CHAPTER 5. ENGINEERING ANALYSIS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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 Security Act
M*	M15, M19, M56 - grade of core steel
MSP	Manufacturer Selling Price
MPC	Manufacturer Production Cost
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 Technical Support Document (TSD) chapter 8) as well as the national impact analysis (see TSD chapter 10).

As discussed in chapter 3 of this 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 number series. 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 TSD chapter 3) and the screening analysis (see TSD chapter 4). These inputs include product 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 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 TSD chapter 7) and used as a critical input to the customer's life-cycle cost and payback period analysis (see 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. DOE has quantified the additional costs manufacturers would incur when complying with mandatory efficiency standards using the design specifications outlined in this chapter. For a discussion of those costs and DOE's methodology for quantifying them, see TSD chapter 12, the manufacturer impact analysis.

In this chapter, DOE discusses the product 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 product classes for the national impact analysis.

5.2 PRODUCT CLASSES AND BASELINE MOTORS ANALYZED

Due to the large number of product classes, DOE did not directly analyze all covered motors. Instead, DOE selected representative units from the 61 product classes of small electric motors based on three factors: (1) the motors that were studied in the determination and preliminary analyses, (2) manufacturer's sales catalogs for this equipment, and (3) the ability to scale from these units to other units.

5.2.1 Product Classes Analyzed

In the determination analysis, DOE studied five different motors as the representative units. Two of the motors were capacitor-start, induction-run and three were polyphase. For the capacitor-start, induction-run motors, DOE chose two similar models with 56 and 48 frame series to capture different cost-efficiency characteristics associated with frame series. For the polyphase motors, DOE chose three models, holding frame series constant, but varying the horsepower for two motors. The five motors studied in the determination analysis are presented in Table 0.1.

Table 0.1.Representative Units Selected for the Determination Analysis

Motor Category	Model	Horsepower	Number of Poles	Frame series
CSIR	Dayton 4K856	0.50	4	56
CSIR	Dayton 6K965	0.50	4	48
Polyphase	Dayton 3N641	0.50	4	56
Polyphase	Dayton 2N103	0.50	4	56
Polyphase	Dayton 3N102	1.0	4	56

In the preliminary analysis engineering analysis, DOE studied four motors: two CSIR motors, one CSCR motor, and one polyphase motor. The two CSIR motors analyzed had the same pole configuration and horsepower ratings, but were built in different frame series. The CSCR and polyphase motors were at incremental horsepower ratings above the two CSIR motors. The four motors studied in the preliminary analysis are presented in Table 0.2.

Table 0.2. Representative Units Selected for the Preliminary Analysis

Motor Category	Horsepower	Number of Poles	Frame series
CSIR	0.50	4	48
CSIR	0.50	4	56
CSCR	0.75	4	56
Polyphase	1.0	4	56

In the Notice of Proposed Rulemaking (NOPR) engineering analysis, DOE studied three motors: one CSIR motor, one CSCR motor, and one polyphase motor. These were the same motors as studied in the preliminary analysis, but DOE did not continue to examine the 56 frame CSIR motor in the NOPR. Each of the three motors had a four-pole configuration, and were at incremental horsepower ratings of 0.50 for the CSIR motor, 0.75 for the CSCR motor, and 1.0 for the polyphase motor. The three motors studied in the NOPR analysis are presented in Table 0.3. DOE maintained the same baseline units for the final rule analysis as used in the NOPR analysis.

Table 0.3 Representative Units Selected for the Notice of Proposed Rulemaking Analysis

Motor Category	Horsepower	Number of Poles	Frame series
CSIR	0.50	4	48
CSCR	0.75	4	56
Polyphase	1.0	4	56

As mentioned, DOE also reviewed manufacturer catalogs. Also, DOE created a database of over 700 models that represent all the small electric motors manufactured and listed in the catalogs. Although this database does not provide information on unit sales, it does provide an indication of the more popular motors from the standpoint of having a greater variety of certain combinations of horsepower and frame series. Analyzing this data and shipments data enabled DOE to select popular configurations of small electric motors.

Figure 0.1 through Figure 0.9 show shipments data for each motor category broken down by pole configuration and horsepower, as well as the number of models of each motor category broken down by horsepower

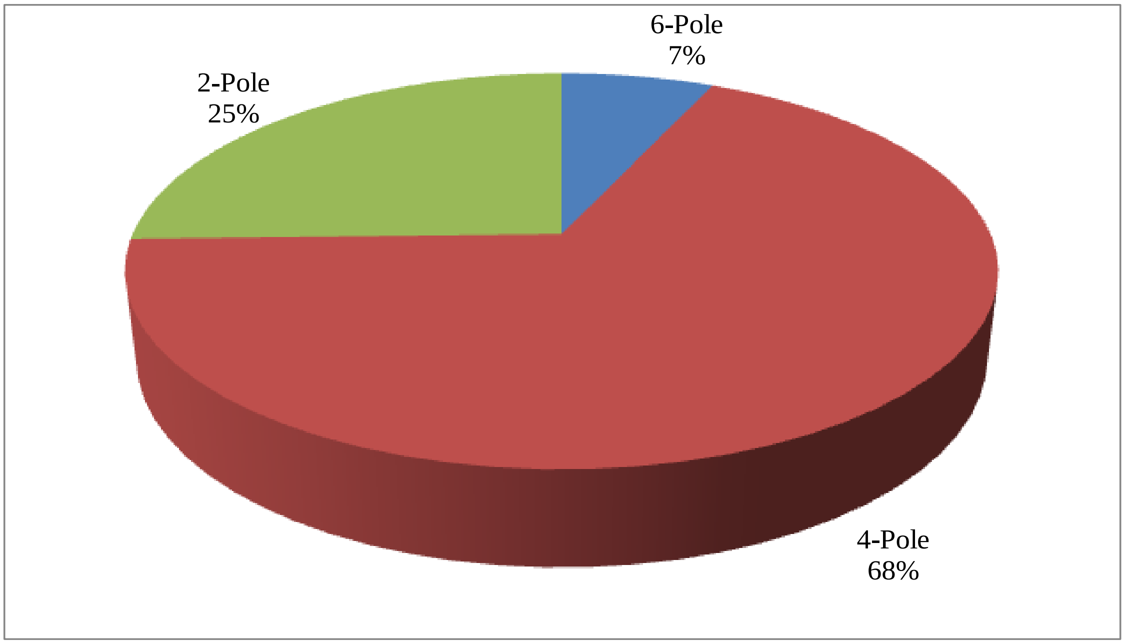

Figure 0.1. Polyphase Small Electric Motor Shipments Broken Down by Pole Configuration

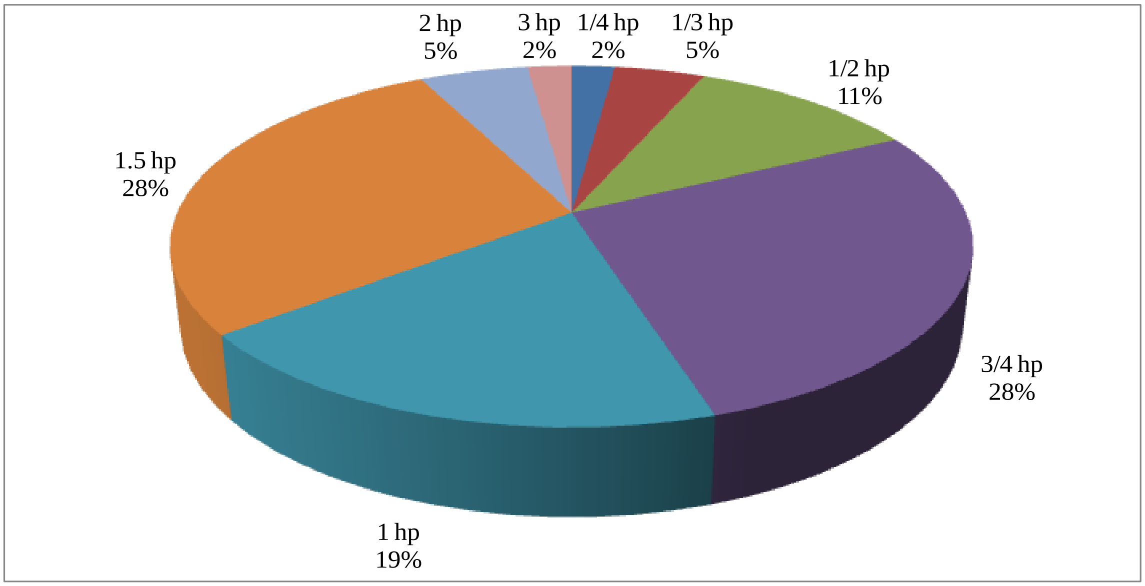

Figure 0.2. Polyphase Small Electric Motor Shipments Broken Down by Horsepower

Figure 0.1 and Figure 0.2 are based on projected shipments data for the National Impacts Analysis (see chapter 6 for more detail on the development of these data). They show the breakdown of shipments by pole configuration and horsepower. An overwhelming majority of polyphase motors shipped are four-pole machines and the weighted average horsepower of shipments is 1 horsepower.

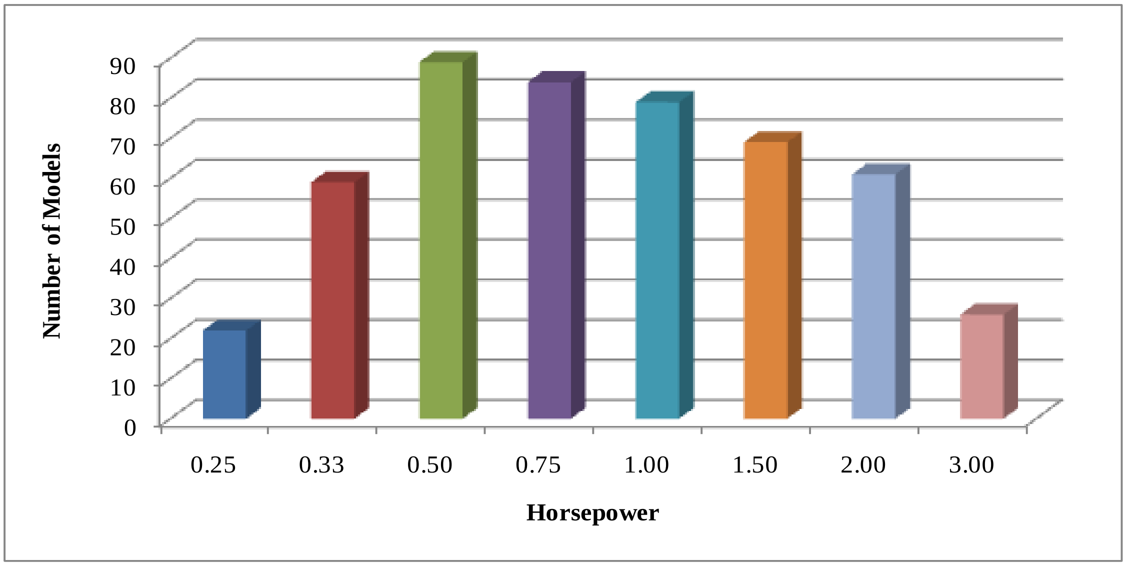

Figure 0.3. Models of Polyphase Small Electric Motors Broken Down by Horsepower

The data in Figure 0.3 are based on DOE's database of small electric motors compiled from several manufacturer's sales catalogs. This figure shows the distribution of models by horsepower for polyphase motors. The most common horsepower model is ½ horsepower, but the data show a skew toward models around 1 horsepower. This data reaffirm the weighted average of 1 horsepower for polyphase motor shipments, which is why DOE selected 1 horsepower for the polyphase representative unit.

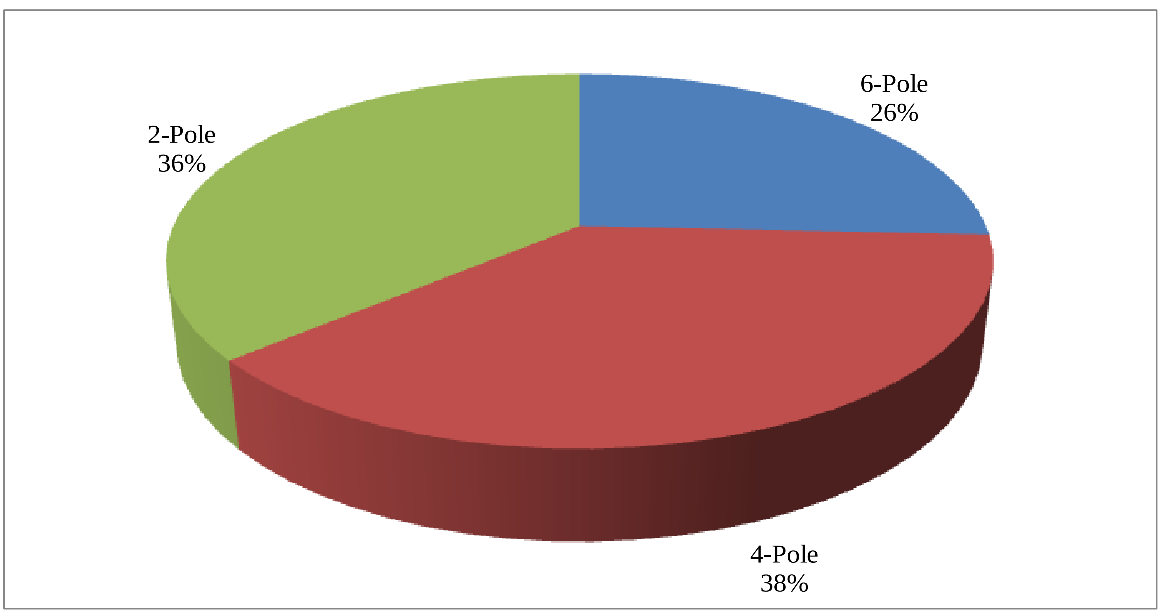

Figure 0.4. Capacitor-Start, Induction-Run Small Electric Motor Shipments Broken Down by Pole Configuration

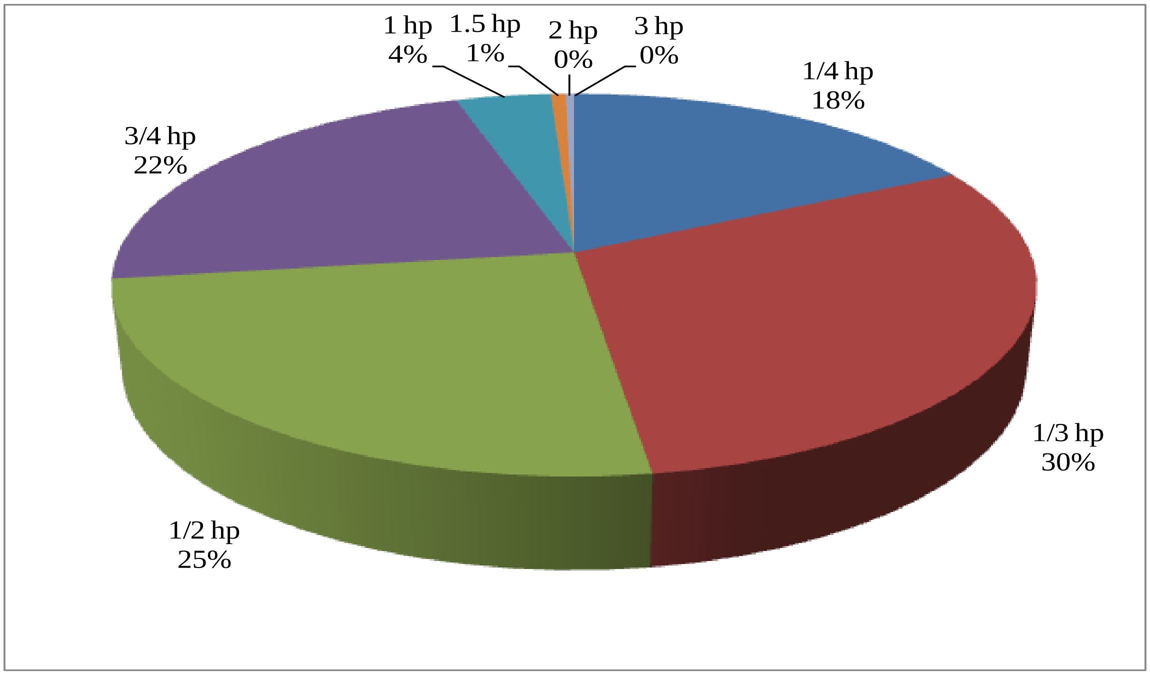

Figure 0.5. Capacitor-Start, Induction-Run Small Electric Motor Shipments Broken Down by Horsepower

Figure 0.4 and Figure 0.5 are based on projected shipments data for the National Impacts Analysis (see chapter 6 for more detail on the development of these data). They show the breakdown of shipments by pole configuration and horsepower. The pole configuration distribution is fairly even among two, four, and six poles, but four pole motors are still the most common. The weighted average horsepower of CSIR motors shipped is ½ hp.

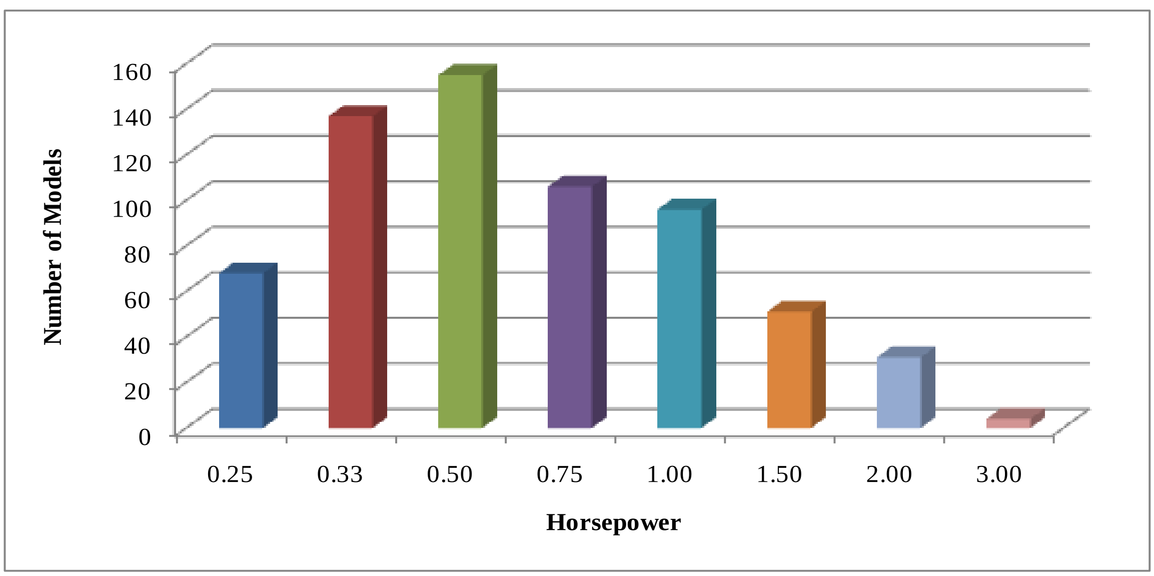

Figure 0.6. Models of Capacitor-Start, Induction-Run Small Electric Motors Broken Down by Horsepower

The data in Figure 0.6 are based on DOE's review of manufacturer catalogs and show the distribution of models by horsepower for CSIR motors. The most common horsepower model is ½ hp which reaffirms the weighted average of ½ horsepower for CSIR shipments. Therefore, DOE selected a rating of ½ horsepower for the CSIR representative unit.

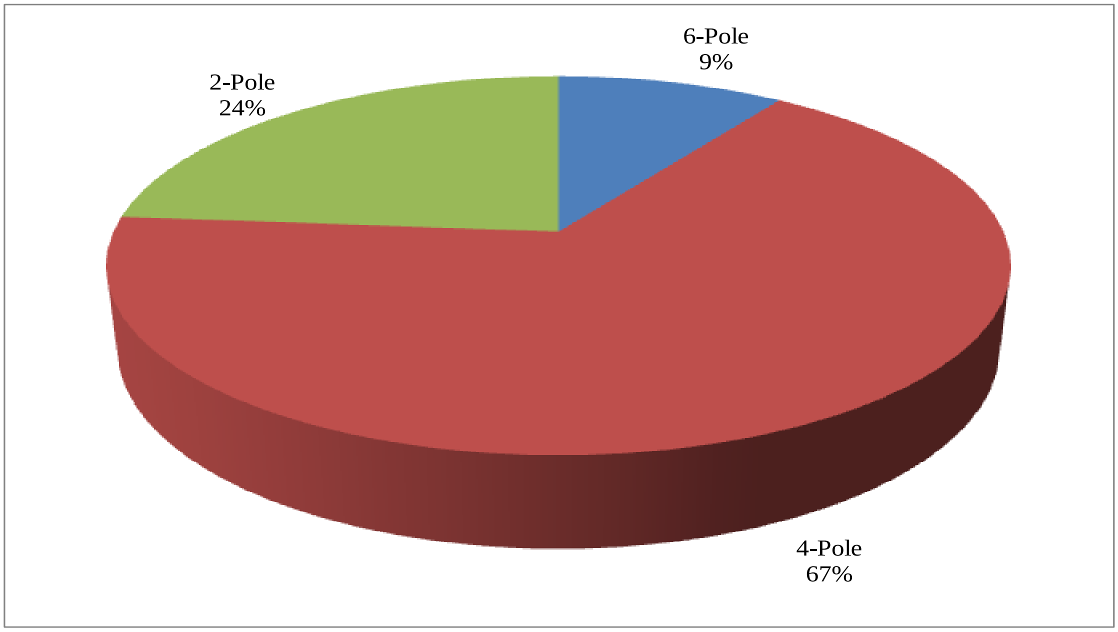

Figure 0.7. Capacitor-Start, Capacitor-Run Small Electric Motor Shipments Broken Down by Pole Configurations

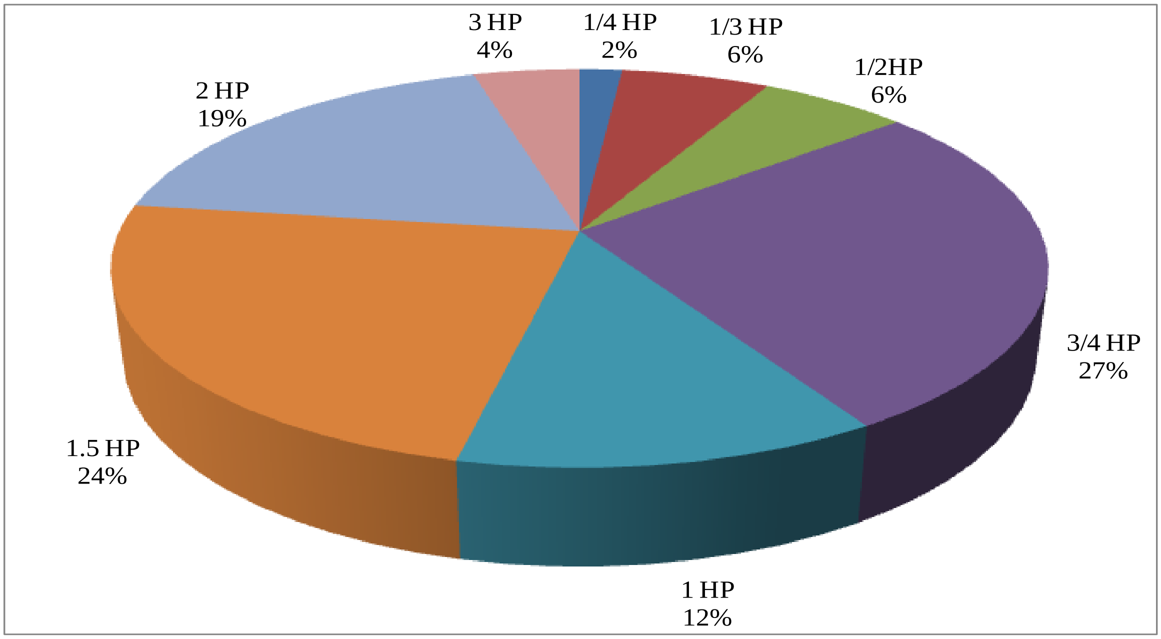

Figure 0.8. Capacitor-Start, Capacitor-Run Small Electric Motor Shipments Broken Down by Horsepower

Figure 0.7 and Figure 0.8 are based on projected shipments data for the National Impacts Analysis (see chapter 6 for more detail on the development of these data). These figures show the breakdown of shipments by pole configuration and horsepower. The pole configuration distribution shows that four pole motors are the most common. The weighted average horsepower of CSCR motors shipped is between 1 and 1½ horsepower.

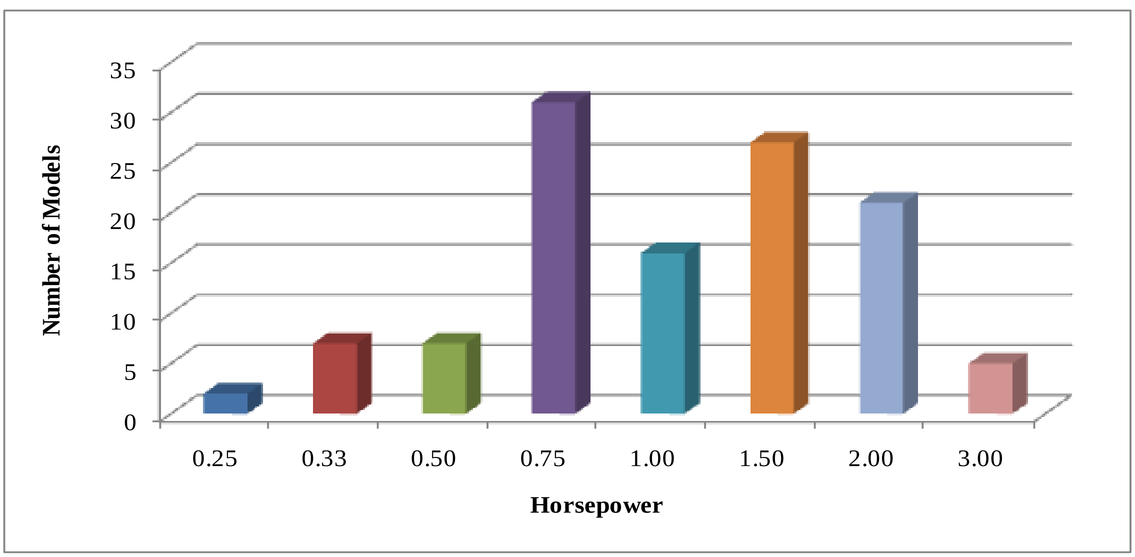

Figure 0.9. Models of Capacitor-Start, Capacitor-Run Small Electric Motors Broken Down by Horsepower

The weighted average horsepower of CSCR motors shipped was between 1 and 1½ horsepower, but the most common horsepower model was ¾ horsepower, shown in Figure 0.9.

DOE did not want to choose another representative unit with a 1 horsepower rating and felt that a rating of 1½ horsepower could overly skew the scaling results by over-representing the high end of the range of horsepower ratings. Therefore, DOE selected its CSCR representative unit to have a horsepower rating of ¾, which was the same as the most common model.

Table 0.4 presents the three representative units DOE selected for this Final Rule analysis. All of the motors are four-pole motors and, in view of DOE's analysis of manufacturer catalogs, this is the most common configuration for these horsepower ratings. DOE selected motors that approximate the middle of the range of covered horsepower ratings, partly to minimize any error that might be introduced as the efficiency of these motors are extrapolated to other horsepower ratings.

Table 0.4. Representative Units Selected for the Final Rule

Motor Category	Horsepower	Number of Poles	Frame series
Polyphase	1.00	4	56
CSIR	0.50	4	48
CSCR	0.75	4	56

DOE identified these three as representative units of interest. All three units fit the requirements of a NEMA general-purpose, single speed, induction motor, rated for continuous duty, and built with open construction in a two-digit frame series. DOE provides additional detail on each motor, including input voltage, baseline efficiency, and other critical performance characteristics in the section that follow.

DOE decided to only consider the minimum frame number series in each product class when determining efficiency standards. Therefore, the baseline motors listed in Table 5.2.4 represent the minimum available frame size in their respective product class. There is more detail on the reason for this decision in section 5.6.

5.2.2 Baseline Models

For each representative product class selected, DOE identified a specific motor as a fundamental design against which it would apply changes to improve the motor's efficiency. These small electric motors were considered DOE's baseline models. DOE chose these small electric motors to represent the characteristics of the least efficient motor for each analyzed product class. Because there are no existing minimum energy conservation standards for small electric motors, the baseline efficiency was selected after reviewing efficiency ratings suggested by manufacturers in the preliminary analyses and products available in the current market. DOE conducted its engineering analysis using the tested efficiency values from these baseline motors. For the polyphase motor, DOE tested five additional motors of the baseline model to validate its tested results in light of comments received from the NOPR analysis. DOE then combined these five tests with the original test for this baseline motor and took the average of the six tests as the baseline efficiency level for polyphase motors. For CSIR and CSCR motors, DOE used the tested efficiency value of the original baseline motor for its baseline efficiency since DOE did not receive comment on these efficiency ratings. Table 0.5 below shows the efficiencies that

DOE found and used as baseline efficiency ratings. Each efficiency level listed below is the tested efficiency of a particular motor that DOE purchased, tested, and modeled in its subcontractor's software program.

Table 0.5. Efficiency Ratings of Baseline Motors Selected for Analysis

Basic Characteristics of Motors Analyzed	Baseline Efficiency %
Polyphase, 1 hp, 4-pole, 56 frame	75.3*
CSIR, ½ hp, 4-pole, 48 frame	57.9
CSCR, ¾ hp, 4-pole, 56 frame	71.4

*The motor purchased was listed at 74%, but the average of six tests was 75.3%.

As mentioned, DOE tested each motor that was purchased and to be used as a baseline model. DOE contracted an independent, accredited laboratory, Advanced Energy, as well as its technical expert, Yeadon Energy Systems, to perform the appropriate IEEE test procedure for each motor. DOE established dimensional and performance specifications in addition to efficiency for the baseline models by examining all outputs of the IEEE test procedures and performing teardowns of the purchased motors. The results of the IEEE test procedures provided several motor performance characteristics including speed, power factor, torque, and line current at various load points. After compiling this test data, DOE's technical expert tore down each motor to obtain dimensions, copper wire gauges, steel grade, and any other pertinent design information. Finally, the purchased motors were modeled in the designer's software and used as the baseline designs in each analyzed product class for the engineering analysis. Again, the three product classes that were analyzed were: CSIR, ½ horsepower, 4-pole; CSCR, ¾ horsepower, 4-pole; and polyphase, 1 horsepower, 4-pole motors. Specific detail on these baseline motors is provided in the results section of this chapter, section 5.5.

5.3 ENGINEERING ANALYSIS METHODOLOGY

DOE conducted the engineering analysis using a modified design-option approach where DOE employed its technical expert, with motor design software, to develop motor designs at several efficiency levels for each analyzed product class. Based on these simulated designs and manufacturer and component supplier data, DOE calculated manufacturing costs and selling prices associated with each efficiency level. DOE decided on this approach after receiving insufficient response to its request for the manufacturer data needed to execute an efficiency-level, approach for the preliminary analyses. The design-option approach allows DOE to make its engineering analysis methodologies, assumptions, and results publicly available, granting advocates, manufacturers, and other interested parties the opportunity to review and comment on this information. The design options considered in the engineering analysis include: using copper die-cast rotor, reducing skew on stack, increasing cross-sectional area of rotor conductor bars, increasing end-ring size, changing the gauge of copper wire in stator, manipulating stator slot dimensions, decreasing air gap between rotor and stator to 12.5 thousandths of an inch, improving grades of electrical steel, using thinner steel laminations, annealing steel laminations, adding stack height, using high efficiency lamination materials, changing run-capacitor ratings, installing better ball bearings and lubricant, and installing a more efficient cooling system.

DOE's technical expert, who specializes in small electric motor designs, prepared six sets of designs, two sets for each motor analyzed with each set spanning a range of efficiency levels. The third-party software design company determined the fundamental design parameters of the baseline motors through the aforementioned testing and teardowns. After modeling the baseline motors and creating theoretical, more efficient designs, DOE attempted to validate the results of the engineering analysis with the testing and teardown of additional motors available in the current market, as shown in appendix 5A.

5.3.1 Subcontractor Software Design Approach

DOE worked with a subcontractor to develop MSP-efficiency curves for the three representative small electric motors. As discussed above, DOE retained a small electric motor expert[a] with design experience and software, who prepared multiple sets of designs with increasing efficiency. The contractor started by testing the baseline motors purchased according to the applicable IEEE test procedure, both IEEE 112 test methods A and B were performed for the polyphase motor and IEEE 114 for the two single-phase motors. After testing the motors, the subcontractor tore down the motor, measured various dimensions, counted the steel laminations, examined the slot fill, and determined all other pertinent design parameters. This data was combined and used as inputs to the design software. The resulting designs served duel purposes. First, by showing that the output of the software program was in line with the results obtained through testing, the subcontractor's proprietary software program was validated as a design tool. DOE feels very confident in its selection of software as it has been used in the past to design, prototype, and produce complete induction motor lines. Second, the designs became the starting point, or baseline models, against which design options were applied to increase efficiency, for each product class analyzed. As new designs were created, careful attention was paid to the critical performance characteristics to ensure that the resulting designs were reasonable and manufacturable replacements of the baseline motors. To this end, DOE established a set of design limitations that are applied across all six sets of designs.

However, there is one design limitation that is an exception, stack height, and DOE uses this design option as a sensitivity analysis. Half of the design sets follow a limitation of no more than a 20% increase in stack height, while the other half follow another less stringent restriction of no more than a 100% increase in stack height. Both restrictions are listed below and the following list presents all of the design limitations DOE imposed.

One performance characteristic that DOE used as a limitation in the final rule that wasn't used in the NOPR analysis is thermal viability. In the NOPR, DOE assumed that each incremental design above the baseline would retain or improve the thermal viability characteristics of the baseline motor. For the final rule, however, DOE examined the temperature rise for each of its designs and ensured that it did not exceed the 90 degree Celsius temperature rise limit associated with the insulation class of the baseline motor.

- Peak slot fill – the minimum value of this parameter should exceed 50% while the maximum value should not reach more than 65% for an assumed high volume

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

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 0.0125 inches for any design. Having air gaps tighter than this minimum could be problematic and may cause contact between the spinning rotor and the stationary stator, especially as shaft length increases.

- Stator slot opening – the slot opening width 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.

- Locked-rotor torque – for single-phase motors, the locked-rotor torque must be within the specifications set forth by NEMA MG1-1987 in Section 12.32.2. For polyphase motors, no such requirements exist in NEMA MG1-1987 for the covered motors, but all of DOE's designs are within the limits specified in Section 12.38.1 for medium electric motors.

- Locked-rotor current – for single-phase motors, the locked-rotor current should not exceed the values of NEMA MG1-1987 Section 12.33.2. For the covered polyphase motors, there are no requirements for locked-rotor current in NEMA MG1, but DOE did ensure that the locked-rotor current values of its designs did not exceed 30 amps, which is the requirement for medium motors as outlined in Section 12.35.

- Breakdown torque – for single-phase motors, the breakdown torque must fall within NEMA MG 1-1987 Section 12.32.1.. For polyphase motors, the breakdown torque should follow the guidelines established in NEMA MG1-1987 Section 12.37.

- Power factor – the power factor of the baseline motor should be maintained or increased for all designs.

- Speed at rated load – the speed of the baseline motor should be maintained or increased for all designs.

- Service factor – the service factor of each design should be within the limits set forth in NEMA MG1-1987 Table 12-2.

- Stray load loss – the assumed value of stray load loss should be 1.8% when it is not determined through testing. DOE used the tested value of 2.4% for polyphase designs, and the assumed value of 1.8% for single-phase designs.

- Motor diameter – the motor diameter of the baseline motor should be that of the baseline and remain constant for all designs.

- 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 (*e.g.* completely removing it) or introduce cusps in the acceleration curve. (Note: this design limitation is subjective and relies on the design of the baseline motor and the expertise of the designer).

- Stack height – as mentioned before, DOE's expert prepared two sets of designs for each motor analyzed. The first set of designs for each motor allows a maximum increase in stack height of 20% relative to the baseline. The second set of designs are less restricted and allow a 100% increase in stack height (*i.e.* the stack height may double the original value).

Working within these parameters, the subcontractor prepared eight to nine designs of increased efficiency for each of the two design sets for each representative motor. The design levels prepared for the space constrained designs were at the baseline, intermediate levels, a level for a design using a copper rotor, and a max-tech level with a design using a copper rotor and exotic core steel. The non-space constrained design (100% increase of stack height) efficiency levels corresponded to the efficiency levels created for the space-constrained designs.

As mentioned previously, DOE then shifted each efficiency level so the modeled baseline efficiency level aligned with the tested efficiency results for the baseline motors. This shift was done by calculating the percentage change in motor losses necessary to shift the modeled value to the tested value, and then applying the same percentage change to the motor losses of all subsequent designs. Since these shifts applied the same percentage change to each efficiency level in the analyses, the impact of the shift did not alter the comparative economics of the various TSLs analyzed. For this reason, the shift in efficiency was implemented after all analyses were performed on the units. Table XX shows the shift necessary for each motor category, and Table 0.7 through Table 0.9 show the original modeled efficiency values and the final shifted efficiency values.

Table 0.6 Percent Change in Motor Losses to Align Modeled Baseline with Tested Baseline

	Modeled Baseline Efficiency (%)	Tested Baseline Efficiency (%)	Percent Change in Motor Losses (%)
Polyphase	77.7	75.3	14.6
CSIR	57.9	57.9	0.0
CSCR	70.7	71.4	-3.3

Table 0.7 Shifting Modeled Polyphase Efficiencies to the Tested Baseline

Efficiency Level	Modeled Efficiency (%) (Design 1/Design 2)*	Shifted Efficiency (%) (Design 1/Design 2)*
Baseline	77.7	75.3
EL 1	79.6	77.3
EL 2	81.0	78.8
EL 3	82.5	80.5
EL 4	83.1	81.1
EL 4b	85.3 / 85.3	83.5 / 83.5
EL 5	86.9 / 86.8	85.3 / 85.2
EL 6	87.7 / 87.8	86.2 / 86.3
EL 7 (Max-tech)	89.1 / 89.2	87.7 / 87.8

*Design 1 denotes the space-constrained design, and Design 2 denotes the non-space-constrained design. If only one value is listed, then the space-constrained design is the same as the non-space-constrained design.

Table 0.8 Shifting Modeled CSIR Efficiencies to the Tested Baseline

Efficiency Level	Modeled Efficiency (%) (Design 1/Design 2)*	Shifted Efficiency (%) (Design 1/Design 2)*
Baseline	57.9	57.9
EL 1	61.1	61.1
EL 2	63.5	63.5
EL 3	65.7	65.7
EL 4	70.6 / 70.5	70.6 / 70.5
EL 5	71.8 / 71.8	71.8 / 71.8
EL 6	73.1 / 73.3	73.1 / 73.3
EL 7 (Max-tech)	77.6 / 77.7	77.6 / 77.7

*Design 1 denotes the space-constrained design, and Design 2 denotes the non-space-constrained design. If only one value is listed, then the space-constrained design is the same as the non-space-constrained design.

Table 0.9 Shifting Modeled CSCR Efficiencies to the Tested Baseline

Efficiency Level	Modeled Efficiency (%) (Design 1/Design 2)*	Shifted Efficiency (%) (Design 1/Design 2)*
Baseline	70.7	71.4
EL 1	74.5	75.1
EL 2	79.0 / 79.0	79.5 / 79.5
EL 3	81.2 / 81.3	81.7 / 81.8
EL 4	82.3 / 82.3	82.8 / 82.8
EL 5	83.6 / 83.5	84.1 / 84.0
EL 6	84.4 / 84.2	84.8 / 84.6
EL 7	86.4 / 86.3	86.8 / 86.7
EL 8 (Max-tech)	87.7 / 87.5	88.1 / 87.9

*Design 1 denotes the space-constrained design, and Design 2 denotes the non-space-constrained design. If only one value is listed, then the space-constrained design is the same as the non-space-constrained design.

5.3.2 Market Motor Validation

After DOE created its theoretical designs, DOE attempted to validate those results with data from motors currently available in the small electric motors market. DOE selected two to three motors from each representative product class, each with a different catalog listed efficiency level. DOE then had its subcontractor perform testing on these motors to verify its efficiency level. Next, the motors were torn down and a bill of materials was constructed and marked up to create an MSP using the same pricing scheme developed and discussed in section 5.4. The results of the test data and the MSP developed from the tear downs of these motors were plotted along with the curves of the theoretical designs developed for the representative units. DOE found that the data points at comparable efficiency levels were consistent with the curves of the theoretical designs. The results of this validation analysis are illustrated along with the curves developed for the analyzed product classes in appendix 5A.

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 0.10, where production costs and non-production costs are combined to determine the manufacturer selling price (MSP).

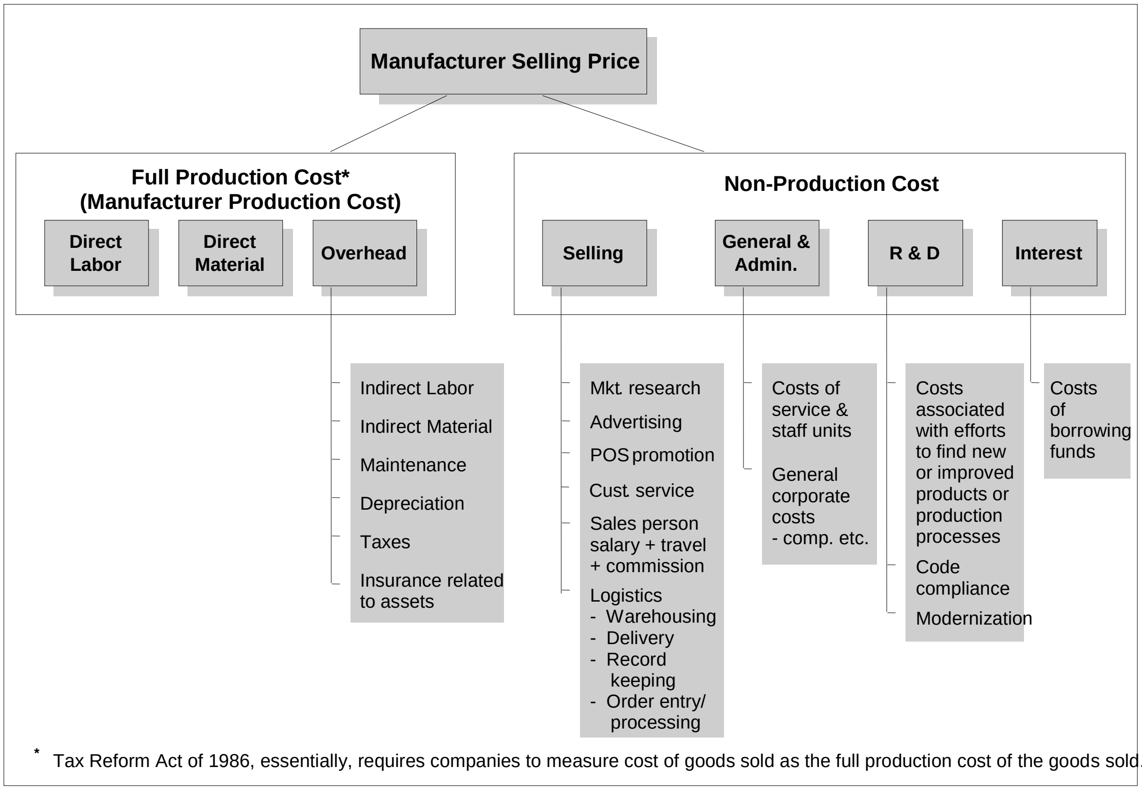

Figure 0.10. Standard Method of Cost Accounting for Standards Rulemaking

DOE developed estimates of some of the cost multipliers shown in Figure 0.10 by reviewing Security and Exchange Commission (SEC) SEC-10K reports from A.O. Smith Corporation, Baldor Electric Company, Emerson Motor Technologies, Regal-Beloit Corporation, and WEG Electric Corporation as well as through conversations with industry experts. Together, the full production cost or manufacturer production cost (MPC) and the non-production costs equal the MSP. 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 design limitations mentioned in section 5.3.1), the next step was applying this cost model to all of them. A standard bill of materials (BOM) was constructed that includes direct material costs and labor time estimates along with costs. The BOM is then multiplied by a markup for overhead to obtain an MPC which in turn is marked up again 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 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 have different component lists, but for a given motor category the total fixed costs remain constant for all designs. 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, but vary in cost from design to design as a function of the amount used in the motor designs. An example of this is the cost of the die-cast aluminum or copper 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 depending upon the design (*e.g.* a longer motor will require more aluminum).

DOE presents a detailed bill of materials for one design from each of the three motor categories analyzed in 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 component of the motor to which they apply. For example “end cap assembly” is a heading and under this label there are several itemized parts with associated costs. The BOM includes the following headings, each with an itemized parts list: stator assembly, rotor assembly, end cap assembly, housing assembly, hardware, and final assembly.

As mentioned, each heading has an itemized list of components. 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 prices 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).

5.4.2 Commodity Prices

A significant portion of the costs associated with small electric motors is attributed to the fluctuating metal prices of several motor components. These include steel laminations, copper wiring, and rotor die-casting aluminum or copper. DOE understands that it is difficult to choose an accurate price point for these components because their underlying commodity prices have seen great fluctuations over the past several years, translating into large variations in cost. As a best estimate for these prices, DOE used an inflation adjusted five-year average price point for these components. In calculating the five-year average prices for these commodities, DOE adjusted historical prices to $2009 using the historical Bureau of Labor Statistics Producer Price Indices (PPI) for each commodity's industry[2].

Additionally, DOE performed a cost sensitivity analysis in which they examined both a high and low commodities cost scenario. For all commodity prices, DOE used the PPI to determine the high and low cost points and then input those component costs into the model. This allowed DOE to generate a high commodities case and a low commodities case for the engineering analysis results. Please see appendix 5A for greater detail on the high and low cost scenarios.

DOE utilized the PPI for each commodity's industry to calculate these prices. The PPI is an index that tracks the average change in prices that domestic producers receive for their product. This allowed DOE to scale its current 2009 component prices back for the previous five years for an inflation adjusted comparison. Once DOE had prices for 2005 through 2009, it was able to take a five-year average of these prices, as well as determine the maximum and minimum prices over the time period. The following figures depict the component prices over the five-year timeframe.

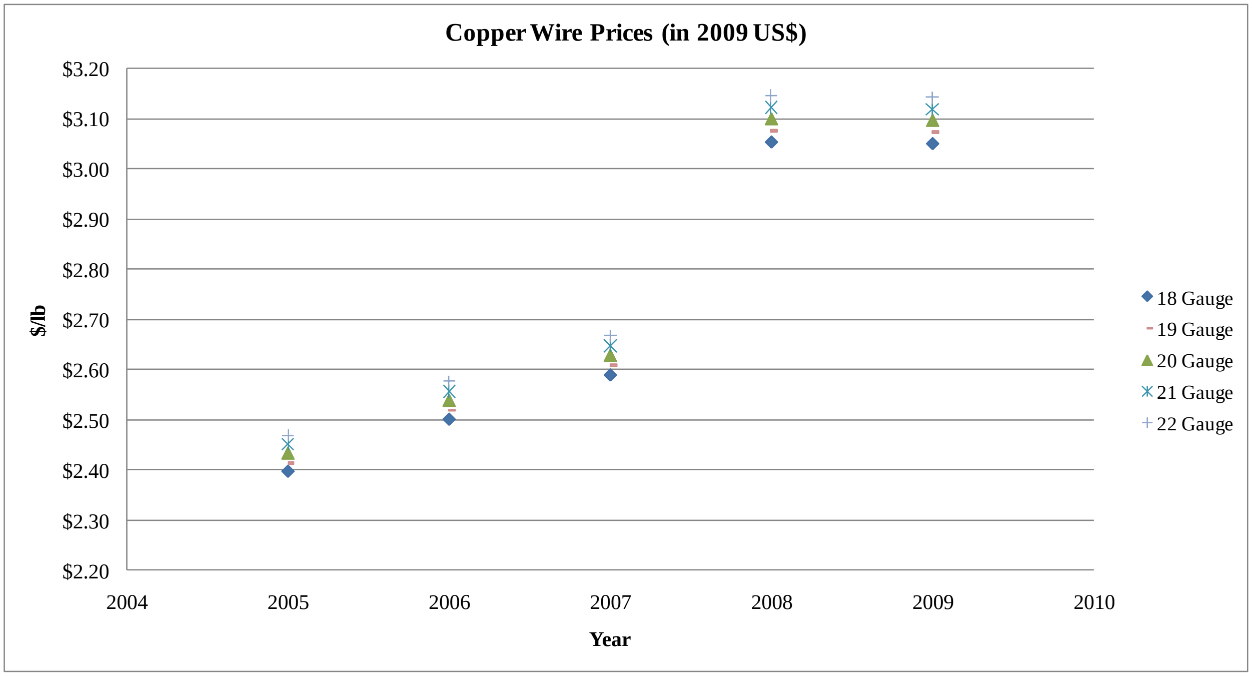

Figure 0.11. Five-Year Copper Wire Prices in $2009 US

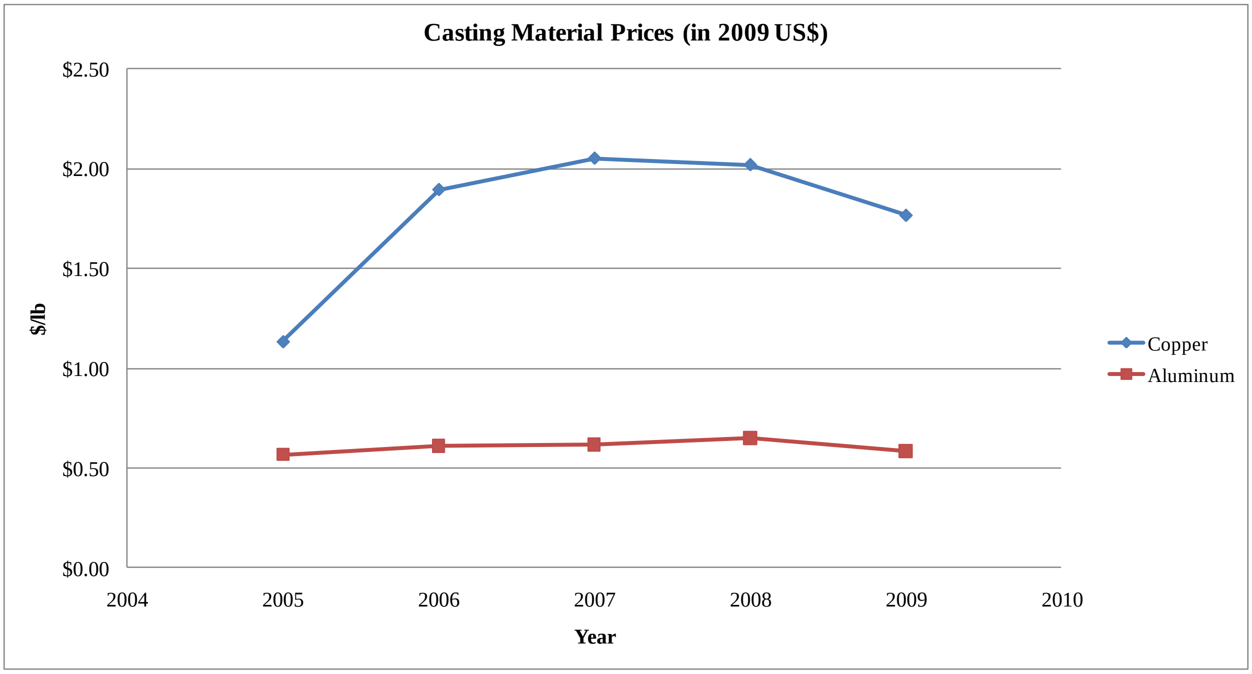

Figure 0.12. Five-Year Die-Casting Prices in $2009 US

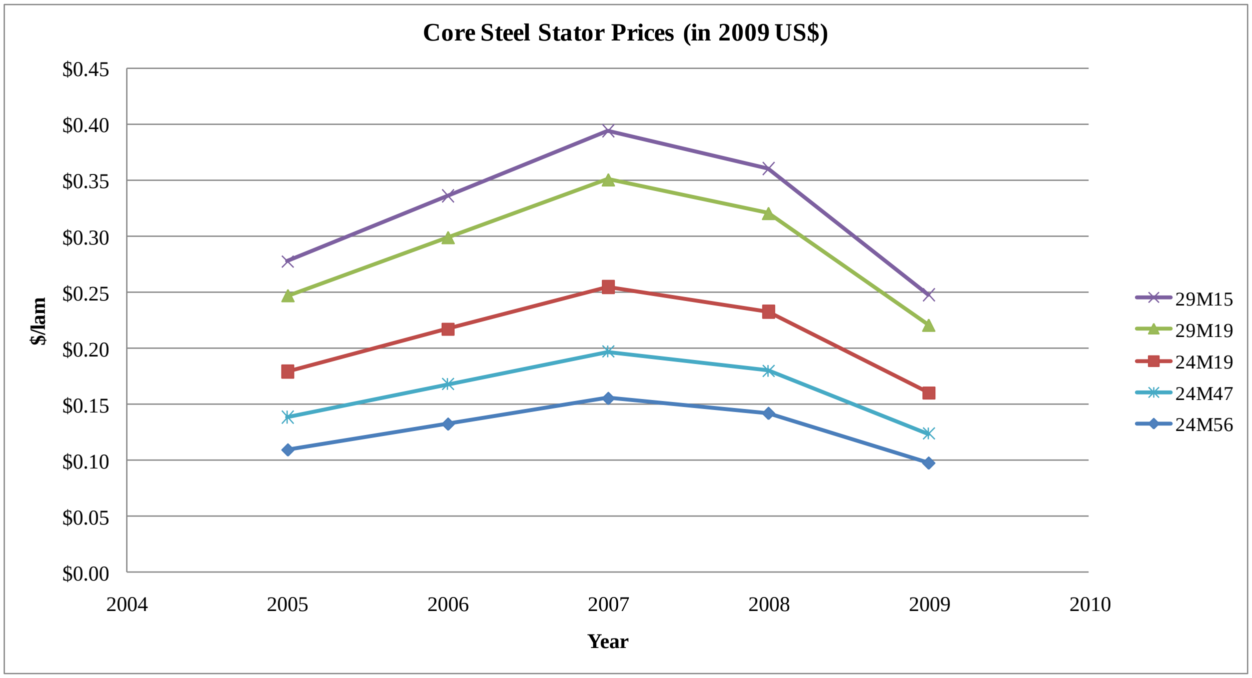

Figure 0.13. Five-Year Steel Lamination Prices in $2009 US

5.4.3 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 time 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[3] by the U.S. Census Bureau. Several markups were applied successively and with cumulative effect to the base hourly rate to obtain a fully burdened rate which was intended to be representative of the labor costs associated with manufacturing these motors. Table 0.10 shows the base labor rate DOE started with, each markup with its corresponding markup percentage and the resulting partially burdened rate after that markup, and a final fully burdened labor rate. The markups were applied in the order they appear in the table and to the "rate per hour" listed for the previous markup. For example, the 28 percent markup for fringe was applied to the $18.02 (*i.e.*, 1.28 x $18.02 = $23.07) that DOE obtained after marking up the base labor rate by 33 percent for indirect production.

Table 0.10. Labor Markups for Small Electric Motor Manufacturers

Item description	Markup	Rate per hour
Labor cost per hour*		$ 13.55
Indirect Production**	33 %	$ 18.02
Fringe†	28 %	$ 23.07
Assembly Labor Up-time††	43 %	$ 32.99
Cost of Labor Input to Spreadsheet		**$ 32.99**

* 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.
† 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.

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 categories that identify an overall activity, such as stator assembly, rotor assembly, and housing assembly. Within these categories, subheadings denote process steps for specific parts of the motor. Summing the list of process steps gives a total time estimate for manufacturing the motor, which is multiplied by the fully burdened labor cost, shown as $32.99.

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 a copper rotor. The reason for the increased labor time is because copper has a higher melting point than aluminum does, so die-casting the rotor takes more time to heat the metal sufficiently.

The remainder and the majority of the labor costs calculated were fixed costs. The following categories are associated with the 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 for the rotor assembly. For end cap assembly there are time estimates 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. Included in the final assembly section are times for actual assembly, motor testing, labeling and packaging.

5.4.4 Manufacturer Markups

DOE used the three markups described below to account for 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, 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: 17.5 or 18.0 percent markup. Factory overhead includes all the indirect costs associated with production, indirect materials and energy use, taxes, insurance, and depreciation. DOE applies factory overhead to the direct material production costs, including the handling and scrap factor, and labor estimates. For aluminum rotor designs a 17.5 percent markup was used, but for all copper rotor designs an 18.0 percent markup was used to factor in increased depreciation for the equipment.

- Non-production: 45 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 handling and scrap, the direct labor, and the factory overhead otherwise known as the MPC. The MPC plus the non-production markup gives a manufacturer selling price MSP.

5.5 RESULTS OF ENGINEERING ANALYSIS

For the CSIR motor analyzed, DOE developed eight efficiency levels using a motor design software tool, and for the polyphase and CSCR motors analyzed DOE developed nine efficiency levels. These included a baseline design, intermediate designs, then a copper rotor design, and a max-tech design that uses a copper rotor and an exotic core steel. Then by using the methodology and pricing scheme outlined in the previous section, DOE developed manufacturer selling prices for each small electric motor design created. Throughout this section, DOE shows the bottom-up derived MSP's.

The engineering analysis results are essentially six manufacturer selling price-versus-full-load efficiency curves that represent two relationships for each of the three representative product classes analyzed. For each of the three motors analyzed, DOE created designs that allowed stack height to double and designs that only allowed stack height to increase by 20 percent over the baseline design. This was done to determine how the cost-efficiency relationship would change for space constrained OEMs (only 20 percent increase) versus non-space constrained OEMs (doubled stack height maximum). Thus, each of the three motors analyzed have two curves plotted to depict these two scenarios. The six graphs shown in Figure 0.14 through Figure 0.19 provide the MSP versus efficiency curves and Table 0.11 through Table 0.16 present the tabulated results.

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

Figure 0.14 presents the relationship between the MSP and full-load efficiency for the polyphase motor analyzed. DOE developed an exotic maximum technology (max-tech) design using a non-traditional steel type (*i.e.*, Hiperco 50™) that makes the motor considerably more expensive than other designs analyzed. Use of this premium electromagnetic steel greatly increases the MSP of the motor, thereby skewing the Y-axis. For this reason, the engineering analysis results are presented twice, first with the max-tech design (Figure 0.14) and then again without the max-tech design (Figure 0.15).

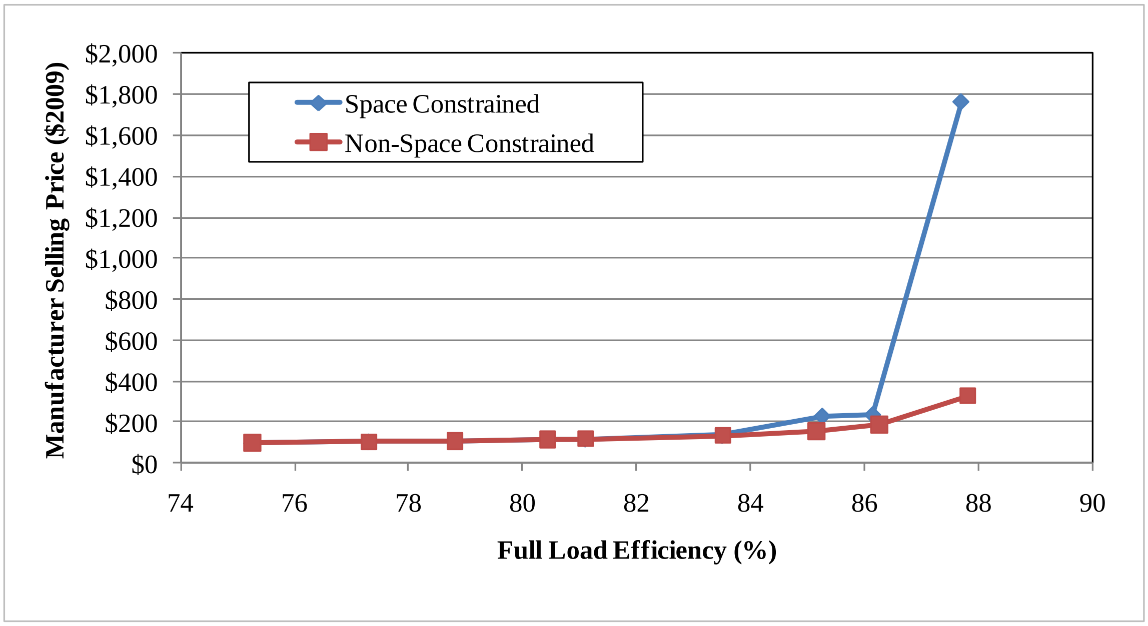

Figure 0.14. Polyphase 1 Horsepower, 4-Pole, 56-Frame Motor Engineering Analysis, with Maximum Technology Point

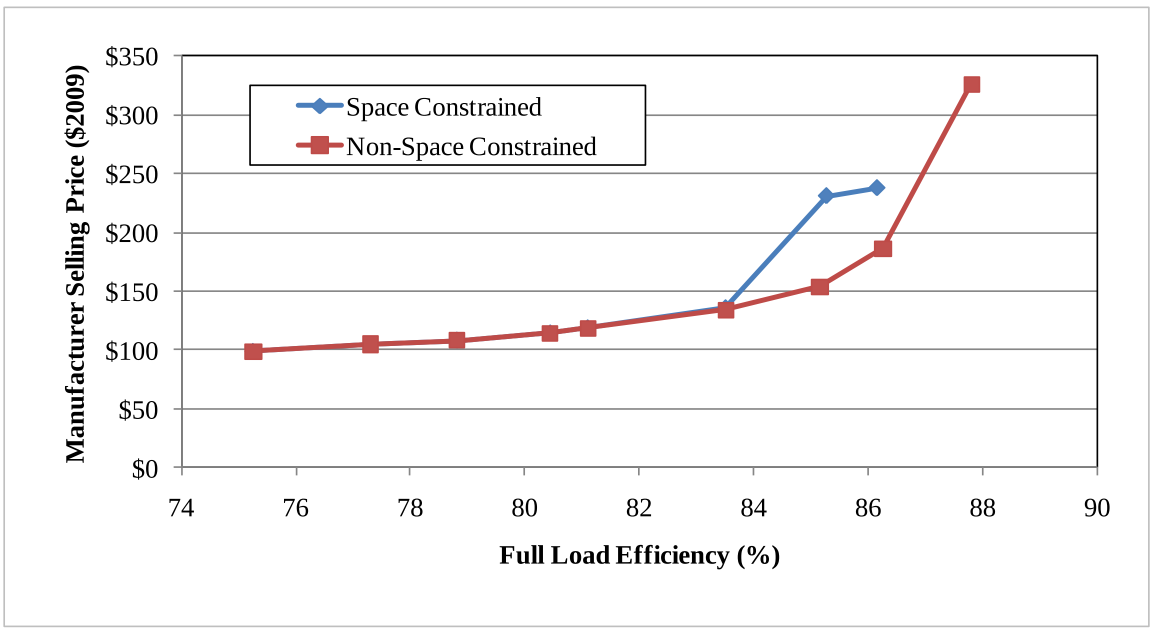

Figure 0.15. Polyphase 1 Horsepower, 4-Pole, 56-Frame Motor Engineering Analysis, without Maximum Technology Point

Table 0.11 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 max-tech motor, DOE found that the full-load efficiency would increase 12.54 percentage points, for a 16.7-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to more than triple, increasing from $98.54 for the baseline model to $326.18 for the non-space constrained max-tech motor. The difference in MSP is even greater for the space-constrained max-tech motor, which has a MSP of $1,766.06.

Table 0.11. Efficiency and MSP Data for Polyphase Motor

Efficiency Level	Efficiency % (Design 1 / Design 2)*	MSP $ (Design 1 / Design 2)*
Baseline	75.3 %	$ 98.54
EL 1	77.3 %	$ 104.83
EL 2	78.8 %	$ 108.17
EL 3	80.5 %	$ 114.24
EL 4	81.1 %	$ 118.54
EL 4b	83.5 % / 83.5 %	$ 135.62 / $ 134.04
EL 5	85.3 % / 85.2 %	$ 230.92 / $ 153.92
EL 6	86.2 % / 86.3 %	$ 237.70 / $ 186.37
EL 7 (Max-tech)	87.7 % / 87.8 %	$ 1,766.06 / $ 326.18

*Design 1 denotes the space constrained design, and design 2 denotes the non-space constrained design. If only one value is listed, then the space constrained design is the same as the non-space constrained design.

Table 0.12 presents some of the design and performance specifications associated with the nine polyphase designs presented above. Additionally, DOE provides more details and performance characteristics for polyphase designs in appendix 5A.

Table 0.12. Polyphase, 1 Horsepower, 4-Pole, 56-Frame Motor Designs

Parameter (Units)	Baseline	EL1	EL2	EL3	EL4	EL4b	EL5	EL6	EL7
-	-	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2
Efficiency (%)	75.3	77.3	78.8	80.5	81.1	83.5 83.5	85.3 85.2	86.2 86.3	87.7 87.8
Power Factor	69.0	70.6	71.0	73.9	73.5	72.9 69.7	71.2 74.0	74.2 73.8	71.6 69.7
Speed (RPM)	1728	1735	1735	1728	1729	1728 1729	1733 1737	1741 1743	1741 1761
Torque (in-lbs)	36.8	36.3	36.3	36.7	36.4	36.6 36.8	36.7 36.6	36.4 36.2	36.6 36.2
Current (A)	3.52	3.32	3.25	3.08	3.06	3.01 3.17	3.06 2.94	2.89 2.89	2.96 3.04
Core Steel	24M56	24M56	24M56	24M56	24M56	24M19 24M47	29M15 24M19	29M15 24M19	Hiperco 50 29M15
Stack Height (in)	3.0	3.2	3.425	3.5	3.6	3.6 4.4	3.6 4.45	3.6 6	3.6 5.525
Rotor Material	Al	Al	Al	Al	Al	Al Al	Al Al	Cu Al	Cu Cu
Main Wire (AWG)	22	21	20.5	20	19.5	20 20	19.5 21	19.5 20	19.5 20
LR Torque (in-lbs) (at 25˚ C)	123.2	126.7	126.8	11.2	113.1	111.7 117.8	121.1 115.7	102.3 124.0	106.2 138.6
LR Current (A) (at 25˚ C)	19.7	20.1	19.9	17.9	18.1	17.8 18.4	18.9 18.6	17.9 19.6	18.3 23.2
Service Factor	1.15	1.15	1.15	1.15	1.15	1.15 1.15	1.15 1.15	1.15 1.15	1.15 1.15

*Design 1 denotes the space constrained design, and design 2 denotes the non-space constrained design. If only one value is listed, then the space constrained design is the same as the non-space constrained design.

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

Figure 0.16 presents the relationship between the MSP and full-load efficiency for the 48-frame capacitor-start, induction-run motor DOE analyzed. The max-tech design incorporates a high-grade non-traditional electromagnetic steel (Hiperco 50™) alloy that is much more expensive than the high quality electromagnetic steel alloy used in any of the other designs. Use of such steel greatly increases the MSP of the motor, thereby skewing the Y-axis. For this reason, the engineering analysis results are presented again without the max-tech design in Figure 0.17.

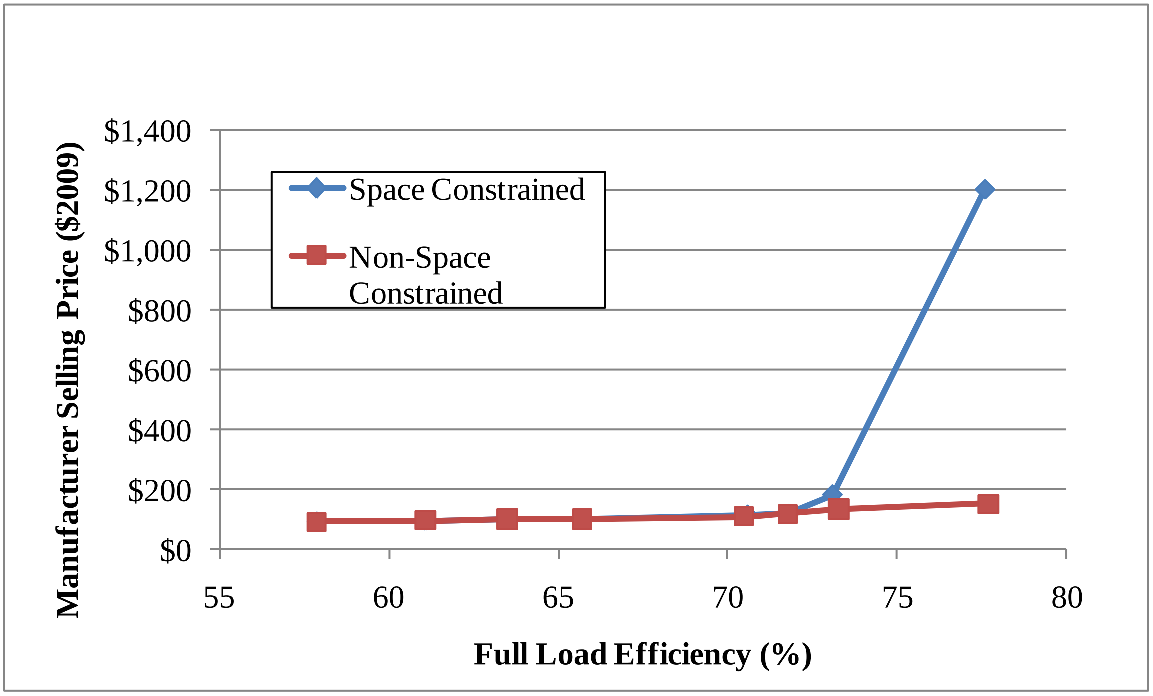

Figure 0.16. Capacitor-Start, Induction-Run, ½ Horsepower, 4-Pole, 48-Frame Engineering Analysis Curve, with Maximum Technology Point

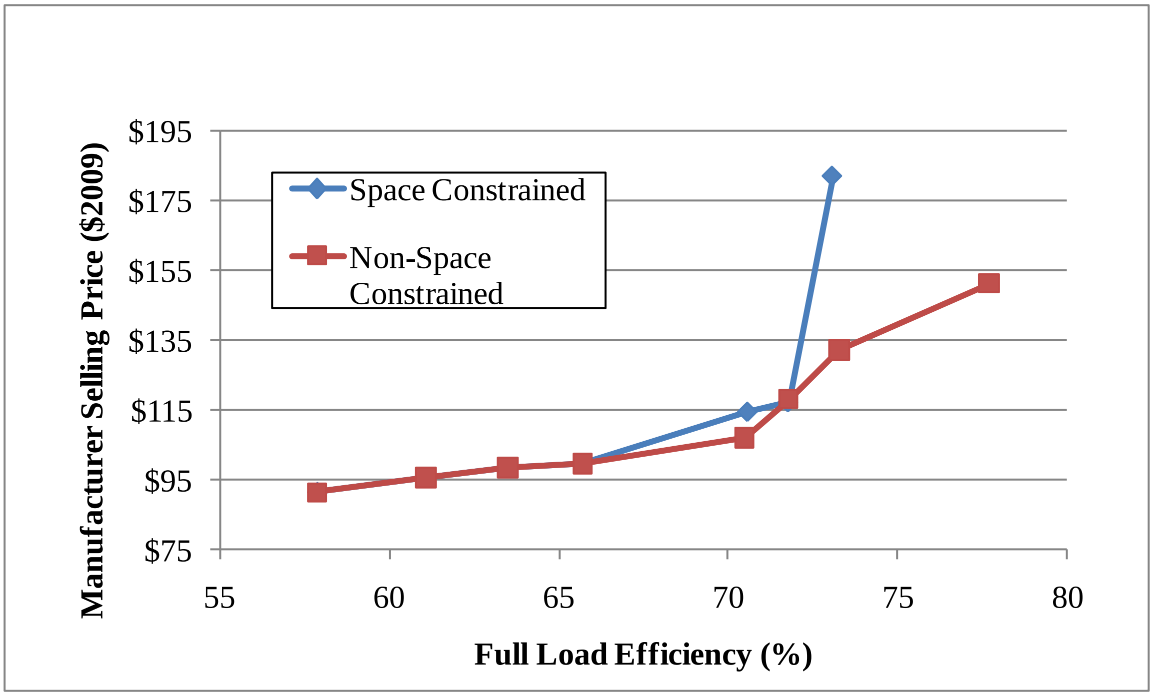

Figure 0.17. Capacitor-Start, Induction-Run, ½ Horsepower, 4-Pole, 48-Frame Engineering Analysis Curve, without Maximum Technology Point

Table 0.13 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 max-tech motor, DOE found that the full-load efficiency would increase 19.8 percentage points, for about a 33-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to increase by more than 65 percent, increasing from $91.24 for the baseline model to $151.25 for the non-space constrained max-tech motor. The difference in MSP is significantly greater for the space-constrained max-tech motor, which has a MSP of $1,200.98.

Table 0.13. Efficiency and MSP Data for Capacitor-Start, Induction-Run, 48-Frame Motor

Efficiency Level	Efficiency % (Design 1 / Design 2)*	MSP $ (Design 1 / Design 2)*
Baseline	57.9 %	$ 91.24
EL 1	61.1 %	$ 95.43
EL 2	63.5 %	$ 98.45
EL 3	65.7 %	$ 99.58
EL 4	70.6 % / 70.5 %	$ 114.31 / $ 106.99
EL 5	71.8 % / 71.8 %	$ 117.07 / $ 118.00
EL 6	73.1 % / 73.3 %	$ 182.09 / $ 132.22
EL 7 (Max-tech)	77.6 % / 77.7 %	$ 1,200.98 / $ 151.25

*Design 1 denotes the space constrained design, and design 2 denotes the non-space constrained design. If only one value is listed, then the space constrained design is the same as the non-space constrained design.

Table 0.14 presents some of the design and performance specifications associated with the eight CSIR efficiency levels presented above. Additionally, DOE provides more details and performance characteristics for CSIR designs in appendix 5A.

Table 0.14. Capacitor-Start, Induction-Run, 1/2 Horsepower, 4-Pole, 48-Frame Motor Designs

Parameter (Units)	Baseline	EL1	EL2	EL3	EL4	EL5	EL6	EL7
-	-	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2
Efficiency (%)	57.9	61.1	63.5	65.7	70.6 70.5	71.8 71.8	73.1 73.3	77.6 77.7
Power Factor	56.9	58.2	58.5	60.8	60.0 65.3	62.8 67.6	61.9 61.6	66.3 65.6
Speed (RPM)	1730	1730	1732	1732	1735 1746	1742 1740	1731 1739	1734 1754
Torque (in-lbs)	18.3	18.4	18.4	18.3	18.2 18.1	18.1 18.3	18.4 18.0	18.2 18.3
Current (A)	9.49	8.86	8.48	7.82	7.49 6.67	6.99 6.40	7.12 6.92	6.23 6.26
Core Steel	.028M56	24M56	24M56	24M56	24M19 24M56	24M19 24M56	29M15 24M19	Hiperco 50 24M19
Stack Height (in)	2	2.1	2.2	2.3	2.4 2.9	2.4 4	2.4 3.275	2.4 4
Rotor Material	Al	Al	Al	Al	Al Al	Cu Al	Cu Al	Cu Cu
Main Wire (AWG)	18.5	21	20.5	20.5	20.5 20	21 21.5	20.5 21	20.5 21
Aux. Wire (AWG)	21.5	21.5	21.5	21.5	21.5 21.5	21.5 21.5	21.5 21.5	21.5 21.5
Start Cap. (μF)	333	300	300	275	260 275	350 275	350 325	380 375
LR Torque (in-lbs) (at 25˚ C)	64.0	65.2	64.0	64.1	64.9 64.0	64.5 67.4	64.2 64.9	63.8 64.5
LR Current (A) (at 25˚ C)	43.4	41.1	40.6	37.5	35.8 36.0	38.3 35.7	35.5 41.2	34.6 37.0
Service Factor	1.25	1.25	1.25	1.25	1.25 1.25	1.25 1.25	1.25 1.25	1.25 1.25

*Design 1 denotes the space constrained design, and design 2 denotes the non-space constrained design. If only one value is listed, then the space constrained design is the same as the non-space constrained design.

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

Figure 0.18 presents the relationship between the MSP and full-load efficiency for the CSCR motor. The max-tech design incorporates a high-grade non-traditional electromagnetic steel alloy (Hiperco 50™) that is much more expensive than the high quality electromagnetic steel alloy used in any of the other designs. 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 0.19.

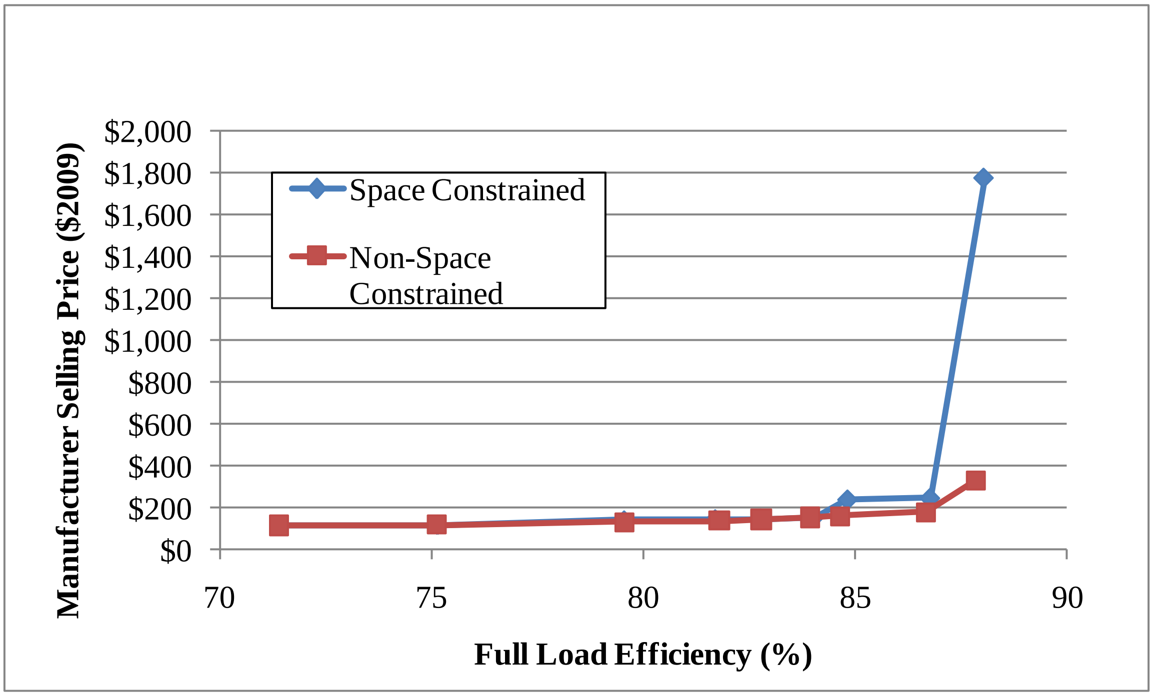

Figure 0.18. Capacitor-Start, Capacitor-Run ¾ Horsepower, 4-Pole, 56-Frame Engineering Analysis Curve, with Maximum Technology Point

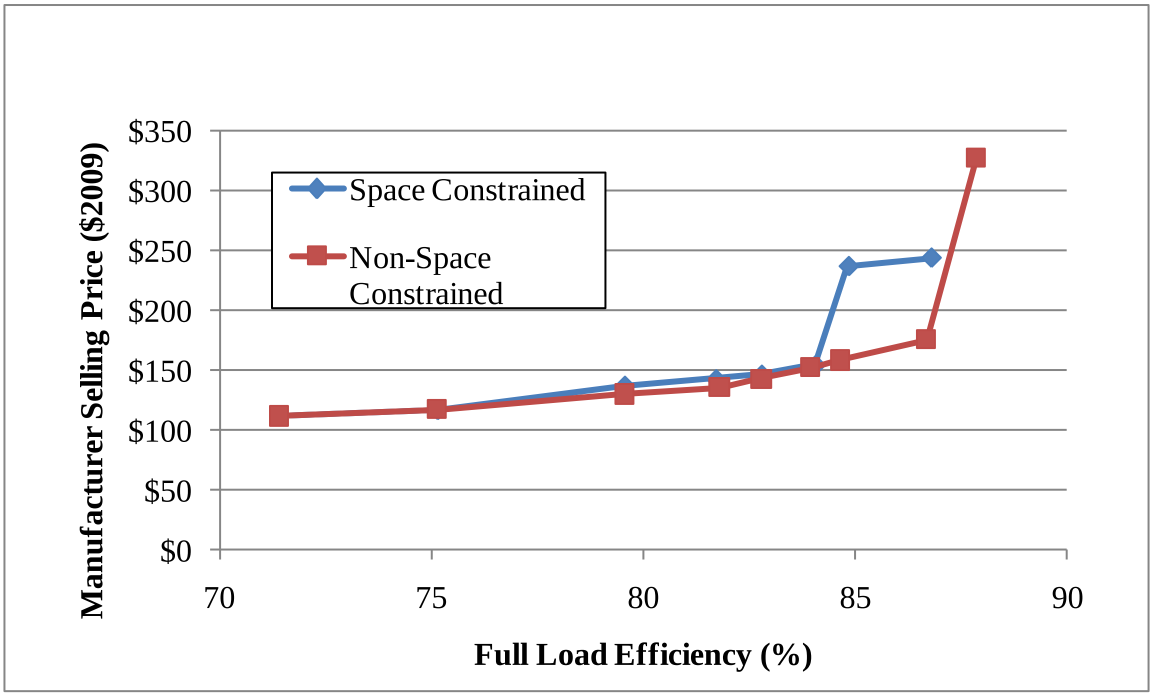

Figure 0.19. Capacitor-Start, Capacitor-Run ¾ Horsepower, 4-Pole, 56-Frame Engineering Analysis Curve, without Maximum Technology Point

Table 0.15 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 max-tech motor, DOE found that the full-load efficiency would increase 16.5 percentage points, for about a 23-percent improvement over the baseline motor. Raising the efficiency to that level caused the MSP to nearly triple, increasing from $111.72 for the baseline model to $327.69 for the non-space constrained max-tech motor. The difference in MSP is significantly greater for the space-constrained max-tech motor, which has a MSP of $1,771.47.

Table 0.15. Efficiency and MSP Data for Capacitor-Start, Capacitor-Run Motor

Efficiency Level	**Efficiency *%* (Design 1 / Design 2)***	**MSP *$* (Design 1 / Design 2)***
Baseline	71.4 %	$ 111.72
EL 1	75.1 %	$ 117.13
EL 2	79.5 % / 79.5 %	$ 137.20 / $ 129.88
EL 3	81.7 % / 81.8 %	$ 142.63 / $ 135.56
EL 4	82.8 % / 82.8 %	$ 146.44 / $ 142.76
EL 5	84.1 % / 84.0 %	$ 154.55 / $ 151.91
EL 6	84.8 % / 84.6 %	$ 236.98 / $ 158.25
EL 7	86.8 % / 86.7 %	$ 244.03 / $ 175.75
EL 8 (Max-tech)	88.1 % / 87.9 %	$ 1,771.47 / $ 327.69

*Design 1 denotes the space constrained design, and design 2 denotes the non-space constrained design. If only one value is listed, then the space constrained design is the same as the non-space constrained design.

Table 0.16 presents some of the design and performance specifications associated with the nine CSCR efficiency levels presented above. Additionally, DOE provides more design details and performance characteristics for CSCR designs in appendix 5A.

Table 0.16. Capacitor-Start, Capacitor-Run, 3/4 Horsepower, 4-Pole, 56-Frame Motor

Parameter (Units)	**Baseline**	**EL1**	**EL2**	**EL3**	**EL4**	**EL5**	**EL6**	**EL7**	**EL8**
-		Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2	Design 1 Design 2
Efficiency (%)	71.4	75.1	79.5 79.5	81.7 81.8	82.8 82.8	84.1 84.0	84.8 84.6	86.8 86.7	88.1 87.9
Power Factor	69.0	77.4	75.9 83.6	82.0 82.8	92.2 95.9	92.1 95.8	92.9 97.4	94.4 97.5	90.0 99.0
Speed (RPM)	1733	1740	1745 1736	1747 1742	1749 1757	1774 1767	1744 1758	1760 1769	1757 1751
Torque (in-lbs)	27.3	27.4	27.1 27.2	27.2 27.0	27.0 26.7	26.4 26.9	27.3 27.2	26.9 26.5	27.2 27.1
Current (A)	9.99	8.51	8.11 7.36	7.35 7.19	6.41 6.11	6.25 6.10	6.25 6.00	5.97 5.74	6.21 5.64
Core Steel	24M56	24M56	24M19 24M56	24M19 24M56	24M19 24M56	24M19 24M56	29M15 24M56	29M15 24M19	Hiperco 50 29M19
Stack Height (in)	3	3.15	3.3 4.1	3.45 4.6	3.6 4.5	3.6 5	3.6 5.5	3.6 4.75	3.6 6
Rotor Material	Al	Al	Al Al	Al Al	Al Cu	Cu Cu	Al Cu	Cu Cu	Cu Cu
Main Wire (AWG)	18	20.5	20.5 20.5	20 21.5	20 21.5	20 21.5	20 21.5	20 21.5	20 21.5
Aux. Wire (AWG)	19	21.5	21.5 21.5	21 21	21 21	21 21	19 21	19 21	21.5 21
Start Cap. (μF)	433	433	433 433	433 515	433 433	400 525	350 525	440 525	433 495
Run Cap. (μF)	7.5	20	20 20	25 25	35 35	40 40	35 40	35 45	35 45
LR Torque (in-lbs) (at 25˚ C)	89.7	91.2	92.0 102.7	95.5 91.3	91.2 90.0	92.8 89.3	98.9 89.6	89.3 89.7	99.2 90.8
LR Current (A) (at 25˚ C)	58.2	58.1	59.4 51.6	59.6 40.9	57.3 49.8	59.0 54.9	46.9 53.1	49.7 54.1	47.9 48.6
Service Factor	1.25	1.25	1.25 1.25	1.25 1.25	1.25 1.25	1.25 1.25	1.25 1.25	1.25 1.25	1.25 1.25

*Design 1 denotes the space constrained design, and design 2 denotes the non-space constrained design. If only one value is listed, then the space constrained design is the same as the non-space constrained design.

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 61 product classes, DOE developed a systematic 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 analysis. It then extrapolated the results of this analysis from the units studied to the other product classes. This section describes the methodology DOE followed to scale to product classes that were not directly analyzed.

To scale to the product classes that were not analyzed, DOE followed a few steps. First, DOE evaluated the efficiency relationships presented in the proposed standards provided by NEMA. DOE then compiled efficiency data for as many manufacturers and product classes as possible, and filtered the data to ensure an accurate representation of the small electric motors that are covered by the statute. Next, DOE modeled all the efficiency data in terms of motor losses and used a best-fit curve to project values to fill in any potential gaps in data. An independently accredited laboratory validated the efficiency data by testing certain small electric motors according to the applicable IEEE test procedures: IEEE 112 (test methods A and B) for polyphase motors and IEEE 114 for single-phase motors. Finally, DOE scaled the results of the engineering analysis based on the relationships found from the combined NEMA data, catalog data, and test data.

5.6.1 NEMA Provided Efficiency Data

One new source of data that DOE utilized in the final rule but not in the NOPR was the NEMA recommended standard levels for polyphase, CSIR, and CSCR motors built in small frames (42 and 48 frames) and in 56 frames. These recommended standard levels included efficiencies for motors with horsepower ratings less than and equal to 1 horsepower and with two-, four-, or six pole configurations. DOE first examined this data to see how it compared to the efficiency data of motors currently on the market. DOE noted that the efficiency relationships that NEMA presented between product classes were comparable to the market data that DOE had collected for the NOPR. For this reason, DOE felt that NEMA's recommended standard levels could be used to establish appropriate efficiency (or loss) relationships for lower horsepower polyphase, CSIR, and CSCR motors.

For the high horsepower (greater than or equal to 1 horsepower) polyphase motors, DOE considered the relationships found in the NEMA premium standards for electric motors. As seen in Table 0.17, the majority of the NEMA Premium standards between 1 and 3 horsepower are based on motors with a frame size in the 140T series, which has the same foot to shaft dimension as the 56 frame motor. Therefore, for these 140T series product classes, DOE used NEMA premium efficiencies to develop relationships across horsepower ratings and poles. DOE did not use the efficiency relationships found from NEMA premium classes associated with larger frame sizes (182T). For these horsepower/pole configurations, DOE felt that it did not have sufficient efficiency data to determine appropriate scaling relationships. Thus, though efficiency generally increases with horsepower, in order to ensure that all efficiency levels were technologically feasible, DOE decided that the 3 horsepower, four-pole motor and 1½ horsepower, two-pole motor would have the same minimum efficiency standards as the 2 horsepower, four-pole motor and 1 horsepower, two-pole motor, respectively.

Table 0.17 Frame Sizes Associated with NEMA Premium Standards

Motor Horsepower/Standard Kilowatt Equivalent	Six Poles	Four Poles	Two Poles
1 hp/0.75 kW	56	143T	145T
1½ hp/1.1 kW	143T	145T	182T
2 hp/1.5 kW	145T	145T	
3 hp/2.2 kW	145T	182T	

5.6.2 Market Efficiency Data

To determine the existing efficiency relationships between product classes as identified by motors on the market, DOE examined all the publicly available efficiency data for small electric motors covered by this rulemaking. DOE compiled available catalog data and online listings for polyphase, CSIR, and CSCR motors to see how efficiency changes across different pole configurations and with varying horsepower ratings. DOE developed a database of over 3,000 motors built in a NEMA two-digit frame sizes. This database was filtered to create a comprehensive list of motors that met the statutory definition of a small electric motor. DOE also filtered the database to only include efficiency data for the smallest frame series seen for each product class. The smallest frame series for a given product class is the most restricted frame series in terms of possible efficiency. The reason for this is that there is less room to add core material (in terms of diameter), which helps increase efficiency, therefore any efficiency the smallest frame series motor can achieve should also be achievable for the larger frame series in the same product class. Additionally, individual manufacturer motor lines were examined independently so that design characteristics (*e.g.* steel grade) would be consistent. Since each manufacturer was looked at individually, if a manufacturer did not have a nearly complete product line, or if the manufacturer did not provide enough efficiency data to create an accurate assessment of the product line, then that manufacturer's data was not included in the initial efficiency relationship data set.

5.6.3 Independently Tested Motor Results

At the time of this data collection and analysis, there were no energy-efficiency standards or mandated test procedures for small electric motors. Therefore, when one manufacturer lists efficiency in their catalog it was not necessarily calculated and reported in the same way that another manufacturer calculates and reports it. So, DOE contracted an independently accredited electric motor testing company. In addition to using catalog data and online listings to determine the existing efficiency relationship between product classes, DOE purchased and tested a sample product line of polyphase and CSIR motors to verify efficiency relationships. DOE was unable to purchase and test a complete product line of CSCR motors because no manufacturers currently offer a complete product line of this motor category. This issue is discussed further in Section 5.6.6 dealing with CSCR scaling. This data was intended to validate the efficiency relationships seen across product classes, not necessarily to confirm the value of efficiency listed by the manufacturer. Results of this testing are available in appendix 5A.

5.6.4 Modeling Small Electric Motor Efficiency

After compiling the NEMA, catalog, and test data, DOE modeled the data and began drawing conclusions about the relationship between product class and efficiency. To do this DOE converted efficiency into motor losses using the equation: $(100/\mu) - 1$, where μ is full-load efficiency. By converting the efficiency data into motor losses, DOE could generate the most accurate line of best fit. DOE used a power equation to model motor losses and then plotted the results for the NEMA values, the manufacturer catalog data, and the tested motors on graphs with logarithmic axes. Using the generated equations, DOE interpolated and extrapolated the catalog and test data to approximate data for any gaps of information. This allowed DOE to generate complete sets of data, a set being the 24 product classes within a motor category. After modeling motor losses for the various sources of efficiency data, DOE evaluated the data from each pole of each data source independently to determine how best to scale each pole.

5.6.5 Scaling Polyphase Motor Data

As mentioned previously, DOE was able to use the efficiency relationships found in the NEMA recommended and NEMA Premium levels for polyphase motors. Since the combination of these two data sets spanned the majority of polyphase product classes, and since they represented efficiency relationships evidenced in the market and confirmed by NEMA, DOE utilized this data to develop its polyphase scaling.

First, DOE graphed the motor losses of the NEMA recommended levels and the NEMA premium levels on a log-log chart. DOE then used a best-fit line to project motor losses from NEMA's recommened values so data would be available up to the 1 horsepower rating. DOE then aligned the recommended 4-pole values with the NEMA premium values by shifting their motor losses based on the percentage change necessary to equate their 4-pole, 1 horsepower values. Since the NEMA recommended values closely aligned with the NEMA premium values, this was a minimal shift of only -3.8 percent. DOE then applied this same percentage change to the 2-pole and 6-pole product classes to maintain the relationship evident across poles in NEMA's recommended values. This gave DOE a table of efficiency values that categorizes the relationships between poles and horsepower ratings that could be expected on the market for polyphase motors. Figure 0.20 shows the 4-pole values recommended by NEMA with the projected 1 horsepower value and the resulting shifted NEMA recommended values based on the -3.8 percent shift in motor losses.

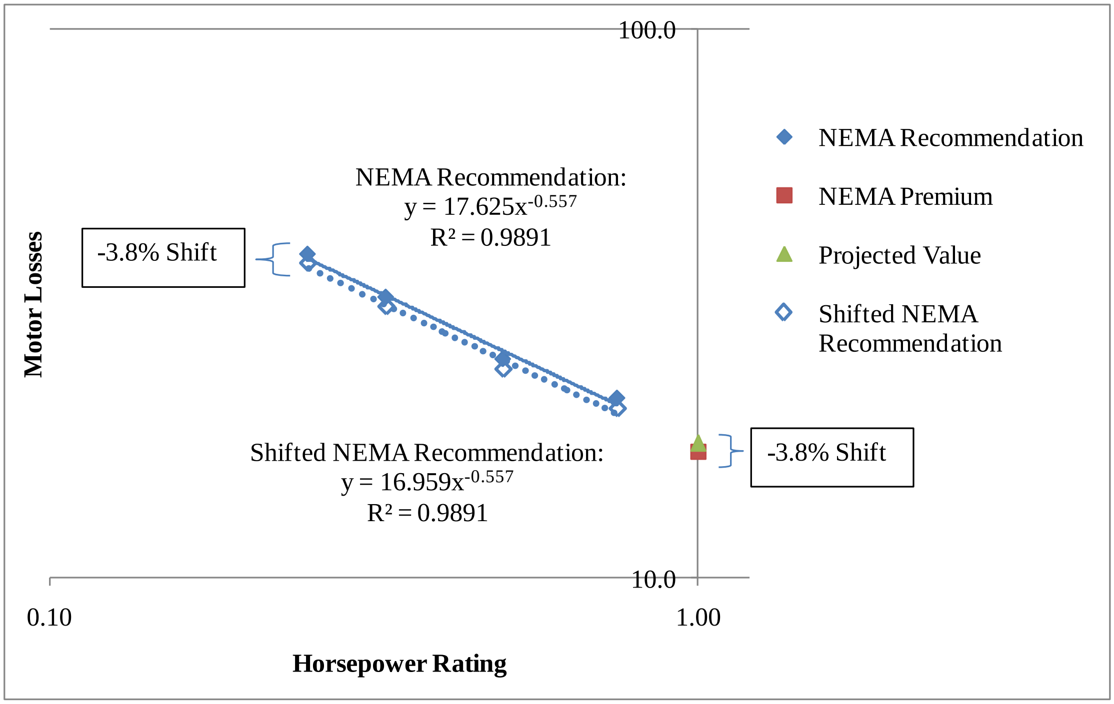

Figure 0.20 NEMA Recommended 4-Pole Values Shifted to NEMA Premium

Using the table of motor losses derived by shifting each line of NEMA recommended motor loss values by -3.8%, combined with the NEMA premium values, DOE was then able to scale this table by the percentage change in motor losses needed to reach the new 4-pole, 1 horsepower efficiency level specified for each TSL. This was done by adjusting the motor loss value for each product class by the percentage change in motor losses between the 4-pole, 1 horsepower product class and the desired scaled value. For example, to scale to a value of 83-percent efficiency, DOE would convert into motor losses (20.5), compare that number to the motor losses in its reference table (17.0), and then apply the relevant percentage shift (21%) to all values in its table of motor losses.

After the motor losses for each product class were scaled, DOE adjusted for frame size to ensure that the efficiency level designated for each product class considered the most restrictive frame size available in that product class. To do this, DOE adjusted the scaled motor loss values of the relevant product classes by the percentage difference between the 56 frame motors and the 48 and 42 frame motors evidenced in NEMA's recommended efficiency levels. This percentage difference is roughly equal to a 20 percent increase in motor losses when going from a larger frame size to a smaller one. After doing this, DOE converted the scaled motor losses back to efficiency, and used these values as the scaled efficiencies for polyphase motors.

5.6.6 Scaling Single-Phase Motor Data

The methodology DOE used for single-phase motors was very similar, and DOE relied on the relationships presented in the NEMA recommended efficiency levels for the lower horsepower ratings. In the absence of any previously standardized efficiency levels above 1 horsepower (such as provided in the NEMA premium table), DOE examined its catalog data and test data and considered the manufacturer with the most conservative change in efficiency between horsepower ratings to characterize efficiency relationships at the higher horsepower ratings. This equated to the manufacturer with the flattest slope when plotting motor losses on a log-log plot. Each pole configuration was examined independently to ensure that scaling would be specific to the considered pole.

As mentioned in the NOPR, DOE was unable to locate sufficient market data for CSCR motors. This is because manufacturers do not currently make CSCR motors for all of the horsepower and pole configuration combinations that DOE uses to define its product classes. However, the data that DOE reviewed indicated that CSCR motors exhibit efficiency relationships similar to CSIR motors, but shifted to higher efficiency levels. This relationship can be seen in Figure 0.21. For these reasons, DOE decided to continue to utilize CSIR market data to characterize the efficiency relationships present in the CSCR market. However, for the lower horsepower ratings DOE utilized the CSCR data provided by NEMA.

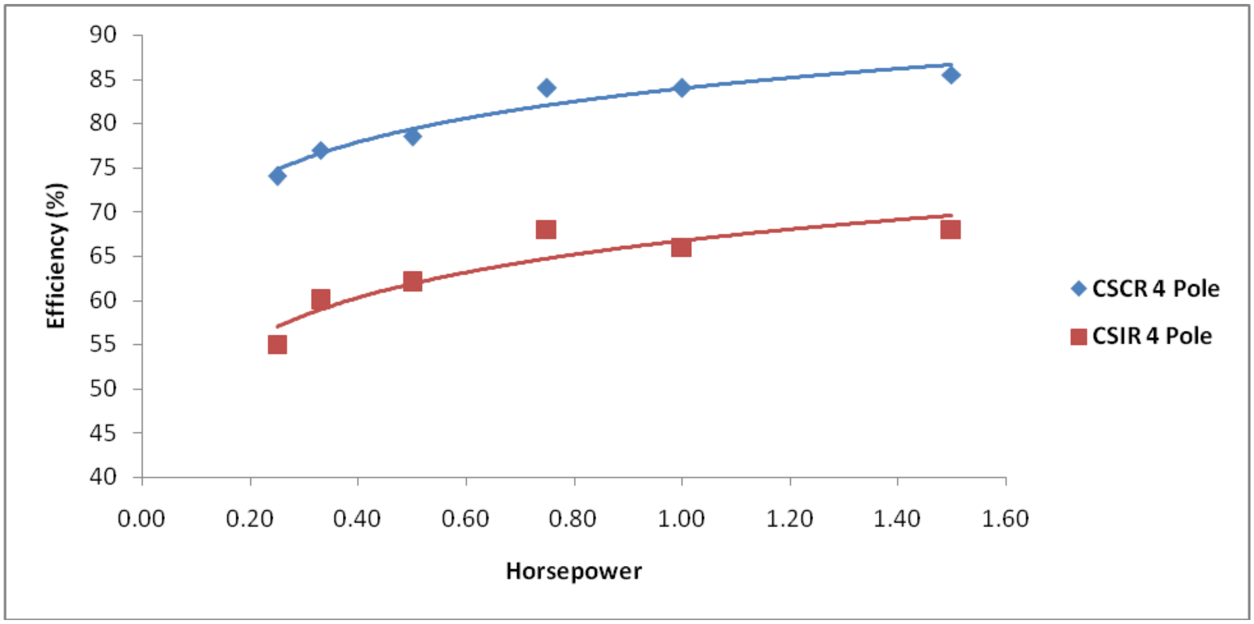

Figure 0.21 Four Pole CSIR Efficiency vs. Four Pole CSCR Efficiency

DOE took the manufacturer with the most conservative efficiency relationships across the higher horsepower ratings for a given pole configuration and plotted its motor losses on a log-log plot alongside the NEMA recommended values for the lower horsepower ratings. Then, DOE determined the percentage shift necessary to align the manufacturer data with the NEMA recommended levels and applied this percentage change to the manufacturer data. By maintaining the relationships evidenced across pole configurations in the NEMA recommended values, DOE ensured accurate scaling across pole configurations. Figure 0.22 shows an example of this shift for the 4-pole, CSIR motor data. After shifting values for each pole configuration, DOE had developed a reference table of motor losses for CSIR motors and a separate reference table for CSCR motors.

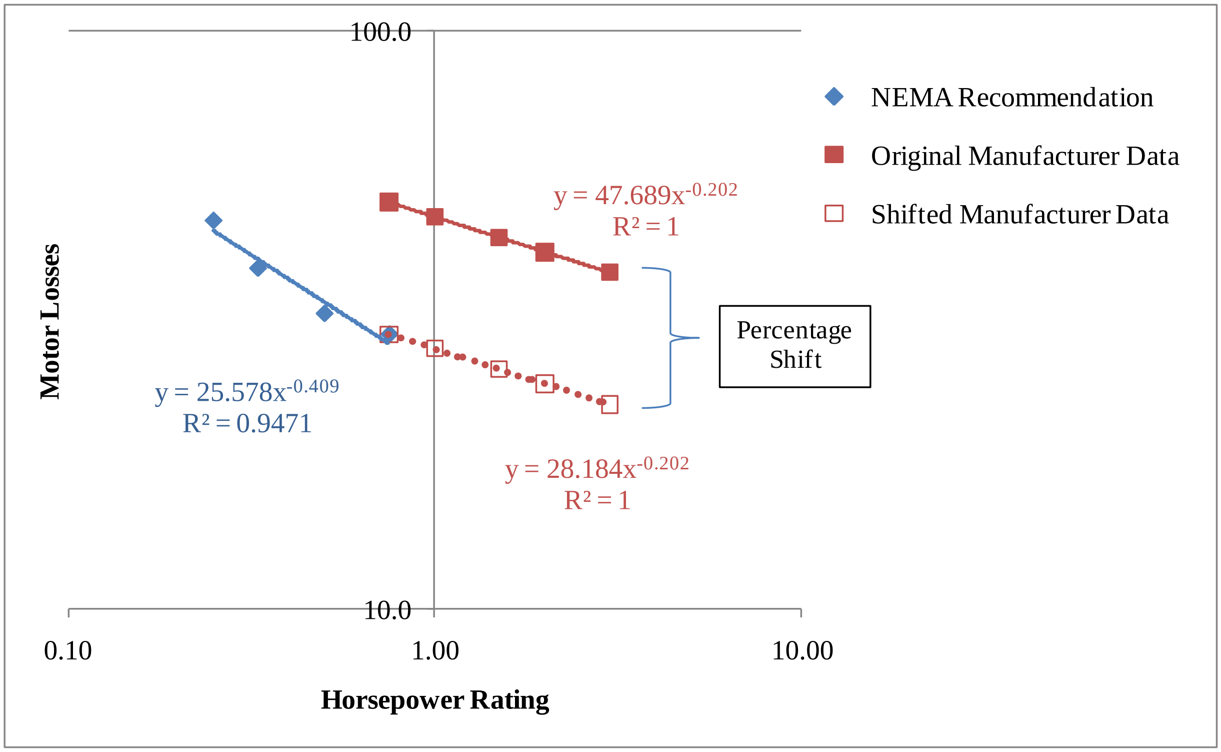

Figure 0.22 Manufacturer 4-Pole Values Shifted to NEMA Recommended Values

DOE then followed the same methodology employed in the polyphase scaling. It adjusted its reference table of motor losses by the percentage change necessary to reach the new 4-pole, ½ horsepower value for CSIR motors, or the new 4-pole, ¾ horsepower value for the CSCR motors. Similar to polyphase motors, the percentage change calculated for the representative product class was applied to each scaled product class.

Once these motor losses were scaled, DOE adjusted for frame size to ensure that the efficiency level designated for each product class considered the most restrictive frame size available in that product class. After doing this, DOE converted the scaled motor losses back to efficiency and used these values as the scaled efficiencies for CSIR or CSCR motors.

REFERENCES

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

[2] U.S. Department of Labor, Bureau of Labor Statistics, Producer Price Indices. Last accessed January 20, 2010. <http://www.bls.gov/ppi>.

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