EFFICIENCY POTENTIAL AND DATA DEVELOPMENT FOR INDUSTRIAL ELECTRIC MOTOR-DRIVEN SYSTEMS

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ABSTRACT

Traditionally, the focus of efficiency efforts for electric motor-driven systems has been on the electric motor itself. This emphasis is readily observed by reviewing the numerous utility DSM programs that have provided incentives strictly for the motor component of the drive system. Such efforts are limited in the overall potential for energy use reductions, and may be neglecting significant factors in the overall efficiency of a drive system. One goal of programs such as the DOE's US Motor Challenge Program is to bring a broader perspective to efficiency considerations of drive systems, thereby ensuring that all sources of inefficiency are addressed appropriately.

We can view a motor-driven system as being composed of a number of components including the motor, transmission, driven equipment or appliance, controls and ancillary equipment. The type and capacity of all of these components can have significant effects on the overall system efficiency. The system efficiency is also largely a function of the original design, current application strategy, and maintenance procedures.

In this paper we will discuss a systems approach for establishing efficiency improvements, detailing how the various system components effect motor-driven system efficiency. A protocol to classify and describe motor systems, across manufacturing sectors and for a range of specific industrial processes, is described. Two specific case study examples of drive systems in a number of industry types and processes will be presented. The energy reduction goals that could be achieved with retrofits of motors alone will be compared to the broader reduction goals possible when the complete electric motor-driven system is studied.

INTRODUCTION

More than two thirds of the electricity used by U.S. industry is for electric motor-driven systems. Such motor "systems" consist of motors, drives and control systems, and the connected mechanical loads and processes. There are numerous means to reduce energy consumption in electric motor-driven systems. Traditionally, the energy saving approach that has received the most attention is the installation of energy efficient motors. However, the savings potential is considerably larger if we focus on the full drive system by considering measures such as electronic adjustable speed drives, improved motor-driven equipment, and advanced motor-driven processes or systems.

Energy savings from efficient electric motor systems represent the largest potential source of savings among industrial end uses. The Department of Energy has established preliminary estimates that improving the efficiency of industrial electric motor systems could save approximately 240 billion kWh of electricity annually, with an associated reduction of electric demand of 50,000 MW, and an electric bill reduction of $13 billion. These figures correspond to an annual decrease in greenhouse gas emissions by 44 million metric tons[1].

The Department of Energy (DOE) Office of Industrial Technologies has taken the lead in attempting to create a national focus on energy efficient industrial motor-driven systems. They have developed the DOE

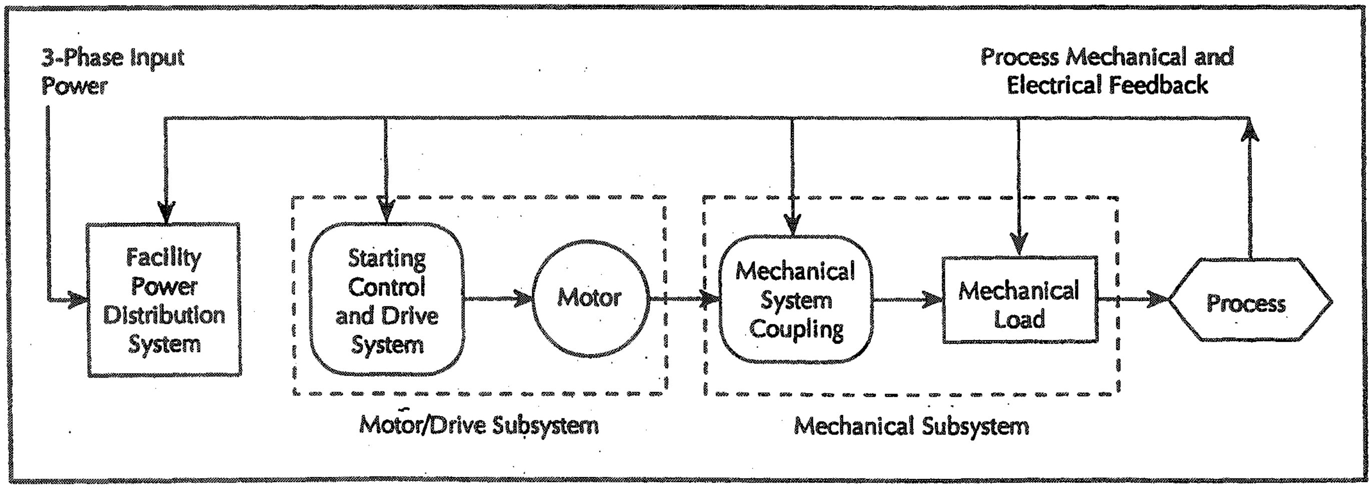
Motor Challenge Program with the objective of quantifying potential electric motor-driven system energy saving and promoting the systems approach to energy efficient electric motor-driven technology.

Technology Discussion

There are several components and operations that must be successfully integrated in order to achieve an efficient electric motor-driven system. The components that typically make up such a system include: electric motors; electronic adjustable speed drives; and driven mechanical equipment (pumps, fans, air compressors, conveyors, etc.). System efficiency can be achieved by the use of efficient separate components, but is also dependent on an efficient system design and integration, as well as efficient operation and maintenance.

The different components of an industrial electric motor-driven system are shown in Figure 1, *Electric Motor System*. From the figure we can see that the electric motor is only one component of the drive system. While savings of 3 to 10 percent are often possible through implementation of energy efficient electric motors, additional and potentially more significant savings can be achieved through retrofit or operational modification of other aspects of the system. For example, implementation of electronic adjustable speed drives can improve the overall system efficiency by allowing driven equipment to operate at optimum speed and torque points that require lower input kW. Also, adjustable speed drives reduce the requirement for belt drives and other speed reducing power transmission devices that are sources of inefficiency. Retrofit or modifications to the driven equipment (air compressors or pumps, for example) can result in energy savings considerably in excess of the 3 to 10 percent achievable with motor retrofits. In essence, focus on motors alone results in a disregard for the potential to achieve considerably greater savings by improving the efficiency and operation of other aspects of the motor-driven system.

Figure 1
Motor-Driven System Schematic



Through roundtable discussions[1] administered by the DOE's Office of Industrial Technologies experts on motor-driven systems and industrial technologies identified four areas of savings opportunity for these systems. These areas are presented in Table 1.

Table 1
Electric Motor-Driven Systems
Efficiency Improvement Opportunities

Efficiency Opportunity	Description	Estimated Percentage Savings Potential*
Efficient Motor Component	Retrofit Standard Motors (80-90% Efficient) with High Efficiency Motors (90-95% Efficient)	18 Percent
Process Optimization	Downsizing of Driven Equipment; Installing More Efficient Driven Equipment; Alternative Operation or Process.	33 Percent
Improved Motor-Mechanical Subsystem Matching	Better Matching of Motor-Drives to Mechanical System and Process Requirements with Adjustable Speed Drives (ASDs)	41 Percent
Electrical Distribution Correction	Balancing of Three Phase Voltage Supply; Upgrading of In-Plant Distribution Equipment; Power Factor Improvement	8 Percent

* These figures represent percentage of the overall savings potential in industrial motor-driven systems.

As part of the US Motor Challenge Program, the DOE is performing an assessment of industrial electric motor-driven systems. The objective of this assessment is to help target the emphasis of DOE strategies to encourage earlier adoption of energy efficient systems. A major component of the assessment is to develop a comprehensive and reliable baseline of the current installed base of operating electric motor-driven systems equipment within the industrial sector. The baseline will be established from the bottom up, through field measurements and statistical surveys at industrial facilities throughout the United States. Historical and other secondary data sources will be used to enhance and reinforce the baseline database.

The subsequent sections of this paper will describe the planned efforts to develop the national electric motor-driven systems baseline database. The development of such a database will allow for a better understanding of the characteristics of electric motor-driven systems and will lead to the development of demonstration cases that indicate the savings potential that can be achieved by considering the systems approach rather than focusing solely on energy efficient motors or other portions of the full system.

The paper will then review two industrial case studies comparing the energy use reduction potential for specific applications - one for an air compressor system and one for an injection molding operation. Savings listed for these systems will be compared to the energy reduction that would be achieved by considering only an energy efficient motor retrofit.

ELECTRIC MOTOR-DRIVEN SYSTEMS DATA DEVELOPMENT APPROACH

The most recent national assessment of industrial electric motor-driven systems was completed in the late 1970's[2]. Due to the age of the database and because the data collection was not field based, the study now needs to be updated. The overall objective of the current DOE data development effort is to produce the most useful, comprehensive, and accurate database of the universe of installed U.S. industrial motor-driven systems given constraints on funding, schedule, and the coverage of existing information. Building the database of motor systems will be done using a combination of sources, including:

- primary data collected through audits conducted specifically for this project;
- primary data collected through audits conducted by other parties concurrent with this effort; and
- existing audit databases and other secondary sources.

The work elements of the expected data development process are summarized in the following sections.

Research and Planning

Once the policy and program planning, management, and evaluation applications for the database are identified, the usefulness of secondary audit data sources for sample design can be assessed. The existing literature and data on industrial motor-driven systems is useful for developing a motor system classification. Finally, a framework for sample design, data collection, database development, and data analysis must be developed.

Secondary data sources. Secondary data sources are important resources for framing the sampling and data collection efforts. This information is important in sample stratification and in developing indices for projecting survey data to the larger population. The sources of particular interest are:

- the Manufacturing Energy Consumption Survey (MECS);
- the Annual Survey of Manufacturers;
- Dun and Bradstreet data;
- unpublished data compiled by the National Electrical Manufacturers Association (NEMA);
- sales data maintained by large distributors; and,
- utility audit and survey databases.

Relevant literature and a motor-driven systems definition. One key question to be addressed concerns approaches to classifying motor-driven systems. Many industrial motor systems can be described at three levels: components (the motor, drive, blower, etc.), packages (air compressor package), and systems (compressed air system, conveyor system). In developing the database and conducting the data collection, issues will surface regarding the appropriate level at which to make observations.

Preliminary field tests. Field tests of data collection techniques can address specific research issues. These will include:

- testing alternative methods for classifying motor-driven systems in the field;
- comparing data obtained through on-site observation to data obtained through telephone surveys of site personnel in the same facilities to assess the feasibility of nested sampling and ratio estimation approaches.

Secondary Audit Data

There are numerous existing databases of useful on-site observations of motor systems. The availability and appropriateness of these data sets for incorporation into the national baseline database should be assessed. Furthermore, concurrent field data collection projects planned by utilities and other parties may be influenced to use common protocols through partnership arrangements. It is anticipated that some of these data can be acquired or accessed to enhance the motor systems database.

In summary, the secondary audit data development process will include the following activities:

- Identify and obtain existing secondary audit data resources.
- Assess the quality and usefulness of existing audit data resources.
- Share concurrent data collection efforts.
- Negotiate acquisition of, or access to, data records.
- Collect "lessons learned" by other organizations in collecting and using motor systems data.

Sample Design

A sampling approach must meet the study objectives developed through initial research and planning within the constraints on the number of sites visited and surveyed by phone. After a sample frame is identified, a sampling strategy is developed.

Identify the sample frame. Ideally, the sample frame or list from which the sample is drawn would have the following attributes:

- inclusion of all facilities in the targeted SIC classifications;
- data attached to each facility record that characterizes it in terms of economic activity and size; and,
- contact information, including addresses, telephone numbers, and responsible personnel.

Develop the basic sampling strategy. The sample design will provide:

- coverage of the range of facilities by type and SIC;
- geographic coverage;
- coverage of application types;
- precision in the estimates of population parameters such as hours of use and part load;
- precision in the estimates of population proportions, such as the percentage of efficient motors in the installed base; and,
- precision of estimates in key subgroups of the population, defined by SIC or application.

The final sample strategy will balance these objectives according to priorities set during initial research and planning activities.

Observations on Sampling Strategies

Preliminary analysis of population data provides insights into potential sampling strategies and tradeoffs among alternative approaches. The following paragraphs briefly describe some key observations.

Concentration of motor energy usage and sample allocation by SIC, region, and size. The distribution of total motor energy use is highly concentrated in a few industries. The top five two-digit SIC codes (Chemicals, Paper, Primary Metal, Food, Petroleum) account for more than half of total motor electric use in the manufacturing sector. There are, however, wide variations in motor electric consumption by SIC code by region[3]. Standard sampling procedure suggests that allocation of sample points in proportion to usage will result in more representative and precise estimates of population proportions and parameters.

Distribution of energy savings potential. A recent study by the American Council for an Energy-Efficient Economy indicated that opportunities for motor systems energy savings are concentrated in the same SICs as energy usage.

Diversity within SIC codes. Informal review of industry literature suggests that facilities in some industries encompass a wider variety of processes and systems than others. For example, it appears that food processing applications are very diverse.

Sampling within facilities. It is not practical or necessary to collect detailed information on every motor at every site visited. On-site sampling procedures will ensure the selection of a representative sample of motors at each site.

Field Data Collection

The prescribed data from the sample of sites will be collected, maximizing rate of response (to limit bias), and ensuring accuracy of data. The variables to be collected will include motor size, type, duty factor, operating load factor, age, nameplate efficiency, spares inventory, average annual hours of usage, energy efficient system market penetration, population of rewound motors, use of belt drives, ASD applicability, over sizing tendencies for motors and mechanical systems as well as others that will be identified during initial research and planning at the outset of the project.

Data Consolidation

Data will be mapped from both primary and secondary audit sources into a database structure so that all data can be analyzed using consistent routines.

After producing the baseline motor-driven systems database, analysis on the data can be performed based on DOE's current research objectives. The goal of this analysis will be to optimize the direction of DOE efforts to nationally promote complete efficient electric motor-driven system technologies rather than just efficient motors.

CASE STUDIES

Two case studies are described below to demonstrate the value of the system approach for motor-drive efficiency, rather than solely pursuing the energy efficient motor strategy. For each case study, the existing electric motor-driven system is described. Then, the application of energy efficient motors is reviewed followed by a discussion of the application of systems approach measures. These approaches are then compared. As is demonstrated in these case studies, savings that can be achieved are markedly higher when we consider measures that address the entire electric motor-driven system.

Case Study 1: Multiple Air Compressor System

System Description. Case 1 considers the air compressor system at an electrical conduit and fitting manufacturer in Connecticut. The operations of this company include formation of sand molds, iron melting and casting, plating, grinding, machining, scrap recovery, and packing and shipping.

There are six air compressors at this industrial site, using 2.7 million kWh annually, representing approximately 15 percent of the overall plant electric use. All of the air compressors are rotary screw type machines, and they are in two locations: the old boiler house and the machine shop area. These two supply sources are interconnected to form one air distribution system.

Table 2 lists the compressors that are used in the existing system, and summarizes the air compressor's manufacturer and model number, control scheme, location, motor size, full-load CFM and kW input requirements, and the percentage usage. Note that a full load "efficiency" value for these compressors can be determined by dividing the full load kW by the full load CFM, resulting in a kW per CFM figure. Different types of compressors (rotary screw, reciprocating, centrifugal, scroll, etc.) have different full load efficiency values. Further, different compressors have different part load efficiency characteristics.

Table 2
Existing Compressed Air System Units

ID	Compressor Make/Model	Type	Control	Location	Size HP	Est. Full Ld. CFM	Est. Full Ld. kW	Est. Usage
AC-1	Atlas Copco GA1407 Pack	Air-cooled Rotary	Load/No Load	Old Boiler House	200 HP	1,000	193.6	84%
AC-2	Atlas Copco GA75	Air-cooled Rotary	Load/No Load	Old Boiler House	75 HP	350	72.6	standby
AC-3	Atlas Copco GA345-60	Air-cooled Rotary	Load/No Load	Machine Shop	60 HP	300	57.5	95%
AC-4	Atlas Copco GA509-50	Air-cooled Rotary	Load/No Load	Machine Shop	50 HP	235	48.4	27%
AC-5	Worthington Rollair 100	Air-cooled Rotary	Modulating	Old Boiler House	100 HP	495	94.8	70%
AC-6	Worthington Rollair 60	Air-cooled Rotary	Modulating	Machine Shop	60 HP	300	58.7	90%
				Totals	545 HP	2,680	525.6	

Energy Efficient Motor Application. The simplest consideration to improve the efficiency of this system of air compressors involves installation of energy efficient motors to replace the standard motors currently used on the compressors. Most of the motors are large and the percentage savings are lower than they would be achieved for smaller motors. The energy savings from the motor retrofit is estimated to be 84,350 kWh annually, just over 3 percent of the current electricity used by the air compressors.

Energy Efficient Compressor and Alternative Control System Application. Additional or alternative savings are achievable in this air compressor system by replacing two of the air compressors with higher efficiency reciprocating units, and installing a controller that would optimize the operation of the system so that the ideal number of compressors is used in an effort to minimize energy use. The controller would also schedule the compressors with the best part-load operating efficiency (i.e., the new reciprocating machines) to be the "peaking" units for the system, while other units would serve baseload requirements.

Table 3 shows the selected air compressors in the proposed system. AC-5A and AC-6A replace units AC-5 and AC-6 of the original system. Note the low full load energy use of the reciprocating air compressors is approximately 0.165 kW per CFM. This is considerably better than that of the existing equipment, all of which use greater than 0.19 kW per CFM at full load conditions. Part load performance data were necessary for our analysis of the savings - Table 4 shows such data for the proposed reciprocating air compressors. The total system kW requirements (addressing compressor brake-horsepower, motor efficiency, and auxiliary fans and pumps) are determined at 10 percent loading increments. The total energy savings that result from installation of the new compressors and controls is approximately 392,000 kWh with an associated cost of about $260,000.

Efficient Motor vs. Systems Approach. Energy savings strategies that address an entire electric motor-driven system can be far more complicated than simple installation of retrofit motors. And the costs for such system approach measures can certainly be greater than for efficient motor installations. However, this is not always the case, and in an example like this, the energy reduction associated with the air compressor modifications is 4 to 5 times greater than that for the energy efficient motors. Further, additional savings can be achieved by integrating the compressor, controls, and motor measures to achieve a complete system retrofit.

Table 3
Proposed Compressed Air System Configuration

ID	Compressor Make/Model	Type	Control	Location	Size HP	Est. Full Ld. CFM	Est. Full Ld. kW	Est. Usage
AC-1	Atlas Copco GA1407 Pack	Air-cooled Rotary	Load/No Load	Old Boiler House	200 HP	1,000	193.6	standby
AC-2	Atlas Copco GA75	Air-cooled Rotary	Load/No Load	Old Boiler House	75 HP	350	72.6	standby
AC-3	Atlas Copco GA345-125	Air-cooled Rotary	Load/No Load	Machine Shop	60 HP	300	57.5	12%
AC-4	Atlas Copco GA509-50	Air-cooled Rotary	Load/No Load	Machine Shop	50 HP	235	48.4	4%
AC-5A	Ingersoll Rand LL5A-150	Water-cooled Recip.	2-stage	Machine Shop	150 HP	810	133.3	100%
AC-6A	Ingersoll Rand LL5A-150	Water-cooled Recip.	2-stage	Machine Shop	150 HP	810	133.3	73%
				Totals	685 HP	3,505	638.6	

Table 4
Part Load Data for Proposed Reciprocating Compressors

AC-5A & 6A Ingersoll Rand LL5A-150 Volts: 480

150 HP capacity	100 PSI CFM	% HP	BHP	motor eff.	cooling fan kW	cooling pump kW	Est. P.F.	Est. Amps	Total KW	KW/CFM
100%	810	106%	159	0.930	3.35	2.4	0.900	178.4	133.3	0.165
90%	729	91%	145	0.928	3.00	2.4	0.898	164.0	122.3	0.168
80%	648	83%	132	0.924	2.77	2.4	0.894	150.3	111.6	0.172
70%	567	74%	118	0.917	2.55	2.4	0.887	137.3	101.1	0.178
60%	486	66%	105	0.905	2.34	2.4	0.876	125.0	91.0	0.187
50%	405	57%	91	0.890	2.15	2.4	0.861	113.0	80.8	0.200
40%	324	49%	78	0.870	1.98	2.4	0.842	102.2	71.5	0.221
30%	243	41%	66	0.830	1.82	2.4	0.810	93.8	63.1	0.260
20%	162	33%	53	0.780	1.68	2.4	0.752	87.3	54.5	0.337
10%	81	25%	40	0.690	1.10	2.4	0.670	84.0	46.7	0.577
0%	0	11%	0	0.100	0.00	0.0	0.100	0.0	0.0	0.000

Case Study 2: Injection Molding System

System Description. Case 2 considers motor-driven systems for injection molding machines. A company in Connecticut has eight injection molding machines ranging in size from 30 to 150 tons. These machines comprise essentially a control panel, drive motor, mold, hydraulic pump and material conveying screw.

The drive motor is the prime mover of the hydraulic pump, which in turn actuates both the screw and mold. The molding process may be broken down into five main steps as follows:

- Mold Close - The mold is driven to a closed position.
- Boost & Inject - These two steps are essentially coupled. The output of the hydraulic pump increases significantly and the screw is used to inject molten plastic into the mold.
- Screw Recovery - The screw retreats to its initial position and the hydraulic pump output is throttled to a low pressure.
- Minimum Speed (Cooling) - The drive motor operates in an idle mode and the plastic in the mold is cooled and solidifies.
- Mold Open - The mold is driven open so that the part may be retrieved.

The cooling stage comprises approximately half of the operating cycle time. Since the hydraulic drive unit is idling during this stage, hydraulic fluid is throttled and bypassed around the drive back to pump, though the drive motor is still loaded due to pressure and flow losses.

Energy Efficient Motor Application. The input power to the motor for the 75 ton (20 hp) machine was measured to be 15.28 kW. This represented approximately 91 percent of the full rated motor load. The existing motor had a 88.7 percent full load efficiency, whereas an energy efficient replacement would have an efficiency of 93.0 percent at full load. The predicted annual energy savings over 4420 hours of operation (two shifts) from installing the energy efficient motor on this system and making no other changes would be approximately 3000 kWh, or 4.5 percent. This efficiency measure would have a simple payback period of approximately 6 years given the applicable electric rate for this case.

Variable Speed Drive Application. A variable speed drive (ASD)can be used to retrofit an injection molder primarily to allow the molder's drive motor to use only the amount of power required during each operational step. The output from the existing control panel is fed to the new interface where potentiometers are used to control the inverter, thereby controlling the speed of the drive motor. The potentiometers are adjusted such that the motor delivers only that amount of power required to perform a given function. The cooling stage discussed above comprises approximately half of the operating cycle time. Since the hydraulic drive is idling during this stage, there is a substantial opportunity for energy savings through a ASD application during half of the operating hours of an injection molder.

Savings documented by EPRI[4] for ASD retrofits on fixed fluid delivery injection molding machine drive systems range from 23 to 63 percent and average 41 percent. Furthermore, though newer machines use variable delivery pumps, the majority of existing injection molding machines use fixed fluid delivery.

Efficient Motor vs. Systems Approach. Installing a variable speed drive for the drive motor is a far more effective systems approach than simply installing an energy efficient motor in place of the conventional drive motor in this case. This approach optimizes *system* energy use for this motor-driven technology by reducing energy input to the motor whenever the hydraulic drive unit is idling. Since the idle period is approximately half of each cycle of an injection molding machine, the potential for savings from this approach is substantial. In fact, 41 percent savings from the ASD retrofit is over 900 percent greater savings than that available from the efficient motor installation, though the capital cost of approximately $7,600 is also much greater for the VSD installation.

Still, the investment would pay back in approximately 4.3 years through energy savings in this case. Due to the high cycling frequency of the injection molding process (one cycle generally lasts for one to two minutes) demand savings also accrue, because average demand is equal to metered demand. This is particularly true if multiple machines are operating simultaneously as in this case. The simple payback period becomes 3 years when demand savings are included. Note that this measure is less attractive for injection molding systems employing more than one motor, because ASDs would have to be installed for each motor.

CONCLUSION

Savings of 3 to 10 percent are typically possible through implementation of energy efficient electric motors. However, additional, and often more significant, savings can be achieved through optimizing the complete electric motor-driven system. The two case studies above provide examples of this approach. Implementation of electronic adjustable speed drives, for example, allows lower speed operation of the driven equipment during a portion of the operating cycle with corresponding lower power requirements *from the driven equipment.* Retrofit or modification to the driven equipment also provides greater savings than that from motor retrofits in many cases. To achieve the greatest savings, the complete motor-driven system should be the focus of efficiency projects, rather than the motor alone. The motor-driven systems baseline database being developed for DOE will facilitate promoting this approach.

The goal of programs such as the US Motor Challenge Program is to bring this broad perspective to efficiency considerations of drive systems, thereby ensuring that all sources of inefficiency are addressed appropriately. It is anticipated that adopting this perspective in industrial efficiency efforts will greatly enhance the potential for energy and demand savings in many sectors given the large proportion of industrial energy use by motor-driven systems.

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