CHAPTER 4. SCREENING ANALYSIS

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CHAPTER 4. SCREENING ANALYSIS

4.1 INTRODUCTION

The purpose of the screening analysis is to identify design options that improve small electric motor efficiency and determine which options the Department of Energy (DOE) will either evaluate or screen out. DOE consults with industry, technical experts, and other interested parties in developing a list of design options for consideration. Then DOE applies the following set of screening criteria to determine which design options are unsuitable for further consideration in the rulemaking (1 Title 10 of the Code of Federal Regulations, Part 430, Subpart C, Appendix A at 4(a)(4) and 5(b)):

(1) *Technological feasibility.* Technologies incorporated in commercial products or in working prototypes will be considered technologically feasible.

(2) *Practicability to manufacture, install, and service.* If mass production of a technology in commercial products and reliable installation and servicing of the technology could be achieved on the scale necessary to serve the relevant market at the time of the effective date of the standard, then DOE will consider that technology practicable to manufacture, install, and service.

(3) *Adverse impacts on product utility or product availability.* If DOE determines that a technology will have significant adverse impact on the utility of the product to significant subgroups or consumers or result in the unavailability of any covered product type with performance characteristics (including reliability), features, sizes, capacities, and volumes that are substantially the same as products generally available in the United States at the time, that technology will not be considered further.

(4) *Adverse impacts on health or safety.* If DOE determines that a technology will have significant adverse impacts on health or safety, that technology will not be considered further.

This chapter discusses the design options that DOE considered for improving the energy efficiency of small electric motors and describes how DOE applied the screening criteria.

4.2 DISCUSSION OF DESIGN OPTIONS

Several well-established engineering practices and techniques exist for improving the efficiency of a small electric motor. Improving the construction materials (*e.g.*, the core steel, winding material, cooling system) and modifying the motor's geometric configuration (*i.e.*, the core and winding assemblies, the rotor, and stator) can make an electric motor more energy efficient.

As discussed in the market and technology assessment (chapter 3), there are four general areas of efficiency loss in small electric motors: I^2R, core, friction and windage, and stray load.

DOE presented an initial list of technology options used to reduce energy consumption and thus improve the efficiency of general purpose induction motors. Unfortunately, methods of reducing electrical losses in the equipment are not completely independent of one another. This means that some technology options that decrease one type of loss may cause an increase in a different type of loss in the motor. Thus, it takes a great degree of engineering skill to maximize the efficiency gains in a motor design overall, balancing out the loss mechanisms. In some instances, motor design engineers must make design tradeoffs when finding the appropriate combination of materials and costs. However, there are multiple design pathways to achieve a given efficiency level.

Although I^2R and core losses account for the majority of the losses in an induction motor, friction and windage losses and stray load losses also contribute to the total loss. In an induction motor, friction and windage losses can manifest in the bearings, bearing lubricant, and cooling fan system. Stray load losses are electromagnetic losses that generally require process changes in manufacturing. These various technologies can constrain the design parameters of a motor and thus limit the improvement in efficiency.

Table 4.2.1 presents a general summary of the methods that a manufacturer may use to reduce losses in small electric motors. The approaches presented in this table refer either to specific technologies (*e.g.*, aluminum versus copper die-cast rotor cages, different grades of electrical steel) or physical changes to the motor geometries (*e.g.*, cross-sectional area (CSA) of rotor conductor bars, additional stack height).

Table 4.2.1 Summary List of Options from Technology Assessment

Type of Loss to Reduce	Technology Option Applied
I^2R	Use a copper die-cast rotor cage
	Remove skew on conductor cage
	Increase cross-sectional area of rotor conductor bars
	Increase end ring size
	Change gauges of copper wire in stator
	Manipulate stator slot size
	Decrease air gap between rotor and stator
Core	Improve grades of electrical steel
	Use thinner steel laminations
	Anneal steel laminations
	Add stack height (*i.e.*, more electrical steel)
	Use high-efficiency lamination materials
	Use plastic bonded iron powder
	Use a permanent magnet electric motor
Friction and Windage	Install better bearings and lubricant
	Install a more efficient cooling system

4.3 DESIGN OPTIONS NOT SCREENED OUT OF THE ANALYSIS

This section discusses the technology options that DOE considers viable means of improving the efficiency of small electric motors.

4.3.1 Copper Die-Cast Rotor Cage

Aluminum is the most common material used today to create die-cast rotor bars in small motors. Some manufacturers that focus on producing high-efficiency designs have started to offer electric motors with die-cast rotor bars made of copper. Copper offers better performance than aluminum because, per unit area, copper has a higher electrical conductivity (*i.e.*, a lower resistance). However, copper has a higher melting point than aluminum, so the casting process becomes more difficult and is likely to increase both production time and cost for manufacturing a motor.

Considering the four screening criteria for this technology option, DOE did not screen out copper as a die-cast rotor cage conductor material. Because this material is in commercial use today, DOE concluded that this material is technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with the use of copper as a die-cast rotor cage material.

4.3.2 Remove Skew on Conductor Cage

In the rotor, the conductor bars are not straight from one end to the other, but skewed or twisted slightly around the axis of the rotor. Straightening these bars can improve a motor's efficiency. The conductor bars are skewed to help eliminate harmonics that add cusps, losses, and noise to the motor's speed-torque characteristics. Reducing the degree of skew can help reduce the rotor resistance and reactance, which helps improve efficiency. However, reducing the skew also may have adverse effects on the speed-torque characteristics.

Considering the four screening criteria for this technology option, DOE did not screen out adjusting rotor skew as a means of improving efficiency. Rotor skew is one of the variables that motor design engineers manipulate to obtain certain performance and efficiency targets. The rotor skew is part of the overall motor design, which is input into automated production equipment that punches and stacks the steel to create a rotor with the desired skew. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with properly manipulating the rotor skew to obtain improved performance.

4.3.3 Increase Cross Sectional Area of Rotor Conductor Bars

Increasing the cross-sectional area of the rotor conductor bars, either by making the diameter of the conductor bars larger or changing the geometric shape of the rotor in cross-section, can improve motor efficiency. Either way, increasing the cross-sectional area of the rotor conductor bars will decrease the resistance, lower losses, and increase current flow. Note that the shape of the rotor may affect the size of the end rings.

Considering the four screening criteria for this technology option, DOE did not screen out increasing the cross-sectional area of rotor conductor bars as a means of improving efficiency. Motor design engineers adjust this particular variable when manufacturing to obtain performance and efficiency targets. The rotor conductor bars are created by automated production equipment that have certain tolerances and allow variance in this parameter. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with increasing the cross-sectional area of rotor conductor bars to obtain increased efficiency.

4.3.4 Increase End Ring Size

Creating an electrical connection between the rotor bars by increasing the size of the end-rings can increase motor efficiency. Increasing the size of the end rings reduces the resistance and thus lowers the I^2R losses in the end rings.

Considering the four screening criteria for this technology option, DOE did not screen out increasing end ring size as a means of improving efficiency. As with some of the previous technology options, motor design engineers adjust this variable when manufacturing an electric motor to achieve performance and efficiency targets. Automated production and casting equipment, which allow some degree of variability, determine the end ring size. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with increasing the size of the rotor end rings to obtain increased efficiency.

4.3.5 Change Gauges of Copper Wire in Stator

Increasing the cross-sectional area of the wire used in winding the stator, by using larger wire gauges (*i.e.*, lower numeric values) or multiple strands of wire operating in parallel, can increase motor efficiency. As with the benefits associated with larger cross-sectional area of rotor conductor bars, using greater cross-sectional area in the stator windings decreases the winding resistance and associated losses. However, this change could affect the packing factor of the wire in the stator slots. The stator slot openings must fit the wires so that machinery can pull (or push) the wire into the stator slots. DOE used 75 percent as a maximum peak slot fill percentage in all of the designs presented in chapter 5 of the preliminary Technical Support Document (TSD).

Considering the four screening criteria for this technology option, DOE did not screen out changing gauges of copper wire in stator as a means of improving efficiency. Motor design engineers adjust this technology option in fractions of a half a gauge when manufacturing an electric motor to achieve desired performance and efficiency targets. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with changing the wire gauges in the stator to obtain increased efficiency.

4.3.6 Stator Slot Size Manipulation

Varying the stator slot size and geometry associated with a given motor design can improve motor efficiency. This variable property affects the losses in the windings and packing factor and can affect motor torque and performance (including efficiency).

Considering the four screening criteria for this technology option, DOE did not screen out changing stator slot size as a means of improving efficiency. Motor design engineers modify this technology to achieve desired performance and efficiency targets. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with changing stator slot sizes to obtain increased efficiency.

4.3.7 Air Gap Between Rotor and Stator

Reducing the radial air gap between the rotor and stator can improve motor efficiency. For small electric motors, the air gap is commonly set at 15 thousandths of an inch. However, reducing the air gap to 10 thousandths of an inch per side is still practicable to manufacture. Although DOE is aware that some stepper motors have tighter tolerances, radial air gaps less than 10 thousandths of an inch are not achievable for continuous duty motors, such as small electric motors, as defined by the Energy Policy and Conservation Act, as amended, 42 U.S.C. 6291–6317 (EPCA).

Considering the four screening criteria for this technology option, DOE did not screen out decreasing the radial air gap to 10 thousandths of an inch as a means of improving efficiency. DOE recognizes that reducing the radial air gap is a means design engineers use to achieve desired performance and efficiency targets. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with reducing the radial air gap to 10 thousandths of an inch.

4.3.8 Improved Grades of Electrical Steel

Losses generated in the electrical steel of an induction motor can be significant for an electric motor. Generally, these losses are classified as either hysteresis or eddy current. Hysteresis losses are caused by magnetic domains resisting reorientation to the alternating magnetic field (*i.e.*, 60 times per second, or 60 hertz). Eddy currents are physical currents that are induced in the steel laminations by the magnetic flux produced by the current in the windings. Both of these losses generate heat in the electrical steel.

One way to reduce hysteresis losses is to incorporate a higher grade of core steel into the electric motor design (*e.g.*, switching from an M56 to an M19). Even for the same thickness (*i.e.*, gauge) of core steel lamination, losses are reduced as the grain size increases, thus reducing magnetic resistance to reorientation by the alternating current.

Considering the four screening criteria for this technology option, DOE did not screen out improved grades of electrical steel as a means of improving efficiency. Design engineers use this approach to achieve desired performance and efficiency targets. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with improving the electrical steel.

4.3.9 Thinner Steel Laminations

DOE can use thinner laminations of core steel to reduce eddy currents. DOE can either change grades of electrical steel as described above, or simply use a thinner gauge of the same grade of electrical steel. The magnitude of the eddy currents induced by the magnetic field become smaller in thinner laminations, making the motor more energy efficient.

Considering the four screening criteria for this technology option, DOE did not screen out thinner steel laminations as a means of improving efficiency. Design engineers use this approach to achieve desired improvements in performance and efficiency. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with using thinner steel laminations.

4.3.10 Anneal Steel Laminations

Annealing the laminations can also reduce the losses in the electrical steel. This process subjects the laminations to an extremely high temperature to alleviate the stresses from punching and assembly. There is reduced stress, but also grain growth, which alleviates hysteresis losses. In addition to these benefits, the steels are oxidized to create a resistive coating that helps reduce eddy current flow and thus core losses.

Considering the four screening criteria for this technology option, DOE did not screen out annealing steel laminations as a means of improving efficiency. Design engineers use this approach to achieve desired improvements in performance and efficiency. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with annealing steel laminations.

4.3.11 Additional Stack Height

Adding electrical steel to the rotor and stator to lengthen the motor can also reduce the efficiency losses in steel. Lengthening the motor by increasing stack length reduces the magnetic flux density, which lowers the core watts lost overall. However, increasing the stack length affects other performance attributes of the motor, such as starting torque. Issues can arise when installing a more efficient motor with additional stack height, because the motor becomes longer. The longer motor may not fit into applications with dimensional constraints.

Considering the four screening criteria for this technology option, DOE did not screen out additional stack height as a means of improving efficiency. Design engineers use this approach to achieve desired improvements in performance and efficiency. Because this design technique is in commercial use today, DOE considers this technology option technologically feasible. Regarding the second screening criterion–practicable to manufacture, install, and service–DOE is concerned that increasing motor length makes installation of these motors too problematic. However, DOE recognizes that the majority of small motor applications are not constrained by motor length. Thus, DOE is drawing a preliminary finding that this technology option meets the second screening criteria. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with increased stack height.

4.3.12 High-Efficiency Lamination Materials

Another technology option to improve the efficiency of small electric motors is using nontraditional lamination materials. These materials are steel alloys that contain boron or cobalt (*e.g.*, Hiperco 50™[a], vanadium permendur, amorphous metals such as METGLAS[b]), which are used instead of conventional and silicon steel when assembling a stator and rotor stack.

These materials offer lower core losses because the laminations are extremely thin and the magnetic permeability is extremely high. These steels are not typically used in small electric motors, as defined by EPCA. However, DOE is not aware of any technical impediment preventing their use, because these are commercially available steels used in the manufacture of electric motors. DOE is aware of some small electric motor designs that were prepared for a manufacturer using one of these high-efficiency lamination materials. Thus, DOE believes that such steels are technologically feasible and practicable to manufacture, install, and service, because of their use in mass-produced electric motors. However, DOE is concerned that there may not be an adequate supply of these materials to meet the manufacturing requirements of all the small motors manufactured in the United States today. DOE is not aware of any adverse impacts on product utility, product availability, health, or safety for this technology option.

4.3.13 Better Bearings and Lubricant

Another technology option to improve the efficiency of small electric motors is using better ball bearings and a lower-friction lubricant. Using improved bearings and lubricants minimizes mechanical resistance to the rotation of the rotor, which also extends motor lifetime.

Considering the four screening criteria for this technology option, DOE did not screen out better ball bearings and lubricants as a means of improving efficiency. Design engineers use this approach to achieve desired improvements in performance and efficiency. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with better ball bearings and lubricant.

4.3.14 More Efficient Cooling System

Using a more efficient cooling system that circulates air through the motor is another technology option to improve the efficiency of small electric motors. Improving the cooling system reduces air resistance and associated frictional losses and decreases the operating temperature (and associated electrical resistance) by cooling the motor during operation.

Considering the four screening criteria for this technology option, DOE did not screen out a more efficient cooling system as a means of improving efficiency. Design engineers use this approach to achieve desired improvements in performance and efficiency. Because this design technique is in commercial use today, DOE considers this technology option both technologically feasible and practicable to manufacture, install, and service. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with improved cooling systems for small electric motors.

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[a] Registered trademark of the Carpenter Technology Corporation.

[b] Registered trademark of Metglas, Inc., a wholly-owned subsidiary of Hitachi Metals, Ltd., Tokyo, Japan.

4.3.15 Summary of Technology Options Not Screened Out

Table 4.3.1 summarizes the design options that DOE did not screen out of the analysis.

Table 4.3.1 Design Options Not Screened Out of the Analysis

Type of Loss to Reduce	Technology Option Applied
I^2R	Use a copper die-cast rotor cage
	Remove skew on conductor cage
	Increase cross-sectional area of rotor conductor bars
	Increase end ring size
	Change gauges of copper wire in stator
	Manipulate stator slot size
	Decrease the air gap between rotor and stator (down to 10 thousandths)
Core	Use improved grades of electrical steel
	Use thinner steel laminations
	Anneal steel laminations
	Add stack height (*i.e.*, more electrical steel)
	Use high-efficiency lamination materials
Friction and Windage	Install better bearings and lubricant
	Install a more efficient cooling system

4.4 DESIGN OPTIONS SCREENED OUT OF THE ANALYSIS

DOE screened out the following design options from further consideration because they do not meet the screening criteria.

4.4.1 Air Gap Between Rotor and Stator

Reducing the air gap between the rotor and stator can improve motor efficiency. For small electric motors, the air gap is commonly set at 15 thousandths of an inch. Although reducing this air gap can improve efficiency, there is some point at which the air gap is too tight and becomes impracticable to manufacture. DOE believes that air gaps below 10 thousandths of an inch would exceed the threshold for practicability to manufacture.

Considering the four screening criteria for this technology option, DOE screened out decreasing the radial air gap below 10 thousandths of an inch as a means of improving efficiency. DOE considers this technology option technologically feasible, because smaller air gaps do not present any technological barrier. DOE also is not aware of any adverse impacts on health or safety associated with reducing the radial air gap below 10 thousandths of an inch.

However, DOE believes that this technology option fails the screening criterion of being practicable to manufacture, install, and service. Such a tight air gap may cause problems in manufacturing and service, with the rotor potentially coming into contact with the stator. This technology option fails the screening criterion of adverse impacts on consumer utility and reliability, because the motor may experience higher failure rates in service when the manufactured air gaps are less than 10 thousandths of an inch.

4.4.2 Plastic Bonded Iron Powder

Plastic bonded iron powder (PBIP) could cut production costs while increasing the output of electric motors. Although other researchers may be working on this technology option, DOE is aware of a research team at Lund University in Sweden that recently published a paper about PBIP. This technology option is based on an iron powder alloy that is suspended in plastic, and is used in certain motor applications such as fans, pumps, and household appliances.[1] The compound is then shaped into motor components using a centrifugal mold, reducing the number of manufacturing steps. Researchers claim that this technology option could cut losses by as much as 50 percent. The Lund University team already produces inductors, transformers, and induction heating coils using PBIP, but has not yet produced a small electric motor. In addition, it appears that PBIP technology is aimed at torus, claw-pole, and transversal flux motors, none of which fit EPCA's definition of small motors.

Considering the four screening criteria for this technology option, DOE screened out PBIP as a means of improving efficiency. Although PBIP has the potential to improve efficiency while reducing manufacturing costs, DOE does not consider this technology option technologically feasible, because it has not been incorporated into a working prototype of a small electric motor. Also, DOE is uncertain whether the material has the structural integrity to form into the necessary shape of a small electric motor steel frame. Furthermore, DOE is uncertain whether PBIP is practicable to manufacture, install, and service, because a prototype PBIP small electric motor has not been made and little information is available on the ability to manufacture this technology to make a judgment. However, DOE is not aware of any adverse impacts on product utility, product availability, health, or safety that may arise from the use of PBIP in small electric motors.

4.4.3 Permanent Magnet Electric Motor

A permanent magnet synchronous motor is a rotating machine whose stator is similar to that of a three-phase induction motor, except that it has surface-mounted permanent magnets. The permanent magnet motor is the same as an induction motor except that permanent magnets produce the air gap magnetic field. This use of magnets to create the air gap magnetic flux makes it possible to design highly efficient permanent magnet motors.

Considering the four screening criteria for this technology option, DOE screened out permanent magnet electric motors as a means of improving efficiency. This technology option is not technologically feasible for small electric motors because a permanent magnet motor cannot meet the EPCA definition of a small electric motor. Also, because of the associated controls necessary to start and operate the motor, there are problems with installing the electric motor in certain installations. However, DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with permanent magnet electric motors.

4.4.4 Summary of Technology Options Screened Out of the Analysis

Table 4.4.1 shows the criteria DOE used to screen radial air gaps below 10 thousandths of an inch, PBIP, and permanent magnet electric motors out of the analysis.

Table 4.4.1 Design Options Screened Out of the Analysis

Design Option	Screening Criteria
Radial Air Gaps Below 10 Thousandths of an Inch	Practicability to manufacture, install, and service; adverse impacts on product utility or product availability
PBIP	Technological feasibility
Permanent Magnet Electric Motor	Technological feasibility; practicability to manufacture, install, and service.

REFERENCES

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[1] Horrdin, H., and E. Olsson. *Technology Shifts in Power Electronics and Electric Motors for Hybrid Electric Vehicles: A Study of Silicon Carbide and Iron Powder Materials.* 2007. Chalmers University of Technology. Göteborg, Sweden.