CHAPTER 11

ELECTROMECHANICAL ENERGY

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CHAPTER CONTENTS

KEY WORDS

Design Improvement
Energy Conversion
Equipment Modification
Equipment Substitution
Industrial Use
Manufacturing Industries
Material Substitution
Mechanical Energy Sources
Motors
Prime Movers
Process Modification

SUMMARY

In the United States today, the residential, commercial, and industrial sectors use a considerable quantity of electrical energy, much of it in the form of electromechanical energy. For example, of total electrical energy use, approximately 60 percent is for electrical drives. Thus, improvements in electrical drive efficiency would have a significant effect on reducing industrial electrical energy requirements.

Improvements in the utilization efficiency of electrical prime movers can be achieved by good maintenance practices. The efficiency of electric motors can also be significantly increased (particularly for small motors rated less than 1 kW) by improved motor design and manufacturing practices.[1] In recent years the older practices have been discarded to achieve less expensive motors, but the result has been lower efficiencies.[2] With current energy price trends, higher initial cost motors will be cheaper in the long-term when energy use, maintenance requirements, and usable life are considered. Recent technological developments can also provide greater electrical use efficiency (e.g., utilization of pulse-width modulation techniques for the control of motor speed).

Material shaping and forming operations have potential for improved electrical use efficiency. Some examples

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are the use of cold forgings from easily wrought alloys to replace hot forgings; use of fine blanking (a shaping operation that uses close-fitting dies) to produce precision stampings requiring no subsequent finishing, thereby lowering the energy content of the part; and the use of stretch forming (pre-stretching the material 2 to 3 percent prior to forming) which reduces the energy used to form the part and increases the strength of the finished part.

The transport of material and products within a given industrial facility presents special requirements for electrical energy use. For any given process a comparison can be made of the advantages and disadvantages of providing continuous versus a discontinuous (batch) mode of transport and product movement. Energy requirements and costs for the two types can have an effect on the outcome of the decision.

Based on estimates of potential improvements in motor efficiency and projected electricity demand, there is a potential for saving electricity equivalent to that generated by 100 to 200 1000 MWe power plants over the period 1975-2000.

11.1 INTRODUCTION

In industry, approximately 80 percent of electrical energy use is for electrical drives which form part of electromechanical systems. Thus, even small improvements in the utilization efficiency of these systems could have a significant effect on reducing industrial electricity requirements.

Electromechanical systems generate mechanical forces which move and form products within the manufacturing operation. *Motion* refers to the transportation of material from one point to another within the facility, while *formation* refers to changes in the material's physical dimensions and characteristics. Both motion and formation of products normally require conversion of electrical energy (EE) to mechanical energy (ME) and are traditionally performed by means of electrical motors.

Figure 11.1 shows schematically the process by which this energy conversion takes place. The equation governing this process is:

$$ME_{\text{end use}} \propto EE \cdot \eta_p \cdot \eta_c \cdot \eta_t \cdot \eta_d \quad (11.1)$$

where ME = Output mechanical energy, joules (ft·lbf);

EE = Input electrical energy, joules (kWh);

η_p = Prime mover efficiency, energy out/energy in;

η_c = Clutch efficiency, energy out/energy in;

η_t = Transmission efficiency, energy out/energy in; and,

η_d = Mechanical device efficiency, energy out/energy in.

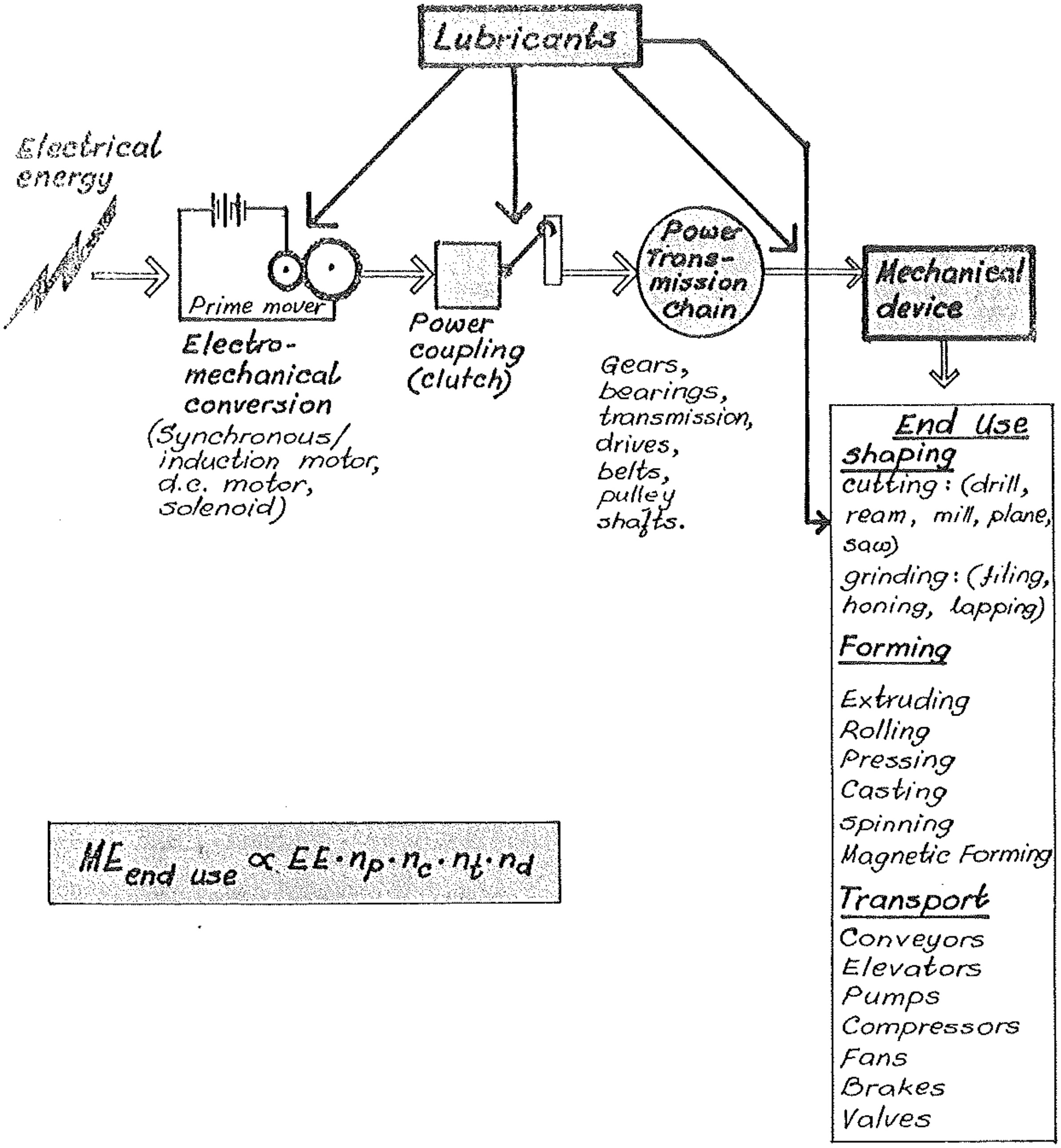
In this approach, efficiency can be improved in four principal areas:

- prime mover,
- clutch,
- transmission, and
- device.

This chapter presents information on improving the efficiency of energy use in the conversion from EE to ME (i.e., by an electric motor) and in the employment of the required ME, thus reducing the need for ME and, in turn, reducing EE requirements. There are three methods for improving energy efficiency:

- modification of user operating procedures;
- modification of equipment at the user level; and,
- redesign at the electric motor manufacturer level.

Improvements in efficiency by the first method will result in less energy demand and subsequent dollar savings. Efficiency improvements by the second method will result in less net use of energy for the same requirements. Improvements by the third method will result in reduced operating costs and reduced total life cycle costs for a given electric motor.



ELECTROMECHANICAL
ENERGY CONVERSION

FIGURE 11.1

Over the years there has been a rapid and continuous proliferation of motorized household equipment. Today electric motors in this equipment collectively use about 38 percent of all electricity sold to residential customers in the US (see Table 11.1). In the commercial sector, power for mechanical drive apparatus accounts for about 70 percent of electrical energy demand. By far the majority of this motive power is used for running refrigeration machines, including air-conditioning equipment. In the residential sector, refrigeration accounts for 88 percent of the electrical power used for mechanical drive. In the commercial sector, 62 percent of the electricity used for mechanical drive is for refrigeration or air motion for cooling.[3] Although this chapter concentrates on motor problems, a complete discussion would also have to consider the efficiency of the equipment driven by motors. In the case of refrigeration, this would include compressors, heat exchangers, and insulated enclosures.

11.2 OBJECTIVE, SCOPE, ASSUMPTIONS

A. Objective

The objective of this chapter is to provide basic data, suggestions, and information needed to improve the efficiencies of processes for conversion of electrical energy to mechanical energy.

B. Scope

The scope of this chapter is limited to electromechanical energy conversion processes, devices, and equipment. Emphasis has been placed on manufacturing applications, which account for a major part of electromechanical energy use.

C. Assumptions

This book is not a reference work on mechanical design; therefore, the reader, assumed to have an engineering background, is considered to be familiar with appropriate references and handbooks for this purpose. An attempt has been made, however, to draw together sufficient information to permit mechanical engineers, electrical engineers, industrial engineers, product designers, shop foremen, supervisors, or plant engineers to review and evaluate electromechanical processes. Following such an evaluation this information should suggest measures for improved energy management: techniques to improve energy use efficiency, reduce losses and waste, and save money.

It should be noted that for most manufacturing processes, saving materials also saves energy since the materials themselves contain embodied energy.

11.3 PRIME MOVERS

Electrical prime movers form the basis for the majority of motion and product formation within most of US industry. Other sources of prime motion are internal combustion engines, steam engines, wind machines (e.g., windmills), hydropower (e.g., water turbines, water wheels), and gravity-powered devices. These sources are not considered here directly, but some of the suggestions for reducing energy use by changing operating procedures would apply for these sources as well.

Electric motors may be thought of as one part of an overall scheme for distributing the output of large central mechanical devices (heat engines, hydroturbines) to machines too distant to be driven by direct mechanical transmissions. The end user is primarily concerned, therefore, with the conversion of this EE to ME via electric motors. Motor efficiency, defined as the ratio of useful work output to electrical energy input, varies from as low as about 15 percent for small universal motors to about 95 percent for 500 kW, three-phase machines (see Figure 11.2).

Currently, modern motors are less efficient than older units because current designs minimize material costs and labor. Larger motors are more efficient than smaller motors. It has not been considered important, for example, if a small room exhaust fan uses 100 as opposed to 50 watts, while a factor of two in an air-conditioning system using a several horsepower motor does warrant more careful design and higher initial costs.

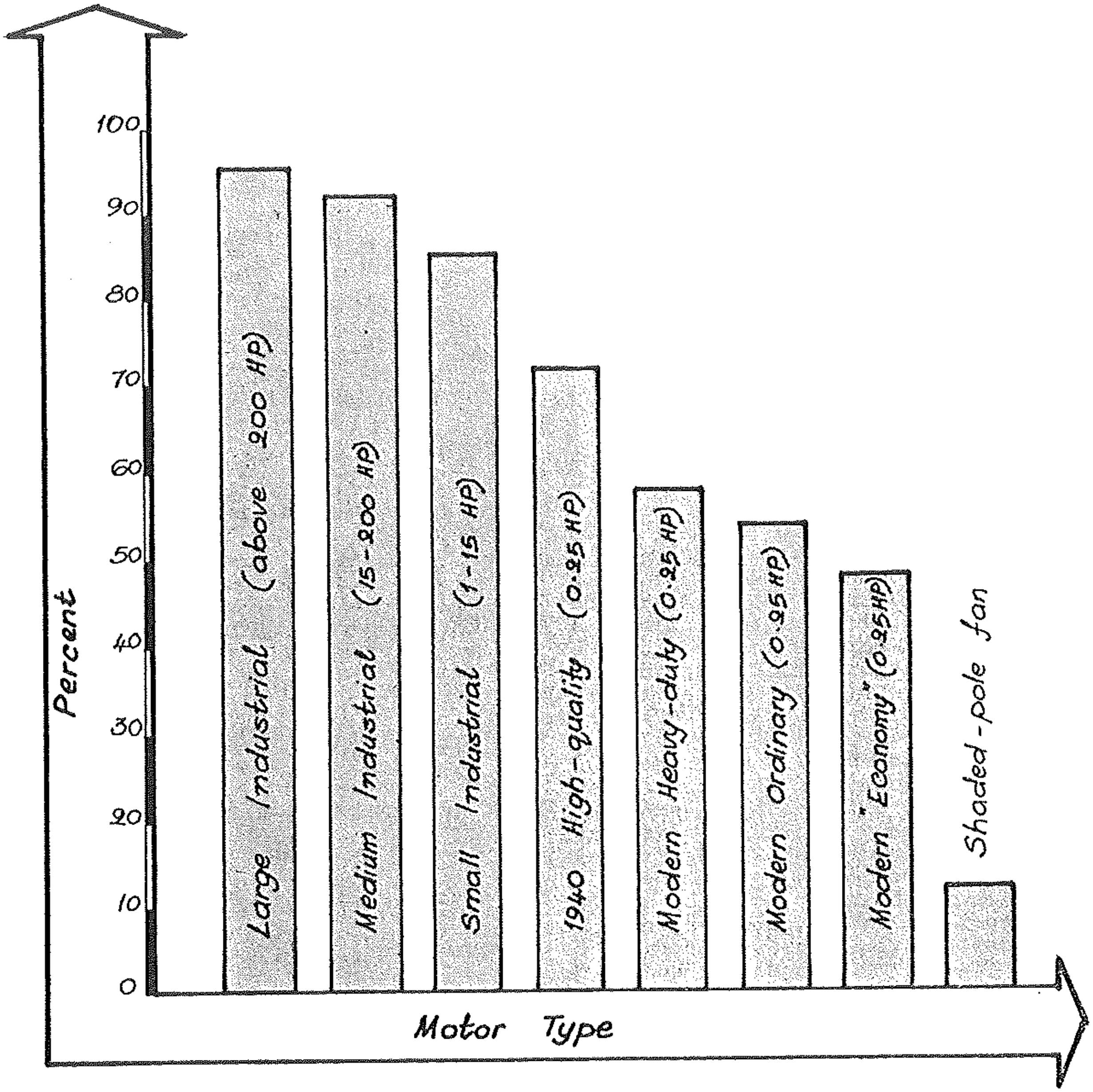
Most residential motors are rated at less than 0.75 kW (1 hp), although

Sector	Total Use		% of Sector	Electric Motor Use	
	10^9 kWh	10^6 GJe		10^9 kWh	10^6 GJe
Residential	373	1,343	38.6	144	518
Commercial	290	1,044	68.9	200	720
Sub-total	663	2,387	--	344	1,238
Industrial	549	1,976	79.8	438	1,576
Transportation	4.8	17.3	--	--	--
	1,217	4,381	∿64.2	∿782	∿2,814

Reference 3

ELECTRICITY USED FOR ELECTRIC MOTORS

TABLE 11.1



References 2 and 4

EFFICIENCY OF REPRESENTATIVE ELECTRIC MOTORS FIGURE 11.2

a few as large as 3 to 4 kW (4 to 5 hp) are installed in residential central air conditioners. Almost all of these motors operate on single-phase, alternating current, which is the service utilities normally sell to households. Commercial establishments, however, use a greater variety of motors, some rated up to thousands of kilowatts (thousands of horsepower). Unlike most residential customers, commercial customers can obtain three-phase, alternating current. This electrical service offers large businesses the better economy of purchase, operation, and maintenance associated with polyphase motors.

A. Operational Procedure Improvements

Certain improvements in the utilization efficiency of electrical motors can be obtained by modifications in the user's operational procedures. This section assumes that the user has already purchased a motor for his particular needs and has made whatever modifications to the equipment that he can in order to improve the efficiency. The next section presents several suggested methods of improving electricity utilization efficiency by means of modifying user equipment. (See Chapter 4 for specific recommendations related to home appliances and their associated motors.)

1. Optimum Power

Electric motors operate most efficiently at rated voltage. The supplying utility will check the service voltage upon a customer's request and, if the voltage is outside the permitted range, will correct it. Figures 11.3 and 11.4 show typical torque, speed, and operating curves for typical induction and single-phase motors. Voltage balance of three-phase power supply to motors, for example, is important.[5] An unbalance of 3 percent can increase losses 25 percent.

2. Equipment Scheduling

All electric motorized equipment should be turned off when not in use. Peak demand should be controlled by rescheduling operations to level off-peak demand periods. For example, test run large motors on fire pumps at off-peak hours. While this does not affect user efficiency, the generating efficiency is improved, and some utilities give reduced rates for off-peak hours. At lower load levels fewer motors should be used, and if possible, off-shift operation could be performed by a small motor selected just for the application. (See also Chapters 2 and 3.) Note that very large motors can not be stopped and started as often as smaller motors without decrease of life and possible impact on electrical distribution systems.

3. Equipment Maintenance

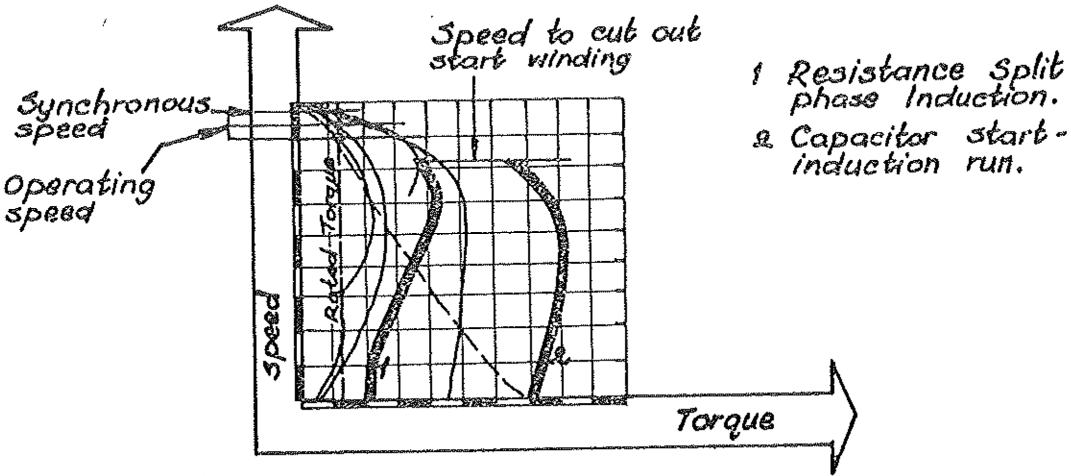
Regular maintenance of electric motors will help retain their original efficiency and increase their life. Cleaning air filters will reduce heating (lowering resistance) of motors. Regular lubrication of bearings will minimize frictional losses and heating of motor materials (see the Case Studies). Connections should be checked periodically to insure that arcing or corrosion is not taking place. The efficiencies of mechanical equipment in general can be increased typically 10 to 15 percent by proper maintenance.

4. Continuous versus Batch Processes

Depending on the type and volume of production, considerable energy can be saved by considering the trade-offs between continuous and batch-type processes. For example, for low production processes requiring equipment with little warmup time, batch processes can be employed most economically while shutting down operations completely between batches. For high volume and high-peak production work, a more moderate and continuous process will conserve energy by lowering peak-load demands on equipment.

5. Power Factor Correction

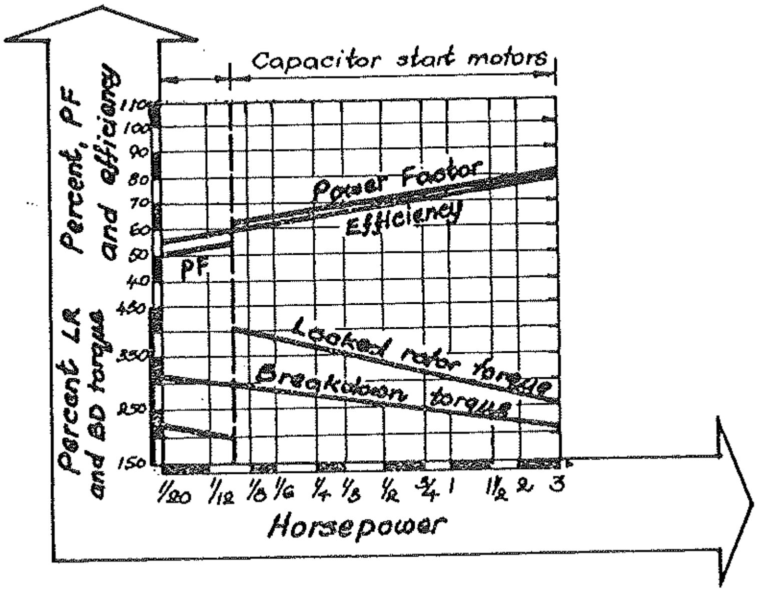
In some cases the use of power factor correction may be justified to reduce energy loss in feeder and branch circuit equipment. Such correction is also helpful to the utility supplying the power and results in reduced transmission losses.



Reference 6

COMPARISON OF TORQUE VERSUS SPEED CURVES FOR INDUCTION MOTORS

FIGURE 11.3



Reference 7

FIGURE 11.4

TYPICAL OPERATING CURVES, SINGLE PHASE MOTORS

B. User Equipment Improvements

Improvements in the utilization efficiency of electrical motors can also be obtained by changes in the equipment. Following are several recommendations.

1. Improve Heat Removal

Cooler motors operate slightly more efficiently. If a motor is tending to heat up, it may be relocated to a cooler area or some form of cooling may be used to remove heat. An improved thermal heat sink for the motor frame and supports will aid in heat removal. Any unnecessary restrictions to air flow or thermal insulation should be removed from around the motor. For example, resistance of the copper windings in a motor increases roughly linearly with absolute temperature. A rise in temperature from 27°C (80°F) to 32°C (90°F) results in a 2 percent increase in resistance and energy loss due to resistive heating. Efforts spent in cooling motors must be consistent with the cost of the cooling system and benefits achieved.

2. Equipment replacement

Replacement of old, inefficient equipment with newer, more efficient equipment will improve the electrical utilization efficiency of a given facility. Grossly oversized motors should be replaced since motors operate more efficiently near rated capacity and develop a better power factor. (See Table 11.2.)

3; Equipment Selection

Avoid oversize motors, pumps, and compressors. Smaller pumps and compressors with receivers or storage tanks should be used for sustained periods of low demand operation. When ordering electrical equipment, demand rigid compliance with specifications and verify the efficiency of the equipment once it is installed.

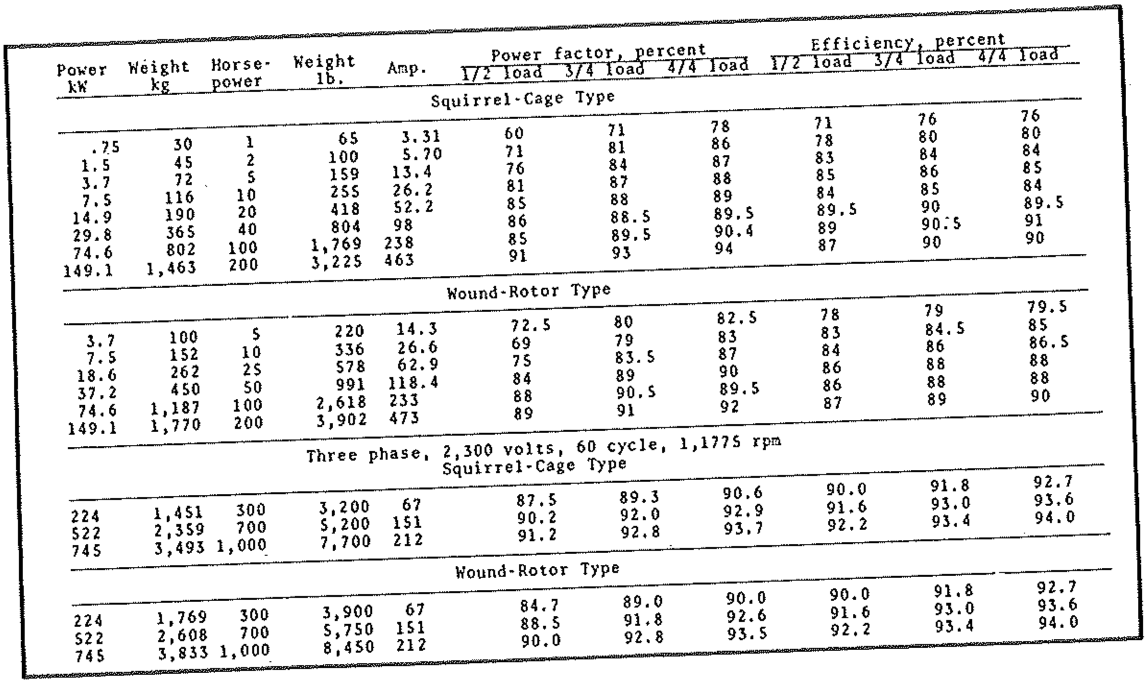
Figure 11.5 indicates the various types of electric motors available for different applications. [8,9] Table 11.2 shows the power factor and efficiency of typical induction motors, demonstrating the increase in efficiency with motor size.

Reference [5] points out that electric motors are relatively efficient machines well suited as a prime mover where loads are highly variable. It stresses the following points for proper selection:

"A. Determine the optimum motor rating to handle the load. Where the load is constant, the appropriate motor rating is readily indicated. Since the motor efficiency is nearly constant in its normal load range, the exact matching of a motor to its load is not necessarily required. Adequate matching of the motor rating to the load is important to avoid overheating of the motor. The use of motors having an output rating greater than the load (oversizing) causes a reduction in the system power factor with resultant added losses in the distribution system.

"B. With a widely varying load involving a number of stops and restarts necessary to perform the function of the driven machine, a careful analysis of the application can result in energy savings. Operating conditions, such as starts, plug stops, reversals, speed changes, dynamic braking, etc. all consume energy at rates much higher than that when the motor is operating continuously at a constant load. When variable duty cycles are encountered, two actions can be taken to minimize energy usage. The first is to reduce the mass of moving parts wherever possible, because the energy used to accelerate these parts is proportional to the mass. Secondly, all aspects of the load should be carefully analyzed which should involve consultation with the motor and control manufacturer for recommendations as to the motor and control best suited to the application. Motors designed for optimum full load efficiency would in a number of instances be totally unsuitable for many applications. Applications often have characteristics such as frequent starting, duty cycle operation, repetitive shock loading where motor torques and motor slip characteristics are the more important factors.

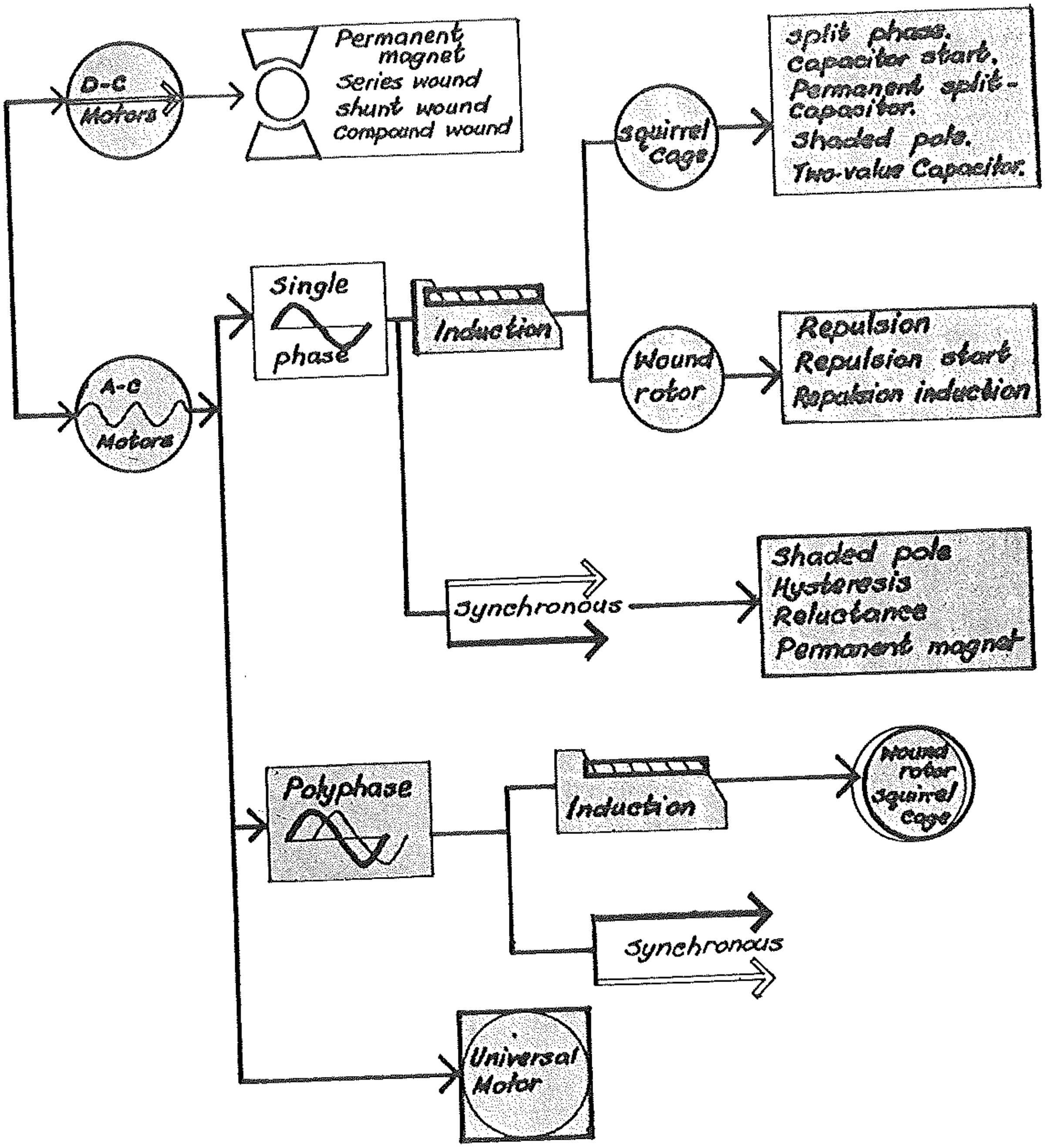
"C. Select the most efficient process and machinery. Often alternate means are available for doing a job and a variety of machines often exist that are capable of performing a task. Once these determinations are made, the lowest motor rating consistent with system economics can be specified.



Power kW	Weight kg	Horse-power	Weight lb.	Amp.	Power factor, percent			Efficiency, percent		
					1/2 load	3/4 load	4/4 load	1/2 load	3/4 load	4/4 load
Squirrel-Cage Type										
.75	30	1	65	3.31	60	71	78	71	76	76
1.5	45	2	100	5.70	71	81	86	78	80	80
3.7	72	5	159	13.4	76	84	87	83	84	84
7.5	116	10	255	26.2	81	87	88	85	86	85
14.9	190	20	418	52.2	85	88	89	84	85	84
29.8	365	40	804	98	86	88.5	89.5	89.5	90	89.5
74.6	802	100	1,769	238	85	89.5	90.4	89	90.5	91
149.1	1,463	200	3,225	463	91	93	94	87	90	90
Wound-Rotor Type										
3.7	100	5	220	14.3	72.5	80	82.5	78	79	79.5
7.5	152	10	336	26.6	69	79	83	83	84.5	85
18.6	262	25	578	62.9	75	83.5	87	84	86	86.5
37.2	450	50	991	118.4	84	89	90	86	88	88
74.6	1,187	100	2,618	233	88	90.5	89.5	86	88	88
149.1	1,770	200	3,902	473	89	91	92	87	89	90
Three phase, 2,300 volts, 60 cycle, 1,1775 rpm Squirrel-Cage Type										
224	1,451	300	3,200	67	87.5	89.3	90.6	90.0	91.8	92.7
522	2,359	700	5,200	151	90.2	92.0	92.9	91.6	93.0	93.6
745	3,493	1,000	7,700	212	91.2	92.8	93.7	92.2	93.4	94.0
Wound-Rotor Type										
224	1,769	300	3,900	67	84.7	89.0	90.0	90.0	91.8	92.7
522	2,608	700	5,750	151	88.5	91.8	92.6	91.6	93.0	93.6
745	3,833	1,000	8,450	212	90.0	92.8	93.5	92.2	93.4	94.0

Reference 10

TYPICAL INDUCTION MOTOR DATA **TABLE 11.2**



ELECTRIC MOTOR CLASSIFICATION FIGURE 11.5

"D. For variable or multi-speed drives, the first cost and long-range energy costs should be carefully evaluated because drive systems vary widely in first cost and in operating efficiency, i.e. - the choice of multi-speed or adjustable speed motors for process control as compared to throttling control; or the choice of high-speed motors with speed reduction as compared to low-speed motors."

C. Motor Equipment Manufacturer Improvements

1. Small Electric Motor Efficiency Improvements

Over the last 30 years electric motors which power household and commercial machinery have undergone a marked decline in efficiency.[1] Modern motors, especially small ones (<1 kW), are less efficient than earlier models, in part, because manufacturers have designed them for minimum initial cost to satisfy purchaser demands. In addition to lower cost these modern motors have also been more compact than the massive, more efficient, older designs. Because of this trend, the amounts of copper and iron have been reduced and design factors essential to efficient machines have been de-emphasized. Thus, while new motors may be cheaper initially, the extra power they dissipate as waste heat makes them less efficient and more costly to operate.

As one solution the decline in motor efficiency could be reversed by engineering design that combines a carefully analyzed structure, new tooling methods, and quality control with the best modern insulating and magnetic materials. Such an approach would create a new generation of motors that would, with occasional maintenance, last considerably longer than standard electric motors. This new generation of electric motors would probably be larger, heavier, and more expensive. With rapidly rising energy costs, the higher initial cost would be justified through longer life and improved operating economy. A complete conversion to more efficient motors throughout the commercial and residential sectors would reduce total US electrical usage by nearly 6 percent.[2,11]

As an example of the economic benefits which can be gained by using a more efficient electrical motor, the total savings for a motor can be calculated using variable efficiencies and initial costs. Table 11.3 illustrates the significance of efficiency in a dramatic way. The life cycle cost of providing 3600 GJ (10^6 kWh) of mechanical energy with motors ranging in size from 0.1875 to 75 kW (0.25 - 100 hp) was selected to compare the effects of efficiency and of using numerous small motors rather than a central power source. For simplicity this calculation does not consider several factors such as investment tax credit, financing, maintenance, and regional variation of electricity costs. For a more detailed consideration of these factors, see Appendix E.

Note that the life cycle cost is up to ten times greater for smaller motors. This is due to greater initial cost and greater energy cost. The greater initial cost is due to the fact that small size motors require more material per unit power capacity and have to be replaced more often. (See Table 11.2, for example, which indicates that a 0.75 kW (1 hp) squirrel cage motor requires about 50 kg/kW, while the 150 kW (200 hp) motor requires about 10 kg/kW.) Over the full range of motor powers, from fractional to 1000 kW (1340 hp), the specific weight (kg/kW) varies by as much as a 10:1 ratio.

The greater energy cost results from the fact that the less efficient motors require more kWhe to deliver a specified amount of work. This has an important effect on life cycle cost. For example, consider Table 11.4 which compares two 1 hp motors with different efficiencies. The greater first cost of the more efficient motor is more than compensated for by the life cycle cost savings. Additional benefits would result as the more efficient motor will run cooler and probably have a longer life. Escalating energy costs further enhance the benefit of the more efficient unit. Note that for motors which operate infrequently, the extra cost of an efficient unit may not be warranted.

	Motor 1	Motor 2	Motor 3	Motor 4	Motor 5
Motor Size, kW	0.1875	0.375	0.75	7.5	75
Motor Size, hp	0.25	0.5	1.0	10	100
Initial Cost $ (b)	25	60	110	420	2,200
Assumed Motor Life (Years)	5	5	10	20	50
Number of Motors	3,995	1,998	499	25	1
Efficiency (%)	50	60	80	85	95
Cost of Motors $	99,875	119,880	54,890	10,500	2,200
Annual Energy Cost (c) $	2,002	1,669	1,252	1,178	1,054
Present Value of AEC $ (d)	19,855	16,548	12,414	11,680	10,450
Life Cycle Cost (e)	119,730	136,428	67,304	22,180	12,650
Cost Relative to Motor 5	9.5	10.8	5.3	1.8	1.0

Notes:
(a) Assume 267 hrs per year operation, 50 year life, 10^6 kWh total delivered
(b) Source: References [11,12]
(c) At 0.05 $/kWhe
(d) At 50 years at i = 10%, PWF = 9.915
(e) Equals initial cost plus present worth of annual energy cost (AEC)

TABLE 11.3

COMPARISON OF MOTOR LIFE CYCLE COSTS(a)

	Typical Values	
	Motor 1	Motor 2
kW	.75	.75
hp	1.0	1.0
Initial Cost(b) $	100	120
Life, years	10	10
Efficiency %	75	85
Annual Energy Cost(c) $	66.67	58.82
Present Value of AEC(d) $	409.60	361.41
Life Cycle Cost(e)	509.60	481.41
% Savings Compared to Base	base	6

Notes:
(a) Assume 1333 hr/yr operation, 10 year life, delivering 10^4 kWh
(b) Source: Reference[11]
(c) At 0.05 \$/kWh
(d) At 10 yr and i = 10%; PWF = 6.144
(e) Equals motor cost plus present worth of energy cost

COMPARISON OF MOTOR EFFICIENCIES AND LIFE CYCLE COSTS(a)

TABLE 11.4

Finally, more energy is required to manufacture a more efficient motor. Is it justified? Consider two 0.75 kW (1 hp) motors selected for air-conditioner service.

Motor #1 = 0.75 kW, 24 kg, 60 percent efficient, 10 yr, 1000 hr/yr

Motor #2 = 0.75 kW, 30 kg, 75 percent efficient, 10 yr, 1000 hr/yr

At roughly 100 MJ/kg to manufacture (Appendix B), the more efficient motor requires 3 GJ versus 2.4 GJ for the less efficient one.

The 10 year output of both motors is 27 GJ (7.5×10^3 kWh). The 60 percent efficient unit requires an input of 27 GJ ÷ 0.6 = 45 GJe, against 36 GJe for the 75 percent efficient unit. Thus, the added energy investment (in materials and manufacturing) of 0.6 GJ to produce the more efficient unit saves 45 - 36 = 9 GJe.

For small electric motors, one trend in the direction of increasing efficiency has been the increased popularity of the capacitor-run (or permanent-split capacitor) motor which tends to be more efficient under constant load conditions than other types of single-phase motors.[2] Yet within the class of capacitor-run motors, efficiency is still dependent on the same rules of good design and construction as in other classes.

Modern motors are, of course, smaller and lighter than their predecessors. They weigh about one-third to two-thirds as much; and a 0.5 kW motor of today is actually smaller in size than the 0.25 kW motor of 30 years ago.[2] Clearly, modern motors save on materials (representing some energy savings) and labor, but do so at the sacrifice of efficiency (see Figure 11.2).

A possible alternative would be to construct motors with designs similar to those of 30 to 40 years ago, but with the best modern insulating materials.[2] Magnetic materials would be selected for optimum performance with minimum losses, and, finally, the bearings would be of the best quality and easily replaceable with ordinary tools as is now done for better quality motors. The result would be an extremely long-lived motor. The high initial cost (perhaps twice that of a modern motor or more) could be partially offset by complete standardization of frames and mounts, an arrangement which already exists for large industrial motors.[2] When the machine containing the motor is eventually scrapped or becomes obsolete, its motor could be saved and transferred into some new apparatus. (A few commercial refrigeration companies have actually been applying this concept on a very limited basis by rebuilding old motors with modern insulation and supplying them to special customers.)

Efficiently designed motors (1 to 200 hp) are beginning to appear in the marketplace.[11] Motors with efficiencies 2 to 15 percent greater than standard units are available at cost increases up to 25 percent. The reduced cooling requirement for these new motors is also a significant advantage. Note that proper motor selection, operating strategy, maintenance, and driven equipment design may offer opportunities for efficient energy use far greater than fundamental motor efficiency.

It was pointed out earlier that most of the output from motors in homes and businesses is used to run refrigerator and air-conditioner compressors. Virtually all refrigerators and air-conditioners made for residential use, and the majority of those made for commercial use, employ what is called the hermetically sealed motor compressor unit.[2] That means the motor and compressor are directly coupled and sealed inside a welded steel case. The advantages here are that the coupled system runs more quietly, occupies less space, and requires less maintenance. It would clearly be wasteful, however, to attach a non-depreciating motor inseparably to a compressor destined to wear out within a few years, and then add a housing which makes repair impossible and salvage for copper difficult. Thus, the proposal to return to efficient motors would also require a return to an open-type, coupled (possibly belt-driven) compressor--a change which also would be for the better. Belt-driven compressors run at lower rotational speeds, thus having a potential for longer life. Even more important, with proper design less waste heat from the motor will be added to the working fluid than in the hermetic machines. Thermodynamically, this is advantageous for it permits one to get more refrigerating effect per motor unit power. There would be, therefore, a further gain in conservation of energy resources.

If such motors were to be adopted generally, the saving in electric power would be sizable. Suppose motor efficiency were raised to the levels typical of the better units of the 1930s. For a low cost 0.25 kW motor, this would mean more than a 20 percent reduction in the power use of motorized appliances. (Larger motors would not have such a drastic reduction of power losses.) The residential sector would save 20 percent of 518 x 10^6 GJe (144 x 10^9 kWh) total annual residential motor energy use, or 104 x 10^6 GJe (28.8 x 10^9 kWh) per year, and the commercial sector would save 20 percent of 720 x 10^6 GJe (200 x 10^9 kWh) total annual commercial motor energy use, or 144 x 10^6 GJ (40 x 10^9 kWh) per year. The total savings of 248 x 10^6 GJ (69 x 10^9 kWh) would amount to 5.7 percent per year of the total 1968 US electrical use of 4381 x 10^6 GJe (1,217 x 10^9 kWh) (see Table 11.1).[11,13]

In addition to the energy savings, there also would be a commensurate long-term cost savings. The 70 percent efficient, 0.25 kW motor demands $\sim$100 watts less than the 55 percent efficient one. If electricity sells for 0.05 $/kWh, the motor would save $5 for every 1000 hours of operation. Thus, if the efficient motor costs $30 extra, this investment would be paid back in about 1-1/2 years if the motor ran continuously.

In a typical refrigerating machine, the motor operates about one-third to one-half of the time (33-50 percent duty cycle). In this case the repayment time would be about three or four years. These repayment times are computed on the basis of the present price of energy. If that price continues to rise as it has done recently, the efficient motor would become that much more attractive.

One exception to these long-range savings would be the case of a motor which is used infrequently, as in a power tool. There would be no compelling economic reason to install the more efficient motor in such a tool, except perhaps to increase reliability and to improve resistance to periodic overloads during operation.

The possibility of major improvements in motor design should not be ruled out. Recent use of rare earth magnets in DC motors results in motors with more power, faster response, lighter weight, and interesting new designs (for example with the magnets on the rotor and windings on the stator).[14] Recently the development of a "controlled torque motor" was reported with improvements in efficiency claimed to be as large as 30 percent. [15,16] (See the Case Studies.)

2. Large Electric Motor Efficiency Improvements[4]

In the following discussion, large motors are considered to be those in excess of 37.5 to 45 kW (50 to 60 hp). Such motors would normally be NEMA frame 360 and larger. Motors of this size are normally polyphase (usually three-phase), either synchronous or squirrel cage induction. These motors operate on voltages ranging from 200 V to 13 to 15 kV.

Large motors are usually custom designed to meet specific customer application requirements. This custom design must account for all the requirements of the driven load and of the electrical system supplying power to the motor.

Such factors as load speed-torque characteristics, load inertia, duty cycles, impact loading, and voltage drops while starting and running must be considered by the designer. Customer specifications on power factor and efficiency are also considerations. In addition, motor design is affected by noise level requirements.

Motor purchasers have tended to emphasize low initial cost and, therefore, manufacturers have supplied motors which are competitive on this basis. As energy costs continue to escalate rapidly, it becomes profitable for users to evaluate motors on a life cycle cost basis including initial costs, maintenance, and energy costs.

With energy costs high, it may well be more profitable to pay a higher initial cost for a premium efficiency motor and reap the savings in energy cost differences during the life of the motor.

The general procedure for such a comparison among several bids is to normalize all bids to a given efficiency. For example, all bids would be normalized to 95 percent efficiency by applying a penalty of X dollars for each percentage point below the 95 percent, and a similar credit for each point above 95 percent. The X dollars represents the present worth of energy costs over the lifetime of the motor. In this way the user recognizes which motor will be most economical to use.

Motor manufacturers are subject to the demands of motor users. If the user will make such a comparison of actual costs rather than only initial costs, manufacturers will respond by providing higher efficiency motors.

The user must realize, however, that there are many application requirements which must take precedence over motor efficiency. Safe acceleration of the load without injurious thermal and mechanical strain on the motor, under all expected conditions, is a primary concern. The environment in which the motor will operate dictates the minimum requirements of motor enclosure to protect electrical parts. Maximum efficiency is obtained with an open motor, but a protective enclosure is required in many applications, such as some outdoor, chemically corrosive, or explosive atmospheres.

Many of the steps which can be taken to improve efficiency are in conflict with other desirable motor performance characteristics, and, therefore, proper application of motors designed for premium efficiency will require careful analysis of the load requirements and of the electrical power system. The user must be responsible for this careful analysis and for using this analysis as part of his purchase specifications.

The design and construction of a premium efficiency motor will definitely be more expensive in the initial cost stage. Furthermore, motor manufacturers will require several years to complete development and evaluation of the design concepts involved. This trend will be helped if users begin now to evaluate motors based on life cycle costs.

In order to explore the concept of a premium efficiency motor, let us first consider the various factors affecting motor efficiency. Equation (11.2) defines the efficiency of an electric motor:

$$\text{EFFICIENCY} = \frac{\text{POWER OUT}}{\text{POWER IN}} = \frac{\text{POWER IN} - \text{POWER LOSS}}{\text{POWER IN}}. \quad (11.2)$$

The "power loss" term is composed of the following elements:

1. <u>STATOR LOSS</u> (WS). This is the I^2R loss in the stator winding.
2. <u>ROTOR LOSS</u> (WR). This is the I^2R loss in the rotor winding.
3. <u>CORE LOSS</u> (WC). This is the hysteresis and eddy current loss of the laminated stator and rotor core.
4. <u>FRICTION AND WINDAGE LOSS</u> (FW). This is the loss due to fans and the bearing friction.
5. <u>STRAY LOSS</u> (WL). This is the lump sum of all losses in the motor which cannot be attributed to one of the other four components. It is principally due to electrical harmonics and stray currents in the motor.

Various design steps can be taken to reduce each of the above components. Some of these steps, and associated problems, are as follows:

- *Increasing the amount of copper in the stator will lower stator resistance and thus lower stator loss.* The major penalty for this is increased motor size to accommodate the larger coils.
- *Reducing the number of turns in the stator cells reduces stator resistance and stator loss.* The penalties are higher magnetic density and higher starting current. The higher magnetic density causes lower motor power factor and higher core loss. In an induction motor the higher magnetic strength also reduces rotor loss. The net result is usually improved efficiency, unless carried to extremes.
- *By increasing the air gap (the clearance between rotor and stator), stray loss can be reduced because the strength of the harmonics is reduced.* The penalty is a reduction in motor power factor.
- *Use of high-silicon laminated steel can reduce core loss due to decreased hysteresis loss.* High-silicon steel has more reluctance than carbon steel, so the penalty is a slight reduction in motor power factor.
- *Use of thinner lamination steel can reduce core loss by reducing eddy current loss.*
- *In squirrel cage induction motors, use of large, high-conductivity rotor bars and end rings will reduce rotor loss*, The penalty may be very severe since rotor cage resistance greatly affects motor starting torque and current. The end result may be such a reduction in torque and severe starting voltage reduction, due to high starting current, that the motor will not accelerate to full speed.
- *Stray loss can be reduced by eliminating the skew in the rotor.* This skew is normally used to reduce or eliminate certain harmonics. Without the rotor skew, the motor noise level may increase by 2 to 5 db.
- *Insulating rotor bars from the laminations reduces stray loss due to stray rotor currents.* On aluminum rotors this is accomplished by anodizing the rotor bars before they are inserted in the core.

There are many other steps which the designer can take in some instances. It should be obvious that for a designer to establish maximum efficiency for a given application, he must have complete data on the load characteristics and expected maximum voltage drop during starting. Environmental requirements, such as noise level, also must be known.

The preceding discussion centered on the efficiency of the motor itself. The user has the additional responsibility of optimizing the overall system efficiency and his energy costs by means of a system analysis. This optimization includes motor losses, distribution cable losses, transformer losses, and utility charges based on system power factor. The system analysis will determine which of the following systems to use:

- high voltage distribution system with high voltage motor;
- low voltage distribution system with low voltage motor; or,
- high voltage distribution system with step down transformer and low voltage motors.

The decision should be based on energy costs as well as initial costs of motor, switchgear, and distribution cable costs.

Specifying high voltage for low power motors usually results in a motor which costs more and has a lower efficiency and decreased power factor. Logical horsepower and voltage relationships are shown in Table 11.5.

Voltage Class	Power	
200-600	Up through 500 hp	Up through 375 kW
2300-4000	300 through 5000 hp	225 kW through 3750 kW
6000-6900	1500 through 10,000 hp	1025 kW through 7500 kW
13-15 kV	3000 hp and up	2250 kW and up

TABLE 11.5

LOGICAL VOLTAGE AND MOTOR POWER RELATIONSHIPS

Because many of the steps which can be taken to improve motor efficiency also cause a decrease in power factor, it is worth noting that decreased power factor causes higher distribution losses. This occurs because the motor draws more electrical current despite the improved efficiency. An effective method of overcoming this is to install power factor correction capacitors as near the motor terminal as possible.

Warning: Improper sizing of power factor correction capacitors can result in extremely high voltages which are dangerous to personnel and equipment. Consult with your motor manufacturer to verify specific requirements.

An indirect effect on overall efficiency is the selection of motor space heaters. Two basic types of heaters are used: the cartridge heater and the belt heater. The cartridge heater mounts in the motor frame; the belt heater is wrapped around the stator coil end turns. The purpose of space heaters is to prevent moisture condensation on coils when the motor is not running. Because belt heaters apply the heat directly on the coils, they can operate on less power than cartridge heaters. In addition, because belt heaters operate at a lower power density, they usually have a longer life, comparable to the life of the motor winding.

In summary, the following important considerations should be reiterated:

- responsibility for the selection and utilization of premium efficiency motors rests with the motor user;
- motor selection should be based on life cycle costs and not on initial cost;
- closer liaison between manufacturer and user should be established; and,
- user specifications should be written for the particular application rather than for all motors in general.

3. Control Systems

Motor controllers are not power utilizing equipment, but only transmit and control power. For example, the losses in an across-the-line controller at full load are small compared to the total load.

While controllers themselves do not use much energy, their design and operating strategy can greatly affect the efficiency and life cycle costs of the motor/equipment/controller system. In the control of DC motors, for example, recent advances in solid state electronics have allowed efficient control of motors ranging from fractional to in excess of 100 hp by pulse-width modulation (PWM).[17] These systems, which include conventional transistors (low power applications), high current transistors (moderate power), and SCR units (high power), are a marked improvement over earlier control systems which, for example, simply routed a portion of the energy through a resistor bank to achieve speed control.

Motor controller choice is primarily governed by specific operational requirements and motor type. More modern solid state control systems and "intelligent" circuitry often offer both improved control and energy savings.[18] Microprocessors and minicomputers allow the control system and operating strategy of the motor to be merged into one efficient unit.[19] (Also see Chapter 5.)

11.4 MECHANICAL ENERGY TRANSFER

The ultimate need for electrical energy is dependent upon the efficiency of mechanical energy use once electromechanical conversion has taken place. The purpose of this section is to consider a few of the concepts related to the transfer of mechanical energy and the important factors affecting system efficiency.

An excellent review of mechanical drives is given in Reference [20]. The reader is directed to this source for detailed information on the types, characteristics, and operation of mechanical drive systems, bearings, and seals. Review of the information will provide guidance for deciding which type of mechanism would be the most efficient for the system being used.

The information presented here deals primarily with the efficiencies of a few examples of standard methods and mechanisms for transferring mechanical energy.

Table 11.6 shows the more commom mechanisms for transferring mechanical energy. Each of the mechanisms has an inherent efficiency and each is suited for certain types of operations. For example, for high precision speed control and ratio of drive rotation as used in precision threading, conventional or worm gearing is preferable to belts which can slip under certain load conditions. The following paragraphs briefly describe the important aspects of the efficiencies of a few typical mechanical energy transfer systems.

The approximate dollar sales breakdown of the product groups making up mechanical systems is shown in Figure 11.6. The dominant product group among components is mechanical drives; and nearly 50 percent of these drives are gear type.[21] Over the next ten years, industrial purchases of all mechanical drive components are expected to increase by $1 billion.[21] The single most important factor in future applications is expected to be the introduction of new materials, principally plastics, high strength metals, and powdered metal parts.[21] Improved design of mechanical energy transfer mechanisms utilizing new materials can have an effect on increasing the efficiency of systems. The Case Studies illustrate several examples of recent design improvements aimed at improving energy transfer efficiency.

A. Effect of Friction

Friction is the resistance to motion which takes place when one body is moved upon another.[22] The force of friction, F, bears--according to the conditions under which sliding occurs--a certain relation to the normal force between the sliding surfaces. The relation between force of friction and the normal force N is given by the "coefficient of friction":

$$\text{coefficient of friction} = \mu = F/N. \quad (11.3)$$

For well lubricated surfaces, the laws of friction are considerably different from those governing dry or poorly lubricated surfaces. If the surfaces are flooded with oil, the frictional resistance is almost independent of the pressure per unit area and the nature of the surface materials in contact.[22] For well lubricated surfaces, friction varies directly as the speed, at low pressures; but for high pressures friction is very great at low velocities, approaching a minimum at about 60 cm/sec (2 ft/sec) linear velocity, and afterwards increasing approximately as the square root of the speed.[22] With less lubrication the coefficient of friction becomes more dependent upon the material of the surfaces. Typically, coefficients of friction for various materials (sliding friction) range from 0.05 (continually greased smooth surfaces) to 0.56 (leather on dry metal).[22] Friction between machine parts lowers the efficiency of machine elements. Table 11.7 shows typical values of efficiency for common machine elements when carefully made.

When a body rolls on a surface, the force resisting the motion is termed "rolling friction". This has a different value from that of the ordinary, or sliding friction:

$$\text{Resistance to Rolling, newtons} = \frac{Wf}{r} \quad (11.4)$$

where W = total weight of rolling body or load on wheel, in newtons;

r = radius of wheel, in meters; and,

f = coefficient of rolling friction, meters.

The coefficient of rolling friction varies with the conditions. Typical values range from 0.5×10^{-3} m (iron on iron) to 5×10^{-3} m (iron on wood).

The value of an oil as a lubricant depends mainly upon its film-forming capacity; that is, its capability of maintaining a film of oil between the bearing surfaces. Film-forming capacity depends to a large extent on the

Adjustable Speed Drives:

- Gear drives
- Belt drives
- Chain drives
- Hydroviscous drives
- Variable-stroke drives
- Traction drives

Gears:

- Spur gears
- Helical gears
- Worm gears
- Bevel gears
- Celestial gears
- Combination of above

Chains:

- Bead chains
- Detachable chains
- Pintle and welded steel chains
- Offset sidebar chains
- Roller chains
- Double pitch chains
- Inverted tooth silent chains

Belts:

- Film belt
- Flat belt
- V-belt
- Synchronous drive belt

Mechanical Clutches:

- Positive clutches
- Friction clutches
- Overrunning clutches
- Overload clutches
- Centrifugal clutches

Electric Clutches:

- Friction clutches
- Tooth clutches
- Magnetic spring clutches
- Hysteresis clutches
- Magnetic-particle clutches
- Eddy-current clutches

Fluid Couplings:

Mechanical Brakes:

- Band brakes
- Drum brakes
- Disk brakes

Electric Brakes:

- Friction brakes
- Hysteresis brakes
- Eddy-current brakes
- Magnetic particle brakes

Couplings:

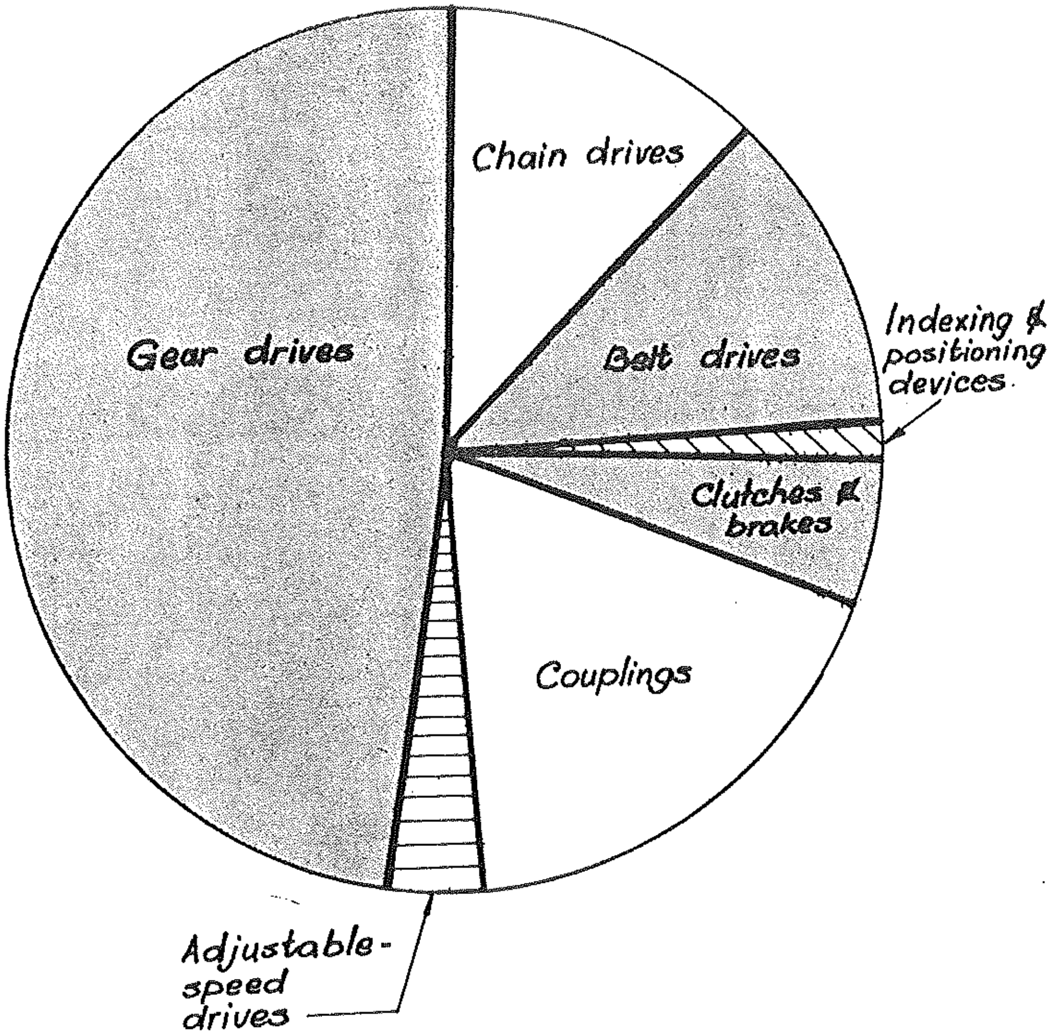
- Rigid couplings
- Flexible couplings

Universal Joints:

- Cardan joints
- Constant velocity joints

TABLE 11.6

MECHANICAL ENERGY TRANSFER MECHANISMS



Reference 21

FIGURE 11.6

INDUSTRIAL USE OF MECHANICAL COMPONENTS

Description	% Efficiency
Ordinary Bearings	95-98
Roller Bearings	98
Ball Bearings	99
Spur Gears with Cast Teeth, Including Bearings	93
Spur Gears with Cut Teeth, Including Bearings	96
Bevel Gears with Cast Teeth, Including Bearings	92
Bevel Gears with Cut Teeth, Including Bearings	95
Belting	96-98
High-class Silent Power Transmission Chain	97-99
Roller Chains	95-97

* Table generated from numbers given in text of Ref. [22]

TABLE 11.7

EFFICIENCY OF SMALL MACHINE ELEMENTS*

viscosity of the oil, but this should not be understood to mean that the oil of the highest viscosity is in every case the most suitable lubricant. An oil of the lowest viscosity which will retain an unbroken oil film between bearing surfaces is the most suitable for purposes of lubrication because a higher viscosity than that necessary to retain the oil film results in a waste of power, due to the expenditure of energy necessary to overcome the internal friction of the oil itself.

The use of bearings permits smooth low-friction movement between two surfaces. The movement can be either rotary (a shaft rotating within a mount) or linear (one surface moving along another).[21] Bearings can employ either a sliding or rolling action (governed by the laws of sliding and rolling friction, respectively). For both cases, a strong attempt is made to provide enough lubrication to separate the bearing surfaces by a film of lubricant. The long service lives of most bearings are attributable to the absense of contact provided by the lubrication.[21]

In order to provide additional protection under conditions of heavy shock or cyclic loading, as well as during periods of abnormally high temperatures, lubricant suppliers make use of both oil-soluble chemical additives and sub-micron sized particles of solid additives in suspension as lubricant supplements. These additive components are carefully selected to fit specific application requirements and to protect working surfaces when sudden shock loading may rupture the oil film or when extreme temperatures severely reduce oil film strength due to lowered oil viscosity. Such materials also serve to extend the useful service life of the lubricant. Effective lubrication reduces power losses in a mechanical system and the improved efficiency can appear as a measurable energy saving.

Effective lubrication deserves plant management consideration as an opportunity to save energy and improve the cost effectiveness of mechanical systems. Savings of 9 percent on energy usage have been reported with improved lubrication programs. (See the Case Studies.)

B. Flywheels

Flywheels may be classified as either balance wheels or flywheel pulleys. The object of all flywheels is to equalize energy exerted and work done over a cycle and thereby prevent excessive or sudden changes of speed. The permissible speed variation is an important factor in all flywheel designs. The allowable speed change varies considerably for different classes of machinery; for instance, it is about 1 or 2 percent for certain machinery, while in punching and shearing machinery a speed variation of 20 percent may be allowed.[22]

When a flywheel absorbs energy from a variable driving force, the velocity increases; when this stored energy is given out, the velocity diminishes. When the driven member of a machine encounters a variable resistance in performing its work--as when the punch of a punching machine is passing through a steel plate--the flywheel gives up energy while the punch is at work and, consequently, the speed of the flywheel is reduced. The total energy that a flywheel would give out if brought to a standstill is given by:[22]

$$E = \frac{mv^2}{2} = \frac{Wv^2}{2g} \qquad (11.5)$$

in which E = total energy of flywheel, joules;

W = weight of flywheel rim, newtons;

m = mass of flywheel rim, in kg;

v = velocity at mean radius of flywheel rim, m/sec; and,

g = acceleration due to gravity = 9.8 m/sec^2.

If the velocity of a flywheel changes, the energy it will absorb or give up is proportional to the difference between the squares of its initial (v_1) and final (v_2) speeds, and is equal to the difference between the energy which it would give out if brought to a full stop and that which is still stored in it at the reduced velocity.[22] Hence:

$$E_1 = \frac{Wv_1^2}{2g} - \frac{Wv_2^2}{2g} = \frac{W(v_1^2 - v_2^2)}{2g} \quad (11.6)$$

in which E_1 = energy in joules which a flywheel will give out while the speed is reduced from v_1 to v_2; other symbols are defined in equation (11.5)

The general method of designing a flywheel is to determine first the value of E_1 or the energy the flywheel must either supply or absorb for a given change in velocity which, in turn, varies for different classes of service. The mean diameter of the flywheel may be assumed, or it may be fixed within certain limits by the general design of the machine. Ordinarily the speed of the flywheel shaft is known, at least approximately; the values of v_1 and v_2 can then be determined, the latter depending upon the allowable percentage of speed variation. When these values are known, the weight of the rim and the cross-sectional area required to obtain this weight may be computed.[22]

C. Clutches

When the driving and driven members of a clutch are connected by the engagement of interlocking teeth or projecting lugs, the clutch is said to be "positive" in order to distinguish it from the type in which the power is transmitted by frictional contact fluids or magnetic fields.[22] A positive clutch is employed when a sudden starting action is not objectionable and when the inertia of the driven parts is relatively small. The various forms of positive clutches differ merely in the angle or shape of the engaging surfaces. The least positive form is one having planes of engagement which incline backward, with respect to the direction of motion. The tendency of such a clutch is to disengage under load, in which case it must be held in position by axial pressure. This pressure may be regulated to perform normal duty, permitting the clutch to slip and disengage when overloaded. Positive clutches, with the engaging planes parallel to the axis of rotation, are held together to obviate the tendency to jar out of engagement, but they provide no safety feature against overload. So-called "undercut" clutches engage more tightly as the loads become heavier and are designed to be disengaged only when free from load.[22]

When selecting a clutch for a given class of service, it is advisable to consider any overloads that may be encountered and base the power transmitting capacity of the clutch upon such overloads. When the load varies or is subject to frequent release or engagement, the clutch capacity should be greater than the actual amount of power transmitted. Design equations are tabulated in the literature.[22]

The approximate amount of power that a disk clutch will transmit may be determined from the following formula:

$$H = \mu RFnS \quad (11.7)$$

where H = power transmitted by the clutch, watts;

μ = coefficient of friction, dimensionless;

R = mean radius of engaging surfaces, meters;

F = axial force (spring pressure) holding disks in contact, newtons;

n = number of frictional surfaces; and,

S = Speed of shaft, hertz.

While the frictional coefficients used by clutch designers differ somewhat and depend on variable factors, typical values range from 0.1 (lubricated disk clutches) to 0.35 (metal and cork on dry metal).

Clutches of the electric type, like other electrical apparatus, are adapted to remote and automatic control. They are especially applicable for high-speed drives; for heavy duty (for use with motors that cannot start heavy loads); and for stopping machinery quickly, in which case a brake is used in combination with the other clutch. Clutches and brakes have similar operating principles: a brake is basically a clutch with one member held stationary.[21]

Electric clutches use two different operating principles. One class consists of clutches that are essentially mechanical but are electrically actuated (all of the friction and tooth-type electric clutches). The other class uses electrical forces to engage input and output without direct mechanical connection (hysteresis, eddy-current, and magnetic-particle clutches).

One type of the electrically actuated clutch, the Cutler-Hammer magnetic clutch, has a field or driving member and an armature or driven member.[22] Each of these parts is carried by a flexible spring steel plate so that when current passes through the winding of the field, the armature is attracted to it and the friction surfaces come into engagement. The turning power of the clutch depends entirely upon the friction surfaces which are held together by magnetic attraction. Current is conducted to the magnetizing winding of the field through two collector rings and graphite brushes. These clutches are operated by direct current. The ratings of two of the different sizes are given in Table 11.8 [22]

D. Worm Gearing

Primary considerations in industrial worm gearing are usually:

- to transmit power efficiently;
- to transmit power at a considerable reduction in velocity; and,
- to provide considerable "mechanical advantage" when a given applied force must overcome a comparatively high resisting force.

Worm gearing for use in such applications is usually a relatively coarse pitch.

Efficiency of worm gearing at a given speed depends on the worm lead angle, the workmanship, lubrication, and the general design of the transmission. When worm gearing consists of a hardened and ground worm running with an accurately hobbed wheel properly lubricated, the efficiency depends chiefly upon the lead angle and coefficient of friction between the worm and wheel. In the lower range of lead angles, the efficiency increases considerably as the lead angle increases. This increase in efficiency remains practically constant for lead angles between 30° and 45°. Handbooks provide equations for calculating gearing efficiency. Table 11.9 shows typical values.

Although not discussed herein, similar efficiency considerations apply to other elements of the power transmission chain, such as belts, flexible shafts, and other gear types (see Figure 11.1). Also see the Case Studies.

11.5 MATERIAL SHAPING AND FORMING

The shaping and forming of materials to produce commercial products is one of the main functions of industry. Some production processes have a considerable technological base; the metal working industries, woodworking industries, plastics, and chemicals are representative of these. Metal working processes have been chosen to illustrate energy use efficiency principles because they are widespread and also because the metals'cutting and forming processes have their counterparts in the processing of other materials, such as wood and plastics.

Metal production processes can be classified into four groups, having the following basic purposes:[23]

- processes used primarily to shape or form metals, such as casting, forging, extrusion, stamping, bending, and spinning;
- processes used for machining parts to specified dimensions, such as turning, planing, drilling, and milling, as well as those used primarily to produce a surface finish, such as polishing, tumbling, electroplating, honing, and shot blasting;
- heat treatment to change physical properties; and,
- processes used to join parts and materials, such as welding, soldering, riveting, screw fastening, and adhesive joining.

		Ratings Type H-30 Clutches			Ratings Type H-60 Clutches		
Nominal Size, Inches	Maximum Speed, rpm	Maximum Torque, Lbs. at 1 Ft. Radius	Safe hp at 100 rpm	Current Consumption, Watts	Maximum Torque, Lbs. at 1 Ft. Radius	Safe hp at 100 rpm	Current Consumption, Watts
10	2000	89	1.1	78	......	......	......
12	1680	154	2.0	93	......	......	......
14	1440	245	3.0	115	490	6	130
16	1260	366	4.5	133	732	9	160
20	1000	714	9.0	177	1,428	18	200
24	840	1233	15.5	260	2,466	31	247
28	725	1960	25.0	280	3,920	49	253
32	635	2920	37.0	315	5,840	74	250
40	500	5710	72.0	380	10,420	132	341
48	420	9860	124.0	460	19,720	250	400
60	340	......	......	......	38,600	485	645

Source; Cutler-Hammer Mfg. Co.

TABLE 11.8

MAGNETIC CLUTCH RATINGS

Coefficient of Friction	Lead Angle of Worm								
	5 Deg.	10 Deg.	15 Deg.	20 Deg.	25 Deg.	30 Deg.	35 Deg.	40 Deg.	45 Deg.
0.01	89.7	94.5	96.1	97.0	97.4	97.7	97.9	98.0	98.0
0.02	81.3	89.5	92.6	94.2	95.0	95.5	95.9	96.0	96.1
0.03	74.3	85.0	89.2	91.4	92.7	93.4	93.9	94.1	94.2
0.04	68.4	80.9	86.1	88.8	90.4	91.4	92.0	92.2	92.3
0.05	63.4	77.2	83.1	86.3	88.2	89.4	90.1	90.4	90.5
0.06	59.0	73.8	80.4	84.0	86.1	87.5	88.2	88.6	88.7
0.07	55.2	70.7	77.8	81.7	84.1	85.6	86.4	86.9	86.9
0.08	51.9	67.8	75.4	79.6	82.2	83.8	84.7	85.2	85.2
0.09	48.9	65.2	73.1	77.6	80.3	82.0	83.0	83.5	83.5
0.10	46.3	62.7	70.9	75.6	78.5	80.3	81.4	81.9	81.8

TABLE 11.9

EFFICIENCY OF WORM GEARING FOR DIFFERENT LEAD ANGLES AND FRICTIONAL COEFFICIENTS

The major metal production processes are listed in Table 11.10.

Forming processes are often done by specialized plants that produce semifinished shapes which serve as raw material for other plants where the finishing operations take place. Examples are steel and aluminum rolling mills, which produce various standard and nonstandard shapes such as angles, I-beams, and tubes. Foundry operations also are often specialized and produce rough castings to order according to specified shapes and dimensions. Other forming operations such as forging, drawing, bending, and shearing are more often integrated within a manufacturing plant which performs finishing operations.

In all machinery operations, metal is removed from the part in small chips by the cutting action of a tool. The cutting action is accomplished by either a rotating or reciprocating action of the tool relative to the part. In combination with this motion, either the tool or the work must "feed" to produce a continuous cutting action over an entire surface. Figure 11.7 shows a summary of tool and work piece motion for the main machine tools.[24]

The physical properties of the metal specified by the design engineer are not always consistent with the ability to process it; that is, the functional demands of the part may require a hard material which would be difficult or impossible to cut. Fortunately, by means of heat treatment, the physical properties of metal can be altered at almost any point during fabrication so that machining can take place while the metal is in the most machinable state, the final properties being produced at the time desired.

The joining of material is related to the fabrication of products. Some methods require the direct use of energy (e.g., welding) whereas others use a bond (fastener, glue). Energy needed for the various joining operations depends on the type of process and the quantity of material.

Power requirements for performing various metal cutting operations can be calculated from consideration of the cutting forces. For a lathe, for example, the power at the cutting tool is defined by equation (11.8):

$$P = F_t v \tag{11.8}$$

where P = power of the cutting tool, watts;

v = cutting speed, m/sec; and,

F_t = tangential cutting force component, newtons.

The radial cutting force does not contribute to the power. Although the feed force can be considerable in magnitude, feeding velocity is generally so low that the power required to feed the tool can be neglected.

Although some variations of tangential cutting force with respect to changes in speed may occur at low cutting speeds, the cutting force can be considered to be independent of cutting speed within the practical ranges of normally used cutting speed. The effect of feed and the depth of cut on the cutting force is illustrated in Figure 11.8.[25] The figure indicates that the cutting force is proportional to the feed and depth of cut, each raised to some power. Equations relating power requirements to the cutting rate (amount of material removed per unit time) are available in the literature.[25] Depending on the material, tool shape, and material hardness, the power per cutting rate is in the range of 4.7 to 94 W per cm^3/min (0.1 to 2.0 hp per in^3/min) when the materials range from aluminum to alloy steel.

Force and power predictions for multiple-point tools are more complex than those for a single-point tool. Varying numbers of teeth may be in contact with the work, the chip size can vary in different parts of the cut, and the orientation of the cutting teeth may not be constant with respect to the work piece. The best method to determine forces on such tools is by actual measurement on the machine to be used or on a simulated setup in a

Metal Forming

	Tolerance
Casting:	
Sand casting	1/32 in. (0.03 n.)
Permanent mold casting	0.0025 to 0.010
Die casting	0.002 to 0.010
Centrifugal casting	±1/64 in.
"Lost wax" precision casting	±0.2 %/in.
Continuous casting	
Power metallurgy	±0.001 in.
Hot Forming:	
Hot rolling	
Hot drop forging	
Press forging	+0.09/-0.03 in.
Extrusion	
Cold Forming:	
Cold rolling	
Roll forming	
Cold forming with presses (stamping)	
Gruerin process	
Spinning	

Metal Machining

Metal Cutting:	Metal Finishing:	
Turning	Grinding (fine)	Electric discharge
Boring	Tumbling	Electroarc
Grinding (coarse)	Shot blasting	Electrolytic
Milling	Polishing (buffing)	Laser cutting
Shaping	Honing	Chem-milling
Planing	Electroplating	Ultrasonic
Broaching		
Drilling		

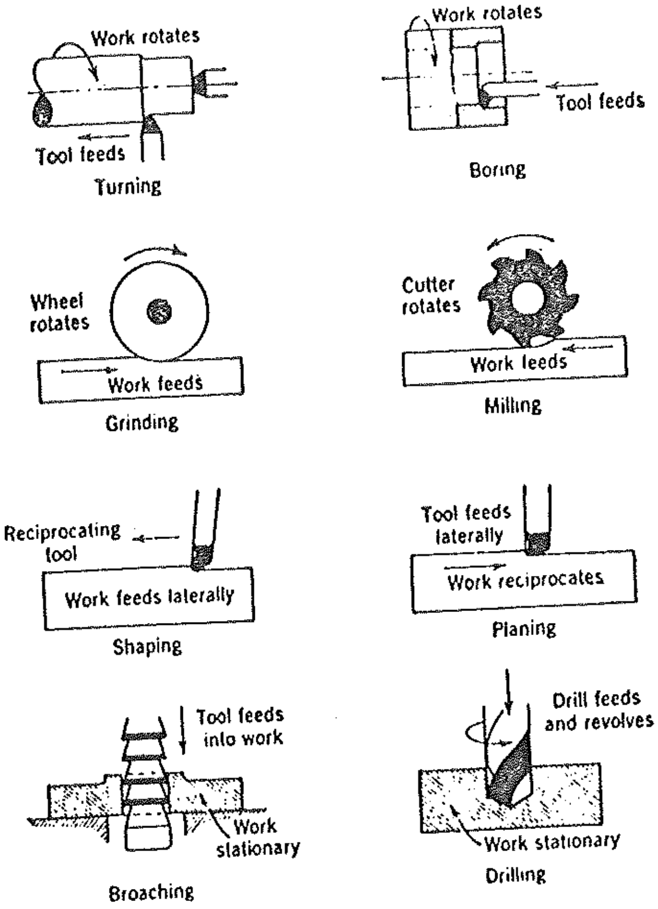
Heat Treatment

Hardening	Induction hardening
Tempering	Flame hardening
Case hardening	Annealing
Carburizing	Normalizing
Nitriding	Spheriodizing
Cyaniding	

Joining

Welding:	Fastening:	Adhesive Joining:
Acetylene torch	Riveting	Bonding
Heliarc	Screwing	Gluing
Brazing	Bolting	Tape
Soldering		

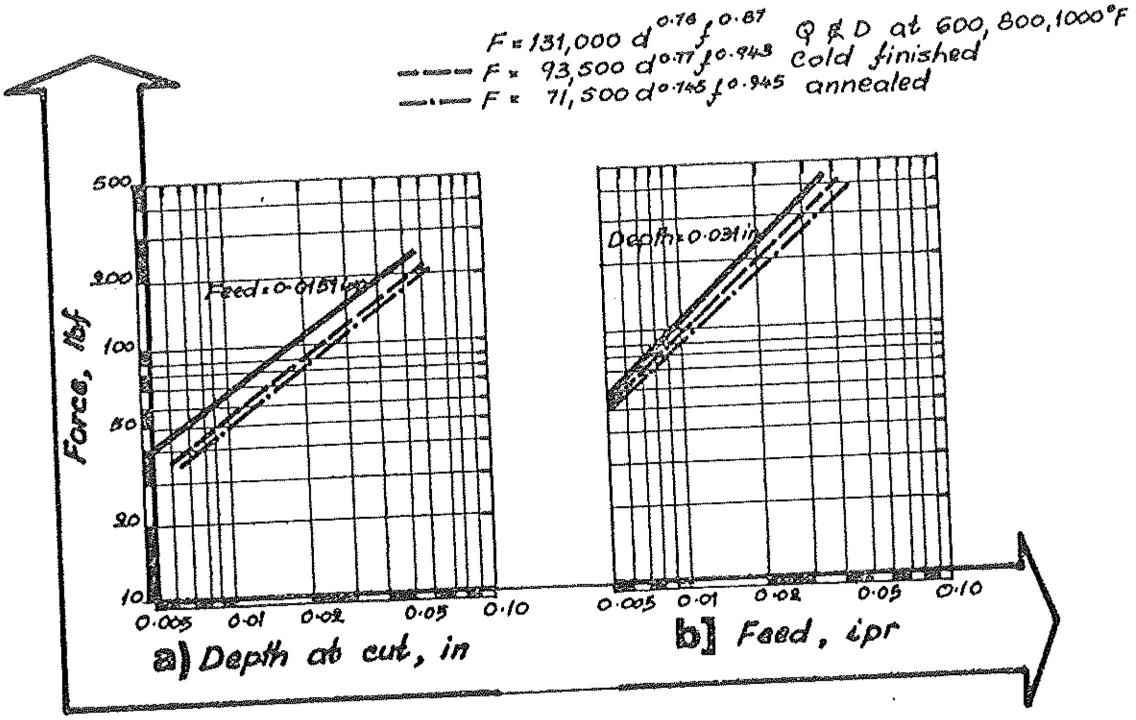
METAL PRODUCTION PROCESSES TABLE 11.10



Reference 24

MACHINING OPERATIONS

FIGURE 11.7



a) Cutting force vs depth of cut.

Tool material - HSS
Tool geometry, 6, 11, 6, 6, 6, 15, 0.01
Work material - SAE 1045 steel

b] Cutting force vs feed.

Depth - 0.031 inches
ipr - inches per reduction

Reference 25

FIGURE 11.8

EFFECT OF DEPTH AND FEED ON CUTTING FORCE metal-cutting laboratory. Since such measurements are sometimes impossible or inconvenient to make, methods for making reasonable force and power estimates may be of value.

One approach is to consider the multiple-point tool equivalent to a series of single-point tools, then estimate the contribution of each tool, and sum these to arrive at the resultant forces.[25] For rotary axial-feed tools, such as twist drills, core drills, and reamers, reasonably accurate estimates of forces and power can be made through the use of formulae developed experimentally and analytically by Shaw and Oxford.[26] In calculating power requirements using these methods, an allowance of at least 25 percent should be made for increases due to tool dulling, and further allowances should be made for the efficiency of the machine drive train.

The concepts discussed above must be applied with caution. If applied to the average rate of metal removal (rather than the maximum rate), they will indicate only average torque or average force, and this could be considerably below the peak forces in the case of intermittent cutting as might be encountered in milling or broaching. Furthermore, many of the equations presented in the references ignore the even higher peak forces resulting from impact or vibration during cutting.

Milling machines, like other machine tools, dissipate part of the input power. Some of the reasons are frictional losses, gear-train inefficiencies, spindle speeds that are too high for the particular machine, and mechanical condition. Consequently, the power for milling must include the machine power losses and the power actually used at the cutter. Efficient use of power at the cutter is influenced by cutter speed, design, and material, and by work piece material. [27]

The total power required at the cutter is given by equation (11.9):

$$P = \text{cmm}/K \qquad (11.9)$$

where P = power at the cutter, watts;

cmm = metal removal rate, cm^3 per second; and,

K = a factor reflecting the efficiency of the metal-cutting operation.

The K factor varies with type and hardness of material; for the same material it also varies with the feed per tooth, increasing as the chip thickness increases. Time consuming trials are required to determine the quantities involved, because in each case, the K factor represents a particular rate of metal removal and not a general or average rate. Typical values range from $K = 0.18 \times 10^{-3}\ \text{cm}^3/\text{J}$ for hard alloy steels, to $1.5 \times 10^{-3}\ \text{cm}^3/\text{J}$ for aluminum and magnesium.*

To make available a quick approximation of total power requirements and machine efficiencies, a milling machine selector table has been devised (see Table 11.11) which estimates the metal removed in cubic inches per minute for various machine and horsepower combinations operating under constant load conditions.[28]

Methods similar to those described above can be developed for other types of milling operations and for other material shaping and forming operations.[29,30] By comparing the power requirements for various operations, a manufacturer will be able to decide on the importance of the relative energy utilization of various processes. As energy costs increase, efficient energy use will have a greater influence on decisions related to process selection, particularly for high production processes.

Opportunities for Improved Energy Utilization

In the field of material shaping and forming, important energy savings can be obtained through better organization of production, standardization of products, and avoidance of over-specification of material quality.

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*In American usage cmm (equation 11.9) is expressed in cubic inches per minute, P in hp, and K has units of $\text{in}^3/\text{min hp}$. Representative values for K are 0.05 (alloy steels) and 4.0 (aluminum and magnesium).

Rated hp of machine	3	5	7.5	10	15	20	25	30	40	50
Overall machine efficiency, percent	40	48	52	52	52	60	65	70	75	80
Material	Max metal removal (cu in/min)									
Aluminum	2.7	5.5	8.7	12	18	27	37	48	69	91
Brass, soft	2.4	4.7	7.5	10	16	24	32	41	60	79
Bronze, hard	1.7	3.3	5.3	7.3	11	17	23	30	43	56
Bronze, very hard	0.78	1.6	2.5	3.4	5.3	7.8	11	15	20	26
Cast iron, soft	1.6	3.2	5.2	7.1	11	16	22	28	41	54
Cast iron, hard	1	2	3.3	4.6	7	10	14	18	26	35
Cast iron, chilled	0.78	1.6	2.5	3.4	5.3	7.8	10	13	19	26
Malleable iron	1	2.1	3.4	4.7	7.3	11	14	18	26	36
Steel, soft	1	2	3.3	4.6	7	10	14	18	26	35
Steel, medium	0.78	1.6	2.5	3.4	5.3	7.8	10	13	19	26
Steel, hard	0.56	1.1	1.8	2.5	3.9	5.7	7.7	10	14	19

Reference 28

MILLING MACHINE SELECTION

TABLE 11.11

These savings can be obtained without technical research or development effort.

Inasmuch as material shaping processes absorb an appreciable portion of total energy use in industrialized countries, shaped products should be made to last longer. Life can often be prolonged with negligible extra energy outlay by improving the quality of the material, e.g., by protection against corrosion and wear.[31] (See Chapter 12.)

The primary material processes for conversion of metal ores into the semi-finished materials which constitute the starting point for the shaping processes use as much and frequently even more energy than the latter. Furthermore, shaping is mostly a multi-stage operation, much of it carried out at elevated temperatures, involving repeated intermediate reheating and final heat treatments. Heating uses several times more energy than shaping operations. Additional energy is required in ancillary treatments., e.g., pickling and coating. These facts lead to the following general conclusions about achieving energy economies.[30]

- As far as practicable, replace shaping processes having a low metal yield--i.e., those processes whose end products contain only a small fraction of the metal used--(e.g., machining) by high yield processes, notably casting and plastic forming (e.g., extrusion, spinning). Use fabrication extensively as a means of producing complex shapes.
- Favor processes in which the final shape is achieved in the least number of intermediate stages, e.g., casting, extrusion, powder compacting.
- Favor shaping at lower temperature, even though the mechanical forces required are greater in this case. Where appropriate, electroforming should be developed further.
- Develop scrap recycling processes which bypass the primary stage, e.g., direct compaction of turnings into reinforcing bar.

Much energy is lost between the points of input into the machine and application to the material which is being shaped. For example, in machining a transmission or coupling, efficiency of less than 50 percent is common. There is room for considerable improvement by engineering of more efficient shaping machinery, and even more readily by appropriate operating practices and adequate machine maintenance.

The utilization of shaping machinery is generally low, and energy is wasted by idling. The most obvious way of reducing idling losses is by employing continuous processes. Not all the technology is available; however, even where it is applied, there is room for further development, e.g., in continuous casting of tubular and other slender shapes.

The potential of casting needs to be explored further with the aim of achieving greater complexity of slender shapes in the more "difficult" metals, coupled with the right mechanical properties of the finished product. Powder technology is probably the most promising of the shaping processes with reference to future energy economy.

Processes which use high pressures to force cold metal through or against dies have a triple energy savings in that heating the material is not required, energy is not spent in cutting or removing the material, and less energy intensive material is used. Reference [32] reports a high-pressure process that cut electricity usage 93 percent in the manufacture of coaxial cable connectors (compared to machining), 87.5 percent in production of pinion rods, 60 percent in hollow cathodes, and 50 percent in plumbing equipment.

Conventional heating and heat treatment processes are known to be very inefficient. Processes generating heat *in situ* require further development, e.g., induction heating of conducting materials and perhaps microwave heating of nonconducting materials (see also Chapter 10). Development efforts should concentrate on cheaper sources of energy for these processes (e.g., low vs high frequency, chemical maser, and induction coils operating in the superconducting state).[31]

Where multistage (or even single step) operations are unavoidable, possibilities for recovery of the energy lost by cooling should be considered. In cutting and welding there are opportunities for energy economy by the use of more concentrated heat generation (e.g., by electron beam and laser), but at present the cost is prohibitive. Hence, research and development should be devoted to the cost reduction of these systems. Also, in view of the production and transmission inefficiencies of electricity, non-electrical methods (e.g., chemical maser, thermite welding) and cold methods (gluing) should be developed.

11.6 MATERIAL TRANSPORT

The transport of material and products within industrial facilities presents special requirements for electrical energy use. Material transport as discussed in this section is to be differentiated from material transport between facilities or over long distances (as discussed in Chapter 5).

The most common method of transporting material within industrial facilities is by means of conveying machinery. Conveyors are devices for moving material from one point to another at the same or at a different elevation. In intermittent conveying, the material is moved in a succession of separate loads; in continuous conveying, the material is delivered in a steady stream.

In the transportation of package material in industrial plants, freight houses, stations, etc. electric baggage, freight, and fork-lift trucks are used extensively. Storage-battery trucks with lifting platforms are built in two types: a low-lift truck that lifts $\sim$10 cm ($\sim$4 in.) and a high-lift truck that lifts the platform up to a height of 2.4 m (8 ft). The low-lift is a single-purpose truck used in factories and warehouses where material can be stored on skid platforms and transported on the platforms by truck between manufacturing processes and to and from cars. The high-lift truck is a general purpose truck used to convey skid platforms; in addition, the high-lift feature is used for piling cases, barrels, and similar packages in warehouses, lifting the loads from ground level to autotrucks, and to car level. Lift trucks are recommended for hauls up to 360 m (1200 ft) and are built from 1 to 10 mt capacity. Trucks of 2 and 3 mt capacity are generally recommended.

Electric tractors and trailers are recommended for hauls from 100 to 450 m (350 to 1500 ft) when more material must be moved per trip than is possible with lift trucks. The trailer load for an electric tractor is 10 to 20 mt.

Overhead trackage is another means of conveying material. Light rigid trackage consists of tracks of various forms suspended from overhead structures for carrying trolleys to which loads are attached by hooks or chain blocks. The four main types of track are the bar type, the Coburn type, the single I-beam, and the double I-beam. The first two types can accommodate loads up to $\sim$2 mt. The single I-beam is suitable for loads in the range of 1 to 10 mt; the double, in the range of 10 to 20 mt. The trolleys may be moved either by hand or by chain wheel, or a series of trolleys may be attached at suitable intervals to an endless power driven chain (which is called a trolley conveyor). A trolley conveyor may run through several rooms or departments of a factory and up and down between floors. Hooks, trays, or baskets attached to each trolley provide means for carrying the loads. They have their widest application in carrying parts between machines that perform succeeding operations in the manufacture of finished parts and delivering them to the parts storeroom or assembly floor.

Monorails are a form of electric hoist which not only lift the load but transport it along an overhead track from one portion of a plant to another; the operator rides with the machine and controls all movements. Monorails are used to handle any materials that may be suspended from a hook either as units or in quantities in boxes or tubs.

Cableways are aerial hoisting and conveying devices using suspended steel cable for track, the loads being suspended from carriages and moved by gravity or power. The maximum clear span is 600 to 900 m (2000 to 3000 ft). The gravity type is limited to conditions where at least a 20 percent grade is obtainable on the track cable.

Screw or spiral conveyors are used for horizontally conveying dry nonabrasive materials, such as grain, flour, seeds, cement, and fine coal, and also for sand, gravel, fine ashes, etc., although the wear from sand, gravel and ashes is rapid and maintenance costs may be very high. The maximum length when handling grain or light pulverized material is 120 to 150 m (400 to 500 ft), for more abrasive materials, 30 to 45 m (100 to 150 ft). These conveyors may be used as feeders in single sections, on inclines up to 15°.

The power required to drive a typical screw conveyor is given by:[10]

$$P = KCWL/2 \times 10^6 \qquad (11.10)$$

where P = power, hp;
C = capacity, ft^3/hr;
W = weight of material, lb/ft^3;
L = length, ft; and,
K = material constant (1.2 for grain, 2.5 for coal and cement, 4.0 for sand, gravel, and ashes).

Another category of continuous conveyor is the chain conveyor type, including scraper conveyors, apron conveyors, and open top carriers. For these, the power required can be calculated using empirical relations given in the literature.[10] In general the power needed depends on weight, length of the conveyor, speed, and the material being transported. Similar approaches are used to determine power requirements for V-bracket and pivoted-bucket carriers.[10]

If the conveyor is composed of portions on different inclines, the various portions should be considered independently and the results added. Ten percent additional power should be added for each change in direction.

Belt conveyors are used for transporting bulk material in large quantities and will handle practically anything that can be properly fed to the conveyor provided that it will not adhere strongly to, or burn, the belt. The advantages of the belt conveyor are: large capacity (10,000 mt/hr of material can be carried), low power requirement, and low attendance and maintenance costs.

From the standpoint of the application of power to the belt, a conveyor is identical to a power belt; the determining factors are the coefficient of friction between the driver pulley and the belt, tension in the belt, and arc of contact between the pulley and belt.

Electric vibrating feeders are in wide use in industry. They often operate magnetically with a large number of short strokes. They are built to feed from a few kg/min to 1000 mt/hr and will handle any material that does not adhere to the vibrating pan. Other types of feeders in general use are short, slow-moving, belt- and apron-conveyors.

Another type of conveyor is the gravity roller conveyor. The principle involved in the gravity roller conveyor is the control of motion due to gravity by interposing an antifriction trackage set at a definite grade. It finds application in the movement of various types of package goods having a smooth surface sufficiently rigid to prevent sagging between rollers. The rollers vary in diameter and strength from $\sim$2 cm with a capacity of 20 N per roller up to 10 cm with a capacity of 8000 N per roller. Spacing of the rollers in the frames varies with size and weight of the object to be moved. Three rollers should be in contact with the package to prevent hobbling. The grade of fall required to move the object varies from 1-1/2 to 7 percent, depending on the weight and character of the material in contact with the rollers.

Pneumatic conveyors are used for handling: (1) material in bulk such as pulverized coal, grain, wood waste; (2) dust from grinding wheels, sand-blast equipment, and other industrial processes; and (3) ashes in boiler plants. They are also used for handling small packages by placing the material in containers that fit the carrying tube and act as pistons. Pneumatic conveyors for bulk materials may be blower type, exhaust or suction type, or a combination of exhaust and blower type. The majority of installations are probably of the latter type; the material entering under suction passes through the fan and is blown to its destination, the escape of air being accomplished through a dust collector.

For pneumatic conveyors, all pipes should be as straight and short as possible and bends, if necessary, should have a radius of at least three diameters of the pipe. Pipes should be proportioned to keep down friction losses yet maintain air velocities that will prevent material settling. Sudden changes in diameter should be avoided to prevent eddy losses.

Selection of the best material transport mechanism to use for a particular operation should depend on the type of product and the volume of material which must be moved per unit time. The physical limitations of the facility as well as the need for continuous versus batch type processing will affect the final selection. Total energy use for each candidate transport method could affect the final selection. In fact, energy utilization considerations may even affect the decision to use a batch or continuous process.

Efficiency Improvement Opportunities

Several obvious courses of action can provide an improvement in the electrical energy utilization efficiency of material transport systems. They include the following:

- Survey all possible alternative transport system equipment to determine the most suitable for the specific needs of the facility and product operation.
- Determine energy requirements for the operation of the system and factor this quantity into the selection decision.
- Investigate the energy requirement trade-off for intermittent versus continual material movement.
- Use proven design methods and engineering formulations in sizing and constructing material transport mechanisms.
- During operation, do not overload the transport mechanism to cause overworking of the drive motor.
- Provide for regular maintenance and lubrication of all moving equipment parts to keep unnecessary friction to a minimum.
- Make random checks to ensure that equipment is being used at near maximum utilization. Investigate the possibility that transfer equipment can be run for shorter periods of time and during non-peak work times.
- Turn off conveyors, lift trucks, etc. when not in use.
- Recharge batteries on material handling equipment during off-peak demand periods.
- Adjust and maintain fork lift trucks for most efficient operation.
- Use gravity feeds wherever possible.

11.7 POTENTIAL ENERGY SAVINGS

As indicated in Table 11.1, energy used by electrical prime movers for the residential and commercial sectors is significant. The numbers shown in the the table illustrate that 2814×10^6 GJe out of a total of 4381×10^6 GJe (64 percent) for combined residential, commercial, and industrial use is required for electric motors. Extrapolating this number to include transportation and other uses as well, a reasonable assumption is that electric motors require more than 65 percent of the total electrical energy used. Thus, relatively small changes in efficiency potentially can accrue to significant energy savings.

The estimated savings which may be effected are classified as:

- *Intermediate--2 to 5 percent*

  Operational changes for motor use and scheduling, improved maintenance practices, reduced overloading of motors.

- *Near-Term--5 to 10 percent*

  Replacement of multiple small motor applications to improve cooling, replacment of old motors with newer more efficient motors.

- *Long-Term--5 to 10 percent*

  Introduction on market of premium efficiency motors, increased use of new materials, super-conducting motor applications for large engines.

The estimated annual savings (year 2000) due to increased efficiency is 12 to 25 percent. Using the projected year 2000 US energy use for electricity generation of 105 x 10^9 GJ/yr (see Chapter 1), assuming 50 percent is used by electric drives, and applying the potential range of savings (12 to 25 percent), the fuel savings can be calculated as:

$$(105 \times 10^9 \text{ GJ/yr})(50\%)(12\text{-}25\%) = 6.3 - 13 \times 10^9 \text{ GJ/yr}.$$

Since a 1000 MWe power plant operating with a 60 percent capacity factor requires 5.7×10^7 GJ/yr, this saving is equivalent to the energy use of 110-220 power plants.

In round numbers, improved efficiency in electric drives could eliminate the need for 100 to 200 1000 MWe power plants by the year 2000. This large potential saving warrants a significant expenditure of research funds to improve the efficiency of electric motors and motor driven systems.

* * *

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