

## CHAPTER 6. ENERGY USE CHARACTERIZATION

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## CHAPTER 6. ENERGY USE CHARACTERIZATION

### 6.1 INTRODUCTION

The U.S. Department of Energy (DOE) carried out the life-cycle cost (LCC) and payback period (PBP) calculations described in chapter 8 by determining the savings in operating cost consumers would realize from more energy efficient products. Energy costs are the most significant component of consumer operating costs, with maintenance and repair costs the other contributors. 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 small electric motors.

### 6.2 ENERGY USE ANALYSIS FOR SMALL ELECTRIC MOTORS

#### 6.2.1 Introduction

The energy use by small electric motors derives 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 losses and friction and windage losses.<sup>1</sup> 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 losses are also dependent upon loading. DOE models the  $I^2R$  losses and stray losses as load-dependent losses.

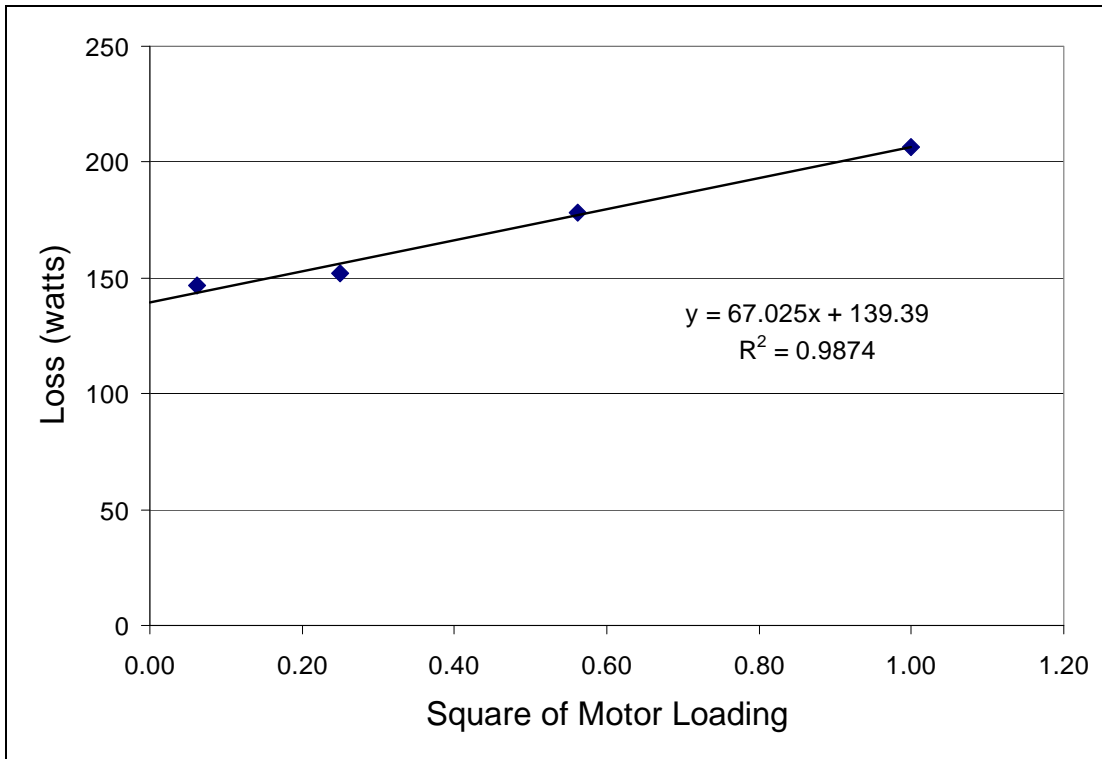
#### 6.2.2 Motor Losses

DOE's mathematical description of energy use separates motor losses into a constant component and a component that depends on motor loading. In DOE's analysis, the design efficiency of the motor at full load determines the total losses at 100-percent motor loading. DOE then estimates the fraction of these losses that is load independent and the fraction that varies as the square of the motor loading. To determine the annual energy use in kilowatt hours (kWh), DOE adjusts the full-load losses using the estimate of the motor duty factor (hours of operation per year) and loading. All losses are proportional to duty factor, and DOE approximates the load-dependent losses as proportional to both the duty factor and the square of the loading. Annual energy use  $E_{ann}$  is represented by the following equation:

$$E_{ann} = H_{op} \times (P_{NL} + P_{LL} \times L^2)$$

Where:

$E_{ann}$	=	annual energy use;
$H_{op}$	=	the annual operating hours, also known as the duty factor;
$P_{NL}$	=	the power of load-independent losses at full load;
$P_{LL}$	=	the power of load-dependent losses at full load; and
$L$	=	motor loading as a fraction of rated power.



**Figure 6.2.1 Average Dependence of Motor Losses on the Square of the Motor Loading for Polyphase 1 Horsepower Motor.**

DOE confirmed the functional form of the dependence of motor losses on loading through a review of motor efficiency data from catalogue data available on the Internet as illustrated in figure 6.2.1 above.

For this preliminary analysis, DOE apportioned the losses at full load equally to  $P_{NL}$  and  $P_{LL}$ . For the notice of proposed rulemaking (NOPR), DOE will use a more sophisticated and potentially more precise method for apportioning full load losses to  $P_{NL}$  and  $P_{LL}$ .

While motor manufacturers do not explicitly publish motor losses as a function of load, many manufacturers do publish efficiency as a function of motor load. This allows the estimate of motor losses as a function of motor loading and a motor-by-motor estimate of  $P_{NL}$  and  $P_{LL}$ . The relationship between motor losses, efficiency and capacity is given by the following equation:

$$Efficiency = (P_W * L) / (P_W * L + Losses)$$

Solving for the losses, we obtain:

$$Losses = (P_W * L) * (1/Efficiency - 1)$$

Where:

$$Efficiency = \text{motor efficiency};$$

$P_w$	=	the motor's rated power in watts;
$Losses$	=	the power of load-independent losses at full load in watts;
$L$	=	motor loading as a fraction of rated power.

DOE collected from the Internet efficiency vs. loading for several hundred listed motor models built in two-digit frame sizes. In some cases, on-line catalogues for at least two manufacturers had efficiency ratings for motors at 25, 50, 75 and 100 percent loading levels.

### 6.2.3 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.

In practice, reactive power may result in only minor increases in energy consumption if capacitors in the electrical system compensate (i.e., mitigate) the reactive power. Also in previous analyses and standards for both small and medium electric motors, DOE has not considered power factor in the estimation of motor losses or efficiency. In this preliminary analysis, DOE assumes that, while reactive power may result in extra energy supply costs, actual losses before power factor compensation (through distribution system capacitor banks) are small. Actual fractional consumptive losses due to reactive power are approximately equal to the fractional losses on the electrical distribution system in general. This means that actual consumptive losses due to reactive power are likely to be less than 10 percent of total reactive power. For the NOPR, DOE will use a more sophisticated and potentially more precise method for accounting for the losses and costs due to reactive power.

While motor manufacturers do not explicitly report reactive power as a function of load, many manufacturers do publish power factor as a function of motor load. Power factor is the ratio of the real power divided by the apparent power, where the apparent power is the sum of the real power and the reactive power. This allows the estimate of motor reactive power as a function of motor loading and a motor-by-motor estimate of reactive power as a function of load. The relationship between reactive power ( $PF$ ), efficiency, and rated power is given by the following equations:

$$PF = P_{real} / P_{apparent}$$

Where:

$$P_{real} = (P_w * L) / Efficiency$$

and where:

$$P_{\text{apparent}} = P_{\text{real}} + P_{\text{reactive}}$$

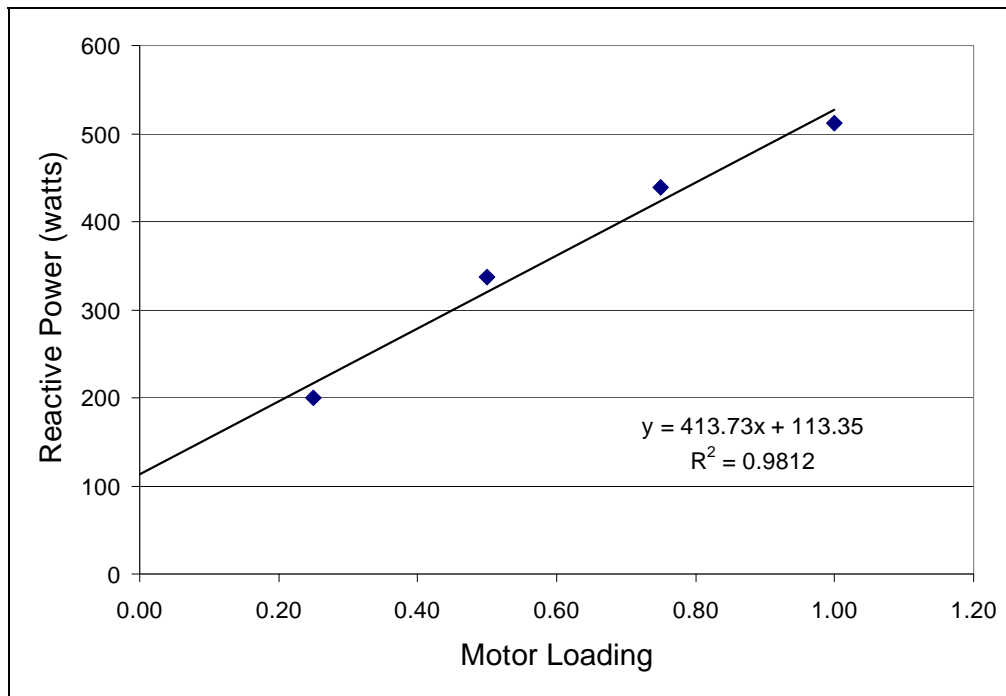
Solving for the reactive power, we obtain:

$$P_{\text{reactive}} = (P_W * L) * (1/\text{Efficiency}) * (1/\text{PF} - 1)$$

Where:

$P_{\text{real}}$	=	real power in watts;
$P_{\text{apparent}}$	=	apparent power in watts;
$P_{\text{reactive}}$	=	reactive power in watts;
$P_W$	=	the motor's rated power in watts;
$\text{Efficiency}$	=	motor efficiency;
$\text{PF}$	=	the motor's power factor;
$L$	=	motor loading as a fraction of rated power.

DOE collected from the Internet efficiency vs. loading for several hundred listed motor models built in two-digit frame sizes. In some cases, on-line catalogues for at least two manufacturers had power factor and efficiency ratings for motors at 25, 50, 75 and 100 percent loading levels.



**Figure 6.2.2 Average Dependence of Reactive Power on Motor Loading for Polyphase 1 Horsepower Motor**

## 6.2.4 Motor Applications

The annual operating hours and loading of small electric motors depends on the application. For different types of motors, the market shares of different motor applications can vary. In preparation for the determination analysis, DOE developed a classification of small electric motor applications and estimated shipments market shares for such motors in 2001. DOE then adjusted these market shares in the determination analysis to account for newly covered products and provided adjusted application market shares in the technical support document for the small motors determination.<sup>2</sup> The estimates from the determination analysis provided information on only polyphase and capacitor start motors. For this analysis DOE used equal application market shares for capacitor-start induction-run (CSIR) and capacitor-start capacitor-run (CSCR) motors.

**Table 6.2.1 Motor Application Market Shares**

No.	Application	Polyphase (%)	CSIR (%)	CSCR (%)
1	Air and gas compressors	9.2	8.1	8.1
2	Commercial and industrial heating, ventilating, air-conditioning (HVAC)/refrigeration equipment	4.3	8.4	8.4
3	Commercial laundry machinery	0.4	1.2	1.2
4	Conveyors	18.8	11.8	11.8
5	Farm machinery	3.0	10.9	10.9
6	Food machinery	8.2	2.1	2.1
7	General industrial machinery	3.4	2.4	2.4
8	Industrial and commercial fans and blowers	5.6	5.9	5.9
9	Machine tools	7.3	1.9	1.9
10	Packaging machinery	1.0	0.3	0.3
11	Pumps and pumping equipment	33.0	41.1	41.1
12	Service industry machinery	1.5	3.0	3.0
13	Textile machinery	1.2	0.4	0.4
14	Woodworking machinery	3.1	2.4	2.4

## 6.2.5 Loading

To calculate the annual kWh use at each efficiency level in each equipment class, DOE used the efficiencies and losses from the engineering analysis, along with estimates of operating hours and motor loading from the determination analysis for the applications that use equipment containing small electric motors (Table 6.2.2).

**Table 6.2.2 Motor Operation Characteristics by Application**

No.	Application	Hours/Year	Motor Loading (Percent of Rated)
1	Air and gas compressors	800	85
2	Commercial and industrial heating, ventilating, air-conditioning (HVAC)/refrigeration equipment	2,500	60
3	Commercial laundry machinery	2,000	60
4	Conveyors	3,000	50
5	Farm machinery	1,000	70
6	Food machinery	3,000	60
7	General industrial machinery	2,000	70
8	Industrial and commercial fans and blowers	5,000	80
9	Machine tools	2,000	60
10	Packaging machinery	3,000	60
11	Pumps and pumping equipment	3,000	65
12	Service industry machinery	1,500	60
13	Textile machinery	3,000	70
14	Woodworking machinery	2,000	35

DOE derived the distribution of values for operating hours and motor loading from the shares of the applications in the motor stock for each equipment class, as estimated in the determination analysis (Table 6.2.1). For this preliminary analysis, DOE used point values for hours of operation and loading for each application. For the NOPR, DOE may use a more sophisticated characterization of motor operating conditions by replacing these point values by distributions that have mean values that approximate the point values. This more precise characterization of motor operating conditions is likely to have a small effect on the mean result of DOE's analyses, but may result in greater variability in the distribution of consumer economic impacts estimated by the life-cycle cost analysis.

Table 6.2.3 shows the average values of operating hours and motor loading for each equipment class, weighted by the shares of each application.

**Table 6.2.3 Average Operating Characteristics for Small Electric Motors**

Equipment Class	Annual Operating Hours	Motor Loading (% of rated)
Polyphase	2,665	63.2
CSIR	2,557	64.8
CSCR	2,557	64.8

### 6.3 ANNUAL ENERGY USE

Depending on the hours of operation and the loading (which are functions of the application) and depending on 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. Table 6.3.1 shows the average annual energy use as a function of efficiency level for the three product classes. In the table, the rated capacity of the representative motor from the product class is in parentheses in each column header. In each case, the motors at the highest efficiency levels have losses that are approximately three times lower than the losses for the baseline designs.

**Table 6.3.1 Average Annual Electricity Use by Efficiency Level for Small Electric Motors**

Candidate Standard Level	Polyphase (1 Horsepower)		CSIR (0.5 Horsepower)		CSCR (0.75 Horsepower)	
	Efficiency (%)	kWh	Efficiency (%)	kWh	Efficiency (%)	kWh
Baseline	75.8	444	62.3	410	68.6	465
CSL 1	84.0	265	70.9	278	80.2	250
CSL 2	85.5	236	73.6	243	82.1	222
CSL 3	86.5	217	75.4	220	83.3	203
CSL 4	88.0	190	78.2	189	85.2	177
CSL 5	90.0	154	81.8	151	87.6	143

## REFERENCES

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<sup>1</sup> National Electrical Manufacturers Association Standards Publication Condensed MG1-2002: *Information Guide for General Purpose Industrial AC Small and Medium Squirrel-Cage Induction Motor Standards*, NEMA, 1300 North 17<sup>th</sup> Street, Suite 1847, Rosslyn, VA 22209, 2002. Also see <http://www.nema.org>.

<sup>2</sup> U.S. Department of Energy-Office of Building Technologies. *Technical Support Document: Analysis of Energy Conservation Standards for Small Electric Motors*, June 2006, U.S. Department of Energy, Washington, DC. Also see [http://www1.eere.energy.gov/buildings/appliance\\_standards/commercial/small\\_electric\\_motors.html](http://www1.eere.energy.gov/buildings/appliance_standards/commercial/small_electric_motors.html).