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 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 impacts 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 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 an 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 electric motors: I^2R, core, friction and windage, and stray load. In the framework document 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. Any losses that are otherwise unaccounted for and not attributed to I^2R losses, steel losses, or frictional and windage losses are considered stray-load losses. General process changes to the manufacturing of rotors and stators could somewhat reduce these losses, such as removing the skew on the rotor bars, or improving the rotor bar insulation. However, 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 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	Design Options Considered
I^2R Losses	Use copper die-cast rotor cage
	Decrease the length of coil extensions
	Increase cross-sectional area of rotor conductor bars
	Increase end ring size
	Increase the amount of copper wire in stator slots
	Increase the number of stator slots
Core Losses	Improve grades of electrical steel
	Use thinner steel laminations
	Add stack length (*i.e.*, add electrical steel laminations)
	Increase flux density in air gap
Friction and Windage Losses	Use bearings and lubricant with lower losses
	Install a more efficient cooling system
Stray Load Losses	Reduce skew on conductor cage
	Improve rotor bar insulation

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 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 electric 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 electrical 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 aware of the higher melting point of copper (1084 degrees Celsius versus 660 degrees Celsius for aluminum) and the potential impacts this may have on the health or safety of plant workers. However, DOE does not believe this impact is sufficiently adverse to screen out copper as a die cast material for rotor conductors. DOE understands many plants already deal with molten aluminum die casting processes and believes similar processes could be adopted for copper.

4.3.2 Decrease the Length of Coil Extensions

One method of reducing resistance losses in the stator is decreasing the length of the coil extensions at the end turns. Reducing the length of copper wire in the stator slots not only reduces the resistive losses, but also reduces the material cost of the electric motor because less copper is being used.

Considering the four screening criteria for this technology option, DOE did not screen out decreasing the length of the coil extensions as a means of improving efficiency. Motor design engineers adjust this particular variable when manufacturing to obtain 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 decreasing the length of coil extensions to obtain increased efficiency.

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 cross-sectional geometry of the rotor, can improve motor efficiency. Increasing the cross-sectional area of the rotor conductor bars will decrease the resistance, increase current flow, and lower losses. However, changing the shape of the rotor bars may affect the size of the end rings and can also change the torque characteristics of the motor.

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

The end rings create an electrical connection between the rotor bars. 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 Increase the Amount of Copper Wire in the Stator Slots

Increasing the slot fill by either adding windings or changing the gauge of wire used in the stator winding can also increase motor efficiency. Motor design engineers can achieve this by manipulating the wire gauges to allow for a greater total cross-sectional area of wire to be incorporated into the stator slots. This could mean either an increase or decrease in wire gauge, depending on the dimensions of the stator slots and insulation thicknesses. As with the benefits associated with larger cross-sectional area of rotor conductor bars, using more total 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 be able to fit the wires so that automated machinery or manual labor can pull (or push) the wire into the stator slots.

Considering the four screening criteria for this technology option, DOE did not screen out changing gauges of copper wire in the 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 Increase the Number of Stator Slots

Increasing the number of stator slots associated with a given motor design can improve motor efficiency. Similar to increasing the amount of copper wire in a particular slot, increasing the number of slots can allow the motor design engineer to incorporate more overall copper into the stator slots. This decreases the losses in the windings, but can also affect motor torque and performance (including efficiency).

Considering the four screening criteria for this technology option, DOE did not screen out increasing the number of stator slots 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 Higher Quality Electrical Steel in Core

Losses generated in the electrical steel in the core of an induction motor can be significant. 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. 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.

In studying the techniques used to reduce steel losses, DOE considered two types of materials: conventional silicon steel and “exotic” steels, which contain a relatively high percentage of boron or cobalt. Conventional steels are commonly used in electric motors manufactured today. There are three types of steel that DOE considers “conventional:” cold-rolled magnetic laminations, fully processed non-oriented electrical steel, and semi-processed non-oriented 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.

The exotic steels are not generally manufactured for use specifically in the electric motors covered in this rulemaking. These steels include vanadium permendur and other alloyed steels containing a high percentage of boron or cobalt. These steels offer a lower loss level than the best electrical steels, but are more expensive per pound. In addition, these steels can present manufacturing challenges because they come in non-standard thicknesses that are difficult to manufacture.

Considering the four screening criteria for this technology option, DOE did not screen out higher quality, more efficient electrical steel in the core 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.

4.3.8 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 use a thinner gauge of the same grade of electrical steel. The magnitude of the eddy currents induced by the magnetic field becomes 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.

4.3.9 Additional Stack Length

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 reduces hysteresis losses. 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 and therefore 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 many motor applications are not constrained by motor length. Thus, DOE believes that this technology option meets the second screening criterion. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with increased stack height.

4.3.10 Increase Flux Density in Air Gap

Another technology option to improve electric motor efficiency is to increase the flux density across the air gap. Typically, the efficiency will increase as the air gap flux density increases as long as the steel laminations are not saturated. Once saturation is reached, core losses increase at a much faster rate than rotor losses thereby negating any efficiency increases beyond the saturation point. Additionally, increasing the flux density also increases the in-rush current. Electric motor designers need to take these limitations into account when using increased air gap flux density to increase overall electric motor efficiency.

Considering the four screening criteria for this technology option, DOE did not screen out increasing the air gap flux density as a means of improving efficiency. DOE recognizes that increasing the air gap flux density 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 increasing the air gap flux density.

4.3.11 Better Bearings and Lubricant

Another technology option to improve the efficiency of 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 life.

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.

4.3.12 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 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. This can be accomplished by changing the fan or adding baffles to the current fan to help redirect airflow through the motor.

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 electric motors.

4.3.13 Reduce 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. Decreasing the degree of skew 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, overly reducing the skew also may have adverse effects on starting, noise, and 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 can 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.

4.3.14 Improved Rotor Bar Insulation

One major source of stray losses in electric motors is inter-bar currents flowing through the laminations between rotor bars. These currents can be reduced by using improved insulation materials between the rotor bars and the steel laminations.

Considering the four screening criteria for this technology option, DOE did not screen out improved rotor bar insulation 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 rotor bar insulation.

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 Summary List of Options from Technology Assessment

Type of Loss to Reduce	Design Options Considered
I^2R Losses	Use copper die-cast rotor cage
	Decrease the length of coil extensions
	Increase cross-sectional area of rotor conductor bars
	Increase end ring size
	Increase the amount of copper wire in stator slots
	Increase the number of stator slots
Core Losses	Improve grades of electrical steel
	Use thinner steel laminations
	Add stack length (*i.e.*, add electrical steel laminations)
	Increase flux density in air gap
Friction and Windage Losses	Use bearings and lubricant with lower losses
	Install a more efficient cooling system
Stray Load Losses	Remove skew on conductor cage
	Improve rotor bar insulation

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 Amorphous Metal Laminations

Using amorphous metals in the rotor laminations is another technology option to improve the efficiency of electric motors. Amorphous metal is extremely thin, has high electrical resistivity, and has little or no magnetic domain definition. Because of amorphous steel's high resistance it exhibits a reduction in hysteris and eddy current losses, which reduce overall losses in electric motors. However, amorphous steel is a very brittle material which makes it difficult to punch into motor laminations.[a]

Considering the four screening criteria for this technology option, DOE screened out amorphous metal laminations as a means of improving efficiency. Although amorphous metals have the potential to improve efficiency, DOE does not consider this technology option technologically feasible, because it has not been incorporated into a working prototype of an electric motor. Furthermore, DOE is uncertain whether amorphous metals are practicable to manufacture, install, and service, because a prototype amorphous metal electric motor has not been made and little information is available on the ability to manufacture this technology to make a judgment. DOE is not aware of any adverse impacts on consumer utility, reliability, health, or safety associated with improved cooling systems for electric motors.

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[a] S.R. Ning, J. Gao, and Y.G. Wang. *Reviewon Applications of Low Loss Amorphous Metals in Motors.* 2010. ShanDong University. Weihai, China.

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 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 an electric motor. In addition, it appears that PBIP technology is aimed at torus, claw-pole, and transversal flux motors, none of which fall under DOE's scope of analysis as defined by the Energy Policy and Conservation Act, as amended by the Energy Independence and Security Act.

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 an electric motor. Also, DOE is uncertain whether the material has the structural integrity to form into the necessary shape of an electric motor steel frame. Furthermore, DOE is uncertain whether PBIP is practicable to manufacture, install, and service, because a prototype PBIP 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 electric motors.

4.4.3 Summary of Technology Options Screened Out of the Analysis

Table 4.4.1 shows the criteria DOE used to screen amorphous metal laminations and plastic bonded iron powder (PBIP) out of the analysis.

Table 4.4.1 Design Options Screened Out of the Analysis

Design Option	Screening Criteria
Amophous Metals	Technological feasibility
PBIP	Technological feasibility

REFERENCES

[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.