CHAPTER 5. ENGINEERING ANALYSIS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

A	ampere
AC	alternating current
AWG	American wire gauge
BOM	bill of materials
CSL	candidate standard level
DOE	United States Department of Energy
EISA	Energy Independence and Security Act of 2007
IEC	International Electrotechnical Commission
in	inch
lbs	pounds
M*	M15, M19, M36, M47, M56 - grade of core steel
MSP	manufacturer selling price
Nm	Newton meter
NCI	Navigant Consulting, Inc.
NEMA	National Electrical Manufacturers Association
NIA	national impact analysis
RPM	revolutions per minute
SEC	Securities and Exchange Commission
SME	subject matter expert
TSD	technical support document
U.S.	United States
V	volt

CHAPTER 5. SCREENING ANALYSIS

5.1 INTRODUCTION

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

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 electric 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 electric motors studied.

At its most basic level, the output of the engineering analysis is a curve that estimates the MSP 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 a manufacturer's costs associated with increasing efficiency levels for an electric motor. The relationship presented in this chapter assumes an ideal situation, where the manufacturer does not incur any costs associated with retooling, product redesign, training, or marketing associated with incorporating design changes to its equipment 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 that the manufacturer would incur when complying with mandatory efficiency standards. For 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 electric motors selected from all motors considered for energy conservation standards. As discussed in chapters 2 and 3 of this TSD, the electric motors in the scope of coverage of this rulemaking include single-speed, squirrel-cage induction, alternating current (AC), polyphase motors from 1 to 500 horsepower and National Electrical Manufacturers Association (NEMA) Design A, B, and C electric motors, including fire pump electric motors. The engineering analysis selected three NEMA Design B electric motors to analyze the NEMA Design A and B equipment class group and two NEMA Design C electric motors to analyze the NEMA Design C equipment class group. The fire pump electric motor equipment class group will be based on the three NEMA Design B electric motors. DOE also presents the methodology, inputs, and results associated with the development of MSP versus efficiency curves for each of the representative electric 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 REPRESENTATIVE UNITS ANALYZED

Due to the large number of equipment classes, DOE did not directly analyze all covered electric motors. Instead, DOE selected certain equipment classes to directly analyze after reviewing electric motors shipments, examining manufacturers' catalog data, and soliciting feedback from interested parties. The equipment classes that DOE directly analyzes and focuses its engineering analysis on are referred to as representative units. Table 5.1 shows the equipment class groups discussed in preliminary TSD chapter 3 and the corresponding electric motor designs they encompass. As mentioned above, DOE selected three representative units to analyze in equipment class group 1 and two representative units in equipment class group 2. For equipment class group 3, DOE plans on developing any potential amended energy conservation standards based off of its analysis of equipment class group 1 because fire pump electric motors are required to meet National Electrical Manufacturers Association (NEMA) Design B performance standards.

Table 5.1 Electric Motor Equipment Class Groups

Equipment Class Group	Electric Motor Design Type	Horsepower Rating	Pole Configuration	Enclosure
1	NEMA Design A & B*	1-500	2, 4, 6, 8	Open
				Closed
2	NEMA Design C*	1-200	2, 4, 6, 8	Open
				Closed
3	Fire Pump*	1-500	2, 4, 6, 8	Open
				Closed

*Includes International Electrotechnical Commission (IEC) equivalent design types.

DOE considered each of the characteristics listed in Table 5.1when selecting its representative units. The sections that follow describe the decisions that DOE made with respect to each of these electric motor characteristics.

5.2.1 Electric Motor Design Type

For equipment class group 1 that includes NEMA Design A and B electric motors, DOE only selected NEMA Design B motors as representative units to analyze in the engineering analysis. DOE chose NEMA Design B electric motors because NEMA Design A electric motors can generally meet NEMA Design B efficiency levels due to their less stringent locked-rotor current limits. In other words, NEMA Design B motors slightly limit the incremental increase in energy conservation standards that could be technologically feasible. However, by directly analyzing NEMA Design B motors, it ensures that any potential amendments to the current energy conservation standards could be met by all motors covered in equipment class group 1. Additionally, NEMA Design B units have much higher shipment volumes than NEMA Design A motors. Figure 5.1 shows the relative shipments of each electric motor design type, which demonstrates that NEMA Design B motors constitute the vast majority of all shipments with a market share of 98.7 percent. Finally, by choosing NEMA Design B motors, DOE could also apply the results of its equipment class group 1 analysis to its equipment class group 3 analysis because fire pump motor designs are held to very similar design constraints as NEMA Design B motors.

For equipment class group 2, DOE selected two representative units to analyze directly. Because Design C is the only NEMA design type covered by this equipment class group, DOE only selected NEMA Design C motors for analysis as its representative units.

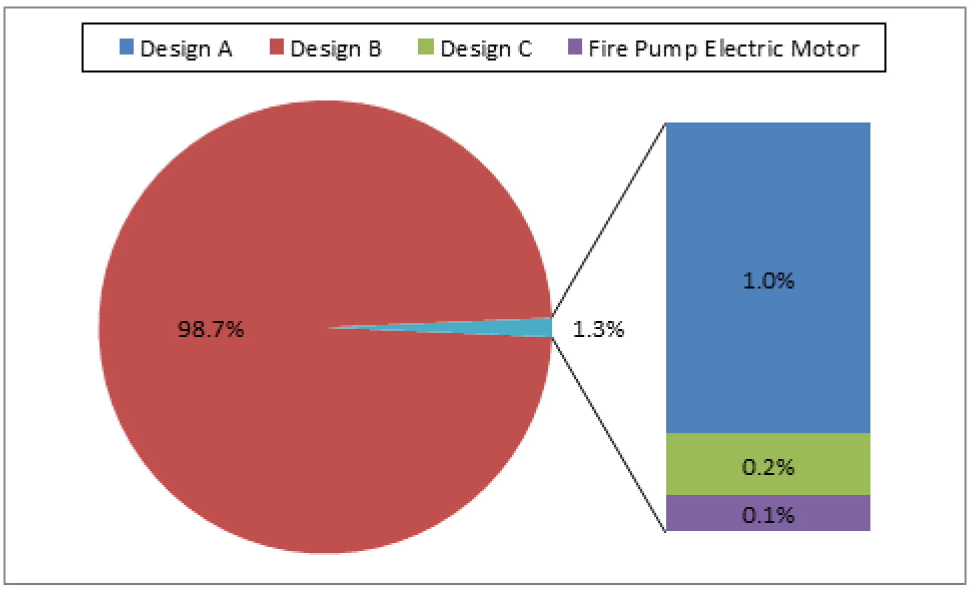

Figure 5.1 Electric Motor Shipments by Design Type for 2011

5.2.2 Horsepower Rating

Horsepower rating is an important equipment class setting criterion, which DOE received multiple comments about when developing its representative units. When DOE selected its preliminary analysis representative units, DOE chose those horsepower ratings that constitute a high volume of shipments in the market and provide a sufficiently wide range upon which DOE could reasonably base a scaling methodology. For NEMA Design B motors, for example, DOE chose 5-, 30-, and 75-horsepower-rated electric motors to analyze as representative units. DOE selected the 5-horsepower rating because it is the rating with the highest shipment volume of the electric motors considered. Figure 5.2 shows shipments of electric motors broken down by horsepower rating and demonstrates that the 5-horsepower rating constituted nearly 15 percent of shipments in 2011. DOE selected the 30-horsepower rating as an intermediary between the small and large frame number series electric motors. For the largest frame number series, DOE elected to analyze a 75-horsepower rated electric motor. DOE believes that this rating is an appropriate choice to represent the highest horsepower ratings because there tends to be minimal change in efficiency at the highest horsepower ratings. For consecutive horsepower ratings above 75, the nominal efficiencies that motors must meet in order to be deemed NEMA Premium tend to repeat.

For NEMA Design C electric motors, DOE only selected two horsepower ratings because of the relatively low shipment volumes. As with NEMA Design B motors, DOE elected to analyze the 5-horsepower rating because of its relatively high market share. For an upper bound, DOE selected the 50-horsepower rating.

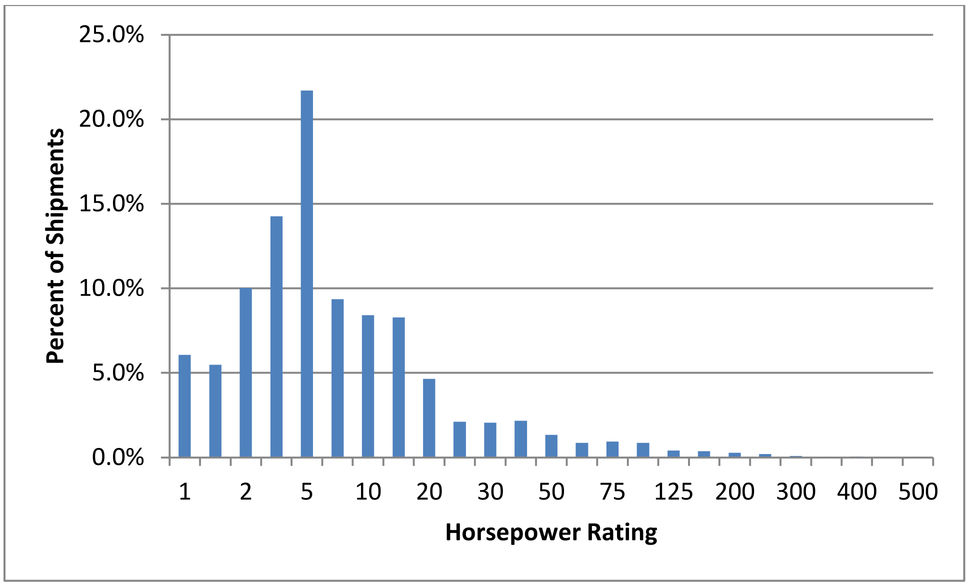

Figure 5.2 Electric Motors Shipments by Horsepower Rating for 2011

5.2.3 Pole-Configuration

Pole-configuration is another important equipment class setting criterion which DOE had to consider when selecting its representative units. For the preliminary analysis, DOE selected 4-pole motors for all of its representative units. DOE chose not to vary the pole configuration of the various representative units it analyzed because it believed that doing so would provide the strongest relationship upon which to base its scaling. By keeping as many design characteristics constant as possible, DOE could more accurately identify how design changes affect efficiency across horsepower ratings. For example, if DOE compared the NEMA Premium efficiencies of a 5-horsepower, 4-pole electric motor and 50-horsepower, 6-pole electric motor it would be difficult to determine how much of the difference was due to the change in horsepower rating and how much was due to the change of pole configuration. Additionally, DOE believes that the horsepower rating-versus-efficiency relationship is the most important (rather than pole configuration and enclosure-type versus efficiency) because there are significantly more horsepower ratings to consider. Finally, as illustrated in Figure 5.3, 4-pole electric motors constitute the largest fraction of the electric motors market. Electric motors built with 4-poles accounted for 69 percent of shipments in 2011, which was more than 2-pole, 6-pole, and 8-pole motor shipments combined.

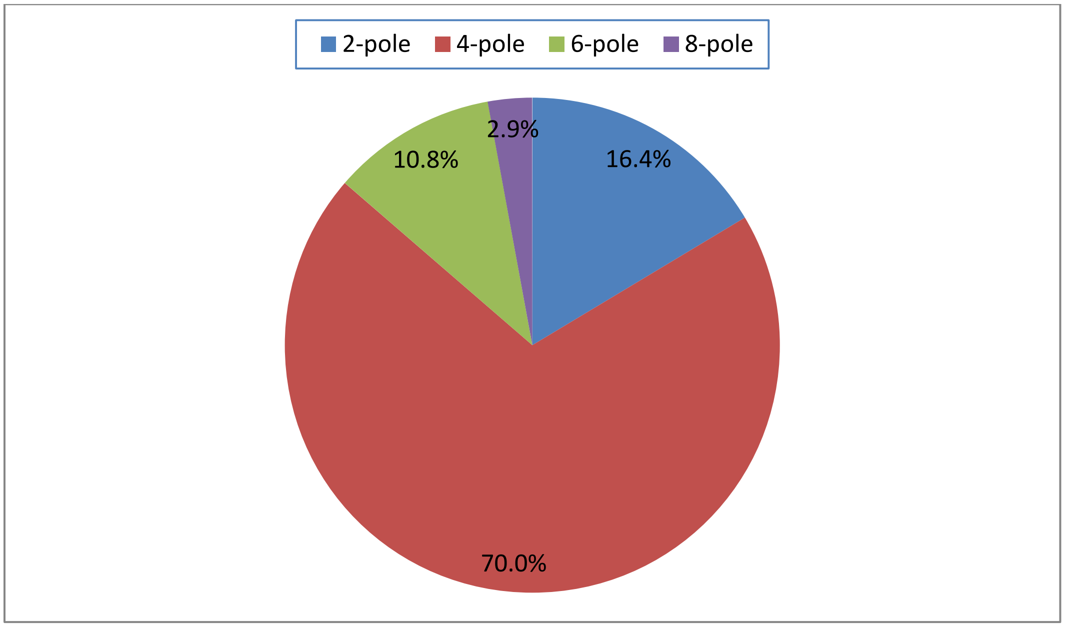

Figure 5.3 Electric Motor Shipments by Pole Configuration for 2011

5.2.4 Enclosure Type

The final equipment class setting criterion that DOE had to consider when selecting its representative units was enclosure type. For the preliminary analysis, DOE elected to only analyze electric motors with totally enclosed, fan-cooled (TEFC) designs rather than open designs for all of its representative units. DOE selected TEFC motors because, as with pole configurations, DOE wanted as many design characteristics to remain constant as possible. Again, DOE believed that such an approach would allow it to more accurately identify the reasons for efficiency improvements. Finally, TEFC electric motors represented more than three times the shipment volume of open motors. Figure 5.4 shows the relative shipments of open and enclosed motors in the year 2011.

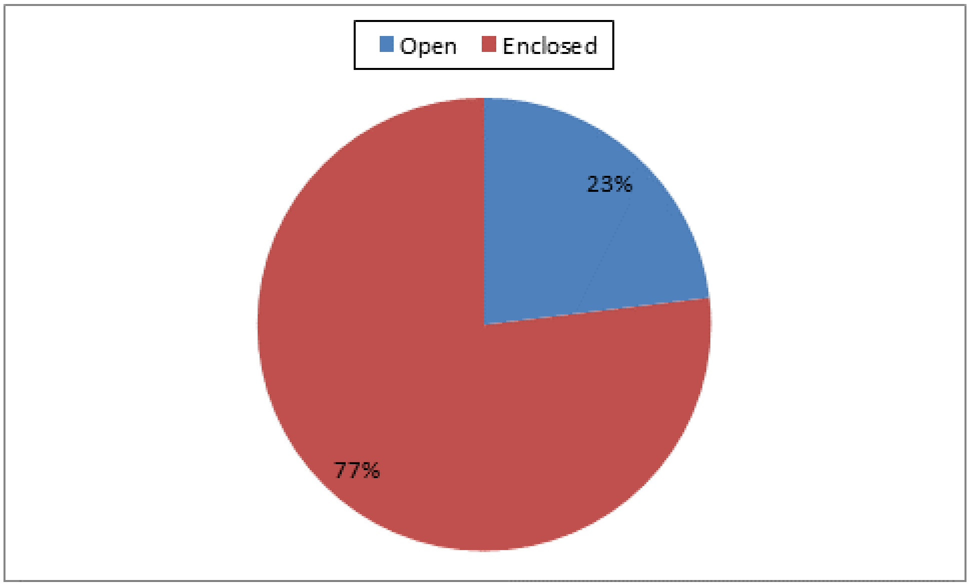

Figure 5.4 Electric Motor Shipments by Enclosure Type for 2011

As addressed above, when identifying which electric motors to evaluate, DOE considered equipment classes that represented motors with a significant volume of shipments. DOE also considered the necessity for scaling its engineering results. Therefore, DOE selected electric motors that would minimize any error that might be introduced through extrapolating between horsepower ratings, pole configurations, and enclosure types. As is discussed in section 5.7, DOE scaled the engineering analysis results of its analyzed representative units to all of the other, not-analyzed, equipment classes. Such scaling is necessary for the national impacts analysis (NIA). For more information on the NIA, please see preliminary TSD chapter 10. Table 5.2 presents the major design characteristics of the five representative units that DOE analyzed and will discuss in detail throughout this engineering analysis.

Table 5.2 Design Characteristics of the Five Representative Units Analyzed

Equipment Class Group Represented	Electric Motor Design Type	Horsepower Rating	Pole Configuration	Enclosure
1 and 3	NEMA Design B	5	4	Totally Enclosed, Fan Cooled
1 and 3	NEMA Design B	30	4	Totally Enclosed, Fan Cooled
1 and 3	NEMA Design B	75	4	Totally Enclosed, Fan Cooled
2	NEMA Design C	5	4	Totally Enclosed, Fan Cooled
2	NEMA Design C	50	4	Totally Enclosed, Fan Cooled

5.2.5 Equipment Class Group 1 (NEMA Design A and B Electric Motors)

DOE decided to focus the analysis of NEMA Design A and NEMA Design B electric motors on three representative units. When selecting these representative units, DOE used the data in Figure 5.2 and Figure 5.11 to select three representative units with high shipping volume that also evenly cover the entire range of horsepower ratings in the scope of this analysis. The graph in Figure 5.11 shows the average efficiencies of 4-pole, enclosed electric motors versus horsepower rating. This data was based on DOE's electric motor database which was compiled from the most current electric motor manufacturer catalog data available. DOE analyzed this curve and segmented the graph into three primary sections.

5.2.6 Equipment Class Group 2 (NEMA Design C Electric Motors)

When selecting the representative units for equipment class group 2 (NEMA Design C electric motors), DOE referred again to Figure 5.2 which also represents the shipment volumes of NEMA Design C electric motors. Based on Figure 5.2, DOE selected a 5-horsepowerelectric motor again because of its high volume of shipments. To cover the higher horsepower ratings, DOE selected a 50-horsepower electric motor. DOE chose to base the analysis on the NEMA Design C equipment class group on two electric motors instead of three due to the lower production volumes of NEMA Design C electric motors and therefore somewhat limited equipment selection. DOE selected the 50-horsepowerrating because it falls between the 30-horsepower and 75-horsepowerratings selected as representative units for equipment class group 1.

5.2.7 Equipment Class Group 3 (Fire Pump Electric Motors)

According to National Fire Protection Association (NFPA) 20,*Standard for the Installation of Stationary Pumps for Fire Protection*, a motor that is used with a fire pump system must comply with NEMA MG1, comply with NEMA Design B standards, and be listed for fire pump service. So, with a few exceptions, fire pump electric motors are very similar to NEMA Design B electric motors. Namely, fire pump electric motors are not required to shut off if they are overheating, and they require more rigorous start/stop capabilities than general purpose NEMA Design B electric motors. Aside from these operating differences, fire pump electric motors are electromechanically similar to NEMA Design B electric motors. Therefore, DOE decided to base the analysis of fire pump electric motors on the engineering data produced from the representative units chosen for equipment class group1.

5.3 BASELINE AND CANDIDATE STANDARD LEVELS OF EFFICIENCY

For each representative unit selected, DOE identified a specific baseline electric motor as a fundamental design against which it would apply design changes to improve the electric motor's efficiency. DOE chose the baseline electric motors to represent the typical characteristics of electric motors in the equipment class of the corresponding representative unit. The baseline efficiency level is used to determine energy savings and changes in price associated with moving to higher efficiency levels. Energy efficiency levels are termed "candidate standard levels" (CSLs) and are intended to help characterize the cost-efficiency relationship. Table 5.3 shows these efficiency levels for each of DOE's selected representative units.

Table 5.3 Baseline Efficiency Ratings of Representative Units

Basic Characteristics of Electric Motors Analyzed	Baseline Efficiency %	Equipment Class Group
Design B, 5-horsepower, 4-pole, enclosed frame	82.5	1*
Design B, 30-horsepower, 4-pole, enclosed frame	89.5	1*
Design B, 75-horsepower, 4-pole, enclosed frame	93.0	1*
Design C, 5-horsepower, 4-pole, enclosed frame	87.5	2
Design C, 50-horsepower, 4-pole, enclosed frame	93.0	2

*Analysis of equipment class group 3 will be based on these representative units.

As discussed in chapters 2 and 3, DOE intends to expand the scope of energy conservation standards to include motors that were not previously covered by regulation. Those motor types not previously covered and that are now within the scope of coverage are listed in chapter 3 of the preliminary TSD. DOE used a motor database of efficiencies and up-to-date manufacturer motor catalogs to find motors with the lowest market efficiency. Since the expanded scope of energy conservation standards includes motors not previously subject to efficiency standards, DOE selected motors whose baseline efficiencies were below the lowest energy conservation levels currently enforced for any motors (levels most recently prescribed by EISA 2007). DOE observed NEMA Design B vertical, hollow-shaft motors, currently outside the scope of regulation, with efficiency levels listed in Table 5.3. For the NEMA Design C equipment class group, DOE selected NEMA MG1-2011 Table 12-11 values as baseline efficiency levels. This approach is based on the lowest efficiency values DOE observed in motor catalogs for NEMA Design C motors. The NEMA Design C representative motors with the lowest observed efficiencies are also listed in Table 5.3.

Should DOE not find any economic justification for amended energy conservation standards above the baseline efficiency level, subtype I and subtype II motors would remain subject to the same efficiency levels (i.e., different from each other) mandated by EISA 2007. Additionally, DOE notes that although the efficiencies in Table 5.3 represent the baseline, DOE's efficiency distribution for equipment class group 1 shows a significant portion of motors already above the baseline efficiency level.

5.3.1 Candidate Standard Levels of Efficiency

NEMA MG1-2011 contains a table of standardized "nominal" full load efficiency values, Table 12-10, from which manufacturers may choose a value to label and market their electric motors. NEMA uses these standardized values of efficiency because of the variability in the performance of materials used in electric motors, such as electrical steel and copper, and the laboratory to laboratory test variation that can occur. Because of these possible sources of performance variation, NEMA and its members in industry use these standardized values of efficiencies, with associated guaranteed minimum values of efficiencies, to represent a specific electric motor model's efficiency with a "band" of efficiency. The standardized values of NEMA nominal efficiencies found in Table 12-10 of NEMA MG1-2011 are fairly evenly spaced in terms of motor losses.[a] Each higher, incremental level of nominal efficiency represents a reduction in motor losses of roughly 10 percent. DOE followed a similar pattern when developing its higher CSLs (i.e., those above NEMA MG1-2011 Table 12-12 and Table 12-11).

As mentioned earlier, DOE selected a baseline model for each representative unit as a reference point against which to measure changes that may result from increasing an electric motor's efficiency. Each increase in efficiency over the baseline level that DOE analyzed was assigned a CSL number. For the preliminary analysis, DOE based its baseline efficiency level, or CSL 0, on the lowest efficiency levels observed in motor catalog data for the motors DOE plans on including in the expanded scope of conservation standards. DOE selected five additional incremental CSLs for equipment class group 1 and three additional incremental CSLs for equipment class group 2 based on other industry specifications, market data, and software modeling.

Table 5.4 shows the CSLs for equipment class group1that DOE used for electric motors during the preliminary analysis. DOE based its first incremental CSL (CSL 1) on NEMA MG1-2011, Table 12-11 and Table 20-A[b], which specify the nominal efficiency levels for motors that NEMA classifies as "energy efficient." Table 12-11 is equivalent to the EPACT 1992 levels for 1 to 200 horsepower NEMA Design B electric motors and the EISA 2007 levels for NEMA Design B electric motors with a horsepower rating greater than 200. EISA 2007 also mandated that general purpose electric motors (subtype I) from 1 to 200 horsepower meet efficiency levels

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[a] Motor losses are calculated with the formula $(1/\eta)-1$, where η represents the value of efficiency.

[b] NEMA MG1-2011 Table 20-A includes efficiency levels for 6- and 8-pole motors at higher horsepower ratings (between 300 and 500 horsepower) that are omitted from Table 12-11. Table 20-A is a new addition to NEMA MG1-2011, and therefore the efficiency levels it specifies are not part of the most recent conservation standards set by EISA 2007.

that correspond to NEMA MG1-2011, Table 12-12 (i.e., equivalent to NEMA Premium levels). However, equipment class group 1 includes motors that are considered general purpose electric motors (subtype II). For these electric motors, EISA 2007 mandated efficiency standards equivalent to Table 12-11, which is why DOE believes Table 12-11 is the appropriate CSL 1 to represent equipment class group 1.

Table 5.4 Candidate Standard Levels

CSL Number	CSL Name	NEMA MG1-2011 Table	Note
0	Baseline	--	Lowest observed efficiency under expanded scope
1	Standard	12-11 & 20-A	EPACT 1992 requirement, with additional efficiency levels added in NEMA MG1-2011
2	Premium	12-12 & 20-B	EISA 2007 requirement for general purpose electric motors (subtype I), with additional efficiency values added in NEMA MG1-2011
3	Best-in-Market	--	One NEMA nominal efficiency level improvement relative to the Premium level
4	Incremental	--	One NEMA nominal efficiency level improvement relative to the Best-in-Market
5	Maximum Technology	--	One NEMA nominal efficiency level improvement relative to CSL 3

DOE based its second incremental CSL (CSL 2) on the NEMA Premium efficiency levels, found in NEMA MG1-2011 Tables 12-12 and 20-B. These tables typically represent a two or three NEMA band improvement above the previously mandated EPACT 1992 levels displayed in NEMA MG1-2011 Table 12-11. The third incremental CSL (CSL 3) is based on motors with the highest efficiencies observed in DOE's motor database and up-to-date motor catalogs. Therefore CSL 3 motors have the "best-in-market" efficiencies for equipment class group 1 (ECG 1). This level was generally one NEMA band above the NEMA Premium level, or CSL 2. This level represents the best or near best efficiency level at which current manufacturers are producing electric motors. CSL 4 represents an incremental level between the maximum available efficiency and the maximum technology ("max-tech") CSL. CSL 4 is based on a theoretical efficiency achievable using technologically feasible design options that were not screened out. CSL 5 represents the maximum technologically available or "max-tech" efficiency level. CSL 5 is based on a motor which incorporates a combination of the best materials potentially available for high-production motor manufacturing. This includes low-loss electrical steel and copper rotor motor technology. DOE based its value of efficiencies for CSL 4 and 5 on computer-modeled designs and subject matter expert (SME) feedback.

The CSLs for NEMA Design C motors (equipment class group 2) were selected differently than for equipment class group 1. For equipment class group 2, DOE selected the NEMA MG1-2011 Table 12-11 values as the baseline efficiency level. This approach is based on the lowest efficiency values DOE observed in manufacturer catalogs for NEMA Design C motors, which apparently are the EPACT 1992 equivalent efficiency levels (as mandated by EISA 2007 under 'general purpose electric motor (subtype II)'). Further CSLs for ECG 2 were selected based on computer modeling results, and are displayed in Table 5.5.

Table 5.5 shows the nominal efficiency values for each representative unit and each CSL. Cells with a '†' indicate the efficiency number is a NEMA nominal nameplate efficiency rating of a physical electric motor which DOE purchased and tore down. Cells with a '*' indicate the efficiency levels are from software modeling data gathered from DOE's SME which were derived using various technology, material, and geometry changes. Cells with a '-' indicate that DOE was not able to further increase efficiency levels for these representative units and still keep an electric motor design within the proper specifications.

Table 5.5 Candidate Standard Levels for each Representative Unit

Candidate Standard Level	5-Horsepower Design B Efficiency (%)	30-Horsepower Design B Efficiency (%)	75-Horsepower Design B Efficiency (%)	5-Horsepower Design C Efficiency (%)	50-Horsepower Design C Efficiency (%)
0	82.5†	89.5†	93.0†	87.5†	93.0†
1	87.5†	92.4†	94.1†	89.5*	94.1*
2	89.5†	93.6*	95.4†	90.2*	94.5*
3	90.2†	94.1†	95.8†	91.0*	95.0*
4	91.0*	94.5*	96.2*	-	-
5	91.7*	-	96.5*	-	-

†Indicates the efficiency of a purchased and physically torn-down electric motor
*Indicates the efficiency of a software-modeled electric motor

5.4 ENGINEERING ANALYSIS METHODOLOGY

As stated, the engineering analysis estimates the cost increment for the efficiency improvement potential of individual design options or combinations of design options that pass the four criteria in the screening analysis. DOE uses this cost-efficiency relationship, developed in the engineering analysis, in the LCC analysis.

DOE can use three methodologies to generate the manufacturing costs needed for the engineering analysis. These methods are:

1. the design-option approach – reporting the incremental costs of adding design options to a baseline model;

2. the efficiency-level approach – reporting relative costs of achieving improvements in energy efficiency; and

3. the reverse engineering or cost assessment approach – involving a "bottom up" manufacturing cost assessment based on a detailed bill of materials derived from electric motor teardowns.

Because DOE targeted certain nominal efficiency levels when improving baseline efficiencies and relied on tear-downs of electric motors, DOE's analysis for the electric motor rulemaking is a combination of the efficiency-level approach and the reverse engineering approach. DOE created baseline costs from bills of materials of electric motor tear-downs and then determined the costs of increasing efficiency levels based on material or technology changes.

5.4.1 Subcontractor Tear-downs

Due to limited manufacturer feedback concerning cost data and production costs, DOE derived its production and material costs by having a professional motor laboratory[c] disassemble and inventory the physical electric motors purchased. DOE performed tear-downs on the electric motors representing CSL 0 through 3 for equipment class group 1as well as electric motors representing CSL 0 for equipment class group 2. These tear-downs provided DOE the necessary data to construct a bill of materials, which DOE could normalize using a standard cost model and markup to produce a projected manufacturer selling price. DOE used the MSP derived from the engineering tear-down paired with the corresponding nameplate nominal efficiency to report the relative costs of achieving improvements in energy efficiency. DOE derived material prices from a consensus of current, publicly available data, manufacturer feedback, and conversations with its subject matter experts. DOE supplemented the findings from its tests and tear-downs through: (1) a review of data collected from manufacturers about prices, efficiencies, and other features of various models of electric motors, and (2) interviews with manufacturers about the techniques and associated costs used to improve efficiency.

DOE’s engineering analysis documents the design changes and associated costs when improving electric motor efficiency from the baseline level up to a max-tech level. This includes considering improved electrical steel for the stator and rotor, interchanging aluminum and copper rotor bar material, increasing stack length, and any other applicable design options remaining after the screening analysis. As each of these design options are added, the manufacturer’s cost generally increases and the electric motor’s efficiency improves.

5.4.2 Subcontractor Software Designs

DOE worked with technical experts to develop the highest efficiency levels (i.e., the max-tech levels) technologically feasible for each representative unit analyzed. DOE used a combination of electric motor software design programs and SME input. DOE retained an electric motor expert[d] with design experience and software, who prepared a set of designs with increasing efficiency. Additionally, DOE purchased another software modeling suite for the SME to check against his personal modeling software. The SME also checked his designs against tear-down data and made alterations to some of his designs to create the most practical designs possible. As new designs were created, careful attention was paid to the critical performance characteristics defined in NEMA MG-1 2009 Tables 12-2, 12-3, 12-4, and paragraph 12.35.1, which define locked rotor torque, breakdown torque, pull-up torque and maximum locked rotor currents, respectively. For a given representative unit, DOE ensured that the modeled electric motors met the same set of constraints (i.e., performance standards) as the purchased electric motors. This was done to ensure that the utility of the baseline unit was conserved as efficiency was improved through the application of various design options.

[c] The Center for Electromechanics University of Texas at Austin, a 140,000 sq. ft. lab with 40 years of operating experience with teardowns overseen by Dr. Angelo Gattozzi, an electric motor expert with previous industry experience.

[d] Dr. Howard Jordan, Ph.D, an electric motor design expert with over 40 years of industry experience.

Additionally, DOE limited its modeled stack length increases based on tear-down data and the maximum "C" dimensions found in manufacturer's catalogs.[e]

DOE limited the amount by which it would increase the stack length of its software-modeled electric motors to preserve the utility of the baseline model torn down. The maximum stack lengths used in the software-modeled CSLs were determined by first analyzing the stack lengths and C dimensions of torn-down electric motors. Then, DOE analyzed the C dimensions of various electric motors in the marketplace conforming to the same design constraints as the representative units (same NEMA design type, horsepower rating, NEMA frame number, enclosure type, and pole configuration). For each representative unit, DOE found the largest C dimension currently available on the marketplace and estimated a maximum stack length based on the stack length to C dimension ratios of motors it tore down. The resulting product was the value that DOE chose to use as the maximum stack length in its software modeled designs. Table 5.6 shows the stack lengths of torn down CSLs and stack lengths used in the software modeled CSLs. The efficiency levels of the software modeled CSLs are displayed in Table 5.5.

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[e] The C dimension of an electric motor is the length of the electric motor from the end of the shaft to the end of the opposite side's fan cover guard. Essentially, the C dimension is the overall length of an electric motor for proper mounting and interface with the driven equipment.

Table 5.6 Stack Length and C Dimension Measurements of Torn Down and Modeled Motors

Representative Unit	CSL	Stack Length (in)
5 HP, Design B	0	2.8*
	1	3.47
	2	5.14
	3	4.65
	4	5.32**
	5	5.32**
30 HP, Design B	0	7.88*
	1	5.53
	2	6.00**
	3	6.74
	4	7.00**
75 HP, Design B	0	8.15*
	1	10.23
	2	10.58
	3	11.33
	4	12.0**
	5	13.0**
5 HP, Design C	0	4.75
	1	4.25**
	2	5.32**
	3	5.32**
50 HP, Design C	0	8.67
	1	9.55**
	2	9.55**
	3	9.55**

*Represents stack length of a vertical, hollow-shaft motor.
**Represents stack length of a software modeled motor.

5.5 COST MODEL

DOE uses a standard method of cost accounting to determine the costs associated with manufacturing. This methodology is illustrated in Figure 5.5, where production costs and non-production costs are combined to determine the full cost of a product.

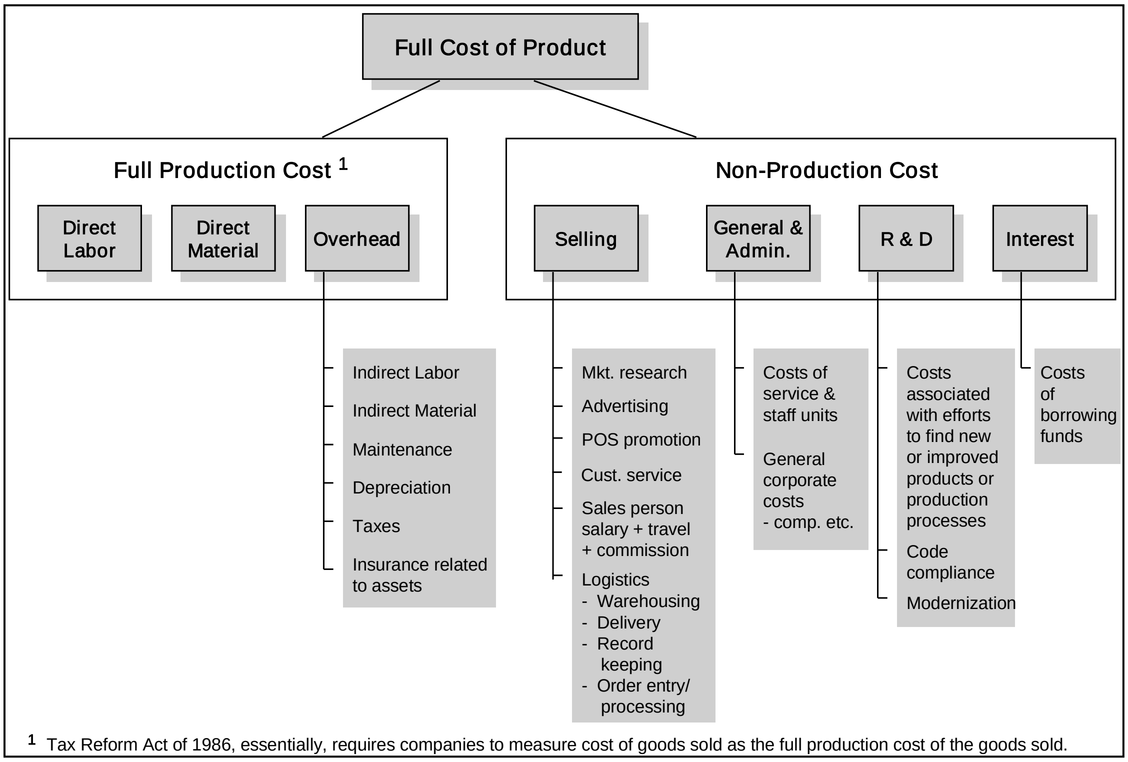

Figure 5.5 Standard Method of Cost Accounting for Standards Rulemaking

DOE developed estimates of some of the cost multipliers shown in Figure 5.5 by reviewing Security and Exchange Commission (SEC) SEC-10K reports from electric motor manufacturers, and examining previous, relevant, rulemakings, and 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 designs examined by DOE's motor experts were completed or the electric motors were torn down and the parts were inventoried, the next step was applying a consistent cost model to all of them. A standard bill of materials (BOM) was constructed that includes direct material costs. From this BOM, labor time estimates (along with associated costs) were added and various manufacturer markups were applied to create an MSP. DOE presents a summary of the production costs and non-production costs for each of the representative units analyzed in Appendix 5A.

5.5.1 Constructing a Bill of Materials

The BOM calculated for each design contained three types of material costs: variable, insulation, and hardware. 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. The insulation cost was aggregated due to the difficulty in pricing out all components of the insulation system. Based on SME feedback, DOE assumed increased efficiency does not incur notable increases in insulation system costs. Therefore, insulation costs increase as representative unit horsepower increases, but remain constant across all CSLs for each representative unit. The total price for insulation was also derived from SME input. Finally, hardware costs are an aggregate cost for all electric motor hardware components. This includes nuts, bolts, gaskets, washers and other miscellaneous hardware components. As with the insulation costs, the hardware cost was aggregated due to the difficulty of pricing individual components. DOE believes hardware costs account for a small percentage of the total material costs of an electric motor and therefore does not believe this aggregation method will have a detrimental impact on the accuracy of the MSP. Additionally, because the motors (within a representative unit) all come from the same manufacturer, DOE believes these costs are likely to be very similar and have minimal variation. The aggregate hardware cost, which is unique for each horsepower rating, was also derived based on SME input and information received about the teardowns.

Each item in the BOM is organized by the type of cost (i.e., variable, insulation, and hardware) and the component of the electric motor to which they apply. The variable costs portion of the BOM includes the following subheadings, each with an itemized parts list: stator assembly, rotor assembly, and other major costs. The insulation cost section of the BOM includes subheadings for each individual component identified during teardown, however they are not priced out individually. As discussed above, an aggregate price is used to cover this entire section. This aggregate price is unique for different horsepower ratings. The hardware cost section of the BOM includes subheadings for individual hardware items identified during the teardown, but again like the insulation costs, they are not individually priced. There is one aggregate price used that covers all of the hardware components. This aggregate price is unique for each horsepower rating.

The subheadings that have an itemized list of components include the stator assembly, rotor assembly, and other major costs. The stator assembly's itemized lists include prices for steel laminations and copper wire. The rotor assembly portion of the BOM includes prices for laminations, rotor conductor material, (either aluminum or copper) and shaft extension material. The other major costs heading contains items for the frame material and base, terminal housing components, bearing-type, and end-shield material.

DOE presents a detailed BOM for one design from each of the electric motor categories analyzed in Appendix 5B. The discussion below describes the level of detail contained in the bill of materials presented in the appendix.

5.5.2 Labor Costs and Assumptions

Due to the varying degree of automation used in manufacturing electric motors, labor costs differ for each representative unit. DOE analyzed teardown results to determine which electric motors were machine wound and which electric motors were hand wound and based on this analysis, DOE applied a higher labor hour amount for the hand-wound electric motors. For the max-tech software modeled electric motors, DOE always assumed hand-winding and therefore a higher labor hour amount. Labor hours for each of the representative units were based on SME input and manufacturer interviews.

DOE used the same hourly labor rate for all electric motors analyzed. The base hourly rate was developed from the 2007 Economic Census of Industry,[f] published by the U.S. Census Bureau, as well as manufacturer and SME input. The base hourly rate is an aggregate rate of a foreign labor rate and a domestic labor rate. DOE weighed the foreign labor rate more than the domestic labor rate due to manufacturer feedback indicating off-shore production accounts for a majority of electric motor production by American-based companies. 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 electric motors. Table 5.7 shows the markups that were applied, their corresponding markup percentage, and the new burdened labor rate.

Table 5.7 Labor Markups for Electric Motor Manufacturers

Item description	Markup percentage	Rate per hour
Labor cost per hour		$ 10.87
Indirect Production	33 %	$ 14.46
Overhead	30 %	$ 18.79
Fringe†	24 %	$ 23.40
Assembly Labor Up-time††	43 %	$ 33.46
Cost of Labor Input to Spreadsheet		**$ 33.46**

Cost per hour is an aggregate number drawn from U.S. Census Bureau, *2007 Economic Census of Industry,* published December 2010 and foreign labor rate estimates based on manufacturer feedback.

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, *2007 Economic Census of Industry,* published December 2010. Data for NAICS code 335312 “Electric Motor and Generator Manufacturer” 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.

5.5.3 Manufacturer Markups

DOE used the three markups described below to account for non-production costs that are part of each electric motor leaving a manufacturer’s facility. Handling and scrap factor,

[f] U.S. Census Bureau, 2007 Economic Census of Industry

overhead, 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 Securities and Exchange Commission (SEC) Form 10K annual 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 electric 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 electric motor (e.g., lengths of wire too short to wind).

- Factory overhead: 17.5 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). The overhead increases to 18.0 percent when copper die casting is used in the rotor. This accounts for additional energy, insurance, and other indirect costs associated with the copper die-casting process.

- Non-production: 37 – 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 direct labor, and the factory overhead. For the analyzed electric motors at or below 30-horsepower this markup was 37 percent and for electric motors above 30-horsepower this markup was 45 percent. This increase accounts for the extra profit margin manufacturers may receive on larger electric motors that are sold in smaller volumes.

5.6 RESULTS OF ENGINEERING ANALYSIS

DOE used the five representative units to develop five manufacturer selling price versus nominal full-load efficiency curves, three for equipment class group 1 (also used for equipment class group 3), and two for equipment class group 2. Figure 5.6 through Figure 5.10 provide the manufacturer selling price versus efficiency curves and Table 5.8 through Table 5.21present the tabulated results.

5.6.1 NEMA Design B, 5-Horsepower, 4-Pole, Enclosed Electric Motor

Figure 5.6 presents the relationship between MSP and nominal full-load efficiency for the 5-horsepower, Design B, 4-pole, enclosed electric motor that was analyzed. Using the tear-down results for CSLs 0 to 3, DOE determined that the manufacturer of these electric motors increased the stack length and used various combinations of increasing the stator copper, electrical steel, or rotor conductor, as well as design changes, to improve the electric motor's efficiency.

DOE used software modeling to develop CSLs 4 and 5. DOE increased the efficiency level of these representative units and all other representative units by employing a combination of changing the slot fill, increasing stator copper or electrical steel amounts, changing the type or amount of rotor conductor material, and changing specifications of the motor design such as rotor cage geometry or rotor skew. For CSL 5, which is the max-tech efficiency level, DOE used a die-cast copper rotor conductor design while keeping the stack length the same as the motor design used for CSL 4. For CSL 5, DOE assumed a 10 percent labor hour increase above CSL 4.

Material cost increases, such as low loss electrical steel and increased stator copper, account for the relatively large increase in MSP from CSL 3 to CSL 4. Additionally, DOE assumed a hand-wound labor hour assumption for CSL 4 and 5 which adds to the relatively large jump in MSP when moving to CSL 4. All of the motors torn down and used for CSLs 0 through 3 were observed to have machine-wound stators.

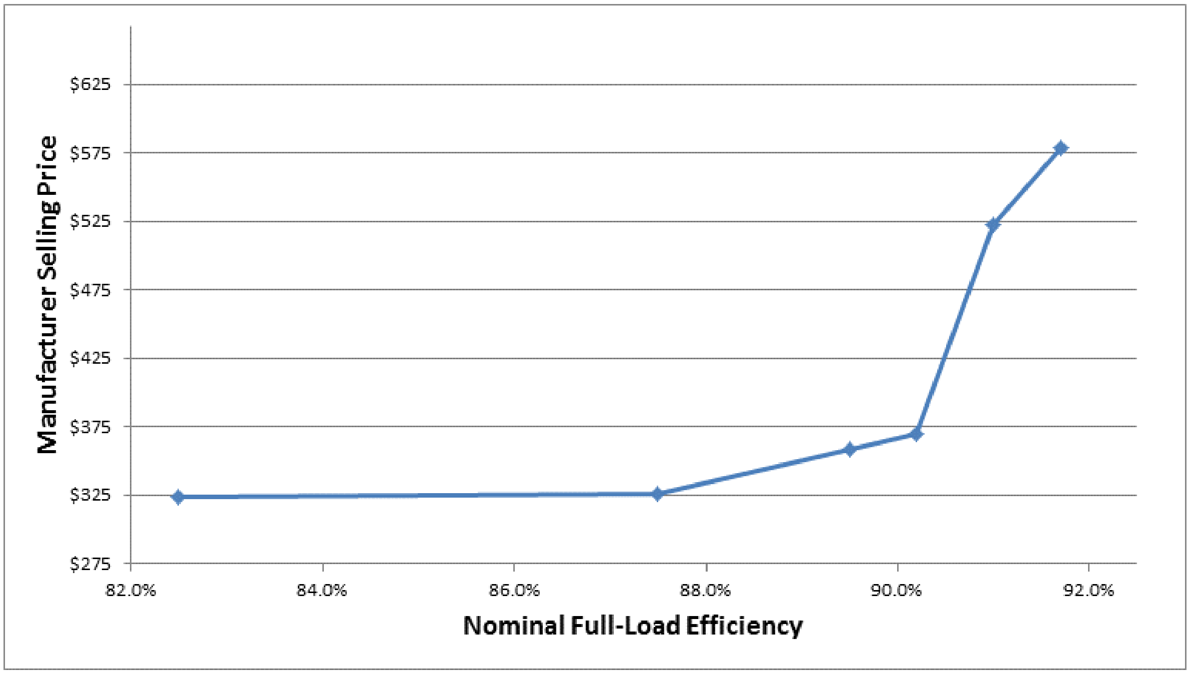

Figure 5.6 NEMA Design B, 5-Horsepower, 4-Pole, Enclosed Electric Motor Engineering Analysis Curve

Table 5.8presents the same engineering analysis results in tabular form, including the nominal full-load efficiency values and the MSPs. From CSL 0 through CSL 3, MSP increases by amounts varying up to 10 percent. When moving from CSL 3 to 4 and from CSL 4 to 5, MSP increases by $153 or about 41 percent and $56 or 11 percent, respectively, for consecutive loss reductions of roughly10 percent. Again, the large price increases when moving to CSLs 4 and 5 are a result of the use of increased labor hour and material increases. Additionally, CSL 5 employs a die-cast copper conductor in the rotor, which accounts for some of the MSP increase of CSL 5. At the time of publishing, copper was approximately 2.7 times more expensive than aluminum per pound and is three times denser. Therefore, filling an equal volume space with cast copper is almost nine times more expensive than filling the same volume with cast aluminum.

Table 5.8 Efficiency and Manufacturer Selling Price Data for the NEMA Design B, 5-Horsepower Motor

CSL	Nominal Full-Load Efficiency (%)	MSP ($)
0	82.5	324
1	87.5	326
2	89.5	358
3	90.2	370
4	91.0	523
5	91.7	579

Table 5.9 presents some of the design and performance specifications associated with the six 5-horsepower NEMA Design B electric motors presented above including stator copper weight, rotor conductor weight, and electrical steel weight. Table 5.10 shows the NEMA MG1-2011 Design B performance criteria as well as those design parameters for the two software-modeled electric motors.

Table 5.9 NEMA Design B, 5-Horsepower, 4-Pole, Enclosed Motor Characteristics

Parameter	Units	CSL 0	CSL 1	CSL 2	CSL 3	CSL 4*	CSL 5*
Efficiency	**%**	82.5	87.5	89.5	90.2	91.0	91.7
Line Voltage	**V**	460	460	460	460	460	460
Full Load Speed	**RPM**	1,745	1,745	1,760	1,755	1,773	1,776
Full Load Torque	**Nm**	20.3	20.4	20.3	20.4	20.1	20.1
Current	**A**	6.9	6.5	6.3	6.2	6.3	6.0
Steel	**-**	M56	M47	M47	M47	M36	M36
Rotor Conductor Material	**-**	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Copper
Approximate Slot Fill	**%**	43.5%	57.2%	70.0%	68.6%	82.4%	85.2%
Stator Wire Gauge	**AWG**	19	19	19	20	20	20
Stator Copper Weight	**lbs**	8.4	10.1	10.1	12.2	14.4	14.4
Rotor Conductor Weight	**lbs**	2.63	2.87	2.6	3.42	2.7	9.1
Stack Length	**In**	2.8	3.47	5.14	4.65	5.32	5.32
Housing Weight	**lbs**	8	9	22	12	14	14

* Software modeled motor

Table 5.10 NEMA Design B, 5-Horsepower, 4-Pole, Enclosed Motor Modeled Characteristics

Parameter	Units	Design B Limit	CSL 4	CSL 5
Efficiency	%	-	91.0	91.7
Breakdown Torque	% of full-load	225 (minimum)	323	305
Pull-Up Torque	% of full-load	130 (minimum)	245	214
Locked-Rotor Torque	% of full-load	185 (minimum)	245	214
Locked-Rotor Current	A	46 (maximum)	41.6	43.9

5.6.2 NEMA Design B, 30-Horsepower, 4-Pole, Enclosed Electric Motor

Figure 5.7 presents the relationship between the MSP and nominal full-load efficiency for the 30-horsepower, Design B, 4-pole, enclosed polyphase motor analyzed. Using tear-down results for CSLs 0, 1, and 3, DOE determined that the manufacturer of these motors used a combination of material grade, material quantities, and design changes to increase the electric motor's efficiency.

Although motors are available at the CSL 2 efficiency level (93.6 percent), DOE used software modeling to simulate this motor because the CSL 2 motor DOE purchased for tear-down had a nameplate and catalog efficiency rating that did not match the efficiency found on the manufacturer's website. Additionally, tear-down results of the CSL 2 motor revealed it to have more stack length, electrical steel, and rotor aluminum as well as lower-loss electrical steel than the CSL 3 motor, which has a nameplate efficiency of 94.1 percent. CSL 2 also had 8 percent lower losses than CSL 3 based on IEEE 112B test results. Results of the IEEE 112B test, as well as tear-down results, are illustrated in Table 5.11.

Table 5.11 30-Horsepower CSL 2 and CSL 3 Testing and Tear-down Results

Parameter	CSL 2	CSL 3	Percent change over CSL 3
Nameplate and Catalog efficiency (%)	93.6	94.1	-
Website efficiency (%)	94.1	94.1	-
Tested efficiency (%)	94.29	93.88	8†
Stack length (in)	8.21	6.74	22
Electrical steel grade*	M36	M47	-
Weight of electrical steel (lbs)	201	156	29
Weight of stator copper (lbs)	37	47	-21
Weight of rotor-slot aluminum (lbs)	6.6	5.9	12

* Estimate based on DOE's metallurgical analysis
† Based on losses

DOE decided that its purchased CSL 2 motor had incorrect nameplate efficiency. This decision is based on comparing the test and tear-down results to the CSL 3 motor. Therefore, DOE decided to use software modeling to replace the CSL 2 motor tear-down, for the preliminary analysis. The CSL 2 software modeled motor is based on measurements taken from the CSL 1 and CSL 3 tear-down results, such as stack length, material weights, and electrical steel grades. The resulting CSL 2 motor specifications are listed in Table 5.13.

DOE also used software modeling to develop CSL4. For this design DOE used a copper rotor and low-loss electrical steel to achieve efficiencies higher than the purchased electric motors. Using a die-cast copper conductor in the rotor also reduced the stack length of CSL 4 compared to the other 30 horsepower CSLs analyzed. Shortening the stack length helps lower the cost of this max-tech design. CSL 4's primary cost increases arise from an increased labor hour amount based on a hand-wound labor assumption as well as other material quantity increases.

Unlike the 5-horsepower and 75-horsepower Design B representative units, the 30-horsepower Design B representative unit does not have a CSL 5. DOE attempted to improve the design of CSL 4 in an effort to reach the next highest NEMA nominal efficiency level. However, DOE was unable to reduce losses by at least 10 percent (one NEMA nominal efficiency band), and therefore DOE was not able to achieve the next NEMA nominal efficiency level.

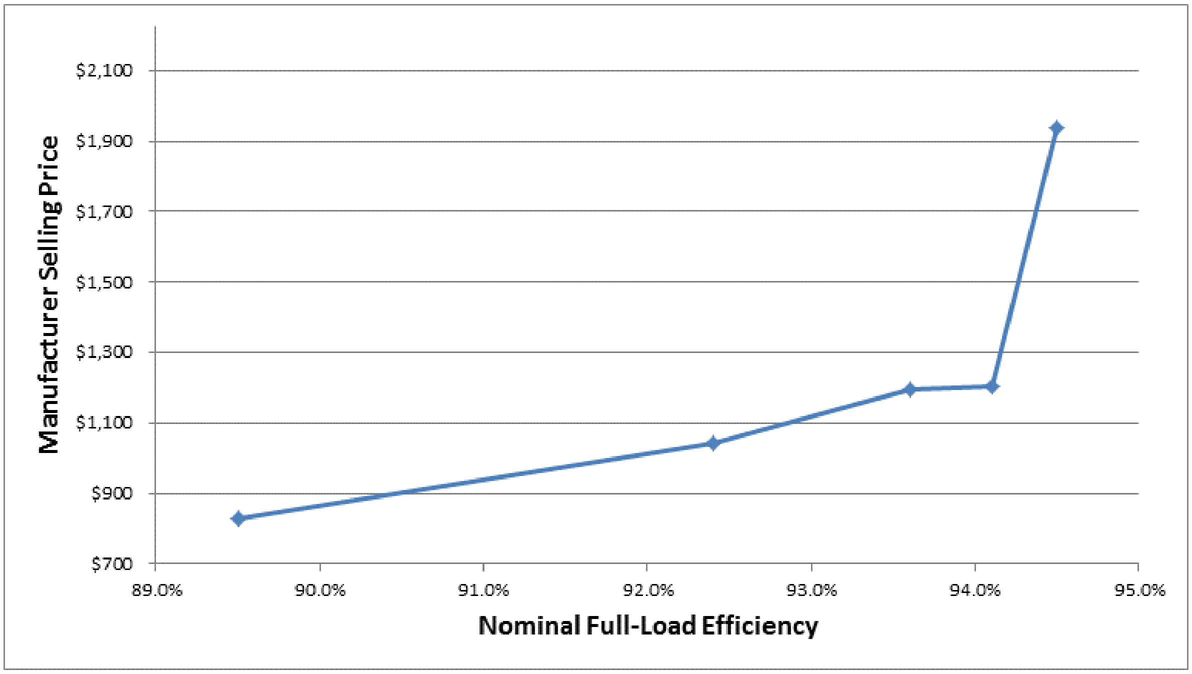

Figure 5.7 NEMA Design B, 30-Horsepower, 4-Pole, Enclosed Electric Motor Engineering Analysis Curve

Table 5.12 presents the engineering analysis results in a tabular form, including the full-load efficiency values and the MSPs. From CSL 0 to 3, DOE found that the full-load efficiency would increase 5.6 nominal percentage points over the baseline, CSL 0, which represents about a 47 percent reduction in electric motor losses. The increase in MSP to move from CSL 0 to CSL 3 is $377, or about a 46 percent increase in MSP over CSL 0. Moving from CSL 0 to CSL 4 provides a 50 percent reduction in electric motor losses for a MSP increase of $1,109 or about a 135 percent MSP increase over CSL 0.

Table 5.12 Efficiency and Manufacturer Selling Price Data for the NEMA Design B, 30-Horsepower Motor

CSL	Nominal Full-Load Efficiency (%)	MSP ($)
0	89.5	827
1	92.4	1,044
2	93.6	1,193
3	94.1	1,204
4	94.5	1,936

Table 5.13 presents some of the design and performance specifications associated with the five 30-horsepower designs presented above, including stator copper weight, rotor conductor weight, and electrical steel weight. Table 5.14 shows the NEMA MG1-2009 Design B performance criteria as well as those design parameters for the software modeled electric motor.

Table 5.13 NEMA Design B, 30-Horsepower, 4-Pole, Enclosed Motor Characteristics

Parameter	Units	CSL 0	CSL 1	CSL 2*	CSL 3	CSL 4*
Efficiency	**%**	89.5	92.4	93.6	94.1	94.5
Line Voltage	**V**	230	460	460	460	460
Full Load Speed	**RPM**	1,755	1,765	1,768	1,770	1,784
Full Load Torque	**Nm**	121.6	121.4	120.8	120.6	119.6
Current	**A**	37	37	36	36	37
Steel	**-**	M56	M56/M47	M47	M47	M36
Rotor Conductor Material	**-**	Aluminum	Aluminum	Aluminum	Aluminum	Copper
Approximate Slot Fill	**%**	48.4	84.0	70.0	70.0	83.2
Stator Wire Gauge	**AWG**	18	17	16	18	18
Stator Copper Weight	**lbs**	20.2	43.5	45.2	47.7	74.5
Rotor Conductor Weight	**lbs**	8.25	9.5	7.5	13.66	42.6
Stack Length	**In**	7.88	5.53	6.00	6.74	7.00
Housing Weight	**lbs**	21	130	131	147	152

* Software modeled motor

Table 5.14 NEMA Design B, 30-Horsepower, 4-Pole, Enclosed Motor Modeled Characteristics

Parameter	Units	Design B Limit	CSL 2	CSL 4
Efficiency	%	-	93.6	94.5
Breakdown Torque	% of full-load	200 (min.)	265.6	202
Pull-up Torque	% of full-load	105 (min.)	173.3	139
Locked Rotor Torque	% of full-load	150 (min.)	183.2	154
Locked Rotor Amps	A	217.5(max.)	204	208

5.6.3 NEMA Design B, 75-Horsepower, 4-Pole, Enclosed Electric Motor

Figure 5.8 presents the relationship between the MSP and nominal full-load efficiency for the 75-horsepower, Design B, 4-pole enclosed electric motor analyzed. Using tear-down results for CSLs 0 through 3, DOE determined that the manufacturer of these electric motors increased the stack length and other material amounts to increase the electric motor's efficiency levels from 93.0 percent to 95.8 percent. The torn-down electric motor representing CSL 3 used increased rotor aluminum and stator copper as well as an increased stack length to achieve 95.8 percent efficiency.

DOE used software modeling to develop CSL 4. For this design, DOE used a die-cast copper conductor in the rotor and low-loss electrical steel in the rotor and stator to achieve efficiencies higher than commercially available electric motors. The stack length of the electric motor for CSL 4 is higher than the stack length of lower CSLs for the 75-horsepower Design B electric motors analyzed, but shorter than the electric motor for CSL 5.

To develop the max-tech efficiency level, CSL 5, DOE again used software modeling. DOE continued to use a die-cast copper rotor conductor design, but increased the stack length to an estimated maximum stack length. This maximum stack length was calculated based on the method described previously in section 5.4.2. The assumption of manual-labor hour amounts and the use of die-cast copper conductors in CSL 4 and 5's rotors account for the larger-than-typical price increase between CSL 3 and CSL 4 for the 75-horsepower Design B representative units.

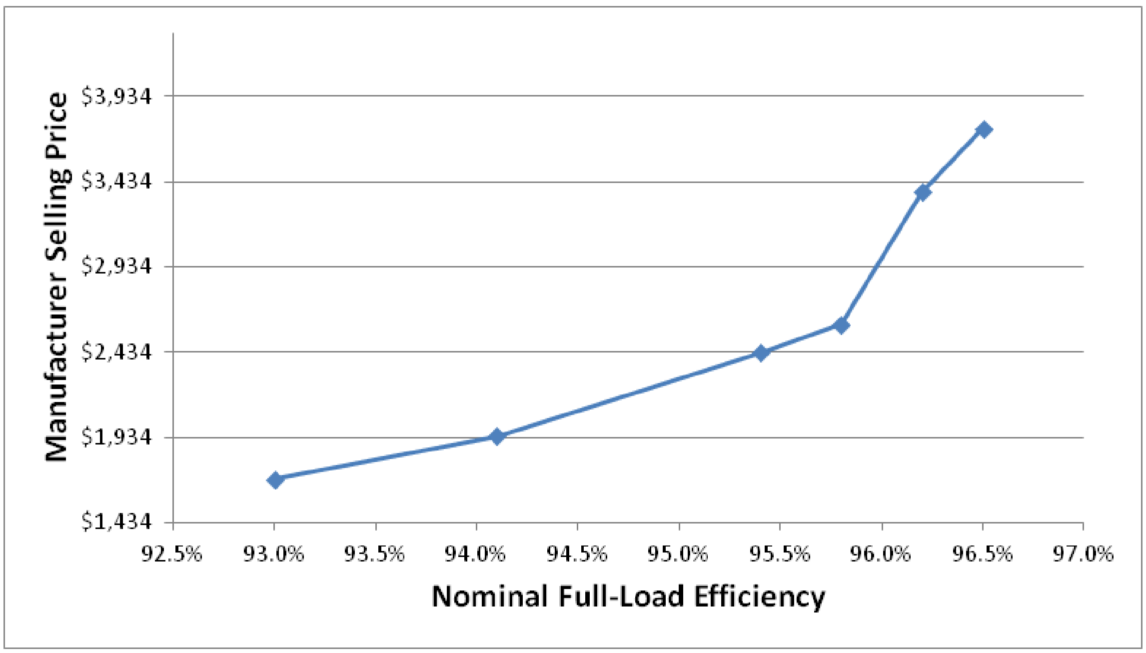

Figure 5.8 NEMA Design B, 75-Horsepower, 4-Pole, Enclosed Motor Engineering Analysis Curve

Table 5.15 presents the same engineering analysis results in a tabular form, including the nominal full-load efficiency values and the MSPs. Moving from CSL 0 to CSL 3, DOE found that the full-load efficiency would increase 2.4 nominal percentage points over the baseline, CSL 0, which represents about a 42 percent reduction in electric motor losses. The increase in MSP to move from CSL 0 to CSL 3 is about $748 or about a 41 percent increase in MSP over CSL 0. Moving from CSL 0 to CSL 4 provides a 47 percent reduction in electric motor losses for a MSP increase of $1,520, which constitutes an 83 percent MSP increase over the CSL 0 electric motor.

To increase the efficiency from CSL 0 to the max-tech efficiency of CSL 5 there is a 52 percent reduction in motor losses for about a 102 percent increase in MSP of $1,879.

Table 5.15 Efficiency and Manufacturer Selling Price Data for the NEMA Design B, 75-Horsepower Motor

CSL	Nominal Full-Load Efficiency (%)	MSP ($)
0	93.0	1,833
1	94.1	1,994
2	95.4	2,270
3	95.8	2,581
4	96.2	3,353
5	96.5	3,712

Table 5.16 presents some of the design and performance specifications associated with the six 75-horsepower designs presented above, including stator copper weight, rotor conductor weight, and electrical steel weight. Table 5.17 shows the NEMA MG1-2011 Design B performance criteria as well as those design parameters for the two software modeled electric motors.

Table 5.16 NEMA Design B, 75-Horsepower, 4-Pole, Enclosed Motor Characteristics

Parameter	Units	CSL 0	CSL 1	CSL 2	CSL 3	CSL 4*	CSL 5*
Efficiency	**%**	93.0	94.1	95.4	95.8	96.2	96.5
Line Voltage	**V**	460	460	460	460	460	460
Full Load Speed	**RPM**	1,775	1,785	1,781	1,785	1,788	1,789
Full Load Torque	**Nm**	299.8	299.8	302.3	300.8	299.6	299.6
Current	**A**	88	91.8	89.4	88.6	89.8	91.9
Steel	**-**	M56	M47	M47	M47	M36	M36
Rotor Conductor Material	**-**	Aluminum	Aluminum	Aluminum	Aluminum	Copper	Copper
Approximate Slot Fill	**%**	48.0	44.5	70.0	70.0	85.1	83.4
Stator Wire Gauge	**AWG**	17	12	12	15	14	14
Stator Copper Weight	**lbs**	77.8	71	82	136	127	160
Rotor Conductor Weight	**lbs**	31.0	20.7	27.3	38.5	79	84.3
Stack Length	**In**	8.15	10.23	10.58	11.37	12.00	13.00
Housing Weight	**lbs**	130	79	168	180	190	206

* Software modeled motor

Table 5.17 NEMA Design B, 75-Horsepower, 4-Pole, Enclosed Motor Modeled Characteristics

Parameter	Units	Design B Limit	CSL 4	CSL 5
Efficiency	%	-	96.2	96.5
Breakdown Torque	% of full-load	200 (min.)	218.2	202.0
Pull-up Torque	% of full-load	100 (min.)	135	139.3
Locked Rotor Torque	% of full-load	140 (min.)	163.8	163.7
Locked Rotor Amps	A	542.5(max.)	530.7	541.3

5.6.4 NEMA Design C, 5-Horsepower, 4-Pole, Enclosed Electric Motor

Figure 5.9 presents the relationship between the MSP and nominal full-load efficiency for the 5-horsepower, NEMA Design C, 4-pole, enclosed electric motor analyzed. DOE purchased only one NEMA Design C electric motor for its tear-down analysis. The remaining three CSLs were based on software modeled electric motors. Therefore, discussion of the NEMA Design C revolves around the design changes DOE's software modeling expert chose to implement to increase the efficiency levels of the electric motors.

DOE achieved the CSL 1 efficiency level by using a lower loss grade of electrical steel and increasing the slot fill higher than that of the CSL 0 electric motor. The CSL 1 electric motor also boasts a smaller stack length and a lower slot fill percentage than the CSL 0 electric motor. DOE increased the efficiency of the CSL 2 motor design by keeping an aluminum die-cast rotor conductor cage, but increasing the stack length to the maximum stack length calculated via the methodology described in section 5.4.2. This increased the amount of electrical steel and stator copper material by 25 and 52 percent, respectively. DOE achieved the CSL 3 efficiency by employing a copper die-cast rotor conductor and while maintaining the same stack length as the CSL 2 motor. The die-cast copper rotor conductor allowed the CSL 3 design to reduce its stator copper winding by almost 15 percent while still achieving a higher efficiency than CSL 2.

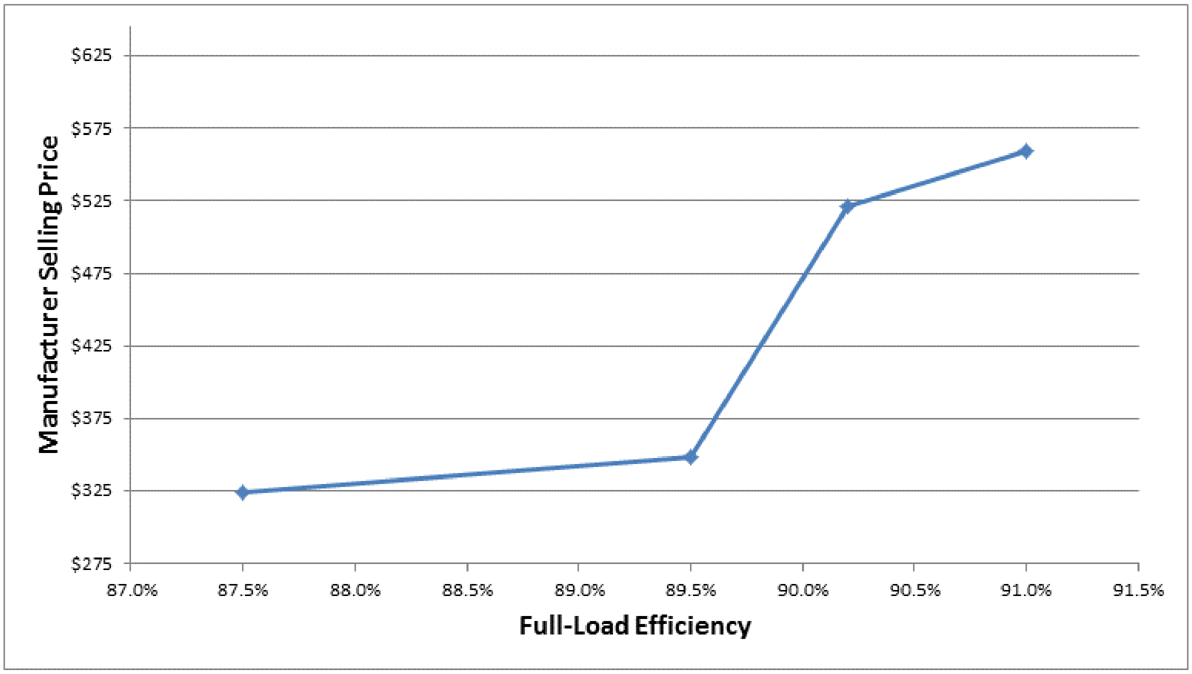

Figure 5.9 NEMA Design C, 5-Horsepower, 4-Pole, Enclosed Motor Engineering Analysis Curve

Table 5.18 presents the same engineering analysis results in a tabular form, including the nominal full-load efficiency values and the MSPs. Moving from CSL 0 to CSL 2, DOE found that the nominal full-load efficiency would increase 2.7 percentage points over the baseline, CSL 0, which represents a 24 percent reduction in electric motor losses. The increase in MSP to move from CSL 0 to CSL 2 is $198, or about a 61 percent increase in MSP over CSL 0. Increasing from CSL 2 to CSL 3 would result in a 10 percent reduction in losses and a 7 percent increase in MSP.

Table 5.18 Efficiency and Manufacturer Selling Price Data for the NEMA Design C, 5-Horsepower Motor

CSL	Nominal Full-Load Efficiency (%)	MSP ($)
0	87.5	324
1	89.5	348
2	90.2	522
3	91.0	559

Table 5.19 presents some of the design and performance specifications associated with the four Design C, 5-horsepower electric motors presented above. The table includes stator copper weight, rotor conductor weight, and electrical steel weight. Table 5.20 shows the NEMA MG1-2009 Design C performance criteria as well as those design parameters for the three software modeled electric motors.

Table 5.19 NEMA Design C, 5-Horsepower, 4-Pole, Enclosed Motor Characteristics

Parameter	Units	CSL 0	CSL 1	CSL 2	CSL 3
Efficiency	**%**	87.5	89.5	90.2	91.0
Line Voltage	**V**	460	460	460	460
Full Load Speed	**RPM**	1,750	1,762	1,767	1,776
Full Load Torque	**lb-ft**	15	14.9	14.9	14.8
Current	**A**	7.1	8.4	7.1	6.5
Steel	**-**	M47	M36	M36	M36
Rotor Conductor Material	**-**	Aluminum	Aluminum	Aluminum	Copper
Approximate Slot Fill	**%**	67.9	79.9	83.9	82.9
Stator Wire Gauge	**AWG**	18	18	18	18
Stator Copper Weight	**lbs**	10	9.9	15	12.8
Rotor Conductor Weight	**lbs**	2.2	2.0	2.4	7.8
Stack Length	**in**	4.75	4.25	5.32	5.32
Frame Weight	**lbs**	12	11	14	14

Table 5.20 NEMA Design C, 5-Horsepower, 4-Pole, Enclosed Motor Modeled Characteristics

Parameter	Units	Design C Limit	CSL 1	CSL 2	CSL 3
Efficiency	%	-	89.5	90.2	91.0
Breakdown Torque	% of full-load	200 (min.)	293	260.2	260.8
Pull-up Torque	% of full-load	180 (min.)	283.9	243.6	260.8
Locked Rotor Torque	% of full-load	255 (min.)	344.1	297.9	260.8
Locked Rotor Amps	A	46 (max.)	38.5	38.3	41.7

5.6.5 NEMA Design C, 50-Horsepower, 4-Pole, Enclosed Electric Motor

Figure 5.10 presents the relationship between the MSP and nominal full-load efficiency for the 50-horsepower, NEMA Design C, 4-pole, enclosed electric motor analyzed. DOE purchased only one NEMA Design C electric motor for its tear-down analysis. The remaining three CSLs were based on software-modeled electric motors. Therefore, discussion of the NEMA Design C revolves around the design changes DOE's software modeling expert chose to implement to increase the efficiency levels of the electric motors.

DOE achieved the CSL 1 efficiency level by using a higher grade electrical steel and the maximum-calculated stack length found by using the method discussed in section 5.4.2. DOE then increased the efficiency level to CSL 2 by increasing slot fill and the amount of stator copper. To achieve the CSL 3 efficiency level, DOE decreased the slot fill and the amount of stator copper but changed the rotor conductor material to die-cast copper.

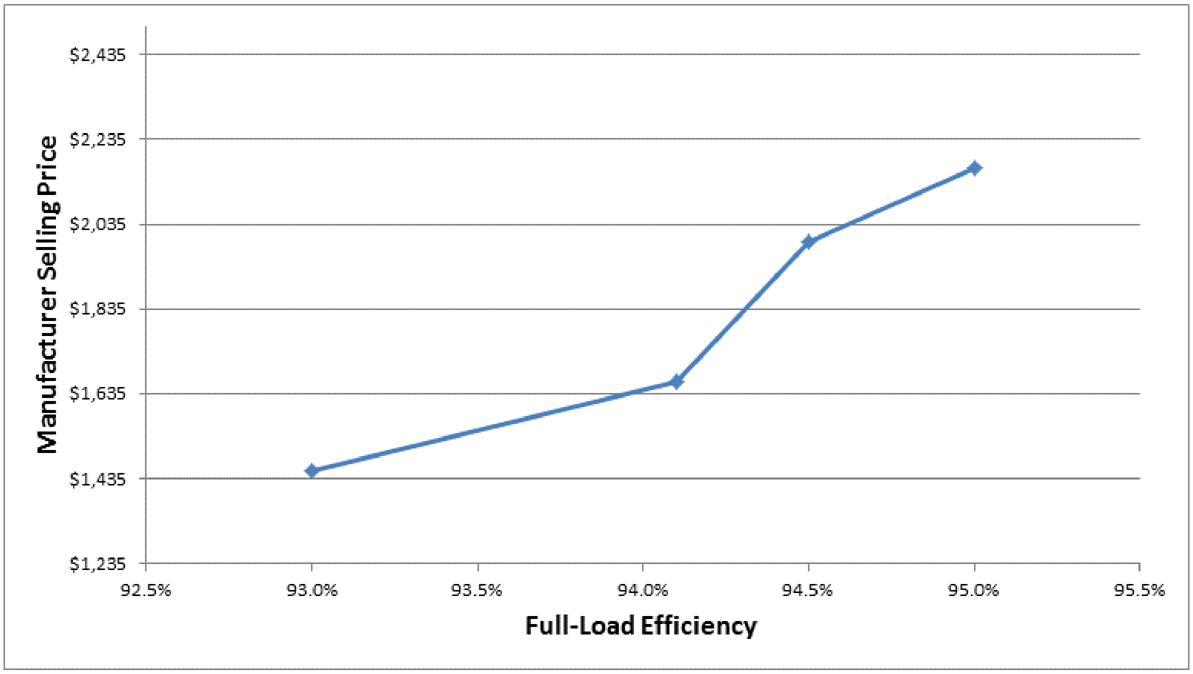

Figure 5.10 NEMA Design C, 50-Horsepower, 4-Pole, Enclosed Motor Engineering Analysis Curve

Table 5.21 presents the same engineering analysis results in a tabular form, including the nominal full-load efficiency values and the MSPs. Moving from the CSL 0 to CSL 2, DOE found that the nominal full-load efficiency would increase 1.5 nominal percentage points over the baseline, CSL 0, which represents about a 23 percent reduction in electric motor losses. The increase in MSP to move from CSL 0 to CSL 2 is $540, or about a 37 percent increase in MSP over CSL 0. To increase from CSL 2 to CSL 3, about a 10 percent reduction in electric motor losses, results in an 8.8 percent increase in MSP.

Table 5.21 Efficiency and Manufacturer Selling Price Data for the NEMA Design C, 50-Horsepower Motor

CSL	Nominal Full-Load Efficiency (%)	MSP ($)
0	93.0	1,452
1	94.1	1,664
2	94.5	1,992
3	95.0	2,168

Table 5.22 presents some of the design and performance specifications associated with the four 50-horsepower electric motor designs presented above including stator copper weight, rotor conductor weight, and electrical steel weight. Table 5.23 shows the NEMA MG1-2009 Design C performance criteria as well as those design parameters for the software modeled electric motors.

Table 5.22 NEMA Design C, 50-Horsepower, 4-Pole, Enclosed Motor Characteristics

Parameter	Units	CSL 0	CSL 1	CSL 2	CSL 3
Efficiency	**%**	93.0	94.1	94.5	95.0
Line Voltage	**V**	460	460	460	460
Full Load Speed	**RPM**	1,770	1,775	1,775	1,782
Full Load Torque	**lb-ft**	148	148	148	147.3
Current	**A**	59.4	63.9	63.7	61.3
Steel	**-**	M47	M36	M36	M19
Rotor Conductor Material	**-**	Aluminum	Aluminum	Aluminum	Copper
Approximate Slot Fill	**%**	79.6	74.8	85.3	81.3
Stator Wire Gauge	**AWG**	17	17	17	17
Stator Copper Weight	**lbs**	66	78	90	85
Rotor Conductor Weight	**lbs**	16.5	11	11	36.6
Stack Length	**In**	8.67	9.55	9.55	9.55
Frame Weight	**lbs**	125	138	138	138

Table 5.23 NEMA Design C, 50-Horsepower, 4-Pole, Enclosed Motor Modeled Characteristics

Parameter	Units	Design C Limit	CSL 1	CSL 2	CSL 3
Efficiency	%	-	94.1	94.5	95.0
Breakdown Torque	% of full-load	190 (min.)	255.2	193.5	233.5
Pull-up Torque	% of full-load	150 (min.)	254.8	165.1	202.9
Locked Rotor Torque	% of full-load	200 (min.)	254.8	258.6	202.9
Locked Rotor Amps	A	362.5 (max.)	353.6	356.2	359.6

5.7 SCALING METHODOLOGY

Due to the large number of equipment classes, DOE was not able to perform a detailed engineering analysis on each one. Instead, DOE focused its analysis on three NEMA Design B equipment classes and two NEMA Design C equipment classes. From these results, DOE scaled to other equipment classes not directly analyzed in the engineering analysis. For the preliminary analysis, DOE considered two methods of scaling, one based on the incremental improvement of motors losses and one that develops a set of power law equations based on the relationships found in the NEMA "Energy Efficient" and NEMA "Premium Efficient"[g] tables of efficiency. Ultimately, DOE did not find a large discrepancy between the two methods and elected to use the, simpler, incremental improvement of motor losses approach.

5.7.1 Scaling Approach Using Incremental Improvements of Motor Losses

Scaling electric motor efficiencies is a complicated proposition that has the potential to result in efficiency standards that are not evenly stringent across all equipment classes. Among DOE's three ECGs, there are several hundred combinations of horsepower rating, pole

[g] NEMA MG1-2011 specifies that motors classified as "energy efficient" shall meet or exceed the efficiency values listed in Table 12-11 (or Table 20-A for certain larger horsepower ratings). Motors classified as "premium efficiency" shall meet or exceed the efficiency values listed in Table 12-12 (or Table 20-B for certain larger horsepower ratings).

configuration, and enclosure. Within these combinations there is a large number of standardized frame number series. Given this sizable number of frame number series, DOE cannot feasibly analyze all of these variants – hence, the need for scaling. Scaling across horsepower ratings, pole configurations, enclosures, and frame number series is a necessity. For DOE's first approach to scaling, it relied on a relatively simple method of analyzing the motor losses of each of its representative units from CSL to CSL and applying those same losses to various segments of the market.

As discussed previously, DOE based the first four of its CSLs for ECG 1 on torn-down motors. As these motors were marketed and sold with NEMA nominal efficiencies, DOE used those values to denote each of those CSLs. Consequently, the efficiency levels that DOE scaled to for the non-representative units were also selected from the NEMA nominal efficiency levels. DOE also used the NEMA nominal efficiency values for the CSLs that were achieved for the representative units using software modeling.

For CSL 1 and CSL 2, DOE only had to do minimal scaling. CSL 1 is based on NEMA MG 1-2011 Tables 12-11 and 20-A, which were left unchanged for all electric motors. However, Table 12-11 does not specify an efficiency level for 1 horsepower, 2 pole, open motors. DOE scaled the missing value by using the same efficiency level as that of 1 horsepower, 2 pole, enclosed motors. By observing that 1 horsepower, 2 pole, both open and enclosed motors had the same Table 12-12 efficiency levels, DOE inferred that the 1 horsepower, 2 pole, open configuration could also meet the Table 12-11 efficiency level of its enclosed counterpart.

CSL 2 is based on NEMA MG 1-2011 Tables 12-12 and 20-B, which specify the nominal efficiencies of electric motors that NEMA classifies as "premium efficiency." The 2011 version of NEMA MG1 omits NEMA Premium efficiency levels for 6-pole motors at 300- and 350-horsepower, leaving a gap in the NEMA Premium efficiency tables where there was no gap in the 2009 version of NEMA MG1. To keep CSL 2 continuous from 1- to 500-horsepower, DOE scaled the missing values from then next closest horsepower ratings (250- and 400-horsepower). Conveniently, the NEMA Premium efficiency levels for 6-pole motors at 250- and 400-horsepower were equivalent, so DOE assumed that 6-pole motors at 300- and 350-horsepower were also at the same efficiency level.

For the higher CSLs, namely 3, 4, and 5, DOE's conservation of motor losses approach relies on NEMA MG1-2011's table of nominal efficiencies and the relative improvement in motor losses of the representative units. As has been discussed, each incremental improvement in NEMA nominal efficiency (or NEMA band) corresponds to roughly a 10 percent reduction in motor losses. After CSLs 3, 4, and 5 were developed for each representative unit, DOE applied the same reduction in motor losses (or the same number of NEMA band improvements) to various segments of the market based on the representative units. DOE assigned a segment of the electric motors market, based on horsepower ratings, to each representative unit analyzed. DOE's assignments of these segments of the markets were in part based on the standardized NEMA frame number series that NEMA MG1 assigns to horsepower and pole configuration combinations. That segmentation of the market is shown in Figure 5.11.

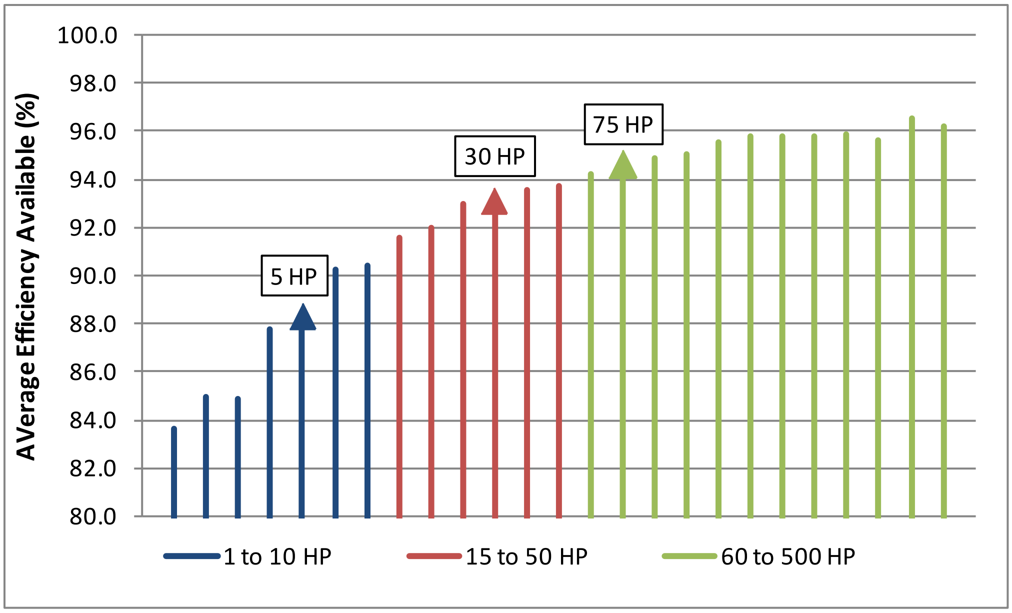

Figure 5.11 Segmentation of Electric Motor Market for Representative Units

The first section, shaded blue in Figure 5.11, consists of smaller frame electric motors whose efficiencies increase at a quicker rate than larger frame electric motors. A 5-horsepower electric motor was selected to represent the electric motors on this section of the graph based on high shipment volume and the fact that this electric motor's efficiency is in middle of this steep section of the graph. The electric motors whose analysis is based on the 5-horsepower electric motor are electric motors between 1-horsepower and 10-horsepower.

DOE then analyzed the mid-section of the graph, or electric motors whose efficiencies do not change as drastically as the blue-shaded region and determined that a 30-horsepower electric motor falls in the middle of this region of the graph. Consequently, DOE selected the 30-horsepower rating to analyze for the red shaded region of the graph, which represents electric motors from 15-horsepower to 50-horsepower.

For the third section, DOE observed the electric motor efficiencies exhibited a fairly "flat" characteristic as frame sizes increase beyond 60-horsepower. DOE selected a 75-horsepower electric motor to represent the electric motors on the final part of the graph because it was large enough to represent electric motors in this horsepower range yet small enough to facilitate various aspects of the engineering analysis, such as physical teardowns of the electric motor. The 75-horsepower electric motor represents electric motors on the large end of the scope of coverage, from 60-horsepower to 500-horsepower.

In the end, for ECG 1, each CSL above CSL 2 was one NEMA band above the previous CSL for each representative unit -- i.e., CSL 3 exceeded Table 12-12 by one band, CSL 4 by two, and CSL 5 by three. The following bulleted line items summarize each CSL for ECG 1:

- CSL 0: Lowest-in-scope efficiencies for all equipment classes
- CSL 1: NEMA MG1-2011 Tables 12-11 and 20-A for all equipment classes
- CSL 2: NEMA MG1-2011 Tables 12-12 and 20-Bfor all equipment classes

- CSL 3: One NEMA band above CSL 1 for all equipment classes
- CSL 4: One NEMA band above CSL 2 for all equipment classes
- CSL 5: One NEMA band above CSL 3 for all equipment classes[h]

The scaling results for ECG 2 were slightly different. As discussed, there is limited equipment selection of NEMA Design C motors, and CSL 0 was the only CSL based on tear-down results. Consequently, CSLs 1 through 3 were modeled using a computer software program. Relative to the baseline CSL, Table 12-11, DOE was able to achieve a max-tech efficiency level that corresponded to an improvement of four NEMA bands for both representative units. Going from CSL 0 to the first modeled design for both representative units constituted an initial jump of two NEMA bands. Each incremental CSL above CSL 1 corresponded to a one NEMA band improvement, totaling four NEMA bands of improvement relative to the baseline at CSL 3. As the improvements in NEMA bands were the same for both representative units, DOE broadly applied these improvements to all equipment classes covered by this ECG. The following bullets summarize each CSL for ECG 2.

- CSL 0: NEMA MG1-2011 Table 12-11 for all equipment classes
- CSL 1: Two NEMA bands above CSL 0 for all equipment classes
- CSL 2: One NEMA band above CSL 1 for all equipment classes
- CSL 3: One NEMA band above CSL 2 for all equipment classes

5.7.2 Scaling Approach Using Regression Equations

DOE developed a second approach for scaling to CSL 3, CSL 4 and CSL 5 which relied on regression equations to predict electric motor losses. The first step DOE took in this approach was to create a model that describes electric motor losses as a function of the electric motor's rated horsepower. To do this, DOE examined the standards adopted by EISA 2007. For polyphase general-purpose electric 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 electric 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 to observe any trends:

- Electric motor losses (defined as $\frac{1}{efficiency}-1$) versus horsepower

If plotted on logarithmic scales, DOE observed that as horsepower increased, electric motor losses decreased following a power law function,as shown in Figure 5.12. That is:

- $MotorLosses(HP) = a \times HP^{-b}$, where a and b vary by pole configuration and electric motor category combination.

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[h] DOE notes that the segment of the market based on the 30-horsepower NEMA Design B representative unit has the same set of nominal efficiencies at CSL 3 and 4 because DOE only developed three CSLs for that representative unit.

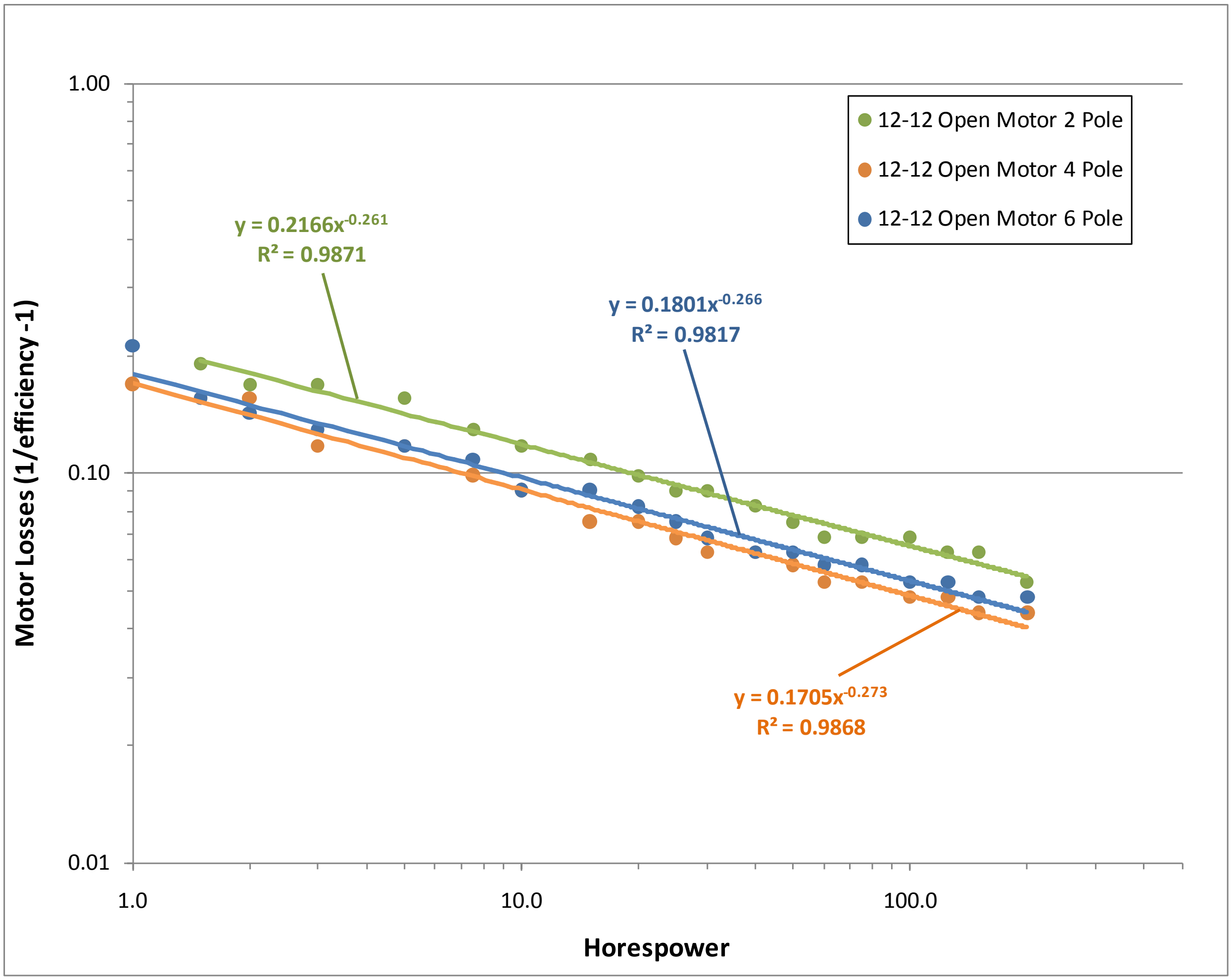

Figure 5.12 NEMA Premium Motor Losses versus Horsepower Rating

As mentioned in section 5.3, for ECG 1 CSL 3 represents a best-in-market efficiency level, CSL 5 represents the maximum technology efficiency level, and CSL 4 is an incremental efficiency level between the two. For the representative units, the efficiency levels at CSL 3, CSL 4 and CSL 5 were already known, either through purchased electric motors or software modeling. Therefore, the DOE scaled the CSLs from the representative units to the equipment classes that were not analyzed. This was done by using the power law function observed in Figure 5.12. Since DOE directly analyzed three horsepower ratings (5-horsepower, 30-horsepower and 75-horsepower), the electric motor losses continuum was split up into three ranges: 1- to 10-horsepower, 15- to 50-horsepower, and 60- to 500-horsepower (as shown in Figure 5.11). A power law function was derived for CSL 1 and CSL 2 for each range in the representative ECGs as shown in Figure 5.13.

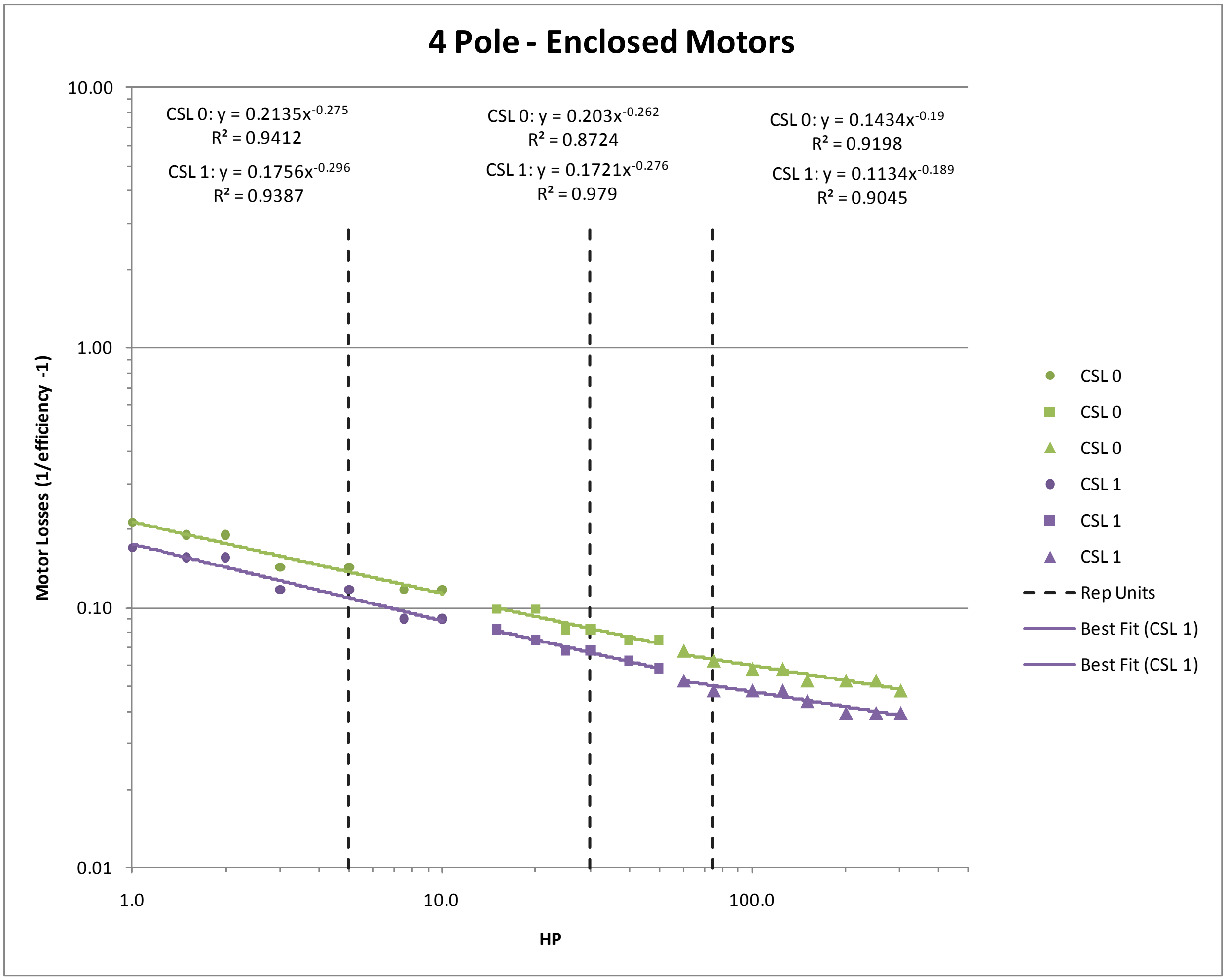

Figure 5.13 Function of Electric Motor Losses with Horsepower for 4-Pole, Enclosed Electric Motors

For each range, the exponents of CSL 1 and CSL 2 were averaged to derive the following three power law equations:

$$MotorLosses(HP) = a \times HP^{-.286} \text{ for 1 horsepower to 10-horsepower}$$

$$MotorLosses(HP) = a \times HP^{-.269} \text{ for 15-horsepower to 50-horsepower}$$

$$MotorLosses(HP) = a \times HP^{-.190} \text{ for 60-horsepower and greater}$$

where '*a*' is a constant that that differs for CSL 3, CSL 4 and CSL 5. As previously mentioned, the efficiency values for CSL 3, CSL 4 and CSL 5 are known at 5-horsepower, 30-horsepower and 75-horsepower as they are the efficiency levels of the representative equipment classes. The value of '*a*' for CSL 3, CSL 4 and CSL 5 can be solved for using these known efficiency values. With the constants and exponents derived for the CSL 3, CSL 4 and CSL 5 power functions, the equations can be used to derive the CSL 3, CSL 4 and CSL 5 efficiency levels for the unanalyzed horsepower ratings. The results of this calculation are shown in Figure 5.14.

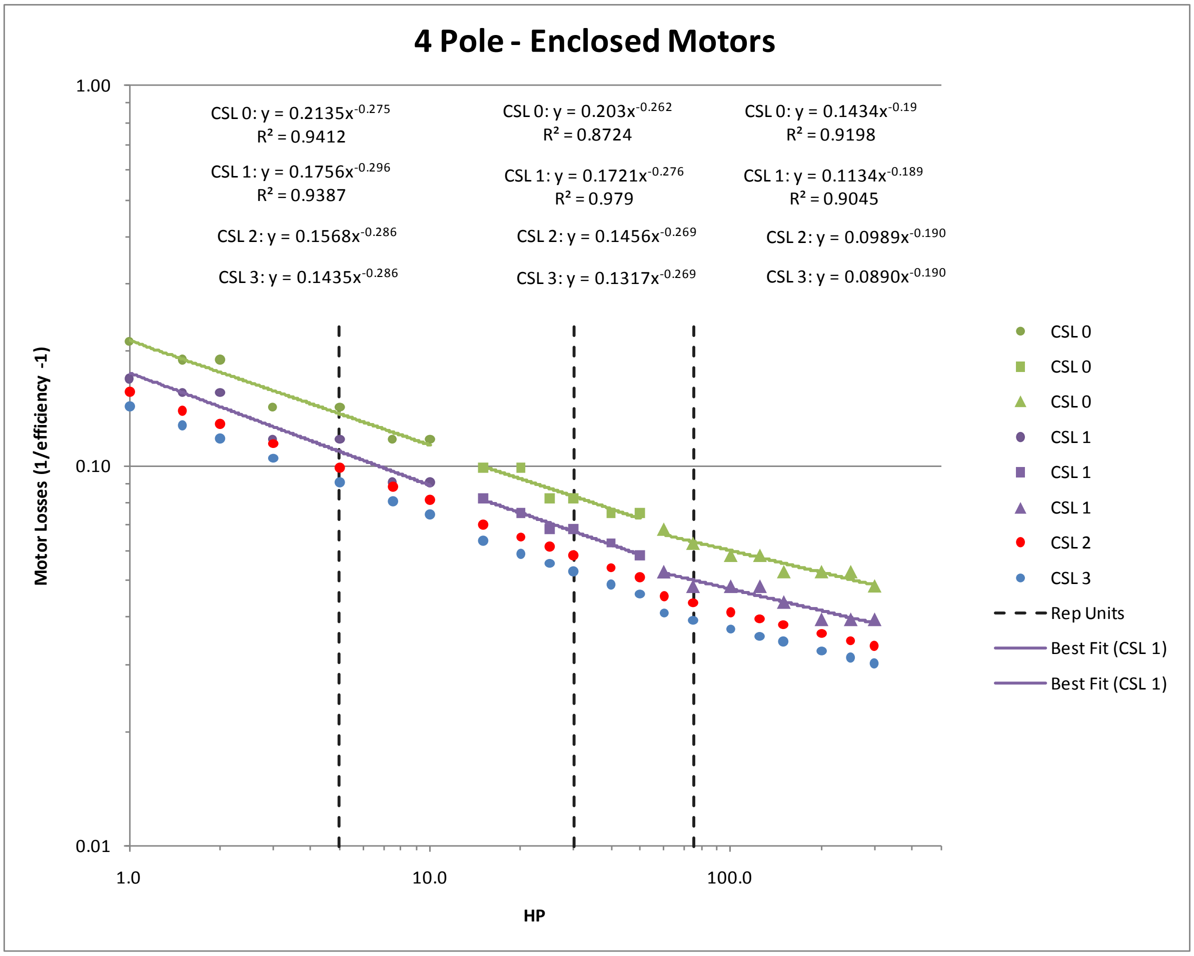

Figure 5.14 Function of Electric Motor Losses with Horsepower Derived for CSL 2 and CSL 3 for 4-Pole, Enclosed Electric Motors of NEMA Design A & B

With CSL3, CSL 4 and CSL 5 determined for the 4-pole enclosed electric motors, DOE then had to scale these CSLs to the other electric motor pole configurations and enclosures. To do this, DOE compared the efficiencies, at a given horsepower rating, of the 4-pole enclosed motors with the efficiencies of other pole configurations and enclosures at the Table 12-12 levels. The ratio of those efficiencies was multiplied by the scaled efficiency (at CSL 3, 4, or 5) of the 4-pole enclosed electric motor efficiency. The resulting product was a scaled efficiency, at a given horsepower rating, of the equipment class not analyzed. To do this, DOE had to assume that the ratio of efficiencies of different equipment classes at CSL 2stayed constant for CSL 3, CSL 4 and CSL 5. The following equation was used to derive the scaled efficiencies:

$$Efficiency(hp) = \frac{Efficiency_{NP}(hp)}{Efficiency_{NP4E}(hp)} Efficiency_{4E}(hp)$$

where

- *Efficiency*- is the resulting scaled efficiency of the desired equipment class at the new CSL (3, 4, or 5).
- $Efficiency_{NP}$-is the NEMA Premium efficiency of the desired equipment class.
- $Efficiency_{NP4E}$-is the NEMA Premium efficiency of a 4-pole enclosed electric motor.
- $Efficiency_{4E}$- is the scaled efficiency of a 4-pole enclosed electric motor at the CSL being scaled to (3, 4, or 5).

HP	Enclosed Frame									
	4 Pole					6 Pole				
	CSL 0	CSL 1	CSL 2	CSL 3	CSL 4	CSL 0	CSL 1	CSL 2	CSL 3	CSL 4
7.5	84.0	89.5	91.7	92.4	93.0	82.5	89.5	91.0		
10.0	86.5	89.5	91.7	92.4	93.0	84.0	89.5	91.0		
15.0	86.5	91.0	92.4	93.0	93.6	88.5	90.2	91.7	92.4	Result
20.0	87.5	91.0	93.0	93.6	94.1	87.5	90.2	91.7		
25.0	89.5	92.4	93.6	94.1	94.5	91.7	91.7	93.0		

Efficiency derived from power law equation

Unknown efficiency

Figure 5.15 Scaling Across Electric Motor Configurations

For example, in order to calculate the efficiency of a 15-horsepower,6-pole, enclosed electric motor at CSL 3, see the equation below along with Figure 5.15.

$$Efficiency(15) = \frac{Efficiency_{NP}(15)}{Efficiency_{NP4E}(15)} Efficiency_{4E}(15) = \frac{91.7}{92.4} \times 93.0 = 92.3$$

As shown above, this method results in an efficiency level of 92.3 percent for a 6-pole NEMA Design A or B electric motor of enclosed construction. However, 92.3 percent falls just short of the NEMA nominal efficiency (see NEMA MG 1-2009 Table 12-10) of 92.4 percent. Therefore, it would have to be "rounded" down to the closest NEMA nominal efficiency level which in this case was 91.7 percent. By having to convert the calculated scaled efficiency levels to NEMA nominal efficiency levels, DOE observed that some of the efficiency levels that were scaled were the same efficiency as the lower CSL. For instance, in the example above CSL 1 and CSL 2 would be equal to each other at 15-horsepower since the 92.3 percent efficiency would have to be rounded down to the closest NEMA nominal efficiency level. As a result, DOE elected not to use this as the primary methodology for scaling the engineering results of its representative units.