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Building Technologies Office

# Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment

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# NOTICE

# ACKNOWLEDGMENTS

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# Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment

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## Acronyms

| | |
|---|---|
| AC | Alternating Current |
| AHU | Air handling unit |
| ARPA-E | Advanced Research Projects Agency-Energy |
| BLDC | Brushless direct current (permanent magnet) motor |
| BTO | U.S. Department of Energy Building Technologies Office |
| BVM | Beverage vending machine |
| CAC | Central air conditioner |
| CSCR | Capacitor Start Capacitor Run |
| CSIR | Capacitor Start Induction Run |
| CUAC | Commercial unitary air conditioning unit |
| DC | Direct Current |
| DOE | U.S. Department of Energy |
| ECM | Electronically commutated motor (permanent magnet) with integrated controls |
| EISA | Energy Independence and Security Act of 2007 |
| EPCA | Energy Policy Conservation Act |
| GaN | Gallium nitride |
| HEMT | High-electron mobility transistors |
| HP | Heat pump |
| HVAC | Heating, ventilation, and air conditioning equipment |
| IEER | Integrated energy efficiency ratio |
| IGBT | Insulated-gate bipolar transistors |
| IPLV | Integrated part load value |
| kWh | Kilowatt-hour |
| MM | Million |
| NEMA | National Electrical Manufacturers Association |
| ODP | Oil Drip Proof, NEMA enclosure type |
| OEM | Original equipment manufacturer |
| PMAC | Permanent magnet alternating current motor |
| PSC | Permanent Split Capacitor |
| PTAC | Packaged terminal air conditioning (or heat pump) unit |
| PWM | Pulse width modulation |
| Quads | Quadrillion Btu |
| RD&D | Research, development, and deployment |
| REACT | Rare Earth Alternatives in Critical Technologies |
| RSIR | Resistance Start Induction Run |
| Si | Silicon |
| Sic | Silicon carbide |
| SPVAC | Single packaged vertical air conditioning (or heat pump) unit |
| SRM | Switched Reluctance Motors |
| TEFC | Totally Enclosed Fan Cooled, NEMA enclosure type |
| TSD | DOE Rulemaking technical support document |

| | |
|---|---|
| UEC | Unit energy consumption |
| VFD | Variable Frequency Drive |
| VSD | Variable Speed Drive |
| WBG | Wide bandgap semiconductors |
| WICF | Walk-in coolers and freezers |

# Executive Summary

This report describes the current state of motor technology and estimates opportunities for energy savings through application of more advanced technologies in a variety of residential and commercial end uses.

The U.S. consumed approximately 96 quadrillion Btu (quads) of primary energy in 2012. Residential and commercial end uses represent approximately 40% of the total energy consumed, as depicted in Figure ES-1. Approximately 10% of total energy consumed can be attributed to electric motor-driven systems in the residential and commercial sectors. Advanced motor technologies provide various opportunities to reduce overall energy consumption in these sectors.

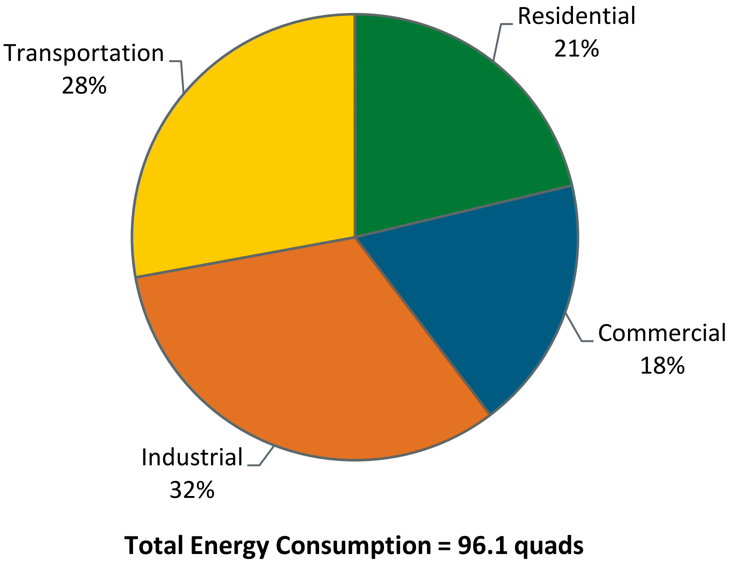


**Figure ES.1** 2013 Primary Energy Consumption by End Use Sector (AEO, 2013)

## Report Objectives

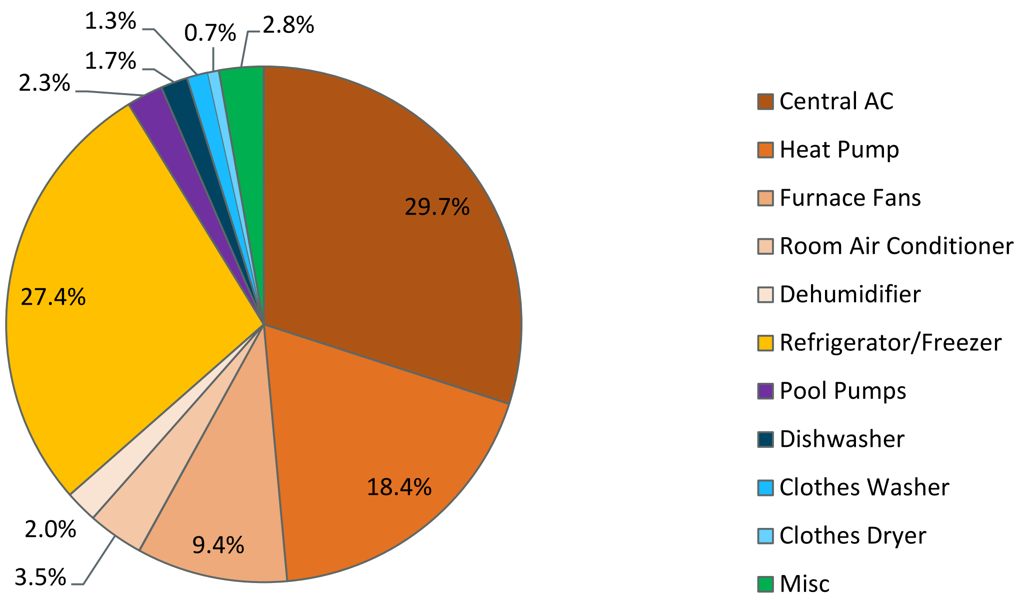
The objectives of this report are:

- To characterize the state and type of motor technologies used in residential and commercial appliances and equipment
- To identify opportunities to reduce the energy consumption of electric motor-driven systems in the residential and commercial sectors through the use of advanced motor technologies.

While non-commercially available technologies are explored, the primary focus of this report is on more efficient single-phase and three-phase alternating current (AC) electric motors, permanent magnet motors, and variable speed drives. This report should not only support the U.S. Department of Energy (DOE) Building Technologies Office (BTO) efforts to reduce energy consumption in the residential and commercial sectors, but also inform equipment manufacturers and building owners of their options when implementing, purchasing, and installing motors and drives.

**Summary of Findings**

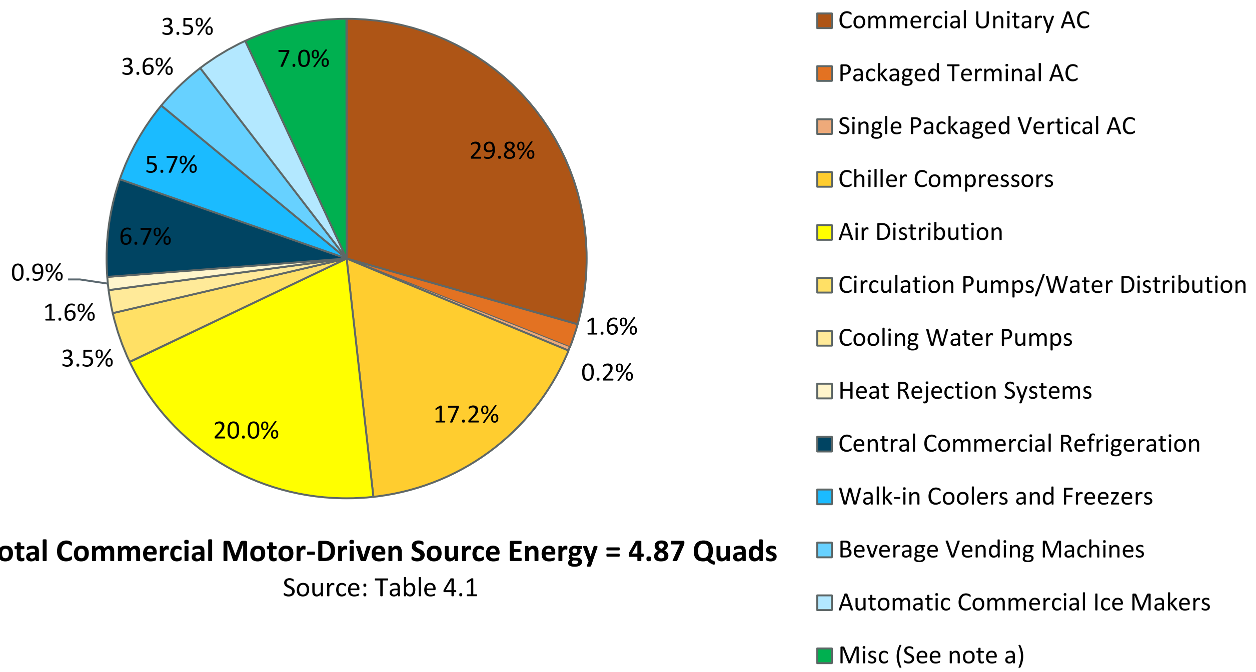
Electric motor-driven systems and motor-driven components in appliances and equipment account for more than 25% of the primary energy consumption in both the residential and commercial sectors. The analysis conducted for this report suggests that the energy consumption of electric motor-driven systems and components is 4.73 quads in the residential sector and 4.87 quads in the commercial sector. Figures ES-2 and ES-3 provide a breakdown of motor-driven energy consumption by end use for the residential and commercial sectors, respectively. The estimates in the figures were developed using knowledge of the installed base and the average unit energy consumption of each equipment or system type.



**Total Residential Motor-Driven Primary Energy = 4.73 Quads**

Source: Table 3.1

**Figure ES.2** Estimated 2013 Residential Sector, Motor-Driven, Source Energy Consumption by End Use



**Total Commercial Motor-Driven Source Energy = 4.87 Quads**

Source: Table 4.1

**Figure ES.3** Estimated 2013 Commercial Sector, Motor-Driven Source Energy Consumption by End Use

Motor-driven components used in heating, ventilation, and air conditioning (HVAC) and refrigeration are the highest energy consumers in both the residential and commercial sectors. In the residential sector, HVAC applications account for 63% of motor-driven energy use, and refrigeration accounts for 28%. In the commercial sector, the HVAC and refrigeration categories together account for 93% of motor-driven energy use.

Technical energy savings potential is the savings achieved by instantaneous replacement of the entire technically suitable installed based. Throughout this report, this metric was used to evaluate the maximum possible energy savings resulting from an increase in motor efficiency or through the use of variable speed technology. Realistically, however, technical potential is not readily achievable because motors in most types of installed equipment cannot be retrofitted, particularly in the residential sector. Instead, most motor upgrades will occur only through the appliance and equipment replacement cycle. Even then, new replacement units may not use the best available motor technologies. Retrofitting may be possible for some variable speed drives installed on existing equipment in the commercial sector. In general, estimates of technical energy savings potential should be used as a relative indicator rather than a measure of absolute attainable savings.

Table ES.1 summarizes the technical energy savings potential by residential end use. The technical energy savings potential achievable through motor upgrades and variable speed technology is estimated to be 536 trillion Btu (0.54 quads) in the residential sector. Energy savings are available through the use of highly efficient motors or variable-speed technology. In particular, the following appliances and equipment have technical energy savings potential greater than 30% of their motor-driven energy consumption:

- Refrigerator and freezer fans
- Central air conditioning and heat pump outdoor fans
- Indoor blowers
- Top loading clothes washers
- Pool pumps.

**Table ES.1** Summary of Technical Energy Savings Potential in the Residential Sector (includes upgrading motors or implementing VFDs)

| Appliance or Equipment Type | Motor Application | Motor Site Energy ($10^9$ kWh/yr) | Motor Primary Energy ($10^{12}$ Btu) | Primary, Technical Energy Savings Potential[a,b] | |
|---|---|---|---|---|---|
| | | | | % | ($10^{12}$ Btu) |
| Refrigerator/Freezer | Compressor | 114.3 | 1209.4 | 6 | 67.2 |
| | Condenser Fan | 4.4 | 46.5 | 62 | 28.7 |
| | Evaporator Fan | 3.7 | 39.2 | 48 | 18.7 |
| Central AC/Heat Pump | Compressor | 193.3 | 2045.0 | 3 | 68.2 |
| | Outdoor Fan | 21.5 | 227.2 | 38 | 85.2 |
| Furnace Fans (Indoor Blowers) | Fan | 41.9 | 442.9 | 30 | 132.8 |
| Room Air Conditioners | Compressor | 13.93 | 147.3 | 10 | 14.7 |
| | Condenser Fan | 1.55 | 16.4 | 4 | 6.1 |
| Dehumidifiers | Compressor | 8.17 | 86.4 | 10 | 8.6 |
| | Condenser Fan | 0.82 | 8.6 | 1 | 0.9 |
| Dishwashers | Drain Pump | 2.98 | 31.5 | 10 | 3.15 |
| | Circulation Pump | 4.47 | 47.3 | 10 | 4.73 |
| Clothes Washer | Top Loading | 3.57 | 37.8 | 60 | 22.8 |
| | Front Loading | 2.28 | 24.2 | 2 | 0.4 |
| Clothes Dryer | Drum Rotation | 3.07 | 32.5 | 2 | 0.6 |
| Pool Pumps | Drum Rotation | 10.10 | 106.8 | 68 | 72.8 |
| **TOTAL** | | | | | **535.7** |

[a] Refer to Section 3.3, Table 3.3 through Table 3.18, and Appendix A for detail.
[b] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

Table ES.2 summarizes the technical energy savings potential by commercial end use resulting from the use of high efficiency motors. For the commercial sector, technical potential due to motor upgrades alone is 461 trillion Btu (0.46 quads). In the table, HVAC equipment categories performing the same function have been combined into a single estimate. Equipment categories with technical energy savings potential greater than 30% of their motor-driven energy consumption include the following:

- Beverage vending machines
- Walk-in coolers and freezers.

**Table ES.2** Summary of Technical Energy Savings Potential in the Commercial Sector (includes upgrading motors only)

| **Component** | **Motor Site Energy ($10^9$ kWh/yr)** | **Motor Primary Energy ($10^{12}$ Btu)** | **Primary, Technical Energy Savings Potential[a,b]** | |
|---|---|---|---|---|
| | | | **%** | **($10^{12}$ Btu)** |
| Packaged and Unitary AC | 145.78 | 1541.95 | 9 | 131.5 |
| Chilled Water System Compressors | 74.37 | 786.63 | 12 | 23.6 |
| Air Distribution | 91.79 | 970.85 | 17 | 121.2 |
| Water Distribution | 15.99 | 169.14 | 3 | 4.6 |
| Cooling Water Pumps | 10.80 | 114.28 | 3 | 2.1 |
| Heat Rejection Systems | 0.55 | 5.86 | 3 | 1.5 |
| Commercial Refrigeration | 30.65 | 324.17 | 23 | 40.0 |
| Beverage Vending Machines | 16.76 | 177.23 | 40 | 58.9 |
| Walk-in Coolers and Freezers | 26.26 | 277.75 | 30 | 51.1 |
| Automatic Commercial Ice makers | 16.23 | 171.72 | 15 | 26.6 |
| **TOTAL** | | | | **461.1** |

[a] Refer to Section 4.3, Table 4.2 through Table 4.26, and Appendix B for detail.
[b] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

Table ES.3 summarizes the technical energy savings potential resulting from the use of VFDs in select applications, while holding the assumed, peak motor efficiency constant. Technical potential resulting from the use of variable-speed drives alone is 528 trillion Btu (0.53 quads). In the commercial sector, technical energy savings potential is less straightforward to quantify than residential sector equipment because reduction in energy consumption depends on the system load, configuration, and duty-cycle. Equipment categories with technical potentials greater than 30% of their motor-driven energy consumption and which could benefit significantly from the use of VFDs include:

- Chilled water distribution systems
- Heat rejection systems (air-cooled chillers, cooling towers).

**Table ES.3** Summary of Technical Energy Savings Potential in the Commercial Sector (includes implementing VFDs only)[a]

| Component | Motor Site Energy ($10^9$ kWh/yr) | Motor Primary Energy ($10^{12}$ Btu) | Primary, Technical Energy Savings Potential[b,c] | |
|---|---|---|---|---|
| | | | % | ($10^{12}$ Btu) |
| Packaged and Unitary AC[d] | 145.78 | 1541.95 | 4 | 58.0 |
| Chilled Water System Compressors | 74.37 | 786.63 | 15 | 116.4 |
| Air Distribution | 91.79 | 970.85 | 20 | 197.0 |
| Water Distribution | 15.99 | 169.14 | 39 | 66.3 |
| Cooling Water Pumps | 10.80 | 114.28 | - | - |
| Heat Rejection Systems | 0.55 | 5.86 | 273 | 16.0 |
| Commercial Refrigeration | 30.65 | 324.17 | - | - |
| Beverage Vending Machines | 16.76 | 177.23 | 8 | 14.7 |
| Walk-in Coolers and Freezers | 26.26 | 277.75 | 21 | 59.6 |
| Automatic Commercial Ice Makers | 16.23 | 171.72 | - | - |
| **TOTAL** | | | | **528.1** |

[a] VFD technical potential is independent of the motor upgrade technical potential. If both motor upgrades and VFDs were to be implanted in a particular category, the resulting technical potential would be less than the sum of the technical potentials for each independently.

[b] Refer to Section 4.3, Table 4.2 through Table 4.26 as well as Appendix B for detail.

[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

[d] Upgrade of CUAC indoor blowers only.

[e] Includes magnetic bearing compressor.

[f] Not used in self-contained commercial refrigeration.

## Summary of Key Opportunities and Market Barriers

Table ES.4 lists the products with the greatest technical energy savings potential. For each product, the table summarizes key opportunities for accelerating the implementation of high-efficiency motors, or market barriers that may hinder their adoption.

**Table ES.4** Summary of Key Opportunities or Barriers for Products with Greatest Technical Energy Savings Potential

| Product Type | Technical Potential ($10^{12}$ Btu) | Key Opportunities or Barriers to Achieving Savings |
|---|---|---|
| Residential | | |
| Furnace Fans (Indoor Blowers) | 132.8 | • Technical potential based on conversion from PSC to permanent magnet motors<br>• Drop in replacement motors may be available for certain furnace fan products<br>• Opportunities for permanent magnet motor installations include both replacement and new construction. Non-energy benefits such as increased comfort and reduced noise may contribute to adoption<br>• Greatest barrier is increased first cost and potentially increased maintenance and repair costs. |
| Central Air Condition and Heat Pump Outdoor Fans | 85.2 | • Technical potential based on conversion from PSC to permanent magnet motors<br>• Less than 1 year payback period for permanent magnet motor upgrade<br>• Products not ideal for retrofits unless compressor is also variable speed.<br>• Greatest opportunities are new installation<br>• Greatest barrier is increased first cost. |
| Central Air Condition and Heat Pump Compressors | 68.2 | • Technical potential based on upgrade to compressor with variable speed controls<br>• A 7 year payback period for a variable speed compressor.<br>• Products not available for retrofit<br>• Greatest opportunities are new installation for non-energy related reasons such as improved comfort level and noise<br>• Greatest barrier is increased first cost. Currently cheaper to increase the size of the heat exchanger rather than upgrade to variable speed compressor. |
| Refrigerator and Freezer Compressors | 67.2 | • Technical potential based on upgrade to compressor with variable speed controls<br>• A 13 year payback period for a variable speed compressor<br>• Products not candidates for retrofitting<br>• Average product lifetime of 16 years is only slightly longer than payback period. |
| Refrigerator and Freezer Evaporator and Condenser Fans | 47.4 | • Technical potential based on conversion of each fan motor type from shaded-pole or PSC to permanent magnet motors<br>• Between a 2-3 year payback period for permanent magnet motor upgrade<br>• Products not candidates for retrofitting. Most opportunity for permanent magnet motor use in new installations. |

| Product Type | Technical Potential ($10^{12}$ Btu) | Key Opportunities or Barriers to Achieving Savings |
|---|---|---|
| Commercial – Motor Upgrades | | |
| Packaged and Unitary AC | 131.5 | • Technical savings potential based on conversion of three phase indoor fan motors to more efficient three-phase AC induction motors and conversion of outdoor fan motors to permanent magnet motors<br>• Depending on the size of the unit, payback period ranges from 1-4 years for outdoor fans. Indoor fan motor payback ranges from 3-30 years depending on the size of the unit<br>• Installed base not ideal for retrofitting and greatest opportunities for permanent magnet motor use is in new installations. |
| Air Distribution | 121.2 | • Technical savings potential based on conversion to permanent magnet motors for Exhaust Fans and more efficient three-phase AC induction motors for AHUs<br>• Exhaust fans have a payback period of 1.5 years while AHUs have an 18 year payback<br>• Existing installed base could be retrofitted with permanent magnet motors<br>• Greatest barriers include first cost and the potential need for more complex system controls<br>• Building standards could help increase adoption of permanent magnet motors with integrated controls. |
| Beverage Vending Machines | | • Technical savings potential based on conversion of shaded pole fan motors to permanent magnet motors<br>• Less than one year payback period for permanent magnet motor upgrade<br>• Installed base not candidates for retrofitting<br>• Opportunities or permanent magnet motor use in new installations. |
| Walk-in Coolers and Freezers | | • Technical savings potential based on conversion of fan motors to permanent magnet motors and the use of more efficient compressor motors<br>• Between a 1-2 year payback period for permanent magnet motor upgrade<br>• Because walk-in coolers and freezers are assembled on-site, it could be possible to replace the existing installed base with more efficient motors. |
| Commercial – Implementing Variable Frequency Drives | | |
| Packaged and Unitary AC | 58.0 | • Technical savings potential based on use of variable speed control on the indoor fan motors<br>• Between a 2-4 year payback period for permanent magnet motor upgrade<br>• Not candidates for retrofitting<br>• Due to relatively short payback period and more stringent building standards, the use of variable speed fan control is likely to increase. |
| | 116.4 | • Technical savings potential based on use of a magnetic bearing centrifugal compressor. |

| Product Type | Technical Potential ($10^{12}$ Btu) | Key Opportunities or Barriers to Achieving Savings |
|---|---|---|
| Chilled Water System Compressors | | • Payback period could be as little as 2 years<br>• Opportunities for new installation and replacement chiller packages<br>• Barriers include high initial first cost of compressor (on the order of $18,000). If building owners understand lifecycle cost they may be willing to make the investment<br>• Non-energy related benefits (oil-free) may increase adoption of this technology. |
| Air Distribution | 197.0 | • Technical savings potential based on use of variable speed control of AHU fans<br>• Payback period could be 1 year<br>• Could be used to retrofit existing installed base and in new installation. |
| Water Distribution | 66.3 | • Technical savings potential based on use of variable speed control on pumps<br>• Approximately 1 year payback<br>• Ideal usage scenario for variable speed control: pumps are often oversized for a given application and experience variable load conditions<br>• Greatest barriers include increased first cost and the perceived complexity of variable speed control implementation. |

## Conclusions

Most of the residential and commercial equipment types covered in this report are covered by DOE energy conservation standards and industry standards such as ASHRAE 90.1. These standards continue to push manufacturers to consider both more efficient motors and variable-speed technologies, among other product design improvements, in order to meet more stringent minimum efficiency requirements. However, research efforts and incentives outside of DOE regulation would enable further reductions in motor-driven system energy consumption in the residential and commercial sectors. Broad research efforts that could improve motor and drive efficiency and reduce costs include:

- The use of wide bandgap semiconductors in place of conventional semiconductor materials
- Identification of alternatives to rare-earth metals
- Commercialization of switched reluctance motor (SRM) technology.

For almost all equipment types in both the residential and commercial sectors, the market is transitioning to permanent magnet motor technology for the highest-efficiency models within each category. Permanent magnet motors are becoming increasingly cost-effective based purely on simple payback period. They also offer other non-energy benefits such as reduced noise and the ability to reach higher rotational speeds.

Variable speed drives are also becoming a cost-effective way to reduce motor-driven system and component energy consumption in variable-load applications. Initial costs of drives have dropped significantly over the last decade. This can be largely attributed to advances in electronics, specifically semiconductors, which have led to reduced thermal loads and smaller drives.

Despite these gains, however, the relatively higher cost of advanced motor technologies compared to traditional technologies remains a significant barrier for applications where first cost is a primary concern. For many types of appliances and equipment, products that just meet the mandatory minimum energy conservation standards represent the majority of overall sales. Typically, these products compete solely on price. Thus, outside of mandatory or voluntary standards programs, efforts to reduce the first cost of advanced motor technologies are essential to accelerate their implementation in both residential and commercial appliances and equipment

Even as motor costs decrease, field retrofits of motors in appliances and equipment are generally unrealistic. This leaves the largest motor-related energy savings to be attained only through original equipment manufacturer (OEM) integration of advanced motor technologies in new products.

Similarly, the additional cost of advanced motor technologies can deter end users who do not consider payback periods or total lifecycle costs. This is particularly prevalent in many commercial properties where tenants are responsible for the energy costs. However, building owners increasingly consider total lifecycle cost in their selection of building equipment, especially if they plan to occupy the building themselves. Such consideration of total lifecycle cost should encourage the adoption of more energy-efficient commercial equipment.

In addition to cost constraints, size and weight constraints could also limit the introduction of some higher-efficiency motor technologies that require larger or heavier components than current motor designs. Conversely, some higher-efficiency motor technologies are smaller and lighter than traditional motor designs, in which case the higher upfront cost remains the primary barrier to widespread implementation.

One particular barrier preventing wider adoption of permanent magnet technology is the threat of supply disruptions or price spikes for scarce rare-earth metals, which provide the magnetic material for the motor. Investment in alternatives to rare-earth metals, or alternative motor technologies such as switched reluctance motors, will ensure that high efficiency motor options remain cost-effective and that alternatives are available if rare-earth metals become scarce or their cost spikes.

In the commercial sector, a key issue preventing greater adoption of VFDs is the additional training required for installation and operation of these higher-efficiency technologies. Building design engineers and contractors often perceive the higher-efficiency technologies to be too complex. Furthermore, operators may not understand variable-speed operation and may override VFD controls, such that energy consumption is not actually reduced by use of the VFD. Supporting the development of training programs, design guides, and software tools to help encourage the integration and proper use of high-efficiency motor designs would help accelerate the adoption of variable-speed motor technologies.

Some manufacturers are addressing the issue of increased complexity by developing product-specific programing and sensorless control schemes to create “plug-and-play” VFDs. Examples include permanent magnet motors with integrated controls in HVAC equipment, as well as factory-mounted drives available from compressor and pump manufacturers. Factory-mounted drives may have the added benefit of reducing installation costs and providing greater convenience, especially where space constraints are a primary concern. Continued emphasis on developing integrated controls for VFDs will help accelerate their implementation in both residential and commercial equipment.

After analyzing the technical savings potential offered by motor upgrades and variable speed technologies in both the residential and commercial sectors, a number of key takeaways emerged. Table ES.5 summarizes the recommended actions discussed above that could contribute to reduced energy consumption of motors in these sectors:

**Table ES.5** Key Takeaways from High Efficiency Motor and Variable Speed Drive Technical Potential Analysis

| | **Key Takeaways** |
|---|---|
| **RD&D** | • Invest in material technologies (such as wide bandgap semi-conductors) so that variable speed drives may continue to decrease in size and cost.<br>• Identify alternatives to rare-earth metals that will allow for stable permanent magnet motor prices and potentially further reduce cost of these motors.<br>• Invest in new technologies, such as switched reluctance motors, which do not rely on permanent magnets. |
| **Residential** | • Seek opportunities to upgrade products with permanent magnet motors and integrated controls in residential fan applications and pumps. |
| **Commercial** | • Motor/unit-mounted variable speed technology with pre-programmed and sensorless controls could become more prevalent with designer/user-educational programs and decreased cost of control technologies.<br>• Seek opportunities to upgrade products with permanent magnet motors and integrated controls in air distribution fan applications and circulation pumps. |

# 1 Introduction

## 1.1 Study Objective

The objectives of this study are:

- To characterize the state and type of motor technologies used in residential and commercial appliances and equipment
- To identify opportunities to reduce energy consumption of electric motor-driven systems and components in the residential and commercial sector.

## 1.2 Background

In 1999, The U.S. Department of Energy's (DOE) Building Technology Office (BTO) supported the publication of a report entitled, "Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Motors," (ADL, 1999). The report has been cited often by industry stakeholders, including manufacturers, engineers, and energy efficiency advocacy groups. It also helped guide DOE BTO RD&D activities related to electric motors. The current study will provide an update to the 1999 report, focusing on electric motor technology advances that may have occurred in the last decade and changes in the type of motors and the energy consumption of motor-driven systems and components currently found in the installed base.

This study employs an application specific, bottom up approach to estimate the energy use of the installed base of electric motor-driven systems and components, as well as the technical energy savings potential. The study is limited to appliances and equipment in the residential and commercial sectors. In evaluating the technical potential of a given appliance or equipment item, DOE considered only the following options:

1. Upgrading to higher-efficiency motors
2. Using variable-speed drives for appliances or equipment that operate at part-load.

The scope does not include an evaluation of system-design related efficiency improvements nor does it include evaluation of non-motor technology options that may be able to reduce overall energy consumption.

## 1.3 Organization of the Report

Chapter 2 provides a basic summary of conventional as well as advanced motor technologies for application in the residential and commercial sectors. The chapter discusses single and three-phase alternating current (AC) induction motors, brushless direct current (DC) permanent magnet motors, permanent magnet AC motors, and switched reluctance. Chapter 2 also provides a basic description of variable-speed motor technology.

Chapters 3 and 4 provide a more detailed analysis of electric motor and drive technologies that are commercially available for residential and commercial appliances and equipment, respectively. This includes a characterization of the installed base of electric motors by shipments, annual operating hours, efficiency, motor type, and energy consumption. This section also includes evaluation of the technical energy savings potential. Cost-effectiveness and simple payback period information are included to inform a discussion of the market barriers manufacturers and end users face when implementing high efficiency motors or drives for the specific appliance and equipment types.

Finally Chapter 5 provides conclusions, a brief commentary on directions for further research, and recommendations on opportunities to increase adoption of high efficiency motors and variable speed drives.

# 2 Motor Technology Overview

A variety of electric motor types are available for use in the residential and commercial sectors, employing a range of methods to convert electrical energy into mechanical energy. Choice of motor type is often determined by cost or the specific application or load; efficiency and energy savings potential are often secondary considerations.

This section describes existing motor technologies that are commonly found in residential or commercial applications and describes some of the advantages of using each technology. The section is generally organized by increasing technological complexity starting with a discussion of simple, low horsepower single-phase alternating current (AC) induction motors and universal motors. Residential and small commercial buildings are typically supplied with three-wire single phase power, making single-phase motors suitable for residential and low-horsepower commercial applications.

The discussion moves to three-phase AC induction motors. Three-phase power service is common in the commercial sector where large horsepower motors and drives are necessary. The section finishes with descriptions of more advanced motor-drive systems as well as recent innovations that could lead to reduced motor-driven system and component energy consumption. The discussion of each technology is not exhaustive, but characterizes the general operating principles of each device.

## 2.1 Single-Phase AC Induction Motors

Alternating current induction motors operate using the principle of electromagnetic induction to produce a motor torque. The stator and rotor make up the two primary motor components, as shown in Figure 2.1. The stator, or stationary portion of the motor, is formed by layers of steel laminations. The stator has a hollow core with slots for conductive material along its interior known as poles. This conductive material is typically composed of wound, insulated copper wire. The rotor, or rotating portion of the motor, is positioned inside the stator’s hollow core and is separated from the stator by an air gap. The rotor is also composed of layered steel laminations that are attached to the motor shaft. Slots on the outer surface of the rotor also contain copper windings or, in the case of the squirrel cage induction motor, conductive bars of aluminum or copper that are joined by rings at their lengthwise ends (ADL, 1999).

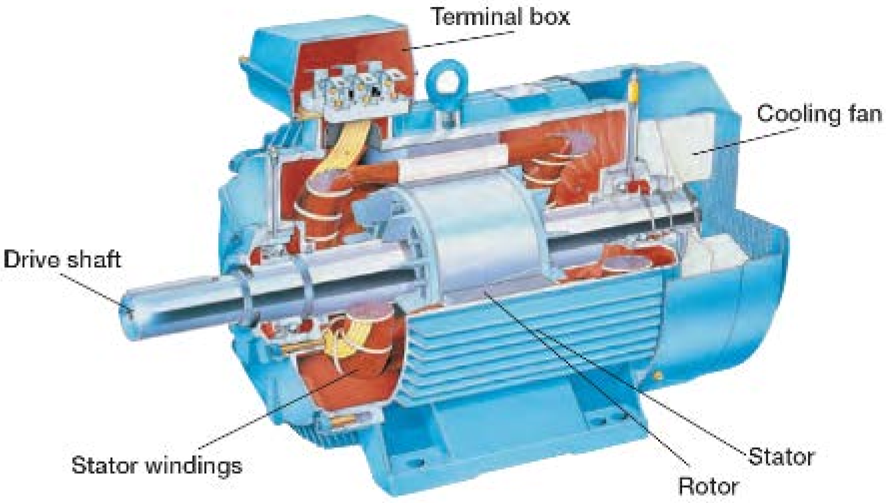


**Figure 2.1** Squirrel Cage AC Induction Motor

Source: http://www.enggcyclopedia.com/2012/09/squirrel-cage-induction-motors/

When a single-phase induction motor is energized, a magnetic field is generated that rotates at a speed dependent on the number of magnetic poles and the electrical input frequency. The number of poles is controlled by the configuration of the windings in the stator. The movement of the stator's magnetic field in relation to the rotor induces a current in the rotor. The induced current in the rotor produces a magnetic field of polarity opposite that of the stator. The interaction of the two magnetic fields results in a torque that turns the rotor and the motor shaft.

Efficiency losses in the motor include resistive losses in the stator or rotor that are dissipated as heat. Hysteresis and eddy current losses in the stator's steel laminations occur due to the type and quality of the steel and the thickness of the laminations. Efficiency losses also result from friction in the bearings and shaft seals (NEMA, 2001).

In general, as motor horsepower increases, the efficiency of the motor at full load also increases. This is partially due to the difficulty in dissipating heat in smaller motors. Higher horsepower motors also operate close to peak efficiency for a wide range of loading conditions (NEMA, 2001). Low-horsepower motors with lighter loads can have wide ranges of efficiency, meaning that under-loading the motor can significantly impact performance.

If the rotor were to turn at speed synchronous to the rotating magnetic field of the stator, no torque would be generated. Instead, the rotor operates at a speed slightly slower than synchronous speed. The difference between actual and synchronous speed is called slip. As an example, a two-pole motor supplied by a 60 Hz power source would have a synchronous speed of 3,600 rpm[1]. Due to slip, the rotor would actually have an operating speed closer to 3,500 rpm. Hence, induction motors are often called asynchronous motors. This slight difference in speed between the stator magnetic field and rotor provides the torque necessary to sustain rotation.

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[1] Motor synchronous speed: RPM = 2x 60 x (f/n); where f = frequency, n = # of poles

Single-phase induction motors require additional components in order to start. If a single-phase motor without any additional components was energized by a single-phase source, a pulsating magnetic field, instead of a rotating field, would result. This pulsating field would generate counteracting torque that would cause the rotor to remain static. Instead, in addition to the primary winding, single-phase motors have either a copper coil wrapped around the stator poles or a secondary winding, often called an auxiliary or start winding, which provides a delay in current to part of the motor's poles. The resulting asymmetric magnetic field produces the starting torque, which initiates rotation of the rotor in the desired direction. Once rotating, torque can be sustained by the primary winding alone. The addition of an auxiliary winding causes single-phase motors to experience fluctuations in torque that impact their efficiency. While a single-phase induction motor may appear to operate smoothly due to the inertia of the motor's rotor for small loads, single-phase motors suffer up to a 10% loss in efficiency compared to their three-phase counterparts (ADL, 1999). Single-phase power is found most often in homes and is used in commercial buildings for fractional horsepower systems.

A single-phase induction motor is often classified by the mechanism used to generate the rotating magnetic field. Table 2.1 provides a summary of the single-phase induction motors covered in this section, their peak efficiencies, and the relative cost of the single-phase motors to one another (Fans & Blowers Twin City).

**Table 2.1** Summary of Single-Phase AC Induction Motor Characteristics

| Single-phase Induction Motor Type | Peak Efficiency Range | Starting Torque | Relative Cost |
|---|---|---|---|
| Shaded-Pole | 20-40% | Low | Least expensive<br>$ |
| Resistance Start Induction Run (RSIR) | 50-60% | Medium | $$ |
| Capacitor Start Induction Run (CSIR) | 50-60% | High | $$ |
| Permanent Split Capacitor (PSC) | 50-70% | Low | $$ |
| Capacitor Split Capacitor Run (CSCR) | 50-70% | High | Most expensive<br>$$$ |

The following sections provide a description of the most common single-phase induction motors found in residential and commercial applications. Three-phase AC induction motors are discussed in Section 2.3.

### *2.1.1 Shaded-Pole Motor*

Shaded-pole motors have a main winding and an additional copper coil, or shading coil, wrapped around the stator poles. Current induced in the shading coil creates the phase lag needed to produce the rotating magnetic field. These motors provide low starting torques and are one of the least expensive, least efficient single-phase configurations. Shaded-pole motors are most often used in small, fractional horsepower systems. One common application is multi-speed household fans, where speed is controlled through a multi-tap winding that allow the motor to operate at multiple speeds. (Heinecke). Shaded-pole motors are increasingly being replaced by other more advanced motor technologies that are more efficient. In stand-alone residential refrigeration units that use shaded-pole motors to drive evaporator fans or compressors, shaded-pole motors were found to be only 15-30% efficient (Blackburn, 2012). Shaded-pole motors also rotate only in one direction, a disadvantage for systems that need to run in reverse, such as heat pump compressors, and can only be reversed by physically flipping the stator to switch the motor poles.

### *2.1.2 Resistance Start Induction Run*

The resistance start induction run (RSIR) motor incorporates an auxiliary winding at a 90-degree angle to the primary winding to impart the rotational energy needed to start the motor. An example schematic is provided in Figure 2.2. The auxiliary winding is usually composed of a higher gauge (smaller diameter) wire with a higher resistance than the primary stator winding. The higher resistance provides the time delay needed to generate the rotating magnetic field. Once started, the auxiliary winding is de-energized via a centrifugal switch. RSIR motors are only suitable for applications requiring low starting torque (GRUNDFOS, 2004). Typical applications of RSIR motors include compressor motors for home refrigerators and freezers or dehumidifiers (Tecumseh).

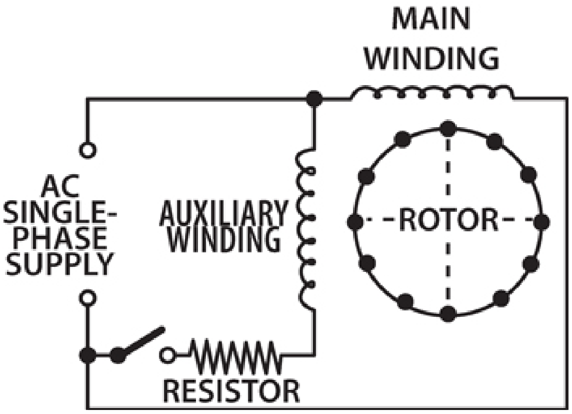

**Figure 2.2** Resistance Start Induction Run Schematic

Source: http://www.pump-zone.com/topics/motors/ac-motors-part-3-single-phase-operation-0

### *2.1.3 Capacitor Start Induction Run*

A capacitor start induction run (CSIR) motor also employs an auxiliary winding to impart the rotational energy needed to start the motor. The auxiliary winding is connected in series to a capacitor and switch. The capacitor delays the flow of current between the two windings and also helps provide a higher starting torque for applications with a high start load. Once the motor reaches speed, the switch connecting the auxiliary winding and capacitor to the primary winding opens and removes the auxiliary winding from the circuit (GRUNDFOS, 2004). CSIR motors are typically used in refrigeration compressors (GRUNDFOS, 2004).

### 2.1.4 Permanent Split Capacitor

A permanent split capacitor (PSC) motor has a capacitor and auxiliary winding joined in series, but, unlike the CSIR, no switch separates the primary and auxiliary windings. Without the switch, the auxiliary winding remains energized throughout operation. PSCs are the current industry standard for HVAC applications and are gaining popularity in all residential appliances. An example schematic is provided in Figure 2.3.

PSCs can be designed to be more efficient at the application's rated load compared to CSIR motors. Many PSCs used in HVAC applications are designed with "speed taps" that allow the motor to operate at multiple speeds. These taps are connected at various points along the primary and auxiliary windings so that voltage, and hence speed, can be changed in set increments. While speed taps can make the PSC more versatile than other simpler motor types, the added functionality is not typically used for speed control. Rather it is a method for installers to adapt the system to installed conditions by selecting a motor speed that most closely matches the system load (Michael, 2009).

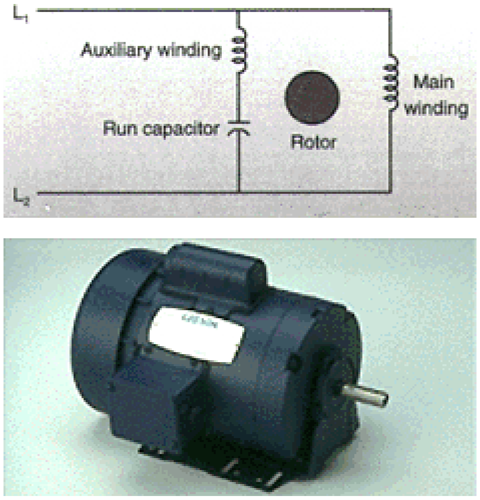

**Figure 2.3** Permanent Split Capacitor Motor

Source: http://www.leeson.com/TechnicalInformation/sphase.html

### 2.1.5 Capacitor Start Capacitor Run

A capacitor start capacitor run (CSCR) motor has a run capacitor and auxiliary winding connected permanently in series, similar to that of a PSC. CSCR motors also have a start capacitor and switch (similar to that of a CSIR) connected in series with the start winding, to offer a high starting torque. An example schematic is provided in Figure 2.4.

The combination of the two configurations makes the CSCR more expensive than other single-phase motors, but also more efficient across the full range of operation. The start capacitor has a high capacitance and helps provide a high starting torque, while the run capacitor has a lower capacitance and helps smooth out any torque pulsations during operation. The sizing of the capacitors is optimized to match the expected starting loads and run loads (ADL, 1999). Due to their higher cost compared to simpler motor types, CSCR motors are typically only used in systems with large loads that require high starting torque.

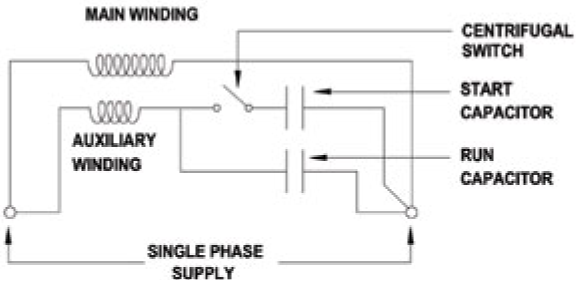

**Figure 2.4** Capacitor Start Capacitor Run

Source: http://www.acpd.co.uk/cw-single-phase-motors.html

## 2.2 Universal Motor

Universal motors are also known as series-wound commutated motors. The windings of the stator are connected in series to the windings in the rotor, typically through a brush-type commutator that reverses the direction of current as the motor rotates to generate constant torque. Universal motors can operate with either AC or direct current (DC) electrical input because the same current that establishes the stator magnetic field also flows through the rotor. As the AC supply alternates, so will the current through the rotor.

The universal motor is commonly used in AC applications because it offers certain desirable features more common to DC motors. For example, universal motors can operate at much higher speeds than are typical of AC induction motors, which are limited by line frequency. Universal motors also provide a high starting torque and can have a more compact design than their induction counterparts. They are commonly used in applications requiring demanding high-speed, intermittent operation, such as vacuum cleaners, power tools, or food mixers. These devices often operate between 15,000 and 20,000 rpm, while basic AC induction motors generally cannot operate over 3,500 rpm (ADL, 1999).

A disadvantage to using universal motors is the limited lifespan of the brush or commutator. The mechanical commutation can also cause the potential for electromagnetic interference and sparking. Historically, universal motors offered an inexpensive way to achieve high-speed operation for small devices, despite these downsides. However, as high-frequency inverter drives (used with permanent magnet and induction motors) become more readily available, the market is transitioning away from universal motors (Hughes et al. 2013).

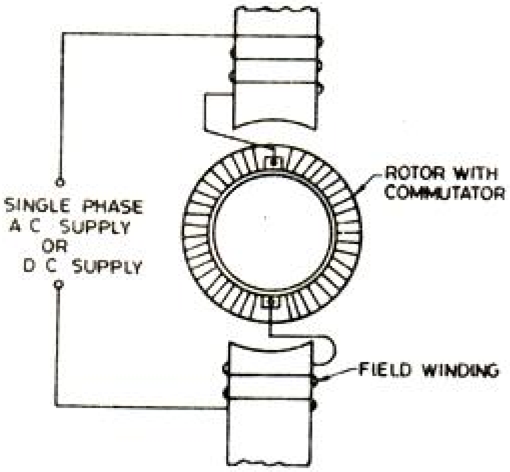

**Figure 2.5** Universal (Series) Motor

Source: http://www.transtutors.com/homework-help/electrical-engineering/single-phase-ac-motors/universal-motor.aspx

## 2.3 Three-phase AC induction motors

Three-phase induction motors are similar in construction to single-phase induction motors, except that the stator contains three distinct windings per motor pole. This configuration eliminates the need for an auxiliary winding to provide the starting torque. The rotating speed of the motor is determined by the frequency of the power input and the number of poles in the stator; a larger number of poles will decrease the rotation speed. Three-phase induction motors require a three-phase power source, which is available in most commercial buildings where large loads are expected. The three-phase induction motor is generally considered reliable when compared to more advanced technologies due to its technological maturity and length of time in the marketplace.

Three-phase induction motors most commonly have an “open” configuration or a totally enclosed fan-cooled (TEFC) configuration. TEFC motors are designed with a fan attached to one end of the rotor and are covered by a sealed enclosure so that contaminants cannot enter. TEFC motors are common in the commercial and industrial sectors where the enclosure provides protection in applications such as pumps, fans, and blowers that are subject to harsh conditions. Because these applications have loads that are highly dependent on individual system design, three-phase induction motors are typically offered in two-, four-, or six-pole configurations for a variety of possible speeds. Three-phase induction motors generally operate with less than 5% slip (NEMA, 2001).

The Energy Policy and Conservation Act (EPCA), as amended, established a minimum energy conservation standard for certain types of electric motors that became effective in 1997. In 2007, EPCA was amended by the Energy Independence and Security Act of 2007 (EISA) which both expanded the scope of motors covered by the regulation, and increased the minimum efficiency requirements, replacing them with the National Electrical Manufacturers Association (NEMA) Premium Efficiency levels.

These minimum allowable electric motor full load efficiencies are provided for select horsepower in Table 2.2. Covered electric motors manufactured either as a component or standalone product after 2010 must meet or exceed these efficiency levels.

**Table 2.2** Full-Load Efficiencies for General Purpose Electric Motors [Subtype I] (DOE, 2012f)

| Motor Horsepower | Nominal Full Load Efficiency (%) | | | | | |
|---|---|---|---|---|---|---|
| | Open Motors | | | Enclosed Motors | | |
| | (Number of Poles) | | | (Number of Poles) | | |
| | 6 | 4 | 2 | 6 | 4 | 2 |
| 1 | 82.5 | 85.5 | 77 | 82.5 | 85.5 | 77 |
| 3 | 88.5 | 89.5 | 85.5 | 89.5 | 89.5 | 86.5 |
| 5 | 89.5 | 89.5 | 86.5 | 89.5 | 89.5 | 88.5 |
| 7.5 | 90.2 | 91 | 88.5 | 91 | 91.7 | 89.5 |
| 10 | 91.7 | 91.7 | 89.5 | 91 | 91.7 | 90.2 |
| 25 | 93 | 93.6 | 91.7 | 93 | 93.6 | 91.7 |
| 50 | 94.1 | 94.5 | 93 | 94.1 | 94.5 | 93 |
| 100 | 95 | 95.4 | 93.6 | 95 | 95.4 | 94.1 |
| 125 | 95 | 95.4 | 94.1 | 95 | 95.4 | 95 |
| 150 | 95.4 | 95.8 | 94.1 | 95.8 | 95.8 | 95 |
| 200 | 95.4 | 95.8 | 95 | 95.8 | 96.2 | 95.4 |

The electric motors covered under the regulation are general purpose, single-speed, polyphase, two, four, six, or eight pole induction motors of NEMA Design A, B, or C. The covered range of horsepower for NEMA Design B motors is 1 to 500 and 1 to 200 for Design A and C. Open drip-proof (ODP), explosion proof, and TEFC configurations are all covered. The increase in efficiency between 1997 levels and 2010 is approximately 1-4% depending on the motor's horsepower.

The efficiency of three-phase induction motors can be increased to meet or exceed the EPCA/NEMA Premium levels through optimization of rotor and stator design. The availability of die-cast copper rotors for squirrel cage induction motors has also enabled improvements in induction motor efficiency. Copper is more conductive than aluminum by approximately 70%. Increased conductivity means fewer thermal losses in the rotor. Using a die-cast copper rotor also means less material is required to maintain the same power and efficiency as an aluminum rotor and thus the motor can be made smaller (Baldwin, 2012). With fewer thermal losses, additions like cooling fins at the end of the rotor can be eliminated and further decrease size. There are concerns that the increased weight of copper, as compared to aluminum, will require the motor to overcome higher inertia at start (Baldwin, 2012). However, studies have shown that since a copper rotor also allows for a shorter stack length (of steel laminations), the added weight is negated by the reduced rotor (Mechler, 2010). Generally, copper die-cast rotors are available for three-phase induction motors from 1 to 30 hp.

Small electric motors are also covered by EPCA, as amended, but DOE has developed a separate energy conservation standard that will not go into effect until 2015. This standard covers single and polyphase motors, as well as CSIR motors ranging from ¼ to 3 horsepower.

## 2.4 Advanced Motor Technologies and Controls

As described above, single and three-phase AC induction motors are still frequently used in baseline residential and commercial products. However, many of the motor-driven products and equipment in these sectors could benefit from the use of more efficient motor technologies or from the use of variable frequency drives to optimize system energy consumption during part-load operation. Sections 2.4.1 to 2.4.4 describe these technologies, first by addressing motor drives and controls and their associated advances and then by discussing the technologies that have developed as a result of these advances.

### *2.4.1 Variable Frequency Drives*

Electronic speed control of electric motors has become increasingly common as the cost of solid-state power electronics decreases. Devices providing speed control have a variety of names, including:

- Inverter drives
- Adjustable speed drives
- Variable speed drive (VSDs)
- Variable frequency drives (VFDs)
- Vector control drives.

The name often varies with the type of motor paired with the device. For example, the term VFD is typically associated with three-phase AC induction motors. While variable speed control devices are not all identical, the primary principles of operation remain the same. This section of the report refers to variable frequency control devices generically as “VFDs” and provides a broad description of their features, efficiency, and application. Any notable differentiation in the construction or operation of a variable frequency control device is addressed in subsequent sections.

Variable loads occur frequently in the commercial and residential sectors. Three-phase induction motors are often paired with variable speed drives for use with fans, compressors, and pumps in commercial and industrial applications. Boiler-feed circulator pumps provide a common example of the benefits of using variable speed motor drives. In conventional designs with fixed-speed motors, pumps are oversized to ensure they can handle the maximum expected load or accommodate any future increase of system capacity. By using a variable frequency drive, motor speed can be adjusted to match the system’s actual operating requirements. Due to affinity laws, for pumps, fans, and compressors, the relationship between speed and power is such that a 10% reduction in speed generally results in 30% reduction in power. Therefore, operating pumps, fans, or compressors at lower speeds for longer periods can lead to reduced total energy consumption. Operating at a lower, more continuous speed also eliminates the abrupt fluctuations in temperature or flow and other system losses associated with the on/off operation of conventional single-speed systems.

In a true constant load application, adding a VFD could actually decrease overall efficiency due to inefficiencies in the drive itself. Realistically, however, most systems in the residential and commercial sectors could benefit from a variable frequency drive. Systems rarely operate at their designed load due to engineered safety factors, deliberate oversizing by building engineers and operators, or environmental conditions. Figure 2.6 shows how variable speed drive efficiency decreases under part load. The greatest decrease in efficiency occurs at part-load conditions less than 25% of a drive's rated power output. Near-peak efficiency is achieved for part-load conditions above 25% of a drive's rated power output.

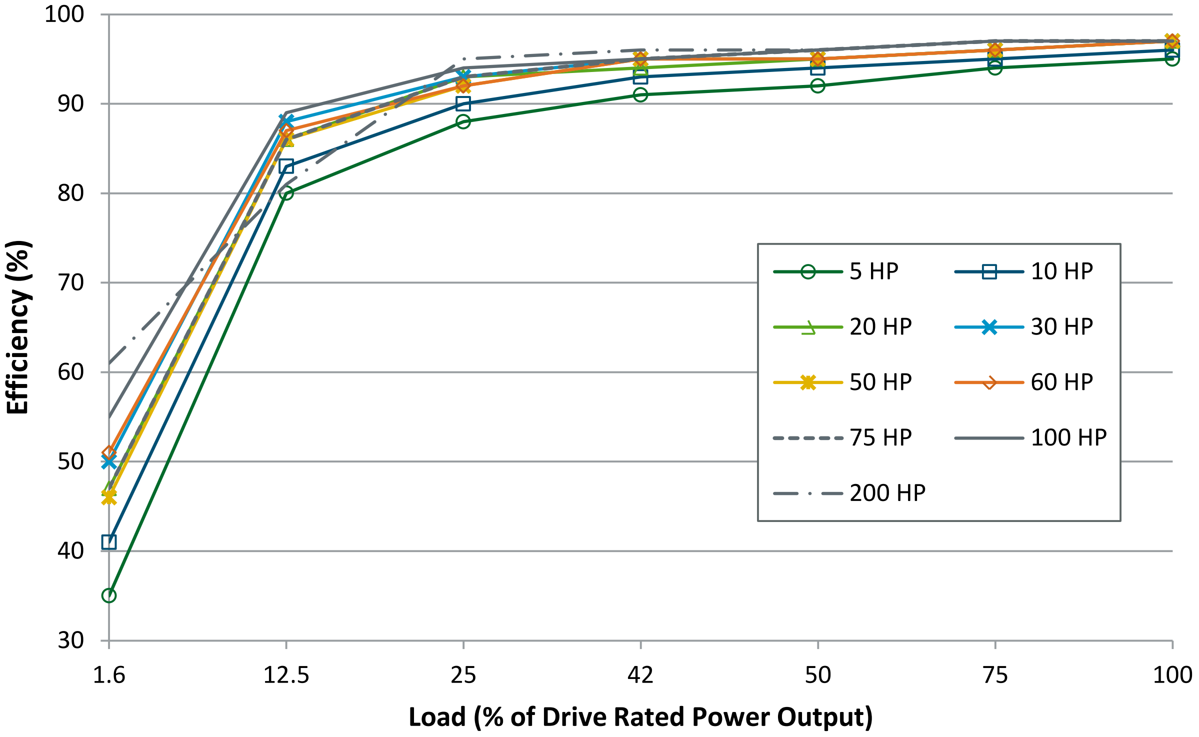

**Figure 2.6** Variable Frequency Drive Efficiency at Part Load (DOE AMO, 2012)

A VFD enables the motor to operate at speeds other than the fixed-speed that is determined by the AC line frequency (60 Hz in North America) and the number of motor poles. This is achieved by modifying the frequency and voltage input to the motor. VFDs consist of a rectifier to convert the AC line input to DC. A diode bridge or power transistor then modulates the DC output to simulate an AC-like waveform with the frequency and voltage (or current) desired for the motor application. The power transistors use pulse-width modulation (PWM) to create the output waveform by switching the DC supply ON and OFF. By changing the duration of the pulse, the VFD can approximate a sinusoidal waveform for smooth operation. During the ON phase of the pulsation, energy is stored in the motor windings as an inductance and is released during the OFF phase. This configuration ensures that uninterrupted current is supplied to the motor (ADL, 1999).

The output power transistors used for switching in commercially available VFDs are typically silicon (Si) based insulated-gate bipolar transistors (IGBT) integrated with freewheeling diodes that reduce the impact of voltage fluctuations associated with PWM. While having rated efficiencies of 95-98%, VFDs with IGBTs have disadvantages that include (Novak, 2009):

- The amount of heat generated by switching operations
- The resulting external cooling costs
- Harmonic current distortions in the simulated sinusoidal waveform.

Additionally, the VFD requires the motor windings to store inductance and may lead to insulation breakdown in the winding or put additional stress on the motor bearings (Wu, 2012).

Recent research suggests that using wide bandgap (WBG) semiconductors in place of conventional semiconductor materials, like silicon, in switches, could improve the performance and efficiency of variable speed drives. Wide bandgap semiconductors have a higher energy gap—the energy range in a solid where no electron states can exist—which allows them to operate at both higher temperatures and higher frequencies. Operation at higher temperatures eliminates the need for external cooling and addresses some issues related to heat generation (Neudeck, 2002). Higher switching frequencies may also result in quieter drives. Converting to WBG materials also has the potential to reduce the overall size of the VFD, which could be beneficial in space-constrained residential or commercial applications (Compound Semiconductor, 2012).

Two WBG materials have been identified for use in VFDs and include:

- Silicon carbide (SiC)
- Gallium nitride (GaN).

SiC-based diodes were first used over a decade ago but have proven difficult to manufacture. GaN transistors may be easier and less costly to manufacture, but both SiC and GaN devices remain significantly more expensive than silicon-based IGBTs. Furthermore, the reliability of WBG materials is unknown. Since these devices have yet to operate over the lifetime of a product, little can be said about their long-term or fatigued performance (Compound Semiconductor, 2012). Nevertheless, studies indicate that significant reduction in switching losses could be achieved using WBG semiconductors. Semiconductor manufacturers continue to explore the technology (Palmour, 2006).

One company has shown that GaN high-electron mobility transistors (HEMTs) are more efficient than IGBTs when used in variable speed drives. The high PWM frequency available to GaN HEMTs can produce a smooth sinusoidal current with fewer harmonic disturbances that is more efficient than IGBT output. GaN HEMTs also eliminate the need for freewheeling diodes. This could prolong motor life by limiting inductances in the motor windings and wear on motor bearings (Wu, 2012).

The widespread adoption of VFDs has been limited in part by the additional cost of the components required to implement them. VFDs also require the design and implementation of control algorithms. Although more recent variable speed motor systems with integrated controls may reduce the complexity of implementing VFDs, many applications will require that system manufacturers have controls expertise to properly incorporate variable speed control into their equipment. Historically, this has been a barrier limiting the rapid adoption of variable speed motor technologies.

### *2.4.2 Permanent-Magnet Motors*

Permanent magnet motors continue to gain popularity as a more efficient alternative to AC induction motors. This increase in popularity is largely due to a decrease in costs associated with electronic control, as discussed above. Instead of using conductive material in the rotor, permanent magnets are integrated into the rotor’s laminations or fixed to the rotor’s outer surface and do not need to be energized. The magnetic field established by the permanent magnets interacts with the field produced by windings in the stator to generate a torque. Permanent magnet motors are synchronous, meaning that no slip is required for the motor to operate. Rather, the phase of the stator windings is switched, or commutated, to align the stator’s field with the magnetic poles of the rotor. To maintain this alignment and rotor rotation, commutation must be timed using feedback of the rotor’s position.

Permanent magnet motors operate using principles similar to those of brushed DC motors, although a major difference is that the electronic commutation of permanent magnet motors eliminates the need for manual commutation classically provided by carbon brushes. Electronic commutation not only improves the efficiency of the motor but extends its life by eliminating the need to maintain or replace the brushes, which wear down over time. The similarity to brushed motor operation has lead permanent magnet motors to be synonymous with the name “brushless DC” (BLDC). The term permanent magnet motor can also refer to permanent magnet AC (PMAC) motors which are similar in configuration to squirrel cage induction motors but that have permanent magnet rotors that eliminate slip and rotate at synchronous speed. However, because they operate at synchronous speed, PMAC motors require a VFD to provide a start to rotation. The terms BLDC and PMAC are sometimes erroneously used interchangeably, as both types are have permanent magnet rotors and use AC line input power.

Electronic commutation of permanent magnet motors can be achieved using a rotary encoder, sensors, or “sensorless” configurations. A common technique to determine rotor position (in brushless DC permanent magnet motors) is to use three Hall-effect sensors (position sensors) embedded in the stator. When a rotor pole passes a sensor, the sensor’s output voltage increases or decreases in response. The combined response of all three sensors in the stator is used to calculate their position relative to the rotor. Another commutation technique utilizes the inherent counter-electromotive force, or back EMF, of the motor to derive position. Back EMF is a voltage that results from motion of an electromagnetic field. The interaction between back EMF and applied voltage leads to a drop in overall voltage. Back EMF is dependent on the angular velocity of the rotor and increases proportionally with rotor speed. Thus, the back EMF can be estimated using known motor properties to provide a form of “sensorless” control. Benefits of "sensorless" control include reduced number of components and potentially reduced cost (Blackburn, 2012).

Despite their similarities, BLDC and PMAC motors contain subtle differences in their control schemes. BLDC motors have a more trapezoidal-shaped back EMF while PMAC motors have a sinusoidal back EMF. Factors contributing to this difference in shape include the geometry of the rotor, the distribution of windings in the stator, and the stator core geometry. Additionally, the shape of the back EMF produced by the motor should ideally match the shape of the waveform driving the motor. A square-wave commutation typically drives a BLDC motor, while a three-phase sinusoidal commutation drives a PMAC type motor. Although the torque density provided by either type of motor and drive configuration is similar, there is some advantage to using a sinusoidally driven PMAC motor, as torque ripple is minimized (Colton, 2010). Other than its impact on efficiency, torque ripple can contribute to acoustic noise, which is undesirable in many residential and commercial applications.

Permanent magnet motors are typically more efficient than alternatives for a variety of reasons. Because permanent magnet motors do not require current to be induced in rotor windings, overall power consumption can be reduced compared to induction motors. The elimination of brushes for commutation also contributes to increased efficiency, reliability, and longevity as described above. Furthermore, because permanent magnet motors have either integrated controls or are paired with drives, they are ideal for use in applications with varied loads. Permanent magnet motors tend to have a more constant efficiency over a range of speeds instead of a high peak efficiency at a single speed.

The magnets used in permanent magnet motors are typically made of rare-earth metals, the most common being an alloy of neodymium, iron, and boron. Rare-earth based magnets can have a magnetic strength up to 2 times more powerful than more typical ferrite based magnets (Murphy). Rare-earth metals, while rare only in name, are difficult to mine and fabricate into components. They are also only found in limited quantities at a given site. Over 90% of the world's rare-earth metals are supplied by China. Small fluctuations in the Chinese supply, often due to environmental or geopolitical factors, can greatly impact the cost of these magnets and thus the cost of permanent magnet motors. To address issues associated with dependency on foreign materials, the US Department of Energy (DOE) has begun funding research into alternatives, including motor designs that utilize magnets of lesser strength, as well as motor designs that do not employ permanent magnets but offer efficiencies similar to that of permanent magnet motors (Witkin, 2012).

Permanent magnet motors can be more efficient than induction motors by up to 10%age points, especially during part-load operation (ADL, 1999). As discussed in previous sections, the design of an asynchronous AC induction motor is inherently less efficient than a permanent magnet motor due to motor slip. However, induction motors do not contain rare-earth metals and are thus both lower cost and more readily available. A number of equipment manufacturers use variable speed AC induction motors in their three-phase power equipment for the commercial sector.

### 2.4.3 Electronically Commutated Motors (ECMs) with Integrated Controls

The term electronically commutated motor (ECM) is another term commonly used for permanent magnet motors described above, but it has a more specific connotation. In general, ECMs refer to low horsepower BLDC motors that have integrated drives and controls and are commonly found in HVAC applications. This makes the ECM ideal for use in existing residential and commercial designs that require a compact and simple motor and control package. In HVAC airflow applications, for example, ECMs can be programmed to operate over a broad range of speeds and deliver constant airflow for a variety of external static pressures.

ECMs are often sought as more efficient replacements to PSC induction motors. As discussed in section 2.1.4, PSC motors are generally considered single-speed devices and manufacturers use speed taps so that installers can manually adjust the motor to meet changing system conditions. Even in a reduced-speed arrangement, PSCs consume more energy than ECMs. The range of efficiency for PSCs is very broad, for example 35-50% in airflow applications, especially when operating at less than full load. ECMs can have a more narrow range of efficiency over different speeds, typically around 70% for motors that have fractional horsepower and above 80% for those at integral horsepower (Blackburn, 2012).

Although the cost of ECM technology continues to decrease as it is incorporated into more high-efficiency products, ECMs remain more expensive than PSC motors. To address this, some manufacturers offer an intermediate device often called a “constant torque ECM.” The constant-torque ECM is still a permanent magnet motor, but it is designed to provide constant torque as opposed to constant speed or airflow. Whereas ECMs can increase or decrease torque to provide desired speed or airflow, constant torque ECMs maintain torque as environmental factors change. Constant torque ECMs may be preferred to PSCs because their permanent magnet configuration makes them more efficient (Michael, 2009).

Constant torque motors may also be easier to integrate into existing products than standard ECMs. Because equipment manufacturers and installers are comfortable with the speed tap configuration of PSCs or lack the expertise to implement the control schemes necessary for optimal operation of ECMs, constant torque ECMs also employ a speed tap interface. Instead of providing reduced speed, the “speed taps” of the constant torque ECM correspond to various programmed levels of torque to meet the desired operating condition (Michael, 2009). The speed tap interface limits the range of operation compared to standard ECMs but still provides a lower cost, more-efficient alternative to PSCs.

### 2.4.4 Switched-Reluctance Motors (SRMs)

A mechanically commutated version of the switched reluctance motor (SRM) predates both DC electric motors and AC induction motors. However, issues associated with control, acoustic noise, and torque ripple made the motor unsuitable for many applications, especially those where quiet operation is important. With advances in variable frequency drives (as discussed in Section 2.4), digital signal processing, and other software-based control solutions, SRMs are again becoming a viable alternative to other motor types with peak efficiencies comparable to ECMs, up to 90% for integral horsepower devices (Teschler, 2008). Interest in SRMs has also increased as these motors do not rely on permanent magnets, and thus do not contain rare-earth metals.

The stator in a switched reluctance motor is configured much like a permanent magnet motor and has copper windings establishing the magnetic poles. The rotor consists of steel laminations with no windings or permanent magnets as shown in Figure 2.7. The rotor laminations are cut in such a way that the steel protrusions act as magnetic poles; this configuration exploits the concept of "magnetic reluctance," in which magnetic flux will follow the path of least magnetic resistance in the presence of a magnetic field. When the stator windings are energized, the magnetic reluctance of the rotor in this geometrical configuration results in a force that aligns the rotor poles with those of the stator. The stator windings are energized in sequence to maintain rotation of the rotor via a switching action provided by a VFD. Like permanent magnet motors, position feedback is required to time the stator switching operations with that of the rotor. To sustain rotation, the number of poles in the stator and the number of poles in the rotor are mismatched. Typically, the number of poles in the stator is higher than in the rotor. This mismatch ensures the SRM will always have a starting torque equivalent to its operational torque (Jin-Woo Ahn, 2011).

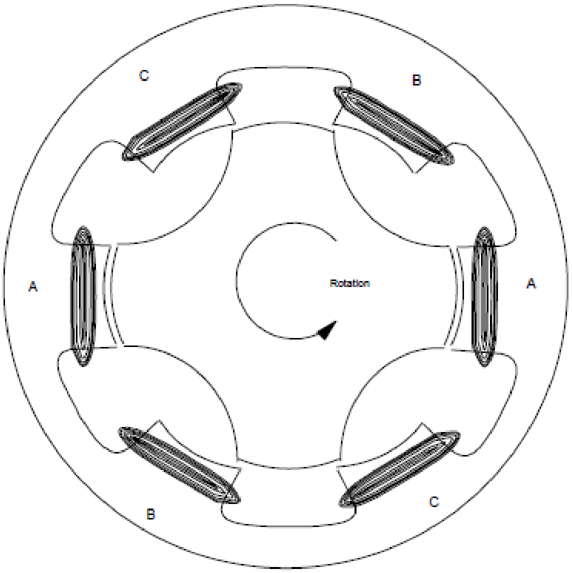

**Figure 2.7** Switched Reluctance Motor

Source: (ADL, 1999)

Due to their simple design and use of readily available materials, SRMs can be easier to manufacture than AC induction motors or permanent magnet motors. This also means that the manufacturing processes and equipment that already exist can be leveraged to bring SRM production up to scale so that SRMs may become competitive with longstanding motor alternatives.  Additionally, SRMs can be made smaller and more compact than AC induction motors. The robustness of SRMs make them ideal for high-temperature applications, where permanent magnets rotors run the risk of being demagnetized (Wai-Chuen Gan, 2008).

Historically, reliance on the rotor's magnetic reluctance has resulted in non-linear motor operation, preventing commercially available VFDs from being suitable for use with SRMs without modification. Lack of compatibility with commercial VFDs has been a major factor preventing the SRM from being widely implemented (Wai-Chuen Gan, 2008). A variety of companies and researchers have proposed solutions to this problem, and the decreasing cost of controls will also supplement SRM-tailored VFD availability. Other factors contributing to the unpopularity of SRMs include:

- High torque ripple
- The acoustic noise and vibration that result from the switching algorithms
- The geometrical configuration of the rotor.

Traditionally, SRMs were used in the transportation industry, because at high speeds, the motors retain torque longer than a permanent-magnet motor. At high speeds, permanent magnet motors must implement field weakening to prevent back EMF from interfering with motor input power (Teschler, 2008). For electric vehicles, SRMs can act as generators so that slowing rotation increases the stored energy in the magnetic field, which can then be used to supply another load.

Currently, manufacturers are investigating SRMs for use in appliances. SRMs and drive systems have been applied to vacuum cleaners, washing machines, and laboratory centrifuges. One manufacturer produces industrial-size SRMs for compressors and high-speed pumps as well as low-speed, high-torque applications like conveyors and extruders (Bartos, 2010). To address the issues of acoustic noise and torque ripple, start-up companies and universities have expressed interest in high rotor-pole technology, where the number of the poles in the rotor is greater than the number of poles in the stator. This reduces the angular travel of the rotor per excitation and addresses issues related to torque ripple (HEVT, LLC, 2013).

## 2.5 Future Innovations in Motor Technology

A number of innovations have occurred in the area of electric motors and variable speed drives, outside the increased interest in switched reluctance motors as mentioned in Section 2.4.4. Although manufacturers have only begun in the last decade to use permanent magnet and other high-efficiency motor drive combinations as standard components, the motivation to find ECM replacements has increased as a result of concerns about the availability and cost of rare-earth metals.

A range of projects at early-stage companies are investigating rare-earth replacements or alternative motor configurations that retain the efficiency of permanent magnet motors without the cost or constraints of rare-earths. The DOE’s Advanced Research Projects Agency-Energy (ARPA-E) Rare Earth Alternatives in Critical Technologies (REACT) initiative has spurred research in rare-earth alternatives. One possible option is to substitute neodymium with a more abundant and less expensive rare-earth metal, cerium (Witkin, 2012). Much of the research associated with rare-earths has been for application in electric vehicles, or industrial integral horsepower motors, but not for home appliances or commercial buildings. However, some companies are exploring the economics of producing these alternatives at the size and scale required for residential or commercial implementation[2].

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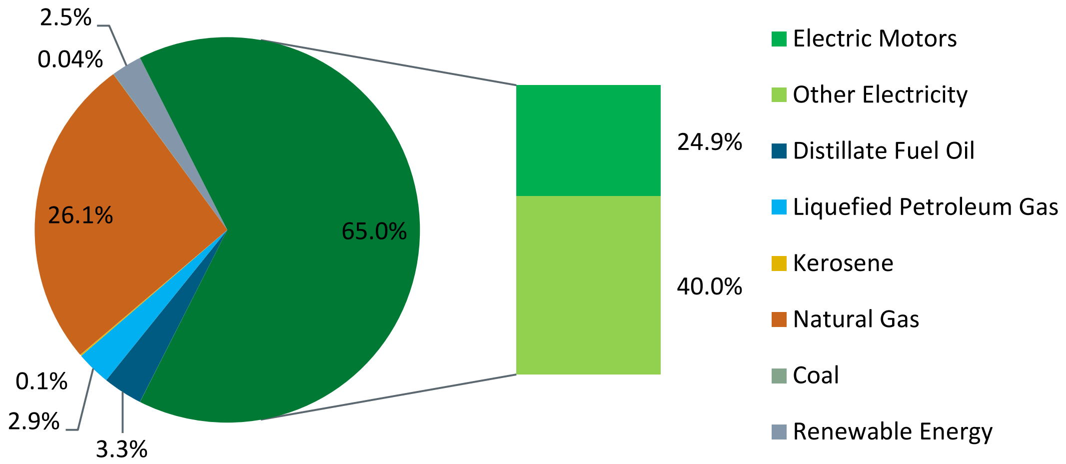
[2] Private phone communication with CEO at motor technology startup.

Other innovations include changes in rotor and stator geometry that result in increased magnetic field strength and more efficient torque output (Jones, 2011). Patents on various technologies claim it is possible to use lower-strength magnetic materials (ferrite) in combination with unique air-gap and winding configurations to boost the magnetic properties of the lower-strength material. Like SRMs, these motors use only steel laminations in the rotor, and employ windings and magnetic material in the stator (Flynn et al.)

Finally, motor manufacturers continue to research and develop lower-cost manufacturing techniques so that motors of all types and variable speed drives can be produced as cheaply as possible. For many of the motor alternatives discussed above to be cost competitive, they must be simple to manufacture, even if the material composition is inherently less expensive.

# 3 Motor Populations, Energy Usage, and Savings Potential in the Residential Sector

As Figure 3.1 illustrates, electrical energy consumption represents 65% of the residential sector's total primary energy consumption. Primary or source energy is the equivalent to the energy consumed on site given in terms of raw fuel before it is converted or distributed to the site of consumption. Electric motor-driven systems and components consume over one third of residential electrical energy and 25% of total residential energy.



**Total = 18.85 Quads**

Electric to Primary Conversion Factor: 3.1 (DOE, 2010a)

**Figure 3.1** 2013 Estimate of Residential Sector *Primary* Energy Consumption by Fuel Type, (AEO, 2013)

This section of the report includes:

- Summary of Motor Population and Energy Use, Section 3.1
- Estimate of Technical Energy Savings Potential, Section 3.2
- Detailed Descriptions of Major Motor-Driven Energy Consumption in Appliances, Section 3.3.

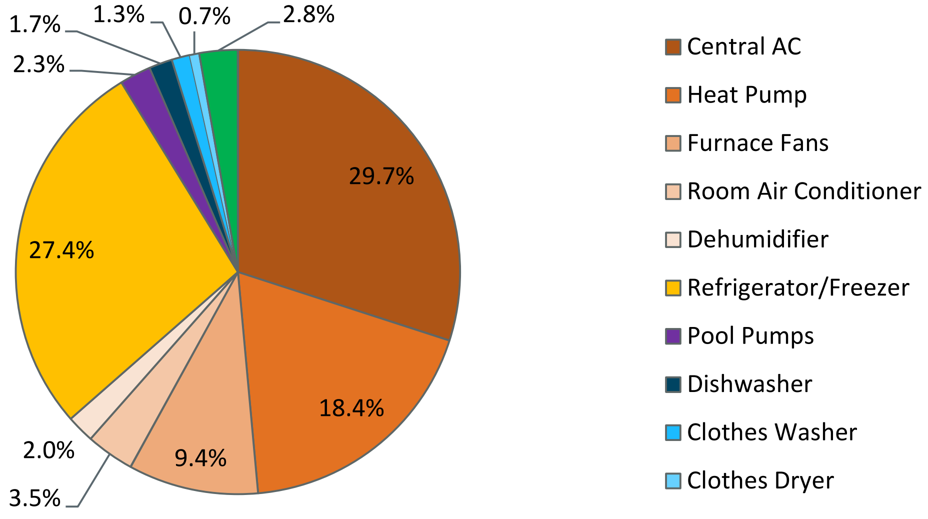
Subsection 3.1 provides a summary of the appliance and equipment types that contain motors and consume significant amounts of energy. Section 3.2 provides a summary and estimate of the motor technical energy savings potential, which is defined as the energy savings associated with a theoretical immediate replacement of the relevant installed base with the most efficient motor or a configuration that reduces overall energy consumption. Finally, Section 3.3 provides detailed descriptions of the major motor-driven energy in appliances, including discussion of overall trends in motor technologies and opportunities for additional research, development, and deployment (RD&D) investments in motor technologies for each appliance type.

## 3.1 Summary of Motor Installed Base and Energy Consumption

In the residential sector, the highest energy consuming motor-driven components, either by horsepower or usage, are primarily found in large appliances and space conditioning equipment. Many of the appliances/equipment sold at the minimum allowable efficiency levels in the residential sector contain single-phase induction motors, often PSC type, ranging from fractional to one horsepower (~746W). Refrigerant compressors used in air conditioners and heat pumps often contain larger integral-horsepower motors of 2 to 5 horsepower size. Motors are also found in many miscellaneous residential applications including power tools, lawn and garden equipment, and small appliances with intermittent use such as vacuum cleaners and kitchen tools.

The primary distribution channel for residential motors is direct from the motor manufacturer to the appliance original equipment manufacturer (OEM). Often, motors are provided in component form, i.e., the rotor and stator, and integrated into the product by the OEM instead of being purchased through a distributor as fully assembled, general-use motors.

Figure 3.2 summarizes residential-sector, motor-driven energy consumption by end use. HVAC applications, including central air conditioners and heat pumps, room air conditioners and dehumidifiers, are the largest energy consumers at approximately 63% of total residential-sector motor-related energy. Refrigeration is the second largest consumer at almost 28%.



**Total Residential Motor-Driven Primary Energy = 4.73 Quads**

Source: Table 3.1

**Figure 3.2** 2013 Estimate of Residential Sector Motor-Driven *Primary* Energy Consumption by End Use

Table 3.1 contains a more detailed breakdown of motor-driven energy use by application and function. The table also provides estimates of the current installed base and annual shipments of residential motors. Most of the applications listed in the table are covered products under the Energy Policy and Conservation Act of 2005 (EPCA), as amended, which provides DOE with the statutory authority to set national energy conservation standards and to develop test procedures for a variety of products. As part of the standards development process, DOE is required to determine the technical feasibility and economic justification of improving the efficiency of a product through individual “technology options,” which could include an upgrade of a motor. It is through this analysis that DOE has collected data on motor usage and cost. Energy conservation standards have been in effect since the 1990s and have contributed significantly to the increased adoption of higher-efficiency motors. For a number of the listed residential products, especially for space conditioning and refrigeration, more efficient motors have been determined to be a low cost technology option for improving overall system efficiency.

**Table 3.1** 2013 Estimate of Motor-Driven Energy Consumption in the Residential Sector

| Product | Installed Base[a] (MM) | Annual Operating Hours | Average UEC[b,c] (kWh/yr) | National Site Energy (kWh/yr x $10^9$) | National Primary Energy Consumption[d] (Quads) |
|---|---|---|---|---|---|
| Clothes Washers | 109.1 | 295 | 53.6[e] | 5.9 | 0.062 |
| Clothes Dryers | 109.1 | 283 | 18 | 3.1 | 0.032 |
| Furnace Fans | 61.8 | 1870 | 678 | 41.9 | 0.443 |
| Dehumidifier Fan | 14.9 | 1095 | 55 | 0.8 | 0.009 |
| Dehumidifier Compressor | 14.9 | 1095 | 548 | 8.2 | 0.086 |
| Dishwasher | 70.0 | 215 | 64 | 7.5 | 0.079 |
| Ceiling Fan | 83.8 | - | - | 4.8 | 0.051 |
| R/F Compressor | 143.5 | 3000 | 625 | 89.9 | 0.951 |
| R/F Condenser | 143.5 | 3000 | 25 | 3.8 | 0.040 |
| R/F Evaporator Fan | 143.5 | 3000 | 21 | 2.5 | 0.027 |
| Freezer Compressor | 49.4 | 3000 | 625 | 24.4 | 0.258 |
| Freezer Condenser | 24.7 | 3000 | 25 | 0.6 | 0.006 |
| Freezer Evaporator Fan | 49.4 | 3000 | 21 | 1.2 | 0.012 |
| CAC Compressor | 59.5 | 1000 | 2008 | 119.4 | 1.263 |
| CAC Fan | 59.5 | 1000 | 223 | 13.3 | 0.140 |
| HP Compressor | 14.7 | 1000 | 2008 | 73.9 | 0.782 |
| HP Fan | 14.7 | 1000 | 223 | 8.2 | 0.087 |
| RAC Compressor | 28.7 | 750 | 515 | 13.9 | 0.147 |
| RAC Blower | 28.7 | 750 | 57 | 1.5 | 0.016 |
| Pool Pumps | 6.7 | 1200 | 1500 | 10.1 | 0.107 |
| Miscellaneous | - | - | - | 12 | 0.042 |

[a] Installed base estimated from percent saturation of U.S. Households, ~114 Million (US Census Bureau 2007-2011). Detailed information on the sources used to derive estimates is provided in Appendix A.

[b] UEC = Unit Energy Consumption

[c] Site-to-Source Conversion Factor: 3.1

[d] Table 3.1 was primarily developed from engineering data collected as part of DOE's energy conservation standards program. Please see Appendix A.

[e] Weighted average of top loading and front loading UEC.

The miscellaneous category listed in Table 3.1 is a catch-all for products with low consumption or intermittent usage, including vacuum cleaners, house fans, food mixers, power tools, garage door openers, etc. Some products in this category may use less efficient motors because of a particular utility. For example, vacuum cleaners require the high rotational speeds of a universal motor. These miscellaneous products fall outside the scope of this report and are not discussed further.

Section 3.3 provides a detailed discussion of the motors used in each product listed in Table 3.1 with the exception of the miscellaneous category.

## 3.2 Estimate of Technical Energy Savings Potential

Motor related energy savings may result from upgrading residential motors to motors with the highest achievable efficiency or by pairing motors with variable speed capability. Evaluating savings for each of the major appliance and equipment categories listed in Section 3.1 allows for determination for the cost-effectiveness, or simple payback, of these motor efficiency improvements at current cost levels. Table 3.2 summarizes the estimated technical potential which is described in detail in Section 3.3. Section 3.3 also describes the motor trends for each appliance type, recommendations for RD&D opportunities, and various market barriers limiting the adoption of more efficient motor technologies in greater detail.

**Table 3.2** Summary of Technical Energy Savings Potential in the Residential Sector

| Appliance or Equipment Type | Motor Application | Primary Energy Consumption[a] ($10^{12}$ Btu) | Technical Energy Savings Potential[b,c] | | Typical Payback Years[b,d] |
|---|---|---|---|---|---|
| | | | % | ($10^{12}$ Btu) | |
| Refrigeration/Freezer | Compressor | 1209.4 | 6% | 67.2 | 13 |
| | Condenser Fan | 46.5 | 62% | 28.7 | 2 |
| | Evaporator Fan | 39.2 | 48% | 18.7 | 3 |
| Central AC/Heat Pump | Compressor | 2045.0 | 3% | 68.2 | 7 |
| | Outdoor Fan | 227.2 | 38% | 85.2 | 0.4 |
| Furnace Fans (Indoor Blowers) | Fan | 442.9 | 30% | 132.8 | 7 |
| Room Air Conditioners | Compressor | 147.3 | 10% | 14.7 | 9 |
| | Condenser Fan | 16.4 | 4% | 6.1 | 15 |
| Dehumidifiers | Compressor | 86.4 | 10% | 8.6 | 9 |
| | Condenser Fan | 8.6 | 1% | 0.9 | 65 |
| Dishwashers | Drain Pump | 31.5 | 10% | 3.15 | 20 |
| | Circulation Pump | 47.3 | 10% | 4.73 | 32 |
| Clothes Washer | Top Loading | 37.8 | 60% | 22.8 | 2 |
| | Front Loading | 24.2 | 2% | 0.4 | 61 |
| Clothes Dryer | Drum Rotation | 32.5 | 2% | 0.6 | 96 |
| Pool Pumps | Drum Rotation | 106.8 | 68% | 72.8 | 4[d] |
| TOTAL | | | | 535.7 | - |

[a] Estimated for 2013
[b] Refer to Section 3.3, Table 3.3 through Table 3.18 as well as Appendix A for detail.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)
[d] Using an EIA 2011 $0.12/kWh electricity rate
[e] Based on pump with VFD replacement cost of approximately $1000.

The technical potential for the residential sector is approximately 0.5 quads. In a 1999 report, Arthur D. Little estimated the technical potential to be 1.9 quads (ADL, 1999). The reduction in technical potential over this 14-year period is likely due to the introduction of more energy-efficient motor designs into residential equipment over that period. The following factors have influenced the adoption of more efficient motors:

- Increase in the number of product types covered by DOE minimum efficiency standards
- Raising minimum efficiency standards levels on products already covered by DOE
- Voluntary standards programs such as ENERGY STAR
- Decreasing costs of permanent magnet motors and variable speed drives.

The applications with the shortest payback period include refrigerator/freezer fan motors, central AC and heat pump compressors and fans, furnace fans, front loading clothes washer motors, and pool pumps.

Pool pumps are not a covered product under EPCA, but energy efficient pool pumps with ENERGY STAR ratings are available. ENERGY STAR pool pumps typically have multi-speed capability and an integrated VFD. The state of California recently implemented an energy conservation standard requiring all new pumps to be sold with variable speed capability. ENERGY STAR pool pumps typically have a payback period of less than 5 years (as shown in Table 3.2 above) and have the opportunity to provide significant savings as their adoption increases.

As of 2013, there are no U.S. minimum energy conservation standards for circulation pumps used in hydronic heating systems [3]. Although not estimated above, there may be an opportunity for energy savings if these products are packaged with integrated controls. In Europe, sales of ECM circulators have increased due to the implementation of an EU Ecodesign Directive that set minimum efficiency standards. Many European manufacturers have upgraded their product lines to include products with ECMs in order to comply with the standard. ECM circulators have only recently entered the U.S. marketplace and the high initial cost of these circulators may limit consumer adoption. However, if the cost of ECMs continues to decrease, or if minimum energy conservation standards were developed for circulators, sales of ECM-based circulators might increase.

## 3.3 Detailed Descriptions of Major Motor-Driven Energy Use in Appliances

### *3.3.1 Central Air Conditioning and Heat Pumps*

Residential central air conditioners (CAC) and heat pumps (HP) typically contain three motors; one each for the compressor, outdoor fan, and indoor blower. Ducted, split-system CACs or HPs are the most common type of residential AC found in the US. Ductless, or mini-split, systems are increasing in popularity in certain regions, but the outdoor units of ducted and ductless types operate similarly. Indoor blowers/fans are described in Section 3.3.2.

Residential CAC and HP systems are regulated under EPCA. These standards have resulted in continuous improvements in overall product efficiency, and have led manufacturers to consider the use of higher efficiency motors to reduce energy consumption and comply with minimum energy conservation standards.

Table 3.3 provides an estimate of the technical potential, i.e., the theoretical energy savings if more efficient technologies were used in place of the installed base. Table 3.4 shows the average unit energy consumption (UEC) and estimated simple payback for each type of motor-related efficiency improvement.

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[3] DOE initiated an ongoing Commercial and Industrial Pumps rulemaking in that is considering whether circulators are covered under the authority of EPCA.

**Table 3.3** Residential CAC and HP Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[c] (Site-Based) | Primary Energy Savings[d] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 2045.0 | 87% | Variable-speed Motor | 90% | 3% | 68.2 |
| Outdoor Fan[b] | 227.2 | 50% | Upgrade to BLDC | 80% | 38% | 85.2 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.

[b] Only an ideal option when paired with variable speed compressor.

[c] Technical potential based on application of the efficiency option to entire installed base.

[d] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.4** Estimated Motor Upgrade Payback Period for Residential CAC and HP

| Component | Avg. UEC (kWh/yr)[a] | Savings ($/yr)[b] | Additional Retail Cost[c] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor | 2007.9 | $8.03 | $56.00 | 7 |
| Outdoor Fan | 223.1 | $10.04 | $4.30 | 0.4 |

[a] Average UEC derived from references in Appendix A.

[b] EIA 2011 $0.12/kWh electricity rate

[c] DOE, 2011d

### Compressor Motors

Compressors with hermetically sealed, integrated motors used for HVAC have transitioned to capacitor based induction motors (CSCR or PSC) from their less efficient single-phase induction counterparts. Current baseline residential CACs and HPs contain PSC motors for both the compressor and the condenser fan. Hermetically-sealed scroll compressors are most commonly used in these products, although reciprocating compressors are also used and offer equivalent efficiency.

The primary techniques to improve compressor efficiency in space conditioning products include variable speed capability and/or permanent magnet motors. Manufacturers find the cost of upgrading to permanent magnet motors prohibitive and can achieve similar efficiency improvements by upgrading to a two-speed or variable-speed induction motor.

The non-energy related benefits to variable speed, such as decreased noise, increased comfort, and the ability to adjust to system load changes after install, have shifted the high-end market towards variable speed. However, limited adoption of variable speed compressors in mainstream product is largely due to the fact that manufacturers can achieve lower-cost efficiency improvements by increasing the surface area of the product's heat exchanger instead. As long as the size of the heat exchanger can be increased without negatively impacting a product's utility, e.g., when the product can no longer fit into certain mechanical spaces, and the cost to increase the size of the heat exchanger remains less than the cost to upgrade to a variable speed compressor, manufacturer implementation of variable speed compressors in CACs and HPs will not become mainstream.

**Fan Motors**
The baseline fan motors used in HVAC have largely transitioned to PSC from less efficient shaded-pole in the last ten years. The efficiencies of PSC motors used in outdoor fan applications range from 50-70%. Upgrading to a BLDC motor offers a potential efficiency of 70-80%, even at fixed speed. The highest possible savings could be achieved through part-load operation of the fan motor through the use of an ECM (e.g., a permanent magnet motor with integrated controls). While variable speed control of the outdoor blower would offer some savings, lower airflow across the heat exchanger may increase compressor runtimes and offset savings. To maximize the benefit of variable speed control, the compressor should also be variable speed.

The savings reported in Table 3.3 above assume that the installed base operates near the bottom of the efficiency range and that an upgrade to BLDC would allow the fan motor to operate at the top end of the efficiency range. Realistically, the potential for savings may be reduced if PSC and BLDC motors operate closer to their peak efficiencies.

### *3.3.2 Furnace Fans (Indoor Blowers)*

The indoor blowers used in ducted split CAC or HP systems are effectively the same components used in furnaces to circulate air. Under EPCA, all air-moving blowers used to circulate air through ductwork are considered furnace fans regardless of the fan’s use for heating or cooling operation. To be consistent, this section of the report refers to all indoor blowers as furnace fans, whether used with a stand-alone furnace, a furnace/air conditioner, or a heat pump.

There are no federal energy conservation standards for furnace fans, but DOE is currently investigating whether furnace-fan standards would be technologically feasible and economically justified. Because no minimum energy conservation standards have been established, the installed base contains a mix of low and high efficiency motors.

The average furnace fan product uses fixed-speed PSC motors. Table 3.5 provides an estimate of the energy savings if the installed base of furnace fan motors were upgraded to variable-speed ECMs with integrated controls. Table 3.6 provides an estimate of the simple payback period if the furnace fan motor were upgraded to an ECM. This estimate assumes that the entire system is modified for variable speed operation, rather than assuming a drop-in motor replacement. The maximum energy savings from a variable speed furnace fan is attainable only when the entire system is designed for variable speed, e.g., when the compressor is also variable speed or the furnace firing rate is modulated.

**Table 3.5** Furnace Fans Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Efficiency Option | Technical Potential Energy Savings (Site-Based)[b] | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|
| Furnace Fan | 442.9 | Upgrade to ECM | 30% | 132.8 |

[a] Motor site energy consumption derived from references available in Appendix A.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.6** Estimated Motor Upgrade Payback Period for Furnace Fan

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost | Simple Payback (Years) |
|---|---|---|---|---|
| Furnace Fan | 677.6 | $24.38 | $180.00[d] | 7 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in Table 3.5
[d] Does not account for installation costs.

Variable-speed operation would significantly improve furnace fan efficiency. Fan power is proportional to the cube of the motor rotational speed, such that reducing fan speed by 25% results in a 58% reduction in power draw. Operating at a reduced speed, however, requires that the fan operate longer, such that the actual reduction in energy consumption compared to fixed-speed operation is roughly half of what is theoretically possible (ADL, 1999).

In 2012, ECMs represented 34% of the furnace fan market (DOE, 2012g). The market share of ECMs may increase if minimum energy conservation standards are introduced, especially if their cost continues to decrease. However, if new furnace fans become more expensive because of the upgrade, consumers might instead decide to repair existing units instead of replacing them. Another permanent magnet motor, the constant-torque ECM as described in Section 2.4.3, may be an ideal alternative and could be implemented at a lower cost than indicated in Table 3.6.

### *3.3.3 Window and Through-Wall Room Air Conditioners*

In window and through-the-wall room air conditioners, motors are used to drive the condenser fan and blower as well as the compressor. The condenser fan and blower are typically driven by a single, double-shafted PSC motor while the rotary compressor contains a hermetically sealed PSC motor. Compressor energy consumption represents about 90% of total room air conditioner energy consumption, while the fan motor consumes roughly 10% of the total energy.

Room air conditioners are regulated under EPCA, and current and future minimum energy conservation standards have considered high-efficiency fan motors as a technology option to improve overall room-air-conditioner efficiency while not explicitly requiring them. Variable-speed compressors have not been considered because the test procedure developed to evaluate the energy consumption of these products only evaluates steady-state maximum capacity operation and would not capture any benefits due to part-load operation.

Table 3.7 provides an estimate of the maximum attainable energy savings if more efficient technologies were used in place of the installed base. Table 3.8 shows the average UEC and provides an estimate of the simple payback for each type of motor related efficiency improvement.

**Table 3.7** Room Air Conditioners Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 147.3 | 87% | Variable-speed Induction Motor | 90% | 10% | 14.7 |
| Condenser Fan | 16.4 | 50% | Upgrade to BLDC | 80% | 4% | 6.1 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.8** Estimated Motor Upgrade Payback Period for Room Air Conditioners

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b.c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor | 515.1 | $6.18 | $56.00 | 9 |
| Condenser Fan | 57.2 | $0.29 | $4.30 | 15 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in Table 3.7
[d] DOE, 2011d

### Compressor Motors

Motors in compressors, of the capacity and type used in room air conditioners, are already nearing their practical limit in terms of efficiency, restricted by factors such as size and weight. As described above, room air conditioners typically use a rotary compressor containing a hermetically sealed PSC motor. Permanent magnet motors are unlikely to be implemented in compressors due to their high cost relative to the low cost of the overall product. Variable-speed compressors could be implemented, but the DOE test procedure only evaluates the product at full-load operation. Thus, there is little regulatory incentive for manufacturers to implement variable speed into their products.

With cost as a major concern, the consumer often opts for smaller capacity than recommended for a space and chooses to operate the unit continuously for a short period of the year. Due to the extreme price sensitivity, consumers would be unlikely to tolerate a higher upfront purchase cost that would result from adding variable-speed capability. Also, because consumers typically use room air conditioners under high-load conditions, a unit with a variable-speed compressor may not provide significant energy savings compared a single-speed compressor because it would operate at part load for a small percentage of the operating time.

**Fan Motors**

As mentioned above, the condenser and blower are typically driven by a single, double-shafted PSC motor, consuming about 10% of the total room-air-conditioner energy. Upgrading the fan motor to BLDC type would increase motor efficiency from about 60 to 80% or higher; however, because the motor-driven fan represents such a small portion of the total energy, the estimated savings resulting from this upgrade is only 4%. Additionally, the payback period of 15 years (see Table 3.8 above) would likely exceed the expected lifetime of the product.

### *3.3.4 Dehumidifiers*

Motor usage in residential dehumidifiers, both portable and whole-house, is similar to room air conditioners, consisting of a compressor and fan motors. The 2007 amendment to EPCA, the Energy Independence and Security Act (EISA), prescribed standards for dehumidifiers based on liters of water removed per kilowatt-hour and did not mandate a particular technology option to achieve incremental improvements in overall product efficiency. While a motor upgrade may improve overall product efficiency, DOE did not explicitly set standards based on efficiency gains attainable through motor upgrades.

Table 3.9 provides an estimate of the maximum attainable energy savings if more efficient technologies were used in place of the installed base. Table 3.10 shows the average UEC and provides an estimate of the simple payback for each type of motor-related efficiency improvement.

**Table 3.9** Dehumidifiers Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 86.4 | 87% | Variable-speed Induction Motor | 90% | 10% | 8.6 |
| Condenser Fan | 8.64 | 50% | Upgrade to BLDC | 80% | 1% | 0.9 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.10** Estimated Motor Upgrade Payback Period for Dehumidifiers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor | 547.5 | $6.57 | $56.00 | 9 |
| Condenser Fan | 54.75 | $0.07 | $4.30 | 65 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in Table 3.9
[d] DOE, 2011d

As the table shows, upgrading to a variable-speed compressor could provide savings of up to 10%, and upgrading to a BLDC fan motor could provide savings of 1%. As with other similar products, the DOE test procedure for dehumidifiers would not capture any benefit of variable-speed operation. Therefore, there is little incentive for manufacturers to use ECMs for either the compressor or condenser fan.

### *3.3.5 Residential Refrigerators and Freezers*

Residential refrigerators and freezers often contain up to three motors. Most refrigeration systems are comprised of at least one refrigerant compressor, an evaporator fan, and a condenser fan, each requiring a motor. Some refrigerators and freezers rely on natural convection instead of fans to force air over the condenser, and thus do not require fan motors.

Residential refrigerators and freezers are regulated under EPCA. These standards have resulted in the continuous improvement of residential refrigerator and freezer efficiency, although only a small portion of that improvement has been through the use of higher-efficiency motors (DOE, 2011d).

Table 3.11 provides an estimate of the maximum attainable energy savings if more efficient technologies were used in place of the installed base. Table 3.12 shows the average unit energy consumption (UEC) and estimates the simple payback for each type of motor-related efficiency improvement.

**Table 3.11** Residential Refrigerators and Freezers Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[c] (Site-Based) | Primary Energy Savings[d] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 1209.4 | 85% | Variable-speed motor | 90%[b] | 6% | 67.2 |
| Condenser Fan | 46.5 | 30% | Upgrade to BLDC | 65% | 62% | 28.7 |
| Evaporator Fan | 39.2 | 30% | Upgrade to BLDC | 65% | 48% | 18.7 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.
[b] Assumes that 90% is the max attainable compressor efficiency, based on conversations with industry experts.
[c] Technical potential based on application of the efficiency option to entire installed base.
[d] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.12** Estimated Motor Upgrade Payback Period for Residential Refrigerators and Freezers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b.c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor | 625 | $4.17 | $56.00 | 13 |
| Condenser Fan | 25 | $1.85 | $4.30 | 2 |
| Evaporator Fan | 21 | $1.20 | $4.10 | 3 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in
[d] DOE, 2011d

## Compressor Motors

Compressors account for over 90% of residential refrigerator and freezer energy use. The majority of refrigerators and freezers employ reciprocating, hermetically sealed compressors that contain a single-phase, two-pole induction motor of the RSCR or RSIR type. Because the device is hermetic, the motor is integrated into the compressor housing and cooled by the refrigerant used in the refrigeration cycle. The compressor motor typically ranges from 1/8 to 1/3 horsepower, and is sized for the capacity required under maximum possible heat load. Because the maximum load rarely occurs, the compressor is cycled on and off to adjust for varying load conditions. This style of operation introduces significant losses that could be eliminated if the compressor were to operate continuously at a lower speed. The primary method to improve compressor efficiency is to integrate variable-speed capability into the compressor through an inverter or variable-frequency drive. Variable-speed refrigeration compressors on the market typically use an induction motor paired with a VFD.

It is possible to upgrade the compressor motor to permanent magnet technology both for fixed- and variable-speed operation. However, the gain in efficiency offered by this upgrade would be minimal, often one or two efficiency percentage points, and would probably not be cost-effective due to both the high cost of permanent magnets and the scarcity of rare-earth metals.

One drawback to implementing variable-speed compressors is that continuous compressor operation also requires continuous operation of the condenser and evaporator fans. As a result, energy savings associated with a variable-speed compressor may be partially offset by an increase in fan-motor energy consumption.

Although the popularity of variable-speed compressors is increasing, most residential systems still use single-speed compressors. Implementation of variable-speed compressors has been hindered primarily by cost. As shown in Table 3.12 above, higher-efficiency compressors have a relatively high upfront cost compared to the typical purchase cost of a new refrigerator/freezer. Proper design of single-speed compressor on-off control can still achieve good performance relative to the savings possible with variable speed. Also, in some cases, the payback period of the variable-speed compressor, as shown in Table 3.12, may be longer than the life of the product since the average refrigerator lifetime is approximately 16 years (DOE, 2011d).

Over the next few years, the introduction of variable-speed compressors will likely be minimal, with manufacturers choosing to focus instead on efficiency improvements resulting from other aspects of refrigerator design. Given the relatively large energy consumption of compressors, RD&D efforts focused on lowering the cost of implementing variable-speed compressors should be considered. Voluntary standards or utility programs incentivizing their use could also be effective.

**Fan Motors**

Upgrading the refrigerator or freezer fan motors to permanent magnet BLDC motors can provide another opportunity for energy savings. Upgrading the fan motors can reduce the energy consumption of both the motor and the compressor because more efficient motors have lower heat loss, resulting in a reduction of the overall heating load in the refrigeration cavity. The cost increase of more efficient fan motors is much lower compared to more efficient compressor technologies, and payback periods, as shown in the table, are only a few years (DOE, 2011d).

Expert opinion suggests that the combination of a variable-speed compressor and BLDC fan motors offers the best savings opportunity. More savings could be possible if ECMs (permanent magnet motors with integrated controls) were used with the condenser and evaporator fans.

### *3.3.6 Residential Dishwashers*

Dishwashers use motor-driven pumps to recirculate and drain the water used during the dishwashing cycle. Some units use a single pump/motor for both operations, while others use separate pump/motors. The pump motors are typically shaded pole or PSC type. In units with two pumps, the recirculating pump typically consumes slightly more energy than the drain pump (DOE, 2012d).

Dishwashers are a regulated product under EPCA, as amended. New energy conservation standards became effective in May 2013. DOE anticipates that, to comply with the new standards, manufacturers might have to implement variable-speed controls and permanent magnet motors, among other features, to improve the overall efficiency of the dishwasher.

Table 3.13 provides an estimate of the maximum attainable energy savings if more efficient technologies were used in place of the installed base. Table 3.12 shows the average UEC and estimates the simple payback for each type of motor related efficiency improvement. The calculations in the table assume an average usage and a national average cost of electricity.

**Table 3.13** Residential Dishwasher Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Efficiency Option | Technical Potential Energy Savings (Site-Based)[b] | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|
| Dishwasher Drain Pump | 31.5 | Upgrade to ECM | 10% | 3.2 |
| Dishwasher Circ Pump | 47.3 | Upgrade to ECM | 10% | 4.7 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.14 Residential** Estimated Motor Upgrade Payback Period for Dishwashers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Dishwasher Drain Pump | 42.6 | $0.51 | $10.34 | 20 |
| Dishwasher Circ Pump | 63.9 | $0.77 | $24.31 | 32 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in Table 3.13
[d] Scaled from cost vs. horsepower information in DOE, 2012g

Permanent magnet motors can provide a 10-20% improvement in motor efficiency as compared to the PSC. In the most efficient compact dishwashers, permanent magnet motors have already been implemented. However, compact dishwashers only make up a fraction of the current dishwasher market. With the new energy conservation standard in effect, there is potential for future dishwasher shipments, both standard and compact, to contain ECMs with integrated controls. Variable-speed control of the dishwasher pump, along with the appropriate control algorithms, helps optimize energy use during the wash cycle. Additionally, the use of a permanent magnet motor allows for direct coupling to the pump impeller and may be used to drive both the drain and circulation operations, helping to reduce overall costs.

### *3.3.7 Residential Clothes Washers*

Clothes washers use a motor to turn the clothing drum during agitation and the spin cycle. Typical motors range from ¼ to 1 horsepower. Clothes washers also typically use a second motor to drive a drain pump, but the energy consumption associated with this component is negligible compared to the energy use for water heating.

This report analyzes top-loading and front-loading clothes washers separately due to the significant difference in typical motor-driven energy consumption and energy savings potential. Most top-loading clothes washers are sold at lower prices than front-loading clothes washers, and the lowest-cost models constitute the majority of top-loading sales. The lowest-cost models are often purchased as an emergency replacement when the household clothes washer fails. Due to consumer price sensitivity, top-loading clothes washers use lower-priced, lower-efficiency components, including the motor. Therefore, top-loading clothes washer motors are less efficient and typically consume more motor-related energy than front-loading clothes washers, despite the fact that front-loading clothes washers typically offer higher spin speeds and a more vigorous spin cycle. (Higher spin speeds increase energy consumption, but this increase is small compared to the clothes-dryer energy savings associated with the reduced residual moisture content in the wash load.)

Within each configuration, motors can be categorized into low (CSIR), medium (PSC), and high (ECM) efficiency categories, all of which are found in the marketplace. For top-loaders, the majority of unit shipments have low-efficiency CSIR motors. For front-loaders, however, the majority of unit shipments have medium and high-efficiency motors.

Table 3.15 provides an estimate of motor-driven energy consumption and potential savings if the entire motor installed based were to use ECM type motors. Table 3.14 estimates the payback period of these upgrades.

**Table 3.15** Residential Clothes Washer Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Efficiency Option | Technical Potential Energy Savings (Site-Based)[b] | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|
| Top Loading Washer | 37.8 | Upgrade to ECM | 60% | 22.8 |
| Front Loading Washer | 24.1 | Upgrade to ECM | 2% | 0.4 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.16 Residential** Estimated Motor Upgrade Payback Period for Clothes Washers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Top Loading Washer | 59.6 | $4.49 | $9.00 | 2 |
| Front Loading Washer | 46.2 | $0.10 | $6.00 | 61 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in Table 3.15
[d] DOE, 2012b

With an estimated savings of 60% and a payback period of only 2 years, upgrading top-load washers with ECMs would seem to be economically attractive. However, consumer price sensitivity remains an important barrier preventing manufacturers from implementing higher-efficiency motors on the lower-cost models. For front-loading clothes washers, however, most of the market already uses medium- and high-efficiency motors, leaving little room for motor-efficiency improvement. In addition, for front-loading clothes washers in particular, the higher spin speeds attained by using permanent magnet motors can negate some of the potential energy savings. While this energy penalty is minimal compared to the energy saved during the dryer cycle, consumers may not consider the energy use of both products in combination when making a purchase.

Clothes washers are regulated under EPCA, and increasingly stringent energy conservation standards have led manufacturers to upgrade to higher efficiency motors. In general, switching from a low-efficiency CSIR motor to a medium-efficiency PSC motor provides the most favorable tradeoff between increased cost and energy savings (DOE, 2012b). Analysis suggests that manufacturers can achieve the more stringent standards scheduled to take effect in 2015 and 2018 with medium-efficiency PSC motors (but not with the lowest-efficiency CSIR motors) (DOE, 2012b). However, until economies of scale are fully leveraged, it is unlikely that the highest-efficiency ECMs will replace the induction motors in these products.

### *3.3.8 Residential Clothes Dryers*

Clothes dryers use a motor to turn the drum during the drying cycle. Typical motors range from ¼ to 1 horsepower. Dryers may also have a second motor to power an exhaust blower. Clothes dryers use induction motors, often of PSC type. The majority of dryer sales are of the lowest-cost units with the least-efficient motors, and are often purchased as an emergency replacement when a household dryer fails, with little forethought on the part of the purchaser

Table 3.17 provides an estimate of the maximum attainable energy savings if a BLDCs were used in place of PSC motors in the installed base. Table 3.18Table 3.12 shows the average UEC and estimates the simple payback the motor-related efficiency improvement. The calculations in the table assume an average usage and an average cost of electricity.

**Table 3.17** Residential Clothes Dryer Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Efficiency Option | Technical Potential Energy Savings (Site-Based)[b] | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|
| Dryer | 32.45 | Upgrade to BLDC | 2% | 0.6 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix A.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 3.18** Estimated Motor Upgrade Payback Period for Residential Clothes Dryers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Dryer | 17.8 | $0.04 | $4.10 | 96 |

[a] Average UEC derived from references in Appendix A.
[b] EIA 2011 $0.12/kWh electricity rate
[c] Calculated using percent savings in Table 3.17
[d] DOE, 2011d

The dryer motor represents only 5% of total dryer energy consumption (DOE, 2011b). New energy efficiency standards for residential clothes dryers take effect in 2015, but the standard levels are unlikely to prompt manufacturers to upgrade the dryer motor. Because motor-driven energy is such a small portion of overall energy consumption, the increase in cost to upgrade the motor is not economically justified nor will it significantly impact overall product efficiency. In addition, the DOE dryer test procedure only accounts for fixed-speed conditions--using a variable-speed motor would not improve the *measured* energy efficiency. For these reasons, manufacturers are unlikely to upgrade to higher efficiency motors in residential clothes dryers in the near future.

# 4 Motor Populations, Energy Usage, and Savings Potential in the Commercial Sector

Electrical energy consumption represents 77% of the commercial sector's total primary energy consumption. Figure 4.1 breaks out commercial sector energy consumption by fuel type. Electric motor-driven system and components consume almost one third of commercial electrical energy and 24% of total commercial energy.

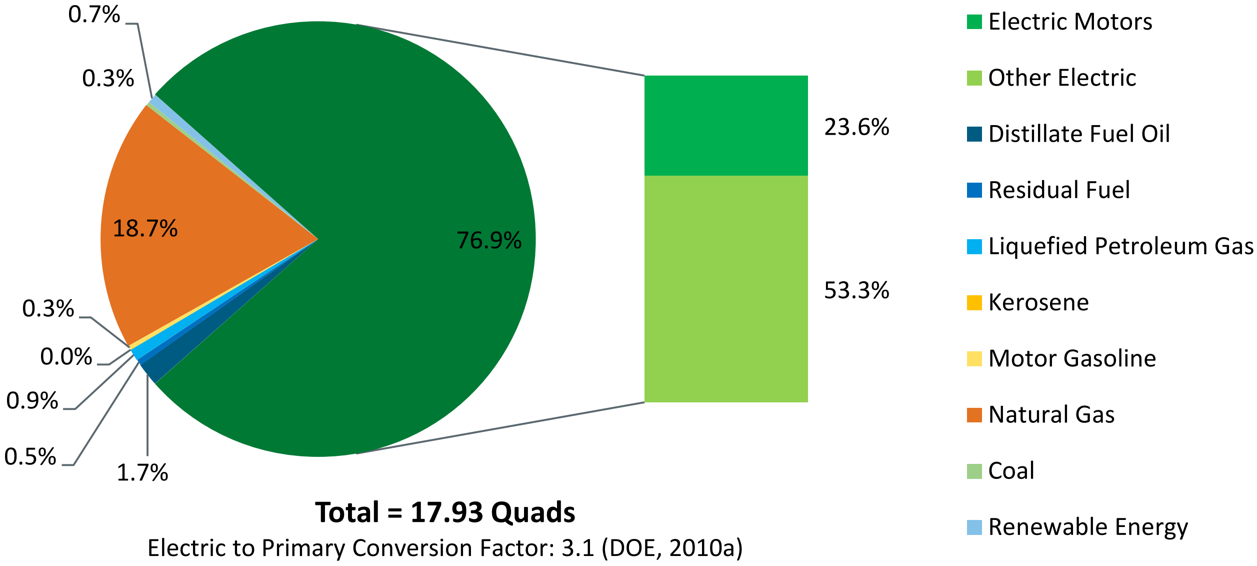


**Figure 4.1** 2013 Estimate of Commercial Sector *Primary* Energy Consumption by Fuel Type (AEO, 2013)

This section of the report includes:

- Summary of Motor Population and Energy Use
- Estimate of Technical Energy Savings Potential
- Detailed Descriptions of Major Motor-Driven Energy Consumption in Commercial Equipment.

The detailed descriptions of the major motor-driven energy consumption in commercial equipment includes discussion of overall trends in motor technologies and opportunities for additional research, development, and deployment (RD&D) investments in motor technologies for each equipment type.

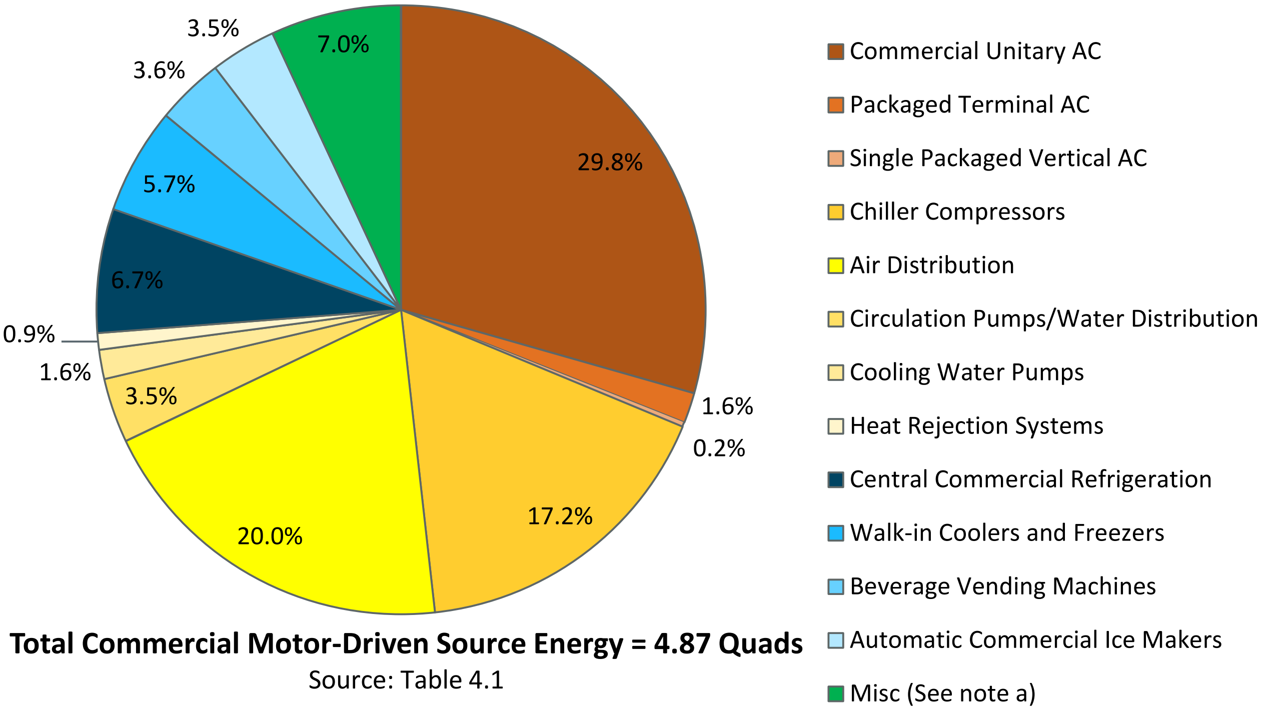
## 4.1 Summary of Motor Installed Base and Energy Consumption

In the commercial sector, the highest energy-consuming motor-driven systems and components, on a national basis, are found in space-conditioning and refrigeration equipment. The average rated motor horsepower for all commercial sector equipment is greater than 10 hp (ADL, 1999). Motors used in the commercial sector are typically three-phase AC induction motors. However, there are some commercial end uses that only require low horsepower motors, such as outdoor blowers in commercial unitary air conditioners, in which single-phase configurations like PSCs are used.

Although upgrading to permanent magnet motor technologies is viable in some commercial applications, these motors are typically cost-effective only up to three horsepower (Navigant, 2013a). For higher-horsepower applications, upgrading to a high-efficiency or “premium” three-phase AC induction motor and applying a VFD, where appropriate, are techniques available to reduce energy consumption. Higher horsepower motors are inherently more efficient compared to smaller motors, and due to their larger physical size, allow for optimization of rotor or stator configurations that eliminate many resistive and heat losses common at lower horsepower.

As in the residential-sector, the primary distribution channel for commercial motors is direct from the motor manufacturer to the OEM for new equipment that is then purchased by building owners and operators. Exceptions to this include retrofits and replacements as well as equipment items like pumps that are not integrated into a larger system. In some cases, an end user can purchase a motor at a lower first cost directly from a distributor rather than an OEM.

Figure 4.2 summarizes commercial-sector, motor-driven system and component energy consumption by end use. HVAC applications account for approximately 78% of total commercial sector motor-related energy. Refrigeration accounts for almost 22%.



**Total Commercial Motor-Driven Source Energy = 4.87 Quads**

Source: Table 4.1

**Figure 4.2** 2013 Estimate of Commercial Sector *Primary* Energy Consumption by End Use

[a] (Encompasses motors such as those found in office equipment, cleaning equipment, commercial laundry, etc.)

Table 4.1 provides a more detailed breakdown of the national, primary energy consumption of commercial motor-driven systems shown in Figure 4.2. The estimates in the table are aggregates of the full range of equipment capacities and all equipment types.

**Table 4.1** 2013 Estimate of Motor-Driven System and Component Energy Consumption in the Commercial Sector by End Use[a]

| Equipment[a] | Installed Base[b] (MM) | Average Annual Operating Hours | Average UEC[c] (kWh/yr) | National Site Energy (kWh/yr x $10^9$) | National Primary Energy[d] (Quads) |
|---|---|---|---|---|---|
| Packaged Terminal AC[e] | 5.0 | 3640 | 1500 | 7.50 | 0.08 |
| Single Packaged Vertical AC[e] | 0.8 | 5666 | 9200 | 1.15 | 0.01 |
| Commercial Unitary AC[e] | 13.3 | 1200 | 71,038 | 137.13 | 1.45 |
| Chiller Compressors | 0.4 | 2000 | 179,808 | 74.37 | 0.79 |
| Air Distribution | 15.3 | 3560 | 29,035 | 91.79 | 0.97 |
| Circulation Pumps/Water Distribution | 0.4 | 2000 | 24,569 | 15.99 | 0.17 |
| Cooling Water Pumps | 0.1 | 2000 | 26,149 | 7.22 | 0.08 |
| Heat Rejection Systems | 0.3 | 2000 | 7634 | 4.13 | 0.04 |
| Central Commercial Refrigeration | 3.1 | - | 9020 | 30.65 | 0.32 |
| Automatic Commercial Ice Makers | 2.0 | 4380 | 7736 | 16.23 | 0.17 |
| Beverage Vending Machines | 3.7 | - | 4516 | 16.76 | 0.18 |
| Walk-in Coolers and Freezers | 2.0 | 365 | 13,052 | 26.26 | 0.28 |
| Misc | - | - | - | - | 0.34 |

[a] Aggregate of all equipment classes within a given equipment type.
[b] Installed base references and calculations available in Appendix B, Table B.1.
[c] Where applicable, sum of all independent motor functions used in the equipment.
[d] Site-to-source conversion factor: 3.1 (DOE, 2010a)
[e] Includes heat pumps

Of the equipment listed in the table, packaged terminal AC units, single packaged vertical AC units, commercial unitary air conditioners, commercial refrigeration, automatic icemakers, beverage vending machines, and walk-in coolers and freezers have energy conservation standards under the authority given by EPCA, as amended. However, chillers are not an EPCA regulated product. Instead, motors used in chiller systems, as well as their auxiliary equipment, are covered by EPCA's energy conservation standards for electric motors (EISA 2007).

Figure 4.3 compares the three-phase induction motor efficiency as mandated by current motor energy conservation standard (EISA 2007), the previous minimum efficiency standard (EPCA 1992), and the maximum technologically feasible efficiency (max tech), which requires the use of a die-cast copper rotor as described in Chapter 2 (DOE, 2012f). For the purposes of this study, the EISA 2007 efficiency levels will be considered representative of the installed motor base, even though the standard only became effective in 2010. While the lifetime of a motor is largely dependent on the application and it is certain that motors with EPCA 1992 efficiencies are still operating in some commercial buildings, the EPCA 2007 levels are equivalent to the NEMA Premium motor efficiency rating that has governed the efficiency of motors sold over the last ten years. As horsepower increases, the spread between minimum allowable and max-tech efficiency decreases. The small efficiency gains resulting from motor upgrades at the higher efficiencies will have an impact on the cost-effectiveness of using max-tech motors for some applications.

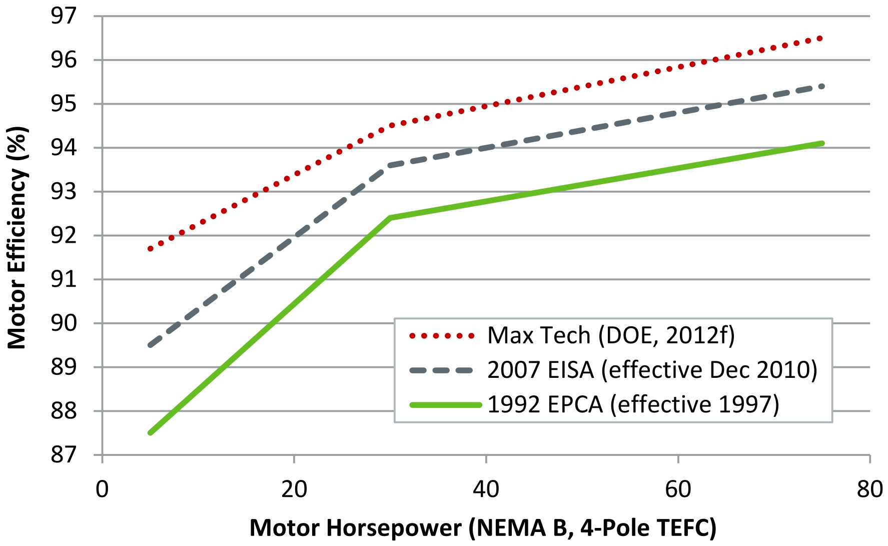


**Figure 4.3** Comparison of Three-Phase Induction Motor Full-Load Efficiencies from 5 hp – 75 hp

Another standard affecting motors in commercial buildings is ASHRAE 90.1-2010, which provides the minimum requirements for energy efficient building design and which has been adopted as a building energy code in many U.S. states. The standard requires various building equipment, primarily in HVAC and pumping systems, to have variable-speed controls and/or highly efficient motors. Greater detail as to how ASHRAE 90.1-2010 applies specifically to the large energy consuming equipment in the commercial sector will be discussed in the following sections. ASHRAE 90.1-2013, an update to the current standard that will be finalized by the end of 2013, includes two addenda affecting motors in commercial buildings. The first will require that fan motors greater than 1/12 horsepower and less than 1 horsepower be ECMs or have a minimum efficiency of 70% with a means to vary speed. The second will require that cooling systems be able to vary indoor airflow through the use of multispeed or modulating fans. These addenda to ASHRAE 90.1 will likely lead to increased adoption of ECMs and VFDs in commercial building systems.

## 4.2 Summary of Motor-Related Energy Savings Potential

Reduction in the overall energy consumption of commercial equipment is not limited to improvements in motor efficiency and is best achieved through system design optimized for the specific building or application. Upgrades to higher-efficiency motors still offer some basic savings, but integration of VFDs or other forms of speed control may be more suitable for systems that spend the majority of their operational life at part-load. Savings resulting from VFDs are difficult to quantify because of the dependency on the system, application, and installation conditions.

The primary technologies used for space conditioning in the commercial sector include packaged terminal air conditioners and heat pumps (PTAC), single packaged vertical air conditioners and heat pumps (SPVAC), commercial unitary air conditioners (CUAC), and chillers. While generally a residential product, room air conditioners may also be used in the commercial sector (see Section 3.0 above). The primary technologies used in commercial refrigeration include self-contained equipment, beverage vending machines, walk-in coolers and freezers/field-erected systems, and automatic commercial ice makers.

Section 4.3 provides a breakout of savings and payback periods. Generally, estimates show that the technical potential due to motor upgrades alone would be at least 0.3 quads for commercial space-conditioning equipment, while a technical potential of at least 0.2 quads may be possible for commercial refrigeration equipment.

## 4.3 Detailed Description of Major Commercial Energy Consumption

### *4.3.1 Packaged Terminal Air-Conditioners and Single-Packaged Vertical Air-Conditioners*

PTACs and SPVACs are typically found in hotels as well as some apartments and office buildings and have cooling capacities of only a few tons (one ton equals 12,000 Btuh). PTACs are similar to room air conditioners given their on/off type of control and intermittent usage. However, unlike room air conditioners, which have double-shafted motors, both PTACs and SPVACs have separate motors for the condensers and evaporators.  Both equipment types use PSCs to drive fans in their basic product offerings, although approximately 5% of the SPVAC market uses BLDC motors to circulate indoor air. PTAC motors range from 1/12 to ¼ horsepower while SPVAC motors range from 1/5 to ¾ horsepower.

Both equipment types are EPCA-regulated products, and efficient motor technologies like ECMs are not necessary to comply with efficiency standards as of 2013 (DOE, 2012c). Instead, manufacturers use BLDCs in SPVACs because they are quieter than the alternatives. Conversely, most end users purchase PTACs based on first cost, and manufacturers often design them to just meet the minimum standard. It is therefore unlikely that PTAC manufacturers will increase adoption of BLDC technology over the next five years. Because the test procedure for these products does not account for variable speed, it appears unlikely that variable-speed compressor adoption will increase.

Table 4.2 provides estimates for the energy consumption and technical potential of motor-driven components in PTACs and SPVACs, respectively. Table 4.3 shows the average UEC and estimates the simple payback associated with increasing motor efficiency to the maximum attainable efficiency listed in Table 4.2. Increasing the motor efficiency in PTACs yields a payback period greater than the lifetime of the product, or approximately 10 years.

**Table 4.2** PTAC and SPVAC Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| ***PTAC*** | | | | | | |
| Compressor | 59.5 | 87% | Improved | 90 | 3% | 2.0 |
| Indoor Fan | 11.9 | 54% | BLDC | 71 | 24% | 2.8 |
| Outdoor Fan | 7.9 | 54% | BLDC | 71 | 24% | 1.9 |
| ***SPVAC*** | | | | | | |
| Compressor | 9.1 | 87% | Improved | 90 | 3% | 0.3 |
| Indoor Fan | 1.8 | 54% | BLDC | 71 | 24% | 0.4 |
| Outdoor Fan | 1.2 | 54% | BLDC | 71 | 24% | 0.3 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.3** Motor Upgrade Payback Period for PTAC and SPVAC

| Component | Avg. UEC[a] (kWh/yr) | Savings (\$/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| *PTAC* | | | | |
| Compressor | 1125 | \$3.75 | \$56.00 | 14.9 |
| Indoor Fan | 225 | \$5.39 | \$107.00 | 19.9 |
| Outdoor Fan | 150 | \$3.59 | \$107.00 | 29.8 |
| SPVAC | | | | |
| Compressor | 6900 | \$23.00 | \$56.00 | 2.4 |
| Indoor Fan | 1380 | \$33.04 | \$107.00 | 3.2 |
| Outdoor Fan | 920 | \$22.03 | \$107.00 | 4.9 |

[a] Average UEC derived from references in Appendix B, Tables B.2
[b] EIA 2011 \$0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.2
[d] Represents industry aggregate based on interviews with representative manufacturers.

### *4.3.2 Commercial Unitary Air Conditioners*

Commercial unitary air conditioners and heat pumps (CUAC) contain three motor-driven components, the compressor, indoor blower, and outdoor blower. The outdoor blower may have multiple fans and motors depending on the capacity of the unit. PSCs are typically used for the outdoor fans and range from ¼ to 1 horsepower, while the indoor blowers are typically driven by three-phase AC induction motors ranging from 1.7 – 7.4 hp. Depending on unit capacity, one or multiple, single-speed, three-phase induction-motor-driven compressors are used in a CUAC unit. A multi-compressor system allows the compressors to be staged to match system load. CUACs currently have minimum energy conservation standards under EPCA.

Table 4.4 lists estimates of the motor technical potential resulting from an increase in CUAC motor efficiency. Table 4.5 provides an estimate of the simple payback period associated with this increase.

**Table 4.4** CUAC Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[c] (Site-Based) | Primary Energy Savings[d] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor - Small | 687.9 | 88% | Max 3PH[d] | 95% | 7% | 50.7 |
| Compressor - Med | 382.9 | 88% | Max 3PH | 95% | 7% | 28.2 |
| Compressor - Large | 89.6 | 88% | Max 3PH | 95% | 7% | 6.6 |
| Indoor Fan - Small | 86.0 | 89.5% | Max 3PH | 91.7% | 2% | 2.1 |
| Indoor Fan - Med | 47.9 | 89.5% | Max 3PH | 91.7% | 2% | 1.1 |
| Indoor Fan - Large | 11.2 | 89.5% | Max 3PH | 91.7% | 2% | 0.3 |
| Outdoor Fan - Small | 86.0 | 54% | ECM | 71% | 24% | 20.6 |
| Outdoor Fan - Med | 47.9 | 54% | ECM | 71% | 24% | 11.5 |
| Outdoor Fan - Large | 11.2 | 54% | ECM | 71% | 24% | 2.7 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.

[b] Technical potential based on application of the efficiency option to entire installed base.

[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

[d] 3PH = three-phase AC induction motor

**Table 4.5** Motor Upgrade Payback Period for CUAC

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Comp - Small | 7360 | $54.23 | $200.00 | 3.7 |
| Comp - Med | 14270 | $105.15 | $200.00 | 1.9 |
| Comp - Large | 35200 | $259.37 | $200.00 | 0.8 |
| Indoor Fan - Small | 920 | $2.21 | $70.00 | 31.7 |
| Indoor Fan - Med | 1784 | $4.28 | $70.00 | 16.4 |
| Indoor Fan - Large | 4400 | $10.56 | $70.00 | 6.6 |
| Outdoor Fan - Small | 920 | $22.03 | $85.00 | 3.9 |
| Outdoor Fan - Med | 1784 | $42.71 | $85.00 | 2.0 |
| Outdoor Fan - Large | 4400 | $105.35 | $85.00 | 0.8 |

[a] Average UEC derived from references in Appendix B, Table B.2

[b] EIA 2011 $0.10/kWh electricity rate

[c] Calculated using percent savings in Table 4.4

[d] Represents industry aggregate based on interviews with representative manufacturers. Does not include additional cost of system controls needed for variable-speed control.

Multi-compressor systems are still considered less expensive than upgrading to VFD-driven compressors. Variable-speed compressors may require additional valves and controls that add to the expense of the drive itself. Multiple, staged compressors can deliver part-load performance approaching that of a variable-speed compressor when measured by the integrated energy efficiency ratio (IEER) metric. Multi-compressor systems also offer redundancy, meaning that if one compressor fails, another can provide at least some cooling capacity, which is attractive to building owners and operators.

Because the CUAC outdoor fan motors are low horsepower, it is possible to use BLDC or ECM technology for outdoor fans. As the capacity of the CUAC increases, the payback period of upgrading outdoor blowers to BLDC is less than one year, as shown in Table 4.5. The additional retail cost listed in the table does not include the cost of system controls that would be necessary for the fans to operate with variable speed. Although variable-speed condenser fans would reduce the overall electrical consumption, lowering airflow rates would increase the condensing temperature, potentially requiring more work from the compressor, which could offset savings. While a few high-end CUACs currently use VFD technology, the industry primarily uses multi-compressor and fixed-speed fans for reasons listed above.

CUAC indoor blowers use three-phase induction motors that could be upgraded to achieve higher efficiency. Table 4.6 shows that the payback periods associated with VFDs in CUACs are less than 4 years. However, building owners and operators may find this payback period too long for only a few points gain in motor efficiency. VFDs are already deployed in some CUAC indoor blower arrangements. Less than half of the CUAC market currently uses VFDs (Navigant, 2013c). Given the short payback period, the number of VFD indoor blower configurations could increase.

**Table 4.6** VFD Indoor Blower Payback Period for CUAC

| Component | Avg. UEC[a] kWh/yr | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Indoor/Evap - Small | 920 | $36.80 | $140.00 | 3.8 |
| Indoor/Evap - Med | 1784 | $71.35 | $235.00 | 3.3 |
| Indoor/Evap - Large | 4400 | $176.00 | $330.00 | 1.9 |

[a] Average UEC derived from references in Appendix B, Table B.2
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.4
[d] Represents industry aggregate based on interviews with representative manufacturers.

### *4.3.3 Commercial Chiller Plants and Hydronic Systems*

Chilled-water HVAC systems are mainly used in large commercial buildings. Chillers and their auxiliary systems have the largest unit energy consumers in the commercial sector, providing cooling capacities anywhere between 30 and 2000 tons. Considering building-owner and operator sensitivity to the energy costs of HVAC, chiller manufacturers continue to design systems and equipment with efficiency in mind (Navigant, 2013a). Chillers themselves are not regulated under EPCA, but some components are covered by regulations.

Chillers almost never run at full load and thus, the industry has developed the Integrated Part Load Value (IPLV) metric, which is a weighted average of power consumption per unit capacity at capacities corresponding to 100%, 75%, 50%, and 25% of full-load. Many chillers cycle multiple compressors on and off to match part-load conditions. However, only small improvements (on the order of 1 point in efficiency gain) are possible through standard improvements of motor efficiency (Navigant, 2013b). Instead of evaluating full-load performance, manufacturers and engineers employ methods that improve system design (such as installing two small capacity chillers instead of one large chiller) as a means to reduce chiller energy consumption (Lorenzi, 2013).

There are many types of chillers, and the appropriateness of a certain type of chiller for an application depends on the individual building constraints and features. Chillers are classified by both their compressor type and heat-rejection system:

- Air-cooled
    - reciprocating
    - screw
    - scroll
- Water-cooled
    - screw
    - centrifugal

Motors are used in a variety of chiller components:

- Compressors
- Air-cooled chillers – condenser fans
- Water-cooled chillers – Cooling tower pumps and fans (to reject condenser heat to the ambient air)
- Chilled-water pumps.

Other space-conditioning equipment, auxiliary to the chiller, and that also rely on motors, include air-handling units (AHUs) and fan-coil units that circulate air. While not necessarily part of the chilled-water loop, hydronic heating systems have also been included for discussion here as they also employ motor-driven centrifugal circulation pumps.

There is limited information on the installed base of chilled-water and hydronic system components in part because the number and configuration of components vary from building to building. Buildings often use multiple chillers, multiple AHUs, and numerous circulation pumps. Chillers and pumps can have long lifetimes, often on the order of 25 years. Although retrofits with efficient motors are becoming more common, chillers are expensive, and building owners tend to repair and continue using the equipment even as performance degrades. Thus, shipments of new systems may not be a good indicator of how the installed base of motors has changed over time. Per the following discussion, estimates of chiller population were derived from the DOE's Building Energy Databook, U.S. Census Bureau data, and the EIA's Commercial Buildings Energy Consumption Survey. Appendix B provides a more detailed description of shipment estimates and the installed base.

#### *4.3.3.1 Chiller Compressors*

Compressors are integral to all types of chilled-water systems.
Table 4.7 provides an estimate of the technical potential if motor efficiency increased. Table 4.8 shows the average UEC by compressor type and provides an estimate of the simple payback of an increase in compressor motor efficiency.

**Table 4.7** Chiller Compressor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Current Efficiency (%) | Possible Efficiency (%) | Technical Potential Energy Savings (Site-Based)[b] | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|
| Reciprocating | 160.7 | 88% | 95% | 7% | 11.8 |
| Scroll | 20.1 | 88% | 95% | 7% | 1.5 |
| Screw | 217.8 | 95% | 96% | 1% | 2.3 |
| Centrifugal | 388.1 | 95% | 97% | 2% | 8.0 |
| Magnetic Bearing Centrifugal | | - | | 30% | 116.4 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.8** Motor Upgrade Payback Period for Chiller Compressors

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Reciprocating | 84773 | $624.62 | $716.00 | 1.1 |
| Scroll | 84773 | $625.12 | $716.00 | 1.1 |
| Screw | 235579 | $240.27 | $873.00 | 3.6 |
| Centrifugal | 314105 | $647.64 | $1,373.00 | 2.1 |
| Magnetic Bearing Centrifugal | 314105 | $9,423.16 | $18,000.00[e] | 1.9 |

[a] Average UEC derived from references in Appendix B, Table B.2
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.7
[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP.
[e] (Barrett, 2011)

As shown by the efficiencies listed in Table 4.8 above, motor efficiencies in compressors are reaching the limit of what is commercially available (Navigant, 2013a). More significant savings may be possible with a permanent-magnet-motor-based centrifugal compressor that has recently come to market for commercial chillers. Not only is the rotor composed of permanent magnets, the compressors use magnetic bearings with frictional losses of less than 2% compared to the 5% loss of the typical hydrodynamic bearings used in an average centrifugal compressor (Barrett, 2011). The magnetic-bearing compressor also has integrated variable-speed control, making it ideal for part-load use. This compressor has the added benefits of being both lighter (permanent magnets eliminate the heavy copper windings), quieter (non-contact bearings), and it does not require an oil distribution system which improves reliability and saves on maintenance. While first costs of the compressor are high, savings offered by magnetic centrifugal compressors can be approximately 30% when compared to the performance of a traditional fixed-speed compressor (McQuay, 2005). However, the installed consumption provided in Table 4.7 assumes standard motor efficiency without variable speed. It is likely that for large water cooled chillers, a large percentage of chillers shipped over the last few years are already equipped with variable speed (Navigant, 2013a). As shown in Table 4.8, the payback period of a magnetic bearing centrifugal compressor could be on the order of 2 years.

#### *4.3.3.2 Air Distribution*

Exhaust fans, room fan coils, and central air-handling units all distribute cool air via chilled water to individual spaces within the commercial building. Variable speed capability for these components is not only essential for reduced energy consumption during part-load operation but also valuable for maintaining uniform temperature and comfort. These indoor fan systems are almost always on, if not for cooling or heating, then for ventilation. Most of the AHUs shipped today include some kind of variable speed control. Previous versions of ASHRAE 90.1 required VFDs for AHU fans greater than five horsepower. ASHRAE 90.1-2013 now specifies that indoor fans have a minimum of two speeds with a limitation on the percentage of full-speed power the fan can draw at the lower speed. Additionally, states like California offer incentives to retrofit existing indoor fans with more efficient motors and VFDs.

Table 4.9 only provides an estimate of the energy savings for highly efficient motors and AHU VFDs. Previous analyses suggest that, when compared to a fixed-speed system, VFDs can deliver up to 40% energy savings when installed on indoor blowers (ADL, 1999).

**Table 4.9** Chiller System – Air Distribution Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Exhaust Fan | 468.6 | 60% | ECM | 80% | 25% | 117.1 |
| Room Fan Coil | 9.7 | 50% | ECM | 70% | 29% | 2.8 |
| AHU | 492.6 | 89.5% | Max 3PH | 92% | 0.3% | 1.3 |
| | | - | VFD | - | 40% | 197.0 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.

[b] Technical potential based on application of the efficiency option to entire installed base.

[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

Table 4.10 provides an estimate of the motor upgrade payback period and indicates that standards have increased the minimum efficiency of three-phase AC induction motors used in commercial space-conditioning to a point that is approaching the limits of economic attractiveness. Upgrading AHU motors to max-tech results in a technical potential of only 1% and a payback period of 18 years. However, upgrades to ECM technology for lower horsepower applications, like exhaust fans and fan coils, yield higher technical potentials and lower payback periods than for AHUs.

**Table 4.10** Motor Upgrade Payback Period for Chiller Air Distribution Systems

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Exhaust Fan | 3532 | $88.29 | $120.00 | 1.4 |
| Room Fan Coil | 497 | $14.21 | $120.00 | 8.4 |
| AHU | 25006 | $6.62 | $120.00 | 18.1 |

[a] Average UEC derived from references in Appendix B, Tables B.2
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.9
[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP.

#### *4.3.3.3 Hydronic Distribution*

Pumps are used to circulate water for both heating and cooling in commercial buildings that use boilers and chillers. Only 10-20% of chillers are sold with an integrated pump, so the selection of the pump is often left up to the mechanical contractor and is sometimes oversized for the application (Navigant, 2013a). An engineer may select a pump with a capacity greater than system capacity as a way to ensure sufficient pressure and flow in case of unpredicted system losses. To compensate for oversizing, historically pumps have been throttled to reduce flow. Instead, properly sizing both the pump and motor, and/or pairing it with a VFD can offer significant technical potential when compared to a throttled system. ASHRAE 90.1-2010 requires VFDs on pumps greater than 5 horsepower and thus variable-flow chiller systems have become more common.

Table 4.11 provides estimates of the technical potentials resulting from upgrades to more efficient three-phase AC induction motors. Table 4.15 lists estimates of the payback periods for these motor upgrades.

**Table 4.11** Commercial Water-Circulation-Pump Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Current Efficiency (%) | Possible Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|
| Reciprocating | 31.6 | 89.5 | 92 | 3% | 0.9 |
| Scroll | 4.0 | 89.5 | 92 | 3% | 0.1 |
| Screw | 15.4 | 89.5 | 92 | 3% | 0.4 |
| Centrifugal | 49.9 | 92.4 | 95 | 3% | 1.4 |
| Absorption | 3.4 | 92.4 | 95 | 3% | 0.1 |
| Boiler | 64.9 | 89.5 | 92 | 3% | 1.8 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.12** Motor Upgrade Payback Period for Commercial Water-Circulation-Pumps

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Reciprocating | 16670 | $45.30 | $221.00 | 4.9 |
| Scroll | 16670 | $45.30 | $221.00 | 4.9 |
| Screw | 16670 | $45.30 | $221.00 | 4.9 |
| Centrifugal | 40368 | $110.48 | $892.00 | 8.1 |
| Absorption | 40368 | $110.48 | $892.00 | 8.1 |
| Boiler | 16670 | $45.30 | $221.00 | 4.9 |

[a] Average UEC derived from references in Appendix B, Tables B.2
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.11
[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP.

The performance of commercial building hydronic distribution systems will typically track with the pump affinity laws, i.e., power is roughly proportional to the cube of the speed. Thus, theoretical energy savings could be on the order of 40% through variable speed control of the pump. However, VFD efficiency decreases as load decreases (see Figure 2.6) and will offset some savings at part-load. Further, lower flow rates may mean that the chiller has to operate at a lower set-point temperature, which lowers chiller efficiency. VFD control for hydronic distribution systems is becoming common, but retrofit opportunities for VFDs may still exist in older installations. Although the actual energy savings potential and payback period are largely dependent on pump and motor horsepower and system design, Table 4.13 provides an estimate for a basic 10 horsepower pump operating 2,000 hours per year, at $0.10/kWh and with a UEC of approximately 16,670 kWh/year.

**Table 4.13** VFD Payback Period Estimate for Commercial Water-Circulation-Pumps

| Component | Avg. UEC[a] (kWh/yr) | Operating Hours (hrs/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|---|
| Pump (for a Reciprocating, Scroll, or Screw Chiller) | 16670 | 2000 | $667 | $815 | 0.8 |

[a] Average UEC of a 10 HP pump.
[b] EIA 2011 $0.10/kWh electricity rate
[c] Theoretical VFD savings of 40%
[d] Represents industry aggregate based on interviews with representative manufacturers. Assumed 10 hp VFD. Not including installation costs.

Assuming a 10 horsepower VFD costs $815, the VFD would have a simple payback period of less than one year. However, this does not include any installation costs like cabling or labor hours. Some pump manufacturers are starting to package VFD technology with their pumps, which may reduce the installation costs associated with VFDs.

### 4.3.3.4 Cooling-Water Circulation and Cooling Towers

In the cooling water loop, a circulator (pump/motor) circulates cooling water between the chiller condenser and the cooling tower, and motor-driven fans aid the cooling tower's evaporative cooling process. VFDs are commonly used for cooling tower fans but variable flow cooling water loops with cooling towers are a recent innovation (SPX, 2013).

Table 4.14 provides estimates of the technical potentials resulting from increasing three-phase AC motor efficiencies. Table 4.15 provides estimates of the payback periods for the motor and VFD upgrades.

**Table 4.14** Chiller Water-Cooling Equipment Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Current Motor Efficiency (%) | Possible Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|
| Reciprocating Pump | 15.8 | 89.5% | 92% | 3% | 0.4 |
| Scroll Pump | 0.4 | 89.5% | 92% | 3% | 0.0 |
| Screw Pump | 6.9 | 89.5% | 92% | 3% | 0.2 |
| Centrifugal Pump | 49.9 | 92.4% | 95% | 3% | 1.4 |
| Absorption | 3.4 | 92.4% | 95% | 3 | 0.1 |
| Cooling Tower Fans | 37.9 | 89.5% | 92% | 3% | 1.0 |
| | | VFD[d] | | 40% | 15.1 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)
[d] Assumes motor efficiency remains unchanged.
[e] (SPX, 2013)

**Table 4.15** Motor-Upgrade Payback Period for Chiller Water-Cooling Equipment

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Reciprocating | 16670 | $45.30 | $221.00 | 4.9 |
| Scroll | 16670 | $45.30 | $221.00 | 4.9 |
| Screw | 16670 | $45.30 | $221.00 | 4.9 |
| Centrifugal | 40368 | $110.48 | $892.00 | 8.1 |
| Absorption | 40368 | $110.48 | $892.00 | 8.1 |
| Cooling tower fans | 20004 | $54.36 | $221.00 | 4.1 |
| Cooling tower fan VFD | | $800.18 | $815.00 | 1.0 |

[a] Average UEC derived from references in Appendix B, Table B.2
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.14
[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP.

#### *4.3.3.5 Fans for Air-Cooled Chillers*

Air-cooled chillers are becoming more popular compared to water-cooled chillers because they offer similar efficiency but can be packaged with auxiliary equipment and have a simpler configurations and maintenance requirements (i.e., no cooling tower or condenser pumps) (Carrier, 2005). They are designed for outdoor use as they have condenser fans reject heat into the ambient air. Air-cooled chillers typically have cooling capacities ranging from 10 to 500 tons, but are more commonly selected for smaller-capacity applications, like mid-rise office buildings. ECMs may be used for the condenser fans of up to 3 horsepower. Additionally, because air-cooled chillers are typically equipped with multiple fans, the fans can be staged for part-load operation.

Table 4.16 provides estimates of the technical potentials associated with upgrading to more efficient three-phase AC induction motors, and Table 4.17 conservatively approximates VFD related savings because they are system dependent. On average, fan motors paired with VFDs in air-cooled chillers could provide up to 30% savings. However, depending on the application and the sizing of various chiller components (pumps, compressors, etc.), adding a VFD may have less than 15% energy savings potential (Dieckmann, 2010). Table 4.18 provides estimates of simple payback periods for motor upgrades.

**Table 4.16** Air-Cooled Chiller Fan Motor Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Current Efficiency (%) | Possible Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|
| Air-cooled Reciprocating | 3.3 | 85% | 92% | 8% | 0.3 |
| Air-cooled Scroll | 0.7 | 85% | 92% | 8% | 0.1 |
| Air-cooled Screw | 1.8 | 85% | 92% | 8% | 0.1 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.

[b] Technical potential based on application of the efficiency option to entire installed base.

[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.17** Air-Cooled Chiller Fan VFD Technical Potential

| Component | Motor Site Energy[a] ($10^9$ kWh/yr) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|
| Air-cooled Reciprocating | 0.3 | 15% | 0.5 |
| Air-cooled Scroll | 0.1 | 15% | 0.1 |
| Air-cooled Screw | 0.2 | 15% | 0.3 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.

[b] Technical potential based on application of VFDs to the entire installed base

[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.18** Fan Motor Upgrade Payback Period for Air-Cooled Chillers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Air-cooled Reciprocating | 3511 | $26.71 | $253.00 | 9.5 |
| Air-cooled Scroll | 3511 | $26.71 | $253.00 | 9.5 |
| Air-cooled Screw | 3511 | $26.71 | $253.00 | 9.5 |

[a] Average UEC derived from references in Appendix B, Table B.2
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.16
[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP.

### *4.3.4 Self-Contained Commercial Refrigeration*

Self-contained commercial refrigeration equipment is primarily found in supermarkets, other food retail establishments, and food-service applications, and is used for storing and displaying refrigerated or frozen food products. Types of self-contained commercial refrigeration equipment include self-contained refrigerators, freezers, display cases, and over-the-counter cases but do not include beverage vending machines which are discussed in Section 4.3.5. Motors are used to drive compressors, evaporator fans, and condenser fans in these equipment items.

Commercial refrigeration equipment is regulated under EPCA, as amended. DOE first established prescribed standards in 2007, which went into effect in 2010 for some products and 2012 for the remaining products. These minimum efficiency standards have influenced the types of motors used in commercial refrigeration equipment.

Table 4.19 provides estimates of the motor technical potentials for more efficient motors in commercial refrigeration equipment. Table 4.20 shows the average UEC and estimated simple payback for each type of motor-related improvement.

**Table 4.19** Self-Contained Commercial Refrigeration Equipment Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 276.8 | 88% | Improved CSCR or 3-ph motor | 90% | 2% | 6.2 |
| Condenser Fan | 37.7 | 20% | BLDC | 70% | 71% | 26.9 |
| Evaporator Fan | 9.7 | 20% | BLDC | 70% | 71% | 6.9 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.20** Motor Upgrade Payback Period for Commercial Refrigeration Equipment

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor - Improved Motor | 8442 | $18.76 | $15.00 | 0.8 |
| Condenser Fan | 1150 | $82.13 | $30.00 | 0.4 |
| Evaporator Fan | 296 | $21.12 | $30.00 | 1.4 |

[a] Average UEC derived from references in Appendix B, Table B.2

[b] EIA 2011 $0.10/kWh electricity rate

[c] Calculated using percent savings in Table 4.19

[d] (DOE, 2011a)

### Compressor Motor

Almost all compressors currently used in self-contained commercial refrigeration are single-speed, hermetically-sealed reciprocating compressors. Depending on the compressor horsepower, compressor motors used in commercial refrigeration may be either single-phase, PSC or CSCR, or three-phase AC induction motors. They are typically one horsepower or less. While variable- speed compressors may present an energy savings opportunity, they are not commonly found in self-contained commercial refrigeration. DOE research suggests that more RD&D will be necessary before variable-speed compressors are commercially viable for this application (DOE, 2011a). The current DOE test procedure only measures stead-state operation and regardless of the compressor's variable-speed capability, the compressor operates at a fixed load for the duration of the test. With this limitation, manufacturers will opt for more efficient single-speed compressors rather than variable speed. If DOE were to modify the test procedure to capture the benefits of using variable speed compressors under part-load conditions, RD&D efforts for variable-speed compressors for used in commercial refrigeration might increase.

Barriers to the use of variable-speed compressors exist on the end user side as well. In particular, the costs of installation may be prohibitive. Traditionally, VFDs are wall-mounted, auxiliary devices that require additional cable or conduit (shielded cables) and labor expenses. However, advances in drive technology have reduced the physical size of VFDs, and some major manufacturers are now offering compressor-mounted VFDs for other applications with specific control algorithms designed for the application. Still, implementation of packaged units (motor, drive, and compressor) may be problematic if space or accessibility to the VFD is a concern.

### Fan Motor

The current installed base of condenser and evaporator fan motors in self-contained commercial refrigeration is primarily shaded-pole. However, manufacturers are now using permanent magnet motor technology in some baseline as well as high efficiency products just coming to market. Because minimum efficiency standards for self-contained commercial refrigeration only became effective in 2010, manufacturers have largely ignored PSC technology in favor of the more significant savings available through permanent magnet motors. Condenser-fan motors are typically ½ horsepower or less (~30-40 watts) while evaporator fans are 1/50 horsepower or less (~6-12 watts). The refrigeration system is running 24/7 with compressors cycling on and off to adjust to load conditions.

Because manufacturers already use permanent magnet motor technology to meet minimum energy conservation standards, the installed base of motors in self-contained commercial refrigeration will likely converge to BLDC in the next few years, as more and more baseline products include them. Currently, barriers to widespread adoption of permanent magnet motors include uncertain reliability and availability. To reduce costs, some commercial refrigeration manufacturers source their BLDCs or ECMs from developing countries, but many have encountered issues with quality and lifetime. Manufacturers should take care to evaluate the reliability of the permanent magnet motors they implement into their products.

Various utilities have also adopted programs designed to increase the use of permanent magnet motors in self-contained commercial refrigeration equipment. Some California utilities as well as Nevada Energy provide rebates for the use of ECM technologies in commercial-refrigeration applications.

Self-contained commercial refrigeration equipment does not use variable-speed fan motors. Even though the condenser fan operation could be varied to match part-load conditions, the current test procedure is conducted only at ambient temperature and thus would not capture the benefits of variable-speed condenser fans, leaving manufacturers little incentive to consider permanent magnet motors with integrated controls (ECM). Additionally, due to the sensitivity of the insulating air curtain in open cases to changes in airflow, savings from variable speed have been determined to be insignificant for evaporator fan motors (DOE, 2011a).

### *4.3.5 Beverage Vending Machines*

Beverage vending machines (BVMs) are similar to the commercial refrigeration equipment described in the previous section. Motors drive compressors and fans. Many of the assumptions made about self-contained commercial refrigeration equipment apply to BVMs, but the two product categories are regulated separately.

BVMs are regulated under EPCA, as amended, with a minimum energy conservation standard that went into effect in August 2012. As with self-contained commercial refrigeration equipment, current shipments of baseline BVMs contain BLDC/ECM fan motors. However, the estimates below assume that the installed base of BVM fan motors is still primarily shaded-pole. Table 4.21 provides estimates technical potentials. Table 4.22 shows the average UEC and estimates of the simple paybacks for selected of motor-related efficiency improvements.

**Table 4.21** Beverage Vending Machine Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 97.8 | 88% | Improved CSCR or 3-ph motor | 90% | 2% | 2.2 |
| | | | VFD | | 15% | 14.7 |
| Condenser Fan | 60.2 | 20% | BLDC | 70% | 71% | 43.0 |
| Evaporator Fan | 19.3 | 20% | BLDC | 70% | 71% | 13.8 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.

[b] Technical potential based on application of the efficiency option to entire installed base.

[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.22** Motor Upgrade Payback Period for Beverage Vending Machines

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor - Improved Motor | 2492 | $18.36 | $15.00 | 2.7 |
| VS Compressor | | $37.37 | $161.00[e] | 4.3 |
| Condenser Fan | 1533 | $109.50 | $30.00 | 0.3 |
| Evaporator Fan | 491 | $35.04 | $30.00 | 0.9 |

[a] Average UEC derived from references in Appendix B, Table B.2

[b] EIA 2011 $0.10/kWh electricity rate

[c] Calculated using percent savings in Table 4.21

[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP.

[e] Based on input from industry experts and aggregated costs from manufacturers. As horsepower increases, the per-horsepower cost of a drive decreases.

### *4.3.6 Walk-in coolers and freezers*

Walk-in coolers and freezers (WICFs) are used to store perishable and frozen goods, and are typically 3,000 square feet or less in size. In 2007, EISA established standards mandating that WICF evaporator fans be equipped with ECMs or high efficiency three-phase AC induction motors. EISA 2007 also mandated that condenser fans be PSCs, ECMs, or high efficiency 3-phase AC induction motors. WICFs are often assembled on-site, using components that meet minimum energy conservation standards. Under the current standard, the envelope (e.g., the insulating panels and doors) and refrigeration system have separate requirements. There are two types of condensing units used in WICFs:

- Dedicated condensing
    - contains only one condensing unit with one or more compressors
- Multiplex condensing
    - may serve multiple walk-in envelopes as well as other large refrigeration applications.
    - has multiple compressors in parallel (aka, compressor racks).

Table 4.23 provides estimates of the maximum attainable energy savings if more efficient motor technologies were used in WICFs. Table 4.24 shows the average UECs and estimates of simple paybacks for selected motor-related efficiency improvements.

**Table 4.23** Walk-in Cooler and Freezer Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 198.0 | 88% | Improved CSCR or 3-ph motor | 90% | 2% | 4.4 |
| | | VFD | | | 15% | 29.7 |
| Condenser Fan | 39.9 | 29% | BLDC | 70% | 59% | 23.4 |
| Evaporator Fan | 39.9 | 29% | BLDC | 70% | 59% | 23.4 |
| | | ECM/VFD | | | 75% | 29.9 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.24** Motor Upgrade Payback Period for Walk-in Coolers and Freezers

| Component | Avg. UEC[a] (kWh/yr) | Savings (\$/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor - Improved Motor | 9302 | \$20.67 | \$15.00 | 0.7 |
| VS Compressor | | \$139.50 | \$485.00[e] | 3.5 |
| Condenser Fan | 1875 | \$109.80 | \$30.00 | 0.3 |
| Evaporator Fan – BLDC | 1875 | \$109.80 | \$30.00 | 0.3 |
| Evaporator Fan – ECM/VFD | | \$140.66 | \$300.00 | 2.1 |

[a] Average UEC derived from references in Appendix B, Table B.2
[b] EIA 2011 \$0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.23
[d] Represents industry aggregate based on interviews with representative manufacturers. Based on assumed motor HP. Appendix B, Table B.2.
[e] Based on input from industry experts and aggregated costs from manufacturers. As horsepower increases, the per-horsepower cost of a drive decreases.

**WICF Compressors**
As mentioned above, multiple or staged compressors coupled in racks are already used to facilitate part-load operation of WICFs. WICF compressors range in size from one to five hp. Often, at least one variable-speed compressor is used on a compressor rack. Capacity is modulated through a combination of selecting which fixed-speed compressors operate and variable-speed operation of the variable-speed compressor. Unlike other commercial refrigeration equipment, the DOE test procedure for WICFs could capture the benefits of variable speed as it requires the condensing unit be tested at three temperature conditions. As shown in Table 4.24, a one-horsepower variable-speed compressor has a payback period of less than 5 years. Generally, as the horsepower of the drive increases above five horsepower, the per-horsepower cost of the drive decreases.

**WICF Fan Motors**
The current DOE regulation requires that single-phase condenser fan motors rated at less than one horsepower be PSC or BLDC, and it requires that single-phase evaporator fan motors be BLDC. EPCA also allows condenser and evaporator fan motors to be three-phase AC induction but, given the horsepower range of the fan motors, single-phase motors may be more common. Unlike other commercial refrigeration equipment, the WICF test procedure includes an off-cycle evaporator fan test that measures any savings that could occur if fan speed was reduced during a compressor off-period. A savings in fan energy consumption of up to 75% may be possible by using variable-speed fan controls or permanent magnet motors with integrated variable speed.

### *4.3.7 Automatic Commercial Ice Makers*

Automatic commercial icemakers (ACIMs) are a DOE-regulated product, and have capacities that range from 50 to 2,500 pounds of ice per 24-hour period. There are two common ice-making processes that require different motor-driven components:

- The batch process, which cycles between freezing and harvesting operations, and requires a pump
- The continuous process, which contains a rotating auger that extrudes ice into the storage container.

Because the DOE regulation has only been in effect since 2010, there are likely opportunities for motor upgrades to produce energy savings. Approximately, 15% of the installed base operates using the continuous process and auger. This ACIM motor analysis considered only higher efficiency motors and not VFDs because ACIM units typically only turned on when the user needs ice and they are not running constantly. Table 4.25 provides technical potential savings estimates, and Table 4.26 provides estimated simple paybacks associated with motor upgrades.

**Table 4.25** Automatic Commercial Ice Maker Technical Potential

| Component | Primary Energy ($10^{12}$ Btu)[a] | Baseline Motor Efficiency (%) | Efficiency Option | Maximum Attainable Motor Efficiency (%) | Technical Potential Energy Savings[b] (Site-Based) | Primary Energy Savings[c] ($10^{12}$ Btu) |
|---|---|---|---|---|---|---|
| Compressor | 150.1 | 45% | CSCR | 55% | 10% | 15.0 |
| Condenser Fan | 11.8 | 25% | BLDC | 83% | 70% | 8.3 |
| Auger | 6.5 | 70% | BLDC | 83% | 16% | 1.0 |
| Pump | 3.3 | 25% | BLDC | 83% | 71% | 2.3 |

[a] Motor site energy consumption and baseline efficiency derived from references available in Appendix B, Tables B.1 to B.3.
[b] Technical potential based on application of the efficiency option to entire installed base.
[c] Site-to-Source Conversion Factor: 3.1 (DOE, 2010a)

**Table 4.26** Motor Upgrade Payback Period for Automatic Ice Makers

| Component | Avg. UEC[a] (kWh/yr) | Savings ($/yr)[b,c] | Additional Retail Cost[d] | Simple Payback (Years) |
|---|---|---|---|---|
| Compressor | 7000 | $70.00 | $40.00 | 0.6 |
| Condenser Fan | 552 | $38.43 | $19.00 | 0.5 |
| Auger | 1877 | $29.4 | $300.00 | 10.2 |
| Pump | 184 | $13.06 | $16.00 | 1.2 |

[a] The average UEC derived from references in Appendix B (Table B.2) is an average over a range of ACIM capacities. It is more likely that a smaller capacity ACIM will have a payback on the order of 2 years rather than 0.6 years.
[b] EIA 2011 $0.10/kWh electricity rate
[c] Calculated using percent savings in Table 4.25
[d] (DOE, 2012a)

The payback periods as estimated in Table 4.26 are less than one year for both the compressor and condenser fan motor upgrades. However, the compressor energy consumption has been estimated conservatively. The data provided in the table is an average of both small and large ACIMs. Realistically, for a smaller capacity unit with a smaller capacity compressor, the payback period will be on the order of 2 years. Auger motors are especially expensive and essentially double in cost when upgraded to BLDCs. Given the small number of continuous process ACIM shipments, upgrading to permanent magnet technology in augers is not an attractive investment. Conversely, upgrading to BLDC motors for batch process pumps has a payback period of just over one-year.

# 5 Conclusions

Most of the residential and commercial equipment types covered in this report are covered by DOE energy conservation standards and industry standards such as ASHRAE 90.1. These standards continue to push manufacturers to consider both more efficient motors and variable-speed technologies, among other product design improvements, in order to meet more stringent minimum efficiency requirements. However, research efforts and incentives outside of DOE regulation would enable further reductions in motor-driven system and component energy consumption in the residential and commercial sectors. Broad research efforts that could improve motor and drive efficiency and reduce costs include:

- The use of wide bandgap semiconductors in place of conventional semiconductor materials
- Identification of alternatives to rare-earth metals
- Commercialization of switched reluctance motor (SRM) technology.

For almost all equipment types in both the residential and commercial sectors, the market is transitioning to permanent magnet motor technology for the highest-efficiency models within each category. Permanent magnet motors are becoming increasingly cost-effective when considering simple payback period. They also offer other non-energy benefits such as reduced noise and the ability to reach higher rotational speeds.

Variable speed drives are also becoming a cost-effective method for reducing motor-driven system energy consumption in variable-load applications. Initial costs of drives have dropped significantly over the last decade. This can be largely attributed to advances in electronics, specifically semiconductors, which have led to reduced thermal loads and reduced size of the drive.

Despite these gains, however, the relatively higher cost of advanced motor technologies compared to traditional technologies remains a significant barrier for applications where first cost is a primary concern. For many types of appliances and equipment, products that just meet the mandatory minimum energy conservation standards represent the largest portion of overall sales and field retrofits are unrealistic. Typically, these products compete solely on price. Thus, outside of mandatory or voluntary standards programs, efforts to reduce the first cost of advanced motor technologies are essential to accelerate their implementation in both residential and commercial appliances and equipment.

Even as motor costs decrease, field retrofits of motors in appliances and equipment are generally unrealistic. This leaves the largest motor-related energy savings to be attained only through original equipment manufacturer (OEM) integration of advanced motor technologies in new products.

Similarly, the additional cost of advanced motor technologies can deter end users who do not consider simple payback periods or total lifecycle costs. This is particularly prevalent in commercial properties where tenants are responsible for the energy costs. However, building owners increasingly consider total lifecycle cost in their selection of building equipment, especially if they plan to occupy the building themselves. Such consideration of total lifecycle cost should encourage the adoption of more energy-efficient commercial equipment.

In addition to cost constraints, size and weight constraints could also limit the introduction of some higher-efficiency motor technologies that require larger or heavier components than current motor designs. Conversely, some higher-efficiency motor technologies are smaller and lighter than traditional motor designs, in which case the higher upfront cost remains the primary barrier to widespread implementation.

One particular barrier preventing wider adoption of permanent magnet technology is the threat of scarce rare-earth metals, which provide the magnetic material for the motor. Investment in alternatives to rare-earth metals, or alternative motor technologies such as switched reluctance motors, will ensure that high efficiency motor options remain cost-effective and that alternatives are available if rare-earth metals become scarce.

In the commercial sector, a key issue preventing greater adoption of VFDs is the additional training required for installation and operation of these higher-efficiency technologies. Building design engineers and contractors often perceive the higher-efficiency technologies to be too complex. Furthermore, operators may not understand variable-speed operation and may override VFD controls, such that energy consumption is not actually reduced by use of the VFD. Supporting the development of training programs, design guides, and software tools to help encourage the integration and proper use of high-efficiency motor designs would help accelerate the adoption of variable-speed motor technologies.

Some manufacturers are addressing the issue of increased complexity by developing product-specific programing and sensorless control schemes to create “plug-and-play” VFDs. Examples include permanent magnet motors with integrated controls in HVAC equipment, as well as factory-mounted drives available from compressor and pump manufacturers. Factory-mounted drives may have the added benefit of reducing installation costs and providing greater convenience, especially where space constraints are a primary concern. Continued emphasis on developing integrated controls for VFDs will help accelerate their implementation in both residential and commercial equipment.

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# **Appendix A** Residential Sector

**Table A.1** Motor-Driven System or Component Unit Energy Consumption in the Residential Sector by End Use

| Product | Installed Base (MM) | Source[a] | Annual Shipments (MM) | Source | Product Lifetime (yrs) | Annual Operating Hours | Source | Average Motor UEC (kWh/yr) |
|---|---|---|---|---|---|---|---|---|
| Clothes Washers: Top Loading | 56.3 | TSD (DOE, 2012b) | 4.0 | (Appliance, 2013) | 14.2 | 295 | TSD (DOE, 2012b) | 59.6 |
| Clothes Washers: Front Loading | 49.1 | TSD (DOE, 2012b) | 3.3 | (Appliance, 2013) | 14.2 | 295 | TSD (DOE, 2012b) | 46.2 |
| Clothes Dryers | 109.1 | TSD (DOE, 2011b) | 5.8 | (Appliance, 2013) | 16 | 283 | TSD (DOE, 2011b) | 17.8 |
| Furnace Fans | 61.8 | TSD (DOE, 2012g) | - | - | 25 | 1870 | TSD (DOE, 2012g) | 677.6 |
| Dehumidifier Compressor | 14.9 | TSD (DOE, 2007) | 1.2 | (Appliance, 2013) | 11 | 1095 | TSD (DOE, 2007) | 547.5 |
| Dehumidifier Fan | 14.9 | TSD (DOE, 2007) | 1.2 | (Appliance, 2013) | 11 | 1095 | TSD (DOE, 2007) | 54.8 |
| Dishwasher | 70.0 | TSD (DOE, 2012d) | 5.7 | (Appliance, 2013) | 15.4 | 215 | TSD (DOE, 2012d) | 63.9 |
| Ceiling Fan | 83.8 | Framework (DOE, 2013) | 17.0 | (Appliance, 2013) | 12.5 | - | (ADL, 1999) | - |
| R/F[b] Compressor | 143.5 | TSD (DOE, 2011d) | 8.6 | (Appliance, 2013) | 16.2 | 3000 | TSD (DOE, 2011d) | 625.0 |
| Freezer Compressor | 49.4 | TSD (DOE, 2011d) | 2.0 | (Appliance, 2013) | 21.7 | 3000 | TSD (DOE, 2011d) | |
| R/F Condenser | 143.5 | TSD (DOE, 2011d) | 8.6 | (Appliance, 2013) | 16.2 | 3000 | TSD (DOE, 2011d) | 25.0 |
| Freezer Condenser | 24.7 | TSD (DOE, 2011d) | 1.0 | (Appliance, 2013) | 21.7 | 3000 | TSD (DOE, 2011d) | |
| R/F Evaporator Fan | 143.5 | TSD (DOE, 2011d) | 8.6 | (Appliance, 2013) | 16.2 | 3000 | TSD (DOE, 2011d) | 21.0 |
| Freezer Evaporator Fan | 49.4 | TSD (DOE, 2011d) | 2.0 | (Appliance, 2013) | 21.7 | 3000 | TSD (DOE, 2011d) | |
| CAC Compressor | 59.5 | TSD (DOE, 2011c) | 3.9 | (Appliance, 2013) | 19 | 1000 | TSD (DOE, 2011c) | 2007.9 |
| HP Compressor | 14.7 | TSD (DOE, 2011c) | 1.7 | (Appliance, 2013) | 16.2 | 1000 | TSD (DOE, 2011c) | |
| CAC Outdoor Fan | 59.5 | TSD (DOE, 2011c) | 3.9 | (Appliance, 2013) | 19 | 1000 | TSD (DOE, 2011c) | 223.1 |
| HP Outdoor Fan | 14.7 | TSD (DOE, 2011c) | 1.7 | (Appliance, 2013) | 16.2 | 1000 | TSD (DOE, 2011c) | |
| RAC Compressor | 28.7 | TSD (DOE, 2011b) | 7.5 | (Appliance, 2013) | 10.26 | 750 | TSD (DOE, 2011b) | 515.1 |
| RAC Blower | 28.7 | TSD (DOE, 2011b) | 7.5 | (Appliance, 2013) | 10.26 | 750 | TSD (DOE, 2011b) | 57.2 |

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[a] % Saturation of US Household (~114M)

[b] R/F = Refrigerator/Freezer combination

| Product | Installed Base (MM) | Source[a] | Annual Shipments (MM) | Source | Product Lifetime (yrs) | Annual Operating Hours | Source | Average Motor UEC (kWh/yr) |
|---|---|---|---|---|---|---|---|---|
| Pool Pumps | 6.7 | Market Study/ (ADL, 1999) | - | - | - | 1200 | - | - |

**Table A.2** Installed Base Motor-Driven Energy Consumption and Technical Potential in the Residential Sector by End Use

| Product | Primary Motor-Driven Energy Consumption[a] (Quads) | Primary Motor Upgrade Reduced Consumption[b] (Quads) | Technical Energy Savings Potential (Quads) | Technical Potential Calculation/Source |
|---|---|---|---|---|
| Clothes Washers - Top Loading | 0.038 | 0.015 | 0.023 | Max Tech Potential (ECM) |
| Clothes Washers - Front Loading | 0.024 | 0.024 | 0.000 | Max Tech Potential (ECM) |
| Clothes Dryers | 0.032 | 0.032 | 0.001 | 2% Reduction in motor consumption, TSD (DOE, 2011b) |
| Furnace Fans | 0.443 | 0.310 | 0.133 | Max Tech Potential (ECM) |
| Dehumidifier Compressor | 0.009 | 0.008 | 0.001 | TSD (DOE, 2007) |
| Dehumidifier Fan | 0.086 | 0.078 | 0.009 | 10% Reduction in motor consumption, TSD (DOE, 2007) |
| Dishwasher | 0.079 | 0.071 | 0.008 | 10% Reduction in motor consumption, TSD (DOE, 2012d) |
| Ceiling Fan | 0.051 | - | - | - |
| R/F Compressor | 0.951 | 0.898 | 0.053 | Motor efficiency increase 85 to 90%[c] |
| Freezer Compressor | 0.258 | 0.244 | 0.014 | Motor efficiency increase 85 to 90%[a] |
| R/F Condenser | 0.040 | 0.015 | 0.026 | 36% Reduction in motor consumption, TSD (DOE, 2011d) |
| Freezer Condenser | 0.006 | 0.003 | 0.003 | 50% Reduction in motor consumption, TSD (DOE, 2011d) |
| R/F Evap Fan | 0.027 | 0.015 | 0.012 | 54% Reduction in motor consumption, TSD (DOE, 2011d) |
| Freezer Evap Fan | 0.012 | 0.006 | 0.006 | 48% Reduction in motor consumption, TSD (DOE, 2011d) |
| CAC Compressor | 1.263 | 1.221 | 0.042 | Motor efficiency increase 87 to 90% (based on conversation with technology expert at leading compressor manufacturer) |
| HP Compressor | 0.782 | 0.756 | 0.026 | |
| CAC Fan | 0.140 | 0.088 | 0.053 | Motor efficiency increase 50 to 80%, TSD (DOE, 2011c) |
| HP Fan | 0.087 | 0.054 | 0.033 | |
| RAC Compressor | 0.147 | 0.133 | 0.015 | TSD (DOE, 2011b) |
| RAC Blower | 0.016 | 0.010 | 0.006 | TSD (DOE, 2011b) |

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[a] Calculated using estimate of installed base, estimated hours of use, and average UEC. (Table A.2). Site to Source Conversion Factor: 3.1

[b] Site to Source Conversion Factor: 3.1

[c] Based on conversation with technology expert at leading compressor manufacturer.

| Product | Primary Motor-Driven Energy Consumption[a] (Quads) | Primary Motor Upgrade Reduced Consumption[b] (Quads) | Technical Energy Savings Potential (Quads) | Technical Potential Calculation/Source |
|---|---|---|---|---|
| Pool Pumps | 0.107 | 0.034 | 0.073 | (DOE, 2012h) |

# **Appendix B** Commercial Sector

**Table B.1** Equipment Characteristics for Motors in the Commercial Sector by End Use

| Product | Installed Base (MM) | Annual Shipments | Source | Typical Product Lifetime (yrs) | Source | Typical Duty Cycle (Hours/Yr) | Source |
|---|---|---|---|---|---|---|---|
| *PTAC* | | | | | | | |
| Compressor | 5[a] | 500,000 | TSD (DOE, 2012c) | 10 | TSD (DOE, 2012c) | 3640 | 10 hrs/day/yr |
| Indoor Fan | 5[a] | 500,000 | TSD (DOE, 2012c) | 10 | TSD (DOE, 2012c) | 3640 | 10 hrs/day/yr |
| Outdoor Fan | 5[a] | 500,000 | TSD (DOE, 2012c) | 10 | TSD (DOE, 2012c) | 3640 | 10 hrs/day/yr |
| *SPVAC* | | | | | | | |
| Compressor | 0.8[a] | 51,000 | TSD (DOE, 2009a) | 15 | TSD (DOE, 2009a) | 5666 | 10/hrs/day, 5 days/week, 35% of the year |
| Indoor Fan | 0.8[a] | 51,000 | TSD (DOE, 2009a) | 15 | TSD (DOE, 2009a) | 5666 | 10/hrs/day, 5 days/week, 35% of the year |
| Outdoor Fan | 0.8[a] | 51,000 | TSD (DOE, 2009a) | 15 | TSD (DOE, 2009a) | 5666 | 10/hrs/day, 5 days/week, 35% of the year |
| *CUAC* | | | | | | | |
| Compressor Small | 8.8[a] | 589,100 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1000 | (ADL, 1999) |
| Compressor Med | 2.5[a] | 169,118 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1200 | (ADL, 1999) |
| Compressor Large | 0.2[a] | 16,040 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1500 | (ADL, 1999) |
| Indoor Fan - Small | 8.8[a] | 589,100 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1000 | (ADL, 1999) |
| Indoor Fan - Med | 2.5[a] | 169,118 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1200 | (ADL, 1999) |
| Indoor Fan - Large | 0.2[a] | 16,040 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1500 | (ADL, 1999) |
| Outdoor Fan - Small | 8.8[a] | 589,100 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1000 | (ADL, 1999) |
| Outdoor Fan - Med | 2.5[a] | 169,118 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1200 | (ADL, 1999) |

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[a] Estimated using shipments and average product life. Neglect differences between source year and 2013.

| Product | Installed Base (MM) | Annual Shipments | Source | Typical Product Lifetime (yrs) | Source | Typical Duty Cycle (Hours/Yr) | Source |
|---|---|---|---|---|---|---|---|
| Outdoor Fan - Large | 0.2 [a] | 16,040 | TSD (DOE, 2012e) | 15 | (ADL, 1999) | 1500 | (ADL, 1999) |
| *Chiller Compressors* | | | | | | | |
| Reciprocating | 0.18[b] | 8,959 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[b] | 2000 | (ADL, 1999)[c] |
| Scroll | 0.02 [b] | 1,122 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Screw | 0.09 [b] | 4,370 | USCB Average 2009, 2010 | 23 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Centrifugal | 0.12 [b] | 5,079 | USCB Average 2009, 2010 | 25 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| *Air Distribution* | | | | | | | |
| Exhaust Fan | 12.54 [b] | 836,238 | Extrapolated from (ADL, 1999) | 15 | (ADL, 1999)[c] | 5681 | (ADL, 1999)[c] |
| Room Fan Coil | 1.84 [b] | 234,650 | Extrapolated from (ADL, 1999) | 15 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| AHU | 1.86 [b] | 336,207 | Extrapolated from (ADL, 1999) | 15 | (ADL, 1999)[c] | 3000 | (ADL, 1999)[c] |
| *Circulation Pumps* | | | | | | | |
| Reciprocating | 0.18 [b] | 8,959 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Scroll | 0.02 [b] | 1,122 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Screw | 0.09 [b] | 4,370 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Centrifugal | 0.12 [b] | 5,079 | USCB Average 2009, 2010 | 25 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Absorption | 0.01 [b] | 500 | Extrapolated from (ADL, 1999) | 23 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Boiler | 0.37 [b] | 16,000 | Extrapolated from | 23 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |

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[b] Adjusted based on expert opinion of major chiller manufacturer.

| Product | Installed Base (MM) | Annual Shipments | Source | Typical Product Lifetime (yrs) | Source | Typical Duty Cycle (Hours/Yr) | Source |
|---|---|---|---|---|---|---|---|
| | | | (ADL, 1999) | | | | |
| Cooling Water Pumps | | | | | | | |
| Reciprocating | 0.09[b] | 8,959 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Scroll | 0.002[b] | 1,122 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Screw | 0.04[b] | 4,370 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Centrifugal | 0.12[b] | 5,079 | USCB Average 2009, 2010 | 25 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Absorption | 0.01[b] | 500 | | 23 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| *Heat Rejection* | | | | | | | |
| Air-cooled Reciprocating | 0.09[b] | 8,959 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Air-cooled Scroll | 0.02[b] | 1,122 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Air-cooled Screw | 0.05[b] | 4,370 | USCB Average 2009, 2010 | 20 | (ADL, 1999)[c] | 2000 | (ADL, 1999)[c] |
| Cooling Tower | 0.18[b] | 8,948 | (ADL, 1999) | 20 | (ADL, 1999)[c] | 2400 | (ADL, 1999)[c] |
| *Commercial Refrigeration* | | | | | | | |
| Compressor | 3.1[a] | 442,830 | (Appliance, 2012) | 7 | TSD (DOE, 2011a) | - | - |
| Condenser Fan | 3.1[a] | 442,830 | (Appliance, 2012) | 7 | TSD (DOE, 2011a) | 6570 | Assumed to run 75% of the year. |
| Evaporator Fan | 3.1[a] | 442,830 | (Appliance, 2012) | 7 | TSD (DOE, 2011a) | 6570 | Assumed to run 75% of the year. |
| *ACIMs* | | | | | | | |
| Compressor | 2[a] | 162,190 | TSD (DOE, 2012a) | 12.5 | TSD (DOE, 2012a) | 4380 | Assumed making Ice 50% of the year.<br>TSD (DOE, 2012a) |
| Condenser Fan | 2[a] | 162,190 | TSD (DOE, 2012a) | 12.5 | TSD (DOE, 2012a) | 4380 | Assumed making Ice 50% of the year. |

| Product | Installed Base (MM) | Annual Shipments | Source | Typical Product Lifetime (yrs) | Source | Typical Duty Cycle (Hours/Yr) | Source |
|---|---|---|---|---|---|---|---|
| | | | | | | | TSD (DOE, 2012a) |
| Auger | 0.3 [a] | 26,038 | TSD (DOE, 2012a) | 12.5 | TSD (DOE, 2012a) | 4380 | Assumed making Ice 50% of the year. TSD (DOE, 2012a) |
| Pump | 1.7 [a] | 136,152 | TSD (DOE, 2012a) | 12.5 | TSD (DOE, 2012a) | 4380 | Assumed making Ice 50% of the year. TSD (DOE, 2012a) |
| *BVMs* | | | | | | | |
| Compressor | 3.7 [c] | 342,000 | TSD (DOE, 2009b) | - | - | 8760 | Assumed annual hourly use. |
| Condenser Fan | 3.7 [d] | 342,000 | TSD (DOE, 2009b) | - | - | 8760 | Assumed annual hourly use. |
| Evaporator Fan | 3.7 [d] | 342,000 | TSD (DOE, 2009b) | - | - | 8760 | Assumed annual hourly use. |
| *WICFs* | | | | | | | |
| Compressor | 2 [d] | 287,430 | TSD (DOE, 2010) | 7 | TSD (DOE, 2010) | 4380 | Assumed to run 50% of the year. |
| Condenser Fan | 2 [e] | 287,430 | TSD (DOE, 2010) | 7 | TSD (DOE, 2010) | 4380 | Assumed to run 50% of the year. |
| Evaporator Fan | 2 [e] | 287,430 | TSD (DOE, 2010) | 7 | TSD (DOE, 2010) | 4380 | Assumed to run 50% of the year. |

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[c] TSD (DOE, 2009b)
[d] TSD (DOE, 2010)

**Table B.2** Motor-Driven System or Component Average Unit Energy Consumption for the Commercial Sector by End Use

| Product | Assumed Horsepower (hp) | Average UEC (kWh/yr) | Source/Comment[a] |
|---|---|---|---|
| *PTAC* | | | |
| Compressor | - | 1125 | TSD (DOE, 2012c) |
| Indoor Fan | - | 225 | TSD (DOE, 2012c) |
| Outdoor Fan | - | 150 | TSD (DOE, 2012c) |
| *SPVAC* | | | |
| Compressor | - | 6900 | TSD (DOE, 2009a) |
| Indoor Fan | - | 1380 | TSD (DOE, 2009a) |
| Outdoor Fan | - | 920 | TSD (DOE, 2009a) |
| *CUAC* | | | |
| Compressor Small | - | 7360 | TSD (DOE, 2012e) |
| Compressor Med | - | 14270 | TSD (DOE, 2012e) |
| Compressor Large | - | 35200 | TSD (DOE, 2012e) |
| Indoor Fan - Small | - | 920 | TSD (DOE, 2012e) |
| Indoor Fan - Med | - | 1784 | TSD (DOE, 2012e) |
| Indoor Fan - Large | - | 4400 | TSD (DOE, 2012e) |
| Outdoor Fan - Small | - | 920 | TSD (DOE, 2012e) |
| Outdoor Fan - Med | - | 1784 | TSD (DOE, 2012e) |
| Outdoor Fan - Large | - | 4400 | TSD (DOE, 2012e) |
| *Chiller Compressors* | | | |
| Reciprocating | 50 | 84773 | [(assumed_hp/average_efficiency)*0.746] |
| Scroll | 50 | 84773 | [(assumed_hp/average_efficiency)*0.746] |
| Screw | 150 | 235579 | [(assumed_hp/average_efficiency)*0.746] |
| Centrifugal | 200 | 314105 | [(assumed_hp/average_efficiency)*0.746] |
| *Air Distribution* | | | |
| Exhaust Fan | 0.5 | 3532 | [(assumed_hp/average_efficiency)*0.746] |
| Room Fan Coil | 0.167 | 497 | [(assumed_hp/average_efficiency)*0.746] |

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[a] Adjusted from (ADL, 1999).

| Product | Assumed Horsepower (hp) | Average UEC (kWh/yr) | Source/Comment[a] |
|---|---|---|---|
| AHU | 10 | 25006 | [(assumed_hp/average_efficiency)*0.746] |
| *Circulation Pumps* | | | |
| Reciprocating | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Scroll | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Screw | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Centrifugal | 25 | 40368 | [(assumed_hp/average_efficiency)*0.746] |
| Absorption | 25 | 40368 | [(assumed_hp/average_efficiency)*0.746] |
| Boiler | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Cooling Water Pumps | | | |
| Reciprocating | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Scroll | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Screw | 10 | 16670 | [(assumed_hp/average_efficiency)*0.746] |
| Centrifugal | 25 | 40368 | [(assumed_hp/average_efficiency)*0.746] |
| Absorption | 25 | 40368 | [(assumed_hp/average_efficiency)*0.746] |
| *Heat Rejection* | | | |
| Air-cooled Reciprocating | 2 | 3511 | [(assumed_hp/average_efficiency)*0.746] |
| Air-cooled Scroll | 2 | 3511 | [(assumed_hp/average_efficiency)*0.746] |
| Air-cooled Screw | 2 | 3511 | [(assumed_hp/average_efficiency)*0.746] |
| Cooling Tower | 10 | 20004 | [(assumed_hp/average_efficiency)*0.746] |
| *Commercial Refrigeration* | | | |
| Compressor | - | 8442 | TSD (DOE, 2011a) |
| Condenser Fan | - | 460 | TSD (DOE, 2011a) |
| Evaporator Fan | - | 118 | TSD (DOE, 2011a) |
| *ACIMs* | | | |
| Compressor | - | 7000 | TSD (DOE, 2012a) |
| Condenser Fan | - | 552 | TSD (DOE, 2012a) |
| Auger | - | 1877 | TSD (DOE, 2012a) |
| Pump | - | 184 | TSD (DOE, 2012a) |
| *BVMs* | | | |

| Product | Assumed Horsepower (hp) | Average UEC (kWh/yr) | Source/Comment[a] |
|---|---|---|---|
| Compressor | - | 2492 | TSD (DOE, 2009b) |
| Condenser Fan | - | 1533 | TSD (DOE, 2009b) |
| Evaporator Fan | - | 491 | TSD (DOE, 2009b) |
| *WICFs* | | | |
| Compressor | - | 9302 | TSD (DOE, 2010) |
| Condenser Fan | - | 1875 | TSD (DOE, 2010) |
| Evaporator Fan | - | 1875 | TSD (DOE, 2010) |

**Table B.3** Installed Base Motor-Driven Energy Consumption and Technical Potential in the Commercial Sector by End Use

| Product | Average (Baseline) Efficiency (%) | Primary Energy Consumption (Quads) | Maximum (Achievable) Efficiency (%) | Primary Motor (Quads) | Maximum Technical Potential (Quads) |
|---|---|---|---|---|---|
| *PTAC* | | | | | |
| Compressor | 87% | 0.059 | 90% | 0.058[a] | 0.002 |
| Indoor Fan | 54% | 0.012 | 71% | 0.009[b] | 0.003 |
| Outdoor Fan | 54% | 0.008 | 71% | 0.006[b] | 0.002 |
| *SPVAC* | | | | | |
| Compressor | 87% | 0.009 | 90% | 0.009[a] | 0.0003 |
| Indoor Fan | 54% | 0.002 | 71% | 0.001[b] | 0.0004 |
| Outdoor Fan | 54% | 0.001 | 71% | 0.001[b] | 0.0003 |
| *CUAC* | | | | | |
| Compressor Small | 88% | 0.688 | 95% | 0.637[a] | 0.0507 |
| Compressor Med | 88% | 0.383 | 95% | 0.355[a] | 0.0282 |
| Compressor Large | 88% | 0.090 | 95% | 0.083[a] | 0.0066 |
| Indoor Fan - Small | 89.5% | 0.086 | 91.7% | 0.084[c] | 0.0021 |
| Indoor Fan - Med | 89.5% | 0.048 | 91.7% | 0.047 | 0.0011 |
| Indoor Fan - Large | 89.5% | 0.011 | 91.7% | 0.011 | 0.0003 |
| Outdoor Fan - Small | 54% | 0.086 | 71% | 0.065[b] | 0.0206 |
| Outdoor Fan - Med | 54% | 0.048 | 71% | 0.036[b] | 0.0115 |
| Outdoor Fan - Large | 54% | 0.011 | 71% | 0.009[b] | 0.0027 |
| *Chiller Compressors* | | | | | |
| Reciprocating | 88% | 0.161 | 95% | 0.149[d] | 0.0118 |
| Scroll | 88% | 0.020 | 95% | 0.019[d] | 0.0015 |
| Screw | 95% | 0.218 | 96% | 0.216[d] | 0.0023 |

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[a] Motor efficiency increase from average to max. Based on conversation with technology expert at leading compressor manufacturer.
[b] Motor efficiency increase from average to max, TSD (DOE, 2011c).
[c] Motor efficiency increase from average to max, TSD (DOE, 2012f).
[d] Installed base*Annual Op hours*[(assumed_hp/max_efficiency)*0.746]

| Product | Average (Baseline) Efficiency (%) | Primary Energy Consumption (Quads) | Maximum (Achievable) Efficiency (%) | Primary Motor (Quads) | Maximum Technical Potential (Quads) |
|---|---|---|---|---|---|
| Centrifugal | 95% | 0.388 | 97% | 0.380[d] | 0.0080 |
| *Air Distribution* | | | | | |
| Exhaust Fan | 60% | 0.469 | 80% | 0.351[d] | 0.1171 |
| Room Fan Coil | 50% | 0.010 | 70% | 0.007[d] | 0.0028 |
| AHU | 89.5% | 0.493 | 92% | 0.491[d] | 0.0013 |
| *Circulation Pumps* | | | | | |
| Reciprocating | 89.5% | 0.032 | 92% | 0.031[d] | 0.0009 |
| Scroll | 89.5% | 0.004 | 92% | 0.004[d] | 0.0001 |
| Screw | 89.5% | 0.015 | 92% | 0.015[d] | 0.0004 |
| Centrifugal | 92.4% | 0.050 | 95% | 0.049[d] | 0.0014 |
| Absorption | 92.4% | 0.003 | 95% | 0.003[d] | 0.0001 |
| Boiler | 89.5% | 0.065 | 92% | 0.063[d] | 0.0018 |
| Cooling Water Pumps | | | | | |
| Reciprocating | 89.5% | 0.016 | 92% | 0.015[d] | 0.0004 |
| Scroll | 89.5% | 0.0004 | 92% | 0.0004[d] | 0.0000 |
| Screw | 89.5% | 0.007 | 92% | 0.007[d] | 0.0002 |
| Centrifugal | 92.4% | 0.050 | 95% | 0.049[d] | 0.0014 |
| Absorption | 92.4% | 0.003 | 95% | 0.003[d] | 0.0001 |
| *Heat Rejection* | | | | | |
| Air-cooled reciprocating | 85% | 0.003 | 92% | 0.003[d] | 0.0003 |
| Air-cooled scroll | 85% | 0.001 | 92% | 0.001[d] | 0.0001 |
| Air-cooled screw | 85% | 0.002 | 92% | 0.002[d] | 0.0001 |
| Cooling tower | 89.5% | 0.038 | 92% | 0.037[d] | 0.0010 |
| *Commercial Refrigeration* | | | | | |
| Compressor | 88% | 0.277 | 90% | 0.271[a] | 0.006 |
| Condenser Fan | 20% | 0.038 | 70% | 0.011[e] | 0.027 |
| Evaporator Fan | 20% | 0.010 | 70% | 0.003[e] | 0.007 |
| *ACIMs* | | | | | |

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[e] Motor efficiency increase average to max, TSD (DOE, 2011a).

| Product | Average (Baseline) Efficiency (%) | Primary Energy Consumption (Quads) | Maximum (Achievable) Efficiency (%) | Primary Motor (Quads) | Maximum Technical Potential (Quads) |
|---|---|---|---|---|---|
| Compressor | 45% | 0.150 | 55% | 0.135[f] | 0.015 |
| Condenser Fan | 25% | 0.012 | 83% | 0.004[e] | 0.008 |
| Auger | 70% | 0.006 | 83% | 0.005[e] | 0.001 |
| Pump | 25% | 0.003 | 83% | 0.001[e] | 0.002 |
| *BVMs* | | | | | |
| Compressor | 88% | 0.098 | 90% | 0.096[a] | 0.002 |
| Condenser Fan | 20% | 0.060 | 70% | 0.017[e] | 0.043 |
| Evaporator Fan | 20% | 0.019 | 70% | 0.006[e] | 0.014 |
| *WICFs* | | | | | |
| Compressor | 88% | 0.198 | 90% | 0.194[a] | 0.004 |
| Condenser Fan | 29% | 0.040 | 70% | 0.017[g] | 0.023 |
| Evaporator Fan | 29% | 0.040 | 70% | 0.017[g] | 0.023 |

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[f] 10% Reduction in motor consumption, TSD (DOE, 2007).

[g] Motor efficiency increase from average to max TSD (DOE, 2010).

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