CHAPTER 5. ENGINEERING ANALYSIS

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LIST OF ACRONYMS AND ABBREVIATIONS

AWG	American wire gauge
BOM	Bill of materials
CSCR	Capacitor-Start, Capacitor-Run Motor
CSIR	Capacitor-Start, Induction-Run Motor
DOE	United States Department of Energy
EISA	Energy Independence and Securities Act
M*	M15, M19, M36, M47, M56 - grade of core steel
MSP	Manufacturer Selling Price
NEMA	National Electrical Manufacturers Association
NCI	Navigant Consulting, Inc
RPM	Revolutions per minute
TSD	Technical Support Document
SEC	Securities and Exchange Commission
U.S.	United States
μF	Microfarads

CHAPTER 5. ENGINEERING ANALYSIS

5.1 INTRODUCTION

The engineering analysis estimates the increase in manufacturer selling price (MSP) associated with technological and design changes that improve the efficiency of small electric motors. This chapter presents the U.S. Department of Energy's (DOE's) assumptions, methodology and findings for the small electric motor engineering analysis. The output from the engineering analysis is a "cost-efficiency" relationship for each motor analyzed which describes how cost changes as efficiency increases. The engineering analysis is used as an input to the life-cycle cost analysis (see preliminary Technical Support Document (TSD) chapter 8) as well as the national impact analysis (see preliminary TSD chapter 10).

As discussed in chapter 3 of this preliminary TSD, the electric motors covered in this rulemaking include general-purpose capacitor-start, induction-run (CSIR), capacitor-start, capacitor-run (CSCR), and polyphase electric motors built in a National Electrical Manufacturers Association (NEMA) two-digit frame size. The engineering analysis selected and analyzed one small electric motor from each of these three categories of covered motors.

The engineering analysis takes input from the market and technology assessment (see preliminary TSD chapter 3) and the screening analysis (see preliminary TSD chapter 4). These inputs include equipment classes, baseline motor performance, methods for improving efficiency, and design options that have passed the screening criteria. The engineering analysis uses these inputs, coupled with material price estimates, design parameters, and other manufacturer inputs, to develop the relationship between the MSP and nominal full-load efficiency of the representative motors studied. For small electric motors, this relationship was evaluated using third-party design software, created and maintained by Yeadon Energy Systems, Inc.

At its most basic level, the output of the engineering analysis is a curve that estimates the manufacturer's selling price for a range of efficiency values. This output is subsequently marked-up to determine the end-user prices based on the various distribution channels (see preliminary TSD chapter 6). After determining customer prices by applying distribution chain markups, sales tax, and contractor markups, the data is combined with the energy-use and end-use load characterization (see preliminary TSD chapter 7) and used as a critical input to the customer's life-cycle cost and payback period analysis (see preliminary TSD chapter 8).

The results presented in this chapter do not provide a full assessment of the manufacturer's costs associated with increasing efficiency levels for a small electric motor. The relationship presented in this chapter assumes an ideal situation, where manufacturers do not incur any costs associated with retooling, product redesign, training, or marketing associated with incorporating design changes to their product lines to achieve the efficiency levels presented. In the notice of proposed rulemaking stage of the rulemaking, DOE will attempt to quantify the additional costs manufacturers would incur when complying with mandatory efficiency standards. For a discussion of these costs and DOE's methodology for quantifying them, see preliminary TSD chapter 12, the preliminary manufacturer impact analysis.

In this chapter, DOE discusses the equipment classes analyzed and the representative motors selected from all covered small electric motors. DOE also presents the methodology, inputs, and results associated with the development of MSP versus efficiency curves for each of the representative motors. Finally, DOE discusses the approach used to scale the engineering analysis to all other equipment classes for the national impact analysis.

5.2 EQUIPMENT CLASSES AND BASELINE MOTORS ANALYZED

Due to the large number of equipment classes, DOE did not directly analyze all covered motors. Instead, DOE selected certain equipment classes to analyze after reviewing the motors studied in the small electric motors determination analysis and examining manufacturers' catalog data.

5.2.1 Equipment Classes Analyzed

When identifying which motors to evaluate, the highest priority in selecting equipment classes was ensuring that each of the three motor categories was represented. DOE selected one model from each of the motor categories (i.e., polyphase, CSIR, and CSCR) in order to minimize any error that might be introduced scaling across motor categories when extrapolating findings to other horsepower (hp) ratings and pole configurations. DOE then scaled from those three representative model motors to all equipment classes covered in this rulemaking.

Table 5.2.1 through Table 5.2.3.present the 72 equipment classes (EC) for polyphase, CSIR and CSCR motors, broken down by number of poles and horsepower/standard kilowatt equivalent ratings. Should DOE establish minimum energy conservation standards for small electric motors, each "EC" cell in the following table would be replaced by the applicable nominal full load efficiency value.

Table 5.2.1 Polyphase Small Electric Motor Equipment Classes

Horsepower/Standard Kilowatt Equivalent	Six Poles	Four Poles	Two Poles
1/4 hp/0.18 kW	EC #1	EC #2	EC #3
1/3 hp/0.25 kW	EC #4	EC #5	EC #6
1/2 hp/0.37 kW	EC #7	EC #8	EC #9
3/4 hp/0.55 kW	EC #10	EC #11	EC #12
1 hp/0.75 kW	EC #13	EC #14	EC #15
1½ hp/1.1 kW	EC #16	EC #17	EC #18
2 hp/1.5 kW	EC #19	EC #20	EC #21
≥ 3 hp/2.2 kW	EC #22	EC #23	EC #24

Table 5.2.2 Capacitor-Start, Induction-Run Small Electric Motor Equipment Classes

Horsepower/Standard Kilowatt Equivalent	Six Poles	Four Poles	Two Poles
1/4 hp/0.18 kW	EC #25	EC #26	EC #27
1/3 hp/0.25 kW	EC #28	EC #29	EC #30
1/2 hp/0.37 kW	EC #31	EC #32	EC #33
3/4 hp/0.55 kW	EC #34	EC #35	EC #36
1 hp/0.75 kW	EC #37	EC #38	EC #39
1½ hp/1.1 kW	EC #40	EC #41	EC #42
2 hp/1.5 kW	EC #43	EC #44	EC #45
≥ 3 hp/2.2 kW	EC #46	EC #47	EC #48

Table 5.2.3 Capacitor-Start, Capacitor-Run Small Electric Motor Equipment Classes

Horsepower/Standard Kilowatt Equivalent	Six Poles	Four Poles	Two Poles
1/4 hp/0.18 kW	EC #49	EC #50	EC #51
1/3 hp/0.25 kW	EC #52	EC #53	EC #54
1/2 hp/0.37 kW	EC #55	EC #56	EC #57
3/4 hp/0.55 kW	EC #58	EC #59	EC #60
1 hp/0.75 kW	EC #61	EC #62	EC #63
1½ hp/1.1 kW	EC #64	EC #65	EC #66
2 hp/1.5 kW	EC #67	EC #68	EC #69
≥ 3 hp/2.2 kW	EC #70	EC #71	EC #72

The next step DOE took in selecting representative equipment classes for the engineering analysis was to choose a range of horsepower ratings. Motors with different horsepower ratings have different cost-efficiency characteristics just like those of different motor categories (i.e., polyphase, CSIR, and CSCR). Therefore, DOE selected a subset of horsepower ratings that were representative of popular models and would facilitate scaling to other horsepower ratings not analyzed. The horsepower ratings selected for the CSIR and polyphase representative motors were the same as those used in DOE's determination analysis. These ratings were recommended by industry for DOE's determination and are considered high-volume, widely produced models produced by small electric motor manufacturers. DOE did not analyze a CSCR motor for the determination analysis, therefore, the horsepower rating for the CSCR motor was chosen by reviewing popular ratings in various manufacturer catalogs.

Finally, for each of the motor categories and horsepower ratings selected, DOE had to choose a pole configuration for the representative motors. After reviewing the determination analysis and manufacturer catalog data, DOE chose four-pole motors, because they appear to represent the most popular configuration.

Table 5.2.4 presents the major design characteristics of the four representative baseline motors that were analyzed by DOE and participating NEMA manufacturers.

Table 5.2.4 Design Characteristics of the Four Baseline Motors Analyzed

Motor Category	Horsepower	Number of Poles	Frame Size
Polyphase	1.00	4	56
CSIR	1/2	4	48
CSIR*	1/2	4	56
CSCR	3/4	4	56

* DOE identified these four motors as the representative units to study, and then conducted an engineering analysis to study the relationship between motor efficiency and manufacturer selling price. DOE found that there was virtually no difference between the 48 and 56 frame sizes for the ½-horsepower, four-pole CSIR motors. Therefore, DOE elected to drop the 56 frame size from its analysis, since frame size tends to scale with horsepower, and at this rating it would be more common to find a 48 frame than a 56.

One observable aspect of the four baseline motors selected is that there are two CSIR motors with the same horsepower rating and number of poles. Even though frame size is not a parameter DOE uses to differentiate between equipment classes, DOE selected these two motors in order to determine if the MSP-efficiency curves would vary across frame size. The 0.5 horsepower CSIR motor is one that is commonly manufactured in both the 48 and 56 frame sizes, therefore this was considered a good unit for analysis. After reviewing the results of the engineering analysis on these two frame sizes DOE found that there was no significant difference between the 48 and 56 frame size CSIR motors. Due to that similarity, DOE decided to remove the 56 frame size CSIR 0.5 horsepower, four-pole motor from its analysis because (1) the analytical findings would be redundant with the 48 frame size model and (2) smaller horsepower ratings tend to be manufactured in smaller frame sizes. Discussion of the draft findings of this representative motor and the rationale behind not continuing to analyze the 56 frame size CSIR motor is presented in the results section of this chapter (see section 5.6).

5.2.2 Baseline Motors Analyzed

For each representative equipment class selected, DOE identified a specific baseline motor as a fundamental design against which it would apply design changes to improve the motor's efficiency. DOE chose the baseline motors to represent the typical characteristics of small electric motors in that equipment class. Because there are no existing minimum energy conservation standards for small electric motors, the baseline efficiency was selected after reviewing efficiency ratings from the determination analysis, manufacturer catalogs, and consultation with technical experts.

Table 5.2.5 Efficiency Ratings of Baseline Motors Selected for Analysis

Basic Characteristics of Motors Analyzed	Baseline Efficiency %
Polyphase, 1 hp, 4-pole, 56 frame	75.8
CSIR, ½ hp, 4-pole, 48 frame	62.3
CSIR, ½ hp, 4-pole, 56 frame	63.3
CSCR, ¾ hp, 4-pole, 56 frame	68.6

In addition to the efficiency rating, DOE used performance and physical characteristics of these small electric motors, such as breakdown torque, locked-rotor torque, and locked-rotor current as well as dimensional characteristics of the motor. In making its selections, DOE ensured that the baseline motors had performance characteristics falling within the specifications of general-purpose motors as defined in NEMA MG 1-1987. Specific detail on these baseline motors is provided in the results section of this chapter, section 5.6.

5.3 ENGINEERING ANALYSIS METHODOLOGY

DOE employed a two-fold approach in conducting the engineering analysis. First, DOE prepared and circulated an interview guide to small electric motor manufacturers requesting detail on their costs and design options at certain efficiency levels. Second, DOE engaged a third-party software design company which specializes in small electric motor designs to prepare four sets of designs, each spanning a range of efficiency levels. Both the manufacturers and the third-party software design company were given the fundamentals of the representative models from which to start.

DOE decided to conduct the engineering analysis using this two-pronged approach in order to best develop practical, manufacturer-derived engineering curves that reflect the relationship between manufacturer selling price and efficiency. The small electric motor designs prepared by the third-party software design company would then be used by DOE to verify and corroborate the manufacturer-supplied curves.

5.3.1 Manufacturer Interview Guide Approach

DOE prepared and circulated a manufacturer interview guide that requested information on design options and costs associated with the four representative units selected for analysis (see TSD Appendix 12A.2 Part A). Due to the fact that DOE is not aware of any United States (U.S.) manufacturers of small electric motors who are not NEMA members, this interview guide was only circulated to manufacturers who were, at the time, NEMA members.

For consistency of reporting the designs, NEMA's electric motors technical committee developed and recommended four efficiency levels that DOE should include in the interview guide, a baseline design level, an EPACT level, a NEMA Premium level, and a maximum technologically achievable level. This fourth level did not include a specific efficiency value, but was left open to manufacturers who would employ different approaches to achieving the maximum technologically achievable level. The efficiency levels recommended by NEMA are shown in Table 5.3.1 below. These levels are the ones used in the manufacturer interview guide, however DOE later refined the baseline model selection for the engineering analysis, which accounts for the difference between the baseline efficiency values presented in this table and in Table 5.2.5.

Table 5.3.1 National Electrical Manufacturers Association Manufacturer Consensus on Efficiency Levels for Equipment Classes Analyzed

Equipment Class	Baseline	EPACT	NEMA Premium	Max Tech
Polyphase, 1 hp, 4-pole, 56 frame	74.0 %	78.5 %	85.5 %	TBD
CSIR, ½ hp, 4-pole, 48 frame	59.0 %	68.0 %	73.0 %	TBD
CSIR, ½ hp, 4-pole, 56 frame	61.5 %	68.0 %	75.5 %	TBD
CSCR, ¾ hp, 4-pole, 56 frame	66.0 %	77.0 %	80.0 %	TBD

DOE issued the manufacturer interview guide incorporating these efficiency levels and requesting a max-tech efficiency design (at an undetermined efficiency level) for each of the four motor types. Manufacturers were given four months to prepare their responses and submit them to DOE's contractor under a confidentiality agreement.

5.3.2 Subcontractor Software Design Approach

Concurrent with the manufacturer-based engineering analysis, DOE worked with a subcontractor to develop MSP-efficiency curves for the same four representative electric motors. As discussed above, DOE retained a small electric motor expert[a] with design experience and software, who prepared a set of designs with increasing efficiency. The contractor started with similar baseline model motors used by the manufacturers and modified the designs to improve the efficiency. As new designs were created, careful attention was paid to the critical performance characteristics to ensure that the resulting small electric motor designs had similar performance characteristics to the baseline motor and were manufacturable. To this end, DOE established a set of design limitations that are applied uniformly across all four sets of designs to ensure that the resulting designs are reasonable and manufacturable. The following list presents the design limitations:

- Peak slot fill – the maximum value this parameter should reach is 75 percent for an assumed high volume simultaneous insertion process. (Note: DOE considers "slot fill" to be the area of the wire (including insulation) divided by the total slot area available for winding.)

- Air gap between rotor and stator – the air gap between the rotor and stator should not be less than 0.010 inches. Having air gaps tighter than this minimum could be problematic

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[a] Yeadon Energy Systems, Inc. (YES) of Iron Mountain, Michigan.

and may cause contact between the spinning rotor and the stator, especially as shaft length increases.

- Stator slot opening – the opening in combination with the copper wire gauges used should graph to a point in the "Level Wind Area" of the "Blade Gap Chart" taken from Alliance Winding[1]. Without this restriction, DOE is concerned there may be too many issues with wire breakage and jamming of manufacturers' winding tools.

- Stack height – the stack height (or length) may change by up to 100 percent relative to the baseline height (i.e., the stack height may double the original value). This design option enables motors to regain induction when steel grades are improved.

- Locked rotor torque – the torque must be kept within 10 percent of the baseline motor, and be within the specifications set forth by NEMA MG 1-1987 in Section 12.32.2. (e.g., for a 0.5 hp, four-pole motor the minimum is 85 oz-ft., [7.2 Newton meters]). Maintaining the locked rotor torque within 10 percent of the baseline motor will help preserve the utility of the more efficient motor designs.

- Locked rotor current – the current should not exceed the values of NEMA MG 1-1987 Section 12.33.2 (Design N) (e.g., 45 amperes for a 115-volt, 0.5 hp motor). .

- Breakdown torque – the breakdown torque must fall within NEMA MG 1-1987 Table 10-5 limits for all ratings (e.g., for 0.5 hp, four-pole small electric motor greater than 40.5 oz-ft, but not to exceed 58.0 oz-ft [3.43-4.91 Newton meters]).

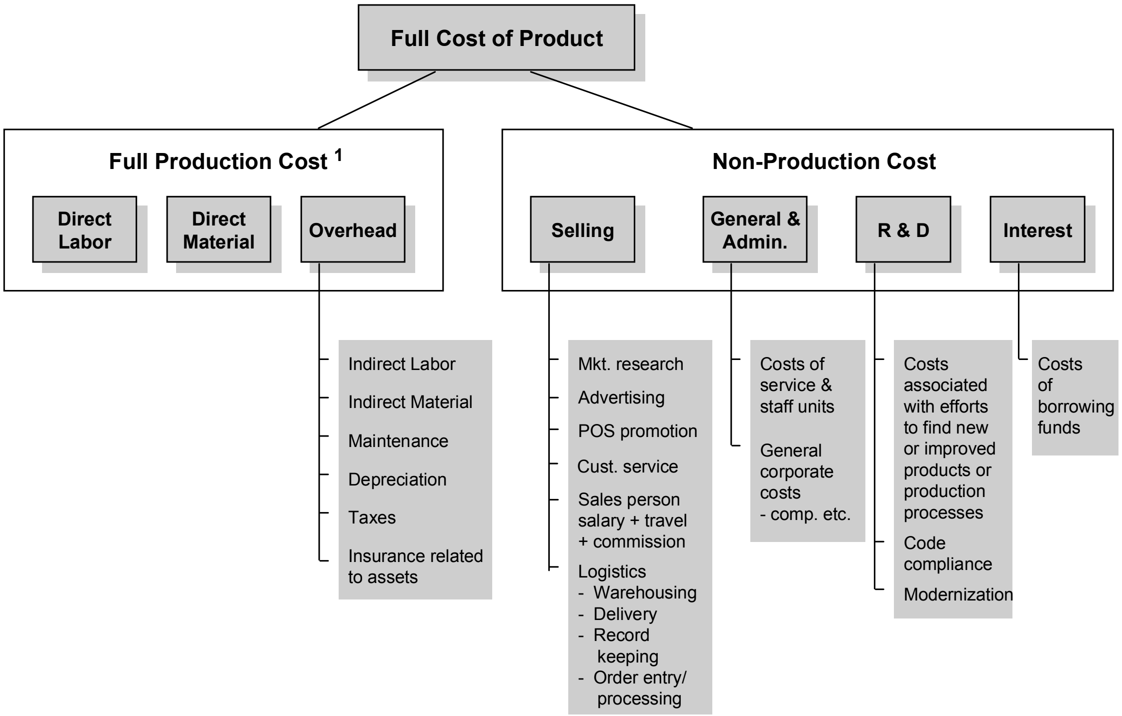
- Cooling system – the parameters directly related to the motor's cooling system, such as ventilation openings in the laminations, should not be modified in a manner that will increase the operating temperature of the motor.

- Rotor skew – the rotor skew may be altered, but it cannot be raised or lowered to a point that will introduce harmonics that adversely affect motor performance or introduce cusps in the acceleration curve. (Note: this design limitation was subjective and relied on the expertise of the designers).

Working within these parameters, the subcontractor prepared five designs for each representative motor that adhered to these requirements while improving the efficiency of the motors. The design levels prepared were at the baseline, an energy efficient level, a premium efficient level, a premium plus efficient level and a maximum technologically achievable level.

5.4 COST MODEL

DOE uses a standard method of cost accounting to determine the costs associated with manufacturing. This methodology is illustrated in Figure 5.4.1, where production costs and non-production costs are combined to determine the full cost of a product.



[1] Tax Reform Act of 1986, essentially, requires companies to measure cost of goods sold as the full production cost of the goods sold.

Figure 5.4.1 Standard Method of Cost Accounting for Standards Rulemaking

DOE developed estimates of some of the cost multipliers shown in Figure 5.4.1 by reviewing Security and Exchange Commission (SEC) SEC-10K reports from A.O. Smith Corporation, Baldor Electric Company, Emerson Motor Company, and Regal-Beloit Corporation as well as through conversations with industry experts. Together, the full production cost and the non-production costs equal the full cost of the product. Full production cost is a combination of direct labor, direct materials, and overhead. The overhead contributing to full production cost includes indirect labor, indirect material, maintenance, depreciation, taxes, and insurance related to company assets. Non-production costs include the cost of selling (market research, advertising, sales representatives, logistics), general and administrative costs, research and development, interest payments and profit factor (not shown in the figure).

After the subcontractor designs were completed and verified for manufacturability (i.e., following the restrictions mentioned in section 5.3.2), the next step was applying this cost model to all of them. A standard bill of materials (BOM) was constructed that calculates direct material costs, labor time estimates along with costs and applies various manufacturer markups for non-production costs to create a MSP.

5.4.1 Constructing a Bill of Materials

The BOM calculated for each design contained three types of material costs: fixed costs, variable costs and semi-fixed costs. Fixed cost materials are those parts and components that remain constant across all designs within a set. That is, these are the parts that do not vary with efficiency, such as switches, ball-bearings and other components. The aggregate fixed cost will vary from one motor category to another because the different motor categories use different parts (e.g., the representative polyphase motor had a total fixed cost of $11.21, however the total fixed costs for CSIR and CSCR motors are different). The variable costs considered are those portions of the BOM that vary based on the cost of the material and the amount of that material used in the design. For example, stator and rotor lamination costs are variable costs because the material price for the different steel grades changes as does the volume of steel needed for each design. Finally, semi-fixed costs are those materials that have a constant price per pound, but vary in cost from design to design as a function of the amount used in the motor designs. An example of this type of cost is the die-cast aluminum or copper used in the rotor bars. The price per pound for aluminum or copper is the same from design to design; however, the cost per design is different because the amount of metal used for die-casting the rotor bars varies with each design.

DOE presents a detailed bill of materials for one design (i.e., the premium efficiency design) from each of the three motor categories analyzed in preliminary TSD appendix 5A. The discussion below describes the level of detail contained in the bill of materials presented in this appendix.

Each item in the BOM is organized by the type of cost (i.e., fixed, variable, and semi-fixed) and the component of the motor to which they apply. For example "end cap assembly" is a subheading under the fixed cost portion of the BOM, and under this subheading there are several itemized parts with associated costs. The fixed costs portion of the BOM includes the following subheadings, each with an itemized parts list: stator assembly, rotor assembly, end cap assembly, housing assembly, hardware, and final assembly. The variable cost section of the BOM includes subheadings for the stator assembly, rotor assembly, and hardware. The semi-fixed costs section includes itemized lists dedicated to the stator assembly, rotor assembly, and housing assembly. There are some subheadings that appear under both the variable cost and semi-fixed cost sections; however these subheadings have different items in their respective lists.

The subheadings that have an itemized list of components include the stator assembly, rotor assembly, end cap assembly, housing assembly, hardware, and final assembly. The stator assembly's itemized lists include prices for cleats, lead wires, capacitor wires (for appropriate motor categories), splices, insulation, slot liner, copper shipping, stator laminations, main and auxiliary (when applicable) copper wire costs. The rotor assembly portion of the BOM includes prices for a fan, bearings, the rotor aluminum or copper, and the lamination costs. The housing assembly list includes paint, a fan shroud, a base, and the actual housing costs. Much of the hardware costs are fixed and include pricing for washers, capacitor covers (when applicable), mounting bolts, cap screws, thermal switch screws, terminal block screws, terminal cover screws, studs, conduit cap, a start switch (when applicable), a nameplate, as well as some variable costs for start and run capacitors (when applicable). All the lists for the subheadings discussed here represent items from the fixed, variable, and semi-fixed cost sections of the BOM.

5.4.2 Labor Costs and Assumptions

Due to the degree of automation used in manufacturing small electric motors, labor costs are not a significant portion of the overall production cost and do not vary significantly with increasingly efficient designs. The modeling software provides an estimate of the amount of labor associated with each small electric motor design. DOE then multiplies that estimate by a marked up hourly rate to determine the proportion of labor cost associated with the manufacturer's production cost.

DOE used the same hourly labor rate for all motors analyzed. The base hourly rate was developed from the 2002 Economic Census of Industry[2] by the U.S. Census Bureau. Several markups were applied to this hourly rate to obtain a fully burdened rate which was intended to be representative of the labor costs associated with manufacturing these motors. Table 5.4.1 shows the markups that were applied and their corresponding markup percentage and new burdened labor rate.

Table 5.4.1 Labor Markups for Small Electric Motor Manufacturers

Item description	Markup percentage	Rate per hour
Labor cost per hour*		\$ 13.55
Indirect Production**	33 %	\$ 18.02
Overhead***	30 %	\$ 23.43
Fringe†	28 %	\$ 29.99
Assembly Labor Up-time††	43 %	\$ 42.88
Non-Production Mark-up†††	37%	\$ 58.75
Cost of Labor Input to Spreadsheet		**\$ 58.75**

* Cost per hour is from U.S. Census Bureau, *2002 Economic Census of Industry,* published December 2004, Table 5, page 5. Data for NAICS code 3353121 "Fractional Horsepower Motors" Production workers hours and wages.

** Indirect Production Labor (Production managers, quality control, etc.) as a percent of direct labor on a cost basis. Navigant Consulting, Inc. (NCI) estimate.

*** Overhead includes commissions, dismissal pay, bonuses vacation, sick leave, and social security contributions. NCI estimate.

† Fringe includes pension contributions, group insurance premiums, workers compensation. Source: U.S. Census Bureau, *2002 Economic Census of Industry*, published December 2004, Table 3, page 3. Data for NAICS code 335312 "Motors and generator manufacturing," total fringe benefits as a percent of total compensation for all employees (not just production workers).

†† Assembly labor up-time is a factor applied to account for the time that workers are not assembling product and/or reworking unsatisfactory units. The markup of 43 percent represents a 70 percent utilization (multiplying by 100/70). NCI estimate.

††† Non-production markup reflects non-production costs, including sale and general administrative, research and development, interest payments, and profit factor markups. Source: SEC 10-K reports for A.O. Smith, Baldor, Emerson, and Regal-Beloit.

As discussed above, the small electric motor design software provides an estimated manufacturing time for each design. The software apportions the labor time estimates into two categories: fixed and variable components. Similar to the material costs, there are subheadings within these categories that identify the activity or process being carried out, such as stator assembly. Summing the list of process steps gives a final time estimate for manufacturing the motor, which is multiplied by the fully burdened labor cost. Since markups are already applied to the labor rate, no additional markups were applied to the calculated fully burdened labor cost.

In consultation with manufacturers, DOE learned that the amount of time necessary to build a motor with a longer stack or more copper wirings is considered negligible. Therefore, there was only one process step that DOE calculated as a variable labor cost, namely the "Rotor Core Assembly" process. This activity changed to a longer time when the subcontractor's designs called for both a copper rotor and the premium steel, Hiperco 50$^{\mathrm{TM}}$. This change occurs when going from premium plus models to the maximum technology (max tech) models for each set of small electric motor designs.

The remainder and the majority of the labor costs calculated were fixed costs. The following subheadings are associated with the fixed cost labor estimates: stator assembly, rotor assembly, end cap assembly, housing assembly, hardware, and final assembly. The stator assembly list includes time estimates for punching and stacking the laminations, adding slot liner, winding coils, inserting coils, forming end-turns, lead stripping and terminal placement, magnet wire or lead splicing, using the stator test system, and applying the varnish. Adding the fan, machining the shaft, pressing the shaft onto the rotor, balancing the rotor, and heat shrinking bearings onto the shaft are labor steps under the rotor assembly subheading. For end cap assembly there are times for machining the bearing bore at each end, pressing the cap, washing, and performing the die-cast press. The labor times under the hardware section are estimates of adding the components to the motor. Various washers, bolts, studs, screws, grommets for capacitor wire (when applicable), start and/or run capacitors (when applicable), and a start switch (when applicable) are among these hardware components. The last section for fixed labor costs is the final assembly section that includes times for actual assembly, motor testing, labeling and packaging.

5.4.3 Manufacturer Markups

DOE used the three markups described below to account for non-production costs that are part of each motor leaving a manufacturer's facility. Scrap factors, overhead costs, and non-production markups will vary from manufacturer to manufacturer because their profit margins, overheads, prices paid for goods, and business structures vary. DOE prepared estimates for these three non-production cost manufacturer markups from SEC-10K reports and conversations with manufacturers and experts.

- Handling and scrap factor: 2.5 percent markup. This markup was applied to the direct material production costs of each motor. It accounts for the handling of material (loading into assembly or winding equipment) and the scrap material that cannot be used in the production of a finished small electric motor (e.g., lengths of wire too short to wind).

- Factory overhead: 12.5 percent markup. Factory overhead includes all the indirect costs associated with production, indirect materials and energy use, taxes, and insurance. DOE only applies factory overhead to the direct material production costs (including the handling and scrap factor).

- Non-production: 37 percent markup. This markup reflects costs including sales and general administrative, research and development, interest payments, and profit factor. DOE applies the non-production markup to the sum of the direct material production, the direct labor, and the factory overhead. Note that this markup is also shown in Table 5.4.1 and is accounted for in the fully burdened labor rate applied to the labor time estimates.

5.5 RESULTS OF ENGINEERING ANALYSIS

For each of the four motors presented above, DOE developed five designs using a motor design software tool. These included a baseline design and four more efficient designs above the efficiency of the baseline motor. Then by using a consistent methodology and pricing scheme including material and labor costs and manufacturer's markups, DOE developed manufacturer selling prices for the baseline and more efficient motor designs. Throughout this section, DOE will refer to these bottoms-up derived and manufacturer marked-up selling prices as "manufacturer selling prices."

Thus, the engineering analysis results are essentially four manufacturer selling price-versus-efficiency curves that represent the four motors analyzed from the representative equipment classes. The eight graphs shown in Figure 5.5.1 through Figure 5.5.8 provide the manufacturer selling price versus efficiency curves and Table 5.5.1 through Table 5.5.8 present the tabulated results.

5.5.1 Polyphase, 1 Horsepower, 4-Pole, 56-Frame Motor

Figure 5.5.1 presents the relationship between the manufacturer selling price and full-load efficiency for the polyphase motor analyzed. DOE developed a maximum technology (max-tech) design using a non-traditional steel type (i.e., Hiperco 50^{TM}) that makes the motor considerably more expensive than other designs analyzed. Use of this premium electromagnetic steel greatly increases the cost to manufacture a motor and consequently the manufacturer selling price, extending the Y-axis. For this reason, the engineering analysis results are presented twice, first with the max tech design (Figure 5.5.1) and then again without the max tech design (Figure 5.5.2).

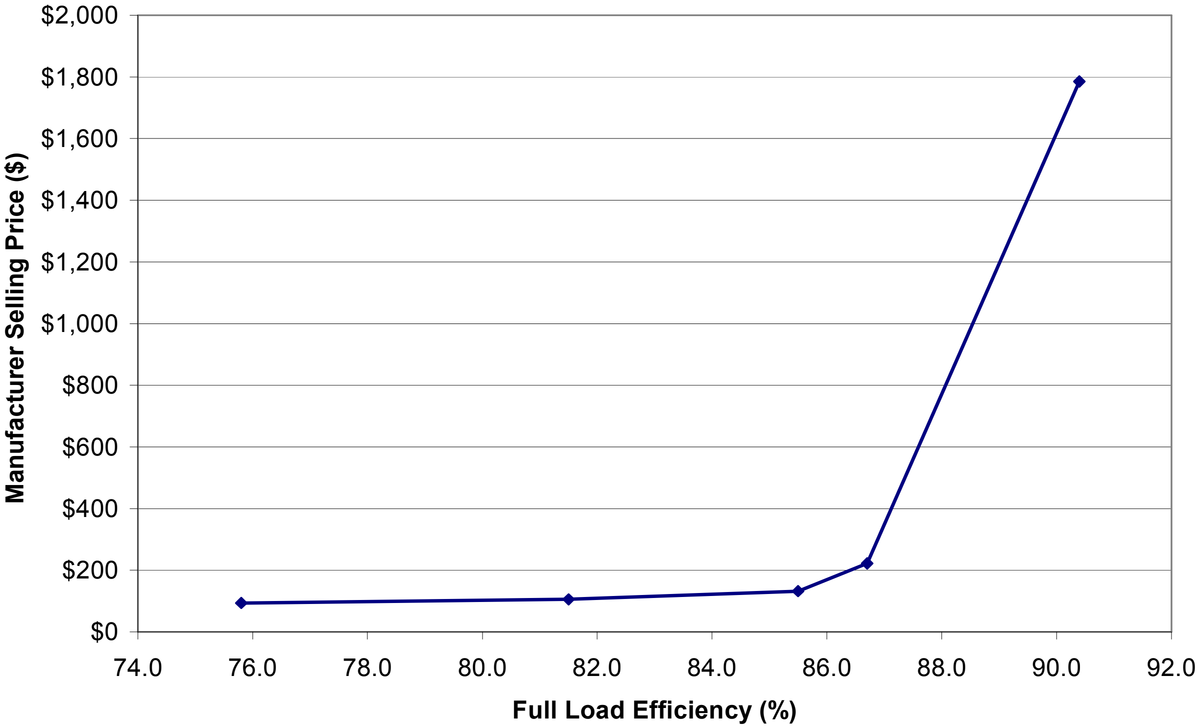


Figure 5.5.1. Polyphase 1 Horsepower, 4-Pole, 56-Frame Motor Engineering Analysis, with Maximum Technology Point

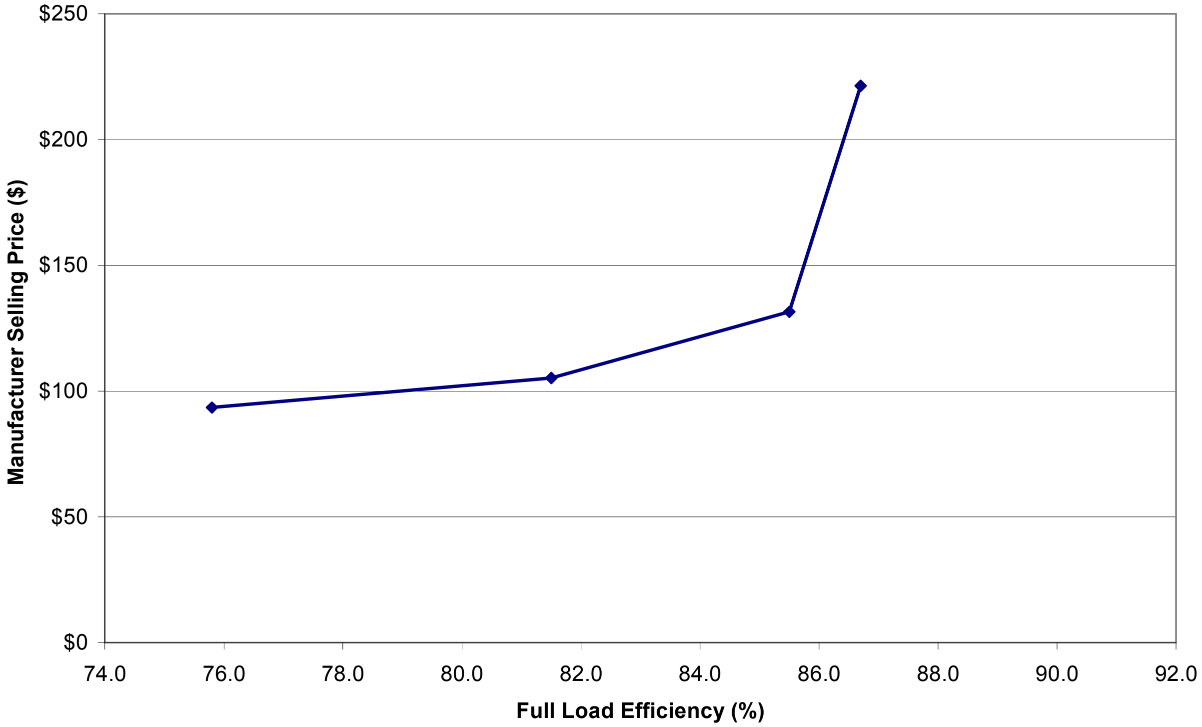


Figure 5.5.2. Polyphase 1 Horsepower, 4-Pole, 56-Frame Motor Engineering Analysis, without Maximum Technology Point

Table 5.5.1 presents the same engineering analysis results in a tabular form, including the full-load efficiency values and the MSPs. Moving from the baseline motor to the premium plus motor, DOE found that the full-load efficiency would increase 10.9 percentage points, for about a 14-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to more than double, increasing from $93.46 for the baseline model to $221.35 for the premium plus motor.

Table 5.5.1. Efficiency and MSP Data for Polyphase Motor

Motor Design	Efficiency (%)	Manufacturer Selling Price ($)
Baseline	75.8 %	$ 93.46
Energy Efficient	81.5 %	$ 105.23
Premium	85.5 %	$ 131.55
Premium Plus	86.7 %	$ 221.35
Max Tech	90.4 %	$ 1,785.49

Table 5.5.2 presents some of the design and performance specifications associated with the five polyphase designs presented above. To convey additional information on a few of these designs, DOE prepared appendix 5A to the preliminary TSD, which presents detailed design and performance specification on one motor design (i.e., the premium motor design) from each of the

representative motors analyzed. For the polyphase motor designs prepared, DOE presents detailed design information on the premium motor design, which is 85.5 percent efficient and has a manufacturer's selling price of $131.55.

Table 5.5.2. Polyphase, 1 Horsepower, 4-Pole, 56-Frame Motor Designs

Parameter	Units	Baseline	Energy Efficient	Premium	Premium Plus	Max Tech
Efficiency	*%*	75.8	81.5	85.5	86.7	90.4
Line Voltage	*V*	230	230	230	230	230
Speed	*RPM*	1714	1703	1709	1719	1729
Torque	*oz-ft*	49.6	51.2	49.8	51.4	48.3
Current	*A*	4.5	4.0	4.0	3.9	3.1
Steel		24M56	24M56	24M19	29M15	Hiperco 50 0.006
Rotor Conductor Material		Aluminum	Aluminum	Aluminum	Copper	Copper
Main Wire	*AWG*	19.0	20.0	19.0	20.5	19.0
Main Wire Weight	*lbs*	2.530	4.250	5.480	5.850	9.584
Rotor Conductor Weight	*lbs*	1.069	1.078	1.174	1.900	4.890
Peak Slot Fill	*%*	32.0	55.0	68.4	74.6	73.9
Locked Rotor Torque	*oz-ft*	125.0	128.0	125.0	127.0	124.0
Locked Rotor Current	*A*	18.5	17.5	17.5	18.6	18.2
Stack Length	*in*	2.75	2.85	3.00	3.00	3.50
Laminations per Stack	*#*	110	114	120	215	584
Housing Weight	*lbs*	6.41	6.50	6.60	6.60	7.56
Slot Liner	in^2	126.186	130.818	137.522	137.522	160.440
Slot Peg	in^2	16.319	16.917	17.795	17.795	20.640

5.5.2 Capacitor-Start, Induction-Run, 1/2 Horsepower, 4-Pole, 56-Frame Motor

Figure 5.5.3 presents the relationship between the MSP and full-load efficiency for the 56-frame capacitor-start, induction-run motor. The max-tech design incorporates a high-grade premium electromagnetic steel alloy that is much more expensive than the high quality electromagnetic steel alloy used in the premium plus (second most efficient) design. Use of such steel greatly increases the MSP of the motor, thereby distorting the Y-axis. For this reason, the engineering analysis results are presented again without the max tech design in Figure 5.5.4.

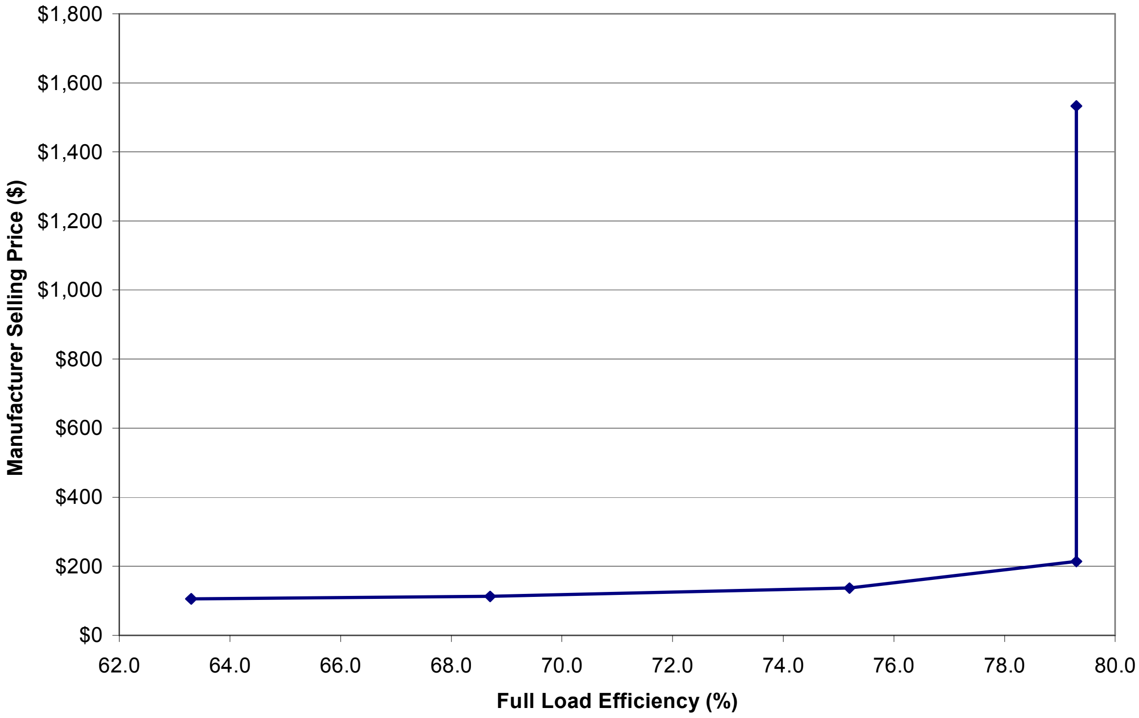


Figure 5.5.3. Capacitor-Start, Induction-Run, ½ Horsepower, 4-Pole, 56-Frame Engineering Analysis Curve, with Maximum Technology Point

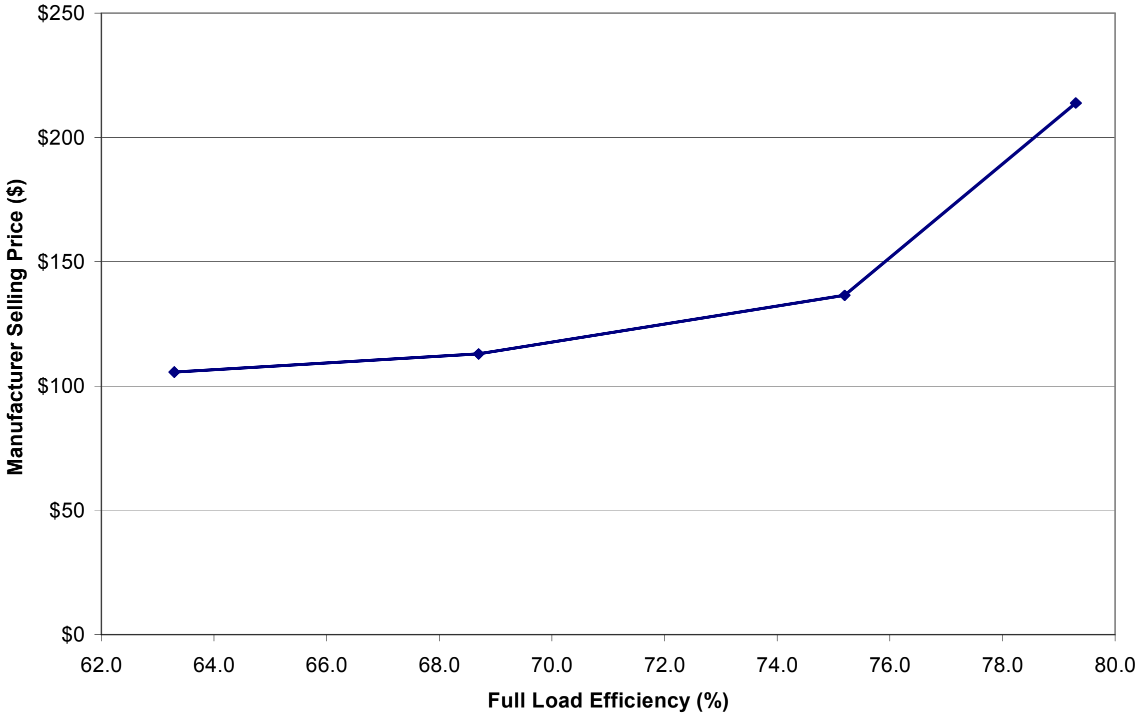


Figure 5.5.4. Capacitor-Start, Induction-Run, ½ Horsepower, 4-Pole, 56-Frame Engineering Analysis Curve, without Maximum Technology Point

Table 5.5.3 presents the same engineering analysis results in a tabular form, including the full-load efficiency values and the MSPs. Moving from the baseline motor to the premium plus motor, DOE found that the full-load efficiency would increase 16 percentage points, for about a 25-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to more than double, increasing from $105.61 for the baseline model to $213.82 for the premium plus motor.

Table 5.5.3. Efficiency and MSP Data for Capacitor-Start, Induction-Run, 56-Frame Motor

Motor Design	Efficiency (%)	Manufacturer Selling Price ($)
Baseline	63.3 %	$ 105.61
Energy Efficient	68.7 %	$ 112.86
Premium	75.2 %	$ 136.51
Premium Plus	79.3 %	$ 213.82
Max Tech	79.3 %	$ 1,532.94

Table 5.5.4 presents some of the design and performance specifications associated with the five CSIR 56-frame designs presented above. DOE also provides additional design detail and performance specifications for the premium motor design in the preliminary TSD, appendix 5A.

Table 5.5.4. Capacitor-Start, Induction-Run, 1/2 Horsepower, 4-Pole, 56-Frame Motor Designs

Parameter	Units	Baseline	Energy Efficient	Premium	Premium Plus	Max Tech
Efficiency	*%*	63.3	68.7	75.2	79.3	79.3
Line Voltage	*V*	115	115	115	115	115
Speed	*RPM*	1727	1727	1727	1760	1760
Torque	*oz-ft*	24.37	24.44	26.41	24.13	24.13
Current	*A*	9.17	7.98	8.48	8.18	8.18
Steel		24M56	24M56	24M19	29M15	Hiperco 50 0.006
Rotor Conductor Material		Aluminum	Aluminum	Aluminum	Copper	Copper
Main Wire	*AWG*	20.5	20	19	19	20
Auxiliary Wire	*AWG*	20.5	20	19.5	19	19
Main Wire Weight	*lbs*	2.586	3.063	3.777	3.777	5.117
Auxiliary Wire Weight	*lbs*	0.955	1.101	1.327	1	1.068
Rotor Conductor Weight	*lbs*	0.723	1.06	1.09	1.71	2.67
Start Capacitor	*μF*	300	300	300	450	450
Peak Slot Fill	*%*	58.82	65.97	74.95	74.12	74.7
Locked Rotor Torque	*oz-ft*	85	85.2	87.08	90.22	93.78
Locked Rotor Current	*A*	36.1	34.6	37.5	41.16	38
Stack Length	*in*	2	2.3	2.6	2.6	3
Laminations per Stack	*#*	80	92	104	186	500
Housing Weight	*lbs*	6.1	6.15	6.3	6.3	7.245
Slot Liner	in^2	91.71	105.56	119.17	119.17	137.3
Slot Peg	in^2	11.86	13.66	15.42	15.42	17.71

5.5.3 Capacitor-Start, Induction-Run, 1/2 Horsepower, 4-Pole, 48-Frame Motor

Figure 5.5.5 presents the relationship between the MSP and full-load efficiency for the 48-frame capacitor-start, induction-run motor. The max-tech design incorporates a high-grade premium electromagnetic steel alloy that is much more expensive than the high quality electromagnetic steel alloy used in the premium plus (second most efficient) design. Use of such steel greatly increases the MSP of the motor, thereby the Y-axis. For this reason, the engineering analysis results are presented again without the max tech design in Figure 5.5.6.

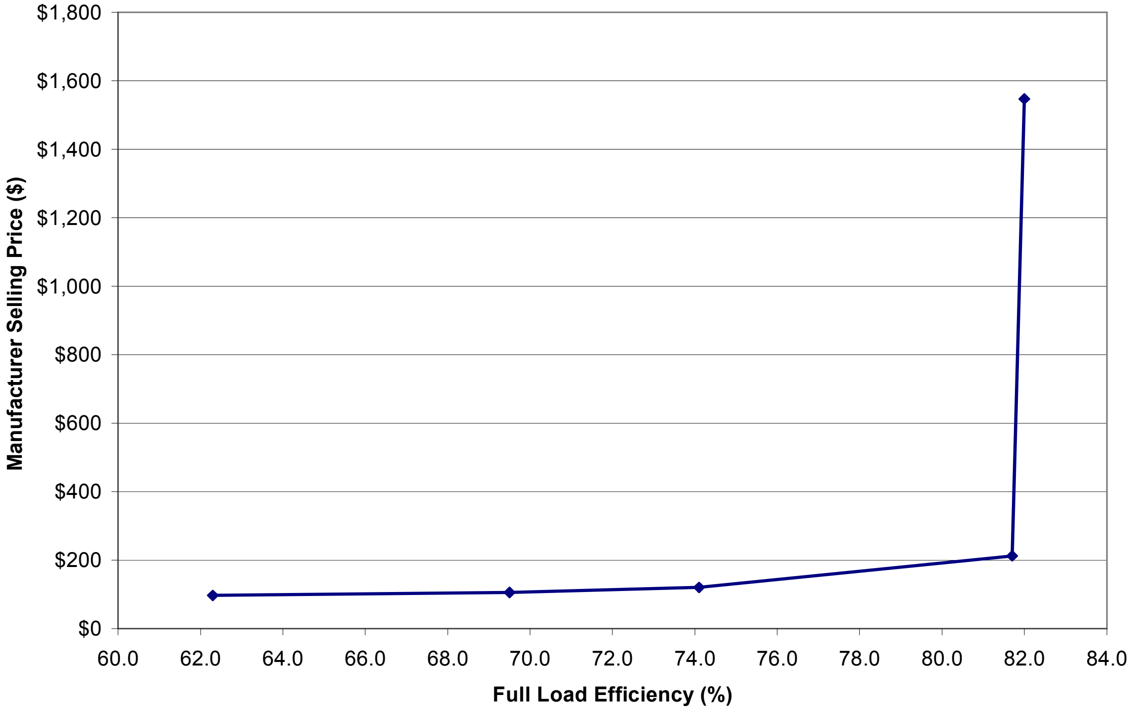


Figure 5.5.5. Capacitor-Start, Induction-Run, ½ Horsepower, 4-Pole, 48-Frame Engineering Analysis Curve, with Maximum Technology Point

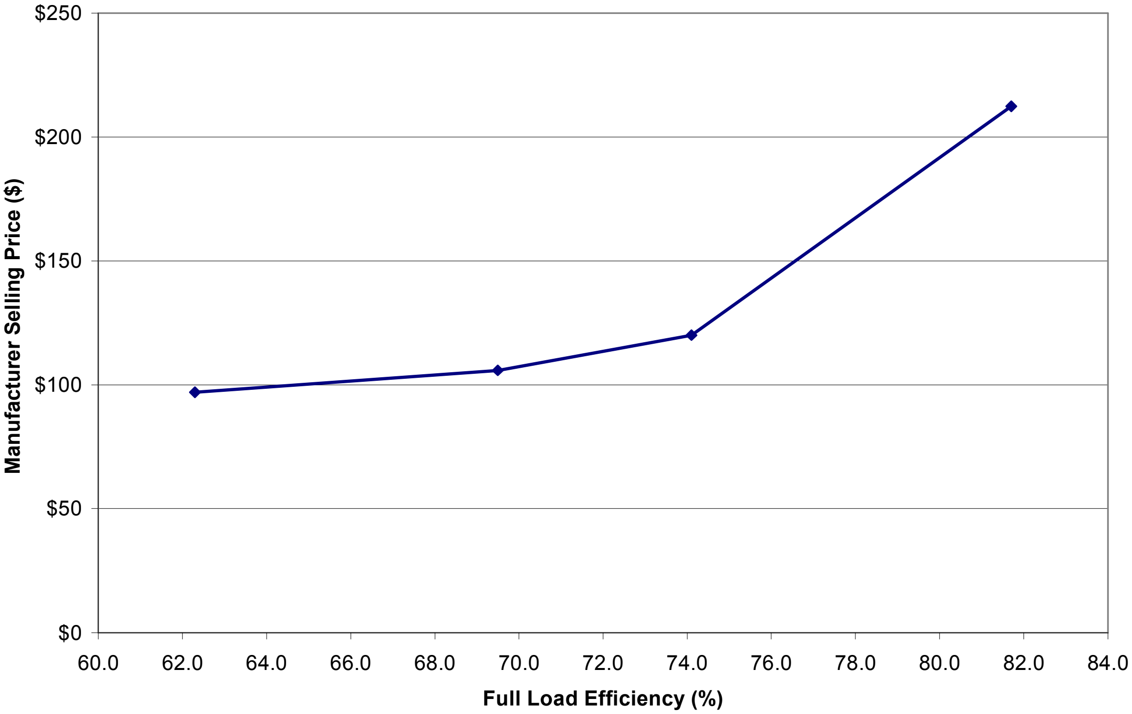


Figure 5.5.6. Capacitor-Start, Induction-Run, ½ Horsepower, 4-Pole, 48-Frame Engineering Analysis Curve, without Maximum Technology Point

Table 5.5.5 presents the same engineering analysis results in a tabular form, including the full-load efficiency values and the MSPs. Moving from the baseline motor to the premium plus motor, DOE found that the full-load efficiency would increase 19.4 percentage points, for about a 31-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to more than double, increasing from $96.97 for the baseline model to $212.40 for the premium plus motor.

Table 5.5.5. Efficiency and MSP Data for Capacitor-Start, Induction-Run, 48-Frame Motor

Motor Design	Efficiency (%)	Manufacturer Selling Price ($)
Baseline	62.3 %	$ 96.97
Energy Efficient	69.5 %	$ 105.79
Premium	74.1 %	$ 120.00
Premium Plus	81.7 %	$ 212.40
Max Tech	82.0 %	$ 1,547.11

Table 5.5.6 presents some of the design and performance specifications associated with the five CSIR 48-frame designs presented above. DOE also provides additional design detail and performance specifications for the premium motor design in appendix 5A of the preliminary TSD.

Table 5.5.6. Capacitor-Start, Induction-Run, 1/2 Horsepower, 4-Pole, 48-Frame Motor Designs

Parameter	Units	Baseline	Energy Efficient	Premium	Premium Plus	Max Tech
Efficiency	*%*	62.3	69.5	74.1	81.7	82.0
Line Voltage	*V*	115	115	115	115	115
Speed	*RPM*	1737	1736	1738	1765	1743
Torque	*oz-ft*	24.2	24.4	24.2	24.2	24.2
Current	*A*	9.0	8.1	8.1	7.3	6.7
Steel		24M56	24M56	24M19	29M15	Hiperco 50 0.006
Rotor Conductor Material		Aluminum	Aluminum	Aluminum	Copper	Copper
Main Wire	*AWG*	19.5	20.5	20.5	20.0	20.5
Auxiliary Wire	*AWG*	20.0	20.0	20.0	21.5	21.5
Main Wire Weight	*lbs*	1.561	2.591	2.636	3.114	4.498
Auxiliary Wire Weight	*lbs*	0.916	0.957	0.974	1.155	1.262
Rotor Conductor Weight	*lbs*	0.645	0.675	0.688	2.392	3.990
Start Capacitor	*µF*	300	300	300	440	440
Peak Slot Fill	*%*	49.0	72.2	72.2	74.9	74.6
Locked Rotor Torque	*oz-ft*	85.3	89.2	90.1	84.1	114.3
Locked Rotor Current	*A*	35.1	34.3	34.4	45.2	42.2
Stack Length	*in*	2.65	2.90	3.00	3.40	4.00
Laminations per Stack	#	106	116	120	243	667
Housing Weight	*lbs*	4.70	4.90	5.00	5.50	6.65
Slot Liner	in^2	121.440	133.008	137.575	155.920	188.990
Slot Peg	in^2	15.710	17.211	17.802	20.177	24.410

5.5.4 Capacitor-Start, Capacitor-Run, 3/4 Horsepower, 4-Pole, 56-Frame Motor

Figure 5.5.7 presents the relationship between the MSP and full-load efficiency for the CSCR motor. The max-tech design incorporates a high-grade premium electromagnetic steel alloy that is much more expensive than the high quality electromagnetic steel alloy used in the premium plus (second most efficient) design. Use of such steel greatly increases the MSP of the motor, thereby distorting the Y-axis. For this reason, the engineering analysis results are presented again without the max tech design in Figure 5.5.8.

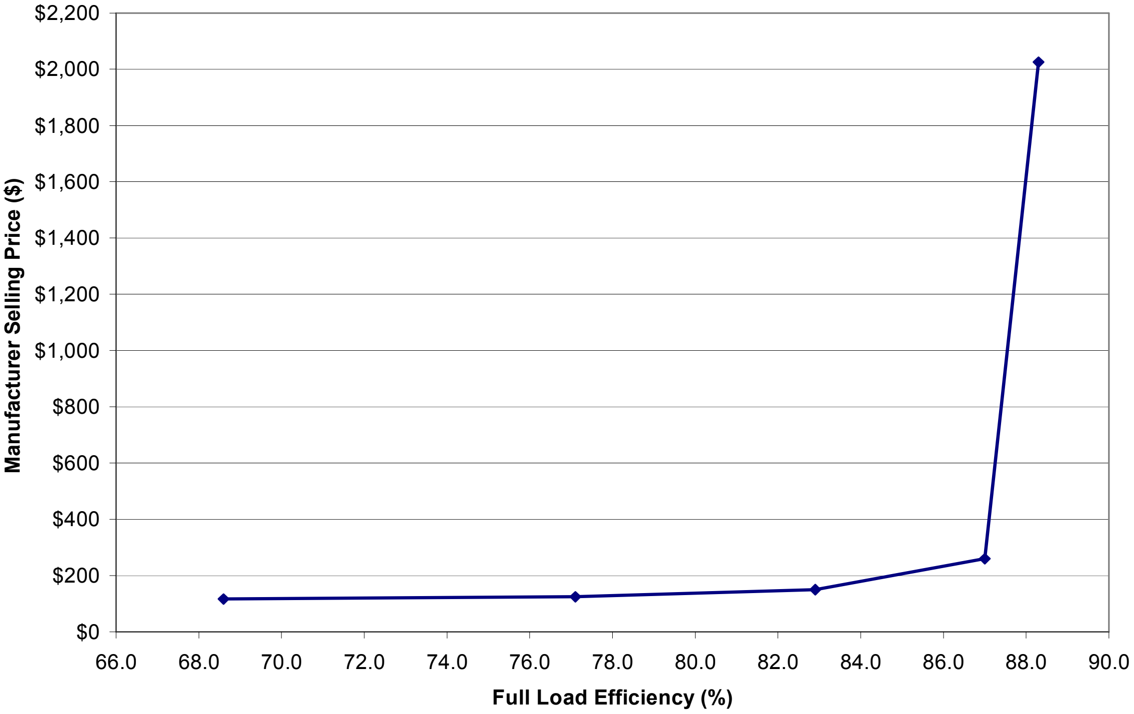


Figure 5.5.7. Capacitor-Start, Capacitor-Run ¾ Horsepower, 4-Pole, 56-Frame Engineering Analysis Curve, with Maximum Technology Point

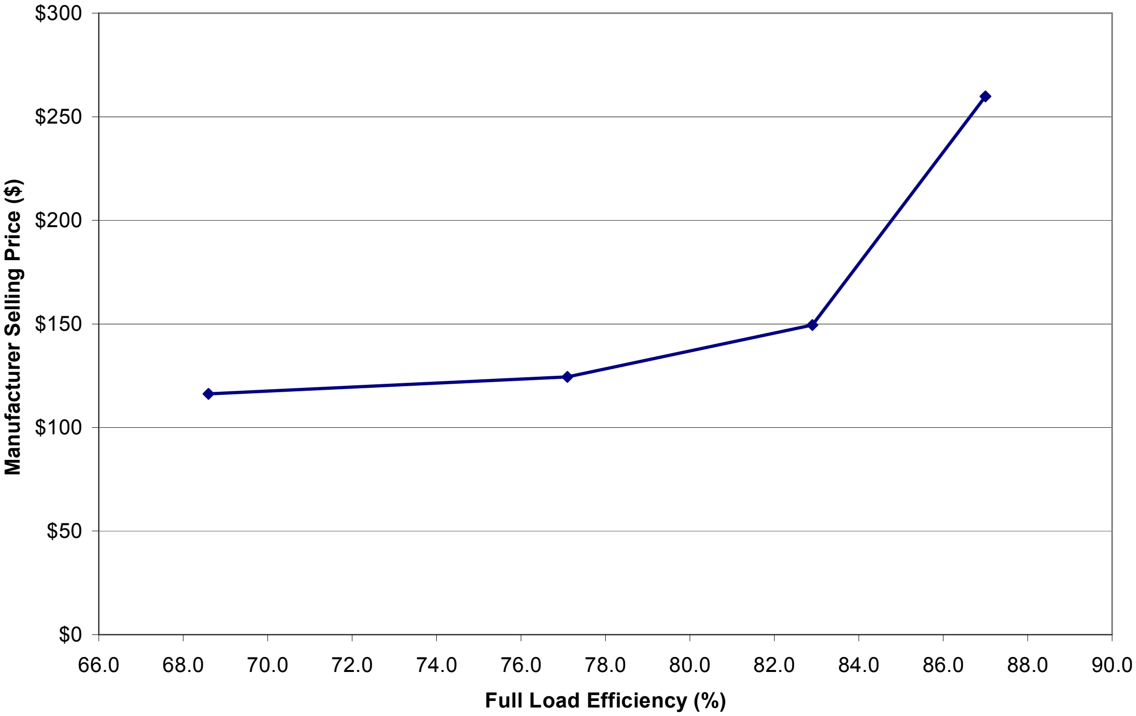


Figure 5.5.8. Capacitor-Start, Capacitor-Run ¾ Horsepower, 4-Pole, 56-Frame Engineering Analysis Curve, without Maximum Technology Point

Table 5.5.7 presents the same engineering analysis results in tabular form, including the full-load efficiency values and the MSPs. Moving from the baseline motor to the premium plus motor, DOE found that the full-load efficiency would increase 18.4 percentage points, for about a 27-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to more than double, increasing from $116.17 for the baseline model to $259.78 for the premium plus motor.

Table 5.5.7. Efficiency and MSP Data for Capacitor-Start, Capacitor-Run Motor

Motor Design	Efficiency (%)	Manufacturer Selling Price ($)
Baseline	68.6 %	$ 116.17
Energy Efficient	77.1 %	$ 124.33
Premium	82.9 %	$ 149.50
Premium Plus	87.0 %	$ 259.78
Max Tech	88.3 %	$ 2,024.82

Table 5.5.8 presents some of the design and performance specifications associated with the five CSCR designs presented above. DOE also provides additional design detail and performance specifications for the premium motor design in the preliminary TSD, appendix 5A.

Table 5.5.8. Capacitor-Start, Capacitor-Run, 3/4 Horsepower, 4-Pole, 56-Frame Motor

Parameter	Units	Baseline	Energy Efficient	Premium	Premium Plus	Max Tech
Efficiency	*%*	68.6	77.1	82.9	87.0	88.3
Line Voltage	***V***	115	115	115	115	115
Speed	***RPM***	1725	1732	1735	1759	1745
Torque	***oz-ft***	36.4	37.6	36.6	36.4	35.9
Current	***A***	11.6	8.7	7.6	7.3	6.3
Steel		24M56	24M56	24M19	29M15	Hiperco 50 0.006
Rotor Conductor Material		Aluminum	Aluminum	Aluminum	Copper	Copper
Main Wire	***AWG***	20.5	19.5	19.0	20.0	19.0
Auxiliary Wire	***AWG***	20.0	20.0	21.5	20.0	20.0
Main Wire Weight	***lbs***	2.201	2.937	3.354	4.124	5.745
Auxiliary Wire Weight	***lbs***	0.741	0.699	1.104	1.495	1.614
Rotor Conductor Weight	***lbs***	0.778	1.123	1.136	2.242	3.516
Start Capacitor	***μF***	550	550	400	550	550
Run Capacitor	***μF***	20	45	50	50	50
Peak Slot Fill	*%*	44.7	55.7	61.6	74.2	71.7
Locked Rotor Torque	***oz-ft***	119.4	119.2	126.7	129.9	156.4
Locked Rotor Current	***A***	51.2	46.9	39.7	53.3	52.1
Stack Length	***in***	2.60	2.95	3.10	3.30	4.00
Laminations per Stack	#	104	118	124	236	667
Housing Weight	***lbs***	6.10	6.15	6.30	6.50	7.86
Slot Liner	in^2	119.168	135.261	142.164	151.220	183.030
Slot Peg	in^2	14.904	17.503	18.396	19.567	23.660

5.6 SCALING RELATIONSHIPS

In order to reduce the analytical burden associated with conducting a detailed engineering analysis of the cost-efficiency relationship on all 72 equipment classes, DOE developed an analytical approach that reduced the number of small electric motors it analyzed while retaining reasonable levels of accuracy. DOE selected one baseline model from each motor category to evaluate in the engineering and the life-cycle cost analysis (see preliminary TSD chapter 8). It then extrapolated the results of this analysis from the unit studied to the other equipment classes. This section describes the methodology DOE followed to develop equations and constants that would enable scaling of analytical results to equipment classes that were not analyzed.

5.6.1 Interpolation of Cost-Efficiency Points

The subcontractor's small electric motor designs are a series of points that describe the relationship between MSP and efficiency. These results are presented in Figure 5.5.1 through Figure 5.5.8 in this chapter. This analysis provides a series of discrete points for each of the motors, but does not necessarily describe the shape of the MSP-efficiency curve in between these points. Due to the fact that the efficiency levels across the various equipment classes may not coincide with the precise efficiency values of the subcontractor's motor designs, DOE needed to develop an approach for interpolating the MSP-efficiency curve between the actual designs.

DOE considered two interpolation approaches, linear interpolation and power law interpolation. Linear interpolation is simply a straight line connecting the discrete cost-efficiency points for each motor design. This approach holds the MSP-efficiency slope constant between each pair of points, and therefore may overestimate MSP for a given interpolated efficiency level. The power law interpolation technique generates a MSP-efficiency curve between each set of points that more closely resembles that of the overall curve. That is, the power law curve results in a better fit of the data and therefore a more accurate representation of the MSP at any interpolated efficiency value. The following equations describe power law interpolation between two points (X_1, Y_1) and (X_2, Y_2) to point (X, Y):

- $Y = Y_1 \times (X / X_1)^P$
- where $P = (\ln(Y_2) - \ln(Y_1)) / (\ln(X_2) - \ln(X_1))$

The following figure presents the difference between the linear and power law interpolation for a section of the small polyphase electric motor analysis. DOE selected the power law interpolation technique for all the representative models analyzed.

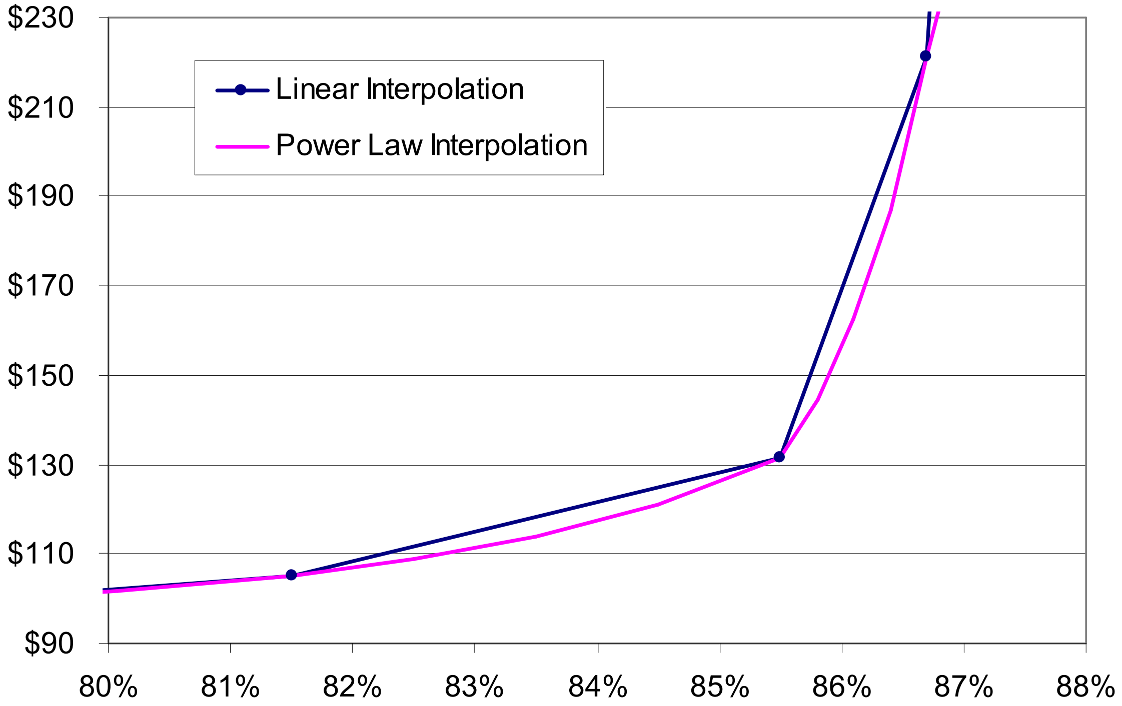


Figure 5.6.1 Polyphase Motor Designs with Interpolated Curve Fits

5.6.2 Motor Losses

After DOE determined the method it would use to interpolate between individual small electric motor designs, DOE developed an approach to scale motor losses between equipment classes. The first step DOE took to develop scaling relationships was creating a model that describes motor losses as a function of the motor's rated horsepower. To do this, DOE examined the standards adopted by the Energy Independence and Security Act of 2007 (EISA). For polyphase, general-purpose motors, built in a three digit frame size, EISA adopted the NEMA Premium Standards, shown in NEMA MG 1-2006 in Table 12-12, as the minimum efficiency levels. This table has standards for motors ranging in horsepower from 1 to 200 horsepower, in two-, four-, and six-pole configurations, and in open and enclosed constructions. DOE plotted this data in two ways to observe any trends:

- Delta (defined as 100 – efficiency level) versus horsepower and
- Delta as a percentage of rating (or (100 – efficiency level)/efficiency level) versus horsepower

If plotted on logarithmic scales, DOE observed that as horsepower increased, delta decreased following a power law function, as shown in Figure 5.6.2. The power law for this particular function is that delta scales according to a negative 0.25 exponent as horsepower increases. That is:

- $Delta(hp) = C \times hp^{-0.25}$, where *C* is a constant for a particular pole configuration and motor category combination

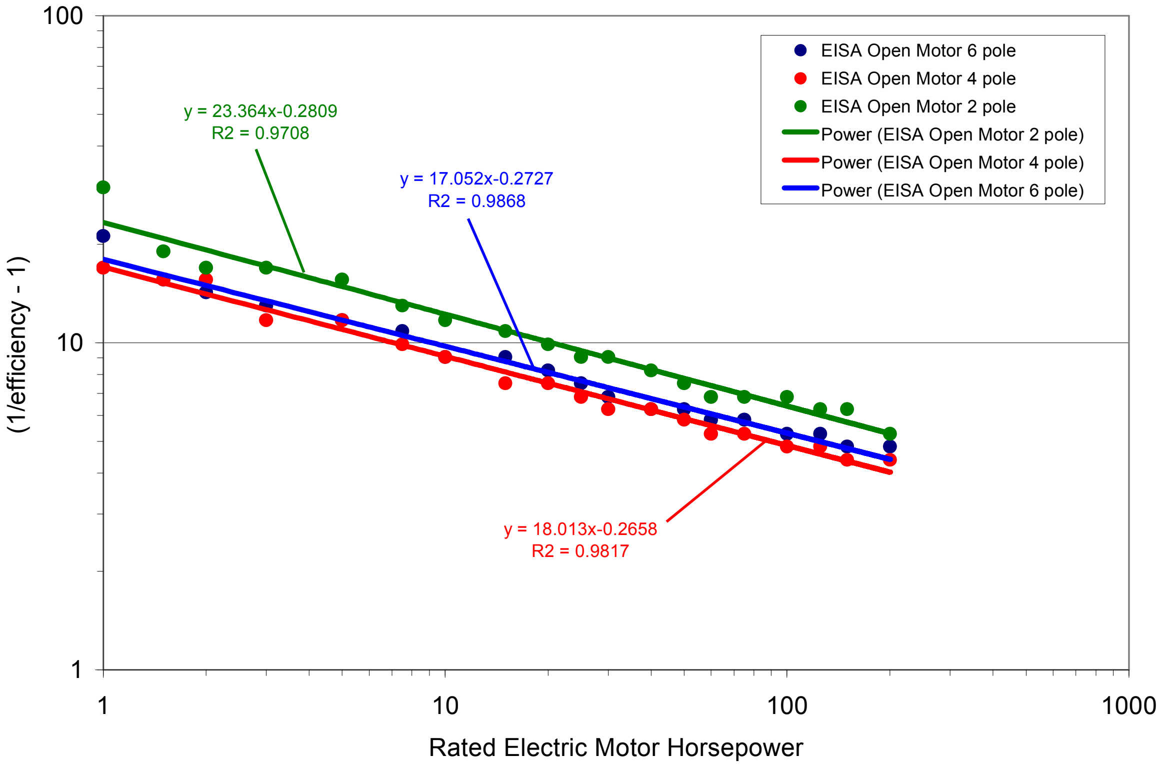


Figure 5.6.2 Function of Delta with Horsepower for 1-200 Horsepower,Energy Independence and Security Act of 2007 Efficiency Standards

5.6.3 Candidate Standard Levels

DOE uses candidate standard levels (CSLs) as incremental units of analysis in the life-cycle cost assessment (see preliminary TSD chapter 8) and the national impacts analysis (see preliminary TSD chapter 10). In order to develop appropriate CSLs for small electric motors, DOE used the trends observed in its analysis of the EISA standard levels. The EISA standards that reference Table 12-12 of NEMA MG 1-2006 are for polyphase motors. Therefore, DOE used the EISA 2007 efficiency standard for 1 hp, four-pole, open construction motors as a basis for selecting CSLs for the 1 hp, four-pole polyphase motor examined for this engineering analysis. The EISA 2007 standard, which is the NEMA Premium level, is 85.5 percent for 1 hp, four-pole, open construction motors. DOE wanted to have at least one analysis evaluation point below this level, therefore it selected an efficiency rating of 84.0 percent for CSL1. From there, four more CSLs were chosen at increasing efficiency ratings, up to a level near the maximum technology efficiency level of the polyphase motor analyzed. The efficiency values were spaced across the efficiency continuum for the polyphase motor analyzed in order to ensure DOE conducted economic analysis across a well distributed range of efficiency values. The efficiency values selected are shown in Table 5.6.1 below, along with the CSL's for the CSIR and CSCR equipment classes that were analyzed. CSL2 was selected as the efficiency rating approximately equivalent to the EISA 2007 level for 1-200 horsepower motors (i.e., the NEMA Premium level).

Table 5.6.1 Candidate Standard Levels for Equipment Classes Analyzed

Candidate Standard Level	Polyphase, 56 Frame 4-pole, 1 hp	CSIR, 48 Frame, 4-pole, 0.5 hp	CSCR, 56 Frame, 4-pole, 0.75 hp
CSL 1	84.0%	70.8%	80.2%
CSL 2	85.5%	73.6%	82.0%
CSL 3	86.5%	75.4%	83.3%
CSL 4	88.0%	78.1%	85.1%
CSL 5	90.0%	81.8%	87.6%

Besides scaling the candidate standard levels for the 1 hp, four-pole polyphase small electric motor to appropriate levels for CSIR and CSCR motors, DOE also needed to scale to other horsepower levels and pole configurations for polyphase small electric motors. These relationships are derived using the above power law equation and the following equation:

$$Efficiency(hp) = 100\% - Delta(hp)$$

Consider the following sets of equations which describe four-pole, polyphase motors, where hp is 1 horsepower level (in our case it is 1) and hp’ is the level being scaled to:

1. $Efficiency(hp) = 100\% - Delta(hp) \Leftrightarrow Delta(hp) = 100\% - Efficiency(hp)$

2. $Delta(hp) = C \times hp^{-0.25}$

3. $Efficiency(hp') = 100\% - Delta(hp') \Leftrightarrow Delta(hp') = 100\% - Efficiency(hp')$

4. $Delta(hp') = C \times hp'^{-0.25}$

Since these equations describe the same set of motors (four-pole, polyphase), C is the same for equations 2 and 4. Solving for C and setting equal gives the following:

5. $\dfrac{Delta(hp)}{hp^{-0.25}} = \dfrac{Delta(hp')}{hp'^{-0.25}}$

Equation 5 can be manipulated to obtain the following description of delta:

6. $Delta(hp') = Delta(hp)\dfrac{hp'^{-0..25}}{hp^{-0.25}} = Delta(hp)(\dfrac{hp'}{hp})^{-0.25}$

At this point, a substitution can be made into equation 3 to give:

7. $Efficiency(hp') = 100\% - Delta(hp)(\frac{hp'}{hp})^{-0.25}$

As previously discussed, DOE chose CSL's for a 1 hp polyphase small electric motor. Therefore, it is possible to scale these CSL's to corresponding CSL's for other horsepowers of four-pole polyphase small electric motors by substituting equation 1 in for *Delta(hp)* and plugging in 1 for hp. These substitutions give:

8. $Efficiency(hp') = 100\% - (100\% - Efficiency(1)) \times (hp')^{-0.25}$, where *Efficiency(1)* is the efficiency rating for a CSL level at 1 horsepower and *Efficiency(hp')* is the corresponding CSL level at a different horsepower level.

Equations similar to 1 through 4 can be manipulated to obtain equations that relate scaling from four-pole, polyphase small electric motors to other equipment classes. To do this though, DOE assumes that the negative 0.25 scaling rule derived for polyphase small electric motors also applies to small CSIR and CSCR motors. Note that DOE found that this rule does apply to different pole configurations.

The only change that would be made to the original set of equations (1-4) would be a change to equation 4. The change would result in the following equation:

4*. $Delta(hp') = C' \times hp'^{-0.25} = K \times C \times hp'^{-0.25}$

In this equation C' is a variable that represents a factor of change relative to 4-pole polyphase motors. The equation is rewritten where K is a multiplier used to describe the relative changes in terms of C. Rewriting the equation in terms of C allows DOE to follow the previously described steps and obtain an equation similar to 8, but with the variable K:

9. $Efficiency(hp') = 100\% - K \times (100\% - Efficiency(1)) \times (hp')^{-0.25}$

K changes depending on the change in equipment class. For example, K can describe a change in the number of poles, a change in motor category, or a change in both. Therefore, K will have different values.

To obtain values of K for the motors analyzed, DOE used the cost-efficiency data developed in the engineering analysis and equation 9 above. DOE chose a CSL close to the max tech efficiency found for the CSIR and CSCR motors. This value was plugged into equation 9 along with CSL5 for four-pole polyphase small electric motors and the corresponding horsepower for the small CSIR or CSCR motors. From there, the equation could be solved for K. For CSIR, four-pole motors, K was found to be 1.53 and for CSCR, four-pole motors K was found to be 1.15. With the value of K found, the other CSL's (1 through 4) for four-pole polyphase motors, which DOE selected, were plugged into equation 9 to obtain corresponding CSL's for the other two motor categories. These values are shown above in Table 5.6.1.

The K values for polyphase small electric motors, two- and six-pole motors were obtained by examining the trend line differences between two-, four-, and six-pole motors. A ratio of the coefficient in the power equations describing the three sets of data gave the K value for changing from four- to two-pole or four- to six-poles. The K value for changing to a two-pole polyphase motor was found as 1.37 and for changing to a six-pole polyphase motor it was found to be 1.06. When changing poles and motor category, the resulting K value is a product of the K values found for changing the motor category and the number of poles.

There are a total of 9 values for the constant K to be calculated, which are presented in Table 5.6.2. This provides the K values derived dependant on the motor category and number of poles.

Table 5.6.2 Matrix of K Values used for Scaling Candidate Standard Levels

	Polyphase	**CSIR**	**CSCR**
6 Poles	1.06	1.62	1.21
4 Poles	1.00	1.53	1.15
2 Poles	1.37	2.10	1.58

DOE presents values for CSL1 at all equipment classes in Table 5.6.3 through Table 5.6.5. This serves as an example of how equation 9 and the derived K values are used to extrapolate CSL1 (shown in Table 5.6.1) to all 72 equipment classes.

Table 5.6.3 Candidate Standard Level 1 for Polyphase Small Electric Motors

Horsepower	**6 Poles**	**4 Poles**	**2 Poles**
¼ hp (0.18 kW)	76.0%	77.3%	68.9%
$^1/_3$ hp (0.25 kW)	77.7%	78.9%	71.1%
½ hp (0.37 kW)	79.9%	80.9%	73.9%
¾ hp (0.55 kW)	81.8%	82.8%	76.4%
1 hp (0.75 kW)	83.0%	84.0%	78.0%
1½ hp (1.1 kW)	84.7%	85.5%	80.1%
2 hp (1.5 kW)	85.7%	86.5%	81.5%
≥3 hp (2.2 kW)	87.1%	87.8%	83.3%

Table 5.6.4 Candidate Standard Level 1 for Capacitor-Start, Induction-Run Small Electric Motors

Horsepower	6 Poles	4 Poles	2 Poles
¼ hp (0.18 kW)	63.4%	65.3%	52.5%
⅓ hp (0.25 kW)	65.9%	67.7%	55.8%
½ hp (0.37 kW)	69.2%	70.8%	60.1%
¾ hp (0.55 kW)	72.2%	73.6%	63.9%
1 hp (0.75 kW)	74.1%	75.5%	66.4%
1½ hp (1.1 kW)	76.6%	77.8%	69.6%
2 hp (1.5 kW)	78.2%	79.4%	71.7%
≥3 hp (2.2 kW)	80.3%	81.3%	74.5%

Table 5.6.5 Candidate Standard Level 1 for Capacitor-Start, Capacitor-Run Small Electric Motors

Horsepower	6 Poles	4 Poles	2 Poles
¼ hp (0.18 kW)	72.5%	73.9%	64.3%
⅓ hp (0.25 kW)	74.4%	75.7%	66.8%
½ hp (0.37 kW)	76.8%	78.1%	70.0%
¾ hp (0.55 kW)	79.1%	80.2%	72.9%
1 hp (0.75 kW)	80.5%	81.6%	74.7%
1½ hp (1.1 kW)	82.4%	83.3%	77.2%
2 hp (1.5 kW)	83.6%	84.5%	78.8%
≥ 3 hp (2.2 kW)	85.2%	86.0%	80.8%

REFERENCES

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[1] Design Considerations to Optimize Stator Manufacturing, Alliance Winding Equipment, Inc., Ft. Wayne, Indiana. Blade-Gap Chart.

[2] U.S. Census Bureau, 2002 Economic Census of Industry Series Reports for Industry, US Department of Commerce, 2003.