CHAPTER 7. ENERGY USE CHARACTERIZATION

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CHAPTER 7. ENERGY USE CHARACTERIZATION

7.1 INTRODUCTION

A key component of the life-cycle cost (LCC) and payback period (PBP) calculations described in chapter 8 of the Technical Support Document is the savings in operating costs that customers would realize from more energy efficient equipment. Energy costs are the most significant component of customer operating costs. The U.S. Department of Energy (DOE) uses annual energy use, along with energy prices, to establish energy costs at various energy efficiency levels. This chapter describes how DOE determined the annual energy use of electric motors.

The analysis focuses on eight representative units identified in the engineering analysis (chapter 5) and for which engineering analysis outputs were obtained. (Table 7.1.1)

Table 7.1.1 Representative Units for Preliminary Analysis

Representative Unit	Equipment class Group	Specifications	Horsepower
1 2 3	NEMA Designs A & B	NEMA Design B, T-frame, enclosed, 4-pole	5 30 75
4 5	NEMA Design C	NEMA Design C, T-frame, enclosed, 4-pole	5 50
6 7 8	Fire Pump	Uses same engineering outputs as units 1, 2, and 3	5 30 75

7.2 ENERGY USE ANALYSIS FOR ELECTRIC MOTORS

7.2.1 Introduction

The energy use by electric motors is derived from three components: energy converted to useful mechanical shaft power, motor losses, and reactive power. Motor losses consist of I^2R losses (both stator and rotor), core losses, stray-load losses, and friction and windage losses.[1] Core losses and friction and windage losses are relatively constant with variations in motor loading, while I^2R losses increase with the square of the motor loading. Stray-load losses are also dependent upon loading. DOE models the I^2R losses and stray-load losses as load-dependent losses.

7.2.2 Motor Losses

For each representative unit, DOE obtained data on part load motor losses from test data developed in the engineering analysis (chapter 5). Based on the test data, DOE modeled the motor losses as a function of loading using a third degree polynomial equation[2]:

$$Loss(L) = A + B \times L + C \times L^2 + D \times L^3$$

where:

Loss(L)	=	the losses of the motor at loading *L* in watts
L	=	motor loading as a fraction of rated power in percent
A/B/C/D	=	polynomial equation coefficients

Table 7.2.1 presents the polynomial equation coefficients for modeling losses as a function of loading for the eight representative units at each efficiency level analyzed by DOE. These efficiency levels correspond to the candidate standard levels (CSLs) analyzed in the engineering analysis (chapter 5).

Table 7.2.1 Polynomial Equation Coefficients for Losses vs. Loading Relationship

Representative Unit	CSL	A	B	C	D
1	0	234.2	115.8	273.4	168.0
	1	169.6	51.2	208.8	103.4
	2	158.0	77.8	68.3	133.6
	3	150.3	21.8	182.8	50.4
	4	143.5	63.0	110.5	51.8
	5	135.3	29.2	147.8	25.2
2	0	1059.3	181.4	1052.5	332.3
	1	863.1	-14.8	856.3	136.1
	2	639.7	102.7	586.8	201.1
	3	509.6	17.5	622.2	253.9
	4	444.6	228.4	358.3	271.3
	5	444.6	228.4	358.3	271.3
3	0	1775.2	267.1	1757.2	411.8
	1	1599.4	91.3	1581.4	236.0
	2	870.8	280.9	1037.9	508.1
	3	809.6	219.7	976.7	446.9
	4	653.5	1006.4	-261.5	811.8
	5	608.3	961.2	-306.7	766.6
4	0	220.3	62.5	159.7	90.3
	1	202.0	85.7	67.8	82.1
	2	194.2	74.6	76.2	60.3
	3	179.7	36.1	115.0	38.0

5	0	1177.8	106.3	1240.8	282.6
	1	829.6	970.7	-111.9	650.4
	2	781.6	907.0	-140.1	622.2
	3	609.3	1019.3	-575.5	910.2
6	0	169.6	51.2	208.8	103.4
	1	158.0	77.8	68.3	133.6
	2	150.3	21.8	182.8	50.4
	3	143.5	63.0	110.5	51.8
	4	135.3	29.2	147.8	25.2
7	0	863.1	-14.8	856.3	136.1
	1	639.7	102.7	586.8	201.1
	2	509.6	17.5	622.2	253.9
	3	444.6	228.4	358.3	271.3
	4	444.6	228.4	358.3	271.3
8	0	1599.4	91.3	1581.4	236.0
	1	870.8	280.9	1037.9	508.1
	2	809.6	219.7	976.7	446.9
	3	653.5	1006.4	-261.5	811.8
	4	608.3	961.2	-306.7	766.6

To determine the annual energy losses E_{loss} in kilowatt-hours (kWh), DOE converts the full-load losses into part-load losses using the estimate of the motor's loading, and multiplies by the annual operating hours. Annual energy losses are represented by the following equation:

$$E_{loss} = H_{op} \times Loss(L)$$

where:

E_{loss}	=	annual energy consumed by motor losses in watts per hour
H_{op}	=	the annual operating hours, also known as the duty factor in hours
L	=	motor loading as a fraction of rated power in percent

7.2.2.1 Impact of Higher Operating Speeds

DOE is aware that the installation of a more efficient motor could lead to less energy savings than anticipated. According to comments from interested parties, a more efficient motor typically has less slip than a less efficient motor, which is an attribute that can result in a higher operating speed and potentially overloading the motor.

DOE acknowledges that the cubic relation between speed and power requirement in many variable torque applications can affect the benefits gained by efficient motors, which have a lower slip. DOE did not obtain sufficient data to incorporate this effect into the LCC analysis. Instead, DOE incorporated this effect as a sensitivity analysis in the LCC spreadsheet, allowing the user to consider this effect following a scenario which described in Appendix 7-A of the technical support document (TSD).

7.2.3 Reactive Power

In an alternating current power system, the reactive power is the root mean square (RMS) voltage times the RMS current, multiplied by the sine of the phase difference between the voltage and the current. Reactive power occurs when the inductance or capacitance of the load shifts the phase of the voltage relative to the phase of the current. While reactive power does not consume energy directly, it can increase losses and costs for the electricity distribution system. Motors tend to create reactive power because the windings in the motor coils have high inductance.

Alternating-current power flow has three components: real power (*P*), measured in watts (W); apparent power (*S*), measured in volt-amperes (VA); and reactive power (*Q*), measured in reactive volt-amperes (VAr). The power factor is defined as *P*/*S*. In the case of a perfectly sinusoidal waveform, *P*, *Q*, and *S* can be expressed as vectors that form a vector triangle such that: $S^2 = P^2 + Q^2$. This implies that the formula for reactive power as a function of real power and power factor is as follows:

$$Q = P * (1/PF^2-1)$$

where:

Q	=	reactive power in reactive volt-amperes,
P	=	real power in watts, and
PF	=	the motor's power factor.

DOE used data on motor power factor as a function of motor loading from test data developed in the engineering analysis (TSD chapter 5) to develop a relationship between power factor and motor loading. This relationship is expressed as a third degree polynomial:

$$PF(L) = A + B \times L + C \times L^2 + D \times L^3$$

Table 7.2.2 presents the polynomial equation coefficients developed to estimate power factor for all representative units at each efficiency level analyzed by DOE.

Table 7.2.2 Polynomial Equation Coefficients for Power Factor vs. Loading Relationship

Representative Unit	CSL	A	B	C	D
1	0	0.036	2.055	-1.856	0.595
	1	0.034	2.053	-1.858	0.592
	2	0.066	1.664	-1.314	0.374
	3	0.071	2.140	-2.034	0.663
	4	0.074	2.140	-2.025	0.661
	5	0.071	2.140	-2.034	0.663
2	0	0.076	2.143	-2.023	0.664
	1	0.034	2.053	-1.858	0.592
	2	0.034	2.053	-1.858	0.592
	3	0.075	1.977	-1.817	0.575

	4	0.047	2.332	-2.387	0.794
	5	0.047	2.332	-2.387	0.794
3	0	0.036	2.055	-1.856	0.595
	1	0.034	2.053	-1.858	0.592
	2	0.074	2.140	-2.025	0.661
	3	0.036	2.055	-1.856	0.595
	4	0.043	2.492	-2.625	0.900
	5	0.038	2.487	-2.630	0.895
4	0	0.033	1.612	-1.276	0.381
	1	0.040	0.860	-0.269	-0.012
	2	0.059	1.324	-0.831	0.177
	3	0.077	1.746	-1.453	0.420
5	0	0.074	2.140	-2.025	0.661
	1	0.044	1.925	-1.704	0.515
	2	0.044	1.925	-1.704	0.515
	3	0.050	2.401	-2.506	0.849
6	0	0.034	2.053	-1.858	0.592
	1	0.066	1.664	-1.314	0.374
	2	0.071	2.140	-2.034	0.663
	3	0.074	2.140	-2.025	0.661
	4	0.071	2.140	-2.034	0.663
7	0	0.034	2.053	-1.858	0.592
	1	0.034	2.053	-1.858	0.592
	2	0.075	1.977	-1.817	0.575
	3	0.047	2.332	-2.387	0.794
	4	0.047	2.332	-2.387	0.794
8	0	0.034	2.053	-1.858	0.592
	1	0.074	2.140	-2.025	0.661
	2	0.036	2.055	-1.856	0.595
	3	0.043	2.492	-2.625	0.900
	4	0.038	2.487	-2.630	0.895

7.2.4 Motor Applications

The annual operating hours and loading of motors depend on the sector (i.e., industry, agriculture, and commercial), motor size (in horsepower), and end-use application (e.g., pump). DOE estimated the share of motors in each type of application depending on the National Electrical Manufacturers Association (NEMA) design and size of the motor, and used a distribution of motors across sectors by motor size. DOE drew upon several data sources to develop a model of the applications for which motors covered in this analysis are used.

Six motor applications (air compressors, fans, pumps, material handling and processing, fire pumps, and others) were selected as representative applications based on a previous DOE study (DOE-ITP study)[3] and a database of motor nameplate and field measurement data compiled by the Washington State University (WSU) Extension Energy Program, Applied

Proactive Technologies (APT), and New York State Energy Research and Development Authority (NYSERDA)[4] ("WSU/NYSERDA database")[a]. The tables below summarize the distribution of NEMA Design A and B motors (Table 7.2.3), and NEMA Design C motors (Table 7.2.4) across applications by horsepower range in the industrial sector. No sufficient data were available to develop similar estimates in the commercial or agricultural sector and, instead, the estimates in the industrial sector were used as an approximation.

Table 7.2.3 Distribution of Motors by Application for NEMA Design A and B Motors (in percent)

	Horsepower (hp) range						
Application	**1-5**	**6-20**	**21-50**	**51-100**	**101-200**	**201-500**	**all *hp***
Air Compressor	1.8	1.3	2.2	5.6	5.4	8.3	2.2
Fans	22.5	24.9	26.6	25.7	18.9	21.7	24.0
Pumps	22.3	31.6	33.0	34.2	36.0	25.5	28.5
Material Handling and Processing	12.0	9.4	6.8	10.6	7.8	7.6	10.0
Other	41.4	32.8	31.4	23.9	31.9	36.9	35.3
Fire Pumps	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7.2.4 Distribution of Motors by Application for NEMA Design C Motors (in percent)

	Horsepower (hp) range					
Application	**1-5**	**6-20**	**21-50**	**51-100**	**101-200**	**all *hp***
Air Compressor	0.0	0.0	0.0	0.0	0.0	0.0
Fans	25.0	11.1	0.0	11.1	10.3	10.3
Pumps	0.0	0.0	28.6	0.0	6.9	6.9
Material Handling and Processing	25.0	11.1	14.3	11.1	13.8	13.8
Other	50.0	77.8	57.1	77.8	69.0	69.0
Fire Pumps	0.0	0.0	0.0	0.0	0.0	0.0

The distribution of motors across sectors by motor size was extracted from an Easton Consultants report[5] which provides the distribution of alternating-current integral-horsepower motors by horsepower across various sectors. DOE adjusted the distribution across sectors to only account for three-digit NEMA frame size motors assuming that two-digit NEMA frame size

[a] The motors database comprised of information gathered by WSU and APT during 123 industrial motor surveys or assessments: 11 motor assessments were conducted between 2005 and 2011 and occurred in industrial plants; 112 industrial motor surveys were conducted between 2005 and 2011 and were funded by NYSERDA and conducted in New York State.

motors account for 30 percent of total integral motors below 5 hp and are primarily used in the commercial sector. (Table 7.2.5)

Table 7.2.5 Motor Distribution across Sector by Motor Size

Horsepower range	Industry %	Agriculture %	Commercial %
1-5	37	0	63
6-20	26	0	74
21-50	26	0	74
51-100	63	7	30
101-200	76	3	21
201-500	69	3	28

7.2.5 Loading

To calculate the annual kWh use at each efficiency level in each equipment class, DOE used the losses versus load curves from the engineering analysis (Table 7.2.1), along with estimates of motor operating hours and average loading.

The average motor loading mainly depends on the motor's end-use application (e.g., fan, pump) and sector (e.g., industrial). In the industrial sector, the DOE-ITP study shows that, for a specific application, loading does not vary significantly across horsepower ranges. DOE estimated application-specific average loading based on approximately 15,000 field measurements provided by the WSU/NYSERDA database. A statistical distribution to characterize variability in the field was also extracted from the WSU/NYSERDA database. Table 7.2.6 presents the average motor loading by applications in the industrial sector. Because sufficient data were not available, the same average loading values and statistical distribution were used in the commercial and agricultural sectors.

Table 7.2.6 Average Motor Loading by Application

Application	Loading %
Air compressors	0.70
Fans	0.60
Pumps	0.68
Material Handling and Processing	0.48
Other	0.71
Fire Pumps	0.62

7.2.6 Motor Hours of Operation/Duty Factor

DOE estimated average annual operating hours by sector, application, and horsepower ranges and developed statistical distributions to use in its Monte Carlo analysis (the Monte Carlo analysis is described in TSD chapter 8).

For the industrial sector, DOE used the WSU/NYSERDA database to determine average annual operating hours by application and horsepower ranges and statistical distributions. For example, Figure 7.2.1 shows the cumulative form of the discrete distributions for motors between 21 and 50 horsepower in various applications.

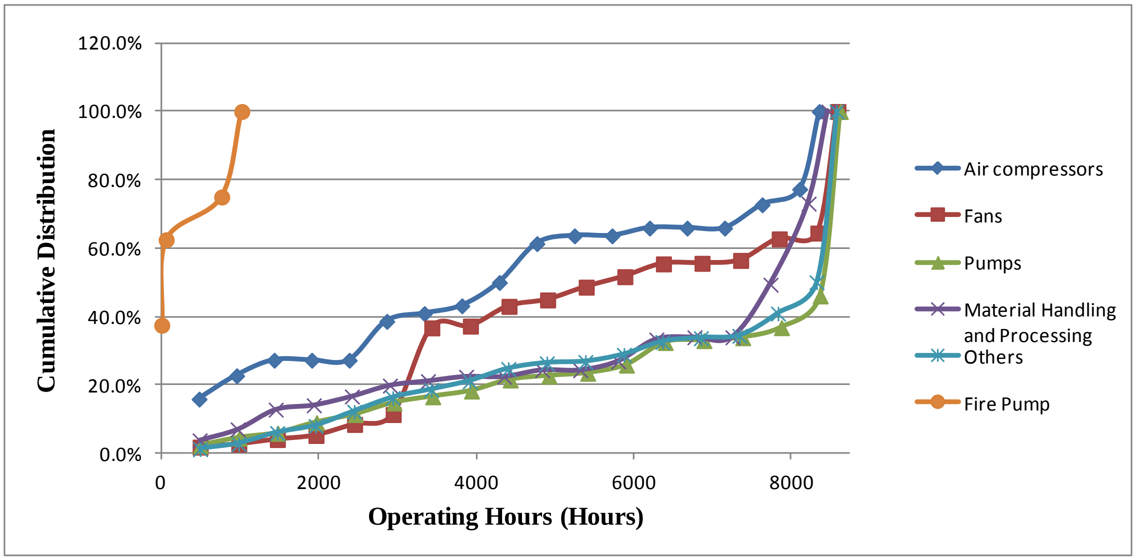

Figure 7.2.1 Cumulative Distribution for 21-50 Horsepower Motors by Applications in Industry Sector.

For the commercial and agricultural sectors, DOE derived estimates of average operating hours by application and horsepower range from various sources: a presentation by Richard A. Peterson[6], an article by Michael Gallaher *et al*.[7], the Regional Technical Forum[8], DOE's own analysis on classification and evaluation of electric motors and pump[9], an Electric Power Research Institute (EPRI) report[10], and a DOE report by Arthur D. Little[11]. For fire pumps, DOE assumed a uniform distribution between 0.5 hours (based on comments from interested parties) to 6 hours.

Table 7.2.7 displays the average hours of motor operation by application and motor sizes for the industrial, commercial, and agricultural sectors.

Table 7.2.7 Average Motor Operating Hours by Application and Horsepower Range

	Horsepower (hp) range					
	1-5	**6-20**	**21-50**	**51-100**	**101-200**	**201-500**
Industry						
Air Compressors	4,647	5,033	4,578	5,337	6,226	6,349
Fans	6,193	6,490	5,849	6,975	7,163	8,015
Pumps	6,028	6,773	6,972	6,869	6,985	6,934
Material Handling	6,486	6,284	6,518	6,315	7,172	6,116
Other	6,571	6,274	6,814	7,128	7,337	7,528
Fire Pump	13	366	366	3,848	4,411	4,411
Commercial						
Air Compressors	1,000	1,200	1,500	1,500	1,500	1,500
Fans	3,000	3,300	3,600	3,900	4,200	4,500
Pumps	1,500	1,650	1,800	1,950	2,100	2,250
Material Handling	1,959	2,165	2,380	2,567	2,753	2,939
Other	1,959	2,165	2,380	2,567	2,753	2,939
Fire Pump	0.5-6	0.5-6	0.5-6	0.5-6	0.5-6	0.5-6
Agriculture						
Air Compressors	1,901	1,901	1,901	1,901	1,901	1,901
Fans	4,800	4,800	4,800	4,800	4,800	4,800
Pumps	1,800	1,800	1,800	1,900	2,000	2,000
Material Handling	1,500	1,500	1,500	1,500	1,500	1,500
Other	1,901	1,901	1,901	1,901	1,901	1,901
Fire Pump	0.5-6	0.5-6	0.5-6	0.5-6	0.5-6	0.5-6

7.3 ANNUAL ENERGY USE

Depending on the hours of operation, the loading, and the efficiency of the motor (which varies with the standard level), the annual energy use varies both by efficiency level and from motor to motor. The annual energy use is calculated using the following expression:

$$E = \frac{HP \times L}{\eta} \times H_{op}$$

where:

E = energy use,
HP = horsepower of the motor, or motor capacity,
L = motor loading as a fraction of rated power in percent
η = operating efficiency, and
H_{op} = motor operating hours.

Table 7.3.1 shows the results of the energy use analysis for the eight representative units at each considered energy efficiency level. Results are given for baseline units (CSL 0) and the three candidate standard levels (CSLs) being considered for motors.

Table 7.3.1 Average Annual Energy Consumption by Efficiency Level for Representative Units

Rep. Unit	Description	*kilowatt-hours per year*					
		CSL 0	**CSL 1**	**CSL 2**	**CSL 3**	**CSL 4**	**CSL 5**
1	Design B, T-frame, 5 hp*, 4 poles, enclosed	10,448	9,869	9,691	9,616	9,567	9,487
2	Design B, T-frame, 30 hp, 4 poles, enclosed	57,642	55,912	55,021	54,492	54,326	54,326
3	Design B, T-frame, 75 hp, 4 poles, enclosed	204,834	202,540	198,496	197,697	197,194	196,604
4	Design C, T-frame, 5 hp, 4 poles, enclosed	9,987	9,808	9,738	9,630	-	-
5	Design C, T-frame, 50 hp, 4 poles, enclosed	89,523	88,507	88,119	87,444	-	-
6	Fire pump, 5 hp, 4 poles, enclosed	19.6	19.2	19.1	19.0	18.8	-
7	Fire pump, 30 hp, 4 poles, enclosed	1,601	1,577	1,562	1,558	1,558	-
8	Fire pump, 75 hp, 4 poles, enclosed	97,791	95,934	95,554	95,313	95,033	-

* hp = horsepower.

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