Electric Motor Remanufacturing and Energy Savings

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1 Introduction to Electric Motors

Electric motors (EM) are devices that convert electrical energy into mechanical energy. Common applications of EMs like pumps, fans, blowers compressors etc. span through most of industrial, commercial and residential sectors. In the US industrial sector alone, over 13.5 billion electric motors are in use and it is estimated that approximately 70% of electricity in industry is consumed by some type of a motor-driven-system [19]. A detailed description of energy consumed by electric motors in different industrial sectors is shown in Figure 1

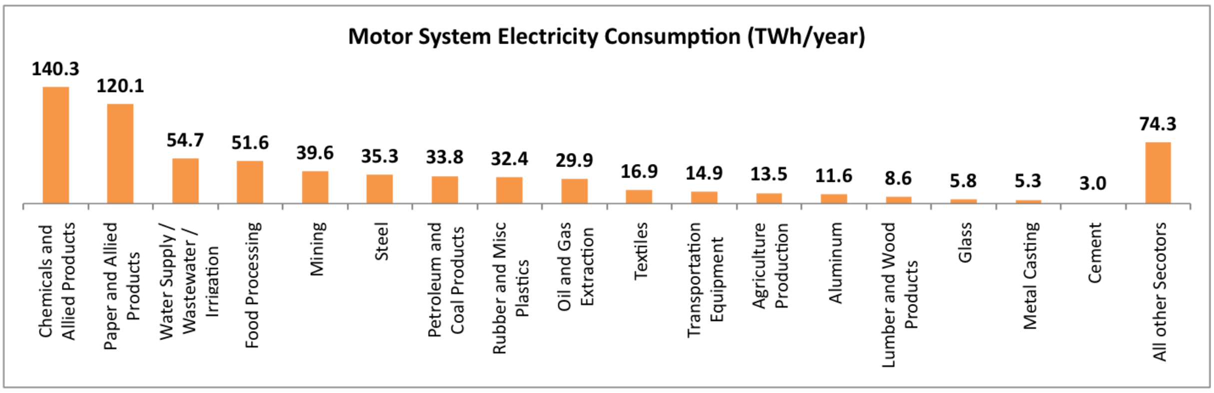


Figure 1: Motor System Electricity Consumption by Industrial Sectors (TWh) for 1994. A total of 691 billion kWh/year was consumed in process motor-driven systems in the US in 1994. [19].

These statistics indicate the gigantic influence that electric motor performance, in other words their efficiencies have on the economic and environmental costs incurred during operation.

1.1 Motor Classifications

Motors can be differentiated based on several characteristics. Some broad classifications for electric motors systems are:

- By Mechanism

  Mechanism refers to the way electrical energy is converted to mechanical energy. This can be through AC induction/asynchronous; AC synchronous; and DC [23]. Figure 2 gives a partial classification of the different kinds of motors available and working on slightly different mechanisms of excitation [14].

- By Design

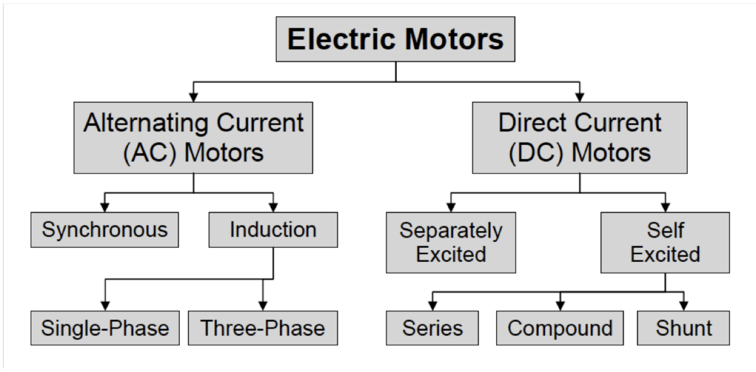


Figure 2: Types of motors, classified predominantly on mechanism [14].

An electric motor can be constructed in various ways. For instance, AC induction motors are available in Squirrel-Cage and Wound-Rotor configurations. Within each of these types of induction motors, there can a variation in the designs used which have been classified by the National Electrical Manufacturers Association (NEMA). A comprehensive description of the different designs of motors can be found in [23], Chapter 2. Amongst all the designs, the NEMA Design B is the most popular. This is expressed in terms of the distribution of input energy for different designs of electric motors in the United States, as shown in Figure 3

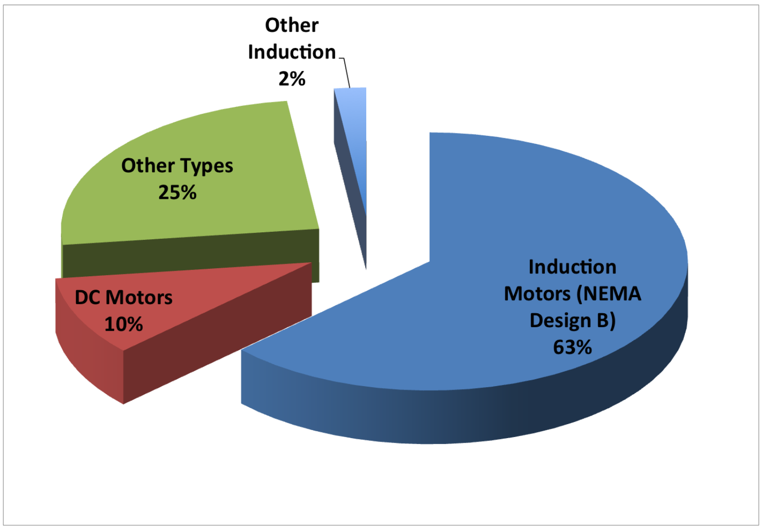


Figure 3: Distribution of input energy for different designs of electric motors in the United States [23].

Another way to distinguish motors is by the type of enclosures used in the design. Different enclosures are constructed to suit different operating environments. Motor enclosures commonly used can be broadly classified into two types: (a) machines with open enclosures, and (b) totally enclosed machines. Within these two categories the most commonly used one is the Open drip-proof (ODP) and the Totally enclosed fan-cooled (TEFC) enclosure respectively. Figure 4 shows a schematic of both. In the ODP design the cooling air goes through the motor cooling it through a direct contact. On the other hand, in the TEFC design, the air is blown over the exterior of the motor enclosure which can be in the form of fins to further enhance cooling.

Figure 4: The most commonly used enclosure designs for motors: (a) Open dip-proof [15]; (b) Totally enclosed fan-cooled [16].

- By Size

  Size refers to the power rating of the motor. This can range from less than 1 hp to greater than 500 hp, depending on the application. Smaller motors can be used for household fans while the larger ones are more often found in industry. Nevertheless, the energy consumed by a motor depends on both its size and usage. Smaller motors also tend to be more common in terms of population and can thus over all impact comparably to larger motors. Figure 5 shows the population and energy consumption for AC induction motors of different sizes inn 1997.

- Speed

  The rotation speed refers to the final rotation of the shaft of the motor. It is a significant characteristic of the mechanical output from a motor.

  The number of pole pairs in a motor and the input frequency dictate the rotation speed. When operated at 60 Hz voltage, the synchronous

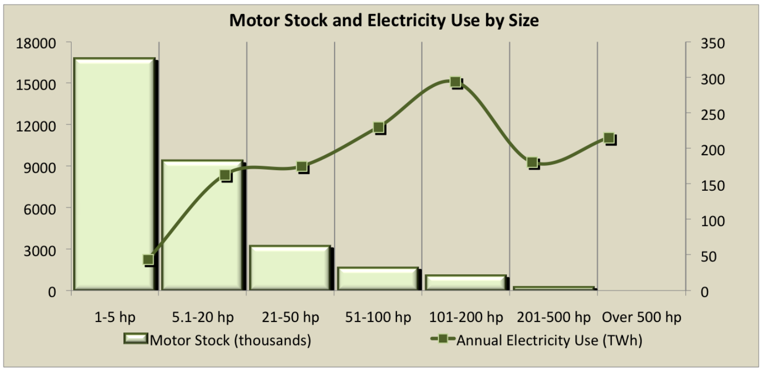


Figure 5: Population and energy consumption for AC induction motors of different sizes inn 1997 in the United States [23].

speeds can be of 3600, 1800, 1200, 900, 720, 600, 450, and 300 rpm, which are 3000, 1500, 1000, 750, 600, 500, 375, and 250 at a 50 Hz operation. It must be noted that the slip between the stator and the rotor will decrease the speed for asynchronous motors (on the other hand synchronous motors are designed to perform with a 0% slip). A general formula to calculate the synchronous speed of an electric motor is (equation 1):

$$synchronousspeed(rpm) = \frac{frequencyofappliedvoltage(Hz) \times 60}{numberofpolepairs} \tag{1}$$

More than 50% of the motor population probably corresponds to a speed of 1800 rpm [23].

1.2 Performance of Motors

The impact of a motor in terms of total energy and economic costs depends on its performance during its use phase. The performance of motors is characterized by the efficiency with which it converts electrical energy into mechanical energy. This can also be understood by the equation 2 and 3:

$$Efficiency = \frac{OutputMechanicalWork}{InputElectricalWork} \tag{2}$$

$$Efficiency = \frac{OutputMechanicalWork}{OutputMechanicalWork + Losses} \tag{3}$$

Hence in order to have a motor perform better, it is important to reduce "losses." Usable energy is lost from various parts of a motor such as the stator and rotor windings, the core, through friction and windage, and stray losses or miscellaneous losses which encompass leakage of flux, mechanical imperfections in air gaps etc ([23]).

Stator losses are I^2R losses or electrical losses caused during the flow of current through the stator windings. Similarly current flowing through the rotor windings creates losses called the *Rotor losses*. Since both are proportional to the resistance to flow, a wire material with a lower resistivity (like copper in place of aluminum) can help reduce these losses. Maintaining the same material but increasing the diameter of the wire will also lower the resistance. Another method of decreasing the losses is by reducing the number of turns. However this can increase the full-load efficiency and the starting current as well as decrease the power factor. It also increases the starting and maximum torque.

Core losses are magnetic losses, in other words, a sum of eddy current (Eddy currents are stray currents in ferromagnetic materials as magnetic fields are induced in them [2]) and hysteresis losses (the energy necessary to change the direction of the magnetic fields [2]) that occur while energizing the motor's magnetic field. Overheating and improper stripping during rewinding can easily damage the insulation in the core and increase core losses [12]. Using larger cross-sections of iron in the stator and rotor; thinner laminations; and improved magnetic materials are common ways of reducing them [23].

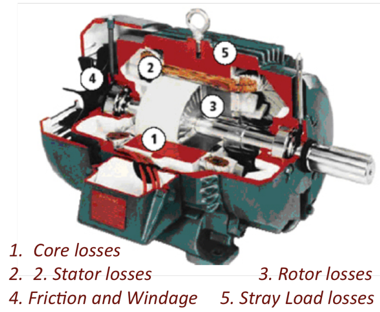
Friction and Windage losses are mechanical losses caused by air density, fans, turbulence within the stator, bearings, and anything else that may cause a friction force on the shaft [2]. These can be decrease with more efficient fans, optimum lubrication etc.

Stray losses as mentioned above accounts for other losses not considered above, like the leakage of flux, mechanical imperfections in the air gaps, and irregularities in the air gap flux density [23].

Figure 6 associates the different kids of losses with the components where they originate within a motor. The distribution of losses into the various kinds is shown besides it.

Since losses are the key deterrents to the performance of an electrical motor, and thus it is necessary to understand the functional dependence of these losses (or efficiency) on operating conditions. Figure 7 gives the variation in loss with (a) motor load (% power being used, of maximum rating of the motor) and (b) motor rating.

As expected, I^2R losses (*Stator and Rotor losses*) go up as the % load increases, as more current is needed to get more power out of the motor. At the same time *Stray losses* increase with load as well, but *Core and Friction losses* do not. It is also true that as motors become bigger and bigger (larger rating), their loss fractions change with I^2R losses being more dominant in smaller motors, and *Windage and Friction losses* gaining influence with increase in the size of motors. This is explained better in figure 7



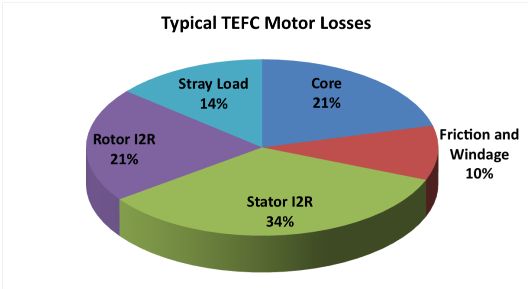
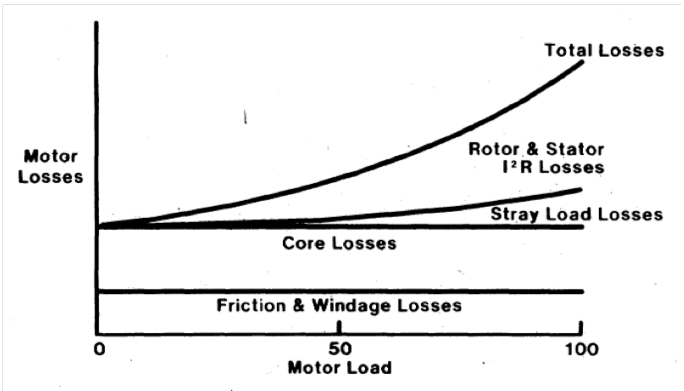


Figure 6: Energy losses in an Electric Motor: (a) Different kinds of losses and the components causing them [22]; (b) Distribution of the different kinds of losses in a typical TEFC motor [8].



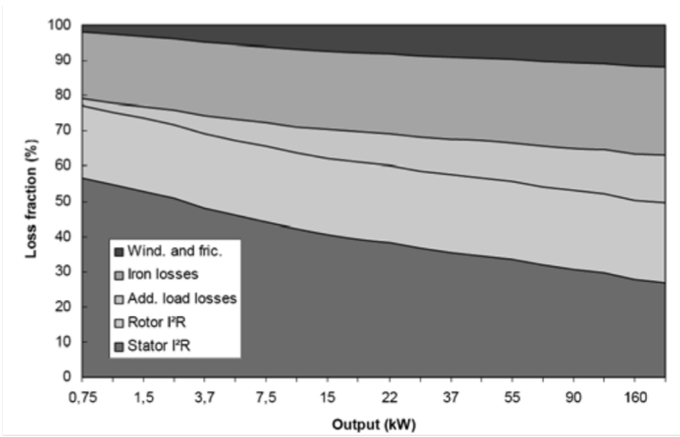


Figure 7: Variation of motor losses with motor load and motor size/rating [17, 6].

It is thus evident that the efficiency of a motor is highly correlated to all its characteristics like construction, size, materials, operating load, maintenance etc. However, this strong correlation of a motor is significant only if the use phase is sensitively impacted by the efficiency of a motor.

1.3 Impact of motor efficiency on the Use phase.

Consider the example of an industrial motor of size 100 hp. A motor of this size is estimated to have a life of approximately 28.5 years [5]. [23] also indicates that such a motor is used for 4,163 hours / year, on an average.

The general formula for energy consumed by a motor is given below:

$$TotalEnergy(MWh) = (RatingofMotor(hp)) \times 0.746 \times \frac{hours}{year} \times (totalyearsused) \times (\%operatedload) \times \tag{4}$$

η = efficiency of the motor at the operated load

The factor of 1000 in the end is to match up the final units to MWh.

Assuming that the motor is operated at a 100% load with an efficiency of 90%,

$$TotalEnergy(MWh) = 100 \times 0.746 \times 4163 \times 28.5 \times 1 \times \frac{1}{0.9 \times 1000}$$

$$TotalEnergy(MWh) = 9,834.363$$

The same calculation with a motor which is 2% less efficient ($\eta = 88\%$) gives

$$TotalEnergy(MWh) = 10,057.902$$

a difference of roughly 223.54 MWh, which is substantial.

Clearly, the motor performance has a hugh impact on the energy consumed during its operation, and thus it is beneficial to choose the most efficient motor available, as long as other requirements are satisfied. In order to promote this, several government regulations have been imposed in the past and many are in discussion.

1.4 Motor Regulations

Motor efficiency standards have been an active subject of debate since over two decades leading to the enforcement of political standards as well as adoption of voluntary standards, by electrical motor manufacturers. Figure 8 presents an interesting trend in average motor efficiency fluctuations in the past, as given by Nadel et al [23]

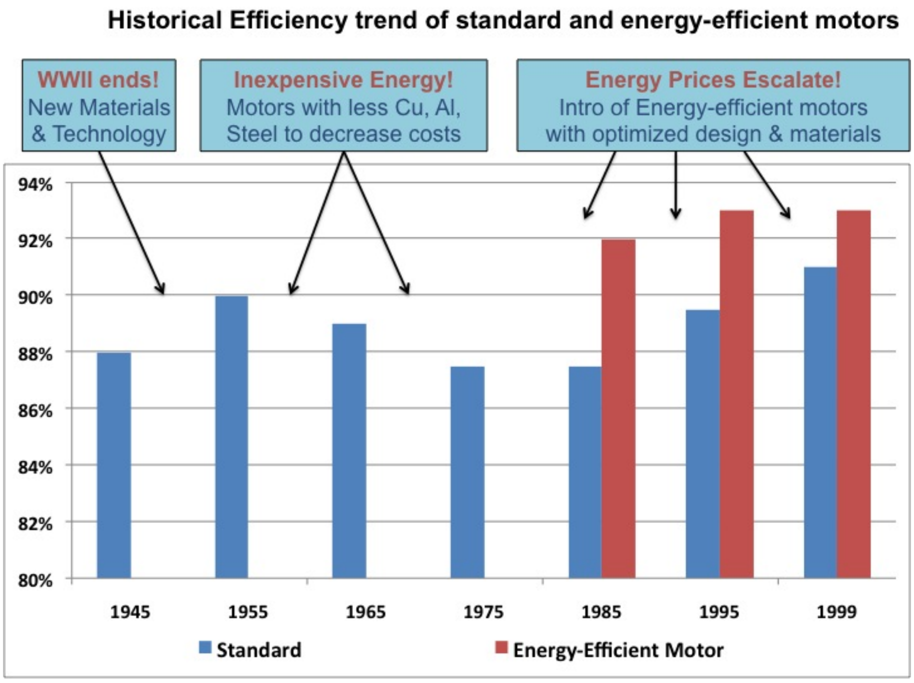


Figure 8: Historical motor efficiency trend and explanations [23].

With the end of World War II, technology boomed and new materials were introduced. This enhanced the performance of motors and led to an increase in its efficiency. However, during the late 1950s through to early 70s, cheap electricity diverted focus from efficiency and thus expending on new materials and technologies was not very common.Thus motors built in this era constituted cheap materials or lesser copper, aluminum and steel and this led to a compromise in their efficiency. Later in the 1970s, energy prices rose, increasing the impact of motor efficiency during its long use phase. New motors built hence forth, concentrated on better efficiency leading to the introduction of a new class of electric motors know as "Energy-efficient motors." The standards defining these motors were set forth by the National Electrical Manufacturers Association (NEMA). NEMA has been promoting electric motor efficiency standardization since the 1970s and has ever since updated these standards with the invention of new materials and designs. NEMA has also been progressively expanding the scope of its standards to include more types of motors. In 1992, the Congress used these stringent energy-efficient performance values generated by NEMA to set mandatory minimum efficiency levels for all new general purpose electric motors manufactured in or imported into the United States after October 1997. This came to be know as the Energy Policy Act (EPAct) of 1992 and it included 2, 4 and 6-pole electric motors with power ratings between 1-200 hp. Seeing the quick response of manufacturers and increasing share of energy-efficient motors after 1992, the Consortium of Energy Efficiency (CEE) set new and higher efficiency levels for the same set of motors, taking them to the next level of "Premium Motors." In 2001, in response to the CEE premium-efficiency specification and the initiation of the Energy Star label by the US EPA, NEMA developed NEMA Premium. The scope of this program was much broader and applied to low and medium voltage; 2, 4, 6 pole motor with power ratings between 1-500 hp. Later that year, NEMA and CEE tentatively agreed to adopt these NEMA Premium specifications as the common definition of premium motors.

A comparison of all these standards is shown in figure 9.

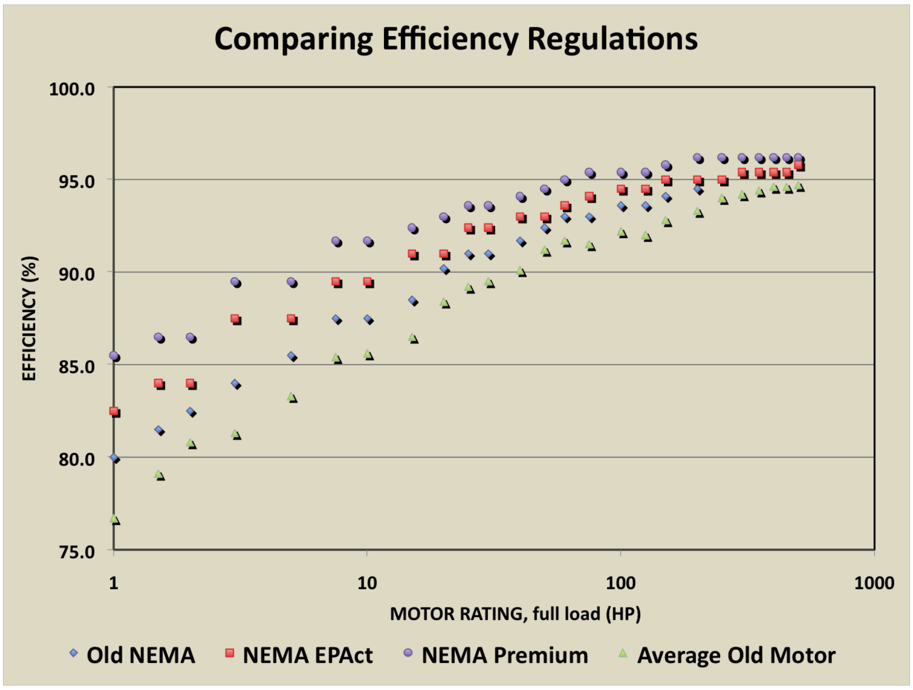


Figure 9: Efficiency standards of different motors compared with the average old motors before NEMA standardization [4].

Note how bigger motors are expected to perform at a higher efficiency, since the losses are lower. This was hinted in Figure 7.

Also note that the EPAct '92 only covered motors from 1-200 hp, and the representation above includes the NEMA energy-efficient standards, proposed at that time, for larger motors too. Another interesting point is the larger efficiency change from one standard to a higher standard for smaller motors compared to larger motors. This is because it is easier to increase the efficiency of a less efficient motor compared to one that is more efficient to start with.

NEMA premium efficiency standards have remained voluntary for a long period now. In spite of this, NEMA premium motors have been progressively gaining market share and popularity as the overall benefits of efficient motors is discovered by more consumers. [9] report this trend which is depicted in Figure 10. As was seen earlier, motors can last for more that 20 years, and hence a decent share of motors being used even today fall short of EPAct standardization.

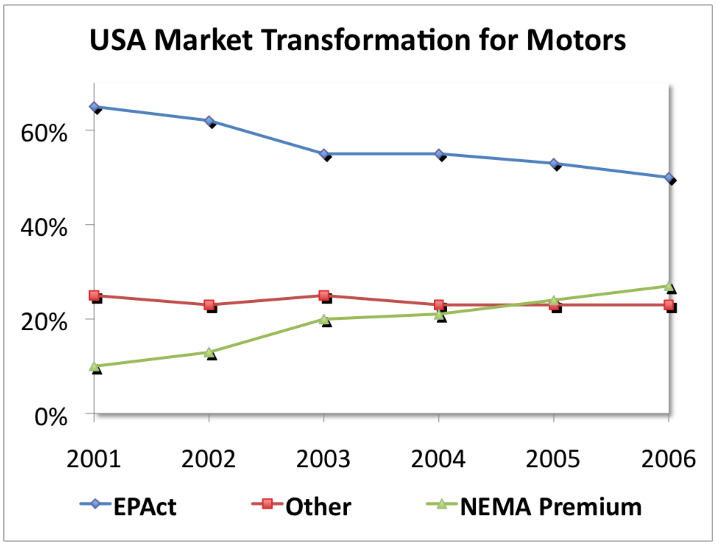


Figure 10: United States electric motor market distribution by motor efficiency standards [9].

To accentuate adoption of NEMA Premium motors the Energy Independence and Security Act (EISA) of 2007 updates changes as follows [3]:

- All EPAct '92 standardized motors must now abide to the NEMA premium standard
- Motors with power rating between 1-200 hp that were not covered in the EPAct '92 must be manufactured to the level of general purpose motors under EPAct
- Motors between 201-500 hp must also be manufactured to the EPAct energy-efficient standard

EISA 2007 will take effect in December 2010, following which the market share of NEMA Premium is expected to rise much faster than that shown in Figure 10. With improved performance in motors, their environmental impact during use phase is expected to reduce.

1.5 Motor Remanufacturing

A motor like any other device does not last forever. Overloading, power supply anomalies, corrosion, friction, contamination can all eventually cause the motor to fail or perform below satisfaction. One of the most common reasons for motor failure are winding and bearing failure. As the motor operates it tends to heat up, which causes the insulation to degrade. Poor ventilation can be one reason for this, and so can overloading. Bearing failure leads to overheating again which can cause the insulation to get damaged and cause failure of the motor.

However, failing of the windings does not demand discard of the motor. A very popular industrial practice called "Motor Rewinding" is the known solution to this problem. Whenever a motor fails or approaches failure, the user can choose to get the motor rewound in which case it can be used for several more years before it fails again and demands another rewinding.

Motor rewind in actuality is motor remanufacturing. [2] gives a detailed description of what the Rewinding process should constitute starting with initial tests, coil removal practices, through stator winding, post winding tests, and finally varnish insulation and final tests of the rewound motor. This has been described in detail in Figure 11. Clearly motor rewinding is not a simple repair process, but a comprehensive procedure to bring to motor back to as good a condition as possible.

It should be understood that different rewinders follow their own protocol. While some might choose to be more extensive, many may skip some of the steps described.

In general [23] reports that each year approximately 2.5 times more motors are repaired compared to the new ones bought. They also report that motors are repaired on the average of every 5-7 years and hence a motor can be repaired, on an average, 4-6 times in its life before being permanently discarded.

Accounting for the large population of motors installed in the US, it is easy to imagine the large expanse of the rewinding industry and the strong role it has in influencing a plant's overall efficiency. This of course depends on the impact that rewinding has on the efficiency of a motor.

1.5.1 Impact of rewinding on efficiency.

While the rewinding process is expected to be extensive and capable of bringing the motor back to a like-new condition, most rewinders do not

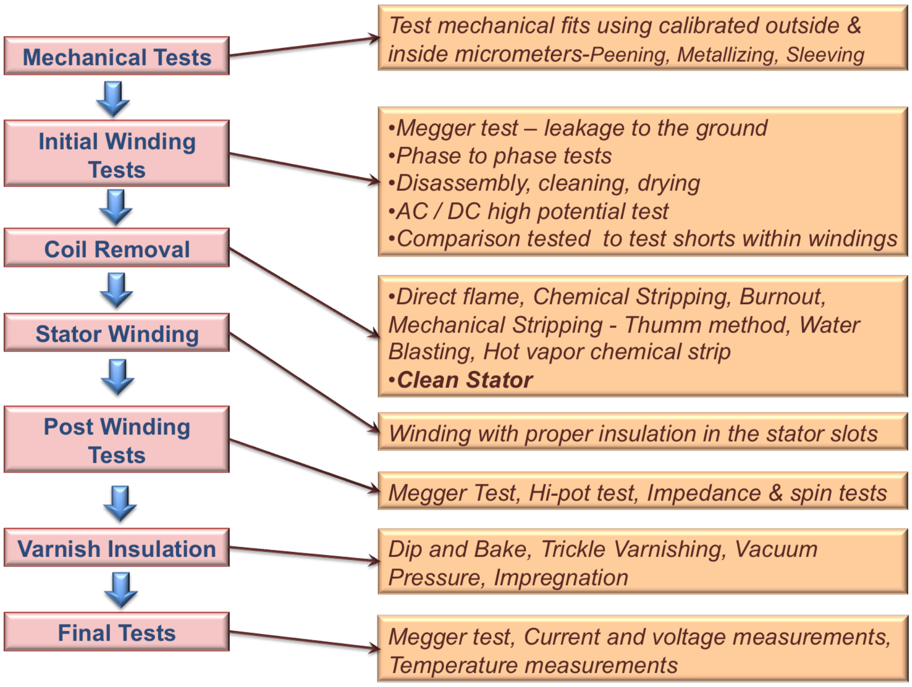


Figure 11: Motor rewinding process [2].

follow every step or the precision needed in every step. This can impact the efficiency of a rewound motor severely in some cases. This problem, very much prevalent in the rewinding practice has been much debated in literature. Given below in Figure 12 is a compilation of a few of the major studies done on the impact of rewinding on motor efficiency.

It should be noted that the last column reports the work used by the United States Department of Energy for its software - MotorMaster+ which is for helping motor users decide which motor to buy and whether to replace or rewind an existing motor. Based on this fact and after personal communication with the Department of Energy, Energy Efficiency and Renewable Energy (EERE), this case study also uses the impact of rewinding on motor efficiency to be a decrease in 1% for motors smaller than 40 hp and a decrease in 0.5% for motors larger than 40 hp.

2 Case Study Objective

With the rising awareness of energy-efficient (EPAct '92 standardized) and premium-efficiency motors (NEMA Premium standardized), through mandatories imposed by the government and new standards proposed by associations such as NEMA, CEE, ACEEE, the "rewind/replace decision" is gain-

Study	Sample Size	Change in Full-Load Efficiency	Comments
McGovern (1984) [1]	27	-2.5 to -1.5%	Motors ranged from 3-150hp (General Electric)
Colby & Flora (1990) [1]	4	-1.0 to -0.5%	Standard and premium efficiency 5-10 hp motors (North Carolina
Zeller (1992) [1]	10	-0.5%	Identical 20hp premium efficiency motors (British Columbia)
Dederer (1991) [1]	9	-1.1%	Identical 20hp standard-efficiency motors (Ontario)
Ontario Hydro (1992) [1, 2]	2	-2.2% (40hp) -0.4% (100hp)	Motors rewound 4 times each
BC Hydro (1993) [2]	11	-0.5%	20 hp Energy-Efficient motors
Hydro Quebec [2]	–	Less than 0.2%	Coils removed by several methods and rewound (repeated 3 times per motor)
Cao & Bradley (2006) [3]	23	~0%	Motors ranging from 5.5-225 kW. If good repair practice is followed, even repeated rewinds do not cause and appreciable change in efficiency
EASA (2002) [4]	23	±0.2%	Motors ranging from 50-300hp – The best rewind/repair procedures maintain motor efficiency ±0.2%
AEMT& EASA (2003) [5]	22	-1% (less than 40Hp) -0.5% (more than 40 hp) *this result has been used in MotorMaster+ software by DOE*	50 hp to 300 hp and 2 motors less than 7.5 hp. This included 50 and 60 Hz motors, low and medium voltage motors, IEC and NEMA designs, ODP and TEFC designs, 2 pole and 4 pole motors

Figure 12: Impact of rewinding on motor efficiency. 1 = [23]; 2 = [2]; 3 = [11]; 4 = [8]; 5 = [20].

ing tremendous significance. It is thus a necessity to analyze and estimate the environmental impact of the possible decision outcomes from such a scenario. This study undertakes this task and calculates the energy and economic consumption for the possible outcomes of a replace/rewind decision. Based on mutual comparison, strategies favorable for energy savings and those favorable for economic savings are highlighted.

3 Product Scope

As already understood, the variety of electric motors available is very large each being distinct in its own way. TEFC induction motors, with NEMA design B, and operated at 1800 rpm are known to be the most popular (as stated before) and are the focus of this study. Two sizes were chosen:

- A smaller motor of size 22kW (approximately 30 hp)
- A larger motor of size 200kW (approximately 270 hp)

4 Methodology

The methodology adopted is the same as that for the other case-studies. Life-cycle assessment (LCA) and Life-cycle costing (LCC) are the major tools used. The boundary of analysis for LCA includes primarily three phases:

- Raw Material Processing - Extraction and production of the raw materials required to manufacture the motor
- Manufacturing - All processes starting with processed raw materials to the final assembly of the product
- Use - Use of the fully manufactured product by the consumer

LCC calculations are done from a consumer's perspective and thus include:

- Product Price or Rewind Price
- Operating Price (during the use phase)

5 Data Sources.

Most of the data has been procured from the available literature. The rewind/replace economic analysis has been discussed by many researchers and is well known [24, 11, 17, 12, 2, 8, 20, 23]. In this study along with the economic analysis, a similar energy analysis is also conducted to estimate the environmental impact of the decision. One of the major sources for use phase calculations has been the MotorMaster+ database. Mototmaster+ is the recommended software by the Department of Energy [24] and is very useful for economic analysis of motor purchase or repair decisions.

A detailed breakdown of data used and its source is given below:

- Raw Materials ([7])
- Manufacturing ([7])
- Use Phase: Usage Hours ([18]); Usage years ([23]); efficiencies ([24])
- List price for new, installation cost for new, rewind costs, discount rates: ([24])
- Electricity Prices ([13])

6 Analysis

6.1 Life Cycle Assessment

Life cycle assessment for the two motors is broken down into the three primary phases - Raw material processing, Manufacturing, and Use phase.

6.1.1 Raw Materials Processing

The energy required to produce raw materials was estimated starting with the material composition of the two motors. The bill of materials (BOM) were available from [7] for motors of sizes 1.1kW, 11 kW and 110 kW. At the same time BOMs for motors of size 22kW and 200 kW were available from the Environmental Product Declarations by ABB [1]. Using these BOMs and specific energy to process the raw materials [21], it was observed that both the weight and total energy to process the raw materials almost scaled linearly with size (kW rating of the motor). Since [7] does a more extensive job in providing the BOMs for different sizes and efficiency classes, the final BOMs and energies chosen were those obtained by scaling the 11kW motor to 22kW and the 110kW motor to 200kW. The BOMs is shown below in Figure 13.

Each material requires its own energy to process. This energy encompasses extraction, processing, purification and other steps to bring the raw materials to a usable condition. The raw material processing data provided by [7] was checked with an estimation using the BOMs and the specific energies obtained from [21]. A conformity in the vales allowed us to choose the values from [7] directly.

	22kW			200kW	
Material (Kg)	**Standard Efficiency**	**Energy Efficiency**	**NEMA Premium**	**Standard Efficiency**	**NEMA Premium**
Electrical Steel	79	106	134	620	800
Other Steel	21	22	23	134	154
Cast Iron	29	22	29	600	600
Aluminium	20	17	24	36	50
Copper	14	20	24	108	140
Insulation Material	0	0	0	2	2
Inpregnation Resin	2	2	2	10	10
Paint	1	1	1	2	2
Total (Kg)	**166**	**190**	**238**	**1,512**	**1,758**
Energy using Smil (MJ)	**13,779**	**15,419**	**19,716**	**90,040**	**109,860**
Energy from EuP Lot 11 (MJ)	**13,216**	**15,590**	**16,754**	**98,822**	**101,316**

Figure 13: Bill of materials for the two products under study [1].

6.1.2 Manufacturing

The manufacturing energies were obtained the same way, by scaling the 11kW motor manufacturing energy to 22kW (linear extrapolation) and the 100kW motor manufacturing energy to 200 kW (linear extrapolation. This was done for all the efficiency classes for each motor.

6.1.3 Energy Consumption during rewinding

All through the case study, most assumptions have been made so as to underestimate the energy consumption incurred when choosing to rewind. In that respect, the energy to rewind a motor has been considered to include only the energy to produce the copper for new copper windings and to repaint the repaired motor (ideally the energy to burn-out, testing and varnishing should also be included, but due to lack of data availability they are neglected so as to bias the calculations slightly in favor of rewinding). Figure 13 gives the amount of copper and paint used in each motor. This is assumed to be used primarily for the windings.

6.1.4 Use.

Since the objective of this study is to compare the rewind vs replacement of motors, the use phase energy is that consumed for operation between subsequent failures of a motor [2]. Hence in order to estimate this energy a number of parameters are needed:

- Rated power of the motor

[2]This is because whatever choice is made (rewind/replace), the motor will be used again for this much amount of time before the decision point reappears.

- The load (% of full load) at which the motor is operated
- The efficiency of the motor at that load
- The total hours of operation between subsequent rewinds of the motor. This is further a product of the hours of operation per annum and the total years of operation between subsequent rewinds

These statistics can then be used to estimate the energy required to operate the motor using equation 4

This study assumes that the load of operation to be 75% just like [23, 10] and hence this is what is used for this analysis as well. Average efficiencies for motors was taken from MotorMaster+ [24] which provides a comprehensive database on motors of 2005-2006. The efficiencies used were all average efficiencies for every motor class (Standard-efficiency, Energy-efficient and NEMA Premium). Figure 14 shows the efficiencies used for this analysis. Note that for the 200kW motor there is no Energy-efficient class since the EPAct '92 did not cover motors beyond 200 hp.

22 kW MOTOR	Efficiency
Stadard Efficiency	90.2%
Standard Efficiency after rewind	89.2%
Energy Efficient	93.2%
Energy Efficient after rewind	92.2%
NEMA Premium	94.1%
NEMA Premium rewind	93.1%

200 kW MOTOR	Efficiency
Stadard Efficiency	94.1%
Standard Efficiency after rewind	93.6%
NEMA Premium	96.3%
NEMA Premium rewound	95.8%

Figure 14: Efficiencies of motors analyzed [24].

Section 1.5.1 mentioned that the MotorMaster+ software uses the results from [20] to account for the impact of rewinding on the motor efficiency. Hence the difference of a motor before and after rewinding is 1% for the 22kW motor and 0.5% for the 200 kW motor, as shown in Figure 14. THe final results also include the case for rewinding where there is no effect on the motor efficiency and it remains the same before and after rewinding.

[23] estimates the years between subsequent rewinds to be approximately from 5 to 7 years and hence this study uses 6 years. The hours of operation were 4,067 per year for the 22kW motor and 6,132 per year for the 200kW motor [18].

A few reports [17, 12] have spoken about the deterioration of motor efficiency as it is operated for several years. Cycling of core temperature as it starts and stops causes aging of the core steel which increases internal losses. New silicon steel and properly decarbonized cold rolled steel do not age significantly. Since no quantitative data was found on this, efficiency deterioration during use is neglected in this study.

Using this information the total energy consumed during use phase for the different types of motors - 22 kW (standard-efficiency, energy-efficient, and NEMA premium) and 200 kW (standard-efficiency and NEMA premium) - was calculated.

6.1.5 Life Cycle Inventories

Compiling all the calculations above, the Life Cycle Inventories, LCIs, for the various motors is shown in Figure 15 (the scale is logarithmic)

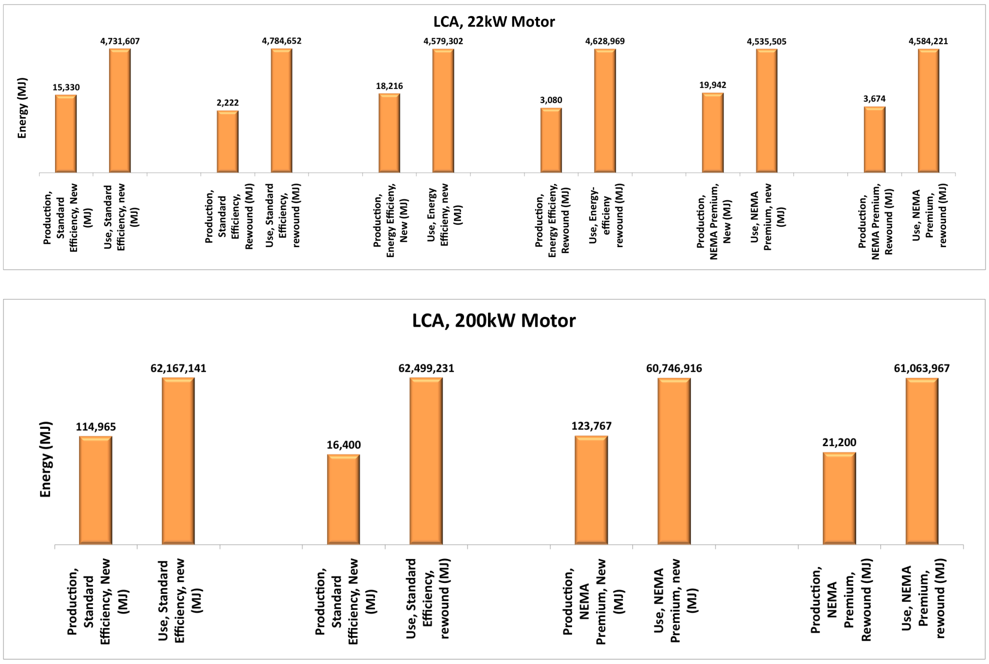


Figure 15: Life Cycle Inventories for the different motor classes for (a) 22 kW motor; and (b) 200 kW motor. The rewound motor use phase values assume deterioration in efficiency.

The first thing to note is the significant dominance of the use phase over the entire LCI.

Also over the entire LCI, the use phase energy consumption for a more efficient motor is considerably lower. A slight degradation in efficiency as a result of rewinding creates an enormous impact on the total use phase energy use (50 GJ for the 22 kW motor with an efficiency degradation of 1% and more than 300 GJ for the 200 kW motor with an efficiency degradation of only 0.5%). This sensitivity of the use phase to the performance efficiency of the motor is a critical issue.

6.1.6 Results and Conclusions

In this Section we analyze the Rewind/Replace decision and present the results. Based on the initial motor being used, consumers have several choices upon the failure of an existing motor. They can either go in for rewind, wherein there may or may not be a efficiency degradation, or they can replace the motor. When choosing the replace, they can either replace it with a motor of the same efficiency class as the current motor or to that of a higher efficiency class.

Overall this gives rise to eighteen scenarios for the two motors, 22kW and 200 kW, being discussed here. Nine choices are as follows:

- *22kW Electric Motor, Standard, rewound Vs Standard, new* - A consumer using a 22kW standard efficiency electric motor is faced with the decision to either rewind his motor or buy a new 22kW standard efficiency motor
- *22kW Electric Motor, Standard, rewound Vs Energy Efficient,new* - A consumer using a 22kW standard efficiency electric motor is faced with the decision to either rewind his motor or buy a new 22kW energy efficient motor
- *22kW Electric Motor, Standard, rewound Vs NEMA, new* - A consumer using a 22kW standard efficiency electric motor is faced with the decision to either rewind his motor or buy a new 22kW NEMA Premium motor
- *22kW Electric Motor, Energy Efficient, rewound Vs Energy Efficient, new* -A consumer using a 22kW energy efficient electric motor is faced with the decision to either rewind his motor or buy a new 22kW energy efficient motor
- *22kW Electric Motor, Energy Efficient, rewound Vs NEMA, new* - A consumer using a 22kW energy efficient electric motor is faced with the decision to either rewind his motor or buy a new 22kW NEMA Premium motor
- *22kW Electric Motor, NEMA, rewound Vs NEMA, new* - A consumer using a 22kW NEMA Premium electric motor is faced with the decision to either rewind his motor or buy a new 22kW NEMA Premium motor
- *200kW Electric Motor, Standard rewound Vs Standard new* - A consumer using a 200kW standard efficiency electric motor is faced with

the decision to either rewind his motor or buy a new 200kW standard efficiency motor

- *200kW Electric Motor, Standard, rebound Vs NEMA, new* - A consumer using a 200kW standard efficiency electric motor is faced with the decision to either rewind his motor or buy a new 200kW NEMA Premium motor
- *200kW Electric Motor, NEMA, rewound Vs NEMA, new* - A consumer using a 200kW NEMA Premium electric motor is faced with the decision to either rewind his motor or buy a new 200kW NEMA Premium motor

Each choice of rewinding can be further broken down in two scenarios:

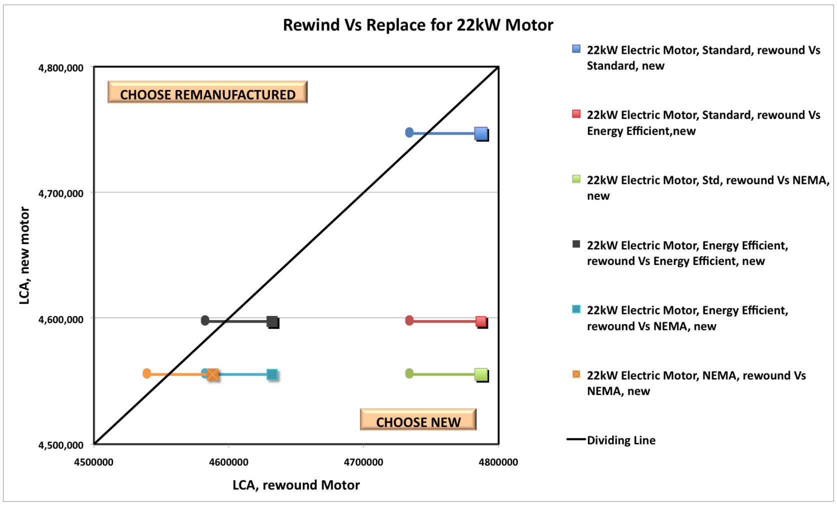
- Rewinding leads to a degradation in efficiency, as used by the MotorMaster+ software [24]. This degradation is 1% for motors smaller than 40 hp and 0.5% for motors larger than 40 hp.
- Rewinding causes no degradation in efficiency, and the motor performs like-new

In the above scenarios *Standard* refers to Standard Efficiency Motors which have an efficiency below the EPAct level. The most efficient motors are the NEMA Premium Motors called *NEMA* above. Motors that are above the EPAct efficiency level but below the NEMA Premium level are called *Energy Efficient* as they are commonly known as the Energy Efficiency Motors.

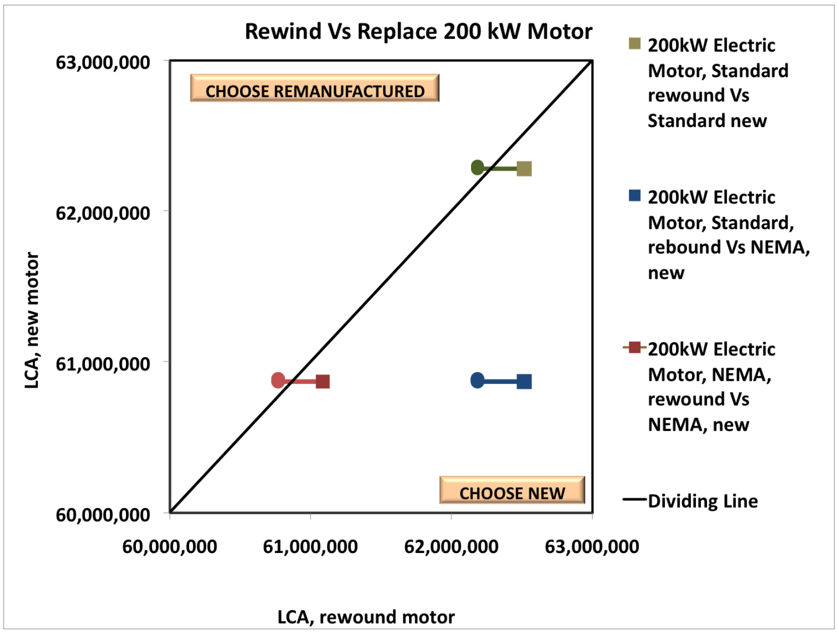
Using the same energy model as used for the other case studies Figure 16 shows the direct comparison between the net life cycle energy consumption for each of the eighteen choices listed above. With assumed degradation upon rewinding, a square is used, while with no degradation, a circle is used. The square and the circle are connected so as to show an error bar dependent on the deterioration. Figure 16(a) deals with the choices for a consumer using a 22kW motor while figure 16(b) deals with the choices for a consumer using a 200 kW motor.

From the above graphs, the following conclusions can be drawn:

- In all cases, it is advised to buy new if the new motor is of a higher efficiency class compared to the existing motor.
- In all the scenarios, if rewinding degrades the efficiency of a motor, going for a new motor will lead to a net energy saving.
- If rewinding does not impact the efficiency of the motor and if the replacement motor is also of the same efficiency class, the savings are minimal and the comparison is nuanced, though more in favor of rewinding.



(a) .



(b)

Figure 16: Replace/Rewind energy consumption comparisons for (a) 22 kW motor; and (b) 200 kW motor. The squares represent the case when rewinding impacts the motor efficiency and degrades it, while the circles represent the case when rewinding has no influence on the efficiency of the motor. The energies are given in MegaJoules.

- The length of the error bar is an indication of the sensitivity of the Life Cycle Energy Assessment of a motor to its efficiency. In all cases, this sensitivity is found to be high.

  This is because the efficiency of a motor directly impacts the use phase which is the dominant phase in terms of energy consumption during the life cycle. Figure 17 shows this for all the motors considered.

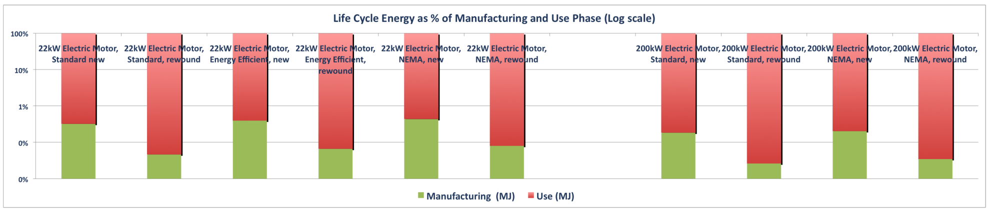


Figure 17: Life Cycle Energy Assessment split into manufacturing (including raw material processing) and use phase (based on the case with efficiency deterioration). Note the scale is logarithmic.

  Clearly, for all the motors, the use phase consumes more than 99.5% of the energy consumed over the entire life cycle. Hence even a 0.5% change in efficiency, impacts the total life-cycle energy significantly.

Another way of looking at the Rewind/Replace decision analysis is by calculating the % Energy savings by choosing Replacement over Rewind. This is shown in Figure 18. The columns refer to the case where rewinding degrades the efficiency of an electric motor (like in the case of the MotorMaster+ software [24]) while the lower end of the error bars are for the case when rewinding does not impact the efficiency of an electric motor.

This figure gives out an interesting result. It shows that for all the comparisons analyzed, the % savings are less than 10%. Though in absolute energy, this value is very large, but in percentage savings it is not. On top of this, if we assume that the general error associated with using Life Cycle Assessment as a tool is roughly 5-10%, then the only conclusion to be drawn from this study is that the Rewind/Replace decision is nuanced. Promoting one over the other requires an analysis of greater detail, taking into account the remaining phases of the life-cycle and also case-specific values for the parameters, and not average values as is done in this study.

Though the result is not conclusive, it is strong enough to declare that the general promotion of one strategy (Rewind/Replace) over the other, for saving new energy, is not correct and that the analysis requires a detailed and accurate calculation using the case-specific values for efficiencies, usage profile, rewind-impact etc.

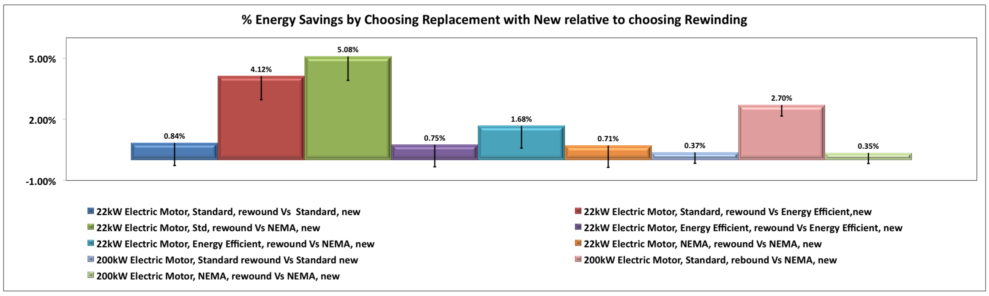


Figure 18: % Energy savings by choosing Replacement over Rewind. The columns refer to the case where rewinding degrades the efficiency of an electric motor (like in the case of the MotorMaster+ software [24]) while the lower end of the error bars are for the case when rewinding does not impact the efficiency of an electric motor.

6.1.7 Assumptions

Though most of the above study is based on data acquired from refereed literature sources and the MotorMaster+ software (*Section 5*), there are a few assumption undertaken which are listed out below.

- The LCAs were assumed to be the sum of Raw Material Processing, Manufacturing, and Use Phase. All other phases were assumed to be negligible.
- The energy to manufacture the motors (including raw material processing) was scaled up from the data available from [7]. This scaling process was verified using list of available BOMs and also through a personal communication with ABB. However, since the impact of the manufacturing and raw materials stage is negligible (less than 0.5% over the life cycle of the motor), this assumption is not likely to change and conclusion.
- The energy to remanufacture the motor was assumed to be the energy to replace the copper winding and repainting it. Though other processes like heating, and refurbishing are also involved, we have tried to keep the calculation in favor of rewinding / remanufacturing.
- The motors were assumed to be operated at a 75% load.
- The degradation in efficiency of a motor during use was neglected.
- The degradation in efficiency of a motor due to rewinding was taken from [24].

- A rewound motor was assumed to last as long as a new motor before needing rewinding (again). This assumption is again in favor of energy savings for rewinding.

6.2 Life Cycle Costing

Life cycle costing in this report is only calculated from the consumer's perspective. An electric motor consumer pays two types of costs to use an electric motor:

1. Purchase price for a new motor or price to rewind an existing motor
2. Operational costs, primarily the electricity cost during use

6.2.1 Upfront Costs

The upfront cost depends on the choice taken between rewinding and replacement with new. In the prior case there is a rewinding cost. In the later case there is a purchase price.

Rewinding cost is the fees given to the rewinding workshop to rewind the motor to the desired specifications. This varies a lot from work shop to work shop and is a negotiable price. [24] uses the average fees for 2005 in the software, which is what is used here.

The purchase price is the list price minus the discount for the motor. List price is the price advertised by the manufacturer and does not include any discount. The list prices of the motors under consideration were taken from [24] for the year of 2005. The same gave the average installation costs. Motors are hardly purchased at the list price and there is often a discount associated with it. Though this discount strongly depends on the manufacturer, dealer, motor, purchaser etc, for simplicity this study uses the default discount rate used by MotorMaster+ Version 4 [24].

6.2.2 Operational Cost

The operational costs is the cost to run the motor. This encompasses the total electricity cost. The price of electricity was obtained from [13], while the total operating hours were calculated just like Section 6.1.4. Cost of maintenance and periodic repair is neglected.

6.2.3 Life Cycle Cost Assessment

Figure 19 shows the evaluated life cycle costs for all kinds of motors considered. Note that the plot is logarithmic.

As in the case of energy in Figure 15, the use phase completely dominates over the life cycle. However, unlike the energy case where the use

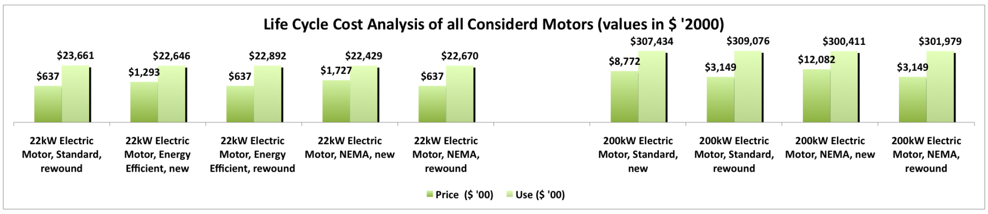


Figure 19: Life cycle cost assessment for all motors (based on the case with efficiency deterioration).

phase accounts for more that 99% of the cost, as per Figure 20, the initial investment is can be close to 5% of the total life cycle cost for all motors.

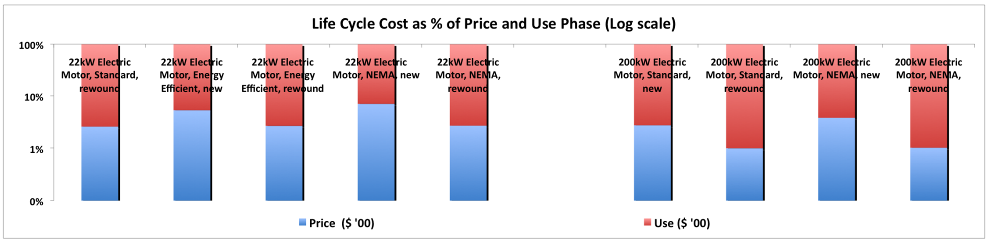


Figure 20: Life Cycle Cost split up into % of initial price and % of use phase cost (based on the case with efficiency deterioration).

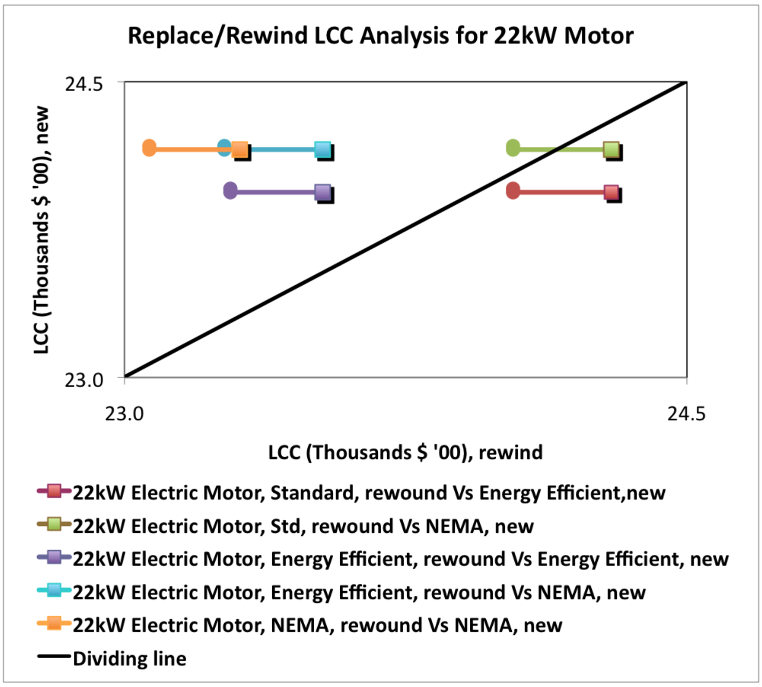
This difference is partially attributable to the relatively high energy cost of electricity (approx 10.6 MJ/kWh) compared to the economic cost of electricity (approximately 0.05 $/kWh in real dollars of 2000). As a result, the impact of use phase is greater when conducting the energy assessment.

6.2.4 Results and Conclusions

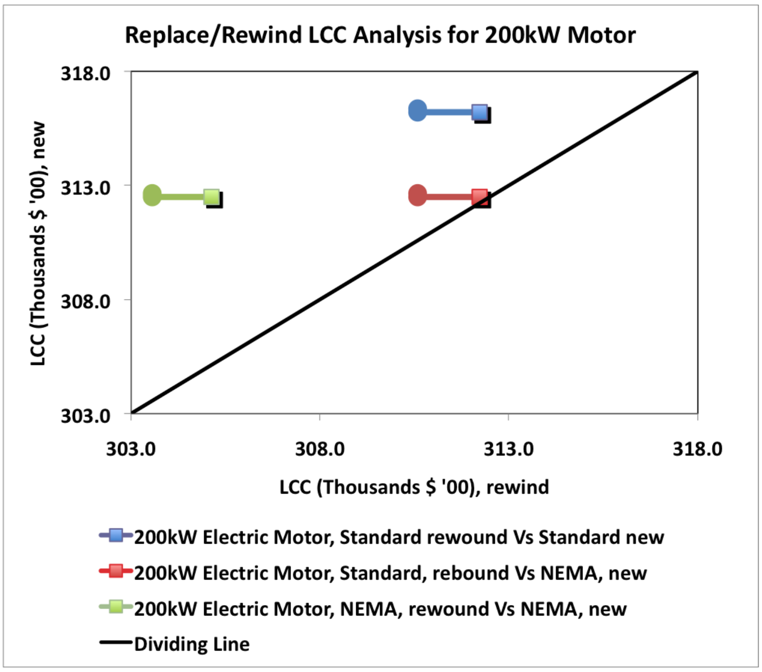
Comparing the total life cycle cost (from a consumer's perspective) after choosing to rewind a motor, with the cost entailed after choosing to replace it with the new one, is shown in Figure 21. Here it is assumed that the replacement motor will at least be of the same efficiency class as the existing one. Once again the "squares" represent the case where the motor efficiency degrades after rewinding, while "circles" correspond to the case of no impact of rewinding on motor efficiency.

The conclusions to draw are as follows:

- The energy and economic analysis are different. This difference is partially attributable to the relatively high energy cost of electricity compared to the economic cost of electricity.



(a) .



(b)

Figure 21: Replace/Rewind cost comparisons for (a) 22 kW motor; and (b) 200 kW motor. The squares represent the case when rewinding impacts the motor efficiency and degrades it, while the circles represent the case when rewinding has no influence on the efficiency of the motor.

- For the larger motors considered, rewinding seems to be the net cost saving option in all cases even though for the case between Standard Efficiency and NEMA Premium, with 0.5% degradation, the savings are minimal. and the analysis seems nuanced.
- For Energy Efficient motors of size 30 hp, rewinding is the cost saving strategy in every scenario.
- In the case of Standard Motors of size 30 hp, if there is a degradation of 1%, then replacing with a new Energy Efficient motor will lead to greater savings. if no degradation expected by rewinding, then the savings are minimal by choosing to rewind replace. This brings out the impact of degradation on the decision scenarios.
- The length of the error bar is an indication of the sensitivity of the life cycle cost of that motor to its efficiency. This sensitivity is high because of the dominance of the use phase cost over the entire life cycle, as shown in figure 17.

Like in the case for energy analysis (figure 18), another way of looking at the savings is as a relative percentage of savings on replacing over choosing to rewind. This is shown in figure 22

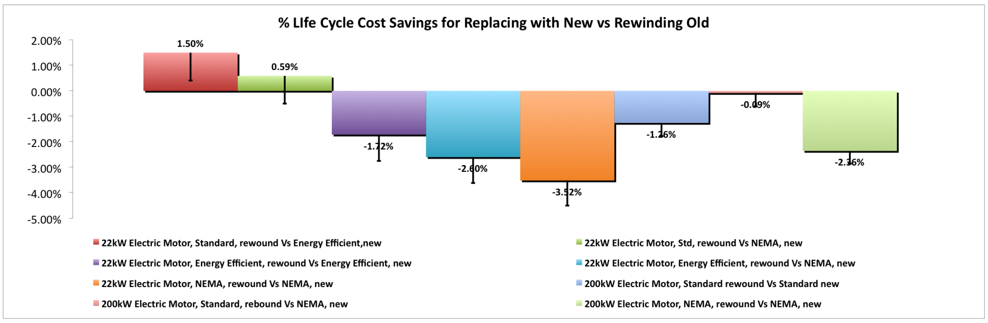


Figure 22: % Cost savings by choosing Replacement over Rewind. The columns refer to the case when rewinding causes a deterioration of the motor efficiency. The lower ends of the error bars refer to the case when rewinding has no impact on the motor efficiency.

This figure gives out an interesting result. It shows that for all the comparisons analyzed, the % savings/expenditures are less than 5%. Though in absolute savings, this value is appreciable, but in percentage savings it is not. On top of this, if we assume that the general error associated with using Life Cycle Costing as a tool is roughly 5-10%, then the only conclusion to be drawn from this study is that the Rewind/Replace economic decision is also nuanced. Promoting one over the other requires an analysis of greater detail, taking into account the remaining phases of the life-cycle and also case-specific values for the parameters, and not average values as is done in this study.

Though the results are not conclusive, it is strong enough to declare that the general promotion of one strategy (Rewind/Replace) over the other, for saving new energy, is not correct and that analysis requires a detailed and accurate calculation using the case-specific values for efficiencies, usage profile, rewind-impact etc.

6.2.5 Assumptions and Comments

Though most of the above study is based on data acquired from refereed literature sources and the MotorMaster+ software (Section 5), there are a few assumption undertaken which are listed out below.

- The list prices used are average prices available from the MotorMaster+ software [24]. Since the discount is a highly variable parameter dependent on the motor, manufacturer, supplier, consumer etc, the default discount rate of 35% was used from [24]

- The demand charges are already embedded in the electricity prices uses and are thus accounted for in the above calculations

- Purchase of more efficient motors is usually incentivized with rebates. Like discounts, rebates are hard to estimate and there is no national average rebate data available. Hence rebates were not accounted for in the calculations above. However, rebates promote replacement, and including them into the calculations will further accentuate the conclusion in favor of choosing new.

- The life cycle cost above is calculated from the consumer's perspective and thus includes purchase price and operational cost. Idealy salvage cost for the product upon reaching end-of life should also be accounted for. This is hard to evaluate and for simplicity left out in the calculation above.

7 Conclusion

This study focussed on the energy and economic saving potential of rewinding relative to replacing electric motors upon failure. To be complete both small (30 hp) and large (270 hp) motors were analyzed. All relevant efficiency classes were included and a varied impact of rewinding on motor efficiency was considered. The tool for analysis was Life Cycle Energy Assessment where in the gross energy required by each motor over its life cycle was estimated. Similarly for the economic analysis, the tool used was Life

Cycle Costing, where the total life cycle cost, from the consumer's perspective, was estimated. It was observed that for energy savings, all comparisons hinted the choice of replacement as the net energy saving strategy (though in the case of rewinding not impacting the efficiency of the motor, some comparisons were nuanced), while for economics in some cases replacement but in most cases rewinding leads to lower life cycle costs. The dominating influence of the use phase over the life cycle was found to be the reason for such a behavior, which make performance efficiency of motor to be one of the most important characteristics. In terms of percentage savings, for both energy and economics the savings were less that 10% for all cases, and hence if the inherent error associated with LCA and LCC in 10%, then all comparisons are nuanced, and no conclusion can be drawn strongly. This calls for more detailed, case by case analysis. Overall it was shown that the common notion that remanufacturing leads to energy savings was challenged an it was shown that replacing with new in the case of electric motors is the energy saving strategy.

References

[1] Abb website. *Internet Source: http://www.abb.com/.*

[2] Anatomy of an energy efficient electric motor rewind.

[3] Energy independence and security act 2007, title iii, section 313. *Internet Source:* $http://www.govtrack.us/congress/billtext.xpd?bill=h110-6$.

[4] US Environmental Protection Agency. Proposed new motor efficiency standards can save industry energy and money. *Energy Matters, Internet Source:* $http://www.energy.wsu.edu/documents/engineering/motors/EfficiencyStandards.pdf$, Spring 2007.

[5] John C Andreas. *Energy-Efficient Electric Motors, Selection and Application, Second Edition.* Marcel Dekker, Inc, 1992.

[6] Joao A. C. Fong Conrad U. Brunner Anibal T. de Almeida, Fernando J. T. E. Ferreira. Electric motor standards, ecodesign and global market transformation. *Industrial and Commercial Power Systems Technical Conference, 2008 (ICPS 2008)*, pages 1–9, 2008.

[7] Joao Fong Paula Fonseco Anibal T. de Almeida, Fernando J. T. E. Ferreira. Eup lot 11 motors. *ISR- University of Coimbra*, 2008.

[8] Brian Gibbon Austin Bonnett. The results are in: Motor repair's impact on efficiency. *White Paper, Electrical Appliance Service Association(EASA)*, 2002.

[9] Conrad U. Brunner and Nils Borg. From voluntary to mandatory: policy developments in electric motors between 2005 and 2009. *ECEEE 2009 Summer Study, European Council for an Energy Efficient Economy*, 2009.

[10] Bruce H. Campbell. Failed motors: Rewind or replace? *IEEE Industry Applications Magazine*, pages 45–50, 1997.

[11] Wenping Cao and Keith J. Bradley. Assessing the impacts of rewind and repeated rewinds on induction motors: is an opportunity for redesigning the machine being wasted? *IEEE Transactions on Industry Applications*, 42(4):958–964, 2006.

[12] James C. Hirzel. Impact of rewinding on motor efficiency. *IEEE*, pages 104–107, 1994.

[13] US Energy Information Administration: $http : //www.eia.doe.gov/emeu/aer/txt/ptb0810.html$. Table8.10averageretailpricesofelectricity,1960-2008.

[14] Internet Souce: $http : //www.energyefficiencyasia.org$. Energy efficiency guide for industry in asia.

[15] Internet Source http://www.hawtx.com/images/Motor Big-229.jpg. Open-drip proof motor representative picture.

[16] Internet Source http://www.microcontechnologies.com/Worldmtr.jpg. Totally enclosed fan cooled motor representative picture.

[17] David C. Montgomery. The motor rewind issue - a new look. *IEEE*, IA-20, NO. 5:1330–1336, 1984.

[18] United States Department of Energy. United states industrial electrical motor systems. market opportunities assessment. Dec 2002.

[19] Mitchell Olszewki Chris Cockrill Julia Oliver Paul E Scheihing, Mitchell Rosenberg. United states industrial motor-driven systems market assessment: Charting a roadmap to energy savings for industry. *US DOE website* - $http : //www1.eere.energy.gov/industry/bestpractices/us_industrial_motor_driven.html$, 2009.

[20] EASA/AEMT rewind study and good practice guide to maintain motor efficiency. The effect of repair/rewinding on motor efficiency. 2003.

[21] Vaclav Smil. *Energy in Nature and Society*. MIT Press, 2008.

[22] Motor Losses. Internet Source. $http : //web.applied.com/base.cfm?page_id = 3556$.

[23] Michael Shepard Steve Greenberg Gail Katz Steven Nadel, R. Neal Elliott and Anibal T. de Almeida. *Energy-Efficient Motor Systems: A handbook of technology, program and policy opportunities, Second Edition.* American Council for and Energy-Efficient Economy, 2002.

[24] EERE US DOE. Motormaster+ ver 4. *Internet Source:* $http://www1.eere.energy.gov/industry/bestpractices/software_motormaster.html$.