Machine Drive Electricity Use in the Industrial Sector

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ABSTRACT

It has been estimated that more than 60 percent of the electricity consumed in the United States is used to power electric motor systems (Nadel et al. 2002). According to the *1998 Manufacturing Energy Consumption Survey* (EIA 2001), more than half of the electricity consumed in the manufacturing sector was used for machine drive. The Energy Policy Act of 1992 set minimum efficiency levels for all motors up to 200 horsepower purchased after October 1997.

Because of the importance of motor system electricity consumption in the manufacturing sector, a motor stock model has been developed for several of the sectors included in the Industrial Sector Demand Module of the National Energy Modeling System (NEMS). This paper will discuss the development of the model, basic projections using the model, and ways in which the model could be used for policy analysis.

Introduction

Machine drive is the largest single end use of electricity in the manufacturing sector. Because of machine drive's importance, a motor stock model has been developed for inclusion in the NEMS Industrial Sector Demand Module. This development was facilitated by the existence of good data on the motor population, the cost and performance of available motors, and industry practices related to motor maintenance. This paper will discuss the development of the model, provide basic projections using the model, and suggest ways in which the model could be used for policy analysis.

Industrial Sector Demand Module Overview

The NEMS Industrial Sector Demand Module (EIA 2003b) is a dynamic accounting model, bringing together the disparate industries in the sector and the uses of energy in those industries, and putting them together in an understandable and cohesive framework. The Industrial Module generates mid-term (up to the year 2025) forecasts of industrial sector energy demand as a component of the NEMS integrated forecasting system. The Industrial Module receives fuel prices, employment data, and the value of industrial shipments from the NEMS system. Based on the values of these variables, the Industrial Module passes back estimates of consumption by fuel types to the NEMS system.

The industrial sector consists of numerous heterogeneous industries. The Industrial Module classifies these industries into three general groups: energy-intensive industries, non-energy-intensive industries, and non-manufacturing industries. The manufacturing industries are modeled through the use of a detailed process flow or by an end use accounting procedure. The nonmanufacturing industries are represented in less detail.

The motor model discussed in this paper pertains to the manufacturing industries modeled by generic end uses. These four industries are Food, Bulk Chemicals, Metal-Based

Durables, and Balance of Manufacturing. The motor model calculates electricity consumption for the machine drive end use in these industries. Table 1 lists all the sectors included in the NEMS Industrial Sector Demand Module, with the sectors for which a motor model has been developed indicated by an asterisk.

Table 1. Industry Categories within the NEMS Industrial Demand Model

Energy-Intensive Manufacturing	**Nonmanufacturing Industries**
* Food and Kindred Products (NAICS 311)	Agriculture, Crops (NAICS 111)
Paper and Allied Products (NAICS 322)	Agriculture, Other (NAICS 112-115)
* Bulk Chemicals (see footnote)	Coal Mining (NAICS 2121)
Glass and Glass Products (NAICS 3272)	Oil and Gas Extraction (NAICS 211)
Hydraulic Cement (NAICS 32731)	Other Mining (NAICS 2122-2123)
Blast Furnaces and Basic Steel (NAICS 331111)	Construction (NAICS 233-235)
Aluminum (NAICS 3313)	
Nonenergy-Intensive Manufacturing	
* Metal-Based Durables (NAICS 332-336)	
* Balance of Manufacturing (all remaining manufacturing NAICS)	

NAICS = North American Industrial Classification System
Bulk Chemicals includes the following NAICS sectors: 325110, 325120, 325181, 325188, 325192, 325199, 325211, 325222, 325311, 325312.
* Sectors for which a motor stock model has been developed.
Source: OMB 1997.

Motor Model Description

According to the *1998 Manufacturing Energy Consumption Survey* (EIA 2001), more than half of the electricity consumed in the manufacturing sector was used for machine drive. The four sectors for which the motor model has been developed accounted for two-thirds of the electricity consumed for machine drive in the manufacturing sector (Table 2).

Table 2. 1998 Electricity Consumption for Machine Drive

Manufacturing Sector	Trillion Btu
Food	121
Bulk Chemicals	373
Metal-Based Durables	290
Balance of Manufacturing	469
Manufacturing Total	1,881

Source: EIA 2001.

Electricity consumption by the machine drive end-use for the food, bulk chemicals, metal-based durables, and balance of manufacturing industries is modeled differently than for the other end-uses in these industries. Instead of using the technology possibility curve (TPC) approach, which is a way to represent the energy intensity of the new capital stock relative to 1998 capital stock and is used for the other end uses in these industries, a motor stock model calculates machine drive electricity consumption. Seven motor size groups are tracked for each industry (1-5 horsepower (hp), 6-20 hp, 21-50 hp, 51-100 hp, 101-200 hp, >500 hp).

The data for the basic motor stock model were derived from *United States Industrial Electric Motor Systems Market Opportunities Assessment* (DOE 2002), a report produced for the U.S. Department of Energy's Office of Industrial Technologies. Table 3 lists the key characteristics for the motor population as of 1998. Nearly 90 percent of the motor stock in 1998 was 20 horsepower or less. Large motors tend to be more efficient than small motors, and they tend to be used for more hours during the year.

Table 3. 1998 Motor Characteristics

Industrial Sector Horsepower Range	1998 Stock	1998 Average Energy Use (kWh/motor)	1998 Average Efficiency	Average Part Load	Average Annual Operating Hours
Food					
1 – 5 hp	610,067	5,568	0.8130	0.61	3,829
6 – 20 hp	209,340	24,840	0.8713	0.61	3,949
21 – 50 hp	57,098	96,574	0.9013	0.61	4,927
51 – 100 hp	22,241	212,729	0.9272	0.61	5,524
101 – 200 hp	16,903	323,470	0.9348	0.61	5,055
201 – 500 hp	7,926	605,525	0.9378	0.61	3,711
> 500 hp	4,049	1,537,901	0.9303	0.61	5,362
Bulk Chemicals					
1 – 5 hp	336,523	5,326	0.8197	0.65	4,082
6 – 20 hp	237,703	29,476	0.8739	0.65	4,910
21 – 50 hp	114,772	86,578	0.9044	0.65	4,873
51 – 100 hp	46,756	213,594	0.9241	0.65	5,853
101 – 200 hp	32,141	484,522	0.9348	0.65	5,868
201 – 500 hp	17,452	1,132,905	0.9333	0.65	6,474
> 500 hp	7,990	5,631,554	0.9324	0.65	7,566
Metal-Based Durables					
1 – 5 hp	4,292,589	2,752	0.8189	0.62	1,985
6 – 20 hp	1,347,038	15,472	0.8704	0.62	2,959
21 – 50 hp	347,691	49,198	0.8992	0.62	3,371
51 – 100 hp	58,700	157,962	0.9198	0.62	4,621
101 – 200 hp	34,199	210,203	0.9348	0.62	4,905
201 – 500 hp	6,372	1,580,555	0.9367	0.62	7,409
> 500 hp	2,860	3,010,632	0.9303	0.62	8,164
Balance of Manufacturing					
1 – 5 hp	1,778,668	4,215	0.8293	0.62	2,927
6 – 20 hp	999,066	17,404	0.8828	0.62	3,169
21 – 50 hp	330,771	61,787	0.9032	0.62	3,774
51 – 100 hp	116,896	189,578	0.9268	0.62	4,981
101 – 200 hp	75,643	336,559	0.9427	0.62	4,587
201 – 500 hp	21,087	832,049	0.9425	0.62	5,432
> 500 hp	6,320	4,277,671	0.9289	0.62	5,362

Source: DOE 2002

The basic stock model calculates the number of motors of each size group within each industry required to produce the projected value of shipments. Value of shipments projections are provided by the Macroeconomic Activity Module of NEMS. When the projected value of shipments for an industry grows, more motors are required to produce that level of output. The characteristics of the motor stock are determined by a sequential economic choice algorithm. The first choice occurs when motors fail. Motors typically fail every five to fifteen years, depending on the size of the motor (DOE 2002). When they fail they can either be replaced or repaired. The second choice occurs when new motors are purchased, either to replace failed motors or to accommodate growth. These new motor purchases can be either EPACT minimum efficiency motors, or NEMA premium efficiency motors[1]. Table 4 lists the cost and performance assumptions used in making the two choices. The costs and efficiency ratings for the alternatives were obtained from the *MotorMaster+ 4.0* database (DOE 2003).

When motors are rewound, their efficiencies typically diminish. This loss is captured by the rewind efficiency drop parameter, which is used to reduce the beginning stock efficiency for those motors that are rewound during the year. The *MotorMaster+ 4.0* database provides the list prices for both EPACT minimum efficiency and NEMA premium efficiency motors. Motor dealers typically offer their motors at a discount. The costs of both the EPACT minimum efficiency motors and NEMA premium efficiency motors in Table 4 assume a 30 percent dealer discount. The EPACT efficiency standards only apply to motors up to 200 horsepower, and the *MotorMaster+ 4.0* database does not include NEMA premium efficiency options for the largest size group. Therefore, there is no NEMA premium efficiency option for the >500 horsepower group.

[1] The Energy Policy Act of 1992 (EPACT) requires that all covered motors purchased after October 1997 meet minimum efficiency levels, and be labeled with a certified minimum efficiency value. NEMA stands for the National Electrical Manufacturers Association. NEMA developed standards for premium efficiency motors and allows manufacturers, which meet the standards to apply the NEMA premium logo to their motors.

Table 4. Cost and Performance Parameters for Industrial Motor Choice Model

Industrial Sector Horsepower Range	1998 Stock Efficiency (%)	Rewind Efficiency Drop (%)	Rewind Cost (2002$)	EPACT Minimum Efficiency (%)	EPACT Minimum Eff. Cost (2002$)	NEMA Premium Efficiency (%)	NEMA Premium Eff. Cost (2002$)
Food							
1 – 5 hp	81.3	2.0	207	86.7	229	88.9	246
6 – 20 hp	87.1	1.8	386	91.4	631	92.7	663
21 – 50 hp	90.1	1.6	602	92.6	1,014	93.7	1,133
51 – 100 hp	92.7	1.4	1,138	94.4	2,337	95.1	2,401
101 – 200 hp	93.5	1.2	2,017	94.6	4,714	95.9	5,369
201 – 500 hp	93.8	1.0	3,945	93.4	8,503	96.1	9,492
> 500 hp	93.0	0.8	5,177	94.8	13,404	na	na
Bulk Chemicals							
1 – 5 hp	82.0	2.0	207	86.9	229	89.1	246
6 – 20 hp	87.4	1.8	386	91.6	631	92.9	663
21 – 50 hp	90.4	1.6	602	92.7	1,014	93.8	1,133
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Metal-Based Durables							
1 – 5 hp	81.9	2.0	207	86.8	229	88.9	246
6 – 20 hp	87.0	1.8	386	91.5	631	92.8	663
21 – 50 hp	89.9	1.6	602	92.6	1,014	93.8	1,133
51 – 100 hp	92.0	1.4	1,138	94.4	2,337	95.1	2,401
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> 500 hp	92.9	0.8	5,177	94.8	13,404	na	na
Sources: DOE 2002 and DOE 2003							

The two choice algorithms in the motor model each consist of two central equations (the equations were adapted from DOE 1996). The first equation calculates the annual energy savings for the more efficient motor choice compared to the less efficient motor choice:

$$Savings = hp * L * 0.746 * hr * C * (100 / E_{le} - 100 / E_{me})$$

where:

Savings	=	Expected annual dollar savings
hp	=	Motor rated horsepower
L	=	Load factor (percentage of full load / 100)
Hr	=	Annual operating hours
C	=	Average electricity costs (2002$ / kWh)
E_{le}	=	Efficiency rating (%) for the less efficient choice. For the repair/replace decision, the less efficient choice is repairing. For the EPACT minimum/NEMA premium efficiency choice, the less efficient choice is the EPACT minimum efficiency motor.

E_{me}	=	Efficiency rating (%) for the more efficient choice. For the repair/replace decision, the more efficient choice is replacing. For the EPACT minimum/NEMA premium efficiency choice, the more efficient choice is the NEMA premium efficiency motor.
0.746	=	Factor for converting horsepower to kW units

Once the savings have been calculated, the simple payback is given by:

$$Simple\ payback\ (years) = Price\ premium\ /\ Annual\ dollar\ savings$$

The payback for each motor size group within each industry is compared to an acceptance curve (Table 5) in order to determine the splits between the more efficient and less efficient choices. Energy consumption for the motor stock is calculated using the stocks and efficiencies of rewound, EPACT minimum efficiency, and NEMA premium efficiency motors.

Table 5. Reference Case Payback Acceptance Rate Assumptions for Motor Choices

Payback Period in Years	Acceptance Rate
1	100.00%
2	80.00%
3	35.00%
4	0.00%

Source: EIA 2003b.

Motor Model Projections

The motor model has been used to produce projections of machine drive electricity consumption based on the value of shipments and electricity price projections in the *Annual Energy Outlook 2003* (EIA 2003a). Value of shipments growth projections vary considerably among the four industries (Table 6). Real electricity prices to the industrial sector are essentially constant over the projection period through 2025.

Table 6. Value of Shipments, Average Annual Growth Rate, 2001 - 2025

Manufacturing Sector	Percent per year
Food	1.36%
Bulk Chemicals	1.82%
Metal-Based Durables	4.15%
Balance of Manufacturing	2.05%

Source: EIA 2003a.

Motors in the 1 - 5 horsepower and 6 - 20 horsepower categories make up nearly 90 percent of the total stock. While the two smallest motor size groups account for nearly 90 percent of the total motor stock, they only consume around 20 percent of the electricity

(Figure 1). At the other end of the size spectrum the two largest motor size groups (201 - 500 hp and > 500 hp) account for less than 1 percent of the motor stock, but consume one-third of the electricity.

Figure 1. Reference Case Electricity Consumption by Motor Size Group

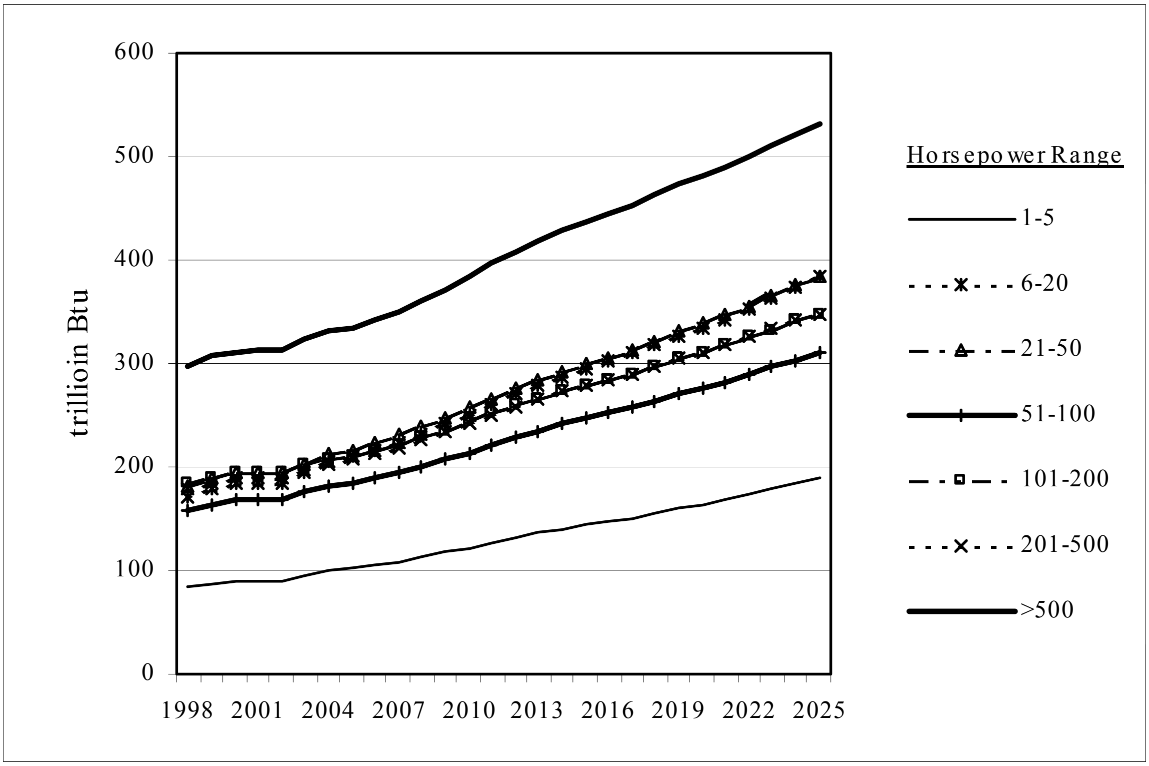
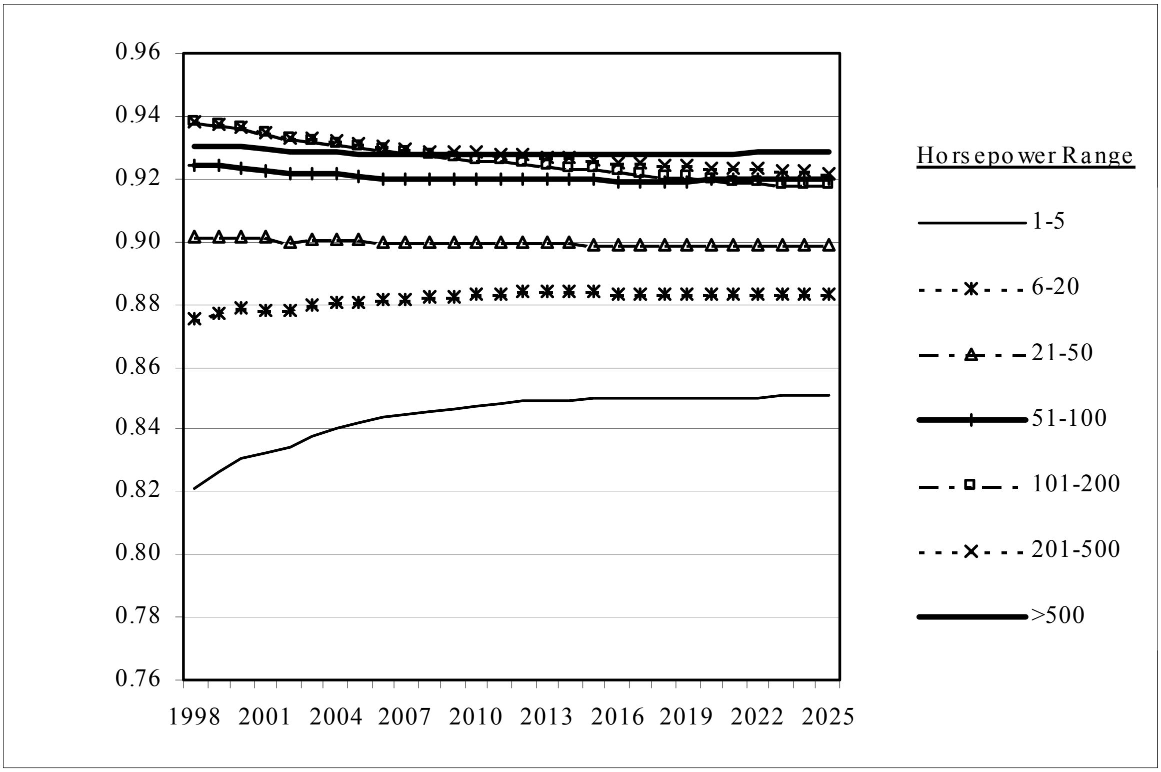


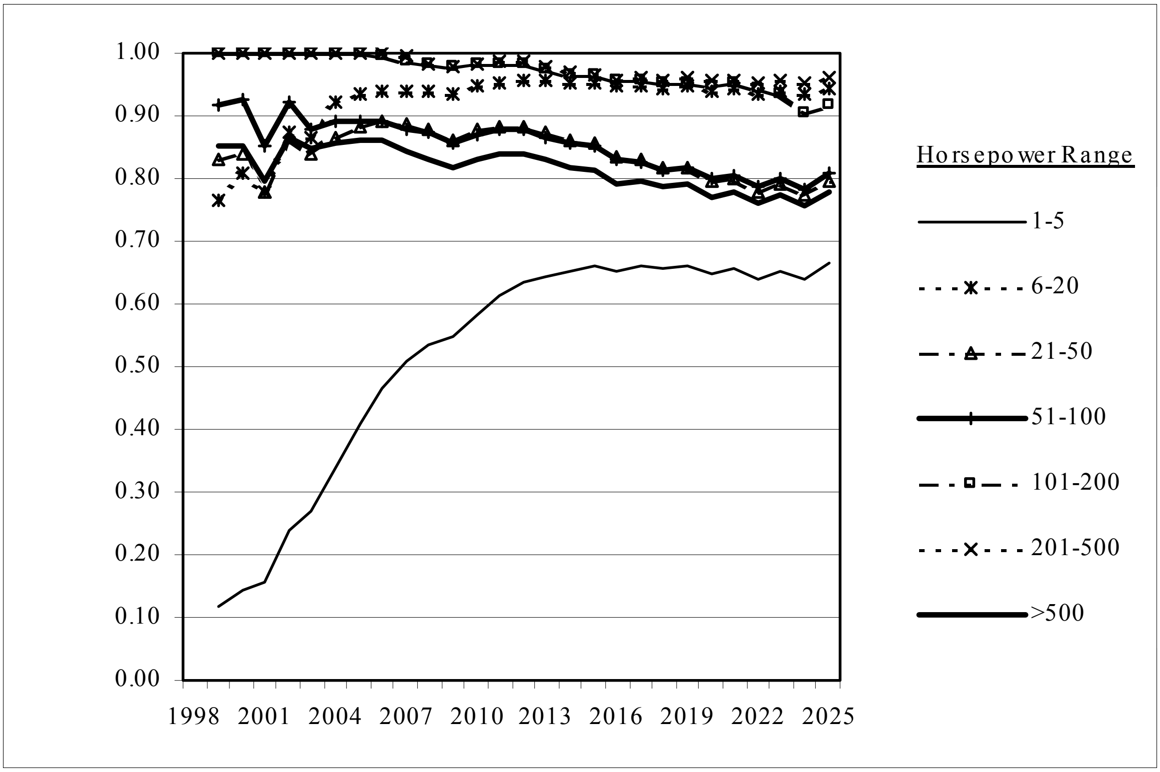
Figure 2 displays the motor stock efficiency by size group. For the smaller motor size groups it is often economic to replace motors when they fail rather than repair them. This leads to rising stock efficiency over the projection period for the smaller motor size groups.

Figure 2. Reference Case Efficiency by Motor Size Group



After approximately fifteen years the least efficient motors in these smaller size groups have been replaced, and the stock efficiency reaches a steady state somewhat below that of the EPACT minimum efficiency motors. Motors in the larger size groups are much more frequently repaired when they fail (Figure 3). Consequently, the stock efficiencies of the larger motor size groups remain somewhat below the efficiency of new motors throughout the projection period. The larger motor size groups maintain a higher stock efficiency than the smaller size groups, despite the fact that larger motors are more frequently repaired, and in the absence of efficiency standards.

Figure 3. Reference Case Percentage of Motors Rewound by Motor Size Group



Alternative Simulations

Several alternative simulations have been run to demonstrate the applicability of the motor model. The first alternative lengthens the acceptable payback period for motor efficiency investments (Table 7). The longest payback accepted in this scenario is eight years, compared with three years in the reference case. The second alternative increases the dealer discount on motor purchases from 30 percent to 50 percent. This spans the range of discounts typically offered by dealers (Nadel et al. 2002). The higher discount applies to the cost of both EPACT minimum efficiency motors and NEMA premium motors. The third alternative dictates that all failed motors are replaced, and that all new motors purchased are NEMA premium efficiency motors. This alternative shows the maximum energy savings available by purchasing the most efficient motors included in the *MotorMaster+ 4.0* database.

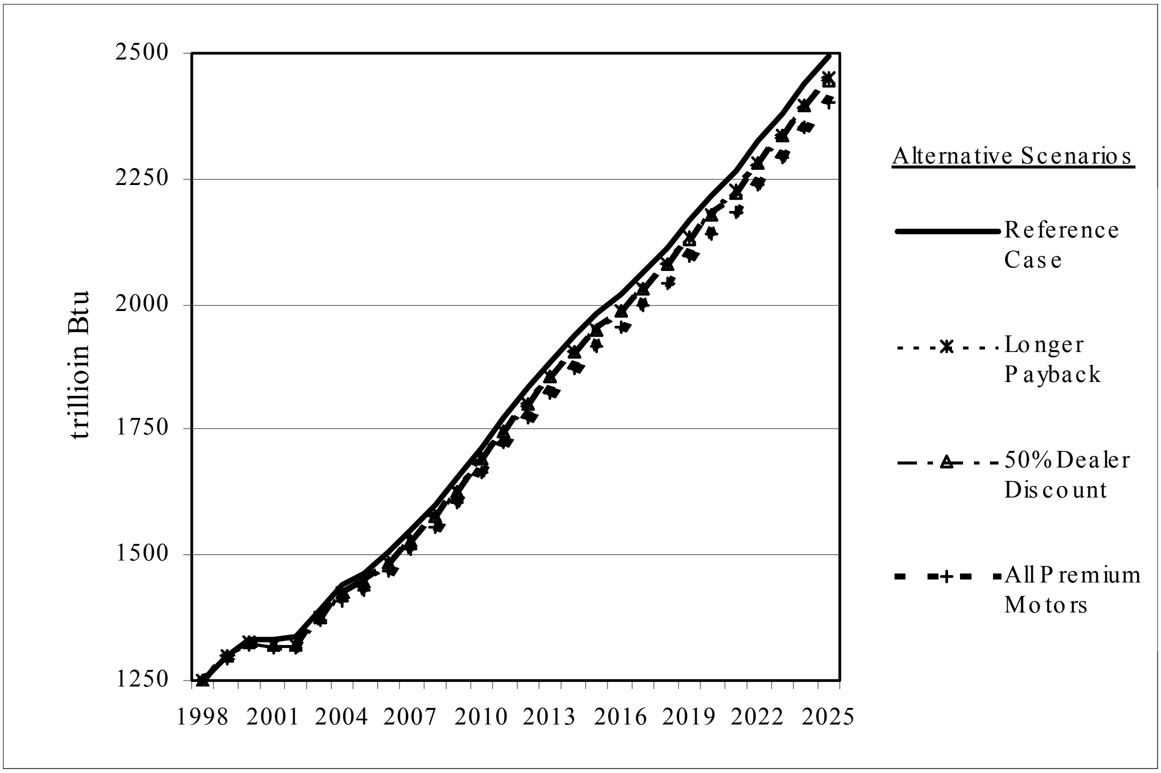
Table 7. Alternative Payback Acceptance Rate Assumptions for Motor Choices

Payback Period in Years	Acceptance Rate
1	100.00%
2	95.00%
3	87.50%
4	77.50%
5	65.00%
6	50.00%
7	30.00%
8	15.00%
9	0.00%

Source: EIA 2003b.

Energy consumption in 2025 is 1.8 percent lower when a longer payback period is accepted (Figure 4). If the dealer discount were increased to 50 percent, 2025 energy consumption would be 1.9 percent lower. In the case when all failed motors are replaced and all new motors purchased are NEMA premium efficiency motors, energy consumption is 3.7 percent lower in 2025.

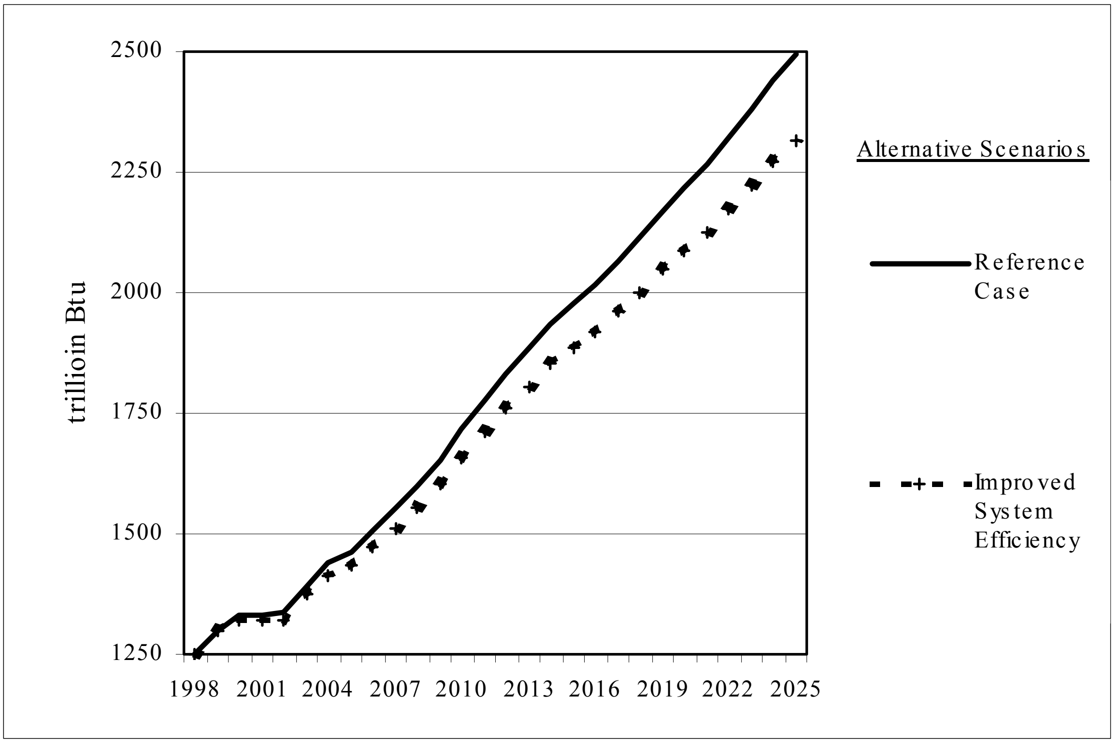
Figure 4. Total Electricity Consumption for Machine Drive



A final alternative scenario increases the overall efficiency of motor systems, rather than that of the individual motors. Over 70 percent of the total potential motor system energy savings are estimated to be available through system improvements (DOE 2002). The potential for system efficiency improvement was assessed for measures such as reducing system load requirements, reducing or controlling motor speed, matching component sizes to the load, upgrading component efficiency, better maintenance practices, and motor downsizing. The motor model has been developed to include the ability to quantify the effect of system efficiency improvements on machine drive electricity consumption.

If the system efficiency improvement potential identified in the Market Opportunities Assessment (DOE 2002) were included in the model, electricity consumption would be 7.2 percent lower in 2025 than in the reference case.

Figure 5. Total Electricity Consumption for Machine Drive



Conclusions

A motor stock model has been developed which covers four sectors within the NEMS Industrial Sector Demand Module. These four sectors account for more than half of the machine drive electricity consumption in the manufacturing sector. Two economic choices are made when developing projections of the motor stock: the choice on whether to replace or repair failed motors, and the choice on whether to purchase an EPACT minimum efficiency motor or a NEMA premium efficiency motor. Even in a scenario with relatively flat electricity prices such as the AEO2003 Reference Case, motor stock efficiency can increase based on economics alone, particularly in the smaller motor size groups. However, with motor efficiency percentages reaching the low to nineties for the larger motor size groups, the potential for improvement in individual motors is limited.

The motor stock model has been constructed to allow for analysis of various policies designed to reduce machine drive electricity consumption. Alternative simulations demonstrate that policies designed to improve the efficiency of individual motors have a limited impact on overall electricity consumption. Improving the efficiency of motor systems holds greater potential for savings in machine drive electricity consumption.

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