ENERGY EFFICIENT DESIGN: TOOLS, TECHNIQUES AND APPLICATIONS TO THE PETROLEUM AND CHEMICAL INDUSTRY

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Abstract - Almost 56% of the total primary energy used (about 100 Quads in 2010) in USA is wasted. 40% of the total energy is used to generate electricity with an overall efficiency of about 32% (or 1/3rd). The transportation sector uses about 27% (1/4th) with an overall efficiency of 25%. The industrial/ commercial sector uses 47% with an overall efficiency of 55%. Energy Efficiency has been a topic of great interest in the Petroleum and Chemical Industry (PCI) since 7-8% of all electricity generated in the US is used by the PCI. This paper discusses recent advancements and best practices in energy efficiency techniques and the impact of new legislation on energy efficiency. It also addresses economic considerations and provides some application guidelines.

Index Terms - Energy Efficiency, Energy Legislation, Energy Sustainability, Energy Conservation, Variable Frequency Drives, Energy Efficient Lighting

I. INTRODUCTION

In order to have a better understanding of energy efficiency, it is essential to have a clearer picture of the relevant problems and definitions. There are two very important distinctions to be made between energy efficiency and energy conservation and between energy and power efficiency.

Energy conservation is frequently confused with energy efficiency. Energy efficiency may be achieved by keeping the net energy output (total work) of a system constant while reducing the energy input. Energy conservation, on the other hand, refers to lowering the total energy input without necessarily keeping the energy output the same.

The word “efficiency” as commonly used with reference to electric devices like motors and transformers typically refers to the power rather than the energy used. Energy consumed by a device is the total amount of power integrated over time. This can be easily understood from the following illustrations. Figure 1 depicts a typical efficiency curve of a motor or transformer. The efficiency number is defined at discrete points like half-load, full-load or 20% over-load, etc. Figure 2 shows load cycle for the same device over several daily load cycles. The energy consumption is given by the area underneath the curve, the integral of the power over the time it is supplied. The input energy will depend on the variable (power) efficiency values during the load cycle. Differing load cycles each day will cause the device to consume daily different amounts of energy. As a simple example, a motor 100HP (74.6kW full-load output) motor may have an efficiency of 94% at full-load and 93% at half-load. If the machine is delivering full-load for 24hrs./day, the machine energy efficiency over that period of time is 94%. However, if the same machine is running at half-load for 12 hours per day and full-load for the remaining 12 hours, the resulting energy efficiency is now only 93.5%. If the same motor is running at no-load for the entire day while doing no actual work, the resulting energy efficiency is now 0%.

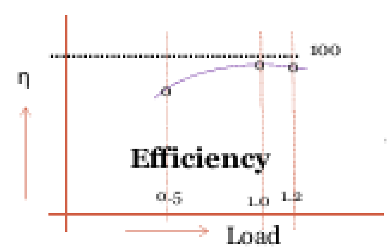

Figure 1: Typical power efficiency curve.

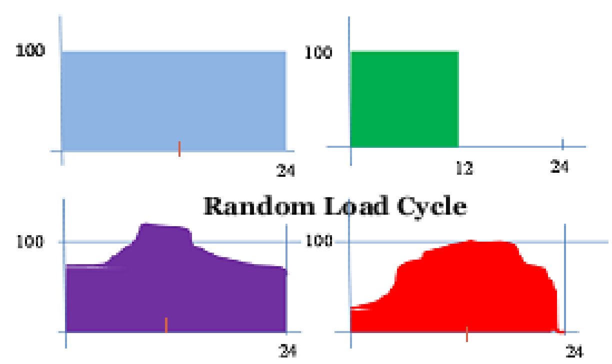

Figure 2: Random daily load cycle.

The same principle could be extended to analyze an entire industrial plant. This paper addresses both the energy and power efficiency of various common devices and how they should be applied.

II. ENERGY LEGISLATION AND EFFICIENCY

Electric energy has been a subject of federal and state legislations since the Public Utility Holding Company Act (PUHCA) of 1935 first regulated electric utilities. Recent trends in legislation include regulations addressing renewable energy portfolios, climate change and greenhouse gases, smart[er] grid activities, and overall economic growth. All of these directly or indirectly impact the need for greater energy efficiency. Some legislation has also directly mandated certain (power) efficiency standards.

Other global concerns have driven an interest in energy efficiency. Political unrest, especially in petroleum rich countries, has prompted an interest in saving energy in energy dependent countries with high energy costs. High unemployment and the overall economic malaise have prompted individual energy users to take a closer look at their own energy usage.

Since the PUHCA Act of 1935 other notable legislations that relate directly to energy usage and efficiency include: The Public Utility Policy Regulatory Act (PURPA) of 1978 enacted right after the oil embargo of the mid 70's; the (1st) Energy Policy Act of 1992 (EPAct) which created higher energy (power) efficiency standards for electric motors for the first time [1]; the (2nd) Energy Policy Act of 2005 which required that higher efficiency motors be purchased for all federal projects and provided tax incentives for improving lighting efficiency [2]; the Energy Independence and Security Act of 2007 (EISA) that abolished many standard efficiency motor types and mandated the use of premium efficiency motors while also setting new higher efficiency standards for general purpose motors through 500 horsepower [3]. EISA also set new efficiency standards for appliances, lighting, and banned incandescent lighting.

The Energy Improvement and Extension Act of 2008 (EIEA) indirectly addressed efficiency when it provided tax credits for the elimination of CO_2 [4]. The American Recovery and Reinvestment Act of 2009 (ARRA) provided energy efficiency block grants that could be used by communities to develop their own energy efficiency standards [5]. It also required the use of energy efficient street and traffic lighting. Furthermore it provided energy efficiency programs for government buildings and provided funding for energy efficient appliance rebates and the ENERGY STAR program. It is clear that when the content of these laws are dissected the term "energy efficiency" as used in most cases actually refers power rather than energy efficiency; however, if done correctly overall energy efficiency should also be increased by increasing the power efficiency of the devices mandated in the bills.

It is important at this point to review the "big" picture [12]. In 2010, USA used approximately 100 Quads (10^{15} BTU or 293 trillion kWh) of primary energy with an overall energy efficiency of 44%. 40 Quads (or 40% of the total of the total primary energy) was used to produce electricity with overall energy efficiency for electricity production of 32%. In other word, we had about 12.7 Quads of real work done by electrical devices. Residential loads used 39% of electricity produced, 35% was used by commercial loads and 26% by industrial loads. An insignificant amount of electricity has been used by the transportation sector thus far in USA. These results are depicted in the Figure 3.

In 2010 total amount of installed electrical capacity in USA was approximately 1.0TW (or 1,000,000 MW) and total amount of electrical energy production was about 4, 200TWh with an overall Capacity Factor of about 46%. It is noteworthy that in the past 3-4 years, the growth rate of both installed capacity and energy production has slowed down becoming zero, or even negative, due to poor economic conditions, higher energy prices and perhaps energy conservation.

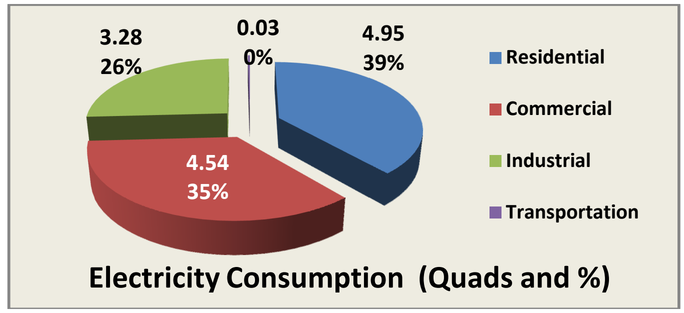

Figure 3: Electricity consumption breakdown.

In recent years, the growth in installed electrical capacity has mainly come from wind and solar installations. The total contribution of electricity production by the non-hydroelectric renewable energy sources is still very small (less than 4.5%).

Figure 4 provides a snapshot of the global electrical picture. It is important to observe that USA, with less than 4.5% of population, is consuming about 20% of the total electricity and has about 20% of the total installed capacity (MW).

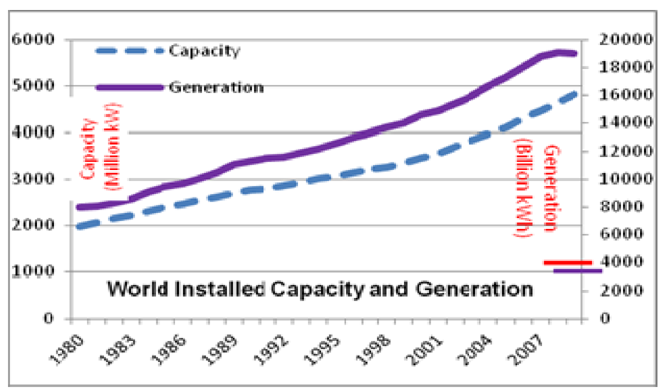

Figure 4: World installed capacity an generation (taken from EIA International Energy Statistics)

III. MOTOR AND TRANSFORMER EFFICIENCY

Motors and transformers are the two most commonly used devices in electric power industry. The federally mandated motor and transformer efficiency changes are of great interest to the Petroleum and Chemical Industries. It is estimated that over 65% of all electric energy used in industry is used by motors, which may range in size from small fractional horsepower (FHP) motors to those exceeding 30,000HP. **Error! Reference source not found.** is an approximate depiction of how motors are used in industry.

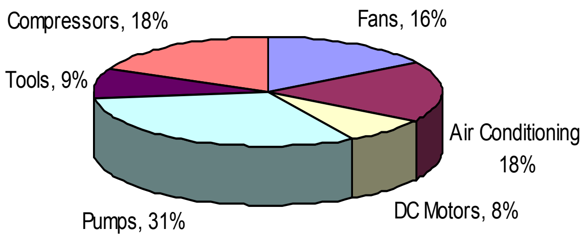

Figure 5: How motors are used.

Since a lot of energy is used in motors, any power efficiency change can make a substantial change in the amount of energy used. **Error! Reference source not found.** shows a comparison of how motor power efficiencies have increased due to federal legislation since the passing of EPAct 1992. The motors included in this table are all of low-voltage (480V) design and the efficiencies are all at full-load. Motors larger than those shown in **Error! Reference source not found.**, from 201-500HP are also required by EISA 2007 to have efficiency increases.

To determine the energy efficiency improvement and actual saving in electricity available from power efficiency improvements, a simple calculation can be performed. If the motor full load, percent of full load and the corresponding efficiency at which it is running is known, and the hours it runs at that load, then the energy losses during that time period may be found using Equation (1).

$$E_{Loss} = 0.746 \left(\frac{1}{\eta} - 1 \right) P_o L_R H \qquad \text{Equation (1)}$$

Where:
E_{Loss} = Energy loss during time H (hr.) in kWh
η = Efficiency at the running load
P_o = Rated motor power output in HP
L_R = Per-unit of the motor rated HP being used
H = Running time in hours at the load L_R

Using Equation (1), if a 50 HP motor is running at approximately 80% of its rated load for the entire year, and its efficiency at 80% rated load is 91.3%, then the annual energy lost by the motor would be:

$$E_{Loss} = 0.746 \left(\frac{1}{0.913} - 1 \right)(50)(0.8)8,760 = 24,908 \text{ kWh}$$

Table 2 shows the energy loss values for three motors running at 80% loading and energy savings that would be expected due to the efficiency improvements from pre-EPAct 1992 to the present.

All of these mandated efficiency increases should result in a decrease in energy usage by industry, however, there are a number of hidden costs associated with this plan. One side effect of increasing a motor's efficiency is that in doing so its physical size may also be increased. This is due to the fact that more steel and/or copper is needed in the motor to reduce core and winding losses. This may require modifications to the driven equipment when existing standard efficiency motors are replaced with premium efficiency motors. All these additional costs must be included in any detailed economic analysis done to determine the payback period of replacing older motors with higher efficiency motors.

Table 1: Motor efficiencies as a result of legislation

IV. Size HP	V. Pre EPAct 1992 %Efficiency	EPAct 1992 %Efficiency	Premium Efficiency (EISA 2007) %Efficiency
1	76.7	82.5	85.5
1.5	79.1	84	86.5
2	80.8	84	86.5
3	81.4	87.5	89.5
5	83.3	87.5	89.5
7.5	85.5	89.5	91.7
10	85.7	89.5	91.7
15	86.6	91	92.4
20	88.5	91	93
25	89.3	92.4	93.6
30	89.6	92.4	93.6
40	90.2	93	94.1
50	91.3	93	94.5
60	91.8	93.6	95
75	91.7	94.1	95.4
100	92.3	94.5	95.4
125	92.2	94.5	95.4
150	93	95	95.8
200	93.5	95	96.2

Table 2: Annual energy loss for motors at 80% loading with the efficiencies shown in Table 1

HP	Pre-EPAct 1992	EPAct 1992	Premium Efficiency EISA 2007	Annual Energy Savings
	kWh	kWh	kWh	kWh
50	24,908.7	19,675.1	15,213.7	9,625
100	43,613.6	30,427.3	25,208.2	18,405
200	72,688.3	55,031.2	41,302,0	31,386

Another electrical machine commonly found in industrial plants is the transformer. Unlike motors which seldom run long at no load, transformers are always energized regardless of loading and may be operated at no-load (or at very light load) for considerable periods of time. As a result transformer losses can be responsible for up to 40% of the distribution (energy) losses in an electrical system. There are two types of losses in a transformer: no load losses caused by hysteresis and eddy currents in the magnetic core, and load losses mainly consisting of I^2R copper losses in the windings.

No-load losses can be improved by the use of more advanced types of high-grade core steel and thinner laminations. If large numbers of small lightly loaded transformers are used in a power system, considerable energy can be saved by employing advanced core steels to increase energy efficiency. Load losses can be decreased by increasing wire sizes used in the windings. If transformers are heavily loaded the load losses may be greater than the no-load losses and purchasing transformers with low load losses can save energy in a plant distribution system. The load profile that a transformer will undergo in use should be taken into account when procuring transformer so the expected energy losses can be minimized.

It is estimated that premium energy transformers may save up to 30% in a distribution system's transformer energy losses. DOE efficiency regulations for low-voltage dry-type distributions went into effect in 2007 and liquid-immersed and medium voltage transformers in 2010. Recently, regulations amending these regulations will go into effect in 2016.

VI. ADJUSTABLE SPEED DRIVES

While not necessarily increasing the efficiency of the motor, the use of an adjustable speed drive (ASD) or variable frequency drive (VFD) can substantially increase the energy efficiency of the overall process in which a motor is used.

Changing a standard constant speed motor drive to one whose speed can be varied can save energy in a process where the motor is not operated at 100% load at all times. Any process that is controlled by valves and dampers can have its energy usage improved by the application of an ASD. This potential has been recognized by the petroleum and chemical industry for long time and it has taken the lead in developing these applications since the 1970's long before the advances in modern day power electronics.

Cooling tower fans often operate for long periods of time partly loaded. Some chillers and compressors run at a constant speed and use valves to restrict flow. Industrial blowers often use dampers or variable pitch sheaves to control flow. In all such applications, it may be advantageous to replace the low-efficiency flow reducing method used with an ASD which will control flow by reducing motor speed.

Variable torque loads such as fans and pumps have the highest potential for energy reduction using ASDs. Constant torque loads such as conveyors, crushers, agitators, winders, and some pumps and air compressors also have potential for energy savings by utilizing ASDs by improving workflow and show energy savings if one were to benchmark kWh per widget produced. Constant power loads such as center winders and machine tools have little potential for energy improvements by varying their speed.

To understand how an ASD may save energy the operating curves of a pump and the system it is installed in will be used [6]. An example of these two curves is shown in Figure 6.

The pump will operate along the pump line and the system will operate along the system line. The operating point will be the point where the two curves intersect, in this case at about 5,500 gallons per minute (gpm) and a head of about 2,500 ft. If the system flow rate is reduced to (say) 4,000 gpm using a valve, the pump head increases to 3,200 ft. while the system only needs about 1,800 ft. The difference between the head on these two curves represents the amount of energy that could be saved if the pump speed was decreased to reduce the flow rate instead of reducing the flow rate by using a valve. The reduction in pump speed would reduce the head produced by the pump at this flow rate which would reduce the energy needed by the motor driving the pump as shown in Figure 7. When properly applied, this could result in a very substantial energy savings with a payback period as low as 2-3 years in many cases.

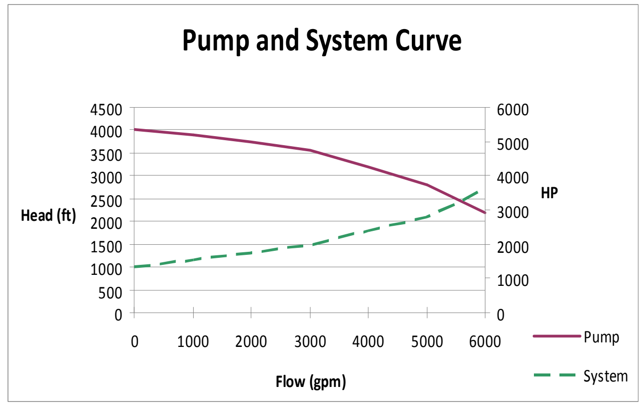

Figure 6: Typical pump and system curve.

Unfortunately ASDs are sometimes misapplied to systems where the industrial process does not permit the reduction of speed of the motor or where a simple reduction in speed results in little energy savings. In these cases no energy savings is realized with the installation of an ASD and the added cost could have been avoided as well as the added energy losses from the ASD (approx. 2%).

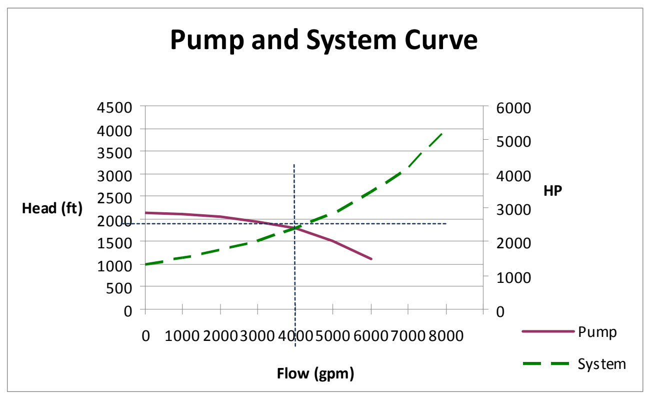

Figure 7: Pump operating curve after reduction in pump speed.

VII. COGENERATION

The overall energy efficiency of an industrial plant may be improved not only on the demand side, but also on the supply side. By installing a power plant in an industrial facility, all or part of a plant's electrical usage may be supplied on-site while at the same time supplying necessary process heat. If a cogeneration (combined heat and power or CHP) plant is used, the overall efficiency of this type of installation may approach 90% compared to an efficiency of 32% for electricity generation alone using steam turbine. This is far higher efficiency than is achievable by either direct electrical production by the electrical utility supplying the plant or the direct production of steam or heat using a boiler.

A combined heat and power plant is an electrical production facility using a prime mover and fuel type that produces waste heat. This waste heat is then used for the manufacturing process either directly as heat or as cooling using an absorption chiller [7].

The possible uses of this waste heat will depend upon the temperature and amount of heat produced by the power plant and the type of process used in production. Temperatures between 30-50°C can be used for water and space heating. Temperatures between 80°-100°C may be used for space heating and/or absorption air conditioning and temperatures above 100°C can be used for industrial processes.

Many types of power plants lend themselves to use in cogeneration. The value of reciprocating engines and gas turbines for CHP are well known and has widely been used. The petroleum and chemical industry has pioneered the use of CHP installations and some have been in use for more the 50 years. Fuel cells and micro turbines also produce considerable quantities of waste heat and lend themselves to use for combined heat and power facilities. Some applications of solar thermal technologies are in use for preheating in steam plants. While some of these techniques may not directly produce electricity and do not precisely increase efficiency, their use can reduce the fossil fuel inputs in some types of steam production facilities while taking advantage of using a renewable source of energy. The PURPA Act of 1978 paved the way for such applications.

VIII. LIGHTING EFFICIENCY

The use of energy efficient lighting has gained momentum in residential, commercial and institutional facilities in recent years. As shown in

Figure 3 approximately 75% of the electricity produced is consumed in residential and commercial applications including heating, HVAC and lighting.

Lighting efficiency and light source types is now the subject of legislative mandates. Certain types of incandescent and fluorescent lights will be abolished and replaced with more efficient types of light fixtures. Although not making up a large percentage of the energy used in industrial facilities, lighting does use about 10TWh. This compares to 4,000TWh or only about 0.25% of the electricity used every year in the US. Nevertheless, simply switching to a more energy efficient light type can save from 20-50% in the energy used for lighting. A side benefit of more efficient lighting is that the more efficient light sources are also the ones having the lowest frequency of replacement, thus requiring the least amount of maintenance. Table **3** compares various light types by the amount of light (lumens) emitted per Watt of electrical power consumed (except in the case of the candle where the Watts used is the total Watt output released by the flame, both heat and light). It may be seen that changing from one type of light source to another can considerably decrease the amount of electricity needed to produce an equivalent amount of light.

IX. SMART METERING

Smart metering is another type of demand side management tool presently receiving much attention. While not specifically designed to increase energy efficiency, a byproduct of using this technology may be a decrease in overall energy usage, improved efficiency and ultimately a reduction in energy costs in some circumstances. .

It costs the utility more to deliver power to a customer at peak demand times than it does at low demand times. Smart metering can be used by the utility to charge a variable rate for energy to a customer depending upon when that energy is used, and let the customer know in advance what those charges will be and how they will vary throughout the day, month, or year.

Table 3: Light output by type. [8][9][10]

Light Type	Lumens/Watt
Candle	0.13
Incandescent	10-17
Halogen	12-22
Fluorescent T12	40-70
Fluorescent T8	60-90
Compact Fluorescent	40-70
LED	20-60
Mercury Vapor	25-60
Metal Halide	70-115
High Pressure Sodium	50-140
Low Pressure Sodium	80-180

This information allows the customer to shift their energy usage to lower cost times thus saving both the customer on cost of electricity and utility the additional costs of delivering power at peak times. This will also increase the overall energy efficiency of both the demand and supply side. In some countries, it is becoming increasingly common for a residential customer to heat water at night during the hours of low energy costs, and use this heated water to heat the premises during the day. This shifting of energy usage reduces the heating costs for the customer and permits the utility to have a more desirable (flat) load profile thus reducing generation costs.

It is the hope that smart metering and the smart infrastructure will allow the future energy generation and usage to operate something like this:

1. Each utility would project a day in advance the amount of energy it will need.
2. The utility will take bids from all producers for the cost of energy for each 30 minute period during the day. This would include wind, solar, and other renewables which would depend on detailed weather projections
3. After accepting the lowest bid for the energy it needs, the utility prepares a tariff profile that will be downloaded into each meter.
4. The new tariff will be available to each user through their meter/computer interface or will be downloaded into the customer's energy conservation system.
5. The customer or automated energy management system decides what electrical systems are run and when.

It is also hoped that smart metering infrastructure, if it ever becomes cost effective to install in all its parts, will have the following benefits.

1. The utility will better be able to control its demand and will have to purchase less power at peak times.

2. The customer will be charged a more fairly computed electrical rate at all times since the electrical rate reflects the utilities actual costs.
3. The customer will be better able to control their energy usage.
4. The use of energy efficient devices will be encouraged.
5. Total energy usage will be reduced (some estimates say between 7-11%).
6. Low capacity factor renewable sources will more easily be integrated into the power system.
7. The utility may directly control the customers' energy usage to curtail usage when needed.

Serious questions still remain about the smart (or smarter) grid and the smart grid infrastructure. Will it significantly affect customer's energy usage? Studies disagree on its actual effects on the consumer. Sophisticated users such is industrial facilities may indeed find the smart infrastructure useful in reducing energy costs. However, some industrial operations do not lend themselves to shifting loads from one time to another making the smart infrastructure of little value.

It is also unclear whether making the grid any smarter will be cost effective. Recent pilot projects to create so called SmartGrid Cities have not proven that the programs are cost effective [11]. Installation of the smart grid will take a large investment in the construction of the communication infrastructure between the utility and customer and it is not clear that the energy saved will pay for these costs in the foreseeable future when the cost of electricity is really cheap.

Smart metering may also extend the payback period of off-peak renewable sources like wind and shorten the pay-back period of on-peak, or nearly on-peak sources such as solar. Another concern is that the system will simply be too complex for wide acceptance among consumers.

X. SYSTEM EFFICIENCY

In the past, solutions to improve energy efficiency have taken the form of replacing older motors with new premium efficiency motors. While this may increase efficiency by an estimated 2-8%, it improves what may be the most efficient part of the system: the motor, while leaving unchanged those parts of the system that may be the least efficient such as the pump which may be only 50% efficient. To optimize overall efficiency, one must look at the efficiency of the complete system which may include all components inside the electric motor, the power distribution transformers, starter or drive, couplings, belts, mechanical power transmission, not to mention the efficiency of the driven load itself. To optimize the overall efficiency process control should be used to make each system work in harmony with all other systems within the plant. Significant energy savings may be available when older equipment is replaced with newer more efficient technologies.
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XI. GOVERNMENT ASSISTANCE

In order to educate and promote both energy conservation and energy efficiency, many countries worldwide have governmental programs. The U.S. Environmental Protection Agency (EPA) and the Department of Energy (DOE) have programs available to assist industry with energy conservation (compared to energy efficiency). Though the programs are similar they provide different degrees of assistance and do not necessarily cooperate with each other.

The EPA Program is part of the ENERGY STAR Program and is called "Industrial Focus Partners". Included industries are:

- Cement Manufacturing
- Corn Refining
- Dairy Processing
- Glass Manufacturing
- Iron & Steel Manufacturing
- Metal Casting
- Motor Vehicle Manufacturing
- Petrochemical Manufacturing
- Petroleum Refining
- Pharmaceutical Manufacturing
- Pulp and Paper Manufacturing
- Ready Mix Concrete Manufacturing

In the ENERGY STAR program, Duke University models the energy required to produce a certain item in an optimized process and then that software is used to report each facility's energy usage. Each facility can compare their performance to others within their company as well as to the industry average. Meetings and web conferences are held throughout the year to discuss results, new technologies and common issues. While all members are competitors and no proprietary data is shared, much is accomplished.

The ENERGY STAR program acknowledges companies for meeting goals and has a yearly awards banquet. Besides certifying commercial buildings ENERGY STAR now has a method to certify industrial facilities. The ENERGY STAR program also identifies Service Providers.

The DOE program was formerly part of the Industrial Technologies Program (ITP) but is now called the Advanced Manufacturing Office (AMO). This office helps develop new technologies and technical solutions that save energy. Many years ago, ITP developed a series of guides showing best practices and these guides have recently been revised and updated. They include:

- Continuous Energy Improvement
- Premium Motors
- Estimating Efficiency
- Extended Motor Life
- Shaft Alignment
- Replace Belts
- Nuisance Trips
- Voltage Unbalance
- Excessive In-Plant Volt Drops
- Improve Motor Operation
- Turn Motors Off
- Adjustable Speed Drives
- Eddy Current Drives
- Magnetically Coupled Drives
- When Should Inverter-Duty Motors Be Specified?
- Minimize Adverse Motor and Adjustable Speed Drive Interaction

DOE AMO also provides grant money to install and test new technologies. This is done through their Advanced Research Projects Agency-Energy (ARPA-E), which is tasked to promote and fund research and development of advanced energy technologies

Canada has Natural Resources Canada (NRCan) that helps promote energy savings in the country. The utility in each province is also involved in energy efficiency.

XII. ISO 50001

ISO 50001:2011 is a specification created by ISO to define an energy management system. The lead for this in the US has been the DOE. As in most ISO systems, it defines the process to achieve continuous improvement, in this case for energy efficiency, security and usage.

XIII. CONCLUSIONS

The Petroleum and Chemical industries use a large quantity of electrical energy and must continue to pay close attention to the effects of future energy legislation on the cost of that energy. Present legislation mandates changes to lighting and motor efficiencies that will result in energy cost savings to all industries while costing some additional money in equipment improvement.

The U.S. Department of Energy recently has started framework meetings to study how efficiencies of fan, pump and compressor systems might be raised and regulated. These meetings are expected to take several years before any rules may be expected.

It will be beneficial for industrial customers to take a closer look at existing and future planned equipment to determine if additional efficiencies may be achieved by utilizing combined heat and power sources installing adjustable speed drives or redesign the entire process.

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XV. VITA

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