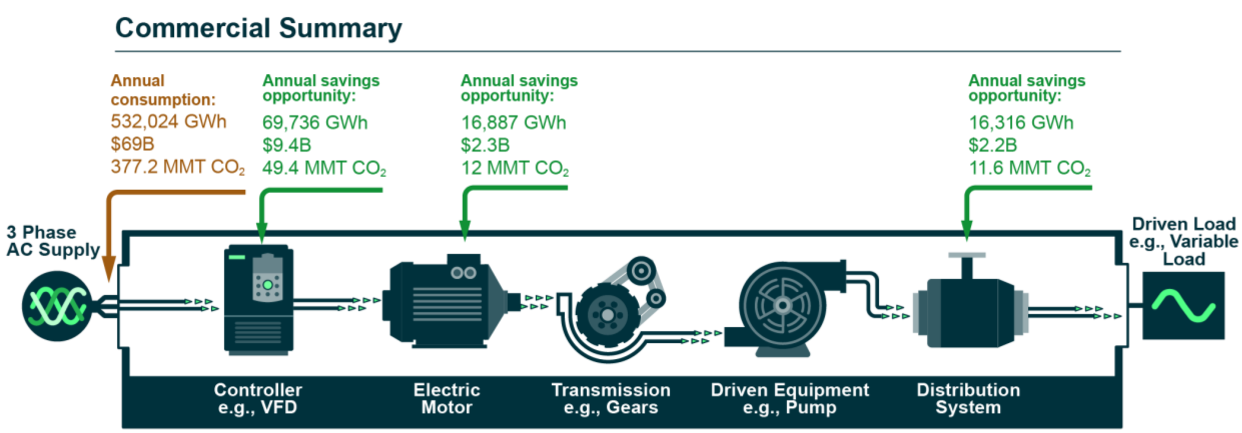

Figure ES 2: Summary of energy consumption, cost expenditures, and CO_2 emissions for commercial motor systems and reduction potential from the most significant opportunities

In the Volume 1 report, it was found that 47% of industrial and 50% of commercial motor systems operate at loads less than 75% of full capacity. Adoption of the right-sized motors and/or installation of a variable frequency drive (VFD) has the potential to save 115,000 gigawatt-hours per year (GWh/yr) across both sectors, translating into reductions of $13.2 billion and 81.7 MMT of CO_2.

The Volume 1 report found that the energy efficiency of industrial motors ranged between 83% and 93%. For commercial motors, the energy efficiency ranged between 82% and 95%. Newer motor designs offer substantial improvements in motor efficiency. The efficiency of Premium Efficiency motors ranges between 86% and 96%. Advanced motor technologies, like Permanent Magnet designs, offer about another 1% improvement in efficiency. Upgrading older inefficient motors to more efficient designs, such as Premium Efficiency, could yield 32,458 GWh/yr in savings, translating to reductions of $3.6 billion and 23 MMT of CO_2 across both sectors.

Also in the Volume 1 report, it was found that most industrial and commercial motor system distribution systems experienced significant energy losses due to insufficient maintenance. Improving these systems such that energy losses are minimized would result in 40,457 GWh/yr in energy savings, translating to reductions of $4.2 billion and 28.7 MMT of CO_2.

This report also examines the energy, cost, and CO_2 reduction potential associated with adoption of advanced motor technologies. Specifically, this report examines[1]: Permanent Magnet (PM; 1–500 hp), Switched Reluctance (SR; 1–200 hp), Synchronous Reluctance (SynRM; 1–500 hp), Permanent Magnet Synchronous Reluctance (PMSynRM; 1–200 hp), and Copper Rotor (CR; 1–20 hp). Except for CR motors, these advanced motors offer improved efficiency at full load and low loads compared to induction motors and variable speed capability. Therefore, these four motor types offer energy, cost, and CO_2 savings potential across all load profiles. CR motors offer improved energy efficiency at full loads. Table ES 1 summarizes the energy, cost, and CO_2 savings from these advanced technologies by sector. Due to their availability in a wide range of sizes and their applicability to improve the energy efficiency of part-load systems, PM motors offer the greatest savings across the two sectors, followed very closely by SynRM motors.

Table ES 1: Energy, cost and CO_2 savings from adoption of advanced motor technologies

	Electricity Savings (GWh/yr)	Cost Savings (million $/yr)	CO_2 Savings (MMT/yr)
Permanent Magnet			
Industrial	45,014	3,788	31.9
Commercial	82,180	10,862	58.3
Switched Reluctance			
Industrial	36,059	3,042	25.6
Commercial	85,927	11,484	60.9
Synchronous Reluctance			
Industrial	44,105	3,711	31.3
Commercial	80,051	10,568	56.8
Permanent Magnet Synchronous Reluctance			
Industrial	31,688	2,668	22.5
Commercial	76,985	10,249	54.6
Copper Rotor			
Industrial	2,430	205	1.7
Commercial	7,004	1,015	5.0

Table ES 2 shows a summary of the energy, cost, and CO_2 emissions savings from the three measures and advanced motor technologies, broken out by industrial and commercial subsector. PM motors have been selected to represent savings from advanced motor technologies since they have the greatest applicability, availability, and consequently greatest savings potential. This report examines additional savings opportunities not included in Table ES 2, including rewind losses, replacing V-belts with cog belts, pump impeller trimming, elimination of inappropriate

[1] The abbreviation used in this report and the size range evaluated are given in parentheses.

uses of compressed air, installation of sequencers on air compressors, and reductions in compressed air pressure set points. Additionally, opportunities associated with improved energy management for pumping, fan, compressed air, refrigeration, materials handling, and materials processing systems are qualitatively summarized in the report.

Table ES 2: Summary of energy, cost, and CO_2 emissions savings potential from improved load control/matching, early retirement of less efficient motors and replacement with Premium Efficiency, improvements to distribution systems, and adoption of advanced technologies (represented by PM motors) for the industrial and commercial sectors

Opportunity	Electricity Savings (GWh/yr)	Cost Savings (million $/yr)	CO_2 Savings (MMT/yr)
Improved load control/matching			
Industrial	45,527	3,824	32.2
Commercial	69,737	9,414	49.4
Early retirement of old motors to Premium Efficiency			
Industrial	15,571	1,308	11.0
Commercial	16,877	2,278	12.0
Improvements to distribution systems			
Industrial	24,141	2,028	17.1
Commercial	16,316	2,203	11.6
Advanced technology (PM)			
Industrial	45,014	3,788	31.9
Commercial	82,180	10,862	58.3

Note: The energy savings associated with the adoption of multiple measures may not be the sum of the energy savings of each individual measure due to interactions between them. Also note that the savings from advanced technologies were only evaluated for size ranges within which the technology is commercially available.

Within each sector, the Volume 1 report identified and quantified motor system electricity consumption by subsector. In the industrial sector, the subsectors with the greatest motor system electricity consumption are: Chemicals, Primary Metals, Food, Paper, Plastics and Rubber, and Petroleum Refining. Table ES 3 identifies the most significant energy, cost, and CO_2 emission reduction opportunities for each of these subsectors. Also shown are the savings from adoption of advanced motor technologies (represented by PM motors). In all subsectors, improving load control, either through installation of VFDs or adoption of advanced technologies, offered the greatest opportunities.

Table ES 3: The top three motor system energy reduction opportunities for the top six industrial subsectors by motor system electricity consumption

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Chemicals			
Baseline	105,699	9,196	74.9
Savings estimates			
VFD	10,459	879	7.4
Premium Efficiency motor upgrade	2,780	234	2.0
Rewind	1,576	132	1.1

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Advanced technology (PM)	8,621	724	6.1
Primary Metals			
Baseline	63,917	5,561	45.3
Savings estimates			
VFD	4,006	337	2.8
Premium Efficiency motor upgrade	2,701	227	1.9
Air duct distribution system improvements	1,528	128	1.1
Advanced technology (PM)	4,897	411	3.5
Food			
Baseline	47,585	4,140	33.7
Savings estimates			
VFD	4,593	386	3.3
Compressed air distribution system improvements	1,376	116	1.0
Premium Efficiency motor upgrade	1,343	113	1.0
Advanced technology (PM)	4,688	394	3.3
Paper			
Baseline	45,026	3,917	31.9
Savings estimates			
VFD	3,116	262	2.2
Premium Efficiency motor upgrade	1,578	133	1.1
Pump distribution system improvements	1,388	117	1.0
Advanced technology (PM)	2,161	182	1.5
Plastics and Rubber			
Baseline	39,898	3,471	28.3
Savings estimates			
VFD	1,586	133	1.1
Premium Efficiency motor upgrade	1,317	111	0.9
Air duct distribution system improvements	701	59	0.5
Advanced technology (PM)	3,051	256	2.2
Petroleum Refining			
Baseline	39,269	3,416	27.8
Savings estimates			
VFD	6,626	557	4.7
Premium Efficiency motor upgrade	797	67	0.6
Pump distribution system improvements	578	49	0.4
Advanced technology (PM)	5,358	450	3.8

Note: The energy savings associated with the adoption of multiple measures may not be the sum of the energy savings of each individual measure due to interactions between them. Also note that the energy savings from adoption of advanced technologies were only evaluated for size ranges within which the technology is commercially available.

Within the commercial sector, the Office, Education, Lodging, Warehouse and Storage, Food Service, and Healthcare Inpatient subsectors consume the most energy for motor systems. The biggest opportunities for each of these subsectors are shown in Table ES 4. Also shown are the savings associated with adoption of advanced technologies (represented by PM motors). In all subsectors, improving load control, either through installation of VFDs or upgrading to an advanced motor technology, offers the greatest opportunity for energy, cost, and CO_2 reductions. In accordance with the significant energy consumption for fan systems (as reported in the Volume 1 report), large savings opportunities exist for improving the condition of air duct distribution systems.

Table ES 4: The top three motor system energy reduction opportunities for the top six commercial subsectors by motor system electricity consumption

	Electricity (GWh/yr)	**Cost (million $/yr)**	**CO_2 (MMT/yr)**
Office			
Baseline	93,335	12,134	66.2
Savings estimates			
VFD	11,930	1,611	8.5
Air duct distribution system improvements	2,660	359	1.9
Premium Efficiency Motor Upgrade	2,128	287	1.5
Advanced technology (PM)	14,544	1,963	10.3
Education			
Baseline	76,339	9,924	54.1
Savings estimates			
VFD	11,546	1,559	8.2
Premium Efficiency motor upgrade	2,597	351	1.8
Air duct distribution system improvements	1,417	191	1.0
Advanced technology (PM)	14,266	1,926	10.1
Lodging			
Baseline	59,189	7,695	42.0
Savings estimates			
VFD	5,636	761	4.0
Premium Efficiency motor upgrade	1,597	216	1.1
Rewind	825	111	0.6
Advanced technology (PM)	7,001	945	5.0
Warehouse and Storage			
Baseline	40,054	5,207	28.4

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Savings estimates			
VFD	2,801	378	2.0
Premium Efficiency motor upgrade	1,773	239	1.3
Air duct distribution system improvements	1,121	151	0.8
Advanced technology (PM)	5,128	692	3.6
Food Service			
Baseline	34,776	4,521	24.7
Savings estimates			
VFD	5,863	792	4.2
Premium Efficiency motor upgrade	1,727	233	1.2
Air duct distribution system improvements	1,190	161	0.8
Advanced technology (PM)	7,718	1,042	5.5
Healthcare Inpatient			
Baseline	34,759	4,519	24.6
Savings estimates			
VFD	4,796	647	3.4
Premium Efficiency motor upgrade	934	126	0.7
Air duct distribution system improvements	702	95	0.5
Advanced technology (PM)	3,481	470	2.5

Note: The energy savings associated with the adoption of multiple measures may not be the sum of the energy savings of each individual measure due to interactions between them. Also note that the energy savings from the adoption of advanced technologies were only evaluated for size ranges within which the technology is commercially available.

Opportunities for energy, CO_2 emissions, and cost reductions for motor systems also can be broken down by the equipment driven by the motor (e.g., pump, fan). For definitions of each type of the driven equipment, please see the glossary in the Volume 1 report. Two commonly sought definitions are for materials processing and materials handling, and those are reprinted here: *Materials processing* includes motor systems that use mechanical means to process materials. Examples include grinders, hydraulics, and extruder motors. *Materials handling* includes motor systems that transport materials, such as conveyor motors.

Table ES 5 provides a summary of the largest opportunities by motor driven equipment. For driven equipment that operates on the principle of applying centrifugal forces (e.g., most pump, fan, air compressor, and refrigeration compressor systems), load control via VFDs or an advanced technology offered the greatest savings opportunity, except for compressed air systems where improvements to the distribution system offers the greatest savings opportunity. For non-centrifugal systems (e.g., materials processing and handling), improvements to the motor itself offers the greatest opportunity.

Table ES 5: Energy, CO_2, and cost reduction opportunities by motor system driven equipment for the industrial sector

	Energy (GWh/yr)	Cost (million $/yr)	CO_2 Emissions (MMT/yr)
Pumping Systems			
Baseline	115,868	10,081	82.2
Savings estimates			
VFD	10,354	870	7.3
Impeller trimming	5,493	461	3.9
Distribution system improvements	4,431	372	3.1
Advanced technology (PM)	11,493	965	8.1
Fan Systems			
Baseline	112,942	9,826	80.1
Savings estimates			
VFD	13,724	1,153	9.7
Air duct distribution system improvements	8,959	753	6.4
Premium Efficiency motor upgrade	2,986	251	2.1
Advanced technology (PM)	13,489	1,133	9.6
Compressed Air Systems			
Baseline	63,613	5,534	45.1
Savings estimates			
Distribution system improvements	10,751	903	7.6
VFD	10,408	874	7.4
Eliminate inappropriate uses	8,913	749	6.3
Advanced technology (PM)	8,461	711	6.0
Refrigeration Systems			
Baseline	68,007	5,917	48.2
Savings estimates			
VFD	9,869	829	7.0
Premium Efficiency motor upgrade	1,935	163	1.4
Rewind	944	79	0.7
Advanced technology (PM)	7,056	593	5.0
Materials Processing Systems			
Baseline	155,783	13,553	110.5
Savings estimates			
Premium Efficiency motor upgrade	5,232	439	3.7
Rewind	2,254	189	1.6
Right sizing	455	38	0.3
Advanced technology (PM)	3,644	306	2.6
Materials Handling Systems			
Baseline	19,998	1,740	14.2

	Energy (GWh/yr)	Cost (million $/yr)	CO_2 Emissions (MMT/yr)
Savings estimates			
Premium Efficiency motor upgrade	644	54	0.5
Rewind	311	26	0.2
Right sizing	69	6	0.05
Advanced technology (PM)	671	56	0.5

Note: The energy savings associated with the adoption of multiple measures may not be the sum of the energy savings of each individual measure due to interactions between them. Also note that the energy savings from the adoption of advanced technologies were only evaluated for size ranges within which the technology is commercially available.

Table ES 6 shows the energy, CO_2 emissions, and cost reduction opportunities by driven equipment in the commercial sector. Here again, systems prominently driven by centrifugal equipment have significant opportunities associated with improved load control, either through installation of VFDs or adoption of an advanced technology. Systems that do not use centrifugal forces have significant opportunities associated with upgrading the motor.

Table ES 6: Energy, CO_2, and cost reduction opportunities by motor system driven equipment for the commercial sector

	Energy (GWh/yr)	Cost (million $/yr)	CO_2 Emissions (MMT/yr)
Pumping Systems			
Baseline	52,907	6,878	37.5
Savings estimates			
VFD	2,884	389	2.0
Impeller trimming	2,031	274	1.4
Premium Efficiency motor upgrade	2,006	271	1.4
Advanced technology (PM)	5,435	734	3.9
Fan Systems			
Baseline	192,085	24,971	136.2
Savings estimates			
VFD	18,875	2,548	13.4
Distribution system improvements	12,935	1,746	9.2
Rewind	2,678	362	1.9
Advanced technology (PM)	27,942	3,772	19.5
Compressed Air Systems			
Baseline	12,564	1,633	8.9
Savings estimates			
VFD	2,110	285	1.5
Distribution system improvements	1,877	253	1.3
Eliminate inappropriate uses	1,572	212	1.1

	Energy (GWh/yr)	Cost (million $/yr)	CO_2 Emissions (MMT/yr)
Advanced technology (PM)	1,519	205	1.1
Refrigeration Systems			
Baseline	251,522	32,698	178.3
Savings estimates			
VFD	44,593	6,020	31.6
Premium Efficiency motor upgrade	7,452	1,006	5.3
Rewind	3,491	471	2.5
Advanced technology (PM)	46,684	6,302	33.1
Materials Processing Systems			
Baseline	1,549	201	1.1
Savings estimates			
Premium Efficiency motor upgrade	78	11	0.1
Advanced technology (PM)	60	8	0.04
Materials Handling Systems			
Baseline	9,282	1,207	6.6
Savings estimate			
Premium Efficiency motor upgrade	513	69	0.4
Rewind	129	17	0.1
Advanced technology (PM)	686	93	0.5

Note: The energy savings associated with the adoption of multiple measures may not be the sum of the energy savings of each individual measure due to interactions between them. Also note that the energy savings from the adoption of advanced technologies were only evaluated for size ranges within which the technology is commercially available.

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Background and Motivation

Decarbonizing the U.S. industrial and commercial sectors has emerged at the forefront of domestic energy policy (Executive Order No. 14057, 2021; National Academies of Sciences Engineering and Medicine, 2021; The White House, 2021; U.S. DOS and EOP, 2021; U.S. Congress, 2020). Reducing energy consumption through energy efficiency and productivity improvements has a central role in cost-effectively achieving a decarbonized economy. A quarter of all U.S. carbon dioxide (CO_2) emissions in 2019 were attributable to the generation, transmission, and distribution of electricity. The companion to this report, *U.S. Industrial and Commercial Motor System Market Assessment Report Volume 1: Characteristics of the Installed Base* (Rao et al., 2021, Volume 1 report), reported that 29% of U.S. electric grid demand (based on 2018 generation) is from polyphase motors 1 horsepower (hp) or greater in the industrial and commercial sectors. This corresponds to 15% of all U.S. energy-related CO_2 emissions, 27% of all industrial sector energy-related CO_2 emissions, and 42% of all commercial sector energy-related emissions in 2018 (U.S. EIA, 2019, 2021). Achieving energy savings for these motor systems can substantially reduce sector-wide and national energy-related CO_2 emissions.

Even under an ideal scenario where the electric grid is supported by 100% renewable electricity generation (and therefore, zero CO_2 emissions), realizing energy savings for industrial and commercial motor systems can significantly reduce the amount of renewable energy generation capacity needed and consequently lower the cost for decarbonizing the electric grid. A recent study by Cole et al. (2021) found that it will cost about $3 trillion to achieve a 95% renewable electric grid in the U.S. by 2050, with costs increasing non-linearly thereafter to reach 100% renewable electricity generation. Improvements to the energy efficiency of motor systems and the resulting energy savings can avoid the higher marginal costs associated with building out a renewable electric grid.

From the perspective of the facility, energy savings through energy efficiency is a decarbonization strategy that will also cut operating costs. The Volume 1 report found that U.S. industrial and commercial motor systems consume 1,078 terawatt-hours (TWh) of electricity annually: 546,963 gigawatt-hours (GWh) for industrial systems and 532,024 GWh for commercial systems. At a national average electric rate of $0.086/kilowatt-hour (kWh) for industry and $0.13/kWh for commercial buildings,[2] industrial and commercial building owners/operators spend $116 billion per year on electricity for motor systems ($47 billion for industry and $69 billion for commercial). A 5% reduction in electricity consumption could deliver nearly $6 billion in savings year-on-year for business owners.

For several years, the U.S. industrial and commercial sectors have been realizing substantial reductions in motor system energy consumption. Most notably, the U.S. has been a global leader in setting minimum energy performance standards (MEPS) for motors. Today, most polyphase motors between 1 and 500 hp produced and/or sold in the U.S. must meet the National Electrical Manufacturers Association (NEMA) criteria for Premium Efficiency (10 C.F.R. § 431.25, 2014). To put this into context, the Volume 1 report found that the average polyphase industrial motor is

[2] These rates were calculated using a weighted average of regional electric rates in 2020 based on the distribution of motor system energy consumption.

27 hp and the average polyphase commercial motor is 8 hp. For a 4-pole open enclosure motor, the Premium Efficiency (and subsequently the legally required minimum) energy efficiency levels for 7.5 and 25 hp motors are 91% and 93.6%, respectively (10 C.F.R. § 431.25, 2014). While there is still room to improve upon existing motor efficiency levels, greater energy savings are achievable when considering the broader system. The broader system (see Figure 1) considers the energy efficiency across a boundary that begins with electricity coming into the facility and ends with mechanical power being transmitted to an end-use application. Commonly, and in this report, it is taken to include the electric drive and controller, motor, power transmission (e.g., gearbox, belt), driven equipment (e.g., pump, fan, compressor), and the fluid distribution system (e.g., compressed air line, air ducts).

To better address the overall system efficiency, energy efficiency labels have been developed to capture more of the system-wide energy losses. These include the Pump Energy Index, which can be applied across the drive, motor, and pump, and is used to establish minimum energy performance standards for pumps sold in the U.S. (10 C.F.R. § 431.465, 2016). Previous analyses have concluded a wide range of energy savings potential across the motor system, from 7% to 57% (De Almeida et al., 2019; McKane and Hasanbeigi, 2011; Waide et al., 2011). Savings can be realized as a result of a variety of energy efficiency actions, such as implementation of variable frequency drives (VFDs), appropriately sizing each component of the system, and eliminating losses within the fluid distribution systems (e.g., repairing compressed air leaks).

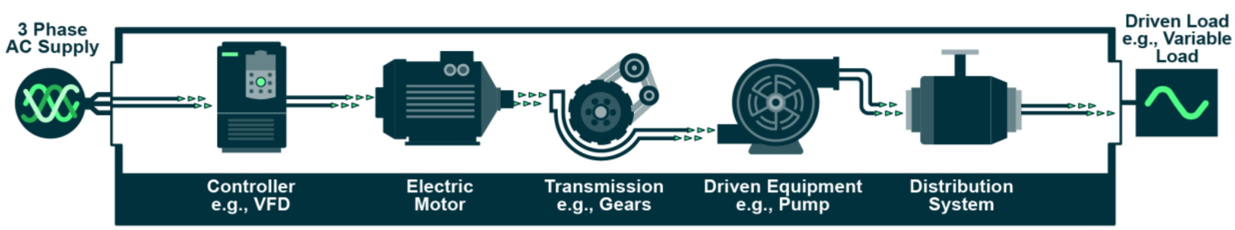


Figure 1: Block diagram of a motor drive system

In recent years, the motor system market has evolved into one that is more conducive to implementation of energy-saving measures. In addition to the aforementioned minimum energy performance standards for motors and pumps, the cost of VFDs has fallen significantly, such that it is approximately equal to the motor cost (Dols et al., 2014). As another example, energy awareness campaigns such as DOE’s Better Plants program, the Compressed Air Challenge, and the Consortium for Energy Efficiency’s Motor Decision Matters have raised awareness of motor system energy efficiency practices. Further, electric utilities have rebate incentive programs around energy efficient motors and drives, thereby reducing their implementation costs (NC State University and NC Clean Energy Technology Center, 2022).

In parallel, the research community has integrated novel materials into motors and drives. The result has been expanded applicability of energy-saving technologies, improved energy performance, and greater power density. For example, the integration of wide band gap materials into VFDs has extended the range of their use to include larger motor systems (e.g., medium voltage, greater than 1,000 hp). Similarly, the integration of rare earth elements, such as neodymium, into magnets has created a class of motors with greater power densities and abilities to operate efficiently across a wide range of loads. Many of these advanced technologies and their benefits were documented in the *U.S. Industrial and Commercial Motor System Market Assessment Volume 2: Advanced Motors and Drives Supply Chain* report (Newkirk et al., 2021, Volume 2 report).

Prior to the publication of the Volume 1 report, the understanding of the installed motor system base in U.S. commercial and industrial facilities was out of date and not reflective of the current motor system market. As a result, the opportunity for energy, operating cost savings, and CO_2 reductions from existing motor system energy efficiency measures and implementation of advanced technologies could not be confidently determined. However, with the publication of the Volume 1 report, the current state of installed motor systems has been comprehensively evaluated and documented. This affords the opportunity to determine with confidence the potential energy, cost, and CO_2 savings associated with implementation of motor system energy efficiency measures and advanced technologies. To that end, this report uses the results from the Volume 1 report to evaluate the electricity, CO_2, and operating cost savings potential from the adoption of several motor system energy efficiency practices and technologies, such as:

- Early replacement of motors with Premium Efficiency models
- Improved load matching through adoption of VFDs and right sizing motors and greater adoption of advanced variable speed motors
- Improvements to fluid distribution systems
- Adoption of advanced technologies

Savings estimates are broken out by sector, driven equipment (e.g., pumps, fan, air compressors), and industrial and commercial subsectors (in Appendix A: Savings Estimates by Industrial Subsectors and Appendix B: Savings Estimates by Commercial Subsector). Additionally, the potential applicability of several energy-saving measures, such as the use of meters and performance curves, is also presented. The findings from this report are intended to help:

- Industrial and commercial business owners reduce the costs of operating their motor systems
- Policymakers at the federal, state, and local levels develop technical assistance, incentives, and other policies intended to spur motor system energy efficiency improvements
- Motor, drive, and driven equipment manufacturers reduce the lifetime running costs of their systems
- Electric utilities design and implement motor system incentive programs that target their most critical needs
- Energy efficiency service providers understand the opportunities and needs of their customers
- Researchers design improved motor systems to achieve deeper savings

With the urgent need to decarbonize the U.S. economy, adoption of these measures and technologies represents a critical path forward towards cost-effectively decarbonizing the U.S. industrial and commercial sectors.

Methods

The method for executing the Motor System Market Assessment (MSMA) was described in the Volume 1 report, with additional details in the appendices. These methods resulted in the collection of information on industrial and commercial motor systems that underpins the analysis presented in this report. In the Volume 1 report, the current state of the installed motor system base was comprehensively characterized, including the motor system counts and consumption distribution by motor size, efficiency, operating mode, driven equipment type, and subsector. Other practices that may affect energy saving opportunities, such as load factors, load controls, distribution system condition, maintenance practices, and purchasing decision were characterized as well.

Using the information from the Volume 1 report, the potential energy, operating cost, and CO_2 savings from the implementation of motor system energy efficiency measures and advanced technologies can be evaluated using a bottom-up approach. This entails evaluating the energy savings for each system physically sampled and rolling the results up to the national level. The engineering equations used to estimate energy savings are presented, along with the resulting energy savings in the ensuing chapter. This section will describe the methods used to roll-up the estimated savings for each individual system to the national level and translate energy savings to cost and CO_2 reductions.

Sample Weighting

To estimate the national energy, operating cost, and CO_2 impact of a given energy savings measure, the savings per representative unit (motor system) were expanded to the national level (within the scope of industries assessed) by using a combination of weights at different levels. The combined weight consists of the reported onsite sample quantity, the motor facility-to-site weight, and the site-to-national weight. An adjustment factor was employed to ensure the final subsector specific electricity consumption aligns with the 2014 Manufacturing Energy Consumption Survey (MECS) (U.S. EIA 2014) and 2012 Commercial Building Energy Consumption Survey (CBECS) (U.S. EIA 2012) estimates. The details of the weighting techniques employed can be found in the Volume 1 report, including Appendix B. With this method, the obtained energy saving estimates for each sample motor system can be multiplied by the corresponding combined weights and summed to the national level to determine the national impact.

Reduction in electricity consumption from motors in the scope of MSMA are expressed as gigawatt-hours (GWh) and can be used to estimate the resulting operating cost savings and CO_2 reduction by applying U.S. Energy Information Administration (EIA) cost information and U.S. Environmental Protection Agency (EPA) CO_2 multipliers, respectively. In the following subsections, the regional electricity price and the method employed to quantify the CO_2 emission reduction are described.

Electricity Prices

For each installed motor system physically sampled, the marginal electricity price was assigned for the census division in which the motor system was located. The marginal electricity price better captures the incremental cost savings associated with the change in energy use resulting from an energy saving action rather than average electricity prices. However, the average electricity price can be used to estimate the current costs associated with operation of the motor system.

In this analysis, the marginal electricity prices were applied to the incremental change in electricity consumption associated with the energy saving measures considered to determine the cost savings. The annual electricity prices in 2020 were derived for each census division using data from the latest Edison Electric Institute (EEI) Typical Bills and Average Rates reports (EEI 2020a, 2020b). The resulting evaluation of the cost savings potential is more accurate because it accounts for regional variability in electricity costs.

For both the industrial and commercial sectors, the electricity prices were calculated using the methodology described in Coughlin and Beraki (2019). The EEI data were used to estimate both marginal energy charges and marginal demand charges. Each EEI utility in a region was assigned a weight based on the number of consumers it serves in a specific sector.

Table 1 and Table 2 show the 2020 average and marginal electricity prices for each geographic area by sector.

Table 1: Average and Marginal industrial electricity prices in 2020

	Geographic Area	**Average 2020$/kWh**	**Marginal 2020$/kWh**
1	New England Census Division	0.148	0.145
2	Middle Atlantic Census Division	0.057	0.049
3	East North Central Census Division	0.082	0.082
4	West North Central Census Division	0.090	0.091
5	South Atlantic Census Division	0.089	0.087
6	East South Central Census Division	0.074	0.074
7	West South Central Census Division	0.068	0.070
8	Mountain Census Division	0.085	0.077
9	Pacific Census Division	0.115	0.106

Table 2: Average and Marginal commercial electricity price in 2020

	Geographic Area	Average 2020$/kWh	Marginal 2020$/kWh
1	New England Census Division	0.182	0.185
2	Middle Atlantic Census Division	0.132	0.136
3	East North Central Census Division	0.111	0.110
4	West North Central Census Division	0.105	0.110
5	South Atlantic Census Division	0.110	0.118
6	East South Central Census Division	0.131	0.145
7	West South Central Census Division	0.097	0.098
8	Mountain Census Division	0.113	0.120
9	Pacific Census Division	0.167	0.177

Weighted national marginal electricity prices were derived based on the geographic distribution of the motor population. The resulting marginal industrial electricity price is $0.084/kWh, and the marginal commercial electricity price is $0.135/kWh. These values were used to estimate cost savings in this report.

The national average industrial and commercial prices were developed using a similar method. The resulting prices used in this report are $0.086/kWh and $0.13/kWh for the industrial and commercial sectors, respectively. The average prices are used when presenting current motor system operating costs.

CO_2 Emission Calculation

The CO_2 emission reductions were evaluated from the reduced electricity consumption of the assessed motor installed base, as shown in equation 1. Site CO_2 emissions were estimated using an emission intensity factor published by the EPA (U.S. EPA 2019) based on a marginal analysis. Note that the estimated CO_2 emission reduction includes the line losses related to electricity transmission.

$$Mt_{CO_2} = elec_{MSMA} \times CO_{2_{kWh}}$$

(Equation 1)

Where:

Mt_{CO_2} = CO_2 emission reduction, metric tons

$elec_{MSMA}$ = electricity consumption savings from annual motor operations, kWh

$CO_{2_{kWh}}$ = 7.09×10^{-4} metric tons of CO_2 per kWh

Payback Period Analysis

The *payback period* (PBP) refers to the time it takes a consumer/business owner to recover the implementation cost for a measure through the resulting cost savings. It is calculated as shown in equation 2.

$$PBP = \frac{\Delta\ Installed\ Cost}{\Delta\ Annual\ Operating\ Cost}$$

(Equation 2)

Where:

PBP = payback period, year

$\Delta\ Installed\ Cost$ = the cost of measures taken to improve the current motor efficiency

$\Delta\ Annual\ Operating\ Cost$ = difference in annual average operating cost between the two scenarios (before and after implementation of measures to improve the current motor efficiency)

The cost-effectiveness of measures taken or adopted to improve the motor energy efficiency was determined at a subsector basis by aggregating the minimum payback period defined by each site sample in the MSMA survey (weighted by the site to the national weight).

The payback period is expressed in years. Based on the equipment cost (labor costs are not considered) and the operating cost per motor system assessed, if the obtained calculated payback period is less than the minimum payback period acceptable for the facility, then the measure is considered cost-effective for that facility.

Cautions in Interpreting Results

As stated in the Volume 1 report, the estimates obtained in this study were based on a statistical sampling of commercial and industrial facilities. These estimates are associated with uncertainties from different sources, including both sampling errors (equal chance to overstate and to understate the value of interest) and non-sampling errors (systematically overestimate or underestimate the value of interest, which cannot be identified easily). These uncertainties will carry over to the savings estimates presented here. To understand and quantify the uncertainties associated with the MSMA estimates, please refer to Appendix B in the Volume 1 report.

Energy, Cost, and CO_2 Reduction Opportunities

This section shows the opportunity for potential energy, cost, and CO_2 savings associated with implementation of motor system energy efficiency measures and advanced technologies. The following opportunities are analyzed:

- Early Replacement with Premium Efficiency Motors
  - Premium Efficiency Motors
  - Cost Effective Early Replacement with Premium Efficiency
- Improved Load Control/Matching with Conventional Technologies
  - Implementation of Variable Frequency Drives on Variably Underloaded Motor Systems
  - Cost Effective Implementation of Variable Frequency Drives
  - Right Sizing Motors in Constant Underloaded Motor Systems
- Adoption of Advanced Technologies
  - Constant Load Systems
  - Variable Load Systems
- Improved Conditions of Distribution Systems
- Rewind Losses
- V-belts to Cog Belts

Early Motor Replacement with Premium Efficiency Motors

Regulations require that the majority of 1–500 hp motors sold in the U.S. must meet Premium Efficiency performance levels. These levels are defined based on NEMA MG1 Table 12-12; for more information on Premium Efficiency motors, see the DOE's *Premium Efficiency Motor Selection and Application Guide* (McCoy and Douglass, 2014). While some motors are exempt from this regulation, most motors surveyed for the Volume 1 report, if bought new today, would be required to meet Premium Efficiency performance levels.

Compared to the energy efficiency of the current installed motor base, Premium Efficiency performance levels exceed current energy efficiency levels at each horsepower range. The current motor efficiency of the industrial and commercial base by size range is compared to the efficiency levels of Premium Efficiency in Table 3.

Table 3: Energy efficiency of the installed base compared to the Premium Efficiency performance level by horsepower range. Premium Efficiency levels are for 4-pole, open enclosure motors.

Motor Size Bin	Average Efficiency of Industrial Installed Base (%)	Average Efficiency of Commercial Installed Base (%)	Premium Efficiency Performance Level (%)
[1.0, 6.0)	83	82	86.4–90.1
[6.0, 21.0)	89	89	89.2–93.1
[21.0, 51.0)	92	91	92–94.7
[51.0, 101.0)	93	92	94.1–95.9

Motor Size Bin	Average Efficiency of Industrial Installed Base (%)	Average Efficiency of Commercial Installed Base (%)	Premium Efficiency Performance Level (%)
[101.0, 201.0)	93	93	94.5–96.2
[201.0, 501.0)	93	94	94.5–96.2
[501.0, 1,001.0)	93	94	-
[1,001.0, 2,001.0)	92	95	-
[2,001.0, 5,001.0)	86	95	-
[5,001.0, inf)	91	N/A	-

While US regulations generally disallow new inefficient general-purpose motors (1-500 hp) from being sold, and several high efficiency motor technologies have emerged and are commercially available (as will be discussed later in this report), Premium Efficiency motors normally only replace inefficient motors as they fail. As shown in Figure 2, about 10% of industrial and commercial motors are older than 20 years. Further, the age of a large percentage of industrial and commercial motors was undeterminable. The inability to identify the age of the motor can be attributed to many reasons, including illegible nameplates due to wear or some other age-induced reason. In some instances, installation of the motor preceded the employment of staff at the facility that could identify the motor's vintage.

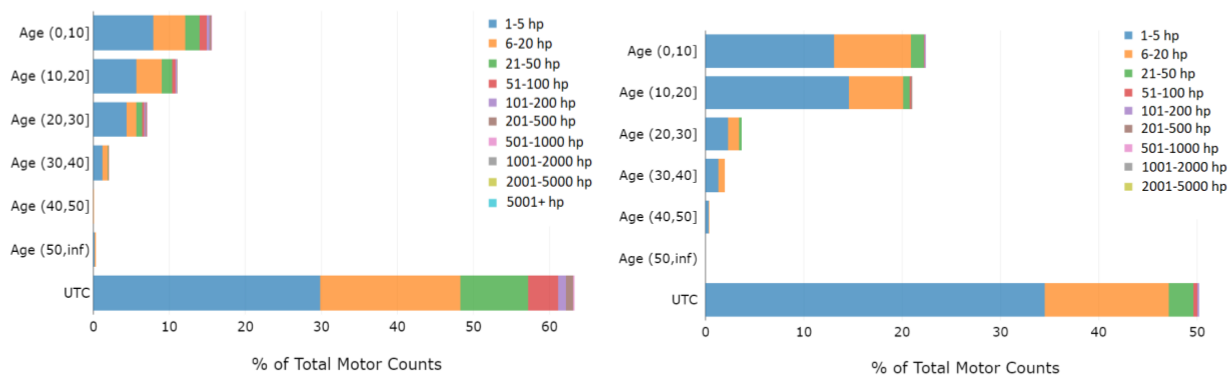


Figure 2: Age of installed motor base for industrial (left) and commercial (right) motors from the Volume 1 report. UTC stands for "unable to collect."

This section evaluates energy, CO_2 emissions, and operating cost savings associated with replacing lesser efficiency motors with Premium Efficiency AC motors.

Premium efficiency motors

The energy efficiency level for Premium Efficiency motors was taken from NEMA MG-1 Table 12-12. The average energy efficiency level for each horsepower size across poles and enclosure types was used to determine the energy savings associated with replacing motors with their Premium Efficiency counterpart. When a motor size in the MSMA inventory fell between two motor sizes on NEMA MG-1 Table 12-12, the Premium Energy performance level was interpolated using the two nearest sizes.

Energy savings associated with early retirement and upgrading motors were calculated using equation 3.

$$Energy\ Savings = current\ electricity\ consumption\ \times (1 - \frac{\eta_{current}}{\eta_{replacement}})$$

(Equation 3)

Where:

Current electricity consumption = electricity consumption for the motor systems as estimated in the Volume 1 report

$\eta_{current}$ = energy efficiency of current motor
$\eta_{replacement}$ = energy efficiency of replacement motor

Table 4 shows the energy savings for upgrading the existing installed motor base to Premium Efficiency motors. Upgrading to Premium Efficiency motors would result in a 2.8% reduction in industrial motor system energy consumption and CO_2 emissions, corresponding to over 15,000 GWh/yr and over $1.3 billion in electricity cost savings. In the commercial sector, upgrading to Premium Efficiency motors would result in a 3.2% reduction in energy consumption and CO_2 emissions, corresponding to nearly 17,000 GWh/yr and $2.3 billion/yr in energy and cost savings. Any efficiency impacts from Premium Efficiency motors having lower slip, resulting in slightly higher speed compared to standard motors, is not accounted for, but for most systems, including those with VFDs, there would be no impact.

Table 4: Energy savings associated with upgrading existing motors to Premium Efficiency motors

	Energy Savings (GWh/yr)	CO_2 Savings (MMT/yr)	% Motor System Energy and/or CO_2 Savings	Cost Savings (million $/yr)
Industrial	15,571	11.0	2.8	1,314
Commercial	16,877	12.0	3.2	2,278
Total	32,448	23.0	3.0	3,592

Exploring the energy savings further, Figure 3 and Figure 4 break down the energy savings by size range for the industrial and commercial sectors, respectively. The resulting energy savings are influenced by two factors: (1) the electricity consumption of the installed base within the size range, and (2) the specific energy efficiency improvement for the size. The greatest savings opportunity in the industrial sector is for 201–501 hp and 21–50 hp motors, with the 6–21 hp and 51–101 hp range also having a considerable opportunity. In the commercial sector, the greatest savings opportunity is for motors in the 6–21 hp range, with the 1–6 hp and 21–50 hp range showing significant savings. Also shown is a theoretical minimum energy consumption achieved from increasing motor efficiency to 100% (meaning no energy losses across the motor). This value is unattainable, as eliminating all energy losses, like stray or thermal losses, will require materials that do not exist. However, the comparison to the minimum energy consumption shows the progress made with Premium Efficiency motors towards eliminating all energy losses.

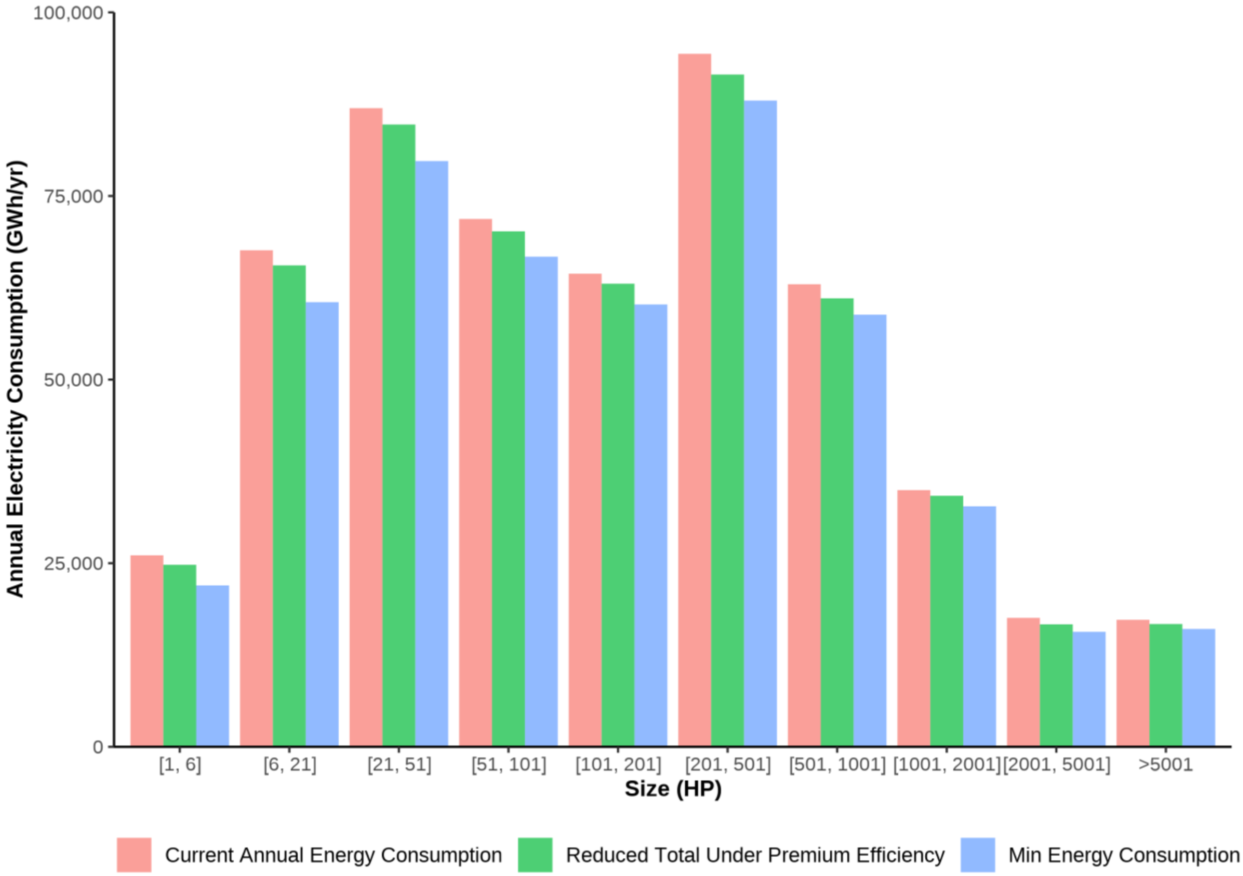


Figure 3: Comparison of current annual energy consumption with energy consumption achieved by replacing less efficient motors with Premium Efficiency motors and the minimum motor system energy consumption requirement in the industrial sector, by size range.

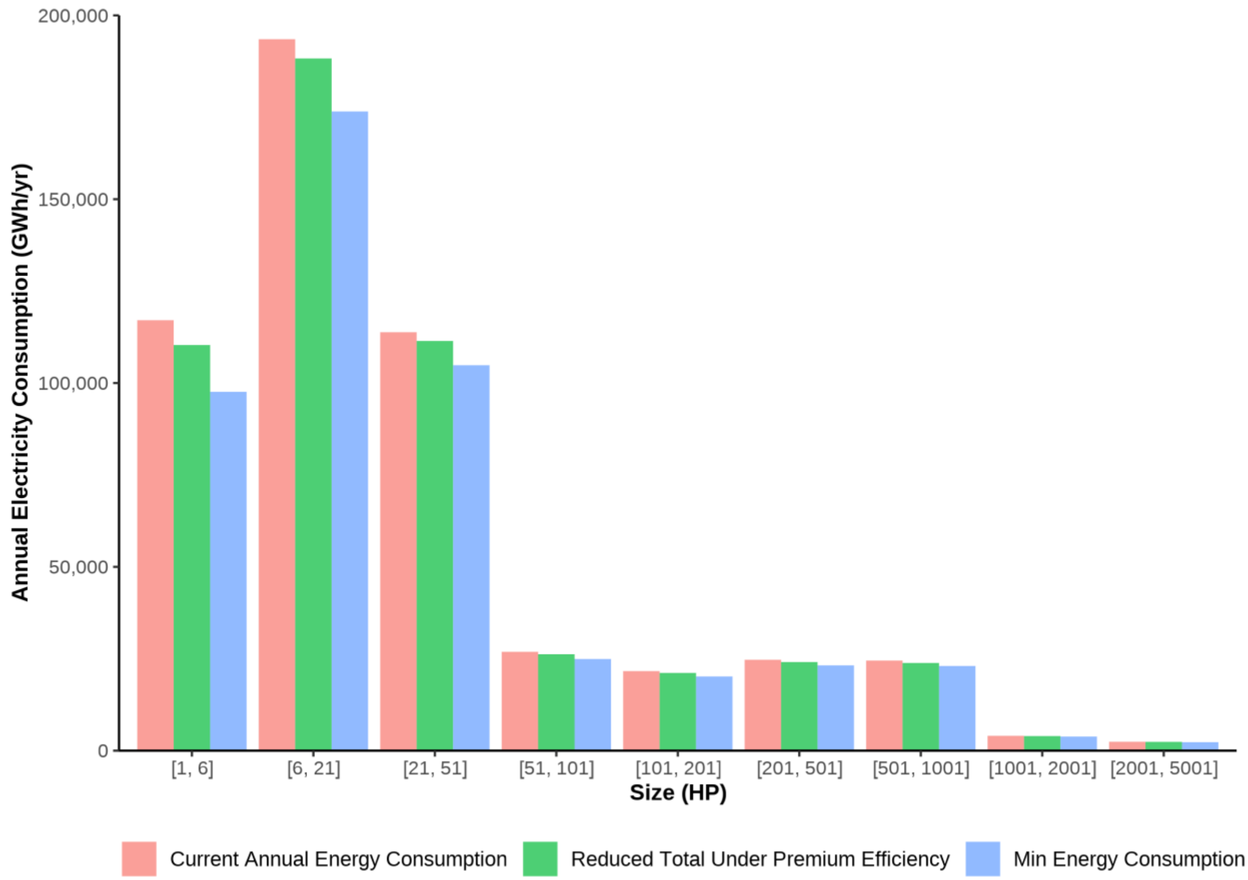
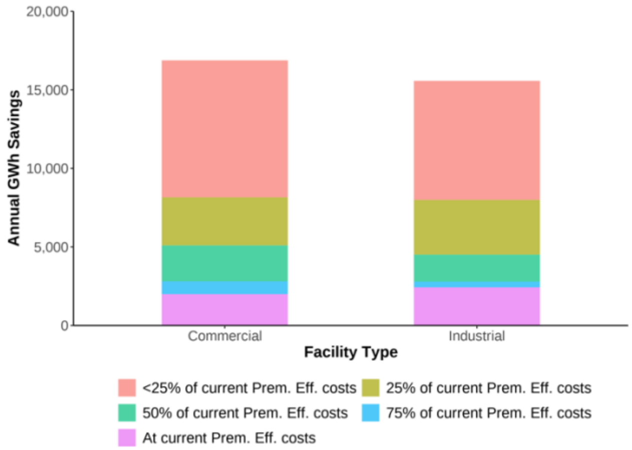


Figure 4: Comparison of current annual energy consumption with energy consumption achieved by replacing less efficient motors with Premium Efficiency motors and the minimum motor system energy consumption requirement in the commercial sector, by size range.

Cost-effective early replacement

The cost-effectiveness of replacing the installed base of motors with Premium Efficiency motors wherever a current motor's energy efficiency is below Premium Efficiency levels was evaluated. As part of the motor system assessments conducted for this study, facilities were asked for their required simple economic payback for capital projects. This value was used for each facility assessed in conjunction with the national average industrial and commercial marginal electricity to determine whether upgrading to a Premium Efficiency motor was cost-effective. To understand the extent to which cost reductions to Premium Efficiency motors would realize additional cost-effective savings (based on the cost effectiveness defined by the Payback Period Analysis detailed in the Methods section), the cost of Premium Efficiency motors (as determined using RS Means) was reduced to 75%, 50%, 25%, and < 25% of current costs. Note that Premium Efficiency motors can cause a higher inrush current compared to older, less efficient motors, so in some cases breakers need to be resized, or a higher wire size is required, but those costs are not included in this analysis. The results are shown in Figure 5.



	Industrial (GWh/yr savings)	Commercial (GWh/yr savings)
Current Prem Eff cost	2,430	1,997
75% of current Prem Eff cost	2,795	2,812
50% of current Prem Eff cost	4,511	5,098
25% of current Prem Eff cost	7,999	8,158
<25% of current Prem Eff costs*	15,571	16,877

*Additional savings associated with reducing the cost of a Premium Efficiency motor to a negligible value

Figure 5: Cost-effectiveness of replacing existing motors with Premium Efficiency motors where the energy efficiency of the current motor is below the Premium Efficiency level. Savings in a given row include those from the rows above.

At current costs, only 16% (2,430 GWh/yr) of the total industrial sector energy savings potential (15,571 GWh/yr) and 12% (1,997 GWh/yr) of the total commercial sector (16,877 GWh/yr) associated with upgrading to Premium Efficiency motors is cost-effective. Reducing costs to 75% of current costs would only achieve an additional 2% and 5% of the potential in the industrial and commercial sectors, respectively. However, achieving 50% cost reductions would realize an additional 11% and 14% of Premium Efficiency savings for the industrial and commercial sectors, respectively.

Summary

In the industrial sector, replacing lesser energy-efficient motors with their Premium Efficiency counterpart would lead to 15,571 GWh of electricity savings, corresponding to $1.3 billion in cost savings and 11 MMT CO_2 reduction annually. Sixteen percent of these savings are cost-effective at current costs.

In the commercial sector, replacing lesser energy efficient motors with Premium Efficiency motors would lead to 16,877 GWh of electricity, 12 MMT of CO_2, and $2.3 billion of electricity cost reductions. At current costs, 12% of these savings are cost-effective.

Substantial incentives to lower the costs of Premium Efficiency motor technologies are needed to make early retirement of motors cost-effective. In the industrial sector, reducing costs to 25% of current costs would make approximately 57% of the technical potential energy savings cost-effective. In the commercial sector, reducing costs to well below 25% of current costs is needed to make 50% of the technical potential energy savings cost-effective.

Improved Load Control/Matching with Conventional Technologies

Motor systems experience significant energy losses at low load factors if not controlled properly. This is particularly true for fluid systems (e.g., pump, fan/blower, compressed air). In this report, the load factor of the motor system is defined as the ratio of the operating output power to the full load output power. When operating at low load factors (demarcated in this report at 40%), the energy efficiency of the motor system will be much lower than the best efficiency point of the system.

Two factors contribute to the lower efficiency at lower loads: (1) the physical relationship between energy consumption and load and (2) the energy efficiency of the motor itself at low loads. For fluid systems, such as pumps, fans, and air or refrigeration compressors, the energy required to impart more power to the fluid theoretically scales with the third power of the flow rate. This relationship is due to the affinity laws for fluid systems. For example, reducing the flow rate of a pumping system in half theoretically should only require one-eighth of the rated input power at full load. However, control systems such as VFDs or a downsized motor are required to achieve the lower energy requirements. Unfortunately, many motor systems use throttles, dampers, or bypasses to dissipate the additional fluid power to achieve the lower system requirements. Additionally, the energy efficiency of the motor begins to decline dramatically at loads lower than 40%. For example, the energy efficiency of a 100 hp motor may hover around 95% for load factors greater than 50% but drops to 78% at a load factor of 10%. For more information on part-load energy efficiency of motor systems, see *Continuous Energy Improvement in Motor Driven Systems* and *Motor System Tip Sheet # 11: Adjustable Speed Drive Part-Load Efficiency* available on the DOE Advanced Manufacturing Office's website.

The Volume 1 report revealed that many motor systems operate at loads below design conditions (see Figure 6). Fourteen percent of industrial motor system energy consumption operates at constant load factors below 0.75, and 45% operate at variable load factors. Similarly, 10% of commercial motor system energy consumption operates at constant load factors lower than 0.75, and 60% operate at variable load factors.

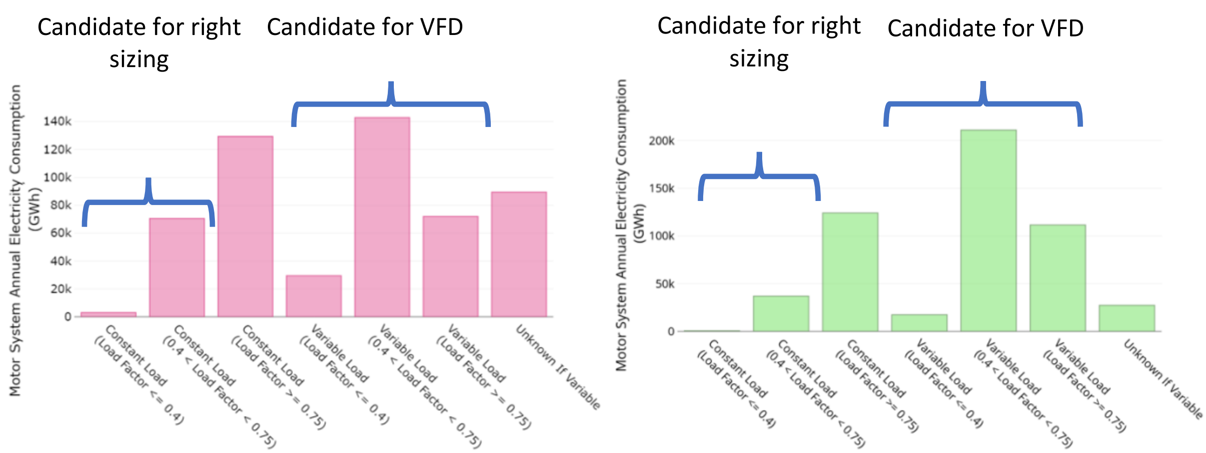


Figure 6: Motor system energy consumption by load factor for industrial (left) and commercial (right) motor systems from the Volume 1 report

Motor systems operating at variable load factors are good candidates for adding a VFD. Motor systems operating at constant and low load factors are good candidates for reducing the size of the motor to be commensurate with the system requirements. In this section, energy, CO_2 emissions, and cost savings associated with installing VFDs or downsizing the motor where appropriate for the installed motor system base are evaluated. In the next section (Adoption of

Advanced Technologies), savings associated with adopting advanced motor technologies to better control and size motors in accordance with their loads are estimated.

Implementation of variable frequency drives on variably underloaded motor systems

When applied properly, VFDs can deliver substantial energy savings to underloaded fluid-power motor systems. A VFD is a type of motor speed controller that changes the frequency of the electric current or voltage from 60 hertz to one better aligned with the needs of the system. Changing the frequency of the electric signal will change the rotational speed of the motor, which in turn allows the motor output to match the system requirements efficiently.

Per the findings from the Volume 1 report, only 16% of industrial sector motor systems and 4% of commercial sector motor systems are under the control of a VFD. To understand the technical potential energy savings, it is important to note that all variably loaded pump, fan, air compressor, and refrigeration compressor motor systems that are not positive-displacement would realize energy savings from installation of a VFD. The following motor systems were not considered candidates for achieving energy savings through installation of a VFD: any constant load system, reciprocating air/refrigeration compressors, air compressors of an unknown type, positive displacement blowers, fans of an unknown type, unknown driven equipment types, materials processing motor systems, materials handling motor systems, positive displacement pumps, pumps of an unknown type, and systems that already have VFDs.

The relationship used to determine the energy savings from implementation of a VFD is shown in equation 4.

$$Energy\ Savings =\ Current\ Electricity\ Consumption \times \left(1 - \frac{LF^x}{\eta_{VFD}}\right)$$

(Equation 4)

Where:

Current electricity consumption = electricity consumption for the motor systems as estimated in the Volume 1 report

LF = load factor

x = practical relationship for affinity laws: 1 for air/refrigeration compressors; 2.1 for pump and fan systems (PG&E and Consortium for Energy Efficiency, 2011; Vaillencourt, 2005; Engineered Systems, 2004)

η_{VFD} = efficiency of VFD; taken to be 97%

In equation 4 a relationship of 2.1 is used for the exponential relationship between load factor and energy savings rather than the theoretical 3. The theoretical value of 3 is rarely, if ever, achieved in practical applications. The theoretical value is for systems with no static losses and only frictional losses. Using 2.1 accommodates for the variability in static losses from system to system and leads a conservative estimate of the energy savings potential. Using equation 4, the technical potential energy, CO_2 emissions, and cost savings attributable to installation of VFDs are shown in Table 5. VFDs could save 44,355 GWh annually in the industrial sector, representing 8% of the sector's overall electricity consumption for motor systems. Using marginal electricity rates, this corresponds to a cost savings of $3.7 billion/yr. Similarly, VFDs could save 68,461 GWh annually in the commercial sector, representing 13% of the sector's overall electricity consumption for motor systems. Using marginal electricity rates, this corresponds to a cost savings of $9.2 billion/yr.

Table 5: Energy, CO_2 emissions, and costs savings technical potential associated with the implementation of VFDs on variable and underloaded motor systems in the industrial and commercial sectors

	Motor System Energy Consumption (GWh/yr)	Energy Savings from VFDs (GWh/yr)	CO_2 Reduction from VFDs (MMT/yr)	Motor System Energy/CO_2 % Reduction from VFDs	Energy Cost Savings from VFDs (million $/yr)
Industrial	546,963	44,355	31.4	8	3,743
Commercial	532,024	68,461	48.5	13	9,241
Total	1,078,987	112,816	80.0	11	12,984

Cost-effective implementation of variable frequency drives

Given the sizeable technical potential energy savings, an economic analysis was performed to understand the cost-effective energy savings potential from installation of VFDs. During the motor system assessments conducted for this project, facilities were asked to provide the simple financial payback they seek on energy-saving projects. Using this value and estimates for the current cost of VFDs, the energy savings potential was determined based on the current cost of VFDs and scenarios where VFD costs dropped to 75%, 50%, 25%, and < 25% of current costs. The results are shown in Figure 7, and the accompanying underlying estimates are shown in Table 6. In the industrial sector, 74% of the technical potential is cost-effective at current VFD costs. In the commercial sector, 45% of the technical potential is cost-effective at current VFD costs. However, if costs dropped by 25% (to 75% of current levels), then 56% of the technical potential would be cost-effective.

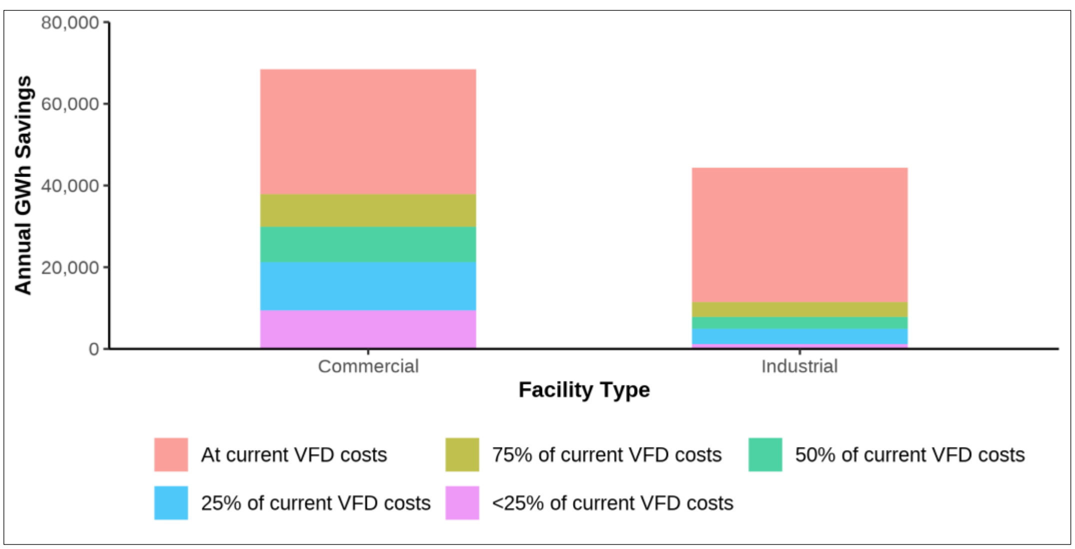


Figure 7: Cost-effective energy savings from installation of VFDs at current, 75%, 50%, 25%, and <25% of current costs for the industrial and commercial sectors

Table 6: Cost-effective energy savings from installation of VFDs at current, 75%, 50%, 25%, and <25% of current costs for the industrial and commercial sectors. Savings in a given row include those from the rows above

	Industrial (GWh/yr savings)	Commercial (GWh/yr savings)
At current VFD cost	32,895	30,595
75% of current VFD cost	36,541	38,562
50% of current VFD cost	39,431	47,236
25% of current VFD cost	43,175	59,046
<25% of current VFD cost*	44,355	68,461

*Additional savings associated with reducing the cost of the VFD to a negligible value

A deeper investigation into the cost-effectiveness of VFDs reveals that the majority of motor systems greater than 5 hp would realize cost-effective energy savings at current VFD costs, whereas VFD costs would have to be reduced substantially to achieve most of the technical energy savings potential for smaller motor systems (less than or equal to 5 hp; see Figure 8). Given that larger motor systems will tend to consume more electricity for a given number of operating hours than a smaller motor system and VFD cost per horsepower reduces as the size increases, this result is expected. It would also explain the low cost-effective potential for commercial motor systems overall, as 22% of all commercial motor system energy consumption is for systems under 5 hp.

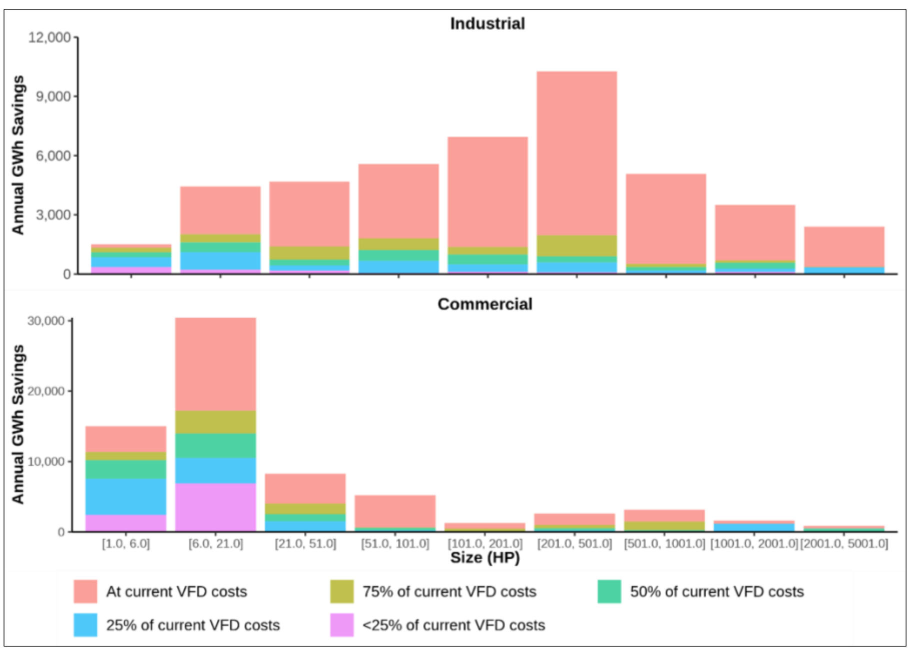


Figure 8: Cost-effective installation of VFDs under current costs, 75%, 50%, 25%, and <25% of current costs disaggregated by size range

Non-energy savings benefits of VFDs

While this report has focused on energy savings from installation of VFDs on underloaded motor systems, there are several benefits of VFDs that have not been explored here. Further, there have been several advancements in VFDs that have extended their range of function, applicability, and benefits. Some of these benefits and advances are outlined below.

The advancement of wide bandgap (WBG) materials and their integration into VFDs have the potential to reduce energy losses and increase the size range of VFDs. The DOE estimates that WBG drives could reduce electricity consumption by 2%–4%, with potential applicability in chemical and petroleum refining, the natural gas infrastructure, and general industrial compressor applications like heating, ventilation, and air conditioning (HVAC) systems; refrigeration; and wastewater pumps (U.S. DOE, 2015). Semiconductors are materials that can allow electricity to flow more readily than insulators but less readily than conductors. This property makes semiconductors extremely useful for fabricating power electronic chips that control and convert electrical power (i.e., adjust the voltage, current, and frequency as required by various types of equipment and applications). A *bandgap* is a term used for the amount of energy needed to release electrons in semiconductor materials so the electrons can move freely, enabling the flow of electricity (Power America, 2014). WBG semiconductors have bandgaps significantly greater than those of silicon semiconductors. Electrical current applied to WBG semiconductors will excite fewer electrons across the gap, enabling superior current control and reducing energy losses. This means 90% of power losses that currently occur during AC to DC and DC to AC electricity conversion is eliminated with WBG semiconductor powered VFDs (U.S. DOE, 2013). They also can operate at higher temperatures (300°C versus 150°C), higher frequencies (10 times), and higher voltages (10 times) than the silicon-based technology. Their greater thermal tolerance reduces the need for bulky insulation and additional cooling equipment; hence, their compact design and greater power density compared to silicon-based VFDs. Commonly used WBG components are gallium nitride (GaN) and silicon carbide (SiC). Other advantages include improved durability, reliability, and compatibility with high speed, megawatt-class motors. See the Volume 2 report to learn more about WBG drives, including a review of their supply chains.

Properly installed motors designed for inverter duty reduce wear and overheating of motors. Motors equipped with VFDs start slowly by ratcheting up the voltage (such as a soft starter), resulting in less mechanical wear and potential overheating of the motor systems. In contrast, motors without VFDs start with full line voltage, as well as 7 to 8 times the full load amps to start, generating heat in the motor windings.

All VFDs will also improve a motor's power factor. Full-wave diode bridge rectifiers in low voltage VFDs draw current at the peak of the voltage wave that results in a power factor of at least 0.95. Higher current VFD units typically come with built-in capacitors that monitor the power factor fluctuation.

VFDs also can lessen the impact on equipment due to fault-induced delayed voltage recovery (FIDVR). *FIDVR* refers to the unexpected delay in the recovery of voltage to its nominal value following normal clearing of an electric grid fault (Lawrence Berkeley National Laboratory, 2019). The voltages in the sub-transmission and distribution parts of a power system do not recover promptly to pre-event levels when the system removes the cause of a depression of voltages (normally an electrical fault). This is mostly due to a transmission, sub-transmission, or distribution system fault causing a depression in system voltage for tens of seconds. These delays could lead to cascading failures, subsequently resulting in large blackouts, and are common to utility distribution systems (but less so in bulk transmission systems). VFDs provide an electric buffer for short duration faults by drawing from stored electricity in their DC bus capacitors. Once the fault is cleared and the voltage and current are returned to normal, the previously described soft-start capabilities of VFDs prevent harmful impacts from inrush current.

Right sizing motors in constant underloaded motor systems

This study estimated energy, CO_2 emissions, and cost savings associated with replacing the current motor with a smaller one for systems that operate at constant load factors below 0.75. The energy savings were calculated using equation 5.

$$Energy\ savings = Current\ Energy\ Consumption\ \times (1 - \frac{\eta_{current\ motor\ efficiency}}{\eta_{efficiency\ of\ right-sized\ motor}})$$

(Equation 5)

Where:

Current electricity consumption = electricity consumption for the motor systems as estimated in the Volume 1 report

$\eta_{current\ motor\ efficiency}$ = energy efficiency of current motor
$\eta_{efficiency\ of\ righ-sized\ motor}$ = energy efficiency of replacement motor

The energy efficiency of the current motor operating at its load factor was determined by using part-load energy efficiency tables. The right-sized motor was selected such that it is sized to 75% of the load. This allows for the motor to be able to meet any increases in load without sacrificing energy efficiency. The energy efficiency of the right-sized motor was selected to meet the NEMA Premium Efficiency criteria. Some challenges can occur when installing a smaller motor, such as the need for a new baseplate coupling. In some cases, reducing the size of both the motor and the driven system (pump/fan/compressor) may be a better solution.

The resulting energy, CO_2 emissions, and cost savings are shown in Table 7. The energy savings are split evenly across industrial and commercial motor systems, with approximately 1,172 GWh annual savings for the former and 1,276 GWh annual savings for the latter. Although this only represents 0.2% of industrial and commercial motor system energy consumption, using marginal electricity rates, the resulting cost savings are $98 million and $172 million for industrial and commercial motor systems, respectively.

Table 7: Energy, CO_2, and cost savings associated with right sizing constantly underloaded industrial and commercial motor systems

	Motor System Energy Consumption (GWh/yr)	Energy Savings from Right Sizing (GWh/yr)	CO_2 Reduction from Right Sizing (MMT/yr)	Motor System Energy/CO_2 % Reduction from Right Sizing	Energy Cost Savings from Right Sizing (million $/yr)
Industrial	546,963	1,172	0.8	0.2	99
Commercial	532,024	1,276	0.9	0.2	172
Total	1,078,987	2,448	1.7	0.2	271

Figure 9 shows the energy savings by horsepower size. Largely attributable to the dominance of motors smaller than 51 hp in the commercial sector, 82% of the savings associated with right sizing are attributable to motors less than 51 hp. Similarly, largely attributable to the dominance of motors smaller than 501 hp in the industrial sector, 70% of the savings associated with right sizing are attributable to motors smaller than 501 hp.

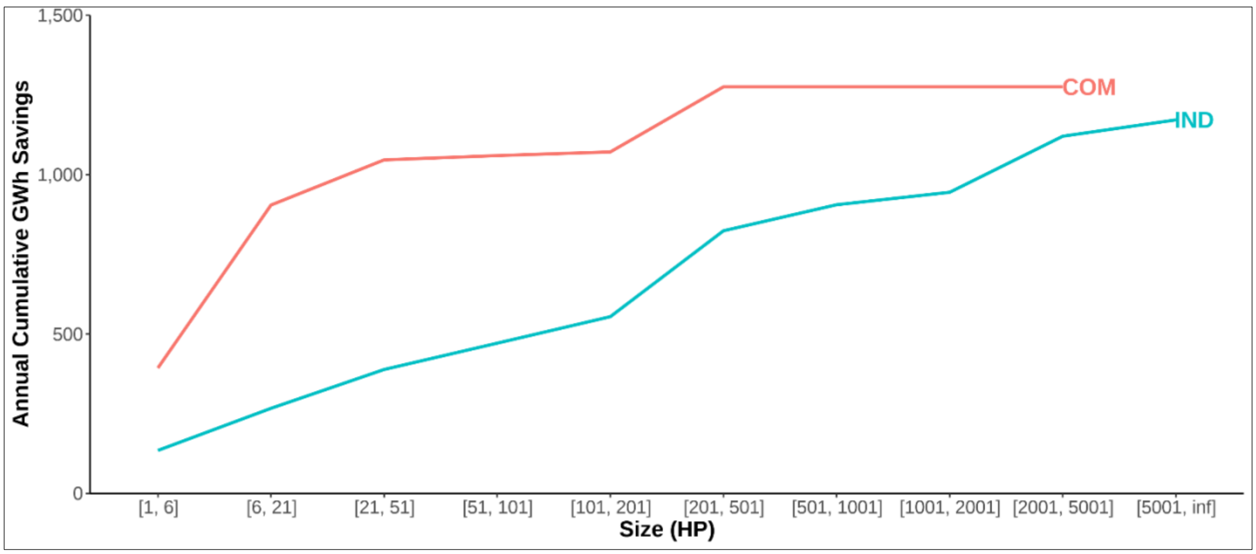


Figure 9: Cumulative annual energy savings associated with right sizing oversized industrial and commercial motor systems by horsepower size range

Summary

Overall, improved load control/matching through installation of VFDs or right-sizing oversized motors using conventional technologies can save more than 115,264 GWh/yr, equating to more than 81 MMT CO_2 and $13 billion per year across the industrial and commercial sectors, as shown in Table 8. Seventy-four percent of the technical potential associated with VFDs in the industrial sector is cost-effective at current costs. In the commercial sector, 45% of the technical potential is cost-effective at current VFD costs. Labor costs are not included in this analysis.

Table 8: Energy, CO_2, and cost savings associated with the installation of VFDs on variably underloaded industrial and commercial motor systems or right sizing constantly underloaded industrial and commercial motor systems

Sector	Motor System Energy Consumption (GWh/yr)	Energy Savings from Improved Load Control/ Matching (GWh/yr)	CO_2 Savings from Improved Load Control/ Matching (MMT/yr)	Motor System Energy/CO_2 % Reduction from Improved Load Control/ Matching	Energy Cost Savings from Improved Load Control/ Matching (million $/yr)
Industrial	546,963	45,527	32.2	8	3,841
Commercial	532,024	69,737	49.4	13	9,413
Total	1,078,987	115,264	81.7	11	13,254

Both are well-known energy efficiency best practices for motor systems. Continuing existing policies, such as utility incentives for VFDs, will continue to increase adoption of VFDs. Other policies or financial assistance that incentivize early replacement of older inefficient motors with Premium Efficiency motors coupled with a VFD can further support achievement of the energy savings opportunity from better load control/matching. In the future, incentives for purchasing entire systems certified as being energy efficient, such as those through the Extended Motor Product Label, will also increase adoption of efficiency motor systems.

Adoption of Advanced Technologies

Where Premium Efficiency sets a performance minimum, advances in motor technologies have led to the availability of motors that can exceed Premium Efficiency performance levels while also delivering the benefits of VFDs. These technologies include Permanent Magnet (PM), Switched Reluctance (SR), Synchronous Reluctance (SynRM), and Permanent Magnet Synchronous Reluctance (PM SynRM). Additionally, Copper Rotor (CR) motors offer efficiency improvements but not the benefits of VFDs. These motor technologies are more efficient than Premium Efficiency motors, particularly at low load factors. Additionally, PM, SynRM, and PM SynRM motors require a controller to operate, thereby making them variable speed capable. SR motors do not need a controller but have inherent load controller capabilities. See the Volume 2 report for more information on these technologies and their performance benefits.

For use in this report, the energy efficiency improvement of the motor (not the entire motor system) above Premium Efficiency for PM, SR, SynRM, PM SynRM, and CR motors was estimated based on extensive literature review. Table 9 shows the nominal full load energy efficiency values. Energy efficiency levels could not be determined for some size ranges of advanced technologies. It was conservatively assumed that the advanced motor technology under consideration is not commercially available in these sizes (as of the writing of this report).

Table 9: Premium Efficiency full load energy efficiency values and additional improvement with Permanent Magnet (PM), Switched Reluctance (SR), Synchronous Reluctance (SynRM), Permanent Magnet Synchronous Reluctance (PM SynRM), and Copper Rotor (CR) motors used in energy savings analysis

		Energy Efficiency Improvement above Premium at Full Load				
Size (hp)	Premium (%)	PM (%)	SR (%)	SynRM (%)	PM SynRM (%)	CR (%)
1–5	86.4–90.1	3.2	3	1.5	1.9	1.5
6–20	89.2–93.1	1.5	2.3	1.2	1.5	1
21–50	92–94.7	1.0	2	0.8	1.1	-
51–100	94.1–95.9	1.0	1	0.7	0.1	-
101–200	94.5–96.2	0.7	1	0.6	0.1	-
201–500	94.5-96.2	0.8	-	0.6	-	-

Figure 10 compares the partial load energy efficiency of PM, SR, SynRM, and PM motors with Premium Efficiency motors, demonstrating the additional benefits at part load for these advanced technologies. Note that Figure 10 only demonstrates the energy efficiency across the motor, however further (and more substantial) energy savings are achieved via the speed reduction in accordance with the partial load.

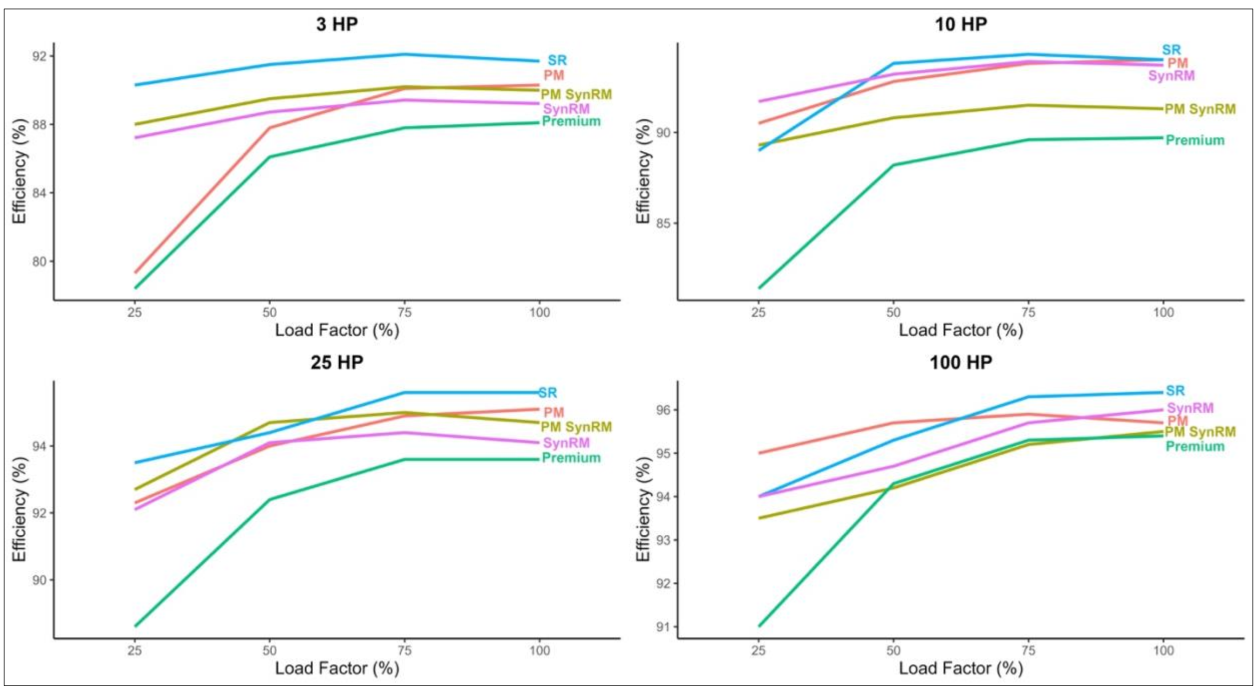


Figure 10: Partial load energy efficiency of Permanent Magnet, Switched Reluctance, Synchronous Reluctance, and Permanent Magnet Synchronous Reluctance motors compared with partial load efficiencies of Premium Efficiency motors

In this section, the energy, CO_2, and cost savings associated with the adoption of advanced motor technologies (PM, SR, SynRM, PM SynRM, and CR motors) is evaluated. Savings are only estimated for the size ranges of the installed stock for which efficiency levels could be determined (see Table 10).

Table 10: HP size ranges for advanced motor technologies considered in analysis

Technology	PM	SR	SynRM	PM SynRM	CR
Constant load - size range evaluated (hp)	1–500	1–200	1–500	1–200	1–20
Variable load - size range evaluated (hp)	1–500	1–200	1–500	1–200	-

The analysis is subdivided into two sections, savings for constant load systems and variable load systems.

Constant load systems

Table 11 shows the energy, CO_2, and cost savings associated with upgrading constant load motors with advanced technologies. The savings are a combination of one-for-one replacement of existing motors that operate at constant loads greater than 75% of full load (using equation 3) and right sizing motors that operate at constant loads less than 75% of full load and replacing them with an appropriately sized advanced motor technology (using equation 5). The improved efficiencies are taken from Table 9. For context, the current energy consumption for industrial and commercial motor systems operating at constant loads greater than 75% of full load is 117,472 GWh and 118,579 GWh, respectively. The current energy consumption for industrial and commercial motor systems operating at constant loads less than 75% of full load is 25,942 GWh and 37,547 GWh, respectively.

Table 11: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
≥75%	**Energy Savings (GWh/yr)**	4,940	5,013	4,492	4,097	2,040
	CO_2 Emissions (MMT/yr)	3.50	3.55	3.18	2.90	1.45
	Cost Savings ($M/yr)	415	423	377	346	173
<75% w/ right sizing	**Energy Savings (GWh/yr)**	1,259	1,038	1,158	842	390
	CO_2 Emissions (MMT/yr)	0.89	0.74	0.82	0.60	0.28
	Cost Savings ($M/yr)	98	86	89	70	32
		Commercial				
≥75 %	**Energy savings (GWh/yr)**	7,479	7,882	6,398	6,749	5,385

		PM	SR	SynRM	PM SynRM	CR
	CO_2 emissions (MMT/yr)	5.30	5.59	4.54	4.78	3.82
	Cost savings ($M/yr)	1,078	1,131	924	974	780
<75% w/ right sizing	**Energy Savings (GWh/yr)**	2,366	2,353	2,105	2,012	1,619
	CO_2 emissions (MMT/yr)	1.68	1.67	1.49	1.43	1.15
	Cost savings ($M/yr)	335	334	299	287	235

Note: Savings are for motor systems within the size ranges shown in Table 10.

Owing to its availability across the largest size range of advanced motor technologies analyzed and its greater improvement over all other motor technologies in the 1-5 hp size range, PM motors offer the largest savings opportunity for constant load systems in both the industrial and commercial sectors.

Variable load systems

The energy, CO_2, and cost savings associated with improved load control using an advanced motor technology with a VFD was determined for PM, SR, SynRM, and PM SynRM motors. Since CR motors do not require a VFD to operate and therefore do not naturally realize energy savings in variable load systems (unless a VFD is selected for the purpose of load control), they are not considered in this analysis. All motor systems operating at variable load were included, with the following exceptions: any constant load system, reciprocating air/refrigeration compressors, air compressors of an unknown type, positive displacement blowers, fans of an unknown type, unknown driven equipment types, materials processing motor systems, materials handling motor systems, positive displacement pumps, and pumps of an unknown type.

Some of the variable load systems may or may not already be fitted with a VFD. For PM, SynRM, and PM SynRM systems already on a VFD, analyses were performed to determine the energy savings associated with replacing the existing motor with an advanced technology and keeping the existing VFD in place. The savings equation used is shown in equation 6 where $\eta_{Current}$ is the efficiency of the current motor and $\eta_{Advanced}$ is the efficiency of the advanced motor.

$$Energy\ Saving = Current\ Electricity\ Consumption\ x\ \left(1 - \frac{\eta_{Current}}{\eta_{Advanced}}\right)$$

(Equation 6)

Where:

Current electricity consumption = electricity consumption for the motor systems as estimated in the Volume 1 report

$\eta_{current}$ = energy efficiency of current motor

$\eta_{avdanced}$ = energy efficiency of advanced motor

For SR systems, the use of an SR motor negates the need for a VFD. Savings arise from both the improvement of the motor efficiency and the elimination of the losses across the VFD. The savings equation used is shown in equation 7, where η_{VFD} is the efficiency of the VFD that is being removed.

$$Energy\ Saving = Current\ Electricity\ Consumption\ x\ \left(1 - \frac{\eta_{Current} \times \eta_{VFD}}{\eta_{Advanced}}\right)$$

(Equation 7)

The energy efficiency of the advanced motor technology is based on the average load factor and taken from Figure 10.

For variable systems not on a VFD but that can be retrofitted with one, energy savings for PM, SyRM, and PM SynRM were determined using equation 4. For SR systems, equation 4 was used without the η_{VFD}term since SR motors do not need a VFD.

Two savings summaries are presented in Table 12 and Table 13. Table 12 shows the savings associated with applying advanced motor technologies to applicable variable load systems already fitted with a VFD. Table 13 shows the savings associated with applying advanced motor technologies with a VFD to applicable variable load systems that are not already fitted with a VFD. For context, the current energy consumption for variably loaded industrial and commercial motor systems that are already on a VFD or cannot use a VFD is 174,616 GWh and 156,930 GWh, respectively. The current energy consumption for variably loaded industrial and commercial motor systems without a VFD is 53,345 GWh and 154,668 GWh, respectively. Note that the energy consumption values, and the savings presented in Table 12 and Table 13, are only for the motor size ranges shown in Table 10.

Table 12: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded systems that are currently fitted with a VFD or cannot use a VFD

	Industrial			
	PM	**SR**	**SynRM**	**PM SynRM**
Energy Savings (GWh/yr)	4,463	5,296	4,105	3,135
CO_2 Emissions (MMT/yr)	3.16	3.76	2.91	2.22
Cost Savings ($M/yr)	377	457	347	269
	Commercial			
Energy savings (GWh/yr)	4,768	7,999	4,267	4,135
CO_2 emissions (MMT/yr)	3.38	5.67	3.03	2.93
Cost savings ($M/yr)	643	1,080	575	560

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Table 13: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded systems not currently fitted with a VFD

	Industrial				
	Prem. Eff. w/VFD	PM	SR	SynRM	PM SynRM
Energy Savings (GWh/yr)	34,030	34,351	24,712	34,351	23,613
CO_2 Emissions (MMT/yr)		24.36	17.52	24.35	16.74
Cost Savings ($M/yr)		2,898	2,076	2,898	1,983
	Commercial				
Energy savings (GWh/yr)	66,392	67,567	67,693	67,281	64,090
CO_2 emissions (MMT/yr)		47.90	47.99	47.70	45.44
Cost savings ($M/yr)		8,806	8,886	8,770	8,428

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed-capable. For comparison, the savings associated with implementing a Premium Efficiency motor with a VFD is shown. Savings are for motor systems within the size ranges shown in Table 10.

Other benefits of advanced motor technologies

Innovations in materials for motor technologies continue to be made and offer benefits beyond energy savings, with some of these benefits potentially compensating for modest energy savings in certain applications. These innovations and their potential are discussed here.

Improved conductors, such as carbon nanotube (CNT) or superconducting materials, offer better electrical and thermal properties than existing copper and aluminum winding materials. As a result, CNT windings can operate at higher frequencies and exhibit reduced material heating. CNT is also oxidation and corrosion resistant. CNTs will result in fewer failures and need for rewinds because of their high flex fatigue resistance. Additionally, with a much lower weight (1/15 of copper, 1/4 of aluminum) but higher strength, CNT wires could replace heavier and mechanically weaker copper and aluminum windings in the future. However, CNTs have only been proven at the molecular scale, and have not yet operated in laboratory-scale cables (and subsequently, commercial-scale applications) (U.S. DOE, 2018).

Improved insulation materials can mitigate the effects of higher switching frequencies and voltage ramp rates that can accelerate device failure. These materials are produced from polymer tapes under high-pressure processing methods that reduce the incidents of defects. Resistive coatings are applied on both sides of the polymer tape, shielding defects from the fields that lead to partial discharge and device failure. In addition to less failure, energy savings of 5%–10% are predicted for silicon carbide converter-fed motor systems.

High Temperature Superconducting (HTS) motors (>1,000 hp) offer a 50% volume reduction and 60% loss reduction compared to conventional motors of the same rating. These motors are lightweight because these materials can achieve very high flux densities, eliminating the need for additional components and windings. The superconductivity removes/lessens the resistive losses, increases efficiency, and delivers energy savings (Schiferl et al., 2008).

Ultra-efficient and power dense motors combine the line-start capability of induction motors with the energy efficiency of PM motors. The result of these "hybrid" motors is a lighter (30%), smaller in volume (30%), and more efficient motor than Premium Efficiency motors (a 30% reduction in motor losses as compared to Premium Efficiency motors). These motors aim to combine the ease of installation and ease of use attributes of industrial induction motors with the low loss and small size and weight advantages of PM motors (achieved by reducing the amount of active material used). They can be started across the line or operated from a standard drive without the need for a rotor position feedback device. These motors employ a starting cage to the rotor of the PM motor to achieve these benefits. They could be applicable for and replace almost 90% of existing commercial and industrial applications; specifically, a wide range of line-start and variable speed applications with motor ratings from 20–500 hp (Melfi et al., 2013; U.S. DOE, 2011).

Soft magnetic materials, such as Metal Amorphous Nanocomposite materials (MANCs), can withstand higher speeds (higher frequency) without experiencing the same amount of thermal losses as their existing magnetic steel counterparts (such as silicon steels). These materials can be used to produce rotor cores and low energy ferrite magnets instead of rare earth permanent magnets. MANCs have higher resistivity, and therefore, do not heat up as much, resulting in low power loss at high frequencies. This leads to smaller size motors for the same power density or higher power density. Another advantage is that efficient MANCs can enable the usage of relatively lower cost and energy permanent magnets because MANCs act as a soft magnet to begin with (Simizu et al., 2018).

Volume 2 addresses topics such as rare-earth magnets that impact the widespread adoption of advanced motors.

Summary

Where available, advanced motor technologies offer energy, CO_2, and cost saving benefits for most motor systems observed. For constant load systems, they offer improved efficiency for the motor. For variable load systems, they offer improved efficiency and improved load control. A summary of the combined savings potential for constant and variable load systems for each advanced motor technology considered in the report is shown in Table 14.

Table 14: Energy, cost, and CO_2 savings potential from adoption of advanced motor technologies

	Electricity Savings (GWh/yr)	Cost Savings (million$/yr)	CO_2 Savings (MMT/yr)
Permanent Magnet			
Industrial	45,014	3,788	31.91
Commercial	82,180	10,862	58.27
Switched Reluctance			
Industrial	36,059	3,042	25.57

	Electricity Savings (GWh/yr)	Cost Savings (million$/yr)	CO_2 Savings (MMT/yr)
Commercial	85,927	11,484	60.92
Synchronous Reluctance			
Industrial	44,105	3,711	31.27
Commercial	80,051	10,568	56.76
Permanent Magnet Synchronous Reluctance			
Industrial	31,688	2,668	22.47
Commercial	76,985	10,249	54.58
Copper Rotor			
Industrial	2,430	205	1.72
Commercial	7,004	1,015	4.97

Note: See Table 10 for the size ranges considered for each advanced technology type.

PM motors offer the greatest savings benefits across both sectors. In the industrial sector, adoption of PM motors would reduce motor system energy consumption by 8%. In the commercial sector, adoption of PM motors would reduce motor system energy consumption by 15%. Additionally, the non-energy benefits of PM designs, such as higher power density, would be realized. Upgrading to SR motors offers similar but slightly less savings than PM motors across both sectors. However, while these motors are easier to manufacture (see the Volume 2 report), they make significantly more noise than their AC or PM counterparts.

Conditions of Distribution Systems

Distribution systems convey the energized fluid (e.g., compressed air) from the motor driven equipment (e.g., the air compressor) to the load (e.g., a pneumatic actuator). Figure 11 schematically shows the section of the motor system considered to be the distribution system for the purposes of this report.

Figure 11: Position of distribution system within the motor system. The distribution system does not include the controller, motor, transmission, or driven equipment.

The energy efficiency of these distribution systems is often overlooked when designing motor driven systems. Many times, this is unintentional, as the distribution system in a facility predates the current motor driven system utilizing it. As a result, excessive distances, dead ends, unnecessary changes in pipe/duct size, excessive bends or elbows, and other suboptimal configurations are often present. Once designed, maintaining distribution systems to minimize losses can be an arduous task, especially if it is not done systematically. For example, leaks in compressed air lines can occur frequently and lead to substantial energy losses if left unchecked or unrepaired.

When characterizing the installed motor system base, the design and current condition of compressed air, pumping, and fan distribution systems were graded using marks of poor, fair, good, or best practice. Sufficient literature was found and complemented with expert consultation to quantify the potential energy savings associated with improving the current condition of distribution systems. The grade for a distribution system's condition was evaluated through visual inspection and determined based on a grading scale. The definitions for grades were developed by the authors of this report and are summarized in Table 15. Quantifying the energy savings associated with redesigning a distribution system would require in-depth analysis and modeling of the losses in the current system. Further, there was no literature known to the authors that provided a range of possible energy savings/losses associated with poorly designed distribution systems. As a result, quantifying the energy savings associated with improving the design of distribution systems was not considered in this report.

Table 15: Grade used to characterize the condition of motor driven system distribution systems and the energy losses associated with each grade based on literature review and expert consultation

System	Grade	Grade Description	Range of % Energy Loss	Value Used in Analysis (%)
Condition of the pump system distribution	Best practice	No leakage observed; where installed, insulation in excellent condition	≤ 8	8
	Good	Minimal leakage observed; where installed, insulation has been maintained; current maintenance practices appear to be sufficient	8–16 (authors' estimate)	12
	Fair	Leakage observed but not throughout the plant; where installed, insulation often found in need of repair; current maintenance practices could be improved	16–24 (U.S. EPA, 2013)	16
	Poor	Many instances of leakage observed; where installed, insulation in need of repair; no evidence of existing maintenance practices	8–24 water loss as leaks (Farley et al., 2001)	24
Condition of the compressed air distribution	Best practice	No leaks observed; air is free from moisture	0–5 (expert consultation)	5
	Good	Minimal leaks observed; air is mostly dry	10–20 (expert consultation)	15
	Fair	Leaks observed but not throughout the plant; moisture is found in the air, but evidence that air has been dried	30–40 (expert consultation)	35
	Poor	Many instances of leaks observed; no evidence that air has been dried; age observed; where installed, insulation in need of repair; no evidence of existing maintenance practices	60+ (expert consultation)	60
Condition of the fan air distribution system (ducts)	Best practice	No air distribution leakage observed; where installed, insulation in excellent condition	<5	5
	Good	Minimal air distribution leakage observed; where installed, insulation has been maintained; current maintenance practices appear to be sufficient	15 (NREL, 2004)	15
	Fair	Air distribution leakage observed but not throughout the plant; where installed, insulation often found in need of repair; current maintenance practices could be improved	25 (NREL, 2004)	25
	Poor	Many instances of air distribution leakage observed; where installed, insulation in need of repair; no evidence of existing maintenance practices	>40 (NREL, 2004)	40

Using these definitions, grades were assigned to characterize the condition of each distribution system observed. Figure 12 shows the breakdown of grades for industrial and commercial pump, fan, and compressed air distribution systems as reported in the Volume 1 report.

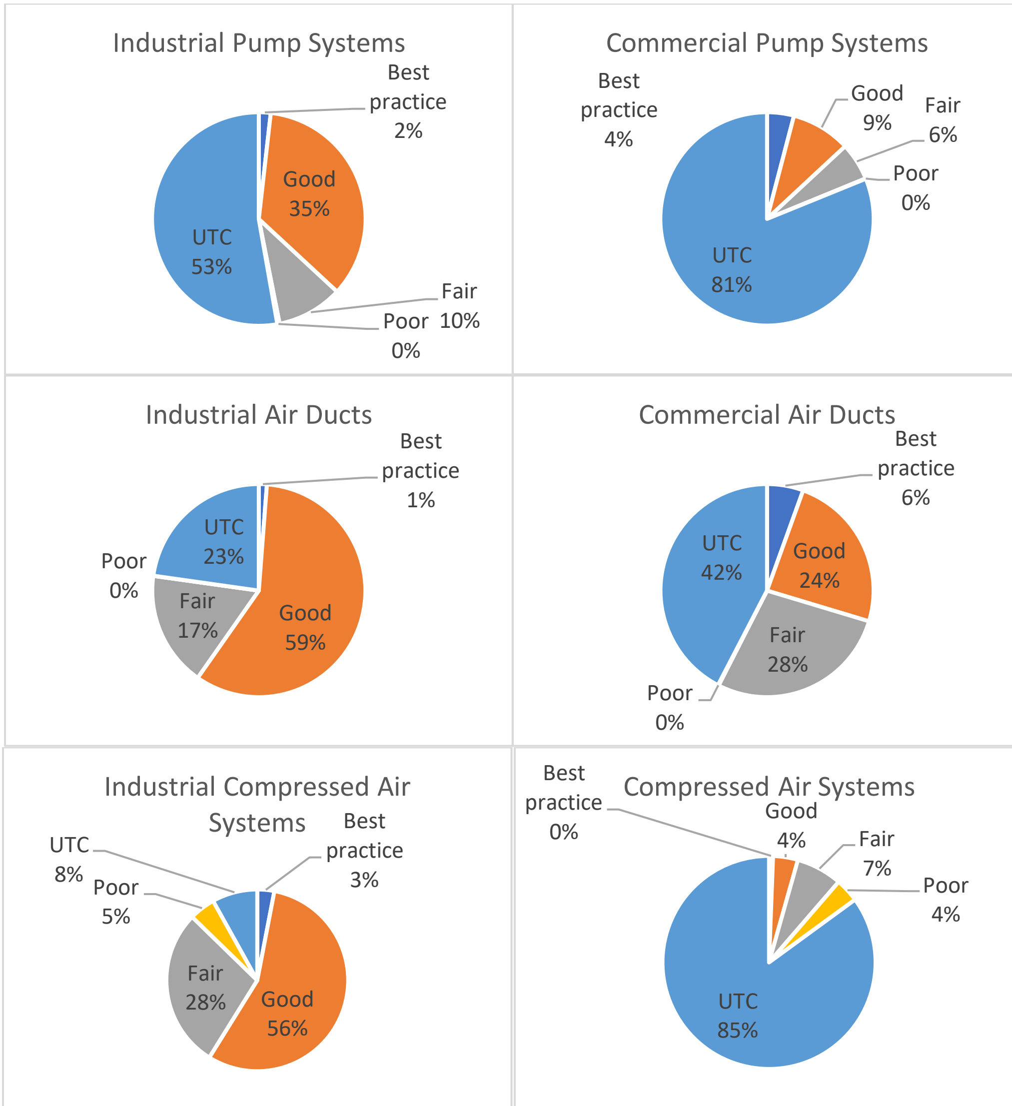


Figure 12: Grades for the condition of industrial and commercial pump, air (air ducts), and compressed air systems. UTC indicates that the grade could not be collected ("unable to collect").

When determinable, the majority of industrial distribution systems were graded as being in "good" condition, with "fair" being the next most common condition. Aside from fan system air ducts, the condition of the majority of the commercial distribution systems were indeterminable for a variety of reasons, such as the distribution system being out of view. For air ducts, the majority of systems were in either fair or good condition. Given the low use of compressed air systems (only 2% of commercial sector motor system energy consumption is for compressed air systems), improvements to the condition of compressed air distribution systems in commercial systems would likely lead to minimal energy savings nationwide.

Improving condition of distribution systems

With the grades evaluated, the energy savings associated with improving the condition of compressed air, pumping, and fan systems from its current state to "best practice," as qualified in Table 15, was estimated. This subsection focuses only on savings from improvements to the distribution system itself. The energy savings are shown in Table 16. In the industrial sector, significant energy savings could be realized from improving compressed air distribution systems. Improving them to a best practice level could reduce compressed air electricity consumption by nearly 17%, equating to 10,751 GWh, 7.6 MMT of CO_2, and $900 million in savings annually. In the commercial sector, significant energy savings could be realized from improving fan system distribution systems. Improving them to a best practice level could result in reducing fan system energy consumption by nearly 8%. This corresponds to savings of 12,935 GWh, 9.2 MMT of CO_2, and more than $1.7 billion annually.

Table 16: The energy, CO_2, and electricity cost savings technical potential for upgrading industrial and commercial distribution systems to a best practice level

	Annual Savings from Upgrading from Current Condition to a Best Practice Level	Industrial	Commercial
Compressed Air Systems	Electricity consumption savings (GWh)	10,751	1,877
	% of current compressed air system electricity consumption	16.9	14.9
	CO_2 emission reduction (MMT)	7.6	1.3
	Electricity cost savings (million $)	907	253
Pump Systems	Electricity consumption savings (GWh)	4,431	1,504
	% of current pump system electricity consumption	3.8	2.8
	CO_2 emission reduction (MMT)	3.1	1.1
	Electricity cost savings (million $)	374	203
Fan Systems (air ducts)	Electricity consumption savings (GWh)	8,959	12,935
	% of current fan system electricity consumption	8.6	6.7
	CO_2 emission reduction (MMT)	6.4	9.2
	Electricity cost savings (million $)	756	1,746
Total	Electricity consumption savings (GWh)	24,141	16,316
	% of current motor system electricity consumption	8.5	6.3
	CO_2 emission reduction (MMT)	17.1	11.6
	Electricity cost savings (million $)	2,037	2,202

Summary

The industrial sector could realize a 4.4% reduction in energy consumption for motor systems, and the commercial sector could realize a 3% reduction in energy consumption for motor systems, if all compressed air, pump, and fan distribution systems (as defined Table 15) were improved from their current state to "best practice" conditions. This would result in more than $2 billion in electricity cost savings in each sector and a reduction of 28.7 MMT of CO_2 across the two sectors (17.1 MMT CO_2 for industry and 11.6 MMT CO_2 for commercial buildings).

It is speculated that far greater savings could be achieved if distribution systems were designed such that energy efficiency was prioritized. Unnecessary bends, dead ends, and expansions/reductions in pipe sizes lead to additional frictional losses that cause the motor driven systems to consume more energy than necessary. In addition to continued guidance on proper maintenance of distribution systems, development of guidance to support energy-efficient design, especially when adding to an existing distribution system, is needed to reduce the significant losses in motor driven distribution systems.

Rewind Losses

Proper maintenance of motor systems is essential for operating a motor at or near design energy efficiencies. The Volume 1 report characterized the maintenance practices for motor systems. It was determined that motor rewinds are far less common than other maintenance practices; 4% of industrial motors and less than 1% of commercial motors were rewound within the previous two years from the date of the assessment. For context, the most common maintenance practice for either sector was belt tightening, with 27% of industrial motors and 18% of commercial motors having undergone the procedure within the previous two years from the date of the assessment.

When done correctly, rewinding motors can lead to minimal performance degradation. However, improper rewinds can degrade motor efficiency, thereby leading to excessive energy losses. From the Volume 1 report, 19% of industrial facilities use an accredited[3] service center at least occasionally when rewinding motors, and <1% of commercial facilities use them at all. Use of an accredited center can ensure energy efficiency is maintained when rewinding a motor. For motors not rewound in accredited service centers, those greater than 40 hp can lose 0.5% of their energy efficiency per rewind, while those less than 40 hp can lose 1% per rewind (McCoy and Douglass, 2014). However, as reported in the Volume 1 report, lowest first cost is the most common criteria when considering options for repairing or replacing a failed motor—not energy consumption. Therefore, facilities are more likely to repair a motor at as low a cost as possible than they are to find an accredited service center or replace it with a new motor. Rewinds for general purpose motors 50 horsepower and below are generally not cost effective, and these motors are generally replaced with new Premium Efficiency motors.

In characterizing the installed base, it was determined that motors were rewound on average 1.4 times. The breakdown of rewind occurrences can be seen in Table 17.

[3] These were either an accredited Electrical Apparatus Service Association (EASA) or Green Motor Practices Group motor service center.

Table 17: Breakdown of number of rewinds for industrial and commercial motors

	# of Rewinds	% of Motors
Industrial	0	82.5
	1	11.6
	2	5.4
	3	0.2
	4	0.1
	5	0.0
	5+	0.2
Commercial	0	97.4
	1	1.8
	2	0.8

Given that most facilities do not use an accredited service center, it can be assumed that the majority of rewound industrial and commercial motor systems experience a degradation in energy efficiency.

Energy losses from improper rewinds

Using the above criteria for efficiency losses and assuming that motors that were rewound were done so on average 1.4 times, the energy losses in the commercial and industrial sectors associated with rewound motors are shown in Table 18.

Table 18: Energy losses associated with improper rewinds of industrial and commercial motors

	GWh/yr Loss	% of Motor System Electricity Consumption	CO_2 Reduction (MMT/yr)	Cost Savings (million $/yr)
Industrial	7,794	1.4	5.5	658
Commercial	7,351	1.4	5.2	992
Total	15,145	1.4	10.7	1,650

Figure 13 shows the energy losses by size. Examining the results, the incremental energy losses for larger motors diminishes, reaching nearly zero for very large motors. In the commercial sector, energy losses diminish for motors greater than 50 hp, whereas in the industrial sector the energy losses diminish for motors greater than 500 hp. This could be due to the lower energy efficiency loss associated with rewinds for larger motors combined with less overall motor system energy consumption in these size ranges. It should be noted that rewinds for smaller motors (i.e., less than 20 hp) are usually not cost-effective and not done.

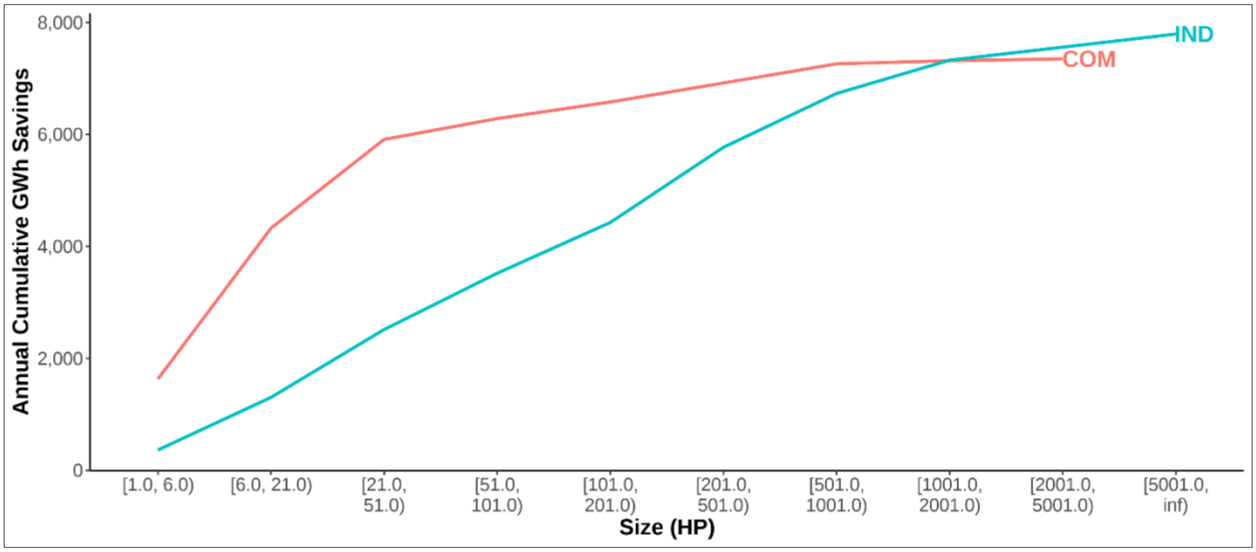


Figure 13: Energy losses associated with motor rewinds by size range in the industrial and commercial sectors

Summary

Although motor rewinds represent a small percentage of motor repairs, improper rewinds can lead to energy efficiency losses. Given that most facilities are not using accredited motor service centers for rewinds, substantial losses in energy efficiency are likely for rewound motors. In the industrial sector, it is estimated that nearly 7,800 GWh/yr are lost due to improper rewinds, correlating to 5.5 MMT of CO_2 and $656 million. In the commercial sector, over 7,350 GWh/yr are lost to improper rewinds, resulting in 5.2 MMT of CO_2 emissions and an additional nearly $1 billion in electricity costs.

Advocating the use of accredited service centers when rewinding motors can mitigate further energy losses. Additionally, promotion of replacing older motors in need of rewind with a Premium Efficiency motor (or advanced technology, such as a Permanent Magnet motor) can not only mitigate the energy losses from rewinds but also achieve higher efficiencies than the nominal nameplate energy efficiency of the existing motor.

V-belts to Cog belts

To transmit the motor shaft work to the motor driven equipment, a coupling may be required. These include belts, gearboxes, and direct shaft couplings. While direct shaft couplings result in minimal to no energy losses, other coupling options do, and the losses can be significant. These losses could be caused by slippage or friction. However, in many cases, it is not possible to directly connect the motor shaft to the driven equipment due to geometric factors, such as the need to change the axis of the rotation or space restrictions. Belts are a common form of coupling, with some designs leading to less energy losses than others. Notched and cog/synchronous belts engage with the motor shaft in a more secure manner than standard V-belts, thereby minimizing losses due to slippage. For more information on the energy savings benefits from cogged and synchronous belts, see the Advanced Manufacturing Office's Motor Tip Sheet #5: Replace V-Belts with Notched or Synchronous Belts.

In the Volume 1 report, the types of couplings observed were reported; a summary is shown in Figure 14 both the industrial and commercial sectors, direct shaft coupling was the most commonly observed transmission type. However, V-belts were also commonly observed (4% of motor counts in the industrial sector and 12% in the commercial sector). Replacing these belts with synchronous/notched belts would reduce system losses. For some systems, there also may be opportunities to transition to direct drive for even greater savings. However, as mentioned above, transitioning to direct drive cannot be assumed to be feasible for all systems.

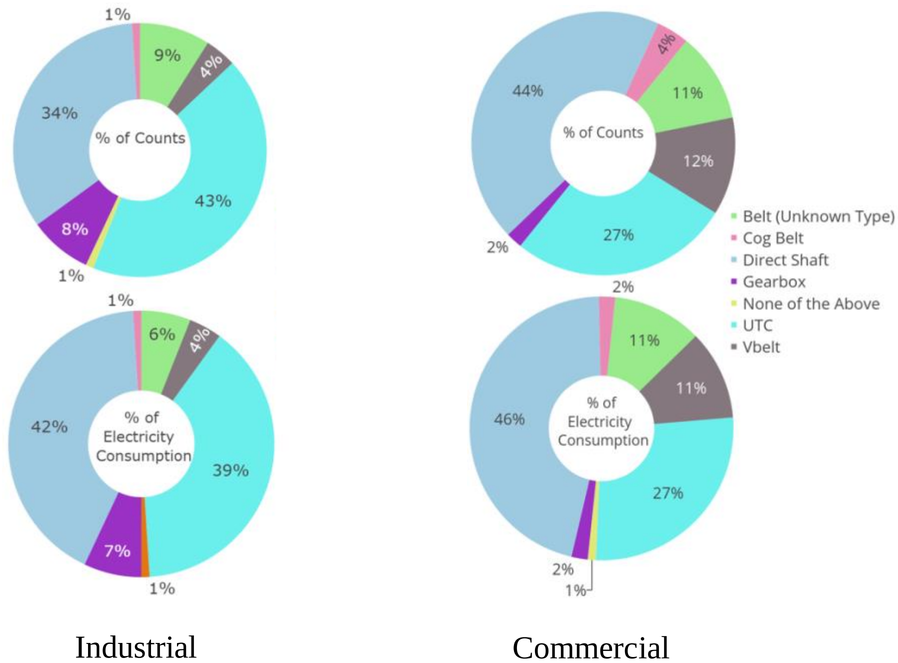


Figure 14: Transmission types observed in the industrial (left) and commercial (right) sector by counts (top) and energy consumption (bottom). UTC ("unable to collect") indicates that the transmission type could not be determined.

Upgrading to synchronous/notched belts

Due to their more secure connection, synchronous or notched belts can achieve a 3% improvement in maximum efficiency over standard V-belts (NREL, 2018). To conservatively estimate operational efficiencies, this study considered synchronous/notched belts to improve overall motor system efficiency by 2%. This improvement in energy efficiency was applied to any current motor system utilizing a V-belt. Note that in many cases, the type of belt could not be determined. These have been categorized as "belts" in Figure 14 without any specification of the type of belt. To generate a conservative energy savings estimate, these were not included in the savings calculations.

Table 19 shows the energy savings associated with upgrading V-belts to synchronous/notched belts. Compared to the other savings measures identified in this report, these savings are fairly modest but would still offset 1.1 MMT/year of CO_2 and save industrial and commercial facility operators $189 million annually.

Table 19: Energy savings from upgrading motor system V-belts to cog belts in the industrial and commercial sectors

Sector	Energy Savings (GWh/yr)	% of Motor System Electricity Consumption	CO_2 Reduction (MMT/yr)	Cost Savings (million $/yr)
Industrial	456	0.1	0.3	38
Commercial	1,116	0.2	0.8	151
Total	1,572	0.1	1.1	189

Summary

The energy savings associated with upgrading V-belts to synchronous/notched belts is 456 GWh/year in the industrial sector and 1,116 GWh/year in the commercial sector. The savings are likely much higher given that the transmission type or belt type could not be determined for many motors and were therefore excluded from these calculations.

Continued awareness regarding the energy savings benefits associated with cog belts would help realize the potential energy savings benefits. Additionally, incentive programs to help defray the increased costs associated with synchronous/notched belts (e.g., installation of a shiv) could promote their adoption. Further, transitioning to direct drive where possible would lead to even greater savings.

Savings Estimates by Driven Equipment

In addition to the opportunities already examined, there are others specific to the driven equipment. This section will identify some of these opportunities and, where possible, quantify their energy savings potential. The previously examined opportunities will also be presented again but framed around the driven equipment. The driven equipment types considered are pumps, fans and blowers, air compressors, refrigeration compressors, materials processing, and materials handling. Examining motor systems from the perspective of the driven equipment provides new insight into realizing the energy savings opportunity for motor systems by focusing on the application and purpose of the motor system.

Additionally, this section summarizes the adoption of several energy management practices specific to the driven equipment. Implementation of these practices would lead to additional energy savings. However, the magnitude of these savings is not calculated here due to a lack of information needed to carry out the calculation. Collecting the required information was outside the scope of the motor system assessments conducted.

In this report, we separate savings estimates by driven equipment and specific opportunities within those systems. New work is being done by DOE to establish efficiency standards for complete systems, including the Pump Energy Index (PEI) and Fan Energy Index (FEI).

Pumping systems

Pumping systems were found to consume 21% of industrial motor system energy consumption and 10% of commercial motor system energy consumption. In addition to the energy, CO_2, and cost-saving opportunities already evaluated in this report, load matching opportunities unique to pumping systems exist; namely, impeller trimming. This opportunity is evaluated below, and a summary of all measures evaluated in this report for pumping systems is provided. Additionally, the adoption of specific pump system energy management practices is summarized.

Impeller trimming

For pumping systems that are constantly underloaded, impeller trimming delivers the same energy savings as installing a VFD but without the losses across the VFD. Impeller trimming is only applicable for certain load ranges (it is not recommended for severely underloaded systems) and is irreversible, meaning the pump will not be able to serve a higher load once the impellers are trimmed to serve a lower load. Therefore, impeller trimming is only done when there is no expectation of future increases in pumping load.

Energy savings for trimming impellers were determined using equation 8:

$$Energy\ savings = current\ electricity\ consumption\ \times (1 - LF^{x})$$

(Equation 8)

Where:

Current electricity consumption = pump electricity consumption as estimated in the Volume 1 report

LF = load factor

x = practical relationship for affinity laws: 2.1 for pump systems (Vaillencourt, 2005; Engineered Systems, 2004)

Pump systems that were considered candidates for impeller trimming were those constantly loaded at sub-75% load factors (see U.S. DOE Pumping Systems Tip Sheet #7) and not positive displacement pumps. There may be some decrease in efficiency in the pump itself that is difficult to quantify and not taken into consideration with equation 8.

Table 20 shows the energy, CO_2, and cost savings associated with trimming candidate pump impellers. In the industrial sector, impeller trimming can lead to a 1% reduction in pump system energy consumption, equating to 3.9 MMT of CO_2 and $463 million per year. The savings opportunity is less in the commercial sector, offering a 0.4% reduction in pump system energy consumption, equating to 1.4 MMT CO_2 and $274 million per year.

Table 20: Energy, CO_2, and cost savings associated with pump impeller trimming

	Electricity Consumption Savings (GWh/yr)	CO_2 Reduction (MMT/yr)	% Pump System Electricity/CO_2 Reduction	Cost Savings (million $/yr)
Industrial	5,493	3.9	1.0	463
Commercial	2,031	1.4	0.4	274
Total	7,524	5.3	0.7	738

Adoption of energy management practices

In addition to the energy-saving measures evaluated above, the adoption of pump system energy management best practices was also examined. Specifically, the use of flow meters, the appropriateness of the pump size for the application, and the availability of the pump curve at the facility were reviewed. The results are shown in Table 21.

Only 26% of industrial and 4% of commercial pumping systems were on a flow meter. This indicates that the volumetric flow rate of fluids in pumping systems is largely unknown. Without this knowledge, an understanding of the energy output of the pumping system cannot be directly calculated but needs to be inferred. Inferred energy output is subject to uncertainty, as assumptions are made in calculations whose veracity may not be known.

In the Volume 1 report, it was found that 84% percent of industrial and 87% of commercial pumps were evaluated to be appropriately sized for their application. This indicates that facilities are mostly selecting the correct pump for their needs.

Only 26% of industrial and 3% of commercial pumping systems had their pump curves available at the facility. The pump curves specify the allowable pressure and flow rate operating points for a pump and the associated energy efficiency for each pair of points. Without this knowledge, one cannot determine how well the pump is operating with respect to its performance specifications.

Table 21: Adoption of pump system energy management best practices

	% Yes (Industrial)	**% Yes (Commercial)**
Is the pump on a flow meter?	26	4
Is the pump appropriately sized?	84	87
Is the pump curve available at the facility?	26	3

Adoption of advanced motor technologies

Additional energy savings for pumping systems can be realized via adoption of advanced motor technologies. The magnitudes of these are shown in Table 22 (for constant load pumping systems), Table 23 (for variable load pumping systems that are already fitted with or cannot use a VFD), and Table 24 (for variable load pumping systems not currently fitted with a VFD but could be). Savings are for motor systems within the size ranges shown in Table 10.

Table 22: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies on industrial and commercial pumping systems

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
>75%	**Energy savings (GWh)**	1,350	1,198	1,244	961	442
	CO_2 savings (MMT)	0.96	0.85	0.88	0.68	0.31
	Cost savings ($M)	114	104	105	83	38
<75% w/ right sizing	**Energy savings (GWh)**	334	315	309	254	100
	CO_2 savings (MMT)	0.24	0.22	0.22	0.18	0.07
	Cost savings ($M)	27	26	25	21	8
		Commercial				
>75%	**Energy savings (GWh)**	1,547	1,642	1,395	1,439	1,040
	CO_2 savings (MMT)	1.10	1.16	0.99	1.02	0.74
	Cost savings ($M)	209	221	188	194	136
<75% w/ right sizing	**Energy savings (GWh)**	334	135	319	114	63
	CO_2 savings (MMT)	0.24	0.10	0.23	0.08	0.04
	Cost savings ($M)	48	21	45	18	10

Note: Savings are for motor systems within the size ranges shown in Table 10.

Table 23: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial pumping systems that are currently fitted with a VFD or cannot use a VFD

	PM	SR	SynRM	PM SynRM
	Industrial			
Energy savings (GWh/yr)	704	1,142	653	511
CO_2 savings (MMT/yr)	0.50	0.81	0.46	0.36
Cost savings ($M/yr)	60	97	55	43
	Commercial			
Energy savings (GWh/yr)	601	1,137	554	488
CO_2 savings (MMT/yr)	0.43	0.81	0.39	0.35
Cost savings ($M/yr)	89	164	82	73

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Table 24: Annual energy, CO2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial pumping systems not currently fitted with a VFD

	Premium Eff. w/VFD	PM w/VFD	SR	SynRM w/VFD	PM SynRM w/VFD
	Industrial				
Energy savings (GWh/yr)	9,038	9,106	7,021	9,097	6,823
CO_2 savings (MMT/yr)		6.46	4.98	6.45	4.84
Cost savings ($M/yr)		762	582	762	566
	Commercial				
Energy savings (GWh/yr)	2,928	2,953	2,967	2,949	2,873
CO_2 savings (MMT/yr)		2.09	2.10	2.09	2.04
Cost savings ($M/yr)		370	373	369	362

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed-capable. For comparison, the savings associated with implementing a Premium Efficiency motor with a VFD is shown. Savings are for motor systems within the size ranges shown in Table 10.

Summary

A summary of the annual energy and CO_2 savings from the industrial and commercial pumping system measures evaluated is shown in Figure 15 and Figure 16, respectively. For both sectors, adoption of advanced technologies (represented by PM motors) offers the greatest source of energy, CO_2, and cost savings. Installation of VFDs and pump impeller trimming offers significant energy and CO_2 savings, as well. All of these measures are associated with improving load matching, indicating that this is the greatest source of energy losses in industrial and commercial pumping systems. When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other. With this caution, industrial and commercial pumping systems could each achieve a 10%–15% reduction in energy, CO_2 emissions, and operational costs by upgrading to a more efficient motor, improving the distribution system, and adopting more VFDs.

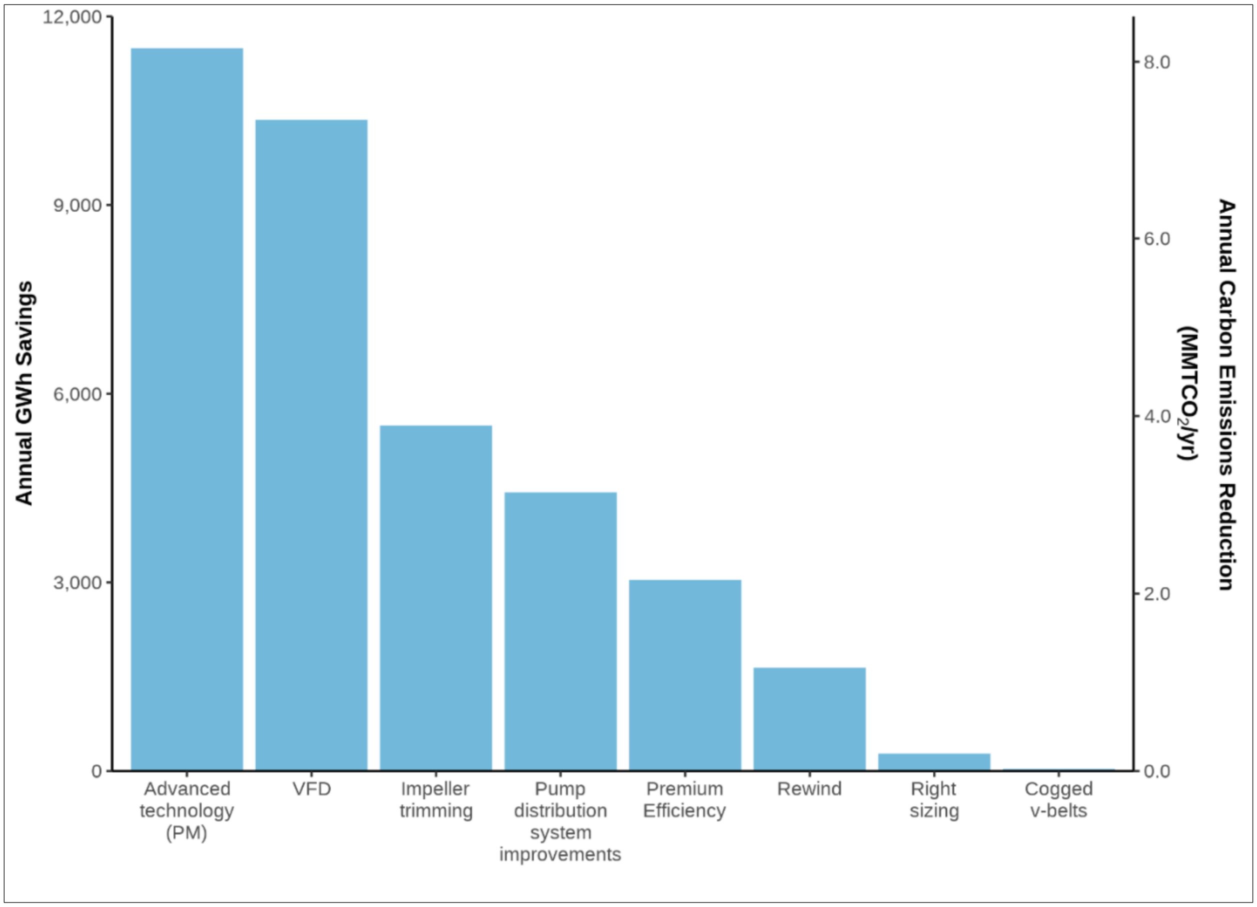


Figure 15: Annual energy and CO_2 savings from measures evaluated for industrial pumping systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

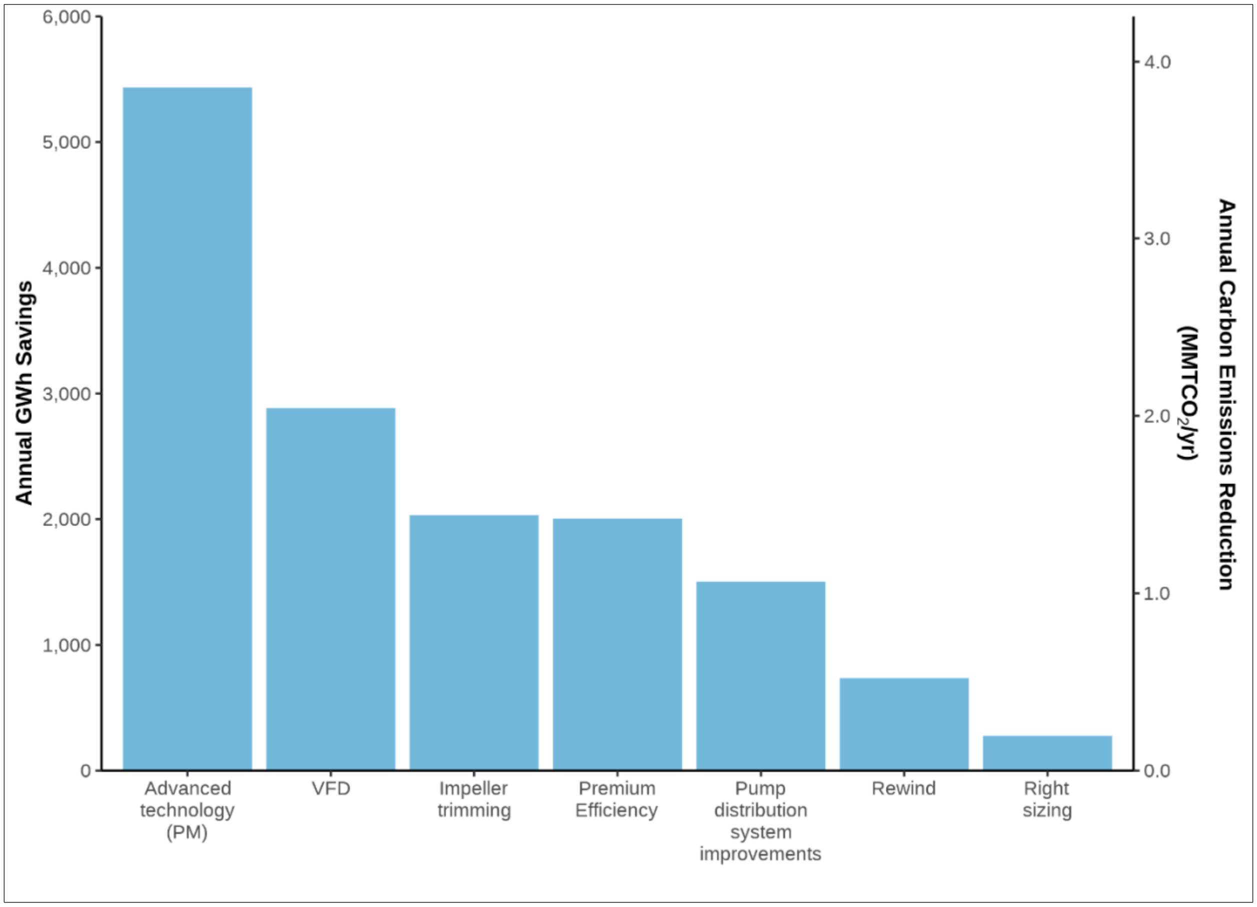


Figure 16: Annual energy and CO_2 savings from measures evaluated for commercial pumping systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Table 25 shows the information presented in Figure 15 and Figure 16, along with the accompanying annual cost savings. The annual energy consumption, CO_2 emissions, and costs for operating industrial and commercial pumping systems are also shown as a point of reference. Nearly $2 billion and over $1.1 billion of cost savings could be realized in the industrial and commercial sectors, respectively, with the adoption of VFDs, impeller trimming, pump distribution systems improvements, and Premium Efficiency motors. Similarly, $965 million and $734 million in the industrial and commercial sectors, respectively, could be saved annually through the adoption of advanced motor technologies (represented by PM motors).

Table 25: Annual energy, CO_2, and cost savings for industrial and commercial pumping systems for the measures evaluated

	Energy (GWh/yr)	CO_2 Emissions (MMT CO_2/yr)	Cost (million $/yr)
Industrial			
Baseline	115,868	82.2	10,081
Savings estimates			
Advanced technology (PM)	11,493	8.1	965
VFD	10,354	7.3	870
Impeller trimming	5,493	3.9	461
Pump distribution system improvements	4,431	3.1	372
Premium Efficiency motor upgrade	3,039	2.2	255
Rewind	1,642	1.16	138
Right sizing	278	0.20	23
Cogged V-belts	35	0.02	3
Commercial			
Baseline	52,907	37.5	6,878
Savings estimates			
Advanced technology (PM)	5,435	3.9	734
VFD	2,884	2.0	389
Impeller trimming	2,031	1.4	274
Premium Efficiency motor upgrade	2,006	1.4	271
Pump distribution system improvements	1,504	1.1	203
Rewind	736	0.5	99
Right sizing	277	0.2	37

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with operating industrial and commercial pumping systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Fan and blower systems

Fan and blower systems were found to consume 21% of industrial motor system energy consumption and 36% of commercial motor system energy consumption. In addition to determining and summarizing the energy, CO_2, and cost-saving opportunities already evaluated in this report attributable to fan and blower systems, the adoption of specific fan and blower system energy management practices is also summarized.

Adoption of energy management practices

In addition to the energy-saving measures evaluated above, the adoption of fan and blower system energy management best practices was also examined. Specifically, the use of flow meters, the appropriateness of the fan size for the application, and the availability of the fan curve at the facility were reviewed. The results are shown in Table 26.

Only 18% of industrial and 3% of commercial fan and blower systems were on a flow meter. This indicates that the airflow rate of the fan and blower systems is largely unknown. Without this knowledge, an understanding of the energy output of the system cannot be directly calculated but needs to be inferred. Inferred energy output is subject to uncertainty, as assumptions are made in calculations whose veracity may not be known.

Only 36% of industrial and 42% of commercial fan and blower systems had their fan/blower curves available at the facility. The fan/blower curve specifies the allowable pressure and flow rate operating points for a fan/blower and the associated energy efficiency for each pair of points. Without this knowledge, one cannot determine how well the fan/blower is operating with respect to its performance specifications.

Table 26: Adoption of fan and blower system energy management best practices

	% Yes (Industrial)	% Yes (Commercial)
Is the fan on a flow meter?	18	3
Is the fan appropriately sized?	72	86
Is the fan curve available at the facility?	36	42

Note: Fans certified by the Air Movement Control Association (AMCA) has information on the fan performance specific to applications.

Adoption of advanced technologies

Additional energy savings for fan and blower systems can be realized via adoption of advanced motor technologies. The magnitudes of these are shown in Table 27 (for constant load fan and blower systems), Table 28 (for variable load fan and blower systems that are already fitted with or cannot use a VFD), and Table 29 (for variable load fan and blower systems not currently fitted with a VFD but could be). Savings are for motor systems within the size ranges shown in Table 10.

Table 27: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies on industrial and commercial fan and blower systems

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
>75%	**Energy savings (GWh/yr)**	1,494	1,639	1,343	1,337	730
	CO_2 savings (MMT/yr)	1.06	1.16	0.95	0.95	0.52
	Cost savings ($M/yr)	124	135	111	110	61

<75% with right sizing	**Energy savings (GWh/yr)**	325	345	292	278	144
	CO_2 savings (MMT/yr)	0.23	0.24	0.21	0.20	0.10
	Cost savings ($M/yr)	26	27	23	22	11
		Commercial				
>75%	**Energy savings (GWh/yr)**	4,678	4,779	3,926	4,148	3,576
	CO_2 savings (MMT/yr)	3.32	3.39	2.78	2.94	2.54
	Cost savings ($M/yr)	693	709	587	619	531
<75% with right sizing	**Energy savings (GWh/yr)**	1,294	1,357	1,124	1,185	1,013
	CO_2 savings (MMT/yr)	0.92	0.96	0.80	0.84	0.72
	Cost savings ($M/yr)	163	170	141	149	129

Note: Savings are for motor systems within the size ranges shown in Table 10.

Table 28: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial fan and blower systems that are currently fitted with a VFD or cannot use a VFD

	Industrial			
	PM	**SR**	**SynRM**	**PM SynRM**
Energy savings (GWh/yr)	805	1,372	743	616
CO_2 savings (MMT/yr)	0.57	0.97	0.53	0.44
Cost savings ($M/yr)	72	123	66	55
	Commercial			
Energy savings (GWh/yr)	1,852	4,420	1,651	1,789
CO_2 savings (MMT/yr)	1.31	3.13	1.17	1.27
Cost savings ($M/yr)	276	678	246	269

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Table 29: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial fan and blower systems not currently fitted with a VFD

	Industrial				
	Premium Eff. w/VFD	**PM w/VFD**	**SR**	**SynRM w/VFD**	**PM SynRM w/VFD**
Energy savings (GWh/yr)	10,788	10,865	9,329	10,853	9,071

CO_2 savings (MMT/yr)		7.70	6.61	7.69	6.43
Cost savings ($M/yr)		887	770	886	748
	Commercial				
Energy savings (GWh/yr)	19,474	19,667	20,208	19,634	19,577
CO_2 savings (MMT/yr)		13.94	14.33	13.92	13.88
Cost savings ($M/yr)		2,420	2,485	2,416	2,410

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed-capable. For comparison, the savings associated with implementing a Premium Efficiency motor with a VFD is shown. Savings are for motor systems within the size ranges shown in Table 10.

Summary

A summary of the energy and CO_2 savings associated with the measures evaluated that are relevant to fan and blower systems are shown in Figure 17 (industrial) and Figure 18 (commercial). For both sectors, load control via use of VFDs or adoption of advanced technologies (represented by PM motors), improvement to air distribution systems, and upgrading to a higher efficiency motor (either Premium Efficiency or PM) offer the greatest opportunities for energy and CO_2 emissions reduction. When examining savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other. With this caution, industrial and commercial fan and blower systems could each achieve a 20% reduction in energy, CO_2 emissions, and operational costs by improving load control, improving the distribution system, and upgrading to a more efficient motor.

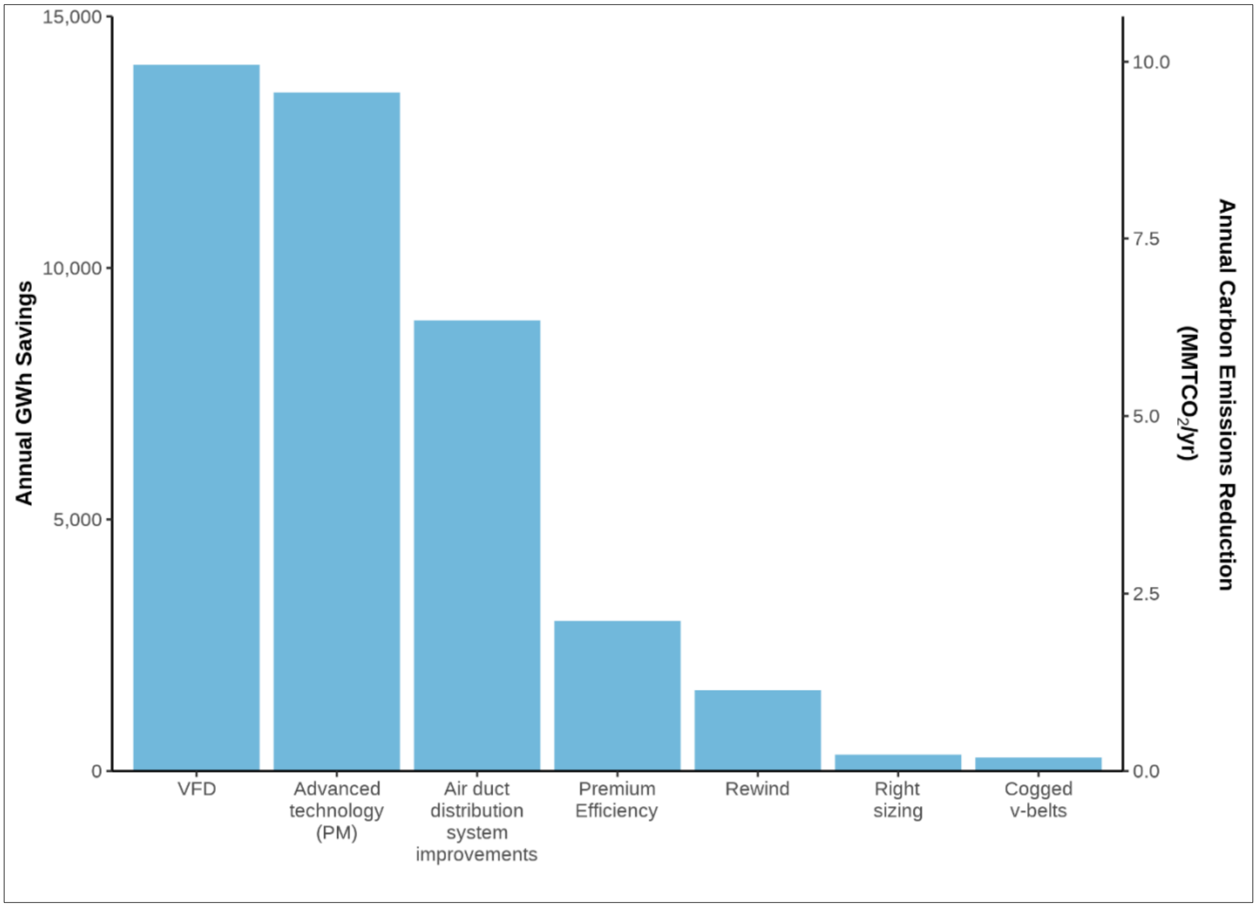


Figure 17: Annual energy and CO_2 savings from measures evaluated for industrial fan and blower systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

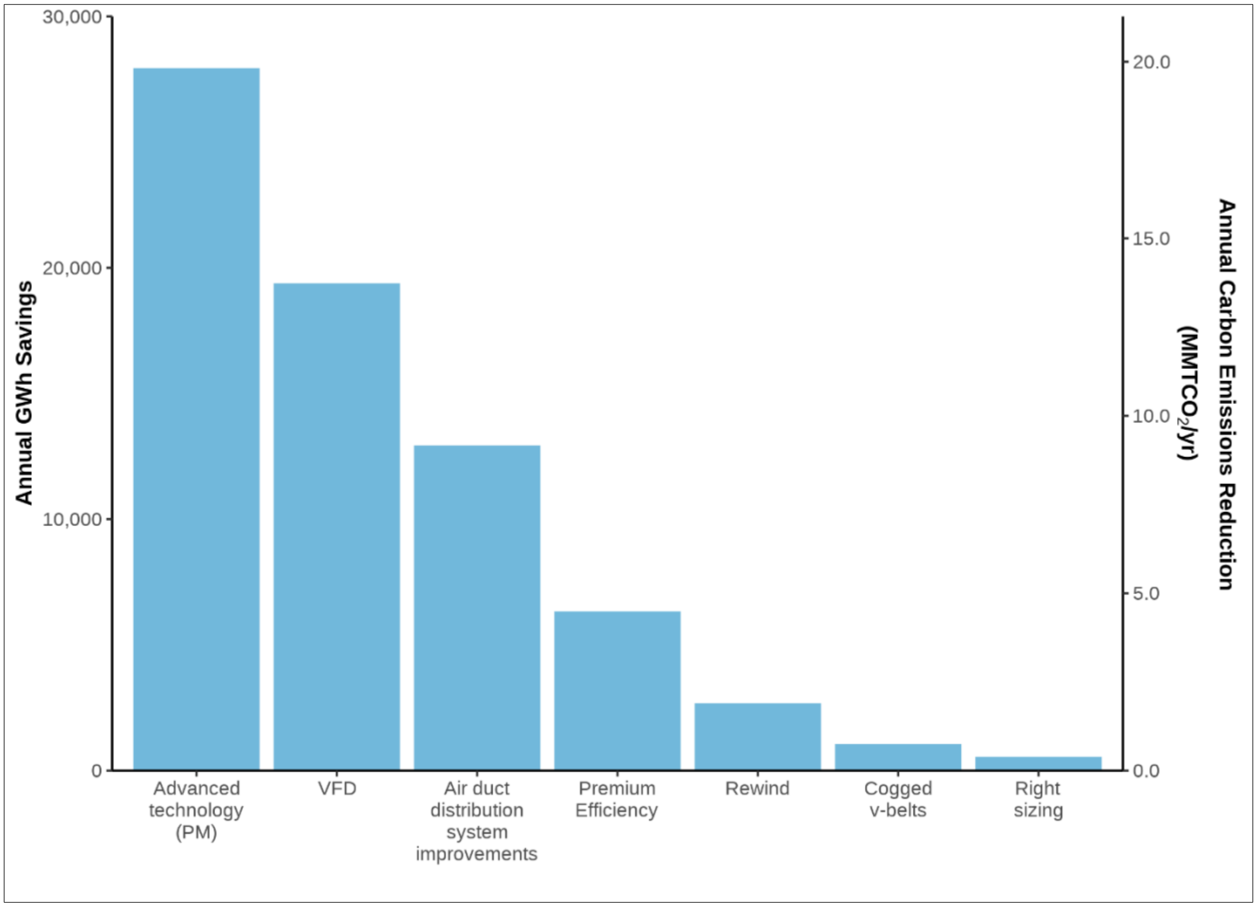


Figure 18: Annual energy and CO_2 savings from measures evaluated for commercial fan and blower systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Table 30 shows the information presented in Figure 17 and Figure 18, along with the accompanying annual cost savings. The annual energy consumption, CO_2 emissions, and costs for operating industrial and commercial fan systems are also shown. Over $2 billion and $5 billion of energy savings in the industrial and commercial sectors, respectively, could be realized through the improvement of distribution systems, adoption of VFDs, and adoption of higher efficiency motors. Similarly, $1.1 billion and $3.8 billion in the industrial and commercial sectors, respectively, could be saved annually through the adoption of advanced motor technologies (represented by PM motors).

Table 30: Annual energy, CO_2, and cost savings for industrial and commercial fan and blower systems for the measures evaluated

	Energy (GWh/yr)	CO_2 Emissions (MMT CO_2/yr)	Cost (million $)
Industry			
Baseline	112,942	80.1	9,826
Savings estimates			
VFD	13,724	9.7	1,153
Advanced technology (PM)	13,489	9.6	1,133
Air duct distribution system improvements	8,959	6.4	753
Premium Efficiency motor upgrade	2,986	2.1	251
Rewind	1,610	1.1	135
Right sizing	329	0.2	28
Cogged V-belts	271	0.2	23
Commercial			
Baseline	192,085	136.2	24,971
Savings estimates			
Advanced technology (PM)	27,942	19.5	3,772
VFD	18,875	13.4	2,548
Air duct distribution system improvements	12,935	9.2	1,746
Premium Efficiency motor upgrade	6,336	4.5	855
Rewind	2,678	1.9	362
Cogged V-belts	1,064	0.8	144
Right sizing	554	0.4	75

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with operating industrial and commercial fan and blower systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Compressed air systems

Compressed air systems were found to consume 12% of all industrial motor system energy and 1% of all commercial motor system energy. In addition to the energy-saving opportunities evaluated above, additional significant opportunities exist from eliminating inappropriate uses of compressed air, installing a sequencer on multi-compressor systems, and reducing the compressed air pressure set point. These opportunities are evaluated below. Additionally, qualitative opportunities are summarized, including using outside air for the compressor intake, conditioning the incoming air, and implementation of various compressed air strategies. The adoption of these opportunities is summarized, but energy savings are not quantified due to insufficient information to conduct a full evaluation.

Eliminate inappropriate uses of compressed air

Compressed air is very expensive to generate and is sometimes considered a utility itself (along with electricity, water, and natural gas). Further, it is inherently an inefficient energy consuming process due to unavoidable thermodynamic losses in the compression process. Given its cost and inefficiencies, it is advantageous from an energy and cost standpoint to only use compressed air when and where needed. However, perhaps due to its convenience and availability within a plant, applications that could be better served by a fan, blower, mechanical device, or more energy-efficient system are served by compressed air. These inappropriate uses include personnel cooling, drying, cabinet cooling, open blowing, and open handheld blowguns.

Energy, CO_2, and cost savings for eliminating inappropriate uses of compressed air were determined using equation 9:

$$\begin{aligned}&Annual\ energy\ savings\\ &\quad = Rated\ Power\ \times LF\ \times \left(\frac{1}{\eta_{eff,motor}}\right) \times\ OH\ \times\ CF\\ &\quad \times \%\ to\ inappropriate\ uses\end{aligned}$$

(Equation 9)

Where:

Rated power = nameplate size of the compressor, hp

LF = load factor, %

$\eta_{eff,motor}$ = energy efficiency of motor

OH = annual facility operational hours, hours/yr

CF = cycling factor, %

% to inappropriate uses = fraction of compressed air going to inappropriate uses as determined during the motor system assessments

The percent of compressed air going to inappropriate uses was collected during the motor system assessments. A list of inappropriate uses was presented to facility staff (see Appendix C in the Volume 1 report for the list), and they were asked to select which were present at the facility, along with the percent of compressed air going to these uses. In equation 9, energy savings associated with eliminating inappropriate uses were assumed to scale linearly with the percent of compressed air for these uses.

The energy, CO_2, and cost savings associated with eliminating inappropriate compressed air uses in the industrial and commercial sectors are shown in Table 31. Largely due to the relatively small contribution from compressed air to commercial motor system energy consumption, the energy savings in the industrial sector are significantly larger than in the commercial sector. In the industrial sector, savings are estimated to be approximately 8,900 GWh of electricity, 6.3 MMT of CO_2, and $752 million annually. In the commercial sector, savings are estimated to be nearly 1,600 GWh of electricity, 1.1 MMT of CO_2, and $212 million annually.

Table 31: Energy, CO_2, and cost savings associated with eliminating inappropriate uses of compressed air

	Electricity Consumption Savings (GWh/yr)	CO_2 Emissions Reduction (MMT/yr)	% Compressed Air System Electricity/CO_2 Reduction (%)	Energy Cost Savings (million $/yr)
Industrial	8,913	6.3	1.6	752
Commercial	1,572	1.1	0.3	212
Total	10,485	7.4	1.0	964

Install sequencers

Whenever multiple compressors are operating at part load in the plant, those compressors can be sequenced using sequencer controls. This will unload the compressors when the compressed air demand is lower, thereby operating the baseline compressor at a higher load. This eliminates low partial load energy efficiencies of the compressors. Zahlan and Cadmus Group Inc. (2017) achieved a 13% reduction in energy consumption by cascading load/unload controls to sequence two 100 kilowatt (kW) air compressors compared to unsequenced air compressors. Greater energy savings (30%) were found when VFDs were used on both air compressors.

To be conservative, a 13% reduction in overall energy consumption for unsequenced air compressors was used to determine energy savings potential from air compressor sequencing. A simple load/unload strategy was considered for unsequenced air compressors. When facilities had more than one air compressor, staff were asked if they were sequenced. Those that were not sequencing were considered eligible for realizing energy savings from sequencing.

The energy savings associated with sequencing air compressors are shown in Table 32. While the savings in the commercial sector are quite small (due to low energy consumption for compressed air systems in the commercial sector), the savings in the industrial sector is over 1,000 GWh of electricity, 0.7 MMT of CO_2, and $86 million.

Table 32: Energy savings associated with sequencing currently unsequenced air compressors

	Electricity Consumption Savings (GWh/yr)	CO_2 Reduction (MMT)	% Compressed Air System Electricity/CO_2 Reduction (%)	Energy Cost Savings (million $/yr)
Industrial	1,015	0.72	1.6	86
Commercial	65	0.05	0.5	9
Total	1,080	0.77	1.4%	95

Reduce compressed air pressure set point

Compressed air set pressure points are often set higher than needed. Many facilities simply keep the compressor set to its default pressure setting. The pressure is reduced at the point of use to match the load requirements. This leads to unnecessary energy consumption, CO_2 emissions, and costs. Facilities whose compressed air pressure set points are much higher than the highest pressure required by a process are good candidates for reducing the pressure set point. As part of the MSMA, the current air pressure setting was observed, and facility staff were asked the pressure requirements for the highest load. Per best practice, the compressed air pressure set point should be approximately 10% higher than that of its highest pressure end use.

Energy savings were calculated by finding the difference between the current pressure set point and the highest pressure required by the processes for each air compressor inventory, as shown in equation 10. If the highest required pressure was lower than the set point by more than 15%, then it was assumed that the set point could be reduced such that it remains 15% greater than the highest demand in the plant. Fifteen percent was used rather than 10% in order to develop more conservative savings estimates.

$$Energy\ savings = \left(\frac{Rated\ power \times 0.746\ \frac{kW}{HP} \times LF \times CF \times OH}{\eta_{motor}}\right) \times \left(1 - \frac{\left(\frac{DP_p + P_0}{P_i}\right)^{\frac{k-1}{kN}} - 1}{\left(\frac{DP_c + P_0}{P_i}\right)^{\frac{k-1}{kN}} - 1}\right)$$

(Equation 10)

Where:

Rated power = air compressor nameplate size, hp

LF = Load Factor, %,

CF = Cycling Factor, %

OH = Annual facility operating hours, hrs/yr

$\eta_{motor,eff}$ = Motor efficiency, %

DP_p = Proposed discharge pressure, psig; assumed 15% of highest pressure requirement

P_o = Atmospheric pressure, 14.7 psia

P_i = Inlet pressure, psia

DP_c = Current discharge pressure, psig

N = 1.25, assuming a polytrophic efficiency of 80%

k = Ratio of specific heat for air (k = 1.4), no units

The energy, CO_2, and energy cost savings associated with reducing air pressure set points are shown in

Table 33. In the industrial sector, reducing air set points could lead to over 850 GWh of electricity, 0.6 MMT of CO_2, and slightly under $72 million of savings annually. Due to the low energy consumption for air compressors in the commercial sector, savings are modest for

commercial air compressors. Better controlling unregulated air demand also leads to substantial savings, but that analysis was beyond the scope of this report.

Table 33: Annual energy, CO_2, and energy cost savings associated with reducing compressed air set points

	Electricity Consumption Savings (GWh/yr)	CO_2 Reduction (MMT/yr)	% Compressed Air System Electricity/CO_2 Reduction	Electricity Cost Savings (million $/yr)
Industrial	852	0.6	1.3	72
Commercial	33	0.02	0.3	4
Total	885	0.6	1.2	76

Adoption of energy management practices

Compressed air system energy management strategies offer additional savings opportunities. The adoption of some of these strategies was evaluated through the motor system assessments. However, quantifying the energy, cost, and CO_2 emissions savings was not possible due to the need to collect more data than what was within the scope of the assessment. The adoption of these compressed air system energy management strategies and their benefits are detailed in Table 34.

Table 34: Adoption of compressed air energy management best practices

Compressed Air Energy Management Strategy	Industrial (% yes)	Commercial (% yes)	Benefit
Outside air not used for intake, but it could be used	22	36	Drawing outside air lowers compression energy requirements when outside air is colder than inside air.
Intake is located away from contaminants	65	98	Drawing cleaner intake air increases the system's energy efficiency.
Incoming air is filtered	71	100	Compressing cleaner air increases the system's energy efficiency.
Have controls been adjusted in last year?	27	0	Periodic adjustments of controls allow the system to meet current demands energy efficiently.
Does the system utilize a pressure and/or flow controller?	19	15	Usage of a pressure and/or flow controller allows the system to meet current demands energy efficiently.
Utilize production or schedule-based pressure setbacks?	3	8	Setbacks reduce energy wasted to generate compressed air when it is not needed.
Were leaks heard during the MSMA assessment?	31	10	Leaks are a major source of energy loss in systems.
Are controls adjusted after repairing leaks?	8	0	Pressure and flow requirements may be lowered after fixing leaks, thereby reducing energy consumption.

Is oil free air used where not required?	9	2	Oil free air is more energy intensive to generate, and avoiding its unnecessary generation saves energy.
Do you have a preventive maintenance program?	69	79	A preventive maintenance program ensures the system continues to operate as expected.
Do you have an ongoing leak management program?	35	0	A preventive maintenance program ensures energy losses are minimized.
Does the facility periodically inspect end use filters, check regulators, and lubricators?	79	53	Proper inspection ensures proper system operation and performance.
In the past five years has there been an energy efficiency assessment of the system?	35	38	Energy efficiency assessments ensure that the system is continuously improving its energy efficiency.

Adoption of advanced motor technologies

Additional energy savings for compressed air systems can be realized via adoption of advanced motor technologies. The magnitudes of these are shown in Table 35 (for constant load compressed air systems), Table 36 (for variable load compressed air systems that are already fitted with or cannot use a VFD), and Table 37 (for variable load compressed air systems not currently fitted with a VFD but could be). Savings are for motor systems within the size ranges shown in Table 10.

Table 35: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies on industrial and commercial compressed air systems

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
>75%	Energy savings (GWh/yr)	211	206	201	175	23
	CO_2 savings (MMT/yr)	0.15	0.15	0.14	0.12	0.02
	Cost savings ($M/yr)	19	18	18	15	2
<75% with right sizing	Energy savings (GWh/yr)	7	8	6	5	1
	CO_2 savings (MMT/yr)	0.01	0.01	0.00	0.00	0.00
	Cost savings ($M/yr)	1	1	1	1	0
		Commercial				
>75%	Energy savings (GWh/yr)	236	259	201	217	181
	CO_2 savings (MMT/yr)	0.17	0.18	0.14	0.15	0.13
	Cost savings ($M/yr)	33	37	28	30	25
<75% with right sizing	Energy savings (GWh/yr)	5	5	4	4	4

	CO_2 savings (MMT/yr)	0.00	0.00	0.00	0.00	0.00
	Cost savings ($M/yr)	1	1	1	1	1

Note: Savings are for motor systems within the size ranges shown in Table 10.

Table 36: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial compressed air systems that are currently fitted with a VFD or cannot use a VFD

	PM	**SR**	**SynRM**	**PM SynRM**
	Industrial			
Energy savings (GWh/yr)	293	439	271	165
CO_2 savings (MMT/yr)	0.21	0.31	0.19	0.12
Cost savings ($M/yr)	25	37	23	14
	Commercial			
Energy savings (GWh/yr)	76	94	66	73
CO_2 savings (MMT/yr)	0.05	0.07	0.05	0.05
Cost savings ($M/yr)	11	14	10	11

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Table 37: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial compressed air systems not currently fitted with a VFD

	Premium Eff. w/VFD	**PM w/VFD**	**SR**	**SynRM w/VFD**	**PM SynRM w/VFD**
	Industrial				
Energy savings (GWh/yr)	7,875	7,950	4,757	7,978	4,366
CO_2 savings (MMT/yr)		5.64	3.37	5.66	3.10
Cost savings ($M/yr)		687	397	690	363
	Commercial				
Energy savings (GWh/yr)	1,189	1,202	1,124	1,201	1,060
CO_2 savings (MMT/yr)		0.85	0.80	0.85	0.75
Cost savings ($M/yr)		174	165	174	155

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed-capable. For comparison, the savings associated with implementing a Premium Efficiency motor with a VFD is shown. Savings are for motor systems within the size ranges shown in Table 10.

Summary

A summary of the energy and CO_2 savings associated with the measures evaluated that are relevant to compressed air systems are shown in Figure 19 (industrial) and Figure 20 (commercial). For both sectors, use of VFDs, improvements to compressed air distribution systems, and elimination of compressed air leaks offer the greatest opportunities for energy and CO_2 emissions reduction. A caveat is made here: on most compressors below about 25 hp, the main drive motor also drives the cooling fan, and VFDs may cause overheating problems. In larger compressed air systems with varying demand, best practice is to split the load among multiple compressors. When doing that, and when properly sized, normally only one compressor is operated with a VFD. This implementation consideration has not been taken into account in this report.

When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other. With this caution, industrial and commercial compressed air systems could each achieve a 40%–50% reduction in energy, CO_2 emissions, and operational costs by adopting more VFDs, eliminating inappropriate uses, and improving the distribution system.

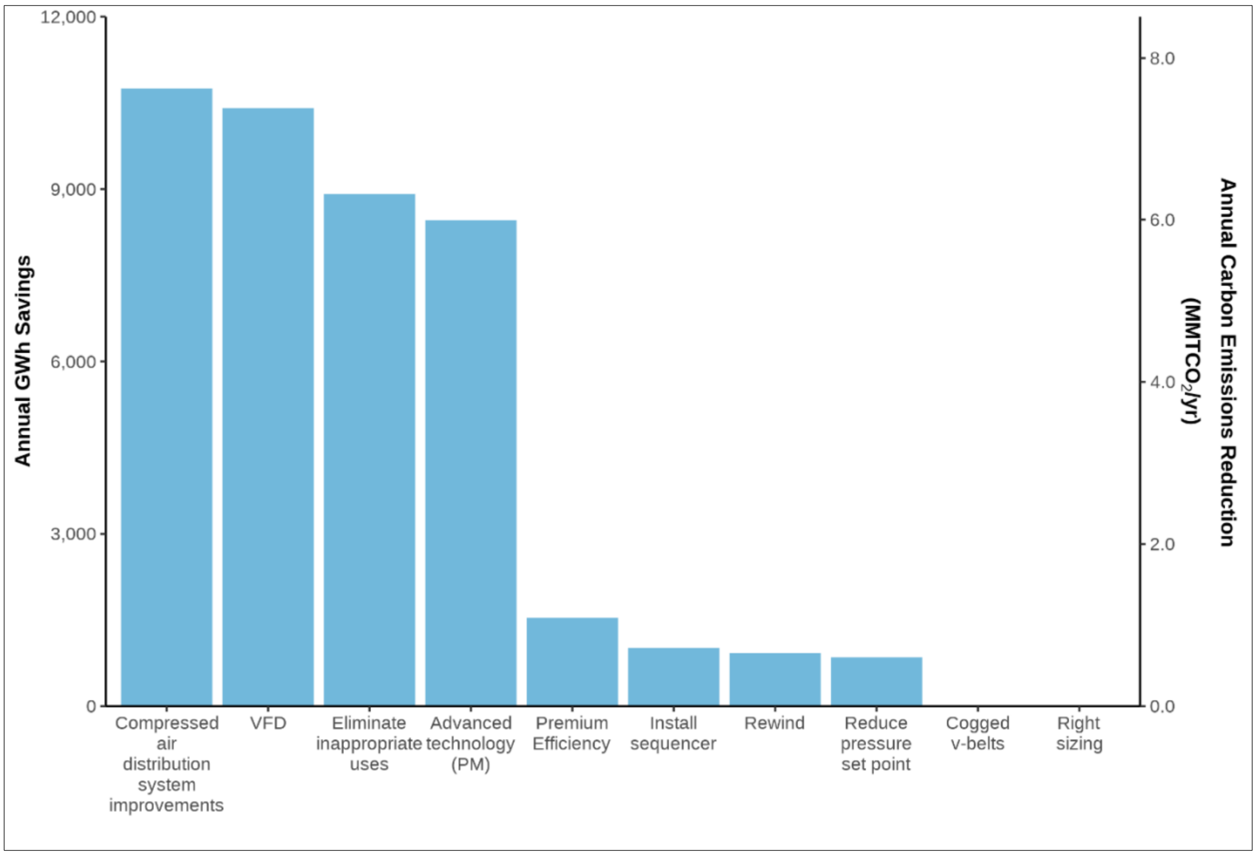


Figure 19: Magnitude of energy and CO_2 savings opportunities for industrial compressed air systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

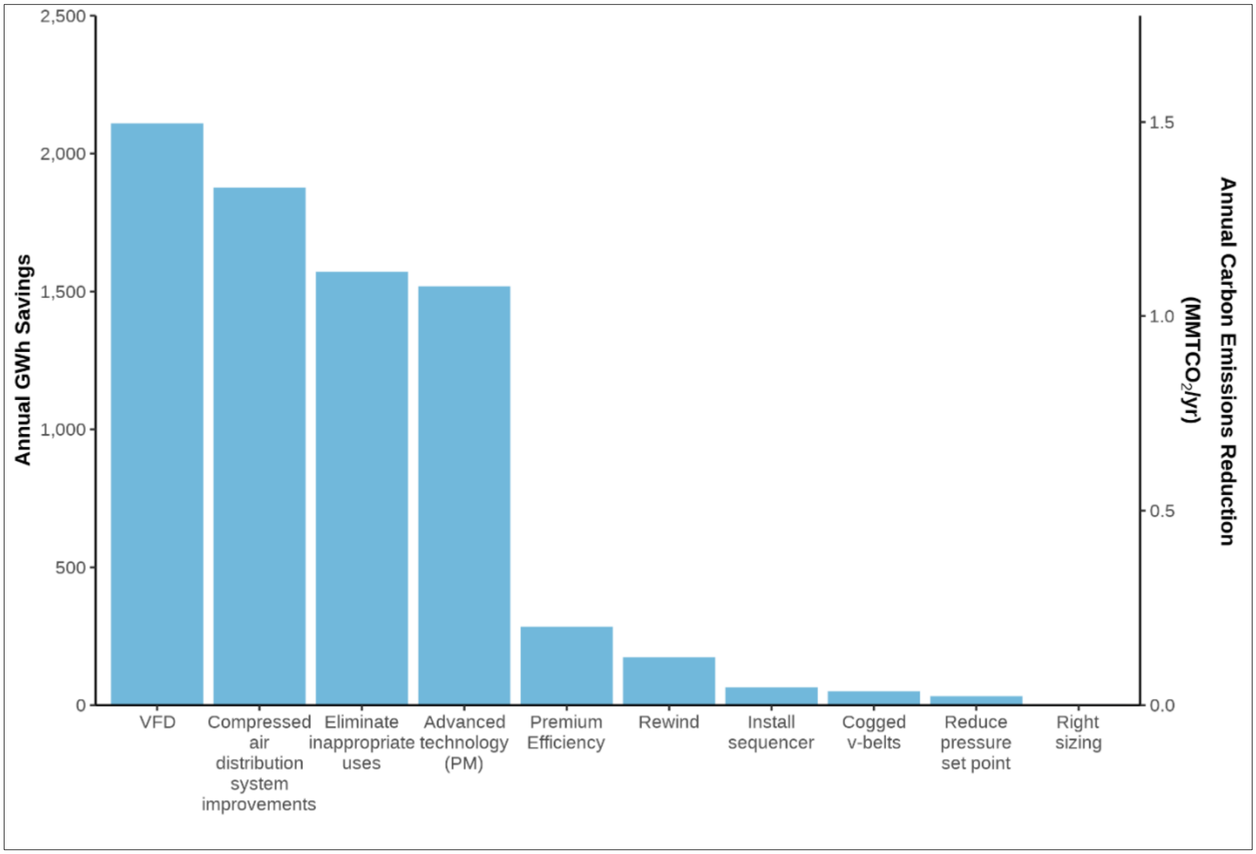


Figure 20: Magnitude of energy and CO_2 savings opportunities for commercial compressed air systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Table 38 shows the information presented in Figure 19 and Figure 20, along with the accompanying annual cost savings. The annual energy consumption, CO_2 emissions, and costs for operating industrial and commercial compressed air systems are also shown. Over $2.5 billion and $750 million of energy savings could be realized through the improvement of distribution systems, adoption of VFDs, and elimination of inappropriate uses in the industrial and commercial sectors, respectively.

Table 38: Annual energy, CO_2, and cost savings for industrial and commercial compressed air systems for the measures evaluated

	Energy (GWh/yr)	CO_2 Emissions (MMT CO_2/yr)	Cost (million $)
Industrial			
Baseline	63,613	45.1	5,534
Savings estimates			
Compressed air distribution system improvements	10,751	7.6	903
VFD	10,408	7.4	874
Eliminate inappropriate uses	8,913	6.3	749
Advanced technology (PM)	8,461	6.0	711
Premium Efficiency motor upgrade	1,539	1.1	129
Install sequencer	1,015	0.7	85
Rewind	927	0.7	78
Reduce pressure set point	852	0.6	72
Cogged V-belts	10	0.01	1
Right sizing	9	0.01	1
Commercial			
Baseline	12,564	8.9	1,633
Savings estimates			
VFD	2,110	1.5	285
Compressed air distribution system improvements	1,877	1.3	253
Eliminate inappropriate uses	1,572	1.1	212
Advanced technology (PM)	1,519	1.1	205
Premium Efficiency motor upgrade	285	0.2	38
Rewind	174	0.12	23
Install sequencer	65	0.05	9
Cogged V-belts	51	0.04	7
Reduce pressure set point	33	0.02	4
Right sizing	3	0.00	0

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with operating industrial and commercial compressed air systems is also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Refrigeration systems

Refrigeration systems were found to consume 12% of industrial motor system energy consumption and 48% of commercial motor system energy consumption. In addition to determining and summarizing the energy, CO_2, and cost-saving opportunities already evaluated in this report attributable to refrigeration systems, the adoption of specific refrigeration system energy management practices is also summarized. These numbers include only the motors driving the chillers and no other motors in the refrigeration system (e.g., those driving heat rejection fans, cooling tower fans, air-cooled condenser fans). These other motor systems are included in the fan and blower, pump, and other driven equipment breakouts.

Adoption of energy management practices

Refrigeration system energy management strategies offer additional savings opportunities over what have already been evaluated in this report. The adoption of some of these strategies was evaluated through the motor system assessments. However, quantifying the energy, cost, and CO_2 emissions savings was not possible due to the need to collect more data than what was within scope of the assessment. The adoption of these refrigeration energy management strategies is detailed in Table 39,
Table 40, and Table 41.

In general, the adoption rate for the energy management strategies evaluated is low for commercial systems. This offers a great opportunity to reduce building loads given the large amount of building energy used for refrigeration systems. For example, only 38% of commercial facilities stated that their maintenance protocols met manufacturer's requirements, and only 29% have developed a strategy to efficiently meet refrigeration demand. For industrial refrigeration systems, only 3% of facilities stated that they adjust set points based on production schedules (although 40% state that they have a control strategy for efficiently matching supply with demand).

Table 39: Adoption of energy management best practices for industrial and commercial refrigeration systems

Refrigeration System Energy Management	% Yes (Industrial)	% Yes (Commercial)
Has a control strategy been developed to efficiently match supply with demand?	40	29
Does the facility meet or exceed compressor manufacturer requirements for maintenance?	75	38
Does the facility have a preventive maintenance program?	85	38
Does the system utilize floating head or condenser temp reset?	15	10
Have any controls been adjusted in the last year?	44	35
Do the suction set points get adjusted based on production schedules?	3	21
In the past five years, has there been an energy efficiency assessment performed on the system?	37	15

The question in Table 40 queried if the facility has explored raising the chilled water set point temperature. Over three-quarters of commercial and industrial facilities have not explored this common energy efficiency practice. Often, chillers run at the set point set by the manufacturer. This is often much lower than needed, and consequently they consume more energy than needed.

Table 40: Potential to raise the suction temperature of industrial and commercial refrigeration systems. UTC stands for "unable to collect."

Has the feasibility of raising the suction temperature (e.g., chilled water temperature) of the system been recently explored, and at what frequency?	%	No	Permanently	Seasonally	Shift-Wise	UTC
	Commercial	76	1	0	18	5
	Industrial	78	12	3	0	7

Table 41 indicates that most commercial facilities (65%) either do not inspect the heat exchangers on their refrigeration systems or do not know if they do. Conversely, 74% of industrial facilities do inspect them. Fouled heat exchangers will lead to less heat transfer and subsequently need to consume more energy to achieve the same cooling load. Given the large fraction of commercial building motor system energy consumption, these findings indicate a potentially large opportunity for energy savings.

Table 41: Frequency of heat exchanger inspection for industrial and commercial refrigeration systems. UTC stands for "unable to collect."

How often are heat exchangers inspected?	%	Weekly	Monthly	Yearly	> One Year	Do Not Know	UTC
	Commercial	0	19	15	1	57	7
	Industrial	28	15	27	4	16	10

Adoption of advanced motor technologies

Additional energy savings for refrigeration systems can be realized via adoption of advanced motor technologies. The magnitudes of these are shown in Table 42 (for constant load refrigeration systems), Table 43 (for variable load refrigeration systems that are already fitted with or cannot use a VFD), and Table 44 (for variable load refrigeration systems not currently fitted with a VFD but could be). Savings are for motor systems within the size ranges shown in Table 10.

Table 42: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies on industrial and commercial refrigeration systems

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
>75%	Energy savings (GWh/yr)	229	273	208	221	149
	CO_2 savings (MMT/yr)	0.16	0.19	0.15	0.16	0.11
	Cost savings ($M/yr)	20	24	18	19	13
<75% with right sizing	Energy savings (GWh/yr)	43	47	40	38	8
	CO_2 savings (MMT/yr)	0.03	0.03	0.03	0.03	0.01
	Cost savings ($M/yr)	4	4	3	3	1
		Commercial				
>75%	Energy savings (GWh/yr)	974	1,155	833	902	572
	CO_2 savings (MMT/yr)	0.69	0.82	0.59	0.64	0.41
	Cost savings ($M/yr)	138	158	117	126	87
<75% with right sizing	Energy savings (GWh/yr)	719	840	648	697	535
	CO_2 savings (MMT/yr)	0.51	0.60	0.46	0.49	0.38
	Cost savings ($M/yr)	122	140	110	118	95

Note: Savings are for motor systems within the size ranges shown in Table 10.

Table 43: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial refrigeration systems that are currently fitted with a VFD or cannot use a VFD

	Industrial			
	PM	**SR**	**SynRM**	**PM SynRM**
Energy savings (GWh/yr)	354	261	330	161
CO_2 savings (MMT/yr)	0.25	0.19	0.23	0.11
Cost savings ($M/yr)	31	25	29	16
	Commercial			
Energy savings (GWh/yr)	1,246	1,259	1,098	863
CO_2 savings (MMT/yr)	0.88	0.89	0.78	0.61
Cost savings ($M/yr)	158	158	139	107

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Table 44: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial refrigeration systems not currently fitted with a VFD

	Premium Eff. w/VFD	PM w/VFD	SR	SynRM w/VFD	PM SynRM w/VFD
	Industrial				
Energy savings (GWh/yr)	6,329	6,431	3,605	6,423	3,352
CO_2 savings (MMT/yr)		4.56	2.56	4.55	2.38
Cost savings ($M/yr)		562	328	561	306
	Commercial				
Energy savings (GWh/yr)	42,800	43,744	43,395	43,496	40,580
CO_2 savings (MMT/yr)		31.01	30.77	30.84	28.77
Cost savings ($M/yr)		5,842	5,864	5,811	5,502

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed-capable. For comparison, the savings associated with implementing a Premium Efficiency motor with a VFD is shown. Savings are for motor systems within the size ranges shown in Table 10.

Summary

A summary of the energy and CO_2 savings associated with the evaluated measures attributable to refrigeration systems are shown in Figure 21 (industrial) and Figure 22 (commercial). For both sectors, improved load control via use of VFDs and/or advanced motor technologies constitutes the greatest opportunities for energy and CO_2 emissions reduction. Greater adoption of VFDs could lead to as much as a 15% reduction in industrial refrigeration system energy consumption and an 18% reduction in commercial refrigeration system energy consumption. Adoption of Premium Efficiency motors could lead to another 3% energy reduction in the industrial and commercial refrigeration systems each. When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other.

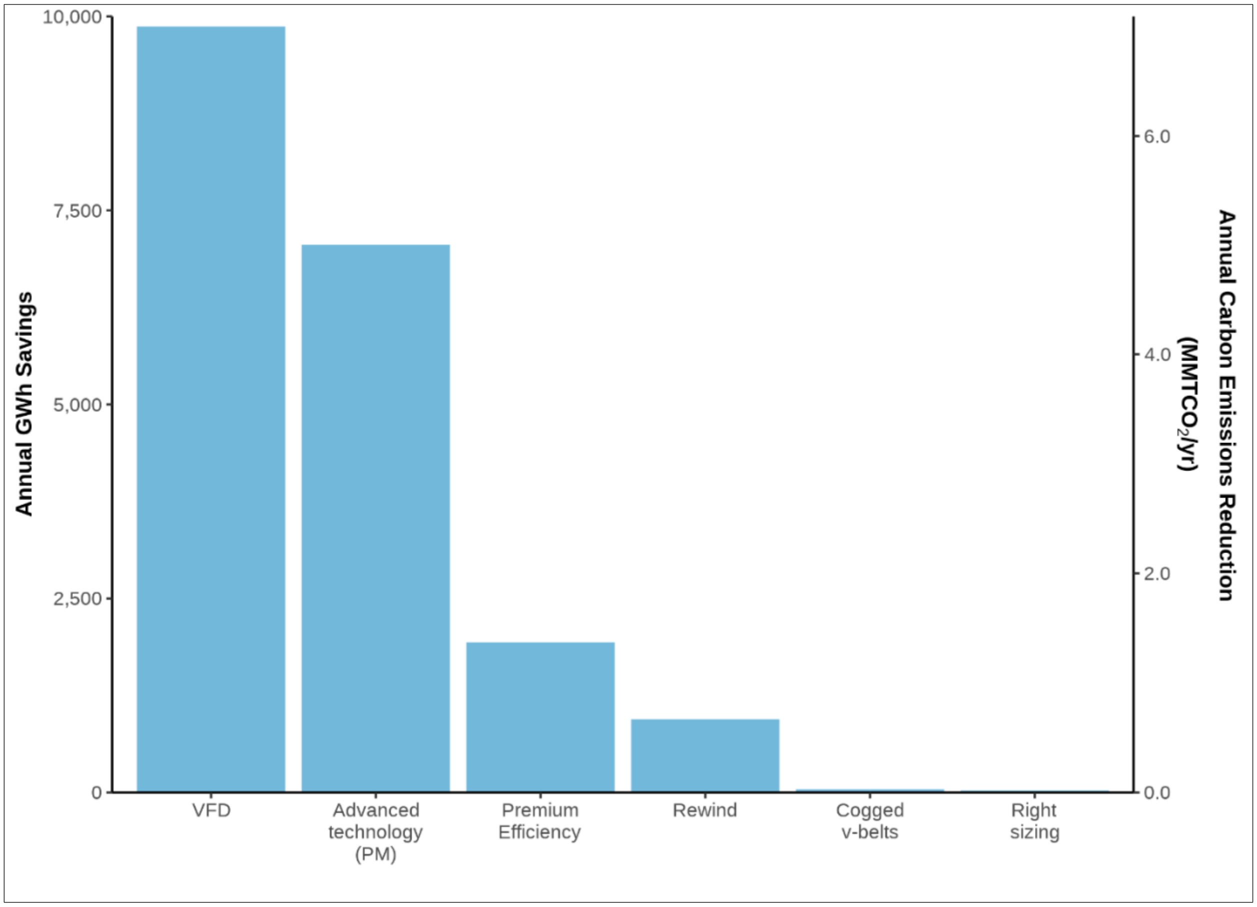


Figure 21: Magnitude of energy and CO_2 savings opportunities for industrial refrigeration systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

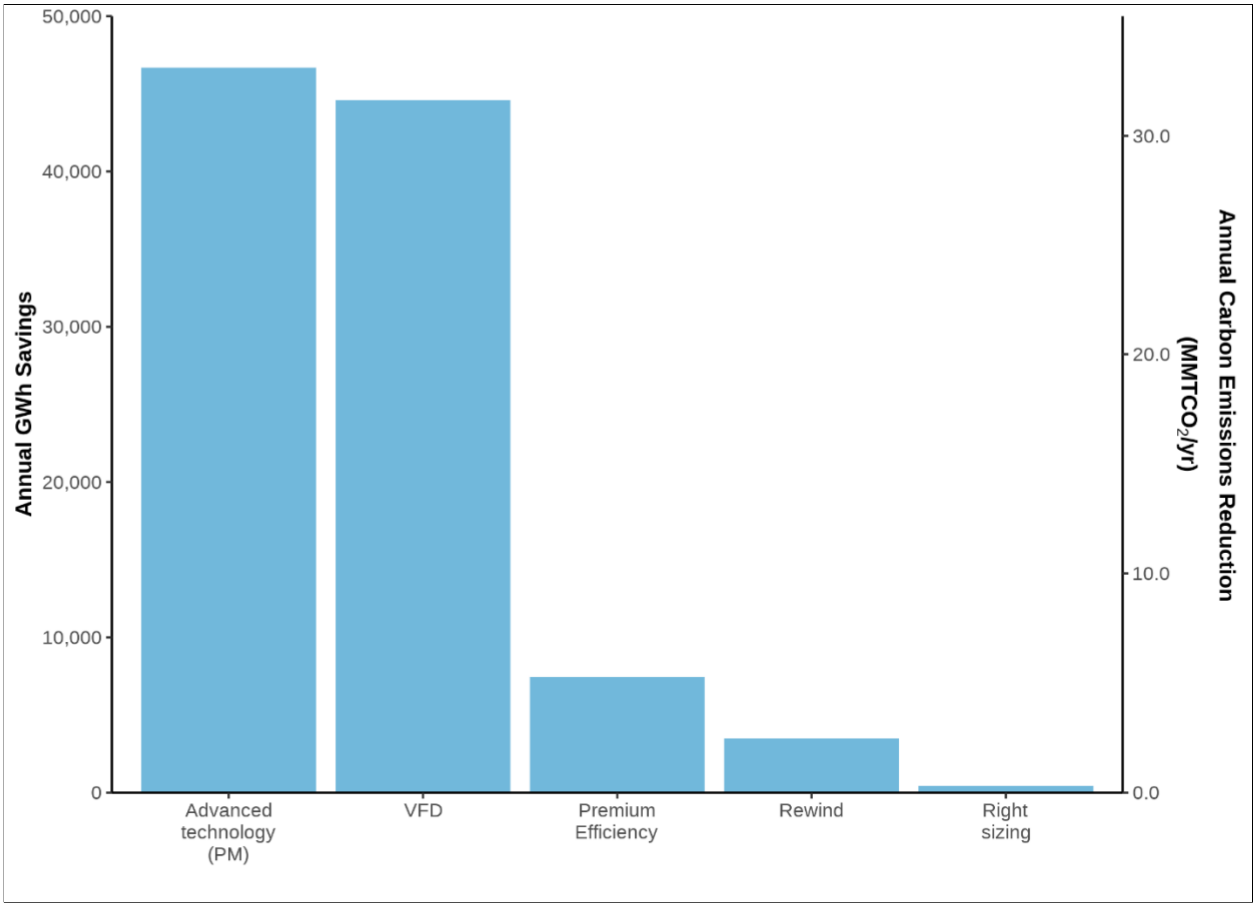


Figure 22: Magnitude of energy and CO_2 savings opportunities for commercial refrigeration systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Table 45 shows the information presented in Figure 21 and Figure 22, along with the accompanying annual cost savings. The annual energy consumption, CO_2 emissions, and costs for operating industrial and commercial refrigeration systems are also shown. Six billion dollars and $833 million of energy savings could be realized with the adoption of VFDs alone in the commercial and industrial sectors, respectively.

Table 45: Annual energy, CO_2, and cost savings for industrial and commercial refrigeration systems for the measures evaluated

	Energy (GWh/yr)	CO_2 emissions (CO_2/yr)	Cost (million $/yr)
Industrial			
Baseline	68,007	48.2	5,917
Savings estimates			
VFD	9,869	7.0	829
Advanced technology (PM)	7,056	5.0	593
Premium Efficiency motor upgrade	1,935	1.4	163
Rewind	944	0.7	79
Cogged V-belts	41	0.03	3
Right sizing	26	0.02	2
Commercial			
Baseline	251,522	178.3	32,698
Savings estimates			
Advanced technology (PM)	46,684	33.1	6,302
VFD	44,593	31.6	6,020
Premium Efficiency motor upgrade	7,452	5.3	1,006
Rewind	3,491	2.5	471
Right sizing	436	0.3	59

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with operating industrial and commercial refrigeration systems is also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Materials processing

Materials processing systems were found to consume 29% of industrial motor system energy consumption and less than 1% of commercial motor system energy consumption. Materials processing systems are motor systems used for processing materials, such as extruders, grinders, and hydraulics.

Adoption of advanced motor technologies

Additional energy savings for materials processing driven equipment can be realized via adoption of advanced motor technologies. The magnitudes of these are shown in Table 46 (for constant load material processing systems) and in Table 47 (for variable load refrigeration systems that are already fitted with or cannot use a VFD). Savings are for motor systems within the size ranges shown in Table 10.

Table 46: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies on industrial and commercial materials processing systems

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
>75%	**Energy savings (GWh/yr)**	1,326	1,377	1,202	1,132	527
	CO_2 savings (MMT/yr)	0.94	0.98	0.85	0.80	0.37
	Cost savings ($M/yr)	111	117	101	96	45
<75% with right sizing	**Energy savings (GWh/yr)**	434	207	412	171	62
	CO_2 savings (MMT/yr)	0.31	0.15	0.29	0.12	0.04
	Cost savings ($M/yr)	31	18	30	15	5
		Commercial				
>75%	**Energy savings (GWh/yr)**	26	27	25	26	2
	CO_2 savings (MMT/yr)	0.02	0.02	0.02	0.02	0.00
	Cost savings ($M/yr)	3	3	3	3	0
<75% with right sizing	**Energy savings (GWh/yr)**	6	6	5	5	5
	CO_2 savings (MMT/yr)	0.00	0.00	0.00	0.00	0.00
	Cost savings ($M/yr)	1	1	1	1	1

Note: Savings are for motor systems within the size ranges shown in Table 10.

Table 47: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial materials processing systems that are currently fitted with a VFD or cannot use a VFD

	PM	SR	SynRM	PM SynRM
	Industrial			
Energy savings (GWh/yr)	1,884	1,650	1,738	1,320
CO_2 savings (MMT/yr)	1.34	1.17	1.23	0.94
Cost savings ($M/yr)	154	136	142	109
	Commercial			
Energy savings (GWh/yr)	29	33	27	28
CO_2 savings (MMT/yr)	0.02	0.02	0.02	0.02
Cost savings ($M/yr)	4	5	4	4

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Summary

A summary of the energy, CO_2, and cost-saving opportunities already evaluated in this report attributable to materials processing systems is provided in Figure 23 (industrial) and Figure 24 (commercial). For both sectors, upgrading to Premium Efficiency motors constitutes the greatest opportunity for energy and CO_2 emissions reduction. Upgrading to more efficient motors could lead to as much as a 3% reduction in industrial materials processing energy consumption and a 5% reduction in commercial systems. When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other.

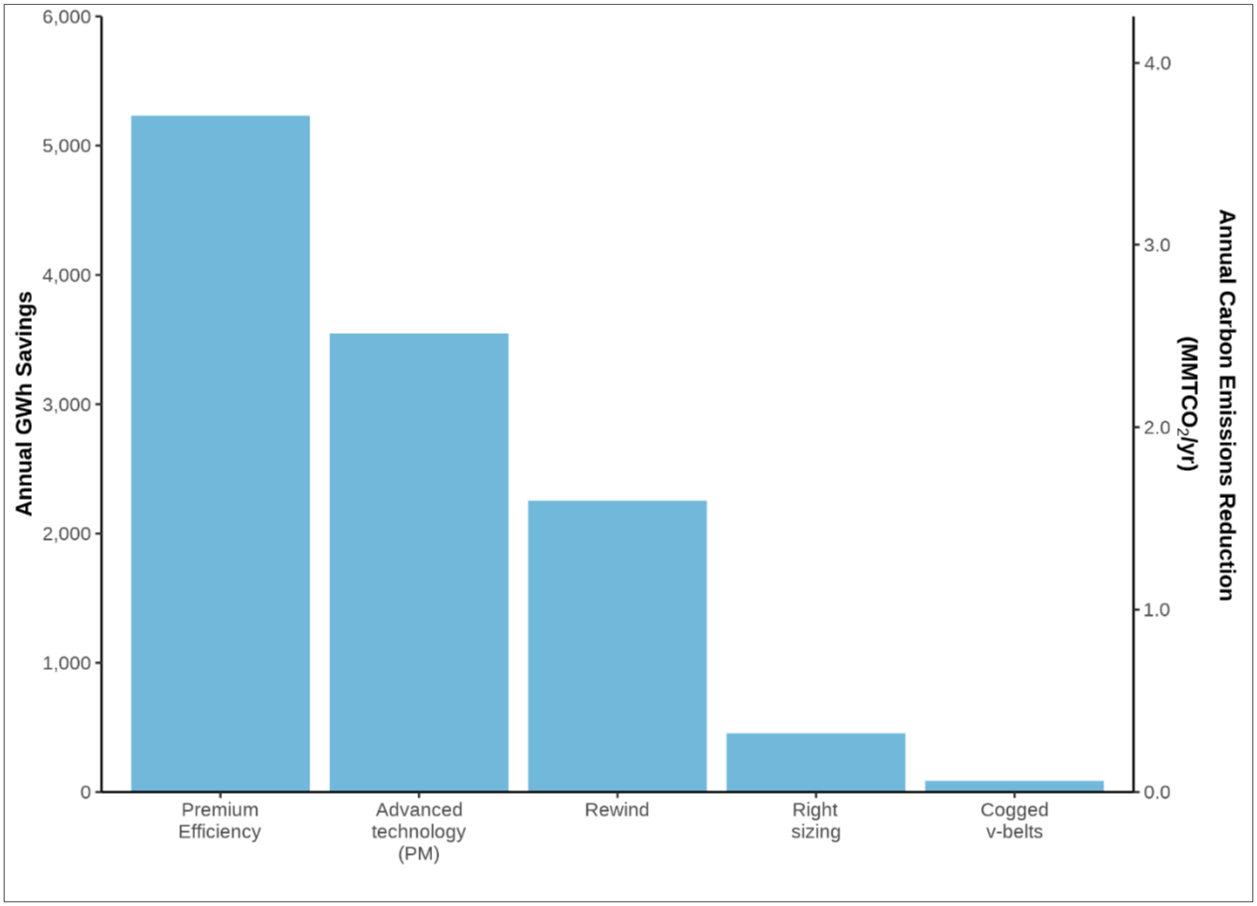


Figure 23: Magnitude of energy and CO_2 savings opportunities for industrial materials processing systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

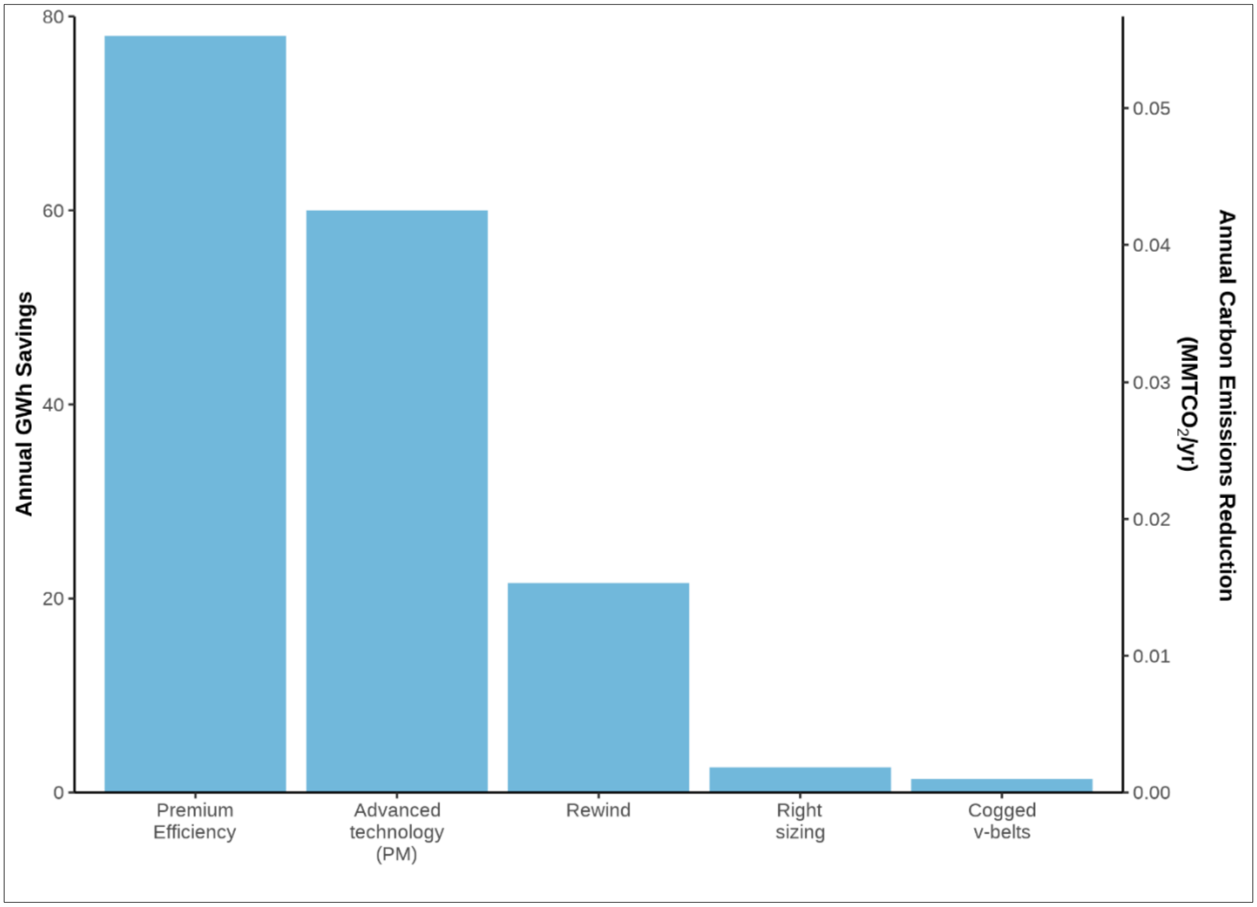


Figure 24: Magnitude of energy and CO_2 savings opportunities for commercial materials processing systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Table 48 shows the information presented in Figure 23 and Figure 24, along with the accompanying annual cost savings. The annual energy consumption, CO_2 emissions, and costs for operating industrial and commercial refrigeration systems are also shown. Four hundred and forty-one million dollars and nearly $11 million of energy savings could be realized with the adoption of more efficient motors alone in the commercial and industrial sectors, respectively.

Table 48: Annual energy, CO_2, and cost savings for industrial and commercial materials processing systems for the measures evaluated

	Energy (GWh/yr)	CO_2 Emissions (CO_2/yr)	Cost (million $/yr)
Industrial			
Baseline	155,783	110.5	13,553
Savings estimates			
Premium Efficiency motor upgrade	5,232	3.7	439
Rewind	2,254	1.6	189
Advanced technology (PM)	3,644	2.6	306
Right sizing	455	0.3	38
Cogged V-belts	88	0.1	7
Commercial			
Baseline	1,549	1.1	201
Savings estimates			
Premium Efficiency motor upgrade	78	0.1	11
Advanced technology (PM)	60	0.04	8
Rewind	22	0.02	3
Right sizing	3	0.00	0
Cogged V-belts	1	0.00	0

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with operating industrial and commercial materials processing systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Materials handling

Materials handling systems were found to consume 4% of industrial motor system energy consumption and 2% of commercial motor system energy consumption. Materials handling systems are motor systems used for transporting materials, such as conveyors.

Adoption of advanced motor technologies

Energy savings for materials handling systems can be realized via adoption of advanced motor technologies. The magnitudes of these are shown in Table 49 (for constant load materials handling systems) and Table 50 (for variable load materials handling systems that are already fitted with or cannot use a VFD). Savings are for motor systems within the size ranges shown in Table 10.

Table 49: Annual energy, CO_2, and cost savings associated with replacing constant load motors with advanced technologies on industrial and commercial materials handling systems

		PM	SR	SynRM	PM SynRM	CR
		Industrial				
>75%	Energy savings (GWh/yr)	260	272	228	229	151
	CO_2 savings (MMT/yr)	0.18	0.19	0.16	0.16	0.11
	Cost savings ($M/yr)	21	22	19	19	12
<75% with right sizing	Energy savings (GWh/yr)	96	94	81	80	66
	CO_2 savings (MMT/yr)	0.07	0.07	0.06	0.06	0.05
	Cost savings ($M/yr)	8	8	6	7	5
		Commercial				
>75%	Energy savings (GWh/yr)	4	4	3	4	3
	CO_2 savings (MMT/yr)	0.00	0.00	0.00	0.00	0.00
	Cost savings ($M/yr)	0	0	0	0	0
<75% with right sizing	Energy savings (GWh/yr)	7	10	6	7	-
	CO_2 savings (MMT/yr)	0.00	0.01	0.00	0.00	-
	Cost savings ($M/yr)	1	1	1	1	-

Note: Savings are for motor systems within the size ranges shown in Table 10.

Table 50: Annual energy, CO_2, and cost savings associated with adoption of advanced technologies and VFDs for variably loaded industrial and commercial materials handling systems that are currently fitted with a VFD or cannot use a VFD

	PM	SR	SynRM	PM SynRM
	Industrial			
Energy savings (GWh/yr)	315	314	274	264
CO_2 savings (MMT/yr)	0.22	0.22	0.19	0.19
Cost savings ($M/yr)	27	27	23	23
	Commercial			
Energy savings (GWh/yr)	676	702	605	616
CO_2 savings (MMT/yr)	0.48	0.50	0.43	0.44
Cost savings ($M/yr)	75	78	67	68

Note: Savings for SR motors do not include a VFD, as these motors are inherently variable speed capable. Savings are for motor systems within the size ranges shown in Table 10.

Summary

A summary of the energy, CO_2, and cost-saving opportunities already evaluated in this report attributable to materials handling systems is provided in Figure 25 (industrial) and Figure 26 (commercial). For both sectors, upgrading to higher efficiency motors constitutes the greatest opportunity for energy and CO_2 emissions reduction. Upgrading to a more efficient motor (e.g., Premium Efficiency or PM) could lead to as much as a 3% reduction in industrial materials handling energy consumption. Upgrading to an advanced technology (e.g., PM) motor would lead to a 7% reduction in commercial systems. When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other.

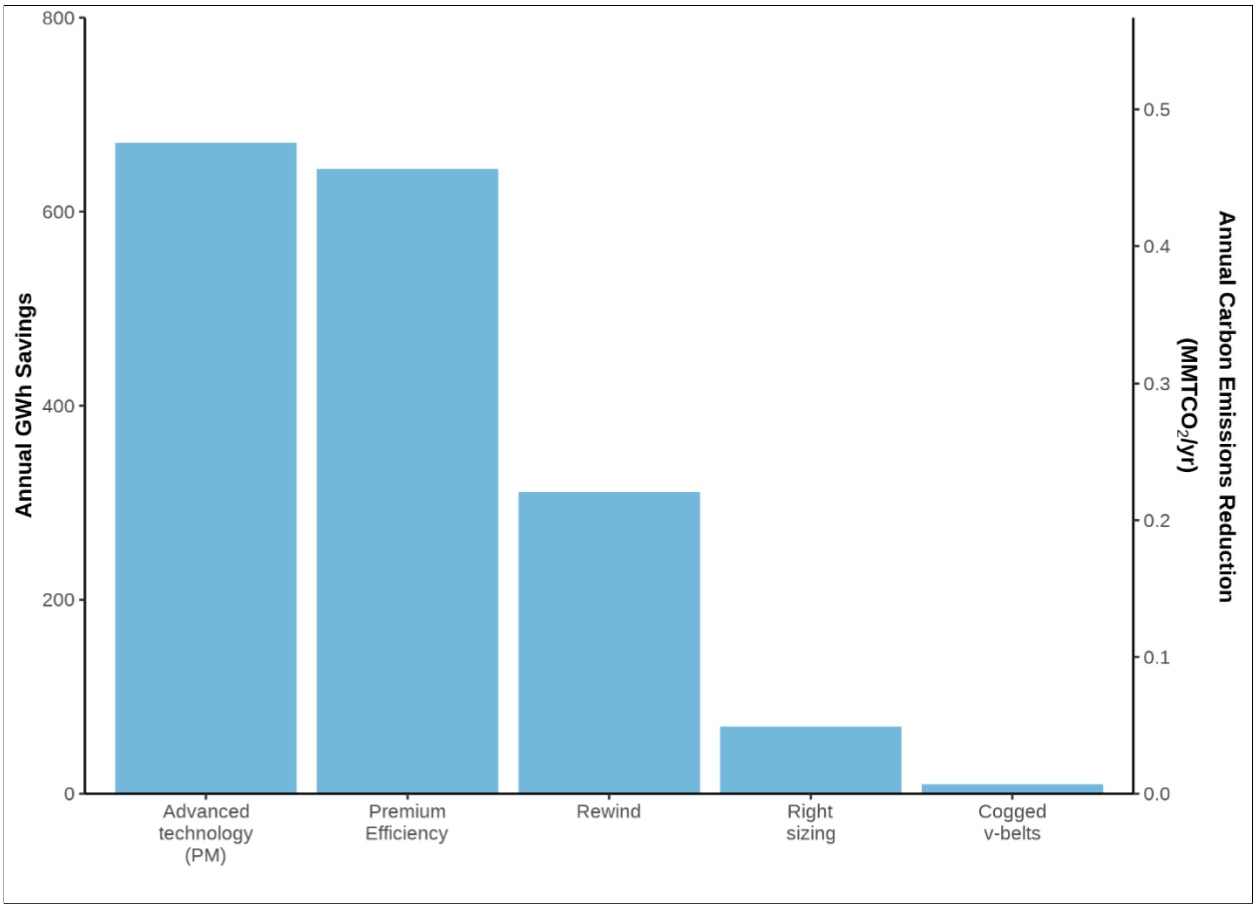


Figure 25: Magnitude of energy and CO_2 savings opportunities for industrial materials handling systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

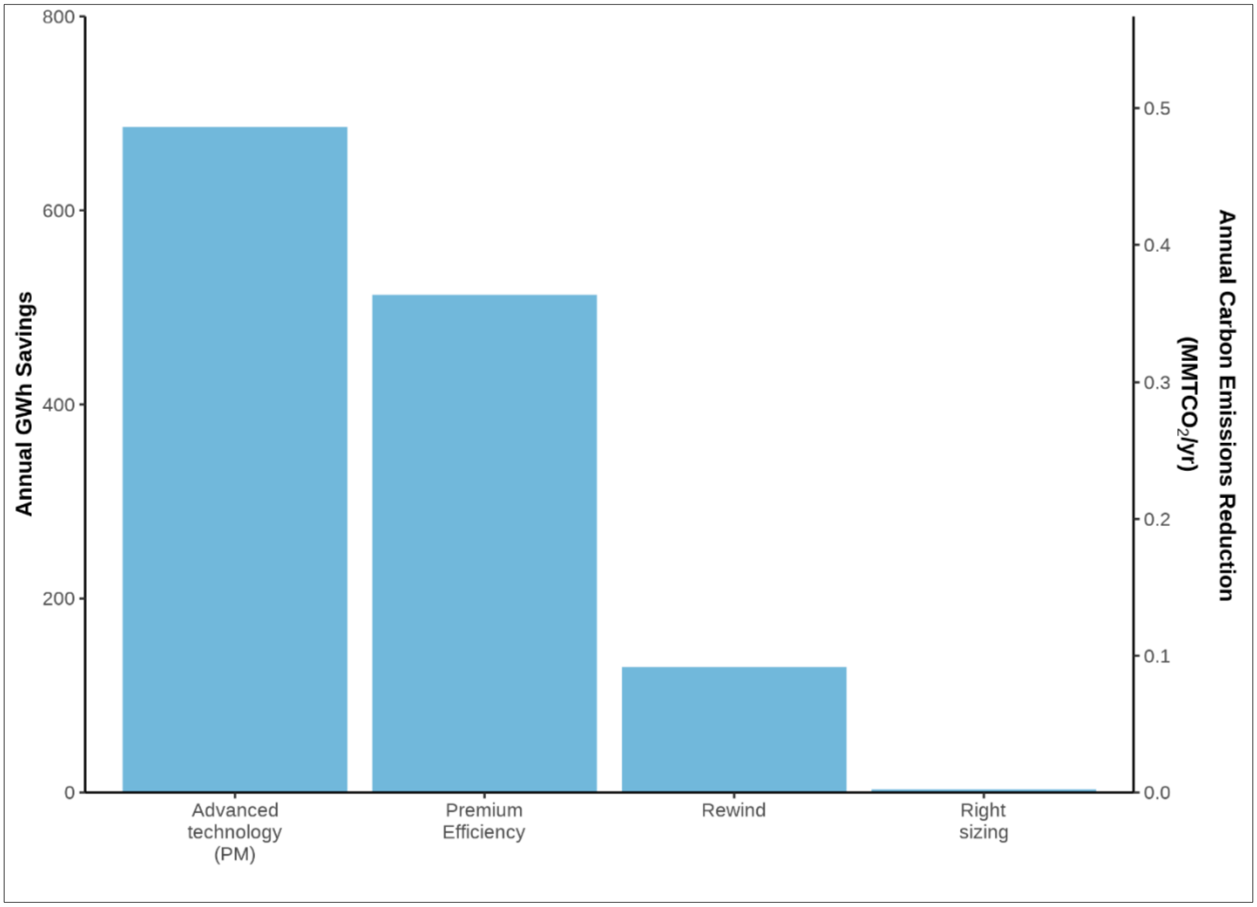


Figure 26: Magnitude of energy and CO_2 savings opportunities for commercial materials handling systems. Savings from adoption of advanced technologies are for motor systems within the size ranges shown in Table 10.

Table 51 shows the information presented in Figure 25 and Figure 26, along with the accompanying annual cost savings. The annual energy consumption, CO_2 emissions, and costs for operating industrial and commercial materials processing systems are also shown. Over $54 million and over $69 million of energy cost savings could be realized with the adoption of Premium Efficiency motors in the commercial and industrial sectors, respectively.

Table 51: Annual energy, CO_2, and cost savings for industrial and commercial materials handling systems for the measures evaluated

	Energy (GWh/yr)	CO_2 Emissions (CO_2/yr)	Cost (million $/yr)
Industrial			
Baseline	19,998	14.2	1,740
Savings estimates			
Premium Efficiency motor upgrade	644	0.5	54
Advanced motor technology (PM)	671	0.5	56
Rewind	311	0.2	26
Right sizing	69	0.05	6
Cogged V-belts	10	0.01	1
Commercial			
Baseline	9,282	6.6	1,207
Savings estimate			
Advanced technology (PM)	686	0.5	93
Premium Efficiency motor upgrade	513	0.4	69
Rewind	129	0.1	17
Right sizing	3	0.00	0

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with operating industrial and commercial materials handling systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another.

Conclusion

U.S. industrial and commercial sectors have realized substantial reductions in motor system energy consumption, with the U.S. as a global leader in setting minimum energy performance standards for motors. This report shows there are still some efficiency gains from existing motor efficiency levels, and even greater energy savings are achievable from considering the broader system that begins with electricity coming into the facility and ends with mechanical power being transmitted to an end-use application. These savings are shown to be realized as a result of a variety of energy efficiency actions, such as implementation of VFDs, appropriately sizing each component of the system, eliminating losses within the fluid distribution systems (e.g., repairing compressed air leaks), and adoption of advanced technologies.

With the publication of the Volume 1 report, the current state of installed motor systems has been comprehensively evaluated and documented, allowing for the determination of the potential energy, cost, and CO_2 savings associated with implementation of motor system energy efficiency measures and advanced technologies. These results are broken out by various factors, such as driven equipment type and sector.

With the urgent need to decarbonize the U.S. economy, this report targets the largest opportunities in motor systems. Adoption of the measures and technologies identified would represent a critical path forward towards cost-effectively decarbonizing the industrial and commercial sectors.

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Appendix A: Savings Estimates by Industrial Subsector

In this appendix, tables 52–57 show the electricity, cost, and CO_2 emissions associated with motor systems and the reduction potential associated with the measures evaluated in this report for industrial subsectors with a significant share of industrial sector motor system electricity consumption. These subsectors include (% of industrial motor system electricity consumption in parentheses): Chemicals (19%), Primary Metals (12%), Food (9%), Paper (8%), Plastics and Rubber (7%), and Petroleum Refining (7%). When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other. Also, note that due to data limitations, savings from advanced motor technologies were not evaluated across all size ranges. See Table 10 for the size ranges evaluated for advanced motor technologies.

Chemicals

Table 52: Annual energy, CO_2, and cost savings in the Chemicals subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	105,699	9,196	74.9
Savings estimates			
Premium Efficiency motor upgrade	2,780	234	2.0
Rewind	1,576	132	1.1
Right sizing	151	13	0.1
VFD	10,459	879	7.4
Cogged V-belts	63	5	0.04
Reduce pressure set point	115	10	0.1
Install sequencer	136	11	0.1
Eliminate inappropriate uses	1,145	96	0.8
Compressed air distribution system improvements	1,255	105	0.9
Impeller trimming	815	68	0.6
Pump distribution system improvements	897	75	0.6
Air duct distribution system improvements	876	74	0.6
Advanced technologies	-	-	-
PM	8,621	680	6.1
SR	6,782	542	4.8
SynRM	8,468	667	6.0
PM SynRM	5,897	468	4.2
CR	306	26	0.2

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Primary Metals

Table 53: Annual energy, CO_2, and cost savings in the Primary Metals subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	63,917	5,561	45.3
Savings estimates			
Premium Efficiency motor upgrade	2,701	227	1.9
Rewind	939	79	0.7
Right sizing	63	5	0.0
VFD	4,006	337	2.8
Cogged V-belts	42	4	0.0
Reduce pressure set point	29	2	0.0
Install sequencer	145	12	0.1
Eliminate inappropriate uses	582	49	0.4
Compressed air distribution system improvements	1,397	117	1.0
Impeller trimming	308	26	0.2
Pump distribution system improvements	385	32	0.3
Air duct distribution system improvements	1,528	128	1.1
Advanced technologies	-	-	-
PM	4,897	405	3.5
SR	4,582	380	3.2
SynRM	4,793	396	3.4
PM SynRM	4,011	333	2.8
CR	322	27	0.2

Note: The “baseline” annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Food

Table 54: Annual energy, CO_2, and cost savings in the Food subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	47,585	4,140	33.7
Savings estimates			
Premium Efficiency motor upgrade	1,343	113	1.0
Rewind	651	55	0.5
Right sizing	29	2	0.0
VFD	4,593	386	3.3
Cogged V-belts	39	3	0.0
Reduce pressure set point	41	3	0.0
Install sequencer	7	1	0.0
Eliminate inappropriate uses	687	58	0.5
Compressed air distribution system improvements	1,376	116	1.0
Impeller trimming	1,143	96	0.8
Pump distribution system improvements	111	9	0.1
Air duct distribution system improvements	408	34	0.3
Advanced technologies	-	-	-
PM	4,688	389	3.3
SR	2,656	223	1.9
SynRM	4,608	382	3.3
PM SynRM	2,307	194	1.6
CR	158	14	0.1

Note: The “baseline” annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Paper

Table 55: Annual energy, CO_2, and cost savings in the Paper subsector for the measures evaluated

	Electricity (GWh/yr)	**Cost (million $/yr)**	**CO_2 (MMT/yr)**
Baseline	45,026	3,917	31.9
Savings estimates			
Premium Efficiency motor upgrade	1,578	133	1.1
Rewind	726	61	0.5
Right sizing	324	27	0.2
VFD	3,116	262	2.2
Cogged V-belts	25	2	0.0
Reduce pressure set point	11	1	0.0
Install sequencer	14	1	0.0
Eliminate inappropriate uses	22	2	0.0
Compressed air distribution system improvements	179	15	0.1
Impeller trimming	1,195	100	0.8
Pump distribution system improvements	1,388	117	1.0
Air duct distribution system improvements	711	60	0.5
Advanced technologies	-	-	-
PM	2,161	180	1.5
SR	1,401	116	1.0
SynRM	2,114	176	1.5
PM SynRM	1,215	101	0.9
CR	76	6	0.1

Note: The “baseline” annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Plastics and Rubber

Table 56: Annual energy, CO_2, and cost savings in the Plastics and Rubber subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	39,898	3,471	28.3
Savings estimates			
Premium Efficiency motor upgrade	1,317	111	0.9
Rewind	552	46	0.4
Right sizing	277	23	0.2
VFD	1,586	133	1.1
Cogged V-belts	7	1	0.02
Reduce pressure set point	97	8	0.1
Install sequencer	44	4	0.03
Eliminate inappropriate uses	456	38	0.3
Compressed air distribution system improvements	675	57	0.5
Impeller trimming	303	25	0.2
Pump distribution system improvements	138	12	0.1
Air duct distribution system improvements	701	59	0.5
Advanced technologies	-	-	-
PM	3,051	224	2.2
SR	2,808	211	2.0
SynRM	2,948	217	2.1
PM SynRM	2,462	185	1.7
CR	313	21	0.2

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Petroleum Refining

Table 57: Annual energy, CO_2, and cost savings in the Petroleum Refining subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	39,269	3,416	27.8
Savings estimates			
Premium Efficiency motor upgrade	797	67	0.6
Rewind	520	44	0.4
Right sizing	47	4	0.03
VFD	6,626	557	4.7
Cogged V-belts	19	2	0.01
Reduce pressure set point	27	2	0.02
Install sequencer	51	4	0.04
Eliminate inappropriate uses	26	2	0.02
Compressed air distribution system improvements	413	35	0.3
Impeller trimming	544	46	0.4
Pump distribution system improvements	578	49	0.4
Air duct distribution system improvements	235	20	0.2
Advanced technologies	-	-	-
PM	5,358	482	3.8
SR	4,007	358	2.8
SynRM	5,339	481	3.8
PM SynRM	3,845	344	2.7
CR	27	2	0.02

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Appendix B: Savings Estimates by Commercial Subsector

In this appendix, tables 58–63 show the electricity, cost, and CO_2 emissions associated with motor systems—and the reduction potential associated with the measures evaluated in this report—for commercial subsectors with a significant share of commercial sector motor system electricity consumption. These subsectors include (% of commercial motor system electricity consumption in parentheses): Office (18%), Education (14%), Lodging (11%), Warehouse and Storage (8%), Food Service (7%), and Healthcare Inpatient (7%). When examining the savings opportunities, caution must be taken when summing the savings opportunities from multiple measures, as one may influence the other. Also, note that due to data limitations, savings from advanced motor technologies were not evaluated across all size ranges. See Table 10 for the size ranges evaluated for advanced motor technologies.

Office

Table 58: Annual energy, cost, and CO_2 cost savings in the Office subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	93,335	12,134	66.2
Savings estimates			
Premium Efficiency motor upgrade	2,128	287	1.5
Rewind	1,300	176	0.9
Right sizing	55	7	0.04
VFD	11,930	1,611	8.5
Cogged V-belts	21	3	0.01
Reduce pressure set point	33	4	0.02
Install sequencer	10	1	0.01
Compressed air distribution system improvements	20	3	0.01
Impeller trimming	59	8	0.04
Pump distribution system improvements	233	31	0.2
Air duct distribution system improvements	2,660	359	1.9
Advanced technologies	-	-	-
PM	14,544	1,546	10.3
SR	15,232	1,632	10.8
SynRM	14,258	1,511	10.1
PM SynRM	13,532	1,441	9.6
CR	588	80	0.4

Note: The “baseline” annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Education

Table 59: Annual energy, CO_2, and cost savings in the Education subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	76,339	9,924	54.1
Savings estimates			
Premium Efficiency motor upgrade	2,597	351	1.8
Rewind	1,062	143	0.8
Right sizing	313	42	0.2
VFD	11,546	1,559	8.2
Cogged V-belts	703	95	0.5
Compressed air distribution system improvements	19	3	0.01
Impeller trimming	172	23	0.1
Pump distribution system improvements	276	37	0.2
Air duct distribution system improvements	1,417	191	1.0
Advanced technologies	-	-	-
PM	14,266	2,018	10.1
SR	15,918	2,294	11.3
SynRM	14,035	1,985	10.0
PM SynRM	13,973	1,984	9.9
CR	1,210	150	0.9

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Lodging

Table 60: Annual energy, CO_2, and cost savings in the Lodging subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	59,189	7,695	42.0
Savings estimates			
Premium Efficiency motor upgrade	1,597	216	1.1
Rewind	825	111	0.6
Right sizing	114	15	0.1
VFD	5,636	761	4.0
Cogged V-belts	36	5	0.03
Compressed air distribution system improvements	5	1	0.0
Impeller trimming	433	58	0.3
Pump distribution system improvements	207	28	0.1
Air duct distribution system improvements	547	74	0.4
Advanced technologies	-	-	-
PM	7,001	972	5.0
SR	7,536	1,041	5.3
SynRM	6,816	951	4.8
PM SynRM	6,894	961	4.9
CR	643	81	0.5

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Warehouse and Storage

Table 61: Annual energy, CO_2, and cost savings in the Warehouse and Storage subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	40,054	5,207	28.4
Savings estimates			
Premium Efficiency motor upgrade	1,773	239	1.3
Rewind	545	74	0.4
Right sizing	274	37	0.2
VFD	2,801	378	2.0
Cogged V-belts	40	5	0.03
Install sequencer	41	6	0.03
Compressed air distribution system improvements	86	12	0.1
Pump distribution system improvements	28	4	0.02
Air duct distribution system improvements	1,121	151	0.8
Advanced technologies	-	-	-
PM	5,128	625	3.6
SR	4,043	525	2.9
SynRM	4,919	596	3.5
PM SynRM	3,596	469	2.5
CR	957	157	0.7

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Food Service

Table 62: Annual energy, CO_2, and cost savings in the Food Service subsector for the measures evaluated

	Electricity (GWh/yr)	Cost (million $/yr)	CO_2 (MMT/yr)
Baseline	34,776	4,521	24.7
Savings estimates			
Premium Efficiency motor upgrade	1,727	233	1.2
Rewind	485	65	0.3
Right sizing	49	7	0.03
VFD	5,863	792	4.2
Cogged V-belts	42	6	0.03
Pump distribution system improvements	81	11	0.1
Air duct distribution system improvements	1,190	161	0.8
Advanced technologies	-	-	-
PM	7,718	1,160	5.5
SR	7,975	1,198	5.7
SynRM	7,458	1,119	5.3
PM SynRM	7,505	1,127	5.3
CR	964	161	0.7

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.

Healthcare Inpatient

Table 63: Annual energy, CO_2, and cost savings in the Healthcare Inpatient subsector for the measures evaluated

	Electricity (GWh/yr)	**Cost (million $/yr)**	**CO_2 (MMT/yr)**
Baseline	34,759	4,519	24.6
Savings estimates			
Premium Efficiency motor upgrade	934	126	0.7
Rewind	439	59	0.3
Right sizing	21	3	0.01
VFD	4,796	647	3.4
Cogged V-belts	40	5	0.03
Compressed air distribution system improvements	187	25	0.1
Impeller trimming	256	35	0.2
Pump distribution system improvements	142	19	0.1
Air duct distribution system improvements	702	95	0.5
Advanced technologies	-	-	-
PM	3,481	401	2.5
SR	3,549	408	2.5
SynRM	3,422	394	2.4
PM SynRM	3,065	349	2.2
CR	104	14	0.1

Note: The "baseline" annual energy consumption, CO_2 emissions, and costs associated with motor systems are also shown for context. Caution must be taken when summing savings across measures to account for the impact of one measure on another. See Table 10 for the size ranges evaluated for advanced motor technologies.