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Energy Efficiency Improvement and Cost Saving Opportunities for the Vehicle Assembly Industry

An ENERGY STAR® Guide for Energy and Plant Managers

Christina Galitsky and Ernst Worrell

Environmental Energy Technologies Division

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ABSTRACT

The motor vehicle industry in the U.S. spends about $3.6 billion on energy annually. In this report, we focus on auto assembly plants. In the U.S., over 70 assembly plants currently produce 13 million cars and trucks each year. In assembly plants, energy expenditures are a relatively small cost factor in the total production process. Still, as manufacturers face an increasingly competitive environment, energy efficiency improvements can provide a means to reduce costs without negatively affecting the yield or the quality of the product. In addition, reducing energy costs reduces the unpredictability associated with variable energy prices in today's marketplace, which could negatively affect predictable earnings, an important element for publicly-traded companies such as those in the motor vehicle industry.

In this report, we first present a summary of the motor vehicle assembly process and energy use. This is followed by a discussion of energy efficiency opportunities available for assembly plants. Where available, we provide specific primary energy savings for each energy efficiency measure based on case studies, as well as references to technical literature. If available, we have listed costs and typical payback periods. We include experiences of assembly plants worldwide with energy efficiency measures reviewed in the report. Our findings suggest that although most motor vehicle companies in the U.S. have energy management teams or programs, there are still opportunities available at individual plants to reduce energy consumption cost effectively. Further research on the economics of the measures for individual assembly plants, as part of an energy management program, is needed to assess the potential impact of selected technologies at these plants.

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1. Introduction

As U.S. manufacturers face an increasingly competitive environment, they seek out opportunities to reduce production costs without negatively affecting the yield or the quality of the product. Uncertain energy prices in today's marketplace negatively affect predictable earnings. This is a concern, particularly for publicly traded companies in the motor vehicle industry. Successful, cost-effective investment into energy efficiency technologies and practices meets the challenge of maintaining the output of high quality product with reduced production costs. This is especially important, as energy-efficient technologies often include "additional" benefits, increasing the productivity of the company further. Finally, energy efficiency is an important component of a company's environmental strategy. End-of-pipe solutions are often expensive and inefficient while energy efficiency can often be the cheapest opportunity to reduce pollutant emissions. In short, energy efficiency investment is sound business strategy in today's manufacturing environment.

Voluntary government programs aim to assist industry to improve competitiveness through increased energy efficiency and reduced environmental impact. ENERGY STAR®, a voluntary program operated by the U.S. Environmental Protection Agency in coordination with the U.S. Department of Energy, stresses the need for strong and strategic corporate energy management programs. ENERGY STAR provides energy management tools and strategies for successful programs. The current paper reports on research conducted to support ENERGY STAR and its work with the vehicle assembly industry. This research provides information on potential energy efficiency opportunities for vehicle assembly plants. ENERGY STAR can be contacted through www.energystar.gov for additional energy management tools that facilitate stronger corporate energy management practices in U.S. industry.

In this report, we assess the energy efficiency opportunities for vehicle assembly plants. Vehicle manufacture in the United States is one of the most important industries, producing 12-13 million cars and light trucks annually and generating almost $350 billion in output (Fulton et al., 2001). The industry (15 companies) operates 76 assembly plants (as of 2001) around the country, and a multitude of other plants manufacture car parts. In this report, we focus on the vehicle assembly plants, although a small number of these plants also manufacture parts onsite (e.g. engines, or vehicle body parts in stamping facilities). In the U.S., the vehicle assembly industry spent $3.6 billion on energy in 1999 (DOC, 2000).

We first describe the trends, structure and production of the industry in the U.S. We then describe the main production processes. Following, we summarize the energy use in vehicle assembly plants and its main end uses. Finally, we discuss energy efficiency opportunities in vehicle assembly plants. We focus on measures and technologies that have successfully been demonstrated in individual plants in the U.S. or abroad, but that can still be implemented in other plants. Although new technologies are developed continuously (see e.g. Martin et al., 2000), we focus on practices that are proven and currently commercially available.

2. The Motor Vehicle Industry

The U.S. motor vehicle industry is the largest industry in the U.S., producing more output (in dollars) than any other single U.S. industry (Fulton et al., 2001). Most of the sector of the industry that we are considering—vehicle assembly—is located in the Midwest, particularly in Michigan and Ohio. Detroit houses the headquarters of the "Big Three" automobile companies, General Motors Corporation (GM), Ford Motor Company and Daimler Chrysler Corporation. Table 1 lists the number of motor vehicle assembly plants in the U.S. for each state that has at least one plant for the year 2000 (which includes automobiles, sport utility vehicles (SUVs), light trucks, as well as buses and heavy-duty trucks). In 2000, the U.S. had 76 motor vehicle assembly plants. Appendix A lists each of these plants along with their capacity, product and operations at the plant. The industry as a whole directly employs over 621,000 workers.

Table 1.Location of U.S. vehicle assembly plants in 2000

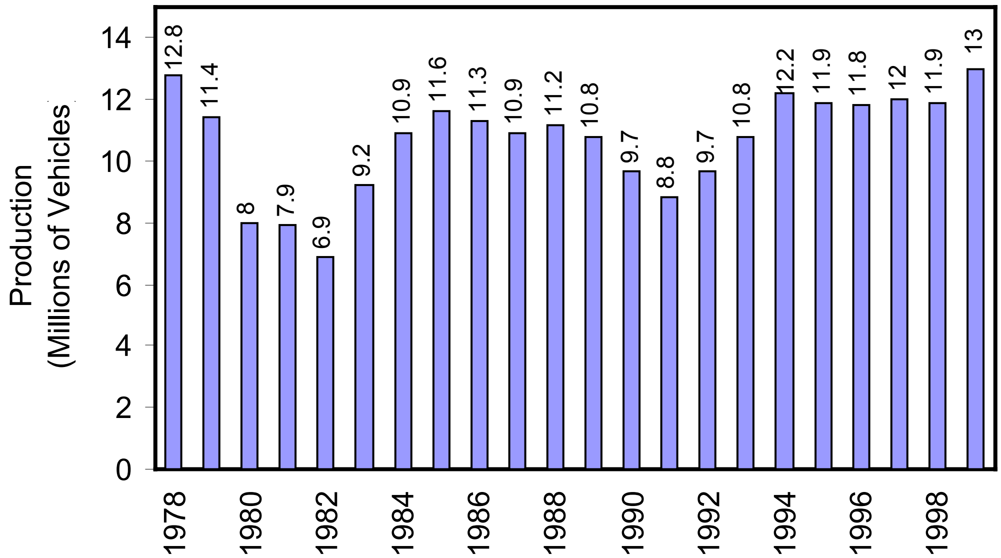
State	# Plants	State	# Plants
MI	18	WA	2
OH	9	AL	1
KY	5	AR	1
MO	5	CA	1
NC	4	KS	1
IL	3	LA	1
IN	3	MD	1
DE	2	MN	1
GA	2	ND	1
NJ	2	OR	1
NY	2	PA	1
OK	2	TN	1
SC	2	VA	1
TX	2	WI	1
Total U.S. motor vehicle assembly plants = 76			

Globally, the U.S. motor vehicle industry is the largest in the world. In 1999, 17 million vehicles were sold in the U.S., over three times that of Japan, the next largest market (Fulton et al. 2001). Thirteen million total motor vehicles were produced in the U.S. in 1999, 30% more than Japan (Fulton et al. 2001). Production data from 1978 to 1999 for the U.S. are shown in Figure 1.

In the automobile or light vehicle sector (cars, SUVs and light trucks), U.S. manufacturers can now compete with Japanese in product development on an international level, since the average time to market for U.S. automakers has decreased in the last few decades bringing it closer to those of Japanese producers (Fine et al., 1996). Within the U.S., foreign automakers have expanded production; Japanese assemblers increased production from 2 to 3 million cars and light trucks per year between 1991and 1996 (Fine et al., 1996).

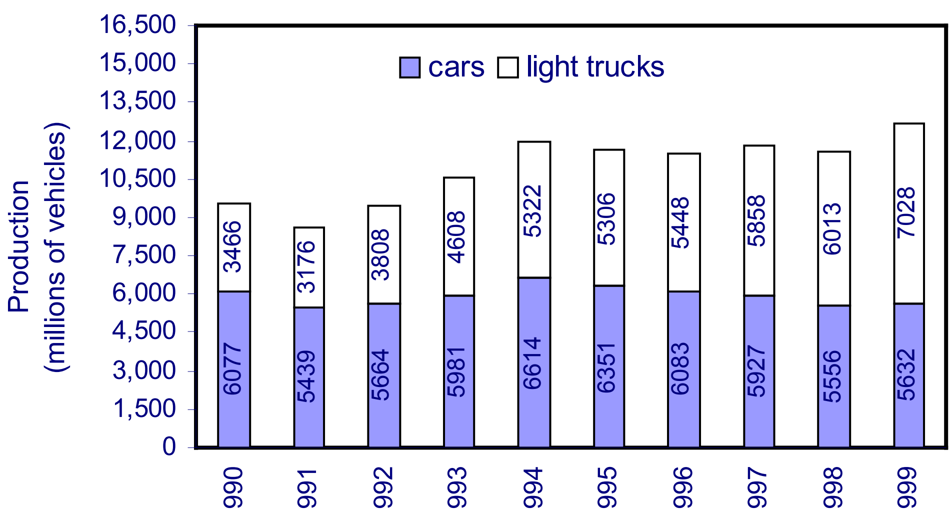
Current domestic production in the automobile sector is shifting from mostly cars to more light vehicles (trucks, minivans and SUVs). Figure 2 shows U.S. light vehicle production from 1990-1999. Light truck production doubled during this time. Several factors caused this shift, including their relatively low costs of production, little competition from foreign markets, and increasing demand, which drives up their prices. In 2001, production of light trucks grew to 56% of U.S. production (Fulton et al. 2001).

Figure 1. Total U.S. Vehicle Production from 1978 to 1999.



Source: 1990-1997: AAMA Economic Indicators, 1998;
1998-1999: Automotive News, 2000.

Figure 2. U.S. Light Vehicle Production from 1990-1999.



Source: 1990-1997: AAMA Economic Indicators, Q1 1998, page 5, Table 1
1998-1999: Automotive News, January 10, 2000, page 58

In addition to trends towards light trucks (which include minivans and SUVs), consumer preferences are tending towards safety and amenities, like airbags and CD players. In the last two decades, average car prices increased faster than average U.S. incomes. This may shift consumers' buying habits more towards used cars or keeping cars longer and away from buying new cars (Fine et al., 1996).

3. Vehicle Manufacturing Processes

Because many of the energy efficiency measures discussed in this report focus on the light vehicle sector, this section provides a description of this process. Automobile manufacturing basically consists of four steps: parts manufacture, vehicle body production, chassis production and assembly. Although we focus on vehicle assembly plants, some of the plants (See Appendix A) have other manufacturing facilities on-site (e.g. stamping). Therefore, we discuss the whole production process in this section, while providing more detail on the assembly process.

Engine and Parts Manufacture
The vehicle industry produces many parts itself (e.g. by subsidiaries), while other parts are purchased. Engines are cast from aluminum or iron, and further processed in engine plants. Metal casting is an energy-intensive production process. The U.S. Department of Energy has a special research effort focusing on the metal casting industry through its Metal Casting Industry of the Future Program, while the U.S. Environmental Protection Agency is helping to reduce the environmental impact of the process (e.g. recycling of casting sand) through its Industry Sector Performance Program for Metal Finishing (DOE, 2003a; EPA, 2003a). Engine parts must be assembled to produce the finished engine. Other major cast parts are axles and transmissions.

Vehicle Body Production
Automotive and other vehicle bodies are generally formed out of sheet steel, although there is a trend toward more plastic and aluminum parts in vehicle bodies. Different steel alloys are used because of their general availability, low cost and good workability. For certain applications, however, other materials, such as aluminum, fiberglass and reinforced plastic are used because of their special properties. For example, Saturn (GM) uses plastic in doors and other vehicle body parts, while most manufacturers use plastic in bumpers. Tooling for plastic components generally costs less and requires less time to develop than that for steel components and therefore may be changed by designers at a lower cost, making it an attractive material for vehicle makers, despite its higher cost per pound. The relative low weight also contributes to higher fuel efficiency in cars.

Chassis
The chassis of the vehicle is the main structure of the vehicle. In most designs, a pressed-steel frame forms a skeleton on which the engine, wheels, axle assemblies, transmission, steering mechanism, brakes, and suspension members are mounted. In modern small car designs, there has been a trend toward combining the chassis frame and the body into a single structural element. In this arrangement, the steel body shell is reinforced with braces that make it rigid enough to resist the forces that are applied to it. Separate frames are used for other cars to achieve better noise-isolation characteristics.

Painting
To protect vehicle bodies from corrosion, special priming and painting processes are used. Bodies are first dipped in cleaning baths to remove oil and other substances. They then go through a succession of painting cycles, which help to maintain the visual quality of the paint and give the required hardness. Enamel and acrylic lacquer are both in common use. The latter is water-based and reduces the output of smog-forming volatile organic compounds (VOCs). Experts disagree whether water based paints cause higher or equal energy consumption in the drying process (Leven, 2001). Electrostatic painting, a process in which the paint spray is given an electrostatic charge (50 – 80 kV) and then is attracted to the surface of the car (which is at ground potential), helps assure that an even coat is applied over the total car body. Ovens with

conveyor lines are used for the drying process. Alternative technologies use infrared-curing to save energy and production time and decrease the size of the dryer (see Section 5.1). After painting, the vehicle body is checked for inaccuracies in paint coverage and repaired if needed.

Assembly

Virtually every new car and light truck comes from the moving assembly line introduced by Ford, although the process has been refined by various companies through such concepts as 'just-in-time' (e.g. especially by Toyota) and other manufacturing experiments (e.g. Volvo's human-centered assembly operations). An accurately controlled flow of materials and parts is essential to maintain production of the assembly plants, to avoid high inventory costs and possible disruptions in the manufacturing process. This was pioneered by Ford, and perfected by Japanese car manufacturers.

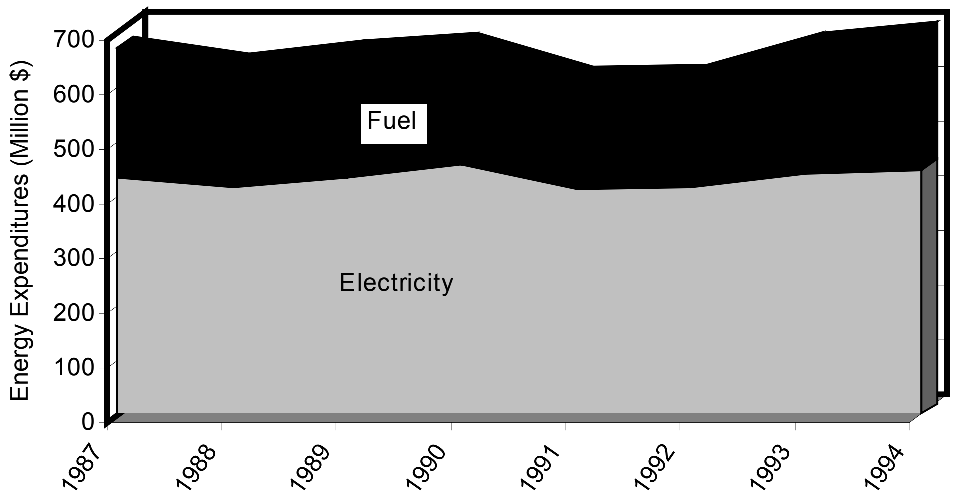
The automobile assembly process itself has a uniform pattern between different plants. Generally, there are two main assembly lines: body and chassis. On the body assembly line, the body panels are welded together, the doors and windows installed, and the body painted and trimmed (wiring, interior). On the chassis assembly line, the frame has the springs, wheels, steering gear, and power train (engine, transmission, drive shaft) installed, as well as brakes and exhaust system. The two lines merge at the point where the body is bolted to the chassis. A variation on this process is "unitized" construction, whereby the body and frame are assembled as a unit. In this system, the undercarriage still goes down the chassis line for the power train, front suspension, and rear axle, to be supported on pedestals until they are joined to the unitized body structure.

Assembly lines have been elaborately refined by automatic control systems and transfer machines, which have replaced many manual operations. Automatic transfer machines were first introduced by Austin Motors in Britain in 1950, and were first used in the U.S. by Ford in 1951. Today, computers manage the assembly process, offering the opportunity to build different versions of the same model, or even different car models on one assembly line, while welding robots do most or all of the welding. After assembly, the car is finished for shipment to dealers and customers.

4. Energy Use in Vehicle Assembly Plants

Motor vehicle assembly plants use energy throughout the plants for many different end-uses. The main energy types used on-site are electricity, steam, gas and compressed air. Total energy expenditures in the transportation equipment manufacturing industry as a whole (NAICS code 336)[1], are estimated at $3.6 billion for 1999 (DOC, 2000). In vehicle assembly plants categorized in SIC 3711, about $700 million is spent on energy (see Figure 3). About two-thirds of the budget for assembly plants is spent on electricity, while fuels are used to generate hot water and steam (mainly for paint booths), as well as heat in curing ovens.

Figure 3. Energy expenditures in vehicle assembly plants (SIC 3711).



Source: U.S. Census, Annual Survey of Manufacturers, various years (DOC, 2000).

Energy costs in assembly plants are equivalent to approximately 1% of the production output by the vehicle assembly plants, making it a relatively small cost factor in the total production process. The energy costs for the assembly of a car have declined from about $70/car in 1990 to about $60/car in 1995. This cost reduction may be due to reduced energy costs during that period, increased capacity utilization at assembly plants or improved energy efficient processing. It is our understanding that relatively low energy costs have led to relatively little attention to energy in the manufacturing processes, despite examples of very cost-effective energy efficiency improvement projects in the industry within the U.S. and abroad (see Section 5).

Electricity use in vehicle assembly plants has increased over time from 8.6 TWh in 1987 to 10 TWh in 1995, while the average specific electricity consumption per car has decreased from almost 1000 kWh/car in 1987 to 860 kWh/car in 1995, although there are large variations between individual plants (DOC, 2000). This figure compares well to the average electricity use of Daimler Chrysler in 1999, estimated at 840 kWh/car (Daimler-Chrysler, 2001). Fuel use is more difficult to track as it is only reported in the Manufacturing Energy Consumption Surveys (MECS) of 1994 and 1991. In 1994 (the last public data point on fuel use in the vehicle assembly

[1] Transportation equipment manufacturing (NAICS code 336) includes manufacturing of automobiles and parts, as well as aerospace, railroad, ship and boat and other transportation equipment like motorcycles and armored cars.

industry), the industry consumed 77 TBtu of fuel, valued at $250 million (EIA, 1997). On a final energy basis, fuels represent 72% of the energy use, while on a primary energy basis fuels represent 45% of total energy use[2]. In 1994, the specific fuel consumption is estimated at 6.5 MBtu/car, while the primary specific energy consumption is estimated at 14.3 MBtu/car, demonstrating the importance of electricity use in the fuel mix.

Energy is used for many different types of end-uses in vehicle assembly facilities. Fuels are mainly used for space heating, steam applications and in the curing ovens of the painting lines, while some facilities may have casting facilities for engines or other parts onsite. Electricity is used throughout the facility for many different purposes, e.g. compressed air, metal forming, lighting, ventilation, air conditioning, painting (fans and infrared (IR) curing), materials handling and welding. Estimates of the distribution of energy use in vehicle assembly plants are rare and may vary among plants based on the processes used in that facility. Also, not many plants have separate metering of energy use at different locations and processes in the plants. Table 2 provides an estimate of the typical electricity end-use distribution in vehicle assembly plants, based on studies of vehicle assembly plants in the U.S. (Price and Ross, 1989), Belgium and Sweden (Dag, 2000), and Germany (Leven and Weber, 2001). Around 70% of all electricity is used in motors to drive the different pieces of equipment in the plant, underlining the importance of motor system optimization in energy efficiency improvement strategies.

Table 2. Distribution of electricity use in vehicle assembly plants.

End-Use	**Share of electricity use (%)**	**Estimated typical electricity consumption (1995) (kWh/car)**	**Average electricity applied in analyses in this study (kWh/car)**
HVAC	11-20%	95-170	160
Paint systems (e.g. fans)	27-50%	230-320	260
Lighting	15-16%	130-140	130
Compressed air	9-14%	80-120	120
Materials handling/tools	7-8%	60-70	60
Metal forming	2-9%	20-80	30
Welding	9-11%	80-95	80
Miscellaneous	4-5%	35-45	20
Total	100%	730-1040	860

The data represent typical uses based on a number of plants in the U.S. and Europe (Price and Ross, 1989; Dag, 2000; Leven and Weber, 2001). The actual distribution in an individual plant may be different due to variations in processes (e.g. engine plant, or body plant), as found in different plants around the U.S. (See Appendix A).

Fuel is mainly consumed for space heating and for drying and conditioning the air (for temperature and humidity) in the painting line (although IR drying may have partially replaced it). In Germany, paint shops use 50 to 60% of the fuel in the plants (Leven and Weber, 2001). These fuels are mainly used for heating vats, conditioning the process air and thermal oxidation of VOCs in the exhaust. Some plants have engine and stamping plants onsite, and so may use extra electricity for machining metal. For the purposes of this study, we focus on assembly

[2] Final energy is the purchased energy by the final user (or plant). Primary energy is calculated using the average efficiency for public power generation to estimate the fuels used to generate the power consumed by the automotive industry. We use an average efficiency of 32% based on U.S. consumption of fuels at power plants. Hence, primary energy is roughly three times final energy.

operations. Large amounts of energy may be used in the manufacture of automotive (or other vehicle) parts, and should be part of a comprehensive energy efficiency strategy for a vehicle maker.

To study the opportunities for energy efficiency improvement, it is important to assess the total amount of energy used in each operation, as well as the load curve of the plant. Price and Ross (1989) and Dag (2000) both show that there may still be a substantial amount of energy used during regular, non-production shutdown. Energy management systems (see Section 5.4) may help to reduce the non-productive energy consumption by controlling lighting and heating, ventilation and air-conditioning (HVAC) equipment. Electricity demand at shutdown can vary between a low of 20% (Price and Ross, 1989) and a high of 40-50% (Dag, 2000; Price and Ross, 1989; Leven, 2001).

In this report, we focus on energy efficiency opportunities available for motor vehicle assembly plants. While we acknowledge that a full life cycle analysis of the motor vehicle construction process would be the best way to capture the entire amount of energy required to manufacture a vehicle, we are not attempting that here. We also point out that operations vary from plant to plant, even in those considered assembly plants (for example, some include stamping and others do not). This presents a challenge when trying to benchmark the energy use between plants. However, in this report we are providing a description of energy efficiency measures that may be applicable to some assembly plants but not all. For this purpose, the differences between plants are less important, noting that only selected measures may apply to certain plants.

5. Energy Efficiency Opportunities

A variety of opportunities exist within U.S. vehicle assembly plants to reduce energy consumption while maintaining or enhancing the productivity of the plant. Below we have categorized energy efficiency measures by their utility systems (general, motors, compressed air, heat and steam distribution, lighting, HVAC, material handling) or by process (painting, welding, stamping). We have included case studies for U.S. vehicle assembly plants with specific energy and cost savings data when available. For other measures, we have included case study data in similar facilities (for example, in metal shops) or for automotive or other vehicle assembly facilities around the world. For U.S. vehicle assembly plants, actual payback period and savings for the measures will vary, depending on plant configuration and size, plant location (particularly for the painting operations) and plant operating characteristics. Hence, the values presented in this report are offered as guidelines. Wherever possible, we have provided a range of savings and payback periods found under varying conditions. Table 3 lists energy efficiency measures that are general utility or cross cutting measures, characterized by the system to which they apply. Table 4 similarly lists energy efficiency measures that are process-specific, characterized by the process to which they apply.

Although technological changes in equipment conserve energy, changes in staff behavior and attitude can have a great impact; staff should be trained in both skills and the company's general approach to energy efficiency in their day-to-day practices. Personnel at all levels should be aware of energy use and objectives for energy efficiency improvement. Often this information is acquired by lower level managers but not passed to upper management or down to staff (Caffal, 1995). Programs with regular feedback on staff behavior, such as reward systems, have had the best results. Though changes in staff behavior, such as switching off lights or closing windows and doors, often save only small amounts of energy at one time, taken continuously over longer periods they can have a much greater effect than more costly technological improvements. Further details for these programs can be found in section 5.1 under "Energy management systems and programs."

Participation in voluntary programs like the EPA ENERGY STAR program or gaining ISO 14001 certification can help companies track energy and implement energy efficiency measures. General Motors notes that using energy management programs in combination with the ISO program has had the largest effects on conserving energy at their plants.

Table 3. Cross cutting (utilities) energy efficiency measures for the vehicle assembly industry.

General Utilities	Motors
Energy management systems Combined heat and power (CHP) CHP combined with absorption cooling District heating Alternative fuels	Sizing of motors High efficiency motors Switched reluctance drives Adjustable/variable speed drives Variable voltage controls
Compressed Air Systems	**Heat and Steam Distribution - Boilers**
Maintenance Monitoring Reduce leaks in pipes and equipment Turn off unnecessary compressed air Modify system instead of increasing system pressure Use sources other than compressed air Load management Use air at lowest possible pressure Minimize distribution system pressure drop Cold air intake Controls Correctly sizing pipe diameter Properly size regulators Systems improvements Heat recovery for water preheating Natural gas engine-driven compressors Energy efficient chillers	Improve process control Reduce flue gas Reduce excess air Correct sizing in design Improve insulation Boiler maintenance Recover heat from flue gas Return condensate Recover steam from blowdown Replace obsolete burners by new optimized boilers **Heat and Steam Distribution - distribution** Improve insulation Maintain insulation Improve steam traps Maintain steam traps Monitor steam traps automatically Repair leaks Recover flash steam
Compressor motors Adjustable speed drives High efficiency motors	
Lighting	**HVAC**
Controls Setting lighting standards Daylighting Replace incandescents with fluorescents or CFLs Replace T-12 with T-8 or metal halides Replace mercury with metal halide or high pressure sodium Replace metal halide HID with high-intensity fluorescents Replace magnetic with electronic ballasts Reflectors Light emitting diodes (LEDs) or radium strips System improvements	Electronic controls Weekend setback temperatures Ventilation and cooling system design improvements Recover cooling water Solar heating (Solarwall) Building shell Modifying fans Other measures **Materials Handling and Tools** High efficiency belts **Miscellaneous** Improvements in electrical harmonic filters Energy efficient transformers

Table 4. Process-related energy efficiency measures for the vehicle assembly industry.

Painting Systems	
Maintenance and controls Minimize stabilization period Reduce air flow in paint booths Insulation Heat recovery Efficient ventilation system Oven type Infrared paint curing UV paint curing Microwave heating	Wet on wet paint New paint—powders New paint—powder slurry coats New paint—others Ultrafiltration/reverse osmosis for wastewater cleaning Carbon filters and other volatile organic carbon (VOC) removers High pressure water jet system
Body Weld	**Stamping**
Computer controls High efficiency welding/inverter technology Multi-welding units Frequency modulated DC-welding machine Hydroforming Electric robots	Variable voltage controls Air actuators

5.1. General Utilities

Energy management systems (EMS) and programs. Changing or implementing an overall energy management program is often the most successful and cost effective way to bring about energy efficiency improvements. Energy management systems can include sub-metering and monitoring systems, control systems and/or changes in staff behavior through a feedback registration system. Staff can be trained in both skills and approaches for including energy efficiency in day-to-day practices, achieving small but continuous improvements. Often it is possible that opportunities have already been identified but not promoted because of real or perceived barriers, such as a lack of understanding on how to proceed, limited support or finances, limited accountability for measures or perceived change from the status quo.

The U.S. EPA ENERGY STAR Program is working with the industrial sector to develop a strategic Energy Management System. The main elements of this system are depicted in Figure 4. A successful program in energy management begins with awareness within the organization and assigning energy duties to a manager. In addition, energy performance or efficiency must be monitored to identify opportunities. When opportunities are identified, a plan to incorporate energy saving measures into the business plan can be adopted. Table 5 shows poor to excellent (0 to 4, respectively) energy management plans, ranked according to their components. For a more detailed energy management assessment, refer to the table in Appendix B.

Figure 4: Main Elements of a Strategic Energy Management System

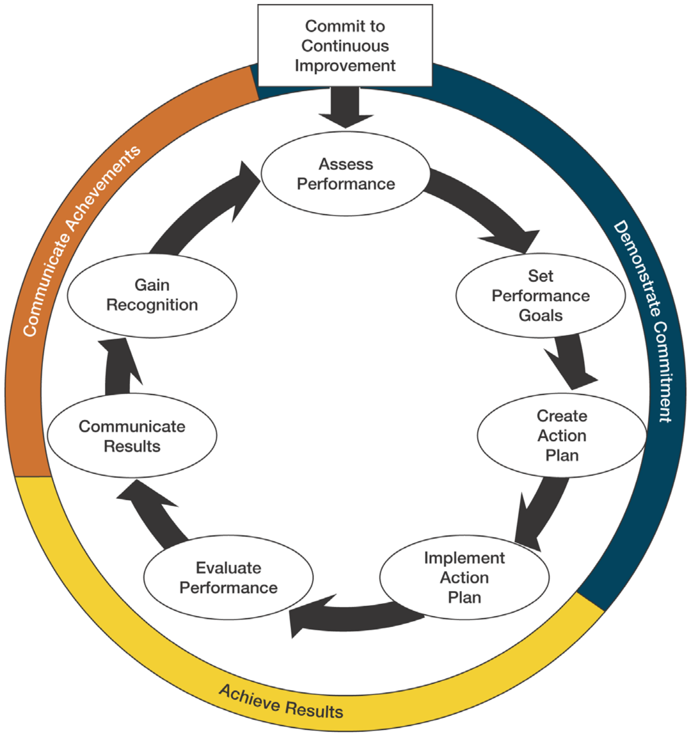


Table 5: Energy Management Plan[1]

		0 ⟶	4
1.	**Accountability**	No awareness	Energy performance information known by all employees. Incentives based on energy use.
2.	**Organization**	No energy manager	Manager with energy as majority of duties.
3.	**Monitoring and Targeting**	Few parameters monitored, no targeting	Daily monitoring, targeting and trending with involvement from staff.
4.	**Utilities Monitoring and Targeting**	No monitoring	Real time monitoring and optimization of steam and power.
5.	**Technology Reviews**	None	Site-wide studies performed and follow-up actions seen to completion.
6.	**Technology Plans**	No published plans	Plans incorporated into business plan.
7.	**Operations and Maintenance**	None available	Procedures available, used and reviewed.

[1] See Appendix B for a more detailed energy management plan.

One of the key steps to a successful energy management program is the involvement of all personnel. Staff can be trained in both skills and the general approach to energy efficiency in day-to-day practices. Personnel at all levels should be aware of energy use and objectives for efficiency. By passing information to everyone, each employee can save energy every day. Examples of some simple tasks employees can do include the following (Caffal, 1995):

- Switch off motors, fans and machines when they are not being used, especially at the end of the working day or shift, and during breaks, when it does not affect production, quality or safety. Similarly, turn on equipment no earlier than needed to reach the correct settings (temperature, pressure) at the start time.

- Switch off unnecessary lights and rely on daylighting whenever possible.
- Use weekend and night setbacks on HVAC.
- Report leaks of compressed air, water (both process water and dripping taps), steam and oil (hydraulic and lubricating) and ensure they are repaired quickly. The best time to check for leaks is a quiet time like the weekend when production has halted.
- Look for heated, unoccupied areas.
- Check that heating controls are not set too high. In this situation, windows and doors are often left open to lower temperatures instead of lowering the heating.
- Check to make sure the pressure and temperature of equipment is not set too high.
- Prevent drafts from badly fitting seals, windows and doors.
- Carry out regular maintenance of energy-consuming equipment.
- Ensure that the insulation on process heating equipment is effective.

Programs with regular feedback on staff behavior, such as reward systems, have had the best results. Below we give some examples of energy management programs that try to change behavior or aim at technological monitoring of energy use. In some cases, a program combines both approaches.

Support for a business energy management program can also come from outside sources. Some utility companies work with industrial clients to achieve energy savings. In these cases, utility personnel work directly with managers onsite to better identify and implement more effective energy management programs and measures for their particular situations. For example, in 1993 Detroit Edison piloted a new energy services program called Energy Partnerships (DTE Energy, 2001). Detroit Edison engineers were sent to automobile manufacturing plants to identify, implement and maintain energy related projects to increase energy efficiency. During the pilot period, each of the two facilities saved 5 to 7 million kWh per year. As of 2001, the program has expanded to include Daimler Chrysler, Ford and General Motors. In addition to energy savings, this program reduces emissions of carbon dioxide (CO_2), sulfur dioxide and nitrogen oxides (NO_x). Castellow et al. (circa 1997) have summarized the "Large Manufacturing Customer Pilot Program (LMCP)" linking three major automotive plants, two steel plants, and a large urban utility to carry out industrial energy projects. Some of the specific measures and data in that project are described in the appropriate sections below.

In another project at an unidentified Canadian plant, an energy management system, using sub-metering, achieved over a 5% reduction in annual electric energy used over a three year period (Price and Ross, 1989). Although sub-metering is usually very costly to install as a retrofit, at facilities where the plant has already been designed with metering in mind, sub-metering costs very little.

The Volvo Car Company at Born (the Netherlands) implemented an energy monitoring and registration system with the additional goal of influencing staff behavior by regular feedback of monitoring results (Ford, 2001). The ventilation and heating controls were readjusted and recalibrated, but the changes in staff behavior produced the best results. Some of these included closing windows and doors, reporting high room temperatures rather than opening a window, adjusting maintenance work in the lacquering line to shorten maintenance periods, switching off unused machinery, switching off lights and coolers when leaving an office, removing superfluous lights and preventing blockage of radiator and ventilation grids. In the program's first year (1989), energy savings totaled \$31,000 1990 U.S.\$ in fuel (9,381 MBtu in natural gas, or 2.5% of total consumption) and \$355,000 1990 U.S.\$ in electricity (6.3 million kWh or 10% of total consumption). The total cost of the system was \$377,000 1990 U.S.\$, resulting in a payback period of less than one year. Volvo noted that close involvement of higher and middle management helped the effectiveness of the project.

Ford has also employed energy management systems at some of its plants. Ford's Cologne-Niehl plant in Germany implemented a computer-based energy management system. The computer system runs the electricity supply for the plant; it automatically adjusts heating and lighting and controls the peak demand of machinery (Ford, 2001).

In the U.S., Ford has begun assessment projects that focus on shutdown procedures, compressed air systems, lighting, building exhaust, and painting RTOs (regenerative thermal oxidizers). Ford has established a shutdown goal of 50% of demand during the week and 25% of demand on the weekends (Ford, 2002). This can significantly reduce energy on down times. For example, Ford's Edison Assembly Plant in New Jersey set up procedures to shut down equipment during non-production periods and issued work instructions to its employees. They found a 14% energy reduction in one year (Ford, 2001). In order to help achieve these objectives, Ford is trying to obtain real time data at its plants. Some European plants have achieved shutdown energy use equal to 20% of full load energy use. For information on the other activities included in their energy efficiency assessment projects, see the appropriate sections on painting, compressed air, lighting and HVAC in this report (Sections 5.1, 5.6, 5.8 and 5.9).

General Motors installed energy management systems in eleven facilities and has achieved more than $3.6 million in annual savings (GM, 2001a). General Motors has also implemented a program called the General Motors Energy Efficiency Initiative. In its first three years, this program has saved a total of 1.9 TWh of electricity and 2.8 TBtu of fuel (GM, 2001). General Motors of Canada, Ltd. installed an energy management system that maintains control of compressed air, lighting, equipment power utilization, steam and innovative energy savings technologies. For the 1999 calendar year, energy reductions from all Canadian facility sources were reduced 6% from the 1997 baseline data. They also established a 20% reduction goal in 1997 to be achieved over the period from 1995 to 2002. Energy saving projects at the Oshawa and Windsor facilities (Canada) have resulted in annual savings of over $750,000 2000 U.S.$. General Motors's overall energy program has been so successful that General Motors was honored with an ENERGY STAR award in 2002 for incorporating energy management into its business operations.

BMW adopted an energy management policy as well. Energy savings were due to both technical and organization measures, and totaled 44% (301 kWh per engine) over the lifetime of the project (Stangl, 1998).

The Rover Group, manufacturer of 36% of all cars built in the UK, implemented a relatively simple employee awareness program at their Longbridge site (Best Practice Programme, 1996). The key to success was raising awareness at all employee levels. This was achieved by forming an energy group, a publicity campaign, a competition and performance reporting against targets. In the first month of implementation, the plant received more energy saving suggestions than they did the entire year prior to the program. The savings achieved were in excess of $1,900,000 1992 U.S.$ in the first 6 months. With costs of just 13,000 1992 U.S.$, the payback period was negligible.

Combined heat and power (CHP)[3]. For industries that have process heat, steam or cooling and electricity requirements, the use of combined heat and power systems can save energy and

[3] Combined heat and power is also known as cogeneration.

reduce pollution. Not all plants will be able to implement cogeneration; in plants with little thermal process or heat requirements, cogeneration will not be a cost-effective strategy. Ford, for example, does not condition air outside of administrative areas and is converting from steam to direct fired gas and hot water at all of its assembly plants. For them, CHP or CHP combined with absorption cooling is not a practical measure unless a third party is involved to defray capital costs (Ford, 2002).

Where process heat, steam or cooling and electricity are used, however, cogeneration plants are significantly more efficient than standard power plants because they take advantage of what are losses in standard plants by utilizing the waste heat. In addition, distribution losses are minimized when CHP systems are located at or near the assembly plant. Utility companies have been developing CHP for use by some automobile assembly plants. In this scenario, the utility company owns and operates the system for the automobile company, who avoids the capital expenditures associated with CHP projects, but gains the benefits of a more energy efficient system of heat and electricity. For systems requiring cooling, absorption cooling can be combined with CHP to use waste heat to produce cooling power. (Absorption cooling is described below under "CHP combined with absorption cooling".)

In the vehicle manufacturing industry, hot water is used for process functions, such as washing and degreasing vehicle components, and maintaining paint at correct temperatures for spraying, while electricity is used to power the motors, pumps and compressors. In addition to the energy savings, CHP also has comparable or better availability of service than utility generation. Typical CHP units are reported to have been online for 95 to 98% of planned operating hours (Price and Ross, 1989). For installations where initial investment is large, potential multiple small-scale CHP units distributed to points of need could be used cost effectively. Typical payback periods for CHP can be as low as 2.4 years (IAC, 2001).[4]

Mazda first installed CHP in 1987 at its Hiroshima plant (Japan), and a more advanced CHP system with heat recovery in 1993 at its Hofa plant in Nishinoura (Japan) (Mazda, 2001). Daimler Chrysler uses CHP in its Rastatt Plant (Germany). They claim an overall efficiency of 85%, compared to efficiencies of up to 40% at conventional power plants (Daimler Chrysler, 1999). In order to implement CHP cost effectively, Land Rover in the United Kingdom agreed to a 10-year contract with its energy supplier under the following conditions: the supplier was responsible for all equipment purchases, installation, and maintenance costs, while Land Rover supplied fuel and contracted to purchase generated electricity from the energy supplier at an agreed rate. The energy supplier owned the plant but Land Rover had no capital or maintenance costs. Hence, the payback period was immediate. Land Rover saved 157 TBtu (461 TWh) annually in primary energy and $460,000 1994 U.S.$ annually (CADDET, 1998; Best Practice Programme, 1998b). They also reduced carbon dioxide emissions by 51%, and eliminated sulfur dioxide emissions (CADDET, 1998). Quixx Corporation, a subsidiary of Southwestern Public Service Corporation, developed CHP for General Motors, who applied it to their truck and sport utility vehicle assembly facility in Linden, New Jersey (TEI, 2001). There they replaced an old oil-fired powerhouse by CHP. Thermal efficiency exceeds 68% (GM, 2001). General Motors has

[4] The Industrial Assessment Center (IAC) database shows a series of case studies where a particular technology was used. It gives a wide variety of information, including implementation costs and savings for each case. Using this information, we calculated a simple payback for each case and an overall payback for a particular technology by averaging all the individual cases. In order to accurately represent applicable technology for the automobile assembly industry, we sampled only SIC codes that contained industries with similar manufacturing processes—34, 35 and 37, fabricated metal products, industrial and commercial machinery and computer equipment and transportation equipment, respectively.

also joined forces with the EPA CHP Partnership at five facilities in 2002. General Motors's Opel Operations (Germany) have also adopted CHP. Ford installed CHP with third party ownership at its River Rouge facility in Michigan where they use the electricity generated and a nearby steel mill uses the thermal energy produced. In addition, Ford uses cogeneration at its research and development facility in Michigan.

Innovative gas turbine technologies can make CHP more attractive for sites with large variations in heat demand. Steam injected gas turbines (STIG, or Cheng cycle) can absorb excess steam, e.g. due to seasonal reduced heating needs, to boost power production by injecting the steam in the turbine. The size of typical STIGs starts around 5 MWe. STIGs are found in various industries and applications, especially in Japan and Europe, as well as in the U.S. International Power Technology (CA) installed STIGs at Japanese plants of Honda and Suzuki in 1999 and 1998, respectively. Energy savings and payback period will depend on the local circumstances (e.g. energy use patterns, power sales conditions).

CHP combined with absorption cooling. Absorption chillers are cooling machines that use heat as the primary source of energy for driving an absorption refrigeration cycle. These chillers require very little electric power (0.02 kW/ton) compared to electric chillers that need 0.47 to 0.88 kW/ton (CHPB, 2002), depending upon the type of electric chiller. Absorption chillers have fewer and smaller moving parts and are thus quieter during operation than electric chillers.

Commercially available absorption chillers can utilize one of the four sources of heat: steam, hot water, exhaust gases or direct combustion. Because absorption cooling produces cooling power using heat, it increases heating demand and decreases electricity demand. For this reason, it is best when combined with CHP. All absorption chillers, except those that use direct combustion, are excellent candidates for providing some, or all, cooling of the load in a CHP system for a building. Modern absorption chillers can also work as boilers for providing heating during winter and feature new electronic controls that provide quick start-up, automatic purge and greater turndown capability than many electric chillers (CHPB, 2002).

These chillers are also environmentally friendly in that they use water as a naturally benign refrigerant. The coolant is based on a mix of water and a salt, like LiBr or LiCl, which is capable of absorbing water very efficiently. District heating or a locally produced low-temperature heat source replaces electricity as the primary energy source for the cooling. Absorption cooling plants should have a minimum size of 500 kW in order to be cost effective (Dag, 2000).

For Volvo's manufacturing plant in Torslanda (Sweden), it is projected that this measure would increase the annual heat usage by 181,000 MBtu but decrease the annual electricity usage by 15.1 million kWh, leading to net energy savings if the power and heat are generated in a CHP facility (Dag, 2000).

Absorption cooling installations using CHP are currently used mainly for large buildings or campuses and industries throughout the U.S. for continuous operation or for peak shaving. Payback periods vary between half a year to over 5 years, depending on local circumstances and utility billing structure. U.S. Department of Energy's distributed generation program is actively pursuing R&D in the area of absorption cooling (DOE, 2003b).

District heating. District heating systems use a central plant in an urban area to supply heat to multiple buildings and complexes. Several Ford plants are supplied by district heating. For example, Ford-Werke AG headquarters (Germany) uses district heat and saves 73,500 tons of coal and 3,500 tons of fuel oil, while reducing CO_2 emissions by 60% annually (Ford, 2001). In

Germany, many plants have replaced their steam network with district heat and hot water at approximately 68°F (20°C). This results in smaller losses in the heating network (Leven, 2001).

Alternative fuels. Some industrial processes produce waste products that can be incinerated exothermically and thus provide an ideal fuel for the boiler. The energy saved by using some of these waste streams (particularly chemical waste streams) must be balanced against the potential release of environmental toxins into the atmosphere (Ganapathy, 1995). At the Orion Assembly Plant (Michigan) in 1998, in affiliation with the voluntary U.S. EPA Landfill Methane Outreach Program, General Motors replaced the coal burned in their boilers with landfill gas from a nearby landfill, reducing coal use by 60,000 tons on an annual basis (roughly equivalent to 1.5 TBtu, or 30% of the fuel used for heating the plant) (GM, 2001). In addition, the new plant reduced sulfur dioxide emissions by 40% and nitrogen oxides by 46%. General Motors also now uses landfill waste as an alternative fuel at its Fort Wayne (Indiana) and Toledo (Ohio) plants. Several other plants at General Motors are in the project development phase aimed to provide over 1% of their total North American energy usage from landfill gas by the end of 2001 (GM, 2001). Ford also introduced the use of landfill gas at the Wayne Stamping and Assembly Plant (Michigan) replacing a coal-fired boiler to produce electricity (approximately 21 million kWh/year) and heat (DEQ, 2001a).

The EPA estimates that more than 700 landfills across the U.S. could install economically viable energy recovery systems; however, plants must be located near viable landfills to implement this measure (EPA, 2003b).

5.2. Motors

Motors are the main electricity consumer in the vehicle assembly industry and are used in a variety of systems in a plant, such as HVAC, compressed air, refrigeration and cooling, and some processes, such as stamping. The following section applies to any system that uses motors. Where appropriate, we listed specific examples detailing to which system the measure has already been applied, and to what success.

Sizing of motors. Motors and pumps that are sized inappropriately result in unnecessary energy losses. Where peak loads can be reduced, motor size can also be reduced. Correcting for motor oversizing can save 1.2% of their electricity consumption, and even larger percentages for smaller motors (Xenergy, 1998). Several case studies suggest the average payback period is about 1.5 years for this measure (IAC, 2001).[4]

High efficiency motors. High efficiency motors reduce energy losses through improved design, better materials, tighter tolerances and improved manufacturing techniques. With proper installation, energy-efficient motors run cooler and consequently have higher service factors, longer bearing and insulation life and less vibration.

Typically, high efficiency motors are economically justified when exchanging a motor that needs replacement, but are not economically feasible when replacing a motor that is still working (CADDET, 1994; Price and Ross, 1989). Sometimes though, according to a case study by the Copper Development Association (CDA, 2000), even working motor replacements can be beneficial. The payback period for individual motors varies based on size, load factor and running time. The best savings are achieved on motors running for long hours at high loads. When replacing retiring motors, payback periods are typically less than one year from energy savings alone (LBNL et al., 1998). Over 950 case studies have shown that average payback periods for energy efficient motors, that include both upgrading and replacing, are higher at approximately 3 years (including replacement of working motors) (IAC, 2001).[4]

To be considered energy efficient in the U.S., a motor must meet performance criteria published by the National Electrical Manufacturers Association (NEMA). However, most manufacturers offer lines of motors that significantly exceed the NEMA-defined criteria, even those defined by NEMA as energy efficient (DOE, 2001b). NEMA and other organizations are sponsoring a "Motor Decisions Matter" campaign to market NEMA approved premium efficient motors to industry (NEMA, 2001). Even these premium efficiency motors can have low a payback period. According to data from the CDA, the upgrade to high efficiency motors, as compared to motors that achieve the minimum efficiency as specified by the Energy Policy Act, have payback periods of less than 15 months for 50 hp motors (CDA, 2001). Because of the fast payback period, it almost always makes sense not only to buy an energy efficient motor but also to buy the most efficient motor available (LBNL, 1998).

Replacing a motor with a high efficiency motor is often a better choice than rewinding a motor. The practice of rewinding motors currently has no quality or efficiency standards. To avoid uncertainties in performance of the motor, a new high efficiency motor can be purchased instead of rewinding one.

Cummins Engine Company, Inc. is a leading manufacturer of diesel engines. The MidRange Engine Plant in Indiana, which produces diesel engines for Daimler Chrysler trucks, exchanged 296 of its standard efficiency motors (motors sold before the Energy Policy Act of 1992) with energy efficient motors, saving 3,771 kW and $79,869 per year with a payback period of less than 2 years (CDA, 2000). In another plant in Columbus (Indiana), Cummins specified new energy efficient motors for their HVAC system and found a payback period of less than 2 years (CDA, 2000). At the Indiana plant, savings totaled 6046 kW and $128,042 annually. Plants that are replacing newer motors will likely have smaller savings than these specific projects.

Aside from uses in HVAC, motors are also used in operating process equipment, which can also be replaced by high efficiency motors. For example, Delta Extruded Metals (UK) replaced five motors used to operate its furnaces with new high efficiency motors. For the sum of motors, they realized a savings of 11,660 kWh/year, equivalent to $765 1992 U.S.$, and implementation costs of $1,250 1992 U.S.$, yielding an average payback period of 1.6 years (CADDET, 1994).

Switched reluctance drives. Switched reluctance drives is an old technology that is being improved, incorporating adjustable speed drives and high efficiency motors. The switched reluctance motor offers variable speed capacity and precision control, in addition to higher torque and efficiency (Martin et al., 2000). Because this is an emerging technology, we have not documented any case studies that have implemented it.

Adjustable speed drives (ASDs)[5]. ASDs better match speed to load requirements for motor operations. Energy use on many centrifugal systems like pumps and fans is approximately proportional to the cube of the flow rate. Hence, small reductions in flow that are proportional to motor speed can yield large energy savings. Although they are unlikely to be retrofitted economically, payback periods for installing new ASD motors in new systems or plants can be as low as 1.1 years (Martin et al., 2000). Adjustable speed drive projects often concern fans, where ASDs reduce energy used to drive the fan by 39% upon a 15% reduction in fan speed (Castellow et al., circa 1997).

[5] ASDs are also commonly known as variable speed drives or VSDs.

At their metal plating facility in Burlington, Vermont, General Dynamics Armament Systems installed ASDs along with an energy management control system (EMS) to control the ASDs as a unit. They found electricity savings of 443,332 kWh and natural gas savings of 17,480 MBtu (CADDET, 1997a; DOE 2001f). The project cost $99,400 to implement, and saved $68,600 annually, providing a simple payback period of 1.5 years. The installation also reduced CO_2 emissions by 213,000 kg/year, improved overall productivity, control, and product quality, and reduced wear of equipment, thereby reducing future maintenance costs.

Another example of the use of ASDs was in the pumping of machine coolant at an U.S. engine plant. Pressure at the pumps was reduced from 64 psi to 45 psi, average flow cut in half, and power usage reduced by over 50% with no adverse effect on part quality or tool life (Price and Ross, 1989). Reducing the coolant system pressure also reduced the misting of the coolant, reducing the ventilation requirements and cleaning costs. ASDs can also be used in draft fans on coal-fired boilers, instead of dampers. The average electricity savings depend on boiler load, but will typically exceed 60% annually (Price and Ross, 1989).

Computer controls can be used with ASDs to control the adjustment of power to match demand. General Motors installed computer chip controls on the electric blower motors in its Fairfax Assembly Plant in Kansas City. The chips were programmed to regulate the motors' speeds by continuously monitoring the speed and adjusting the power to meet the speed demand. The computer chips saved the plant more than 4.3 million kWh of energy annually (DEQ, 2001b). With a total capital investment of $3,724, resultant payback period was approximately one month.

The Lockheed Martin facility (Vermont) used ASDs controlled by a new energy management system. The improvements cost $99,400 and saved $68,600 annually, resulting in a 1.5 year payback period (DOE, 2001c). The electricity savings were 443,000 kWh/year.

Variable voltage controls (VVCs). In contrast to ASDs, which have variable flow requirements, VVCs are applicable to variable loads requiring constant speed, such as stamping presses and metal cutting machine spindles. Several case studies indicate that the payback period for variable voltage controls was, on average, 2.2 years (IAC, 2001).[6]

5.3. Compressed Air Systems

Compressed air is probably the most expensive form of energy used in an industrial plant because of its poor efficiency. Typically, efficiency from start to end use is around 10% for compressed air systems (LBNL et al., 1998). Because of this inefficiency, if compressed air is used, it should be of minimum quantity for the shortest possible time, constantly monitored and reweighed against alternatives. In addition to the measures detailed below, many other motor-directed measures can also be applied to the compressors (see sections on motors and HVAC). Many opportunities to reduce energy in the compressed air systems are not prohibitively expensive; payback periods for some options are extremely short-less than one year.

Maintenance. Inadequate maintenance can lower compression efficiency and increase air leakage or pressure variability, and lead to increased operating temperatures, poor moisture control and excessive contamination. Better maintenance will reduce these problems and save energy.

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[6] For this measure, in order to get a large sample size, and because variable voltage controls can be applied to motors in many industries, we sampled all industries in the IAC database to find the average simple payback. See also footnote 4.

Proper maintenance includes the following (LBNL at al., 1998, unless otherwise noted):

- Blocked pipeline filters increase pressure drop. Keep the compressor and intercooling surfaces clean and foul-free by inspecting and periodically cleaning filters. Seek filters with just a 1 psi pressure drop. Payback period for filter cleaning is usually under 2 years (Ingersoll-Rand, 2001). Fixing improperly operating filters will also prevent contaminants from entering into tools and causing them to wear out prematurely. Generally, when pressure drop exceeds 2 to 3 psig replace the particulate and lubricancant removal elements. Inspect all elements at least annually. Also, consider adding filters in parallel that decrease air velocity and, therefore, decrease pressure drop. A 2% reduction of annual energy consumption in compressed air systems can be expected by more frequently changing filters (Radgen and Blaustein, 2001). However, one must be careful when using coalescing filters because efficiency drops below 30% of design flow (Scales, 2002).
- Poor motor cooling can increase motor temperature and winding resistance, shortening motor life, in addition to increasing energy consumption. Keep motors and compressors properly lubricated and cleaned. Compressor lubricant should be sampled and analyzed every 1000 hours and checked to make sure it is at the proper level. In addition to energy savings, this can help avoid corrosion and degradation of the system.
- Inspect fans and water pumps for peak performance.
- Inspect drain traps periodically to ensure they are not stuck in either the open or closed position and are clean. Some users leave automatic condensate traps partially open at all times to allow for constant draining. This practice wastes substantial amounts of energy and should never be undertaken. Instead, install simple pressure driven valves. Malfunctioning traps should be cleaned and repaired instead of left open. Some automatic drains or valves do not waste air, such as those that open when condensate is present. According to vendors, inspecting and maintaining drains typically has a payback period of less than 2 years (Ingersoll-Rand, 2001).
- Maintain the coolers on the compressor and the aftercooler to ensure that the dryer gets the lowest possible inlet temperature (Ingersoll-Rand, 2001).
- If using compressors with belts, check the belts for wear and adjust them. A good rule of thumb is to adjust them every 400 hours of operation.
- Check water cooling systems for water quality (pH and total dissolved solids), flow and temperature. Clean and replace filters and heat exchangers per manufacturer's specifications.
- Minimize leaks (see also Leaks section, below).
- Specify pressure regulators that close when failing.
- Applications requiring compressed air should be checked for excessive pressure, duration or volume. They should be regulated, either by production line sectioning or by pressure regulators on the equipment itself. Tools not required to operate at maximum system pressure should use a quality pressure regulator. Poor quality regulators tend to drift and lose more air. Otherwise, the unregulated tools operate at maximum system pressure at all times and waste excess energy. System pressures operating too high also result in shorter tool life and higher maintenance costs. Automatic valves were installed in one automobile plant (U.S.) to separate production-line sections of the compressed air network from the main supply. They reduced off-shift compressed air use by 40%, saving more than 10,000 kWh for a single weekend shutdown (Price and Ross, 1989). Case studies show an average payback period for reducing pressure to the minimum required for compressed air applications of about 3 months (IAC, 2001).[4]

Monitoring. Proper monitoring (and maintenance) can save a lot of energy and money in compressed air systems. Proper monitoring includes (CADDET, 1997c):

- Pressure gauges on each receiver or main branch line and differential gauges across dryers, filters, etc.
- Temperature gauges across the compressor and its cooling system to detect fouling and blockages.
- Flow meters to measure the quantity of air used.
- Dew point temperature gauges to monitor the effectiveness of air dryers.
- kWh meters and hours run meters on the compressor drive.

Reduce leaks in pipes and equipment. Leaks can be a significant source of wasted energy. A typical plant that has not been well maintained could have a leak rate between 20 to 50% of total compressed air production capacity (Ingersoll Rand, 2001; Price and Ross, 1989). Leak repair and maintenance can reduce this number to less than 10%. Overall, a 20% reduction of annual energy consumption in compressed air systems is projected for fixing leaks (Radgen and Blaustein, 2001).

The magnitude of a leak varies with the size of the hole in the pipes or equipment. A compressor operating 2,500 hours per year at 6 bar (87 psi) with a leak diameter of 0.02 inches (½ mm) is estimated to lose 250 kWh/year; 0.04 in. (1 mm) to lose 1100 kWh/year; 0.08 in. (2 mm) to lose 4,500 kWh/year; and 0.16 in. (4 mm) to lose 11,250 kWh/year (CADDET, 1997c). Of over one thousand examples of this measure in the vehicle assembly or similar industries, average payback period was about 5 months (IAC, 2001).[4]

In addition to increased energy consumption, leaks can make air tools less efficient and adversely affect production, shorten the life of equipment, lead to additional maintenance requirements and increased unscheduled downtime. Leaks cause an increase in compressor energy and maintenance costs.

The most common areas for leaks are couplings, hoses, tubes, fittings, pressure regulators, open condensate traps and shut-off valves, pipe joints, disconnects and thread sealants. Quick connect fittings always leak and should be avoided (Toyota, 2002). A simple way to detect large leaks is to apply soapy water to suspect areas, or to use a bag to monitor the velocity of the air filling the bag, although this may be time consuming (Toyota, 2002). The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks. After identification, leaks should be tracked, repaired and verified. Leak detection and correction programs should be ongoing efforts.

The General Motors Powertrain Group's Metal Casting Operations in Michigan has reduced energy consumption by over 21 million kWh/year by reducing compressed air leaks (DEQ, 2001g; GM, 2001).

Ford has included a leak program in its assessment projects (see also Section 5.1). Assessors identify compressed air leaks using ultrasonic equipment and note problem areas using leak tags (Ford, 2002). After fixing leaks, controls are added to the compressors to take advantage of the extra capacity gained by the repair. For example, outside the U.S., the Ford Stamping Plant in Geelong, Victoria (Australia) used an ultrasonic inspection tool to search for leaks. After repairs of the leaks, they saved over $83,200 1996 U.S.$ per year. Payback periods were less than 1 month (CADDET, 1997c). In addition, Visteon's Monroe plant in Michigan (formerly owned by Ford Motor Company) implemented a leak management program in 1989. The program included support from management as well as line workers and skilled trades people. They found cost savings from reduced electricity were $560,000 per year, equal to an 11.5% reduction in electricity consumption (8.9 million kWh annually) (DOE, 2000b). They also found reduced wear on all components within the system (compressors, dryers, piping, filters, end use applications) due to lower plant pressure (DOE, 2001d).

For large leaks, Toyota uses one simple method, a bag test, to determine if a leak is worth fixing. In this test, they put a plastic bag up to the leak and monitor the velocity of the air filling the bag. Generally, their policy is that if the leak is not audible, it is not worth fixing. Typical leaks cost $400 to fix (Toyota, 2002). At one plant in Japan, all leaks were identified and fixed. A 15% reduction in compressed air energy was realized, though fixing the smaller leaks was less profitable (Toyota, 2002).

Land Rover's Solihull plant (UK) saved 20% of compressed air by repairing leaks (CADDET, 1995b; Best Practice Programme, 1998a).

Turn off unnecessary compressed air. Equipment that is no longer using compressed air should have the air turned off completely. This can be done using a simple solenoid valve (Scales, 2002). Compressed air distribution systems should be checked when equipment has been reconfigured to be sure no air is flowing to unused equipment or obsolete parts of the compressed air distribution system.

Modify system instead of increasing system pressure. For individual applications that require a higher pressure, instead of raising the operating pressure of the whole system, special equipment modifications should be considered. For example:

- Use a booster;
- Increase a cylinder bore;
- Change gear ratios; and,
- Change operation to off peak hours.

Use sources other than compressed air. Many operations can be accomplished more economically and efficiently using energy sources other than compressed air. Some industry engineers believe this measure has the largest potential for compressed air energy savings. Various options exist to replace compressed air use, including:

- Air motors should only be used for positive displacement.
- Cooling electrical cabinets: air conditioning fans should be used instead of using compressed air vortex tubes.
- Flowing high pressure air past an orifice to create a vacuum: a vacuum pump system should be applied instead of compressed air venturi methods.
- Cooling, aspirating, agitating, mixing, or package inflating: use blowers instead of compressed air
- Cleaning parts or removing debris: brushes, blowers or vacuum pump systems or nozzles that are more efficient should be used instead of compressed air.
- Moving parts: blowers, electric actuators or hydraulics should be used instead of compressed air.
- Blowguns, air lances and agitation: low pressure air should be used instead of high pressure compressed air.
- Efficient electric motors for tools or actuators: electric motors should be considered because they are more efficient than using compressed air (Howe and Scales, 1995). Some, however, have reported motors can have less precision, shorter lives, and lack safety. In these cases, using compressed air may be a better choice.

Numerous case studies in U.S. industries estimate an average payback period for replacing compressed air with other applications of 11 months (IAC, 2001).[4]

By lowering demand, Toyota reduced compressed air energy usage from 7200 scfm to 5100 scfm at their Georgetown (KY) plant (Toyota, 2002).

Load management. Because of the large amount of energy consumed by compressors, whether in full operation or not, partial load operation should be avoided. For example, unloaded rotary screw compressors still consume 15 to 35% of full-load power while delivering no useful work (LBNL et al. 1998). Centrifugal compressors are cost effective when operated at high loads (Castellow et al., 1997).

Air receivers can be employed near high demand areas to provide a supply buffer to meet short-term demand spikes that can exceed normal compressor capacity. In this way, required online compressors may be reduced. Multiple stage compressors theoretically operate more efficiently than single stage compressors. Many multi-stage compressors save energy by cooling the air between stages, reducing the volume and work required to compress the air (LBNL et al., 1998). Replacing single stage compressors with two-stage compressors typically provides a payback period of 2 years or less (Ingersoll-Rand, 2001). Using multiple smaller compressors instead of one large compressor can save energy as well. Large compressors consume more electricity when they are unloaded than do multiple smaller compressors with similar overall capacity. An analysis of U.S. case studies shows an average payback period for optimally sizing compressors of about 1.2 years (IAC, 2001).[4]

ABB Motors (Denmark), a manufacturer of motors, exchanged one large compressor (625 ft^3/min or 17.7 m^3/min) with four smaller compressors (2 of size 201 ft^3/min or 5.7 m^3/min and 2 of size 120 ft^3/min or 3.4 m^3/min) and found a payback period of 3.5 years (CADDET, 1999b). One of Honda's Canadian plants is successfully replacing a 1000 HP compressor with one half its size (CIPEC, 2002). The new 500 HP compressor will do the work that the larger (underutilized) compressor did.

Use air at lowest possible pressure. Although system pressure may be higher, air used for a particular application should be at the lowest pressure needed. In one example in the auto industry, Toyota uses their entire piping system as air receivers/regulators to manage air to applications (see Load Management section, above).

Minimize pressure drop in design of distribution system. An excessive pressure drop will result in poor system performance and excessive energy consumption. Flow restrictions of any type in a system, such as an obstruction or roughness, require higher operating pressures than are needed. Pressure rise resulting from resistance to flow increases the drive energy on positive displacement compressors by 1% of connected power for each 2 psi of differential (LBNL et al., 1998; Ingersoll-Rand, 2001). Highest pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles and lubricators (demand side), as well as air/lubricant separators on lubricated rotary compressors and aftercoolers, moisture separators, dryers and filters (supply side).

Minimizing pressure drop requires a systems approach in design and maintenance. Air treatment components should be selected with the lowest possible pressure drop at specified maximum operating conditions and best performance. Manufacturers' recommendations for maintenance should be followed, particularly in air filtering and drying equipment, which can have damaging moisture effects like pipe corrosion. Finally, the distance the air travels through the distribution system should be minimized.

A pressure reduction of 0.14 bar (2 psi) on a centrifugal air compressor results in savings of about 1% in electrical demand (Castellow et al., circa 1997). Typical pressure for an industrial plant system is 6.89 bar (100 psi). Castellow et al. (c. 1997) have summarized a "Large Manufacturing Customer Pilot Program (LMCP)" linking three major automotive plants, two steel plants and a large urban utility to carry out industrial energy projects. In the LMCP project, 5 to 6% savings of compressed air electrical demand were realized with pressure reductions of about 0.7 to 0.84 bar (10-12 psi).

Cold air intake. If air flow is kept constant, reducing the inlet air temperature reduces energy used by the compressor. In many plants, it is possible to reduce inlet air temperature to the compressor by taking suction from outside the building. As a rule of thumb, each 5°F (3°C) will save 1% compressor energy (CADDET, 1997c; Parekh, 2000). A payback period of 2 to 5 years has been reported for importing fresh air (CADDET, 1997c). In addition to energy savings, compressor capacity is increased when cold air from outside is used. Case studies taken from the IAC database have found an average payback period for importing outside air of about 11 months (IAC, 2001).[4] A sheet metal manufacturer (U.S.) used outside air for compressed air intake and found initial costs to be $400 and a payback period of less than one year (Kirk and Looby, 1996).

Controls. Remembering that the total air requirement is the sum of the average air consumption for each tool, not the maximum for each, the objective of any control strategy is to shut off unneeded compressors or delay bringing on additional compressors until needed. All compressors that are on should be running at full-load, except for one, which should handle trim duty.

To determine proper control systems, compressed air requirements should be assessed over time, establishing a load profile. At times when demand is less than peak, using multiple, smaller compressors with sequencing controls is often most efficient (LBNL et al. 1998). Facilities with a flatter load profile can use simpler control strategies. Positioning of the control loop is also important; reducing and controlling the system pressure downstream of the primary receiver can result in reduced energy consumption of up to 10% or more (LBNL et al., 1998). Radgen and Blaustein (2001) report energy savings for sophisticated controls to be up to 12%. Start/stop, load/unload, throttling, multi-step, variable speed and network controls are options for compressor controls and are described below.

Start/stop (on/off) is the simplest control strategy and can be applied to small reciprocating or rotary screw compressors. For start/stop controls, the motor driving the compressor is turned on or off in response to the discharge pressure of the machine. They are used for applications with very low duty cycles. Applications with frequent cycling will cause the motor to overheat. Typical payback period for start/stop controls is 1 to 2 years (CADDET, 1997c).

An automatic system that controls the operation of air compression can reduce electricity by matching output to demand. At Land Rover's Solihull site (UK), less than 10% of the energy consumed by the air compressors was converted into useful work; air compressors make up the most expensive form of energy at the plant (CADDET, 1995b). By installing a computerized control system for the air compressors, Land Rover's Solihull plant was able to reduce average weekday electricity by 16.5% and average weekend electricity consumption by 25%. Annually, they saved $41,000 1991 U.S.$ on energy costs (CADDET, 1995b). With a system implementation cost of $53,900 1991 U.S.$, they realized a 16 month payback period, and predict similar results for any compressed air system using three or more compressors.

Load/unload control, or constant speed control, allows the motor to run continuously but unloads the compressor when the discharge pressure is adequate. In most cases, unloaded rotary screw compressors still consume 15 to 35% of full-load power when fully unloaded, while delivering no useful work (LBNL et al., 1998). Hence, load/unload controls can be inefficient and require ample primary receiver volume.

Modulating or throttling controls allow the output of a compressor to be varied to meet flow requirements by closing down the inlet valve and restricting inlet air to the compressor. Throttling controls are applied to centrifugal and rotary screw compressors.

Changing the compressor control to a variable speed control can save up to 8% per year (CADDET, 1997c).

Multi-step or part-load controls can operate in two or more partially loaded conditions. Output pressures can be closely controlled without requiring the compressor to start/stop or load/unload.

System controls work on multiple compressors. Single master sequencing system controls take individual compressor capacities on- and off-line in response to monitored system pressure demand and shut down any compressors running unnecessarily. System controls for multiple compressors typically offer a higher efficiency than individual compressor controls.

Ford's Chicago (Illinois) plant has implemented a system wide control scheme that links three water cooled compressors with a heat recovery system (Ford, 2002). They have three modes for their three compressors: 1) full production, 70°F, 3 compressors running, or 2) exhaust off, 70°F, 2 compressors running, or 3) exhaust off, 65°F, 1 compressor running. In this way, only the necessary compressors are being used, saving the energy of the other one or two when the mode is not full production. As a part of their assessment projects (see Section 5.1), Ford has also implemented an entire system dynamics analysis for its compressed air systems (Ford, 2002).

Properly size regulators. Regulators can provide the largest energy savings in compressed air systems (Toyota, 2002). By properly sizing regulators, compressed air will be saved that is otherwise wasted as excess air. Also, it is advisable to specify pressure regulators that close when failing.

Sizing pipe diameter correctly. Inadequate pipe sizing can cause pressure losses, increase leaks and increase generating costs. Pipes must be sized correctly for optimal performance or resized to fit the current compressor system. Increasing pipe diameter typically reduces annual energy consumption by 3% (Radgen and Blaustein, 2001). In a model developed in the Netherlands for a system of three compressors, increasing distribution pipe diameters from 3 to 4 inches (80 to 100 mm) was projected to save 37,000 kWh/year or 2.4% (CADDET, 1997c).

Systems improvements. Adding additional compressors should be considered only after a complete system evaluation. In many cases, compressed air systems' efficiency could be managed and reconfigured to operate more efficiently without purchasing additional compressors. System improvements utilize many of the other measures discussed above. Compressed air system service providers offer integrated services both for system assessments and ongoing system maintenance needs, alleviating the necessity to contact many separate firms for these needs. Compressed Air Challenge® (CAC) offers free web-based guidance for selecting the right integrated service provider and guidelines defining walk-through evaluations, system assessments and fully instrumented system audits (CAC, 2002).

The Ford Woodhaven stamping plant (U.S.) undertook a compressed air systems approach which included several measures, such as identifying and correcting significant leaks, replacing leaking seals on the stamping press die automation valves, lowering the air header pressure and the pressure for some applications, and eliminating high-pressure satellite compressors by replacing them with adequate air from the main header. The aggregate energy savings were 7.9 million kWh, reducing energy costs by $360,000 or more than 3.5% (DOE, 2000a).

Modern Forge of Tennessee, a metal component manufacturing facility, undertook a compressed air system optimization project to correct the following problems: a lack of air storage to respond to demand spikes; high pressure drop from intermittent demand; poorly designed components (such as hoses, fittings, disconnects, regulators, and lubricators); dirty filtration devices; poorly operating controls; lubricant and moisture carryover (contributing to airflow resistance); and excessive compressor power on weekends (DOE, 2000c). System improvements in controls, air storage receivers, piping distribution, as well as installing a new dryer, replacing dirty filters, fixing leaks, replacing and upgrading drains, and purchasing a small compressor for weekend use saved the plant energy and avoided the purchase of an additional compressor, worth $120,000. Total cost for the improvements was $105,000. The annual electricity savings totaled 2.4 million kWh, ($120,000/year), 8% of total electric costs for the plant. These energy savings, together with reduced maintenance costs of $40,000 generated a payback period of 8 months, or even lower when considering the avoided purchase of the additional compressor.

Heat recovery for water preheating. As much as 80 to 93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a heat recovery unit can recover 50 to 90% of the available thermal energy for space heating, industrial process heating, water heating, makeup air heating, boiler makeup water preheating, industrial drying, industrial cleaning processes, heat pumps, laundries or preheating aspirated air for oil burners (Parekh, 2000). It is estimated that approximately 50 kBtu/hour of energy is available for each 100 ft^3/min of capacity (at full load) (LBNL et al., 1998). Payback periods are typically less than one year. Heat recovery for space heating is not as common with water-cooled compressors because an extra stage of heat exchange is required and the temperature of the available heat is lower. However, with large water cooled compressors, recovery efficiencies of 50 to 60% are typical (LBNL et al., 1998). Implementing this measure recovers up to 20% of the energy used in compressed air systems annually for space heating (Radgen and Blaustein, 2001). Numerous case studies estimate the average payback period for this measure at approximately 1.2 years (IAC, 2001).[4]

An Italian plant producing tappets for cars (levers used in vehicle assembly) used the waste heat gained by cooling the compressed air to heat part of the factory not served by the central heating plant. Payback period was less than 1 year (CADDET, 1997c). A metal fabrication plant (U.S.) implementing a heat recovery system had a payback period of 0.3 years for a similar system (Kirk and Looby, 1996).

Compressor motors. Motors are important in compressor systems as well, and are discussed in detail in section 5.2. Below are a few examples of their use with compressors:

- *Adjustable speed drives (ASDs).* Implementing adjustable speed drives in rotary compressor systems can save 15% of the annual energy consumption (Radgen and Blaustein, 2001).

- *High efficiency motors.* Installing high efficiency motors in compressor systems reduces annual energy consumption by 2%, and has a payback period of less than 3 years (Radgen and Blaustein, 2001). For compressor systems, the largest savings in motor performance are typically found in small machines operating less than 10kW (Radgen and Blaustein, 2001).

Natural gas engine-driven air compressors. Gas engine-driven air compressors can replace electric compressors with some advantages and disadvantages. Gas engine-driven compressors are more expensive but may have lower overall operating costs, depending on the relative costs of electricity and gas. Variable-speed capability is standard for gas-fired compressors, offering a high efficiency over a wide range of loads. Heat can be recovered from the engine jacket and exhaust system. This technology is new; it has currently penetrated less than 1% of the total air compressor market, and has some drawbacks. Gas compressors need more maintenance, have a shorter useful life, and sustain a greater likelihood of downtime.

Ultra Creative Corporation (U.S.), a manufacturer of specialty plastic bags, installed gas engine-driven compressors in its plant in Brooklyn, New York (Audin, 1996). The initial costs were $85,000 each for two 220-hp units and $65,000 for one 95-hp unit. They reported savings of $9,000 in monthly utilities (averaging $108,000 annually).

Nestlé (Canada) found their gas engine driven air compressor system to be cost effective when it operated properly, and felt it would eventually reach a payback period of 2.6 years with a 75% efficient heat recovery system, and 4.2 years without heat recovery (Audin, 1996). Total cost of the system was $179,000 1993 U.S.$, $45,000 1993 U.S.$ more than an equivalent electric unit. If heat recovery was included, the incremental cost would have risen to $56,000 1993 U.S.$, but savings would increase as well.

Energy efficient chillers. Energy efficient chillers use larger heat exchange areas and compressors that are more efficient to achieve overall operation that is more efficient. For example, for 500 to 1000 ton machines, energy efficient chillers achieve coefficients of performance (COPs) of 6.4 compared to standard models (particularly those 10 years old) with COPs of 4.1 (Castellow et al., circa 1997). Actual rated efficiency, however, is machine specific. Case studies indicate an average payback period for this measure of 2.8 years (IAC, 2001).[4]

5.4. Heat and Steam Distribution

Boilers are the heart of the steam generation system, and substantial efficiency improvements are feasible here. The main efficiency measures are listed below. These measures center around improved process control, reduced heat loss and improved heat recovery. In addition to the measures below, it is important to note that new boilers should almost always be constructed in a custom configuration. Pre-designed boilers are often out of date designs that cannot be tuned to the needs of a particular steam system (Ganapathy, 1994).

Boiler - improve process control. Flue gas monitors maintain optimum flame temperature and monitor carbon monoxide (CO), oxygen and smoke. The oxygen content of the exhaust gas is a combination of excess air (which is deliberately introduced to improve safety or reduce emissions) and air infiltration (air leaking into the boiler). By combining an oxygen monitor with an intake airflow monitor, it is possible to detect even small leaks. A small 1% air infiltration will result in 20% higher oxygen readings. A higher CO or smoke content in the exhaust gas is a sign that there is insufficient air to complete the fuel burning. Using a combination of CO and oxygen readings, it is possible to optimize the fuel/air mixture for high flame temperature (and thus the best energy efficiency) and lower air pollutant emissions. We assume that this measure can be applied to large boilers only because small boilers will not make up the initial capital cost as easily. Several case studies indicate an average payback period for this measure of about 1.2 years (IAC, 2001).[4]

Boiler - reduce flue gas quantities. Often excessive flue gas results from leaks in the boiler and the flue. This reduces the heat transferred to the steam, and increases pumping requirements. These leaks are often easily repaired. Savings amount to 2-5% of the energy formerly used by the boiler (DOE, 2001b). This measure differs from flue gas monitoring in that it consists of a periodic repair based on visual inspection. The savings from this measure and from flue gas monitoring are not cumulative, as they both address the same losses.

Boiler - reduce excess air. The more air is used to burn the fuel, the more heat is wasted in heating this air rather than in producing steam. Air slightly in excess of the ideal stochiometric fuel/air ratio is required for safety, and to reduce NO_x emissions, but approximately 15% is adequate (DOE, 2001a; Ganapathy, 1994). Poorly maintained boilers can have up to 140% excess air, but this is rare. Reducing this boiler back down to 15% even without continuous automatic monitoring would save 8% of total fuel use. The vast majority of boilers already operate at 15% excess air or lower, and thus this measure is not considered significant (Zeitz, 1997). However, if the boiler is using excess air, numerous case studies indicate an average payback period for this measure of 8 months (IAC, 2001).[4] A rule of thumb often used is that boiler efficiency can be increased by 1% for each 15% reduction in excess air or 40°F (22°C) reduction in stack gas temperature (DOE, 2001a). CIPEC (2001a) estimates reducing oxygen (O_2) in the flue gas by 1% increases boiler efficiency by 2.5%.

Boiler - correct sizing in design. Correctly designing the boiler system at the proper steam pressure can save energy by reducing stack temperature, reducing piping radiation losses and reducing leaks in traps and other sources. In a study done in Canada on 30 boiler plants, savings from this measure ranged from 3% to 8% of the total gas consumption (Griffin, 2000). Savings were greatest when the pressure is reduced below 70 psig.

Using smaller boilers when not operating at or near full load also reduces energy use. Saskatchewan Penitentiary (Canada) installed two new smaller boilers for their summer operations and to supplement their winter operations. These replaced old oversized boilers operating at low fire for most of the year. The found gas savings of 17% or 18,321 MBtu, resulting in $50,000 2001 U.S.$ of energy cost savings per year (CIPEC, 2001a).

Boiler - improve insulation. It is possible to use new materials that insulate better, and have a lower heat capacity (and thus warm up faster). Savings of 6-26% can be achieved if this improved insulation is combined with improved heater circuit controls. Improved control is required to maintain the output temperature range of the old firebrick system. Because of the ceramic fiber's lower heat capacity, the output temperature is more vulnerable to temperature fluctuations in the heating elements (Caffal, 1995). An additional benefit is that heating is more rapid when starting the boiler. Several case studies estimate an average payback period for this measure of about 11 months (IAC, 2001).[4]

Boiler - maintenance. A simple maintenance program to ensure that all components of the boiler are operating at peak performance can result in substantial savings. In the absence of a good maintenance system, the burners and condensate return systems can wear or get out of adjustment. These factors can end up costing a steam system up to 20-30% of initial efficiency over 2-3 years (DOE, 2001a). We estimate a 10% possible energy savings on average (DOE, 2001a). Improved maintenance may also reduce the emission of criteria air pollutants. Numerous case studies estimate an average payback period for boiler maintenance of approximately 8 months (IAC, 2001).[4]

Fouling of the fireside of the boiler tubes or scaling on the waterside of the boiler should also be controlled. Fouling and scaling are more of a problem with coal-fed boilers than natural gas or oil-fed ones (boilers that burn solid fuels like coal should be checked more often as they have a higher fouling tendency than liquid fuel boilers do). Tests show a soot layer of 0.03 inches (0.8 mm) reduces heat transfer by 9.5%, while a 0.18 inch (4.5 mm) layer reduces heat transfer by 69% (CIPEC, 2001a). For scaling, 0.04 inches (1 mm) of buildup can increase fuel consumption by 2% (CIPEC, 2001a).

Boiler - recover heat from flue gas. According to CIPEC (2001a), heat recovery from the flue gas is the best opportunity for heat recovery in the boilerhouse. Heat from flue gasses can be used to preheat boiler feed water in an economizer. While this measure is fairly common in large boilers, there is often still room for more heat recovery. The limiting factor for flue gas heat recovery is that one must ensure that the economizer wall temperature does not drop below the dew point of acids in the flue gas (such as sulfuric acid in sulfur containing fossil fuels). Traditionally this has been done by keeping the flue gases exiting the economizer at a temperature significantly above the acid dew point. In fact, the economizer wall temperature is much more dependent on the feed water temperature than the flue gas temperature because of the high heat transfer coefficient of water. As a result, it makes more sense to preheat the feed water to close to the acid dew point before it enters the economizer. This allows the economizer to be designed so that the flue gas exiting the economizer is just barely above the acid dew point. 1% of fuel use is saved for every 45°F (25°C) reduction in exhaust gas temperature (Ganapathy, 1994). Since exhaust gas temperatures are already quite low but can still take advantage of using the higher temperature feed water mentioned above, we estimate a 1% savings. Several case studies estimate an average payback period for this measure of about 1.7 years (IAC, 2001).[4] Application of this measure in the semiconductor manufacturing industry (U.S.) has shown a payback period as short as 11 months (Fiorino, 2000).

Boiler - return condensate. Reusing the hot condensate in the boiler saves energy, reduces the need for treated boiler feed water and reclaims water at 100°C (212°F) sensible heat savings. Usually fresh water must be treated to remove solids that might accumulate in the boiler, and returning condensate can substantially reduce the amount of purchased chemical required to accomplish this treatment. The fact that this measure can save substantial energy costs and purchased chemicals costs makes building a return piping system attractive. This measure has, however, already been implemented in most of the vehicle assembly plants where it is easy to accomplish. We assume a 10% energy savings (DOE, 2001a) and found an average payback period of about 1.1 years (IAC, 2001).[4] A metal fabrication plant (U.S.) began condensate return with an initial implementation cost of $2,800, found annual savings of $1,790 and a payback period of 1.6 years (Kirk and Looby, 1996).

Boiler - recover steam from blowdown. When the water is blown from the high-pressure boiler tank, the pressure reduction often produces substantial amounts of steam. This steam is low grade, but can be used for space heating and feed water preheating. We assume that this measure can save 1.3% of boiler fuel use in small boilers[7]. Applications in the semiconductor manufacturing industry (U.S.) have shown payback periods of as little as 1.5 years (Fiorino, 2000). Three other case studies from the IAC database had payback periods of 5 months, 8

[7] Based on the following assumptions: 10% of boiler water is blown down (DOE, 2001a) and 13% of the energy can be recovered from this (Johnston, 1995).

months and 1.3 years, respectively (IAC, 2001).[4] In addition to energy savings, blowdown recovery may reduce the potential for corrosion damage in piping in the steam system.

Boiler - replace obsolete burners by new optimized boilers. Replacing inefficient coal-fired boilers with gas-fired boilers increases energy efficiency and reduces emissions. General Motors replaced old coal fired boilers with new gas boilers at its Buick Complex in Flint (Michigan) and with new direct fired gas boilers at the Metal Fabrication Division Facility in Mansfield (Ohio) and at the Powertrain Tonawanda facility (NY) (GM, 2001 and 2002a). Since 1991, General Motors has converted or shut down boilers at twelve sites (GM, 2001 and 2002a). Since June 1998, Ford has successfully replaced steam usage at eight of its twelve assembly plants with direct-fired gas heating and hot water. Another project is scheduled at its Dearborn (Michigan) facility. Bristol Aerospace (UK) replaced two boilers with three higher efficiency dual-fired natural gas/electric boilers and found energy savings of $23,000 (1995 U.S.$) (Caffal, 1995). The average estimate of payback period for replacing obsolete burners has been estimated at approximately 2.3 years (IAC, 2001).[4]

Steam and hot water distribution systems are often quite extensive, and can be major contributors to energy losses at any industrial plant. The purpose of steam distribution is simple: to get steam from the boiler to the process where it will be used. The methods for reducing energy losses are correspondingly simple: retaining more heat and recovering it after it has been used.

Distribution - improve insulation. Using more insulating material or using the best insulation material for the application can save energy in steam systems. Crucial factors in choosing insulating material include low thermal conductivity, dimensional stability under temperature change, resistance to water absorption and resistance to combustion. Other characteristics of insulating material may also be important depending on the application. These characteristics include tolerance of large temperature variation and system vibration and compressive strength where insulation is load bearing (Baen and Barth, 1994). Improving the insulation on the existing U.S. stock of heat distribution systems would save an average of 3-13% in all systems (DOE, 2001a). Numerous case studies indicate payback period is 1 year (IAC, 2001).[4] CIPEC (2001a) estimates that insulating a 10 foot (3 m) long 4 inch (10 cm) steam pipe can be paid back in less than 6 months.

Distribution - maintain insulation. It is often found that after heat distribution systems have undergone some form of repair, the insulation is not replaced. In addition, some types of insulation can become brittle or rot under normal wear. As a result, a regular inspection and maintenance system for insulation can save energy (Zeitz, 1997). Exact energy savings and payback periods are unknown and vary based on the existing practices.

Distribution - improve steam traps. Using modern thermostatic element steam traps can reduce energy use while improving reliability. The main efficiency advantages offered by these traps are that they open when the temperature is very close to that of the saturated steam (within 4°F or 2°C), purge non-condensable gases after each opening and are open on startup to allow a fast steam system warm-up. These traps also have the advantage of being highly reliable and useable for a wide variety of steam pressures (Alesson, 1995). The exact savings and market penetration potential in the vehicle assembly industry are unknown. One disadvantage to thermostatic steam traps is that testing is trickier and therefore maintenance is more difficult than on bucket traps (Toyota, 2002).

Distribution - maintain steam traps. A simple program of checking steam traps to ensure they are operating properly can save significant amounts of energy for very little money. If the steam traps are not regularly monitored, 15-20% of the traps can be malfunctioning. Energy savings for a regular system of steam trap checks and follow-up maintenance is conservatively estimated at 10% (DOE, 2001a; Jones 1997; Bloss, 1997). Several case studies indicate an average payback period for this measure of 4 months (IAC, 2001).[4] Although this measure offers a quick payback period it is often not implemented because maintenance and energy costs are separately budgeted. In addition to energy and cost savings, proper functioning of steam traps will reduce the risk of corrosion in the steam distribution system.

Distribution - monitor steam traps automatically. Attaching automated monitors to steam traps in conjunction with a maintenance program can save even more energy without significant added cost. This system is an improvement over steam trap maintenance alone, because it gives quicker notice of steam trap failure, and can detect when a steam trap is not performing at peak efficiency. Using automatic monitoring is conservatively estimated to give an additional 5% energy savings over steam trap maintenance alone with a payback period of 1 year[8] (Johnston, 1995; Jones, 1997). Systems that are able to implement steam trap maintenance are also likely to be able to implement automatic monitoring.

Distribution - repair leaks. As with steam traps, the distribution pipes themselves often have leaks that (on average) go unnoticed without a program of regular inspection and maintenance. In addition to saving 3% of energy costs, having such a program can reduce the likelihood of having to repair major leaks, thus saving even more in the long term (DOE, 2001a). Average payback period from several case studies is estimated at about 4 months (IAC, 2001).[4]

Distribution - recover flash steam. When a steam trap purges condensate from a pressurized steam distribution system to ambient pressure, flash steam is produced. As with flash steam produced by boiler blowdown, this steam can be used for space heating or feed water preheating (Johnston, 1995). The potential for this measure is extremely site dependent, as it is unlikely that a producer will want to build an entirely new system of pipes to transport this low grade steam to places where it can be used. If, on the other hand, the areas where low-grade heat is useful were very close to the steam traps anyway, this measure would be easy to implement and could save considerable energy. Case studies estimate an average payback period of 1.1 years (IAC, 2001).[4]

5.5. Lighting

Lighting is used either to provide overall ambient light throughout the manufacturing storage and office spaces or to provide low bay and task lighting to specific areas. High-intensity discharge (HID) sources are used for manufacturing and storage areas, including metal halide, high-pressure sodium and mercury vapor lamps. Fluorescent, compact fluorescent (CFL) and incandescent lights are typically used for task lighting and offices. In addition, lighting controls should be used in all areas of the plant. Green Lights, a voluntary program developed by the EPA to encourage the installation of energy efficient lighting and now incorporated into the ENERGY STAR Program, suggested cost-effective ways to save on lighting energy (EPA, 2001a). According to General Motors, who participated in Green Lights and now ENERGY STAR and implemented many of the cost saving measures at several of their U.S. plants, a typical assembly plant can save 10 million kWh per year (5% of a plant's electricity usage) through lighting improvements (GM, 2001 and 2002a). For example, as part of its participation in Green Lights, General Motors converted the lighting system at its Linden Assembly Plant (New Jersey) to an

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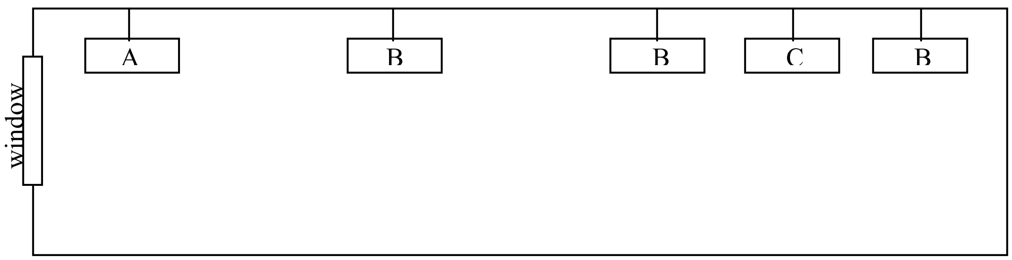
[8] Calculated based on a UK payback of 0.75 years. The U.S. payback is longer because energy prices in the U.S. are lower, while capital costs are similar.

energy efficient lighting system and reduced electric use by 15 million kWh per year (GM, 2001). General Motors also completed lighting improvement surveys for all of their truck assembly plants.

Lighting controls. Lights can be shut off during non-working hours by automatic controls, such as occupancy sensors, which turn off lights when a space becomes unoccupied. Manual controls can also be used in addition to automatic controls to save additional energy in small areas. Numerous case studies indicate average payback period for lighting controls is approximately 1.1 years (IAC, 2001).[4]

When lighting placement is combined with controls, lighting can be reduced throughout the day. The following schematic details a possible method for placing luminaries.

Figure 5. Lighting placement and controls



During the brightest part of the day, only row C needs to be on. When daylight levels drop, all B rows should be turned on to replace row C. Only at night or very dark days would it be necessary to have rows A and B on (Cayless and Marsden, 1983). These methods can also be used as a control strategy on a retrofit by adapting the luminaries already present. (For example, turn on the lighting in the rows away from the windows during the brightest parts of the day and supplemental rows later.)

The electricity savings for Volvo's Torslanda plant (Sweden) for turning off lights during non-working hours were estimated at 630 kW (about 56%) in the final assembly plant; 370 kW (about 30%) in the paint shops; and, 210 kW (about 18%) in the press shop (Dag, 2000).

A metal fabrication plant (U.S.) installed photosensor controls on lighting, costing $3000 to implement and yielding a payback period of 1.9 years (Kirk and Looby, 1996).

Setting lighting standards. Lighting levels (lumen per surface area) should be set in the design stage for each section of the assembly plant and followed in each step of the ordering, manufacturing and installation stages. It is necessary to work both with the manufacturers and the suppliers to ensure that the proper system is installed. For example, Toyota set a standard of 100 lumen/m^2 in the quality check areas. They also set different standards for office buildings. By setting a lumen/surface area standard and sticking to it, Toyota claims savings of 30% on lighting energy use (Toyota, 2002). As a part of their assessment programs (see Section 5.1), Ford is aiming to reduce energy costs for lighting by eliminating some lights where areas are overlit.

Daylighting. Daylighting is the efficient use of natural light in order to minimize the need for artificial light in buildings. Increasing levels of daylight within rooms can reduce electrical lighting loads by up to 70% (CADDET, 2001). Daylighting differs from other energy efficiency measures because its features are integral to the architecture of a building, and so is applied primarily to new buildings and incorporated at the design stage. Daylighting can be combined with lighting controls to maximize its benefits. Because of its variability, daylighting is almost always combined with artificial lighting to provide the necessary illumination on cloudy days or after dark. Daylighting technologies include properly placed and shaded windows, atria, angular or traditional (flat) rooflights, clerestories, light shelves and light ducts. Clerestories, light shelves and light ducts utilize angles of the sun and redirect light with walls or reflectors. Some problems associated with daylighting on industrial buildings have been identified due to the structure of the building. On flat roofed industrial plant buildings, daylights were found to leak and fog from exposure to UV after a number of years (Toyota, 2002). Case studies estimate an average payback period for this measure of 1.6 years (IAC, 2001).[4]

Many daylighting systems have been installed around the world with varying energy savings results. The Tokyo Electric Power Company's R&D center (Japan) uses windows with automatically controlled blinds. They have reduced power used for lighting by about 50% (CADDET, 2001). The National Renewable Energy Laboratory (NREL) Thermal Test Facility in Colorado installed tinted windows, clerestory windows and overhangs, saving 75% of lighting costs ($3,500/year) (CADDET, 2001). Ford's new River Rouge plant (MI) will incorporate daylighting in the assembly facilities.

Replace incandescent lights with fluorescent lights or compact fluorescent lights (CFLs, most efficient). The fluorescent lamp lasts roughly ten times longer than an incandescent light and is three times more effective (EPA, 2001a; Honda, 2001). The payback period for the replacement varies, but can be as low as five months (EPA, 2001a). Honda's Marysville Auto Plant (U.S.) replaced 200 fluorescent lights with 58 metal halide bulbs and found a reduction in electricity usage (Honda, 2001). Honda also claimed the amount of light increased by 118% resulting in higher quality visual inspections at the production line.

Replace T-12 tubes with T-8 tubes or metal halides. Most spraybooths built in the last 30 years have utilized T-12 fluorescent lamps enclosed in vapor-proof fixtures (DEQ, 2001d). T-12 refers to the diameter in 1/8 inch increments (T-12 means 12/8 inch or 3.8 cm diameter tubes). The initial output for T-12 lights is high, but energy consumption is also high. They also have extremely poor efficacy, lamp life, lumen depreciation and color rendering index. Because of this, maintenance and energy costs are high. Replacing T-12 lamps with T-8 lamps (smaller diameter) approximately doubles the efficacy of the former (DEQ, 2001d). It is important to remember, however, to work both with the suppliers and manufacturers on the system as a whole through each step of the process. There are a number of T8 lights and ballasts and the correct combination should be chosen for each system.

Ford North America has retrofitted eleven of its sixteen paint shops and reduced lighting costs by more than 50% (DEQ, 2001d). Initial light levels were lower, but because depreciation is less, the maintained light level is equal and the new lamps last two to three times longer. Energy savings totaled 17.5 million kWh annually; operation savings were $500,000 per year. Ford has also concentrated on lighting as a part of its assessment projects. They have spent over $12 million on the conversion from T-12 to T-8 lights in 20 offices and many of their assembly plants (Ford, 2002). Ford believes that many more opportunities are still available. In the same assessment projects, Ford has also replaced 400 watt metal halide lights with 360 watt lights. There is only a 10% reduction of light and a similar percentage in energy savings (Ford, 2002).

The Gillette Company manufacturing facility in Santa Monica, California replaced 4300 T-12 lamps with 496 metal halide lamps in addition to replacing 10 manual switches with 10 daylight switches (EPA, 2001a). They reduced electricity by 58% and saved $128,608 annually. The total project cost was $176,534, producing a payback period of less than 1.5 years.

Replace mercury lights with metal halide or high pressure sodium lights (most efficient). Where color rendition is critical, metal halide lamps can replace mercury or fluorescent lamps with energy savings of 50% (Price and Ross, 1989). Where color rendition is not critical, high-pressure sodium lamps offer energy savings of 50 to 60% compared to mercury lamps (Price and Ross, 1989). High pressure sodium lamps also produce less heat, reducing HVAC loads.

General Motors's Oshawa Car Assembly Plant (Canada) retrofitted high bay lighting with metal halide lighting. The new system eliminated 3700 kW of lighting, and reduced energy consumption by 26.5 million kWh or 46% (GM, 2001). In addition to energy reductions, the metal halide lights provide better lighting, provide better distribution of light across work surfaces and improve color rendition (GM, 2001). By implementing this measure, General Motors achieved operational cost savings of $2 million annually.

Replace standard metal halide HID with high-intensity fluorescent lights. Traditional HID lighting can be replaced with high-intensity fluorescent lighting. These new systems incorporate high-efficiency fluorescent lamps, electronic ballasts and high-efficacy fixtures that maximize output to the work space. Advantages of the new system are many: lower energy consumption, lower lumen depreciation over the lifetime of the lamp, better dimming options, faster start-up and restrike capability, better color rendition, higher pupil lumens ratings and less glare (Martin et al., 2000). High-intensity fluorescent systems yield 50% electricity savings over standard metal halide HID. Dimming controls that are impractical in the metal halide HIDs can also save significant energy in the new system. Retrofitted systems cost about $185 per fixture, including installation costs (Martin et al., 2000). In addition to energy savings and better lighting qualities, high-intensity fluorescents can help improve productivity and have reduced maintenance costs.

Replace magnetic ballasts with high frequency electronic ballasts. A ballast is a mechanism that regulates the amount of electricity required to start a lighting fixture and maintain a steady output of light. Electronic ballasts save 12-30% power over their magnetic predecessors (Cook, 1998; EPA, 2001a). New electronic ballasts have smooth and silent dimming capabilities, in addition to longer lives (up to 50% longer), faster run-up times and cooler operation (Eley et al., 1993; Cook, 1998). New ballasts also have automatic switch-off for faulty or end of life lamps. If automatic daylight sensing, occupancy sensing and manual dimming are included with the ballasts, savings can be greater than 65% (Turiel et al., 1995).

Reflectors. Reflectors are highly polished "mirror-like" components that direct light downward, reducing light loss within a fixture. Reflectors can minimize required wattage by using less more effectively. Several U.S. case studies estimate an average payback period for reflectors of 1.4 years (IAC, 2001).[4]

Light emitting diodes (LEDs) or radium strips. One way to reduce energy costs is simply switching from incandescent lamps to LEDs or radium strips in exit sign lighting. LEDs use about 90% less energy than conventional exit signs (Anaheim Public Utilities, 2001). A 1998 Lighting Research Center survey found that about 80 percent of exit signs being sold use LEDs (LRC, 2001). In addition to exit signs, LEDs are increasingly being used for path marking and emergency wayfinding systems. Their long life and cool operation allows them to be embedded in plastic materials, which makes them perfect for these applications (LRC, 2001). Radium strips use no energy at all.

System improvements. By combining several of the lighting measures above, light system improvements can be the most effective and comprehensive way to reduce lighting energy. High frequency ballasts and specular reflectors can be combined with 50% fewer efficient high-frequency fluorescent tubes and produce 90% as much light while saving 50 to 60% of the energy formerly used (Price and Ross, 1989).

An office building in Michigan reworked their lighting system using high-efficiency fluorescent ballasts and reduced lighting load by 50% and total building electrical load by nearly 10% (Price and Ross, 1989). Similar results were obtained in a manufacturing facility when replacing fluorescent fixtures with metal halide lamps. Often these system improvements improve lighting as well as decrease energy consumption.

Reducing system voltage can also save energy. Toyota put in reduced voltage HID lights and found a 30% reduction in lighting energy use (Toyota, 2002). Electric City is one of the suppliers of EnergySaver, a unit that attaches to a central panel switch (controllable by computer) and constricts the flow of electricity to fixtures, thereby reducing voltage and saving energy, with an imperceptible loss of light. Bristol Park Industries has patented another lighting voltage controller called the Wattman© Lighting Voltage Controller that works with high intensity discharge (HID) and fluorescent lighting systems with similar energy saving results (Bristol Park Industries, 2002).

5.6. Heating, Ventilation and Air Conditioning (HVAC)

HVAC includes heating, ventilation and air conditioning systems. HVAC comprises a significant amount of the energy used. It is estimated that HVAC uses 11 to 20% of the electricity used in vehicle assembly plants (Table 1), and fuel is mainly used for space heating and drying in painting. Many of the measures applicable to HVAC systems have been discussed under motors, compressed air and heat and steam distribution. A few additional measures are discussed below.

Electronic controls. Electronic controls can be as simple as on/off switches to be switched off during non-operating hours. Several industrial U.S. case studies have indicated an average payback period for computer controls for HVAC of about 1.3 years (IAC, 2001).[4]

Using a simple on/off control, Volvo's manufacturing plant in Torslanda (Sweden), reduced the energy used in ventilation in the paint shop by 50%, or 8.25 million kWh/year (Dag, 2000). A more complicated, climate-adapted ventilation system of control was proposed for the same plant. Reduction in energy use is expected to be approximately 22% or 1.95 million kWh, in addition to the energy savings achieved already (Dag, 2000).

Weekend setback temperatures. Setting building temperatures lower during the winter or higher during the summer over the weekend and during non-production times can save energy by reduced heating or cooling needs (see also Energy Management Systems).

Ventilation and cooling system design improvements. New local ventilation and cooling systems and controls respond to current conditions in their plant, better matching ventilation or cooling output to demand. Three types of cooling systems exist: intermittent air supply systems where air is chilled only when workers are present; variable air volume (VAV) systems with constant temperature for local cooling; or variable air temperature (VAT) with constant volume for local cooling.

Toyota in Japan installed all three systems in their factory workshops with excellent results. The new intermittent air and VAV systems each saved 50% electricity costs annually, while the VAT systems saved 25% annually (CADDET, 1991b). They found that the cost of upgrading an existing air-conditioning system to the new systems cost 25 to 40% less than installing a totally new system. They also noted that the intermittent air supply system and the VAV system can easily be added to existing air-conditioning systems with additional units. The VAT system, however, requires a new system and should only be installed in new workshops. In addition to reducing running costs of cooling systems and reducing energy use, these systems also improve the working environment.

Named the "Big Foot" projects, Ford is replacing steam heating systems, and replacing them by direct-fired heating units and gas-fired hot water heaters for process water. The project includes ductwork to supply ventilation air and uses the existing exhaust fans to vent the buildings. The system is computer controlled and includes monitors inside and outside the buildings. The system maintains a slight positive pressure, which prevents cold outside air from leaking into the building during the winter and warm air in the summer. "Big Foot" refers to the large roof mounted heating and ventilation units. The system has been installed in 8 assembly plants in the U.S. and has resulted in annual savings of $16.6 million ($1.3 million because of decommissioned steam boilers and $15.3 million in energy costs) and 3.2 TBtu in energy. The payback period would have been around 4 years. However, the project is financed and installed by a third party through a performance contract with Ford.

Recover cooling water from other sources to use in cooling chillers. The Boeing Company in Washington partnered with Puget Sound Power and Light and King County Department of Metropolitan Services (Metro) to recycle secondary treated cooling water into its chiller system. By using this treated water from Metro, Boeing reduced its water use by 48 million gallons per year and projected savings of 20% in cooling energy (Michaelson and Sparrow, 1995). They will also save on refrigerant and treatment chemicals for the cooling tower water.

Solar heating (Solarwall). Solarwall heating systems use conventional steel siding painted black to absorb solar radiation for insulation. Fresh air enters the bottom of the panels where it is heated as it passes over the warm absorber. Fans distribute the air. Using this technology, Ford Motor Company's Chicago Stamping plant turned the south wall of its plant into a huge solar collector (CREST, 2001). Energy savings were estimated to be over $300,000 a year compared to conventional gas air systems. Capital costs were $863,000 ($14.90 per square foot, including installation) resulting in a payback period of less than 3 years. In addition to energy savings, the system provides clean fresh air for its employees, evens out hot and cold spots in the plant and reduces emissions. Ford admits, however, that good maintenance is required for successful operation, and that plant expansions may not include the carryover of the Solarwalls, hence, none of its three Solarwalls put in place ten years ago are still in operation today (Ford, 2002).

Building shell. The building shell can serve as insulation from the weather (either hot or cold). For example, use of a reflective coating on the roof of buildings in sunny, hot climates can save on air conditioning costs inside. Two medical offices in Northern California used reflective roofs on their buildings and found summertime daily air-conditioning savings of 13 and 18% and reduced demand of 8 and 12% (Konopacki et al., 1998). For colder climates, heat lost due to cool roofs (in the winter, for example) also needs to be taken into account, and often negates savings. In addition to location and weather, other primary factors influence energy savings, such as roof insulation, air conditioning efficiency and building age.

Roof gardens on a flat roof improve the insulation of the building against both hot and cold by providing both heat and air condition. In winter, green roofs can freeze, so they carry a slight heating penalty but they still yield a net energy savings (Holtcamp, 2001). When temperatures plummet below freezing, the roof surface remains at 32°F (0°C), an advantage in very cold climates. In addition, a roof garden can increase the lifetime of the roof, provide and reduce runoff, and reduce air pollution and dust. Today, Germany installs over 10 million square feet of green roofs a year, helped in part by economic incentives (Holtcamp, 2001). The Gap Headquarters in San Bruno (California) installed green roofs in 1997 (Greenroofs.com, 2001). In addition to saving energy and lasting longer than traditional roofs, their roof garden also absorbs rain, slowing run-off to local storm-drains.

Many other simple options for decreasing energy use exist for certain conditions. Shade trees reduce cooling for hot climates. Shade trees should be deciduous trees (providing shade in the summer and none in the winter) and planted on the southwest side of the building. Trees planted on the North side of the building in cold climates can reduce heating in winter by shielding the building from the wind. Vines can provide both shade and wind shielding. Low emitting windows and more insulation can also save on heating costs in the winter.

Ford, as a part of its assessment projects (see Section 5.1), has begun to examine exhaust from the HVAC systems at its plants. Specifically, assessors are reporting when exhaust is simply blown outside in winter, along with its (wasted) heat energy (Ford, 2002). Ford plans to recapture that energy for heating purposes.

Modifying fans. Changing the size or shape of the sheaves of a fan can save energy by controlling the airflow and running at the design speed. Toyota cut the sheaves of its fans instead of installing ASDs and found better savings and payback periods than they anticipated from ASDs (Toyota, 2002).

Other HVAC measures. Other measures for HVAC in commercial buildings may be applicable to some vehicle assembly plant facilities, particularly office buildings that are similarly designed. For example, resetting thermostat set points by a few degrees can have significant savings. Better insulation of the ducts and repair of duct leaks has been found to save significant energy for homes and offices. For houses in Sacramento (California), approximately 30 to 40% of the thermal energy delivered to ducts is lost through air leakage and conduction through the walls (Jump and Modera, 1994).

5.7. Materials Handling and Tools

High efficiency belts (cog belts). Belts make up a variable, but significant portion of the total motor drive in most plants. Standard vee belts tend to stretch, slip, bend and compress, which lead to a loss of efficiency (CIPEC, 2001b). Replacing standard vee belts with cog belts can save energy and money, even as a retrofit. Cog belts run cooler, last longer, require less maintenance and have an efficiency that is about 2% higher than standard vee belts (DOE, 2001e; CIPEC, 2001b). Upgrading to high-torque cog belts can result in up to 6% savings over standard vee belts (CIPEC, 2001b). Motor load reductions of 2 to 10% have been shown from replacing vee belts with cog belts (Price and Ross, 1989).

A metal fabrication plant (U.S.) replaced vee belts with synchronous belts and sprocket drives for $960 (Kirk and Looby, 1996). Their annual savings of $560 produced a payback period of 1.7 years. CIPEC (2001b) estimates the payback period for replacing standard belts with more efficient ones to be 6 months to 3 years. Other case studies estimate an average payback period for this measure of 1.0 year (IAC, 2001).[4]

5.8. Painting Systems

Paint shops are the major energy-consuming center at automobile assembly plants. Energy is used to condition the air for the painting and drying steps, as well as for the drying process and for treatment of the emissions. Ford reports that 70% of the total energy costs in its assembly plants is used by the painting operations. Within the painting process itself, relatively little energy is required for curing (drying) the thin paint film in comparison to the energy used in raising the temperature of the dollies and the carriers as well as the car bodies (Takahashi et al., 1999). Related to the painting process, the painting booths must be purged to remove evaporated solvent, oversprayed paint particles and regulated pollutants (like VOCs) from the spray application. Like the HVAC-energy needs, ventilation energy is significant (Takahashi et al., 1999).

VOCs emissions are reduced through source control (e.g. powder paints or low VOC/high solids water-based coatings), capturing and concentrating them (with activated carbon, for example) and recycling or destroying them (like incineration). Several of these options are discussed below. The energy required for this process depends heavily on the target outlet concentrations of VOCs. These targets vary from plant to plant (depending on emission regulations), so energy originally spent and potential to save will also vary.

Energy efficiency opportunities can be found in improved management and maintenance of the painting lines, optimization of heat distribution and recovery in existing paint lines, changes in painting systems, as well as optimization of the waste treatment (e.g. VOCs, cleaning).

Maintenance and controls. Over time, painting lines may perform less efficiently. Preventative maintenance before problems occur can help to optimize productivity and energy use. Energy savings will depend on the current situation and are difficult to estimate; however, where possible, we have included data on costs and savings. Generally, preventative maintenance in industry seems to result in savings up to 2% with immediate payback periods (or less than 1 year) (Caffal, 1995). Proper maintenance and controls include the following:

- Temperature, humidity and ventilation must be within the proper ranges for effective operation. Badly functioning or positioned temperature controls may lead to excessive operating temperatures, while insufficient control of the heating time needed for the vehicle entering the painting line may also lead to excessive drying temperatures (Klein, 2000). Make sure thermocouples are positioned correctly, and consider adding more thermocouples or proportional integral device (PID) burner control systems for better monitoring and control (Best Practice Programme, 1999b).
- Avoid over-thinning solvent or water-born coatings by adding too much solvent. Often extra solvent is added to compensate for low temperatures. This should be avoided because it can over-thin coatings and waste solvent (Best Practice Programme, 1999a).
- Heat losses may occur because of badly functioning entry and exit doors and air locks.
- Too large air volumes may lead to excessive energy use (see also ventilation). Make sure the air to fuel ratio is at its optimal level. Too little air will result in incomplete combustion but too much air will reduce energy efficiency, as the excess will have to be heated up as well. In addition, reducing too large an air volume will reduce equipment size and therefore capital costs, as well as avoid design problems in the chiller. Often this requires implementation of additional controls, which, in 1990 cost about $1,600 1990 U.S.$, but provides better oven performance, energy savings and reduced operating costs (Best Practice Programme, 1999a). In addition, too low an air volume and cold spots in the installation may lead to condensation and reduced paint quality (Klein, 2000). Installing an air to fuel control unit reduces energy by 5 to 15%, depending on demand (Best Practice Programme, 1999a).

  In the UK, an oven using $16,000 1999 U.S.$ worth of energy per year has a payback period of less than one year (Best Practice Programme, 1999a). Ford Motor Company (U.S.) lowered energy use in its regenerative thermal oxidizers by reducing the air to fuel ratio (AF) from 10% to 6% and adjusting maintenance hatches. This action reduced the BTUs required to heat up the excess air resulting in a net reduction in gas requirements. Ford also redesigned the access hatches on each regenerative thermal oxidizer (RTO), which decreased the amount of natural gas required to maintain operational temperature. In adopting these measures, Ford invested $160,000 in capital and found $600,000 annual savings (division wide), resulting in a 4 month payback period (DEQ, 2001f). According to Ford (2002), similar projects were initiated at paint shops across the country with equally profitable results: investments of $600,000 produced a return of $1.3 million for all their paint shops combined, even with low gas prices (Ford, 2002).

- For air recirculating ovens, recirculate as much air as possible. Consider adding air flow sensors that measure how well the flows within the oven are balanced. An energy efficient air recirculation oven should recycle 90% of the air within the oven (Best Practice Programme, 1999b). (Some air has to be exhausted to remove combustion products, to ensure enough oxygen for combustion is present and to ensure proper solvent concentrations.) A rule of thumb is that for every 2000 hours/year an oven operates, every 10 m^3/hour (3530 ft^3/hour) of exhaust flow loses 150 kWh at 50°C (122°F), 400 kWh at 100°C (212°F), 600 kWh at 150°C (302°F) and 750 kWh at 200°C (392°F) (Best Practice Programme, 1999b).
- Enclose any automated process and reduce ventilation requirements where possible.
- Regularly service the burners. A service engineer can do this within minutes (Best Practice Programme, 1999a).
- Make sure air movement in hot air recirculating ovens is not too high (e.g., if components swing, air movement is excessive) (Best Practice Programme, 1999a).
- Check that the air exhaust from the oven is not excessive. This requires optimization for safety first and then energy efficiency.
- Separate combustion fans should be installed to control air flow through the dryers. Controlling the air flow can yield the biggest savings in a paint booth (See Reduce air flow in paint booths section).

Minimize stabilization period. Paint booths require some start up time to heat up to the temperature required by the painting process and to remain stable at that point. By minimizing the time for stabilization, significant amounts of energy will be saved since the ovens will be (pre-) heated for a shorter period. Start/stop controls can aid in the functioning of the startup. In addition, ovens can be staged so that they are not ready when the first car begins the first assembly process, but rather when the first car enters that paint booth. Toyota has implemented staging ovens and start/stop times with success (Toyota, 2002).

Reduce airflow in paint booths. Reducing the volume of air put through the paint booths also limits the amount of air that must be heated and treated. These must be balanced with explosion and safety limits. In addition to energy savings, plants will realize savings in capital costs because of the smaller equipment needed.

Insulation. Insulation of the drying tunnel can reduce the heat losses through irradiation. The irradiation losses are estimated to be 5% of the total energy input (Hoffmann & Klein, 1999). Costs for re-insulating existing drying tunnels depend on the layout of the existing process, and may be prohibitive. For new installations, sufficient insulation should be considered in the design and installation. Insulation should be at least 100 mm (4 inches) thick (Best Practice Programme, 1999b). A rule of thumb is increasing insulation thickness of an oven from 75 mm to 100 mm (3 to 4 inches) will reduce the heat losses from the oven wall by about 25% (Best Practice Programme, 1999b).

Heat recovery. Forty to 60% of the heat input is vented through the exhaust from the painting process, while additional heat is lost as waste heat through the oven walls (up to a total of 85%) (Hoffmann & Klein, 1999; Best Practice Programme, 1999b). Heat recovery in paint systems, therefore, can be significant. However, some of this heat recovered from paint stacks is low-grade heat. If the problems of tar contamination and condensation can be overcome, heat can be recovered from the paint oven stack. Different heat recovery technologies are available for dryers (Mercer, 1994). Heat can be recovered using heat wheels or other technologies (Hoffmann & Klein, 1999). Heat wheels consist of rotating devices through which hot and cold air streams pass alternately (Mercer, 1994). Heat wheels do not cope well with entrained particles in the flue gas, but are suitable for recovery of heat from drying processes. A variety of heat wheels exist, and actual energy savings and costs depend on the heat wheel implemented (Toyota, 2002). Semco, Inc. has developed a number of heat recovery and ventilation systems. Their systems include recycling outdoor air (they claim savings up to 71%), pre-conditioners (savings up to 80%), dehumidifying and heat wheels with a desiccant core to recover energy (Semco, 2002).

General Motors's Opel Operations in Eisenach (Germany) installed eleven large rotors in the loft of their paint shop to reclaim heat. This saves Eisenach close to 8,000 tons of heating oil every year (GM, 2001).

According to one group at Toyota as of 1999, 30% of the paint booths have large rotary heat exchangers installed (Rototherm aluminum wheels) saving 50% of the exhausted heat (Takahashi et al., 1999). Takahashi et al. (1999) also note, however, that the heat recovery equipment increases the resistance to the exhaust and the pressure of the recovery rotors need to be monitored and maintained to assure savings. When the capture efficiency of the booth scrubber is low, the rotors can become clogged and consume more energy than is saved in the heat recovery. Toyota has also begun using desiccants on heat wheels and has had much success (Toyota, 2002). Toyota installed a heatwheel at their Georgetown (Kentucky) plant, and claims 75% of all recoverable heat is recouped on their spray booths where this technology was applied. Payback period was about 4 years, but savings were so large that the project received funding.

A sheet metal manufacturer implemented a heat recovery system at an initial cost of $5,700 (Kirk and Looby, 1996). They found annual savings of $2,080, yielding a payback period of 2.7 years.

A heat wheel has been installed to recover heat from the exhaust of a dryer for an adhesive label manufacturer in Australia. Heat was recovered at relatively high efficiencies, although it is not specified how much energy was saved as a function of the dryer inputs. The payback period, with similar energy prices as the U.S., was 1.7 years (CADDET, 1996). Daimler Chrysler also installed thermal wheels for ventilation of its workshops and for some production processes at its Rastatt plant (Germany). They claim a savings of 30 to 50% of the heating energy, totaling 45,000 MWh per year, (Daimler Chrysler, 1999). One Honda plant in Canada also recovered the exhaust heat to preheat the oven burners (CIPEC, 2002).

Efficient ventilation system. The largest energy consumer in industrial painting operations is ventilation, accounting for 60 to 70% of total energy consumption (CADDET, 1991a). Ventilation energy use can be reduced through reduction of ventilation speed, turning down air flow during breaks in the production process and computer-controlled ventilation demand control (Hoffmann & Klein, 1999; Caddet, 1991a). Turning down air flow during breaks will result in immediate cost savings. A computer-controlled system may help to optimize ventilation further. Savings depend on the painting scheduling (see above) and the amount of daily downtime, as well as current practices. We estimate savings at around 5% of the total energy inputs (Mercer, 1994). Payback period of dryer control systems depends on the size of the drying equipment and is generally less than 2 years (Mercer, 1994).

Demand controlled ventilation aims to reduce energy consumption by coordinating it with ambient solvent concentrations or spray gun operations. Pilot plants in Finland determined demand controlled ventilation could be achieved with relatively low investment costs at both new and old painting workshops. In a painting workshop with a load factor of 30%, 60% savings could be achieved. For small Finnish painting shops, the simple payback period could be as low as two years (based on a Finnish case study) with relatively large energy savings (CADDET, 1991a). We expect similar results for similar small painting workshops in the U.S..

Research programs (e.g. in Germany) aim to improve the design of painting lines by optimizing ventilation at different places in the painting line, depending on needs of the process steps, as well as the impact of painting robots on ventilation and air distribution (Hoffmann & Klein, 1999).

Oven type. Some ovens operate more efficiently than others. When selecting a new oven, the following factors should be considered: production rate, operating profile (e.g., batch process with varied paints or continuous production of one paint), coating quality, capital and operating costs, maintenance requirements, level of operator skill and intervention required, health and safety issues and environmental issues. Because paint curing is such a large energy consumer in the automobile assembly process, choosing the correct oven and oven features can lead to a significant reduction in energy and costs.

Generally, two types of ovens are available, box or tunnel ovens. Box ovens are used for low throughput, batch operations (Best Practice Programme, 1999b). For box ovens, there is significant heat input during the heating up and the curing stages of the cycle. However, box ovens offer greater flexibility of operation. Where a variety of paint types will be used on a variety of component sizes and types, box ovens should be used. Alternatively, tunnel ovens should be used for higher throughput, continuous processes. Tunnel ovens only need to be heated up from ambient conditions once per day if running continuously on uniform products.

Infrared (IR) paint curing. Infrared ovens replace gas-fired low-bake ovens to speed up the stoving procedure. IR processes reduce energy by reducing paint booth size and increase productivity by reducing stoving time. Gas-fired ovens require the removal of all plastic components due to the operating temperatures necessary, which is both labor intensive and time-consuming. Further, parts removed are often damaged and cannot be reused. Infrared ovens do not require the removal of parts. In addition, infrared ovens reduce dirt inclusion in the uncured paint. In order to compensate for differences in the distances between vehicles and the infrared lamps, color and ambient air temperature, a control system should be installed with the infrared system.

Chrysler's Belvidere plant (Illinois) implemented electric infrared drying. In addition to the energy benefits and the smaller oven size, this system can also be adapted to water-based paints (CADDET, 1990a). IR also dries the color coat quickly, reduces defects caused by paint sags or trapped solvent and improves gloss and durability because a 25% thicker clear coat can be applied. For high-intensity electric IR ovens at the Chrysler plant, energy efficiency was calculated to be 62.4%, compared to 10% for standard gas ovens. Energy costs for this project were reduced by approximately 50%.

The Peugeot Talbot Motor Company Ltd., part of PSA Group (formerly Chrysler), installed infrared ovens at its Ryton, Coventry plant (UK). Energy savings totaled 29,000 MBtu/year (8.6 million kWh/year) of primary energy, about $2.65 1992 U.S.$/car or 84% (CADDET, 1992a). In addition to energy savings, the night shift has been eliminated, reducing labor costs. With total annual savings of $616,000 1992 U.S.$ and capital costs of $505,000 1992 U.S.$, the payback period was 10 months.

Prévost Car, a bus constructor and distributor, installed IR thermoreactor cells at its Ste-Claire plant (Canada). They found energy efficiency near 100% and a reduction of 4 hours in drying time from air-free drying methods (CADDET, 1990b). With an investment of $170,000 1990 U.S.$, they found a 3 year payback period.

Frigidaire (Canada) has also implemented this technology in the household appliance industry, with energy savings of over 83% and a payback period of 3.25 years (CADDET, 1997b).

Ultraviolet (UV) paint curing. UV has also been used for curing of paint. UV curing requires lower temperatures and shorter residence times compared to conventional (heat) curing (Klein, 2000). Today, it is essentially used for curing paints on plastic autoparts, as consistent curing of three-dimensional surfaces is still difficult. It has also been used in car painting. However, the relative high costs of power make UV curing financially less attractive, while the primary energy savings may be zero or negative. Research aims at reducing the curing problems, as well as reducing energy use to make the technology commercially more attractive.

Microwave heating. Microwave heating is actively being developed for paint curing. A new technique known as “Variable Frequency Microwave” energy (VFM) has overcome some of the earlier problems associated with microwave heating, such as non-uniform heat distribution, hot spots, and overheating of the paint (Best Practice Programme, 1999b). We have found no cost or energy savings data on this emerging technology.

Wet-on-wet paint. Painting wet paint onto wet paint eliminates a baking step between the two coats of paint. Honda implemented a wet-on-wet paint process at their Marysville (Ohio) motorcycle plant and cut the energy needed per unit in half (Honda, 2001). Honda also claims that changing the paint composition also meant a reduction in the supplier's energy requirements for making the paint (Honda, 2001). Takahashi et al. (1999) of Toyota suggest the use of wet on wet paint for the first coat of a two tone color application. The lower color does not need the high appearance quality that the upper color does. The lower color can be applied just after the application of primer surfacer without curing the primer surfacer (baking between the stages). Beginning in May 1998, Toyota began using wet on wet paint for the color and mica bases on a small mini-van model using pearl mica paint (Takahashi et al., 1999).

New paint—powders. In addition to the energy used in painting, plants in the U.S. use considerable energy in removing the VOCs emitted from the paint during the painting process. Powders, including antichip primers, clear coats and lacquers have been developing in industries like the vehicle assembly and bicycle manufacturing industry (CADDET, 1992b; CADDET, 1995c). Powders rely on the electrostatic attraction between the powder and the vehicle to deposit the coating onto the surface. By eliminating solvents in the paint, VOCs and the energy resulting from the required ventilation are reduced. A 1992 analysis of Mercedes-Benz found that the energy requirements for painting using powder painting is 30% lower compared to water based paints and 18% lower compared to solvent-based painting, while drying energy requirements were slightly (+ 3%) higher for powder paints (Berewinkel, 1992). In addition to energy savings, manufacture of powder paints is slightly less energy intensive than solvent paints, resulting in indirect energy savings.

Chrysler used a powder chip primer process at its facility in Newark (Delaware) and found energy and cost savings of 40,700 MBtu and $350,000 per year (CADDET, 1995c). They expect to save nearly $4 million annually once powders are used in other processes. With total project costs of $10.6 million, this would result in a payback period of 2.6 years (CADDET, 1995c). BMW applied powder coats at their Dingolfing site (Germany) (Leven, 2001). Powder chip primer processes have been implemented in 13 paint shops in the U.S. (including 9 Chrysler paint shops) (DOE, 1999).

New paint—powder slurry coats. Germany uses powder slurry coats, as well as powder paints for clear coats. Unlike powder coats, the base coat is not heated up to high temperatures before the powder slurry clear coats are applied. Energy consumption in application and drying is much lower than for other coatings (Leven, 2001). Daimler Chrysler applied powder slurry coats at its Rastatt site (Germany) (Leven, 2001).

New paint—others. Two new paints have been developed that have lower solvent content and higher solid content (CADDET, 1995a) (see, for example, ICI Autocolor Paints). The paints are water-borne latex base coat and solvent-borne clear coat. Because they have lower solvent content, fewer VOCs are released. Hence, energy is saved because less exhaust air is required for ventilation and the drying ovens can be operated at a lower temperature. For those plants that operate in heavily regulated areas, further savings result from reduced VOC removal costs.

Ultrafiltration/reverse osmosis (UF/RO) for wastewater cleaning. For automotive coatings and paints that are water-based products, processing equipment must be cleaned regularly with water. A typical coating manufacturing operation requires thousands of liters of water each week (NREL and Energetics, 1993). Unless contaminants can be removed from this cleaning water once it has been used, all of it must be disposed of as hazardous waste. Reducing this hazardous waste, therefore, reduces transportation and incineration energy associated with its removal.

A combined ultrafiltration/reverse osmosis process cleans the wastewater to the point where it is again suitable for cleaning purposes. The wastewater is prefiltered to remove large solids. Ultrafiltration then removes suspended solids and high molecular weight particles. Reverse osmosis has the smallest pore sizes and hence, removes the smallest impurities. The UF/RO can recover 95% of the wastewater.

PPG Industries, Inc., at an automobile coatings plant in Cleveland (Ohio), implemented a UF/RO system in 1992. They reduced the hazardous waste that required disposal from 400,000 gal (1.5 million L) per year to 20,000 gal (75,000 L) per year (NREL and Energetics, 1993). Because of the reduced requirement for waste transportation and incineration, this translated into large energy savings. The new system did not require any changes to the production processes at the plant and did not affect the rate of product manufacturing. The total cost of the system was $450,000 and annual net savings are $205,000 (savings from waste disposal costs less annual operating costs), resulting in a payback period of just over 2 years (NREL and Energetics, 1993).

Carbon filters and other VOC removers. Active carbon can bind hydrocarbons like VOCs released in painting that must be removed to satisfy emission limits at U.S. vehicle assembly plants. Conventionally, VOCs are removed by regenerative oxidation (combustion). By using activated carbon, much of the exhaust air can be cleaned and recycled, while the rest, a much smaller portion, must then be removed. Because the amount of air containing the pollutants is so much smaller, the energy required to treat it (even with conventional combustion) is much less. A furniture manufacturer (the Netherlands) installed activated carbon filters and saved about 700 MBtu of natural gas and 155,000 kWh of electric energy per year, totaling savings of approximately $24,000 1996 U.S.$ (CADDET, 1996). Investment costs were $104,900 1996 U.S.$, yielding a payback period of 4.4 years.

Other alternatives to traditional VOC removal systems are being developed and are in various testing stages. One emerging system reacts contaminants with an oxygenation source primarily to convert them to more desirable intermediate products that are less volatile or non-volatile (McGinness, 2000). By controlling and limiting the oxygenation reaction to create the intermediate products, the contaminants are modified into components that act as volatile compound absorbents that can emulsify additional volatile components that would not be otherwise captured into the scrubber solution. According to its developers, one advantage to this technology is that it will economically treat smaller amounts of VOCs than traditional scrubber systems (McGinness, 2000). This technology is currently in the pilot testing stage.

High pressure water jet system to replace hot caustic paint stripping. Typically, vehicle assembly plants use skids to transport cars through the assembly process. In these plants, skids receive a coating every time they pass through the painting operations. As the skids circulate, buildup increases until some point when they require cleaning. High pressure jet water can undercut the paint and lift it off the skid. The paint residue, in the form of flakes and suspended particulate matter, is separated from the water by a filtration process and then disposed. Water may be recycled to be reused in the cleaning process. Compared to other methods of cleaning, such as hot caustic immersion of the skid, this system is more energy efficient. In addition, skids using this easier and more efficient process are cleaned more frequently, causing less paint buildup and improving the paint quality of the cars. The main problem with high pressure water jets is the noise.

Ford's Broadmeadows Melbourne Plant (Australia) implemented a high-pressure water jet system. Broadmeadows uses approximately 1700 skids. Formerly, they were cleaned once every 18 months by immersion in hot caustic tanks. The tanks were open and required large amounts of energy to maintain the required temperature. Heat losses were estimated at 80% (EnviroNET, 1997). By replacing this immersion method with the high pressure water system, they found annual savings of $240,000 1997 U.S.$. With an initial cost of $95,000 1997 U.S.$, this resulted in a payback period of 5 months. Ford also reports improved productivity in addition to energy savings; more frequent cleaning increases "first time right" cars through the paint shop by 5%.

5.9. Body Weld

In a seam welding unit, the edges of a metal sheet are pressed together between copper wheels and an electric current is used to melt the steel.

Computer controls. Computer controls can precisely control the electric current in resistance welding applications. One unit, the WeldComputer™ Resistance Welder Adaptive Control, measures both frequency and voltage of available electrical current during each weld to regulate voltage and document weld integrity (DOE, 2000d). The controls reduce the number of rejected welds and eliminate the need for destructive weld testing, saving energy as well as materials and money. With the use of computer controls, welding is more effective, less expensive, faster, more reliable and less energy intensive.

High efficiency welding/inverter technology. High efficiency welding power sources provide better electrical efficiency and an improved power factor (the ratio of real working power to apparent power being provided by the utility). In high efficiency welding, power to the transformer is shut off during system idling and cooling fans only run when needed, avoiding continuous electrical consumption. These new power sources provide 10 to 40% energy savings over older units (Borchert, 2001; Greentie, 2001). In addition, this technology has many other advantages and potential benefits. High efficiency welding power supplies provide a wider power range than traditional technologies, from 5 to 400 welding amps (Borchert, 2001a). Power supplies are smaller and lighter and, therefore, portable, and can result in lower costs for welding robots (Greentie, 2001). Stable arc consistencies improve weld quality and precision (Greentie, 2001). Higher heat rates are possible, which increase productivity and improve control (Greentie, 2001). Design of the new systems is also expected to decrease maintenance costs (Borchert, 2001).

Greentie (2001) reports the use of 1.3 kWh/kg of filler wire while depositing 2.7 kg/hour. Team Industries, a piping and tank fabricator company in Wisconsin, replaced old welding machines with inverter-based welding power sources from Miller Electric Manufacturing Company. They estimate potential savings per inverter to be about $618 per machine, $303 of which is annual electricity savings (Borchert, 2001). J.W. Williams Inc., part of IPEC's Petroleum Equipment and Services Division (Wyoming), also installed this technology. In addition to energy savings due to lower primary power draw, they improved weld consistency with these inverters (Borchert, 2001b).

Multi-welding units. These units allow a number of different welding machines to be run off one power source. Helmark Steel Inc. (U.S.) installed "Multi-Weld 350" units from Lincoln Electric for tack welding and position welding (Lincoln, 2001). They found the units use less power, reduce cleanup time, have higher deposition rate and require no down time for switching between their bridge and building fabrication (Lincoln, 2001). The operators noticed smoother running with less spatter and units that are lightweight and portable. Annual savings totaled $27,000 (Lincoln, 2001).

Frequency modulated DC-seam welding machine. ArpLas, a manufacturer of electric welding equipment, has developed a new energy efficient seam welding machine. The new machine's three-phase converter balances the load on the grid and increases its power factor. The unit has been tested by a manufacturer of steel drums (the Netherlands) who found an electricity savings of 249,700 kWh per year and $32,000 1997 U.S.$ (CADDET, 1999c). They found that a unit retrofit has a payback period of less than two years, while installing a new unit has a payback period of less than one year. They also noted that the new unit is less noisy.

Hydroforming. Hydroforming creates hollow metal structural parts from a tubular element that is three-dimensionally shaped inside a mold by fluid under pressure (Hydroforming.net, 2002). Parts have high stiffness, tensile strength properties and structural integrity. The number of moldings required is reduced, and one part replaces several. Parts also are lighter and have less distortion problems, mainly because is no need for a lot of welds. Engineers can hydroform a variety of metals using the same mold. General Motors's Bochum plant (Germany) used hydroforming technology in manufacturing, resulting in a 20% reduction in the number of welding operations required (GM, 2001). They also found hydroforming to be much quieter and produce a manufactured component that is much lighter.

Electric robots. Converting from hydraulic to electric robots or pneumatic to electric servos in the weld shop can save energy. Electric robots or servos can also increase productivity because fewer fixtures enable quicker turnover. In 1998, at one plant in Canada, Honda began converting from hydraulic to electric robots. By May 2001, most of the approximately 200 robots were replaced (CIPEC, 2002). Toyota claims a 20% reduction in energy use from conversion of pneumatic to electric servos (Toyota, 2002).

5.10. Stamping

Variable Voltage Controls (VVCs). Stamping presses can utilize variable voltage controls, which are discussed in motors, Section 5.2.

Air actuators. Die cushions on large stamping presses are used to support inserts in the lower die. These units, after only 3 months of use on a "moderately sized" stamping press will often produce leaks of 100 ft^3/min (Price and Ross, 1989). In a large stamping plant with 200 presses, this translates to 4 MW of electricity. Air actuators that have replaced the pistons on die cushions have shown little or no leakage for over five years (Price and Ross, 1989). One stamping plant in Michigan reported 25% reduction in compressed air by converting half of its presses. In addition to energy savings, replacing pistons with air actuators produces a more consistent product and greatly reduced maintenance, with maintenance savings comparable to the energy savings.

5.11. Miscellaneous

Improvements in electrical harmonic filters. Harmonic filters are designed to move electricity through wires with less waste. Often they can drift out of calibration and lose efficiency. The General Motors Midsize/Luxury Car Division's Fairfax Assembly Plant in Kansas City, Kansas implemented an energy efficiency improvement program that tested and recalibrated these filters. After calibration, they found energy savings of more than 3.8 million kWh per year (DEQ, 2001e).

Energy efficient transformers. Transformers are electrical devices that convert one voltage to another voltage. Most commercial and industrial buildings require several transformers to decrease the voltage of electricity received from utilities to the levels used by lights, computers, equipment and other indoor applications (EPA, 2001b). Commercial and industrial transformers have a life between 25 and 35 years - typically as long as the building or process they support. Depending on the size of the transformer, an ENERGY STAR labeled transformer can save $100 to $300 each year at an electricity rate of $0.075 cents/kWh, and has an average payback period between 2 and 5 years (EPA, 2001b). According to Haggerty et al. (1998), improved efficiency liquid-filled transformers can be designed with the lowest overall losses and lowest cost. In addition to saving energy, efficient transformers reduce sulfur hexafluoride (SF_6) (a greenhouse gas) emissions. Ford asserts that energy efficient transformers are standard features at all new plants, but currently hurdle rates are too high for upgrades at older plants (Ford, 2002).

6. Summary and Conclusions

The motor vehicle industry in the U.S. spends about $3.6 billion on energy per year. In this report, we focus on auto assembly plants. In the U.S., over 70 assembly plants produce 13 million cars and trucks each year. In assembly plants energy expenditures are a relatively small cost factor in the total production process. Still, as manufacturers face an increasingly competitive environment, energy efficiency improvements can provide a means to reduce costs without negatively affecting the yield or the quality of the product. In addition, reducing energy costs reduces the unpredictability associated with variable energy prices in today's marketplace, which could negatively affect predictable earnings, an important element for publicly-traded companies such as those in the motor vehicle industry.

In this report, we first presented a summary of the motor vehicle assembly process and energy use. This was followed by a discussion of energy efficiency opportunities available for the assembly plants. Where available, we provided specific primary energy savings for each energy efficiency measure based on case studies, as well as references to technical literature. If available, we also listed costs and typical payback periods. We include experiences of assembly plants world-wide with energy efficiency measures reviewed in the report.

We found that although most motor vehicle companies in the U.S. have energy management teams or programs, there are still specific opportunities available at individual plants to reduce energy consumption cost effectively in the motor vehicle assembly industry, both in utilities and in the various processes. In this report, we identified over 90 energy efficient practices and technologies. Specific energy savings data are provided for each efficiency measure based on case studies that describe implementation of the measures as well as provide references to technical literature. If available, typical payback periods are also given. Tables 6 and 7 list these measures.

Cross-cutting utility energy efficiency measures that do not interfere with the assembly process show immediate potential for cost-effective energy savings. In this report we discussed 68 different cross-cutting energy efficiency improvement measures that can reduce energy consumption in the supply and use of motors, compressed air, lighting, hot water and steam distribution, hot water and steam generation, power supply and HVAC. Savings of individual measures may be relatively small. However, the cumulative effect of these measures can potentially be large. Generally, the majority of these measures have relatively fast payback periods. The degree of implementation of these measures will vary by plant and end-use and continuous evaluation for these opportunities will help to identify further cost-savings.

For process-specific measures, some new technologies both reduce energy and improve product quality consistency or yield. We identified 25 different energy efficient practices and technologies in painting, welding and stamping. Implementation of most of these measures will be part of strategic investments and innovation at the assembly plants. Selected technologies will have large additional benefits including product quality improvement.

Further research on the economics of the measures for individual vehicle assembly plants, as part of an energy management program, is needed to assess the potential impact of selected technologies at individual assembly plants.

Table 6. Cross cutting energy efficiency measures for the vehicle assembly industry.

General Utilities
Energy management systems
Combined heat and power (CHP)
CHP combined with absorption cooling
District heating
Alternative fuels

Motors
Sizing of motors
High efficiency motors
Switched reluctance drives
Adjustable/variable speed drives
Variable voltage controls

Compressed Air Systems
Maintenance
Monitoring
Reduce leaks in pipes and equipment
Turn off unnecessary compressed air
Modify system instead of increasing system pressure
Use sources other than compressed air
Load management
Use air at lowest possible pressure
Minimize distribution system pressure drop
Cold air intake
Controls
Correctly sizing pipe diameter
Properly size regulators
Systems improvements
Heat recovery for water preheating
Natural gas engine-driven compressors
Energy efficient chillers

Compressor motors
Adjustable speed drives
High efficiency motors

Heat and Steam Distribution - Boilers
Improve process control
Reduce flue gas
Reduce excess air
Correct sizing in design
Improve insulation
Boiler maintenance
Recover heat from flue gas
Return condensate
Recover steam from blowdown
Replace obsolete burners by new optimized boilers

Heat and Steam Distribution - Distribution
Improve insulation
Maintain insulation
Improve steam traps
Maintain steam traps
Monitor steam traps automatically
Repair leaks
Recover flash steam

Lighting
Controls
Setting lighting standards
Daylighting
Replace incandescents with fluorescents or CFLs
Replace T-12 with T-8 or metal halides
Replace mercury with metal halide or high pressure sodium
Replace metal halide HID with high-intensity fluorescents
Replace magnetic with electronic ballasts
Reflectors
Light emitting diodes (LEDs) or radium strips
System improvements

HVAC
Electronic controls
Weekend setback temperatures
Ventilation and cooling system design improvements
Recover cooling water
Solar heating (Solarwall)
Building shell
Modifying fans
Other measures

Materials Handling and Tools
High efficiency belts

Miscellaneous
Improvements in electrical harmonic filters
Energy efficient transformers

Table 7. Process-related energy efficiency measures for the vehicle assembly industry.

Painting Systems	
Maintenance and controls Minimize stabilization period Reduce air flow in paint booths Insulation Heat recovery Efficient ventilation system Oven type Infrared paint curing UV paint curing Microwave heating	Wet on wet paint New paint—powders New paint—powder slurry coats New paint—others Ultrafiltration/reverse osmosis for wastewater cleaning Carbon filters and other volatile organic carbon (VOC) removers High pressure water jet system
Body Weld	**Stamping**
Computer controls High efficiency welding/inverter technology Multi-welding units Frequency modulated DC-welding machine Hydroforming Electric robots	Variable voltage controls Air actuators

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Appendix A. Vehicle Assembly Plants in the United States (2000)

Company	Plant	State	Capacity/ Prod. (cars/yr)	Product	Operations: Machining/ Casting[1]	Stamping	Body Weld	Assembly	Painting
Daimler/Chrysler	Newark	DE	200,000	SUV				X	
Daimler/Chrysler	Belvidere	IL	211,000	Car		X		X	
Daimler/Chrysler	Detroit-Conner	MI	8,000	Car					
Daimler/Chrysler	Detroit-Jefferson N.	MI	278,000	SUV					
Daimler/Chrysler	Sterling Heights	MI	227,000	Car		X		X	
Daimler/Chrysler	Warren	MI	254,000	Truck		X		X	
Daimler/Chrysler	St. Louis - South	MO	281,000	Van				X	
Daimler/Chrysler	St. Louis - North	MO	125,000	Pickup				X	
Daimler/Chrysler	Toledo - Parkway	OH	185,000	SUV				X	X
Daimler/Chrysler	Toledo - Stickney Ave.	OH	107,000	SUV					
Daimler/Chrysler	Tuscaloosa (MB)	AL	80,000	SUV				X	X
Ford Motor Co.	Hapeville	GA	215,000	Car				X	X
Ford Motor Co.	Chicago	IL	275,000	Car				X	X
Ford Motor Co.	Louisville-Chamberlaine	KY	300,000	SUV				X	X
Ford Motor Co.	Louisville - Grade Ln.	KY	378,000	Truck			X	X	X
Ford Motor Co.	Dearborn	MI	165,000	Car	May close in near future			X	X
Ford Motor Co.	Wayne-Michigan Ave.	MI	252,000	Car		X	X	X	X
Ford Motor Co.	Wayne-Michigan Ave.	MI	210,000	SUV			X	X	X
Ford Motor Co.	Wixom	MI	192,000	Car			X	X	X
Ford Motor Co.	St. Paul	MN	206,000	Truck				X	X
Ford Motor Co.	Claycomo	MO	491,000	Truck/ SUV				X	X
Ford Motor Co.	St. Louis	MO	192,000	SUV				X	X
Ford Motor Co.	Edison	NJ	173,000	Truck				X	X
Ford Motor Co.	Avon Lake	OH	196,000	Van				X	X
Ford Motor Co.	Lorain	OH	150,000	Van				X	X
Ford Motor Co.	Norfolk	VA	239,000	Truck				X	X
GM	Wilmington	DE	290,000	Car				X	X
GM	Doraville	GA	125,000	Car		X	X	X	X
GM	Fort Wayne	IN	230,000	Truck				X	X

Company	Plant	State	Capacity/ Prod. (cars/yr)	Product	Operations: Machining/ Casting[1]	Stamping	Body Weld	Assembly	Painting
GM	Kansas City - Fairfax	KS	139,000	Car		X	X	X	X
GM	Bowling Green	KY	25,000	Car				X	X
GM	Shreveport	LA	206,000	Truck		X	X	X	X
GM	Baltimore	MD	216,000	Van				X	X
GM	Detroit - Piquette Ave.	MI	----------------------	Closed in 2000	--------------------			X	X
GM	Detroit - GM Blvd.	MI	206,000	Car				X	X
GM	Flint	MI	145,000	Van				X	X
GM	Flint - Buick City	MI	270,000	Car	Closed in 2002			X	X
GM	Lake Orion	MI	233,000	Car				X	X
GM	Lansing (Townsend)	MI	420,000	Car				X	X
GM	Lansing - Verlinden Ave.	MI	Production shared with Townsend plant						
GM	Lansing - Grand River	MI	Opened in 2001			X	X	X	X
GM	Pontiac	MI	237,000	Truck					
GM	Wentzville	MO		Van		X	X	X	X
GM	Linden	NJ	160,000	Truck/ SUV				X	
GM	North Tarrytown	NY			Closed in 1996				
GM	Lordstown	OH	233,000	Car		X	X	X	X
GM	Moraine	OH	130,000	SUV				X	X
GM	Oklahoma City	OK	270,000	Car				X	X
GM	Spring Hill	KY	280,000	Car	X	X	X	X	X
GM	Arlington	TX	125,000	Truck				X	X
GM	Janesville	WI	240,000	Truck/ SUV				X	X
Auto Alliance	Flat Rock	MI	240,000	Car		X?	X?	X	X
BMW	Greer	SC	90,000	Car				X	X
Honda	Marysville	OH	440,000	Car/ Cycle		X	X	X	X
Honda	East Liberty	OH	230,000	Car		X	X	X	X
Mitsubishi	Normal	IL	240,000	Car		X	X	X	X
Nissan	Smyrna	TN	450,000	Car/ Truck		X	X	X	X

Company	Plant	State	Capacity/ Prod. (cars/yr)	Product	Operations				
					Machining/ Casting[1]	Stamping	Body Weld	Assembly	Painting
NUMMI	Fremont	CA	390,000	Car/ Truck		X	X	X	X
Subaru/Isuzu	Lafayette	IN	240,000	Car/SUV		X	X	X	X
Toyota	Georgetown	KY	475,000	Car/Van	X	X	X	X	X
Toyota	Princeton	IN	100,000	Truck		X	X	X	X
Freightliner	Cleveland	NC		Heavy-duty truck				X	X
Freightliner	Mt. Holly	NC		Heavy-duty truck			X	X	X
Freightliner	Portland	OR		Heavy-duty truck				X	X
Thomas Built Buses	High Point	NC		Bus		X	X	X	X
Thomas Built Buses	Jamestown	NC		Bus				X	X
Thomas Built Buses	Oriskany	NY	(Closing soon)	Bus				X	X
Mack Trucks	Macungie	PA		Heavy-duty Truck				X	
Mack Trucks	Winnsboro	SC		Heavy-duty Truck				X	
Motor Coach Industries	Pembina	ND						X	
International Truck & Engine Corp.	Garland	TX		Heavy-duty Truck			X	X	X
International Truck & Engine Corp.	Springfield	OH		Medium -duty Truck & Bus Chassis		X	X	X	X
International Truck & Engine Corp.	Conway	AR		Bus and Chassis		X	X	X	X
International Truck & Engine Corp.	Tulsa	OK		Bus & bus chassis		X	X	X	X
PACCAR	Renton	WA							
PACCAR	Seattle	WA							

[1] Includes engine machining and/or casting operations

Appendix B: Energy management systems for best practices in energy efficiency

	ORGANIZATION		SYSTEMS MONITORING		TECHNOLOGY		O & M
	Accountability	**Organization**	**Monitoring & Targeting**	**Utilities Management**	**Reviews**	**Plans**	**Operation & Maintenance**
0	No awareness of responsibility for energy usage. Energy not specifically discussed in meetings.	No energy manager or "energy champion".	Energy efficiency of processes on site not determined. Few process parameters monitored regularly.	No utilities consumption monitoring.	No specific reviews held.	No energy improvement plans published.	No written procedures for practices affecting energy efficiency.
1	Operations staff aware of the energy efficiency performance objective of the site.	Energy manager is combined with other tasks and roles such that less than 10% of one person's time is given to specific energy activities.	Energy efficiency of site determined monthly or yearly. Site annual energy efficiency target set. Some significant process parameters are monitored.	Utilities (like power and fuel consumption) monitored on overall site basis.	Energy only reviewed as part of other type reviews	Energy improvement plans published but based on an arbitrary assessment of opportunities.	No procedures available to operating staff.
2	Energy efficiency performance indicators are produced and available to operations staff. Periodic energy campaigns. Intermittent energy review meetings.	Energy manager appointed giving greater than 10% of time to task. Occasional training in energy related issues.	Weekly trend monitoring of energy efficiency of processes and of site, monitored against targets. Process parameters monitored against target.	Weekly monitoring of steam/power balance.	Infrequent energy review.	Energy performance plan published based on estimate of opportunities.	Procedures available to operators but not recently reviewed.
3	Energy efficiency performance parameter determined for all energy consuming areas. Operations staff advised of performance. All employees aware of energy policy. Performance review meetings held once/month.	Energy manager in place greater than 30% of time given to task. Adhoc training arranged. Energy performance reported to management.	Daily trend monitoring of energy efficiency of processes and of site, monitored against target. Process parameters monitored against targets.	Daily monitoring of steam/power. Steam & fuel balances adjusted daily.	Regular plant/site energy reviews carried out.	A five-year energy improvement plan is published based on identified opportunities from energy review.	Procedures available to operators and reviewed in the last three years.

	ORGANIZATION		SYSTEMS MONITORING		TECHNOLOGY		O & M
	Accountability	**Organization**	**Monitoring & Targeting**	**Utilities Management**	**Reviews**	**Plans**	**Operation & Maintenance**
4	Energy efficiency performance parameter included in personal performance appraisals. All staff involved in site energy targets and improvement plans. Regular weekly meeting to review performance.	An energy manager is in place giving greater than 50% time to task. Energy training to take place regularly. Energy performance reported to management and actions followed up.	Same as 3, with additional participation in energy efficiency target setting. Process parameters trended.	Real time monitoring of fuel, steam and steam/power balance. Optimum balances maintained.	Site wide energy studies carried out at least every five years with follow up actions progressed to completion	A ten year energy improvement plan based on review is published and integrated into the Business Plan.	Procedures are reviewed regularly and updated to incorporate the best practices. Used regularly by operators and supervisors.