J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

ENERGY CONSERVATION AND EFFICIENCY

Energy is essential to modern industrial societies. The availability of adequate and reliable energy supplies is required to maintain economic growth and to improve living standards. The major energy sources include fossil fuels (namely, petroleum, natural gas, and coal), hydropower, and nuclear energy. Table 1 illustrates the progression of energy consumption by region throughout the world. As expected the industrialized countries (including North America and Western Europe) consumed more than 50% of the total energy used throughout the world during 1997. The United States alone, with less than 5% of the world's population, used about one-fifth of the world's total energy consumption.

Associated with energy consumption, environmental and health impacts have been only properly investigated in the last decade. In particular, the burning of fossil fuels has increased significantly levels of carbon emissions as indicated in Table 1. The carbon emissions are believed to have major impacts on the global climate by increasing global temperatures. The high global temperatures could affect agricultural production and sea-level heights. Moreover, the emissions from coal-fired power plants have caused significant damage in the form of acid rain to trees, crops, and animals. In Europe, it is estimated that 20% of the forests have been already damaged by acid rain. The origin of environmental impacts is not limited to fossil fuels but includes other energy sources. Dams for hydroelectric power plants have altered major rivers and harmed fish and wildlife. Nuclear waste from nuclear power plants is radioactive and can affect the health of present and future generations. Unfortunately, the damage is not localized to areas where energy is produced or used but is rather global. The emissions of hydrocarbons, sulfur oxides, and nitrogen oxides are causing severe health problems throughout the world.

To maintain economic growth and reduce the staggering negative environmental impacts of conventional energy resources, energy efficiency has to be implemented in all sectors. In fact, energy efficiency is often considered as a clean source of energy. Indeed, improvements from energy efficiency can avoid the need to build new power plants that use conventional energy sources. Such improvements incur little or no cost and have no adverse environmental impacts. Moreover, energy efficiency has other beneficial impacts including:

- Increasing the economic competitiveness. As stated by the International Energy Agency (*IEA*), investment in energy conservation provides a better return than investment in energy supply.
- Stretching the availability of the limited nonrenewable energy resources and gain time for possible development of renewable and reliable energy resources such as solar energy.
- Decreasing air and water pollution and thus improving health conditions.
- Decreasing greenhouse emissions and thus reducing global warming.

Around the world, there is a vast potential for energy efficiency that has begun to be tapped only in a few countries. This potential exists for all energy-end use sectors including buildings, industries, and transportation. One of the main challenges for all countries in this new millennium is to increase the efficiency of production, distribution, and consumption of energy in order to maintain sustainable economic growth without harming the environment.

Table 1: Energy Consumption and Carbon Emissions by Region (1)

Region	Energy consumption (EJ)^a 1990	1997	2010^b	Carbon emissions (10^6 metric tons) 1990	1997	2010^b
Industrialized countries	193	215	253	2,850	3,039	3,563
Eastern Europe	80	56	66.5	1,337	878	1,151
Developing countries:						
Africa	9.5	11.5	17	180	214	292
Asia	53.5	79	133	1,067	1,522	2,479
Central / South America	15	19	31.5	174	225	399
Middle East	13.5	19	27.5	229	297	552
Total	91.5	128.5	209	1,649	2,258	4,930
Total (World)	364.5	399.5	528.5	5,836	6,175	8,146

^{a}Exajoules = 10^{18} J = 0.948×10^{15} Btu.

^{b} Projections.

Table 2: Indicators for Energy Use and Carbon Emissions for Selected Countries based on 1999 Data.

Indicator	US	France	Brazil	Egypt	China
Per capita energy use					
(GJ/person)	375.4	183.0	54.8	33.1	26.5
[10^6 Btu/person]	[355.8]	[173.5]	[51.9]	[31.4]	[25.1]
Carbon Emissions					
(metric tons/person)	5.5	1.8	0.53	0.52	0.53
Population					
(millions of persons)	272.7	59.3	171.9	68.4	1,200

Source: EIA, 2000.

In this article, existing and emerging tools and technologies used to improve energy efficiency in various energy end-use segments are briefly discussed. First, the energy use conditions of two industrialized nations (US and France) are presented to highlight the potential for energy efficiency in these two countries. As indicated in Table 2, both the United States and France are large energy consumers and carbon polluters. In both countries, energy conservation programs were established just after the oil crisis of 1970s. The impact of these programs will be briefly discussed in the following sections.

Energy Use in the Unites States. The main sources of energy used in the United States include coal, natural gas, petroleum products, and electricity. The electricity is generated either from power plants fueled by primary energy sources (i.e., coal, natural gas, or fuel oil), or from nuclear power plants or renewable energy sources (such as hydroelctric, geothermal, biomass, wind, photovoltaic, and solar thermal sources).

The US energy consumption has fluctuated in response to significant changes in oil prices, economic growth rates, and environmental concerns especially since the oil crisis of the early 1970s. For instance, the US energy consumption increased from 69.6×10^{18} J. (equivalent to 66×10^{15} British thermal units or Btu) in 1970 to 99.2×10^{18} Joules (or 94×10^{15} Btu) in 1998 (2). Table 3 summarizes the changes in the US energy

Table 3. Annual US Energy Consumption by Primary Energy Sources in exajoules[a] (10^{15} Btu (2))

Primary energy source	1972	1982	1992	1998[b]
Coal	12.741 (12.077)	16.165 (15.322)	20.212 (19.158)	22.809 (21.620)
Natural gas	23.705 (22.469)	19.523 (18.505)	21.238 (20.131)	23.041 (21.840)
Petroleum products	34.759 (32.947)	31.895 (30.232)	35.371 (33.527)	38.547 (36.537)
Nuclear power	0.616 (0.584)	3.303 (3.131)	6.970 (6.607)	7.551 (7.157)
Renewable energy	4.724 (4.478)	6.639 (6.293)	6.655 (6.308)	7.462 (7.073)
Total	76.760 (72.758)	77.481 (73.442)	90.197 (85.495)	99.414 (94.231)

[a] 1 # exajoule = 1 EJ = 10^{18} J.

[b] The data for 1998 are preliminary data that may be revised.

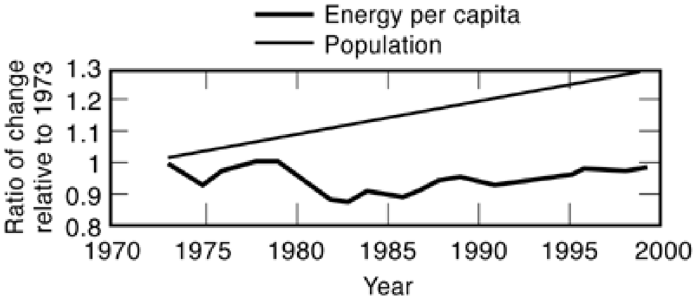

Fig. 1. Per capita energy use and population growth since 1973.

consumption by source from 1972 to 1998. The energy costs in the US economy represents about 8% of the gross domestic product (*GDP*), which is one of the highest among industrialized countries. Moreover, the United States consumes a significant fraction of the total world energy. Thus, the United States has the highest per capita energy use rate in the world with an average of 369.3 GJ (350×10^6 Btu) per year or the equivalent of 26.5 l (7 gal) of oil per person per day.

Figure 1 illustrates the rate of growth over the last 25 years of the per capita energy use and the population relative to 1973. It is interesting to note that the per capita energy use rate remained almost constant—with relatively small fluctuations—since 1973, although the population growth rate has clearly increased throughout the years. The higher oil prices in the 1970s (oil embargo in 1973 and the Iranian revolution in 1979) have mandated energy conservation and increased energy efficiency. However, the trend toward energy conservation was relaxed during the 1980s and in the 1990s. The impact of the 1992 National Energy Policy Act (*EPACT*), to promote more efficient use of energy in the United States, is yet to be felt. In particular, the EPACT revises energy efficiency standards for buildings, promotes use of alternative fuels, and reduces the monopolistic structure of electric and gas utilities.

As indicated in Fig. 2, buildings and industrial facilities are responsible for, respectively, 36% and 38% of the total US energy consumption. The transportation sector, which accounts for the remaining 26% of the total US energy consumption, uses mostly fuel products. However, buildings and industries consume predominantly electricity and natural gas. Coal is primarily used as an energy source for electricity generation due its low price.

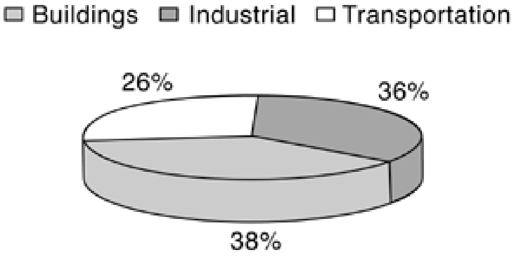

Fig. 2. Distribution of US energy consumption by end-use sector in 1996.

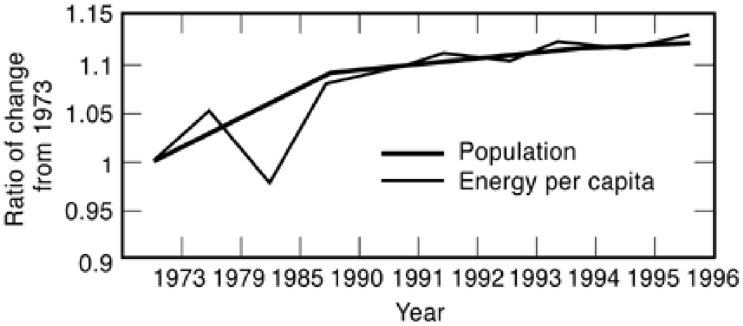

Fig. 3. Per capita energy use and population growth in France.

Despite some improvements in energy efficiency over the last 25 years, the United States remains the most energy-intensive country in the world. If it wants to maintains its lead in a global and competitive world economy, it is imperative that the United States continue to improve its energy efficiency.

Energy Use in France. The energy sources used in France include mostly nuclear energy, natural gas, petroleum, and coal. In 20 years and since the oil crisis of 1973, the total energy consumption increased more than sixfold from 217.7×10^6 GJ (206.3×10^9 Btu) to more than 1364.6×10^6 GJ (1293.4×10^9 Btu) in 1993. The share of the cost of energy on the GDP actually decreased in the last decade from 1.7% in 1973 to only 1.2% in 1993 and even lower to 1.0% in 1995. Figure 3 compares the evolution of the per capita energy use and the population growth in France during the period from 1973 to 1996. Except for a decrease during the 1980s, the per capita energy use increased at the same rate as the population growth. The reduction in energy use during the 1980s is mostly attributed to the energy conservation efforts by the French government in response to high energy prices during the 1970s. The incentives for energy conservation have disappeared with the return to low energy prices in late 1980s and the 1990s.

Energy use can be divided into three end-use categories: transportation, residential and commercial buildings, and industrial uses. In France, the residential and commercial buildings account for almost 45% of the total energy consumed by the country. (See Fig. 4) Meanwhile, the industrial and the transportation sectors use, respectively, 30% and 25% of the total energy consumed in France. Therefore, there is a significant potential for energy conservation especially for buildings and industry in France. In 1999, the national energy agency, *ADEME* (Agence de l'Environment et de la Maitrise d'Energie) started new energy conservation programs aimed at reducing greenhouse emissions and energy use in all sectors of the French economy.

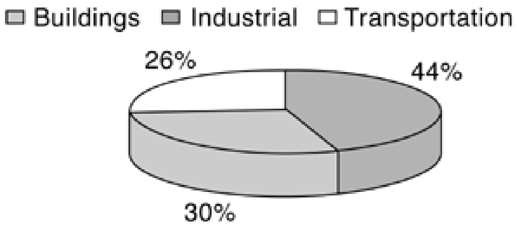

Fig. 4. Distribution of energy consumption in France by end-use sector in 1996.

Table 4: Energy Consumption by Major Energy Sources Attributed to Commercial Buildings in GJ

Energy Source	France[a]	US[b]
Electricity	632 (60%)	2,742 (49%)
Natural gas	193 (19%)	2,005 (36%)
Fuel oil	163 (16%)	314 (6%)
Others	54 (5%)	532 (9%)
All	1042 (100%)	5593 (100%)

[a] *Source*: CEREN based on 1993 energy consumption (3).
[b] *Source*: EIA using 1995 data (4).

Energy Efficiency in Buildings and Industry

Introduction. As discussed earlier, residential and commercial buildings account for 36% of total energy consumption in the United States. This fraction is even higher in most other countries (45% in France). Table 4 summarizes the energy consumption by source for all commercial buildings in both the United States and France. It is clear that in both countries, electricity is the main source of energy for commercial buildings. Indeed, lighting, appliances, and heating–ventilation–air conditioning (*HVAC*) equipment accounts for most of the electricity consumption in nonresidential buildings. Typical energy densities for selected types of commercial and institutional buildings are summarized in Table 5 for both the United States and France.

The industrial sector consumes 38% of the total United States energy use as indicated in Fig. 2. Fossil fuels constitute the main source for the United States industry. Electricity accounts for about 15% of the total United States industrial energy use. In some energy-intensive manufacturing facilities, cogeneration systems are used to produce electricity from fossil fuels. In general, a significant potential for energy savings exists in industrial facilities due to the significant amounts of energy wasted in the industrial processes. Using improved housekeeping measures and recovering some of the waste heat, could save up to 35% of the total energy used in US industry (5).

The potential for energy conservation for both buildings and the industrial sector remains large in the US and other countries despite the improvements in energy efficiency since the 1970s. To achieve energy efficiency improvements in buildings and industrial facilities, systematic analysis tools and procedures do exist and are well documented (6). Some of the energy management procedures are suitable for both buildings and industrial facilities and are provided in the following sections. In addition, some proven and cost-effective energy efficiency technologies are summarized.

Table 5: End-Use Energy Intensity by Principal Building Activity in kWh/m^2

Major building activity	France[a]	US[b]
Office	395	300
Education	185	250
Health care	360	750
Lodging	305	395
Food service	590	770
Mercantile and service	365	240
Sports	405	NA[c]
Public assembly	NA	375
Warehouse and storage	NA	125

[a] *Source*: CEREN based on 1993 energy consumption (3).
[b] *Source*: EIA using 1995 data (4).
[c] Not available.

Energy Management Tools. This section describes general but systematic procedures for energy assessment and analysis to improve the energy efficiency of commercial buildings and industrial facilities. In later sections, some of the commonly recommended energy conservation measures are briefly discussed.

Energy Audits. For existing buildings, energy audits are the first step used to improve the energy efficiency of buildings. Generally, four types of energy audits can be distinguished, as briefly described below (6):

- *The walk-through audit* consists typically of a short on-site visit to a specific facility in order to identify areas in which simple and inexpensive actions (typically, housekeeping, operating, and maintenance measures) can provide immediate energy use and/or operating cost savings.
- *The utility cost analysis* includes a detailed evaluation and assessment of metered energy uses and operating costs of the facility. Typically, monthly utility data over several years are evaluated in order to identify the patterns of energy use, peak demand, weather effects, and potential for energy savings.
- *The standard energy audit* consists of a comprehensive energy analysis for all or selected energy-intensive systems of the facility. In particular, the standard energy audit includes the development of a baseline for the energy use of the facility and the evaluation of the energy savings and the cost effectiveness of appropriately selected energy conservation measures.
- *The detailed energy audit* is the most comprehensive but also the most time-consuming energy audit type. In particular, the detailed energy audit includes the use of instruments to measure energy use for either the entire audited facility or for some selected energy-intensive systems within the audited facility (for instance, by end uses—lighting systems, office equipment, fans, chillers, etc.). In addition, sophisticated computer simulation programs are typically considered for detailed energy audits to evaluate and recommend energy conservation measures for the facility.

Tables 6 and 7 provide summaries of the energy audit procedures recommended, respectively, for commercial buildings and for industrial facilities (6). Energy audits for thermal and electric systems are separated since they are typically subject to different utility rates.

Table 6: Energy Audit Summary for Residential and Commercial Buildings

Phase	Thermal systems	Electric systems
Utility analysis	Thermal energy use profile (building signature) Thermal energy use per unit area (or per student for schools or per bed for hospitals) Thermal energy use distribution (heating, DHW, process, etc.) Fuel types used Weather effect on thermal energy use Utility rate structure	Electric energy use profile (building signature) Electric energy use per unit area (or per student for schools or per bed for hospitals) Electric energy use distribution (cooling, lighting, equipment, fans, etc.) Weather effect on electric energy use Utility rate structure (energy charges, demand charges, power factor penalty, etc.)
On-site survey	Construction materials (thermal resistance type and thickness) HVAC system type DHW system Hot water or steam use for heating Hot water or steam for cooling Hot water or steam for DHW Hot water or steam for specific applications (hospitals, swimming pools, etc.)	HVAC system type Lighting type and density Equipment type and density Energy use for heating Energy use for cooling Energy use for lighting Energy use for equipment Energy use for air handling Energy use for water distribution
Energy use baseline	Review architectural, mechanical, and control drawings Develop a base-case model (using any baselining method ranging from very simple to more detailed tools) Calibrate the base-case model (using utility data or metered data)	Review architectural, mechanical, electrical, and control drawings Develop a base-case model(using any baselining method ranging from very simple to more detailed tools) Calibrate the base-case model (using utility data or metered data)
Energy conservation measures	Heat recovery system (heat exchangers) Efficient heating system (boilers) Temperature setback EMCS HVAC system retrofit DHW use reduction Cogeneration	Energy efficient lighting Energy efficient equiment (computers) Energy efficient motors HVAC system retrofit EMCS Temperature setup Energy-efficient cooling system (chiller) Peak demand shaving Thermal energy storage system Cogeneration Power factor improvement Reduction of harmonics

Source: Reference 6, used with permission.

Performance Contracting. In the last decade, a new mechanism for funding energy projects has been proposed to improve the energy efficiency of existing buildings. This mechanism, often called performance contracting, can be structured using various approaches. The most common approach for performance contacting consists of the following steps:

- A vendor or contractor proposes an energy project to a facility owner or manager after conducting an energy audit. This energy project would reduce energy use and energy cost and thus would reduce the facility operating costs.
- The vendor or contractor funds the energy project using moneys typically borrowed from a lending institution.

Table 7. Energy Audit Summary for Industrial Facilities

Phase	Thermal systems	Electric systems
Utility analysis	Thermal energy use profile (building signature) Thermal energy use per unit of a product Thermal energy use distribution (heating, process, etc.) Fuel types used Analysis of the thermal energy input for specific processes used in the production line (such as drying) Utility rate structure	Electric energy use profile (building signature) Electric energy use per unit of a product Electric energy use distribution (cooling, lighting, equipment, process, etc.) Analysis of the electric energy input for specific processes used in the production line (such as drying) Utility rate structure (energy charges, demand charges, power factor penalty, etc.)
On-site survey	List of equipment that use thermal energy Perform heat balance of the thermal energy Monitor thermal energy use of all or part of the equipment Determine the by-products of thermal energy use (such emissions and solid waste)	List of equipment thqt use electric energy Perform heat balance of the electric energy Monitor electric energy use of all or part of the equipment Determine the by-products of electric energy use (such pollutants)
Energy use baseline	Review mechanical drawings and production flow charts Develop a base-case model using (any baselining method) Calibrate the base-case model (using utility data or metered data)	Review electrical drawings and production flow charts Develop a base-case model (using any baselining method) Calibrate the base-case model (using utility data or metered data)
Energy conservation measures	Heat recovery system Efficient heating and drying system EMCS HVAC system retrofit Hot water and steam use reduction Cogeneration (possibly with solid waste from the production line)	Energy efficient motors Variable speed drives Air compressors Energy efficient lighting HVAC system retrofit EMCS Cogeneration (possibly with solid waste from the production line) Peak demand shaving Power factor improvement Reduction of harmonics

Source: Reference 6, used with permission.

- The vendor or contractor and facility owner or manager agree on a procedure to repay the borrowed funds from the energy cost savings that may result from the implementation of the energy project.

An important feature of performance contracting is the need for a proven protocol for measuring and verifying energy cost savings. This measurement and verification protocol needs to be accepted by all the parties involved in the performance contracting project: the vendor or contractor, the facility owner or manager, and the lending institution. For different reasons, all parties must ensure that cost savings have indeed incurred from the implementation of the energy project and are properly estimated. Over the last decade several methods and protocols for measuring and verifying actual energy savings from energy efficiency projects in existing buildings have been developed (6). Among the methods proposed for the measurement of energy savings are those proposed by the National Association of Energy Service Companies (7), the Federal Energy Management Program (8), the American Society of Heating Refrigeration and Air Conditioning Engineers (9), the Texas LoanSTAR program (10), and the North American Energy Measurement and Verification Protocol

(*NEMVP*) sponsored by DOE and later updated and renamed the International Performance Measurement and Verification Protocol (11).

Commissioning of Building Energy Systems. Before final occupancy of a newly constructed building, it is recommended that commissioning of its various systems including structural elements, building envelope, electric systems, security systems, and HVAC systems be performed. Commissioning is a quality assurance process to verify and document the performance of building systems as specified by the design intent. During the commissioning process, operation and maintenance personnel are trained to follow procedures properly in order to ensure that all building systems are fully functional and are properly operated and maintained. For existing facilities, continuous commissioning procedures have been developed and have been implemented in selected buildings with a substantial reduction in energy use.

Energy Rating of Buildings. In the United States, a new building rating system has been recently developed and implemented by the US Green Building Council. This rating system, referred to as the Leadership in Energy and Environmental Design (*LEED*) rating, considers the energy and the environmental performance of all the systems in a building over its life cycle. Currently, the LEED rating system evaluates new and existing commercial, institutional, and high-rise residential buildings. The rating is based on credits that can be earned if the building satisfies a list of criteria based on existing and proven technologies. Different levels of green building certification are awarded based on the total credit earned.

Other countries have similar rating systems. In fact, England was the first country to develop and implement a national green building rating system, the Building Research Establishment's Environmental Assessment Method (*BREEAM*). The Building Research Establishment estimates that up to 30% of office buildings constructed in the last 7 years have been assessed using the BREEAM rating system. Currently, the BREEAM rating system can be applied to new and existing office buildings, industrial facilities, residential homes, and superstores.

Energy Conservation Measures. In this section energy conservation measures commonly implemented in commercial and industrial facilities are briefly discussed. The potential energy savings and the cost-effectiveness of some of the energy efficiency measures are discussed through illustrative examples. The calculation details of the energy savings incurred for common energy conservation measures can be found in Ref. 6.

Building Envelope. The building envelope (i.e., walls, roofs, floors, windows, and doors) has an important impact on the energy used to condition residential, commercial, and even industrial facilities. The energy efficiency of the building envelope can be characterized by its building load coefficient (*BLC*). The BLC can be estimated either by a regression analysis of the utility data or by a direct calculation that accounts for the thermal resistance of the construction materials used in the building envelope assemblies. Figure 5 illustrates a regression procedure used to estimate the BLC for a given building using utility data. In particular, it can be shown that the slope of the regressed line is proportional to the BLC of the building (6).

Some of the commonly recommended energy conservation measures to improve the energy efficiency of building envelope are as follows.

1. Addition of thermal insulation

For building surfaces without any thermal insulation, this measure can be cost effective, especially for residential buildings.

2. Replacement of windows

When windows represent a significant portion of the exposed building surfaces, using more energy-efficient windows (high R value, low-emissivity glazing, airtight level, etc.) can be beneficial to reduce the energy use and to improve the indoor comfort level.

3. Reduction of air leakage

When infiltration load is significant, leakage area of the building envelope can be reduced by generally inexpensive weather-stripping techniques. In residential buildings, the infiltration rate can be estimated using

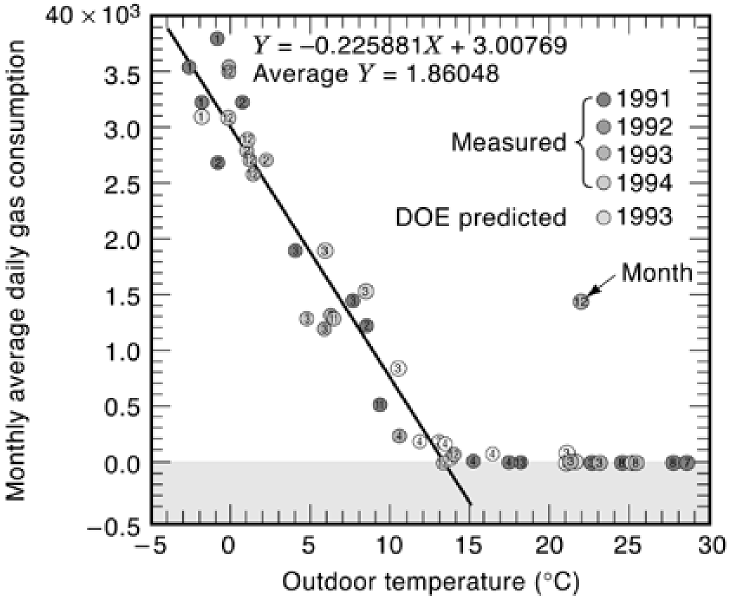

Fig. 5. Estimation of the BLC based on a regression analysis of the monthly gas consumption. (Source: Reference 6, with Permission.)

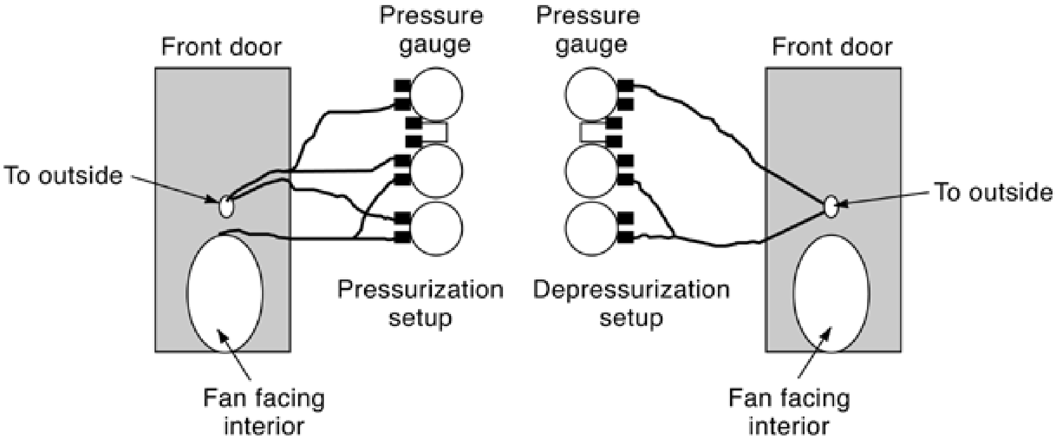

Fig. 6. A blower door test setup for both pressurization and depressurization. (Source: Reference 6, with Permission.)

a blower door test setup as shown in Fig. 6. The blower test door setup can be used to estimate the infiltration or exfiltration rates under both pressurization and depressurization conditions.

The energy audit of the envelope is especially important for residential buildings. Indeed, the energy use from residential buildings is dominated by weather since heat gain and/or loss from direct conduction of heat or from air infiltration or exfiltration through building surfaces accounts for a major portion (50% to 80%) of the energy consumption. For commercial buildings, improvements to building envelope are often not cost-effective due to the fact that modifications to the building envelope (replacing windows, adding thermal insulation in walls) are typically very expensive and require long time periods to recover the initial investment.

Residential Appliances. Appliances account for a significant part of the energy consumption in buildings that used about 41% of electricity generated worldwide in 1990 (6). In general, the operating cost of appliances during their lifetime (typically 10 to 15 years) far exceeds their initial purchase price. However, consumers—especially in the developing countries where no labeling programs for appliances are enacted—do not generally consider energy efficiency and operating cost when making purchases since they are not well informed.

Recognizing the significance and the impact of appliances on the national energy requirements, a number of countries have established energy efficiency programs. In particular, some of these programs target improvements of energy efficiency for residential appliances. Methods to achieve these improvements include energy efficiency standards and labeling programs. Minimum efficiency standards for residential appliances have been implemented in some countries for a number of residential end uses. The energy savings associated with the implementation of these standards are found to be substantial. In the United States, the savings due to the standards are estimated to be about 0.7 exajoules (EJ) per year during the period extending from 1990 to 2010 (1 exajoule $= 1$ EJ $= 10^{18}$ J $= 0.948 \times 10^{15}$ of Btu $= 0.948 \times 10^{15}$ Btu).

Energy standards for appliances in the residential sector have been highly cost-effective. In the United States, it is estimated that the average benefit to cost ratios for promoting energy efficient appliances are about 3.5. In other terms, each US dollar of federal expenditure on implementing the standards is expected to contribute $165 of net present-valued savings to the economy over the period of 1990 to 2010. In addition to energy and cost savings, minimum efficiency standards reduce pollution with significant reduction in carbon emissions. In the period of 2000 to 2010, it is estimated that energy efficiency standards will result in an annual carbon reduction of 4% (corresponding to 9×10^6 metric tons of carbon/year) relative to the 1990 level.

Several countries have established minimum efficiency standards for refrigerators and freezers since this product type has one of the highest growth rates both in terms of sales value and volume. The existing international energy efficiency standards for refrigerators and freezers set a limit on the energy use over a specific period of time (generally, one month or one year). This energy use limit may vary depending on the size and the configuration of the product.

In addition to standards, labeling programs have been developed to inform consumers about the benefits of energy efficiency. There is a wide range of labels used in various countries to promote energy efficiency for appliances. These labels can be grouped into three categories:

- Efficiency type labels used to allow consumers to compare the performance of different models for a particular product type.
- Ecolabels provide information on more than one aspect (i.e., energy efficiency) of the product. Other aspects include noise level, waste disposal, and emissions.
- Efficiency seals of approval, such as the Energy Star program in the United States, are labels that indicate that a product has met a set of energy efficiency criteria but do not quantify the degree by which the criteria were met.

In recent years, labeling of appliances is becoming a popular approach around the world in order to inform consumers about the energy use and energy cost of purchasing different models of the same product. Presently, Australia, the United States, and Canada have the most comprehensive and extensive labeling programs. The European Union, and other countries such as Japan, Korea, Brazil, Philippines, and Thailand have developed labels for a few products.

In addition to energy efficiency, standards have been developed to improve the performance of some appliances in conserving water. For instance, water-efficient plumbing fixtures and equipment have been developed in the United States to promote water conservation.

Ventilation and Indoor Air Quality.

Table 8: Minimum Ventilation Rate Requirements for Selected Spaces in Commercial Buildings

Space and or application	Minimum outside air requirements	Reference
Office space	9.5 l/s (20 ft^3/min) per person	ASHRAE Standard 62-99
Corridor	0.25 l/s per m^2 [0.05 (ft^3/min)/ft^2]	
Restroom	24 l/s (50 ft^3/min) per toilet	
Smoking lounge	28.5 l/s (60 ft^3/min) per person	
Parking garage	7.5 l/s [1.5 (ft^3/min)ft^2]	

Ventilation in Commercial and Institutional Buildings. The energy required to condition ventilation air can be significant in both commercial buildings and industrial facilities especially in locations with extreme weather conditions. While ventilation is used to provide fresh air to occupants in commercial buildings, it is used to control the level of dust, gases, fumes, or vapors in several industrial applications. The existing volume of fresh air should be estimated and compared with the amount of ventilation air that is required by the applicable standards and codes. Excess volume in air ventilation should be reduced as it can lead to increases in heating and/or cooling loads. However, in some climates and periods of the year or the day, providing more air ventilation can be beneficial and may actually reduce cooling and heating loads through the use of air-side economizer cycles. Table 8 summarizes some of the minimum outdoor air requirements for selected spaces in commercial buildings.

If excess ventilation air is found, the outside air damper setting can be adjusted to supply the appropriate air ventilation rates that meet the minimum outside requirements as listed in Table 8. Further reductions in outdoor air can be obtained by using demand ventilation controls that supply outside air only during periods when there is need for fresh air. A popular approach for demand ventilation is the monitoring of the CO_2 concentration level within the spaces. The gas CO_2 is considered as a good indicator of pollutants generated by occupants. The outside air damper position is controlled to maintain a CO_2 set point within the space. Demand-controlled ventilation based on CO_2 has been implemented in various buildings with intermittent occupancy patterns including cinemas, theaters, classrooms, meeting rooms, and retail establishments. Furthermore, air ventilation intake for several office buildings has been controlled using CO_2 measurement (12). Based on field studies, it has been found that significant energy savings can be obtained with a proper implementation of CO_2-based demand-controlled ventilation. Typically, the following building features are required for an effective performance of demand ventilation controls (13):

- Unpredictable variations in the occupancy patterns
- Requirement of either heating or cooling for most of the year
- Low pollutant emissions from nonoccupant sources (i.e., furniture, and equipment)

It should be noted that while CO_2 can be used to control occupant-generated contaminants, it may not be reliable to control pollutants generated from nonoccupant sources such as building materials. As a solution, a base ventilation rate can be maintained at all times to ensure that nonoccupant contaminants are controlled within acceptable concentration levels (12).

Ventilation of Parking Garages. Automobile parking garages can be partially open or fully enclosed. Partially open garages are typically above-grade with open sides and generally do not need mechanical ventilation. However, fully enclosed parking garages are usually underground and require mechanical ventilation. Indeed, in the absence of ventilation, enclosed parking facilities present several indoor air quality problems. The most serious is the emission of high levels of carbon monoxide (CO) by cars within the parking garages. Other concerns related to enclosed garages are the presence of oil and gasoline fumes, and other contaminants such as oxides of nitrogen (NO_x) and smoke haze from diesel engines.

To determine the adequate ventilation rate for garages, two factors are typically considered: the number of cars in operation and the emission quantities. The number of cars in operation depends on the type of the facility served by the parking garage and may vary from 3% (in a shopping area) up to 20% (in a sports stadium) of the total vehicle capacity (14). The emission of carbon monoxide depends on individual cars including such factors as the age of the car, the engine power, and the level of car maintenance.

For enclosed parking facilities, ASHRAE Standard 62–1989 specifies the fixed ventilation rate of 7.62 $\mathrm{l/s{\cdot}m^2}$ [1.5 $\mathrm{(ft^3/min)/ft^2}$] of gross floor area (15). Therefore, a ventilation flow of about 11.25 air changes per hour is required for garages with a 2.5 m ceiling height. However, some of the model code authorities specify an air change rate of 4 to 6 air changes per hour. Some of the model code authorities allow the ventilation rate to vary and be reduced to save fan energy if CO-demand-controlled ventilation is implemented, that is, a continuous monitoring of CO concentrations is conducted, with the monitoring system being connected to the mechanical exhaust equipment. The acceptable level of contaminant concentrations varies significantly form code to code. A consensus on acceptable contaminant levels for enclosed parking garages is needed. Unfortunately, ASHRAE Standard 62-1989 does not address the issue of ventilation control through contaminant monitoring for enclosed garages. Thus, ASHRAE commissioned a research project 945-RP (16) to evaluate current ventilation standards and recommend rates appropriate to current vehicle emissions/usage. Based on this project, a general methodology has been developed to determine the ventilation requirements for parking garages.

Figure 7 indicates also the fan energy savings achieved by the on-off and variable air volume (*VAV*) systems (relative to the fan energy use by the CV system). As illustrated in Fig. 7, when CO-emission density varies strongly over the course of the day, significant fan energy savings can be obtained when demand CO-ventilation control strategy is used to operate the ventilation system while maintaining acceptable CO levels within the enclosed parking facility. These energy savings depend on the pattern of car movement within the parking facility. Figure 8 indicates three types of car movement profiles considered in the analysis (16).

Electric Systems. For most commercial buildings and a large number of industrial facilities, the electric energy cost constitutes the dominant part of the utility bill. Lighting, office equipment, and motors are the electric systems that consume the major part of energy in commercial and industrial buildings. *1. Lighting*

Lighting for a typical office building represents on average 40% of the total electric energy use. There are a variety of simple and inexpensive measures to improve the efficiency of lighting systems. These measures include the use of energy-efficient lighting lamps and ballasts, the addition of reflective devices, delamping (when the luminance levels are above the recommended levels by the standards), occupancy sensors, and the use of daylighting controls. Most lighting measures are especially cost-effective for office buildings for which payback periods are less than one year.

Example: *Problem.* Consider a building with total 1000 luminaires of four 40-W lamps per luminaire. Determine, the energy saving after replacing those with two 32-W high efficacy lamps per luminaire. This building is operated 8 h/d, 5 d/wk, 50 wk/yr.
Solution. The energy saving in kWh is

$$\Delta\,\mathrm{kWh} = 1000\times(4\times40\,\mathrm{W}-4\times32\,\mathrm{W})(8\times5\times50\,\mathrm{h/yr})\frac{1\,\mathrm{kW}}{1000\,\mathrm{W}} = 320{,}000\,\mathrm{kWh/yr}$$

Thus, the energy saving is 320,000 kWh/yr. When implementing this measure, it is important to ensure that the lighting level remains constant and/or is sufficient to meet minimum requirements. In addition to

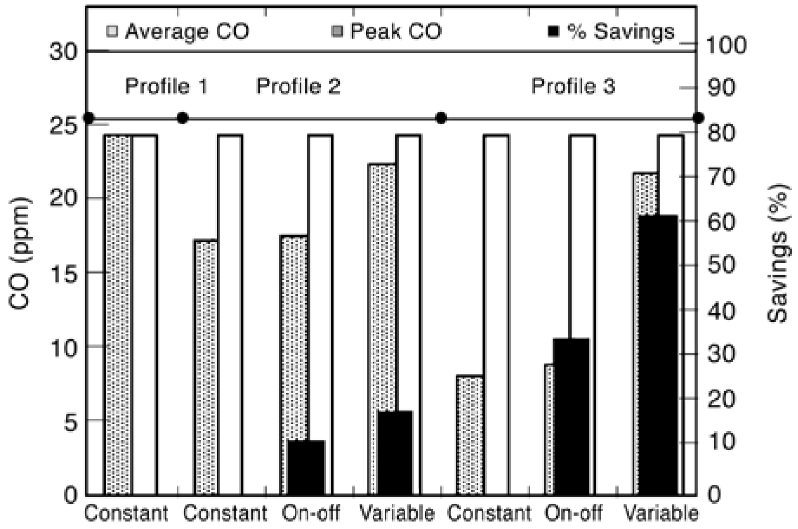

Fig. 7. Typical energy savings and maximum CO level obtained for demand CO-ventilation controls.

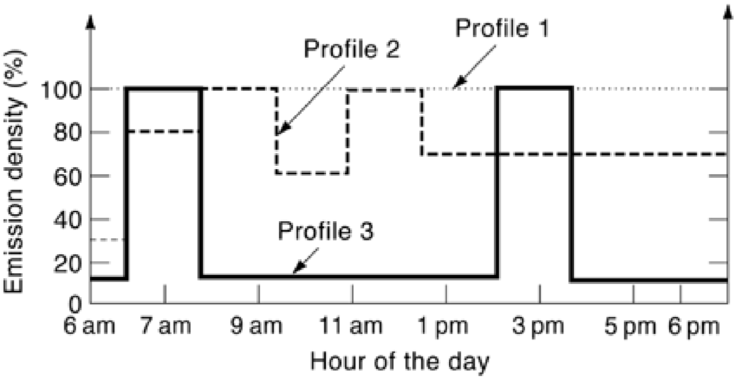

Fig. 8. Car movement profiles used in the analysis conducted in Ref. 16.

reduction in electricity use, lighting retrofits may affect both heating and cooling energy uses. Detailed energy analyses may be needed to determine the impact of lighting retrofits on heating or cooling energy use.

2. Office Equipment

Office equipment constitutes the fasted growing electric load especially in commercial buildings. Office equipment include computers, fax machines, printers, and copiers. Today, there are several manufacturers that provide energy-efficient office equipment [such those that comply with the US Environmental Protection Agency (*EPA*) Energy Star specifications]. For instance, energy-efficient computers automatically switch to a low-power “sleep” mode or off mode when not in use.

3. Motors

The energy cost to operate electric motors can be a significant part of the operating budget of any commercial and industrial building. Measures to reduce the energy cost of using motors include reducing operating time (turning off unnecessary equipment), optimizing motor systems, using controls to match motor output with demand, using variable speed drives for air and water distribution, and installing energy-efficient

Fig. 9. An energy-efficient motor with a control panel (courtesy of Baldor).

Table 9: Typical Efficiencies of Motors

Motor size, kw (hp)	Standard efficiency	High efficiency
0.75 (1)	72%	81%
1.50 (2)	76%	84%
2.25 (3)	77%	89%
3.75 (5)	80%	89%
5.62 (7.5)	82%	89%
7.50 (10)	84%	89%
11.25 (15)	86%	90%
15.00 (20)	87%	90%
22.50 (30)	88%	91%
30.00 (40)	89%	92%
37.50 (50)	90%	93%

source: Reference 6, with permission.

motors. Figure 9 shows an energy-efficient motor with a control panel. Table 9 provides typical efficiencies for several motor sizes. Example 2 illustrates the calculation procedure to estimate the cost-effectiveness of energy-efficient motors.

Example: *Problem.* Consider a 7.5-kW (10-hp) motor that needs to be replaced. There two alternatives for the replacement: either use a standard motor with an energy efficiency of 84% and a cost of \$600 or use of high-efficiency motor (with an energy efficiency of 89%) and a cost of \$900. Determine the payback period for replacing the exiting motor with the high efficiency motor if the annual operating time is 6000 h and the cost of electricity is \$0.08/kWh.

Solution. The energy saving in kWh for using the energy efficient motor relative to the standard motor is

$$\Delta \, \mathrm{kWh} = 7.5 \, \mathrm{kW} \times \left(\frac{1}{0.84} - \frac{1}{0.89} \right) \times 6000 \, \mathrm{h} = 3000 \, \mathrm{kWh/yr}$$

Thus, the simple payback period (*SPB*) for investing in high efficiency rather than the standard motor is

$$\mathrm{SPB} = \frac{\$900 - \$600}{3000 \, \mathrm{kWh/yr} \times \$0.08/\mathrm{kWh}} = 1.25 \, \mathrm{yr}$$

In addition to the reduction in the total facility electric energy use, energy-efficiency improvements of the electric systems decrease space cooling loads and therefore further reduce the electric energy use in the facility. These cooling energy reductions as well as possible increases in thermal energy use (for space heating) should be accounted for when evaluating the cost-effectiveness of energy-efficiency improvements in lighting and office equipment.

HVAC Systems. The energy use due to heating, ventilating, and air conditioning (*HVAC*) systems can represent 40% of the total energy consumed by a typical commercial building. A large number of measures can be considered to improve the energy performance of both primary (i.e., central heating and cooling plant) and secondary (i.e., air and water distribution) HVAC systems. Some of these measures are listed below:

1. Setup and Setback Thermostat Temperatures

When appropriate, setback of heating temperatures can be recommended during unoccupied periods. Similarly, setup of cooling temperatures can be considered.

2. Retrofit of Constant Air Volume Systems

For commercial buildings, variable air volume (*VAV*) systems should be considered when the existing HVAC systems rely on constant volume fans to condition part or the entire building. VAV systems adjust air flow rates in response to the actual cooling and heating loads.

3. Retrofit of Central Heating Plants

The efficiency of boilers can be drastically improved by adjusting the fuel air ratio for proper combustion and by using modulating burners. In addition, installation of new energy-efficient boilers can be economically justified when old boilers are to be replaced.

4. Retrofit of Central Cooling Plants

Currently, there are several chillers that are energy-efficient and easy to control and operate and are suitable for retrofit projects. In general, it is cost-effective to recommend energy-efficient chillers such as those using scroll compressors (see Figs. 10 and 11) for replacement of existing chillers. Example 3 shows a cost-effectiveness analysis of using energy efficient chillers (6).

5. Installation of Heat Recovery Systems

Heat can be recovered from some HVAC equipment. For instance, heat exchangers can be installed to recover heat from air handling unit (*AHU*) exhaust air streams and from boiler stacks. Figure 12 shows a thermal wheel that can be used to recover heat from exhaust air.

Example: An existing chiller with a capacity of 900 kW and with an average seasonal COP of 3.0 is to be replaced by a new chiller with the same capacity but with an average seasonal COP of 4.0. Determine the simple payback period of the chiller replacement if the cost of electricity is $0.08/kWh and the cost differential of the new chiller is $18,000. Assume that the number of equivalent full-load hours for the chiller is 1200 h per year both before and after the replacement.

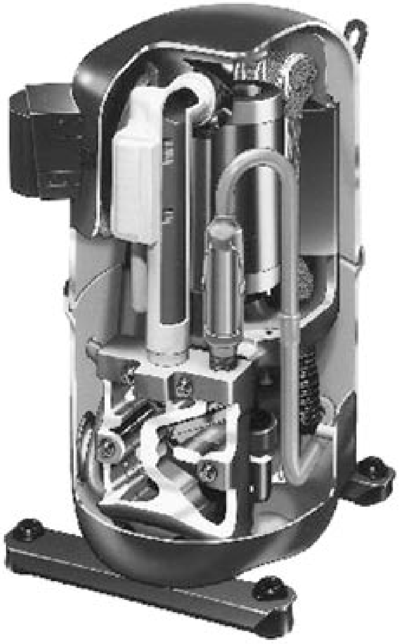

Fig. 10. Cutaway of a hermetic scroll compressor (courtesy of Copeland Corporation, Sydney, OH).

Fig. 11. A pair of matching scroll membranes used in scroll compressors (courtesy of Copeland Corporation, Sydney, OH).

Solution. In this example, the energy use savings can be calculated using a simplified analysis as detailed in Ref. 6:

$$\Delta E_c = 900 \text{ kW} \times 1200 \text{ h/yr} \times \left(\frac{1}{3.0} - \frac{1}{4.0}\right) = 90{,}000 \text{ kWh/yr}$$

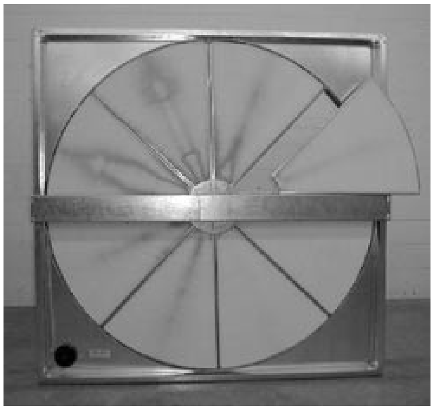

Fig. 12. A rotating thermal wheel for heat recovery applications in HVAC systems.

Therefore, the simple payback period for investing in a high-efficiency chiller rather than a standard chiller can be estimated as follows:

$$\mathrm{SPB} = \frac{\$18,000}{90{,}000\ \mathrm{kWh/yr} \times \$0.08/\mathrm{kWh}} = 2.5\ \mathrm{yr}$$

A life cycle cost analysis may also be required to determine if the investment in a high energy efficiency chiller is really warranted.

It should be noted that there is a strong interaction between various components of the heating and cooling system. Therefore, a whole-system analysis approach should be followed when improving the energy efficiency of an HVAC system. Optimizing the energy use of a central cooling plant (which may include chillers, pumps, and cooling towers) is one example of using a whole-system approach to reduce the energy use for heating and cooling buildings.

Compressed Air Systems. Compressed air is an indispensable tool for most manufacturing facilities and is used in some controls systems for commercial buildings. Its uses range from air-powered hand tools and actuators to sophisticated pneumatic robotics. Unfortunately, staggering amounts of compressed air are currently wasted in a large number of facilities. It is estimated that only 20% to 25% of input electric energy is delivered as useful compressed air energy. Leaks are reported to account for 10 to 50% of the waste while misapplication accounts for 5% to 40% of loss in compressed air (17).

The compressor can be selected from several types such as centrifugal, reciprocating, or rotary screw with one or multiple stages. For small- and medium-sized units, screw compressors are currently the most commonly used for industrial applications. Table 10 provides typical pressure, airflow rate, and mechanical power requirement ranges for different types of compressors (18).

Some of the energy conservation measures that are suitable for compressed air systems are listed below:

- Repair of air leaks in the distribution lines. Several methods exist to detect these leaks ranging from simple procedures such as the use of water and soap to more sophisticated techniques such as the use of ultrasound leak detectors.
- Reduction of inlet air temperature and/or the increase of inlet air pressure.

Table 10. Typical Ranges of Application for Various Types of Air Compressors

Compressor type	Airflow rate (m^3/s)	Absolute pressure (MPa)	Mechanical power requirement [kW/(l/s)]
Reciprocating	0.0–5.0	0.340–275.9	0.35–0.39
Centrifugal	0.5–70.5	3.5–1034.3	0.46
Rotary screw	0.5–16.5	0.1–1.8	0.33–0.41

- Reduction of the compressed air usage and air pressure requirements by making some modifications to the manufacturing processes.
- Installation of heat recovery systems to use the compression heat within the facility for either water heating or building space heating.
- Installation of automatic controls to optimize the operation of several compressors by reducing part load operations.
- Use of booster compressors to provide higher discharge pressures. Booster compressors can be more economical if the air with the highest pressure represents a small fraction of the total compressed air used in the facility. Without booster compressors, the primary compressor will have to compress the entire amount of air to the maximum desired pressure.

Example 4 illustrates the energy and cost savings due to an increase on the inlet pressure air intake for air compressors based on simplified calculation procedures described in Ref. 6.

Example: A compressed air system has a mechanical power requirement of 75 kW (100 hp) with a motor efficiency of 90%. Determine the cost savings of reducing the discharge absolute pressure from 800 kPa (8 atm) to 700 kPa (7 atm). Assume that the compressor is operating 5000 h per year with an average load factor of 80%, and the cost of electricity is $0.08/kWh.
Solution. Assuming that the intake air pressure of the compressor is equal to 100 kPa (i.e., 1 atm), the reduction in the discharge pressure corresponds to a reduction in the pressure ratio P_o/P_i from 8 to 7. The percent reduction in the mechanical power requirements can be calculated using an isothermal compression (refer to Ref. 6 for more details):

$$\Delta\,\mathrm{kWh}_{\mathrm{comp}} = \frac{0.064 \times 75\ \mathrm{kW} \times 5000\ \mathrm{h/yr} \times 0.80}{0.90} = 21{,}333\ \mathrm{kWh/yr}$$

Thus, the cost savings for reducing the discharge air pressure are about $1,750/yr.

Energy Management and Control Systems. With the constant decrease in the cost of computer technology, automated control of a wide range of energy systems within commercial and industrial buildings is becoming increasingly popular and cost-effective. An energy management and control system (*EMCS*) can be designed to control and reduce the building energy consumption within a facility by continuously monitoring the energy use of various equipments and making appropriate adjustments. For instance, an EMCS can auto-

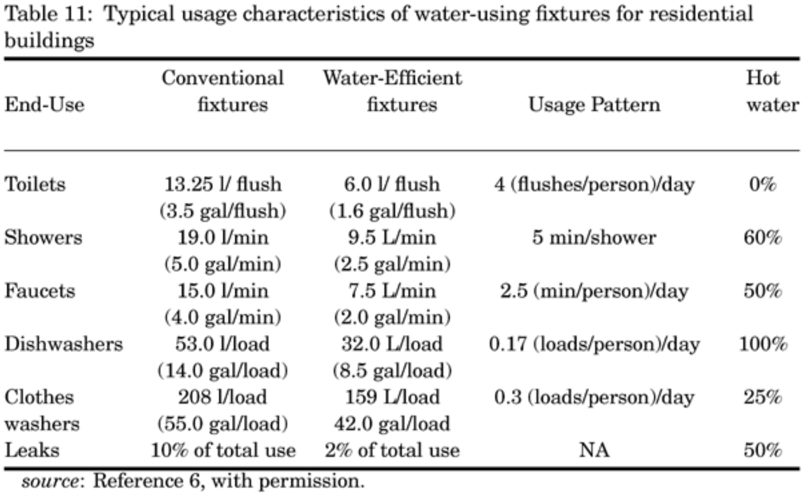

Table 11: Typical usage characteristics of water-using fixtures for residential buildings

End-Use	Conventional fixtures	Water-Efficient fixtures	Usage Pattern	Hot water
Toilets	13.25 l/ flush (3.5 gal/flush)	6.0 l/ flush (1.6 gal/flush)	4 (flushes/person)/day	0%
Showers	19.0 l/min (5.0 gal/min)	9.5 L/min (2.5 gal/min)	5 min/shower	60%
Faucets	15.0 l/min (4.0 gal/min)	7.5 L/min (2.0 gal/min)	2.5 (min/person)/day	50%
Dishwashers	53.0 l/load (14.0 gal/load)	32.0 L/load (8.5 gal/load)	0.17 (loads/person)/day	100%
Clothes washers	208 l/load (55.0 gal/load)	159 L/load 42.0 gal/load	0.3 (loads/person)/day	25%
Leaks	10% of total use	2% of total use	NA	50%

source: Reference 6, with permission.

matically monitor and adjust indoor ambient temperatures, set fan speeds, open and close air handling unit dampers, and control lighting systems.

If an EMCS is already installed in the building, it is important to obtain a system tune-up to ensure that the controls are properly operating. For instance, the sensors should be calibrated regularly in accordance with manufacturers' specifications. Poorly calibrated sensors may cause an increase in heating and cooling loads and may reduce occupant comfort.

Indoor Water management. Water and energy savings can be achieved in buildings by using water-savings fixtures instead of the conventional fixtures for toilets, faucets, showerheads, dishwashers, and clothes washers. Savings can also be achieved by eliminating leaks in pipes and fixtures.

Table 11 provides typical water use of conventional and water-efficient fixtures for various end uses. In addition, Table 11 indicates the hot water use by each fixture as a fraction of the total water. With water-efficient fixtures, savings of 50% of water use can be achieved for toilets, showers, and faucets.

New Technologies. A number of new or improved energy-efficiency technologies have been developed in the last decade. Among the new technologies that can be considered for commercial and industrial buildings include the following.

(1) Building Envelope technologies. Recently several materials and systems have been proposed to improve the energy efficiency of building envelope and especially windows including the following:

- Spectrally selective glasses that can optimize solar gains and shading effects
- Chromogenic glazings that change its properties automatically depending on temperature and/or light level conditions (similar to sunglasses that become dark in sunlight)
- Building integrated photovoltaic panels that can generate electricity while absorbing solar radiation and reducing heat gain through building envelope (typically roofs)

(2) Light Pipe technologies. While the use of daylighting is straightforward for perimeter zones that are near windows, it is not usually feasible for interior spaces, particularly those without any skylights. Recent but

still emerging technologies allow to “pipe” light from roof or wall-mounted collectors to interior spaces that are not close to windows or skylights.

(3) HVAC systems and controls. Several strategies can be considered for energy retrofits including the following.

- Thermal comfort controls can reduce energy consumption for heating or cooling buildings. Some HVAC control manufacturers have recognized the potential benefits from thermal comfort controls—rather than controls relying on only dry-bulb temperature—and are already developing and producing thermal comfort sensors. These sensors can be used to generate comfort indicators such as predicted mean vote (*PMV*) and/or predicted percent dissatisfied (*PPD*).
- Heat recovery technologies such rotary heat wheels and heat pipes can recover 50% to 80% of the energy used to heat or cool ventilation air supplied to the building.
- Dessicant-based cooling systems are now available and can be used in buildings with large dehumidification loads during long periods (such as hospitals, swimming pools, and supermarket fresh produce areas).
- Geothermal heat pumps can provide an opportunity to take advantage of the heat stored underground to condition building spaces.
- Thermal energy storage (*TES*) systems offer a means of using less expensive off-peak power to produce cooling or heating to condition the building during on-peak periods. Several optimal control strategies have been developed in recent years to maximize the cost savings of using TES systems.

(4) Cogeneration. This is not really a new technology. However, recent improvements in its combined thermal and electrical efficiency made cogeneration cost effective in several applications including institutional buildings such hospitals and universities. A simplified analysis procedure is illustrated in Example 5 to evaluate the cost-effectiveness of a small cogeneration system (6).

Example: Consider a 60 kW cogeneration system that produces electricity and hot water with the following efficiencies: (a) 26% for the electricity generation and (b) 83% for the combined heat and electricity generation. Determine the annual savings of operating the cogeneration system compared to a conventional system that consists of purchasing electricity at a rate of \$0.07/kWh and producing heat from a boiler with 65% efficiency. The cost of fuel is \$5.7/GJ (or $\$6/10^{12}$ Btu). The maintenance cost of the cogeneration system is estimated at \$1.20 per hour of operation (relative to the maintenance cost of the conventional system). Assume that all the generated thermal energy and electricity are utilized during 6800 h/yr. Determine the payback period of the cogeneration system if the installation cost is \$2,250/kW.

Solution. First, the cost of operating the cogeneration system is compared to that of the conventional system on an hourly basis.

(1) *Cogeneration System.* For each hour, 60 kW of electricity is generated (at an efficiency of 26%) with fuel requirements of 0.787×10^{12} Btu [= 60 kW $\times$ 0.003413 (10^{12} Btu/kW)/0.26]. At the same time, a thermal energy of 0.449×10^{12} Btu [$= 0.787 \times 10^{12}$ Btu $\times (0.83 - 0.26)$] is obtained. The hourly flow of energy for the cogeneration system is summarized in Fig. 13: Thus, the cost of operating the cogeneration on an hourly basis can be estimated as follows:

Fuel cost:	0.787×10^{12} Btu/h $\times$ \$ $6/10^{12}$ Btu =	\$4.72/h
Maintenance cost:	\$1.20/h	
Total cost:	\$5.92/h	

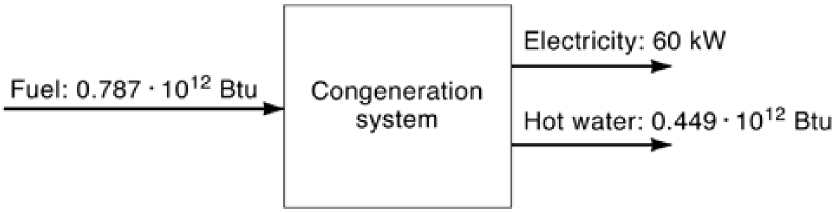

Fig. 13. Energy balance for the cogeneration system used in Example 5.

(2) *Conventional System.* For this system, the 60 kW electricity is directly purchased from the utility, while the 0.449×10^{12} Btu of hot water is generated using a boiler with an efficiency of 0.65. Thus the costs associated with utilizing a conventional system are as follows:

Electricity cost:	60 kWh/h × 0.07 =	\$4.20/h
Fuel cost (boiler):	$(0.449 \times 10^{12}$ Btu/h$)/0.65 \times \$\ 6/10^{12}$Bt	\$4.15/hr
Total cost:		\$8.35/h

Therefore, the annual savings associated with using the cogeneration system are

$$\Delta\,\text{cost} = (\$8.35/\text{h} - \$5.92/\text{h}) \times 6{,}800\ \text{h/yr} = \$16{,}524/\text{yr}$$

Thus, the simple payback period for the cogeneration system is

$$\text{SPB} = \frac{\$2,250/\text{kW} \times 60\ \text{kW}}{\$16{,}524} = 8.2\ \text{yr}$$

A life cycle cost analysis may be required to determine if the investment on the cogeneration system is warranted.

Energy Conservation In Transportation

Introduction. Currently, oil is the primary energy source for fueling transportation systems worldwide. In 1997, the transportation sector represents about 49% of the total world oil consumption (19). The share of the transportation sector is expected to increase even further to 55% in year 2000. Transportation energy use is generally grouped into three categories depending on the travel mode: road (automobiles and trucks), air (airplanes), and other (mostly trains). Figure 14 indicates the share of each travel mode in the world oil consumption during 1997 (1). It is clear that the majority of transportation energy use is attributed to road transport (mostly personal vehicles). However, the energy used by personal motor vehicles varies significantly from region to region and country to country. Table 14 lists the per capita motorization levels (i.e., the number of vehicles per person) for some selected countries and regions. The United States has the highest level of motorization level with almost one car per person. In urban areas, the use of cars represents more than 84% (in passenger-miles) of all travel modes in the United States, while it is only 49% in Germany.

The US highway system is the most extensive in the world and consists of the following:

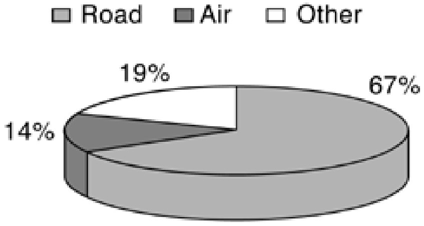

Fig. 14. World energy use for transportation by travel mode during 1997 (1).

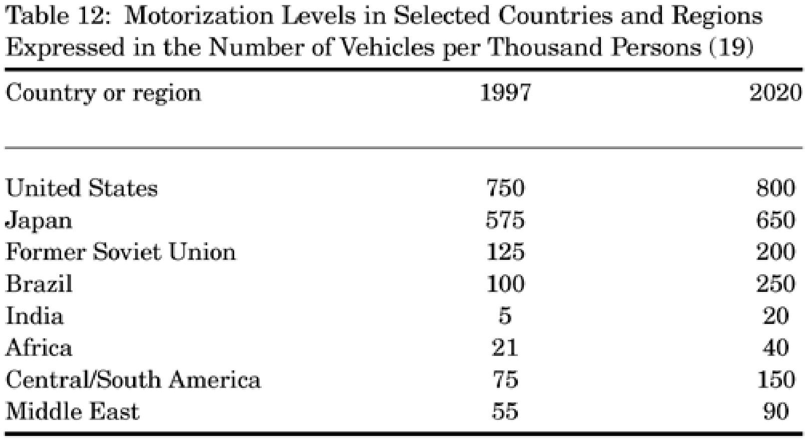

Table 12: Motorization Levels in Selected Countries and Regions Expressed in the Number of Vehicles per Thousand Persons (19)

Country or region	1997	2020
United States	750	800
Japan	575	650
Former Soviet Union	125	200
Brazil	100	250
India	5	20
Africa	21	40
Central/South America	75	150
Middle East	55	90

- Highway system with about 6.1×10^6 km (or 3.8×10^6 mi) of roadway, including 70,400 km (44,000 mi) of the Interstate System and over 570,000 bridges (20)
- Mass transit within most cities of 20,000 or higher population with buses, light rail, commuter rail, trolleys, and subways
- Air travel system with more than 17,000 airports (however, it should be noted that the top 100 United States airports handle 95% of all passenger trips)
- Freight system that moves more than 4.6×10^{12} metric ton-kilometers (or 3.2×10^{12} ton-miles) of freight per year (20) (trucks are the dominant freight transport mode for such nonbulk cargo such as mail, processed food, and consumer products)

Measures to Improve Transportation Energy Efficiency. With the continued growth in travel and increase in energy use, the US government is advocating transportation energy efficiency and conservation. For example, the Clean Air Amendments (*CAA*) of 1990 include transportation demand management as a measure to reduce urban air pollution. Moreover, the Intermodal Surface Transportation Efficiency Act of 1991 (*ISTEA*) promotes energy efficiency in the transport sector by allowing states to shift highway funds to other purposes such as transit and high-speed ground transportation. Similarly, the Energy Policy Act (EPACT) of 1992 provides economic incentives to promote the use of nonpetroleum alternative fuels.

While policy measures to promote energy efficiency exist, there are still several hindrances to the implementation of most of these measures. Among these hindrances are the following:

Table 13: Fuel Use, Fuel Efficiency, and carbon emission Intensity for automobiles in selected Countries (21)

Country	Fuel use gal/100 miles (l/100 km)	Carbon emission lbs/100 miles (kg/100 km)
US	4.89 (11.5)	25.46 (7.18)
Germany	4.00 (9.4)	20.03 (5.65)
U.K	3.82 (9.0)	19.61 (5.53)
Sweden	4.25 (10.0)	21.77 (6.14)

- Transportation is still one of the most important factors to ensure economic development and foster social and cultural opportunities. Thus, the need to increase, or at least maintain, access to reliable transportation means. In the United States, the most reliable means of transportation is the personal vehicle. It is no wonder why the United States has the highest level of personal travel in the world [21,722 km (13,500 mi) per person per year], most vehicles per person in the world as indicated in Table 14 (eight cars for every 10 persons, which is equivalent to two vehicles per household).
- The efficacy of most proposed transportation energy conservation measures remains a highly controversial issue. Indeed, energy efficiency in the transportation sector is mostly driven by policies and standards and is not typically cost-effective.

Some of the measures that are currently considered to reduce energy use in the transportation sector in the United States and other countries are discussed in the following sections. Most of these measures are not cost-effective yet. However, it is expected that future developments and higher oil prices will make these measures economically viable alternatives.

Fuel Economy Vehicles. For a typical car, about 15% of the energy content of the fuel input is actually used to move the car or operate accessories such air-conditioning and power steering. The remainder of the energy is lost in the form of waste heat (engine losses), friction of engine moving parts, engine pumping losses, and standby or idle losses (for urban driving). Table 15 summarizes the average fuel use and fuel efficiency intensities in selected countries based on an International Energy Agency (*IEA*) study. In addition, Table 15 provides the carbon emissions intensities generated by a typical car. The values listed in Table 15 are based on 1995 data. The fuel use and thus the carbon emission by personal vehicles in the United States are the highest among the countries listed in Table 14 with an average of about 11.5 l/100 km (4.89 gal/100 mi) or 8.7 km/l (20.5 mi/gal). One of the reasons for higher fuel use in the United States is that personal light trucks (which are more fuel-intensive than cars) are common and represent about 30% of the total United States household vehicles (21).

New developments in the internal combustion engine (*ICE*) make it possible to improve the fuel efficiency of motor vehicles. In particular, two types of engines have been proposed:

- Turbocharged direct-injection (*TDI*) diesel engines that inject fuel directly—using advanced fuel injectors and computerized control systems—into the combustion chamber instead use a prechamber to perform part of the combustion (indirect injection). These TDI engines can increase fuel economy by 20% compared to conventional diesel engines and by 40% compared to conventional gasoline engines. It should be noted that TDI technology has been in use since the late 1980s in Europe (especially in Germany).

- Direct-injection stratified charge (*DISC*) engines incorporate some of the energy-efficiency features of diesel engines into spark-ignited gasoline engines. In particular, DISC engines reduce fuel intake and air pumping losses when engine speed is lowered. It is reported that DISC engines have 20% higher fuel economy than conventional gasoline engines. However, no DISC engines are currently available in the United States due to their inability to meet the stringent United States emissions standards.

In addition to the development of energy-efficient engines, aerodynamic designs and lightweight materials are being considered and already utilized to improve the fuel economy of vehicles. For instance, carbon-fiber polymer matrix composites are now widely used to construct several parts of vehicles. Moreover, lightweight metals such aluminum and ceramics are being demonstrated to build engines and body parts.

Hybrid Electric Vehicles. Another technology that is currently available to improve the fuel economy of automobiles is the hybrid electric vehicle. Hybrid electric vehicles (*HEVs*) are powered by a combination of internal combustion engines and electric motors. Batteries are typically used to drive the electric motors. The benefits of HEVs include improved fuel economy and lower emissions compared to conventional vehicles. It is estimated that a hybrid electric vehicle reduces fuel use by one-half relative to a conventional vehicle powered solely by an internal combustion engine. For instance, the Honda Insight—a newly developed HEV model—is expected to travel 1120 km (700 mi) using a single tank of gas and thus achieving a high level of fuel economy with more than 30 km/l (70 mi/gal) and meeting California's Ultra-Low Emission Standards (22). Example 6 illustrates the energy and cost savings that can be expected from an HEV model compared to a conventional vehicle.

Example: A buyer of an HEV model drives on average 80 km (50 mi) per day over 250 days per year. Estimate the annual fuel use and cost savings compared to his old vehicle that travels 8.5 km (20 mi/gal). The HEV model has fuel economy of 25.5 km/l (60 mi/gal). Assume the cost of fuel is \$0.40/l (\$1.50/gal).
Solution. The buyer travels 20,000 km/yr (=250 d/yr × 80 km/d). The savings the fuel by switching from a conventional vehicle to a HEV model can be estimated as follows:

$$\Delta\,\text{gallons} = 20{,}000\ \text{km/yr} \times \left(\frac{1}{8.5\ \text{km/l}} - \frac{1}{25.5\ \text{km/l}}\right) = 1{,}568\ \text{l/yr}$$

Thus, the annual fuel cost savings amount to \$627/yr.

There are several configurations for HEVs depending on the types of energy storage, power unit, and vehicle propulsion system. The electric energy can be stored using batteries, ultracapacitors, or flywheels. The types for power units suitable for HEVs include spark ignition engines, compression-ignition direct-injection engine gas turbines, and fuel cells. Two configurations are commonly used for the HEV propulsion system: series configuration or parallel configuration. In the series configuration, the HEV has no mechanical connection between the hybrid power unit and the wheels, and thus electricity to drive the wheels comes solely from the batteries—which are charged by the vehicle's generator. On the other hand, the HEV with a parallel configuration has a direct mechanical connection between the power unit and the wheels—similar to the configuration used in conventional vehicles. Thus, a parallel HEV can use the power generated by the internal combustion engine for long trips (such as highway driving) and the power produced by the electric motor for accelerating (common in urban area driving).

Battery-Operated and Fuel-Cell Vehicles. In several countries, electrical battery vehicles—also referred to as zero-emission vehicles (*ZEVs*)—have been introduced in an attempt to reduce air pollution generated from the transportation sector. In the United States, the California Low-Emission Program (*LEVP*) mandates the introduction of ZEVs in four phases over a 15-year period. In particular, the LEVP—which was originally passed into legislation in 1990—requires the seven largest auto manufacturers to achieve at least the

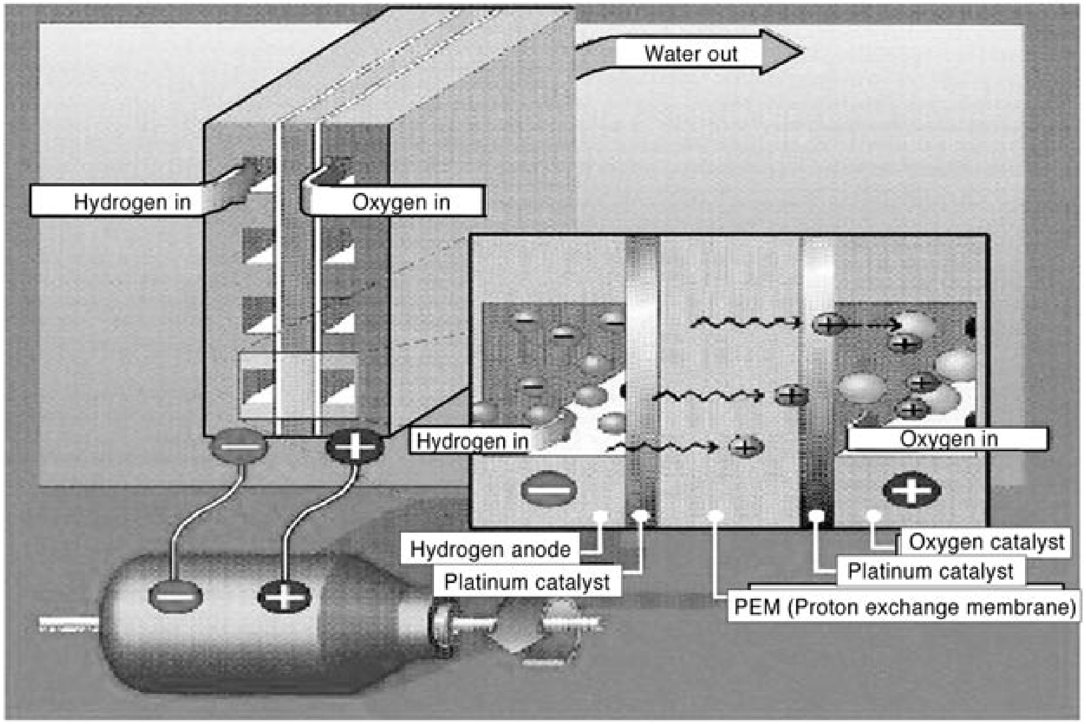

Fig. 15. A basic operation of a fuel cell.

10% of their in-state sales with vehicles emitting no criteria pollutants by 2003. In 2000, the LEVP mandate has been eased and the beginning of required ZEV sales was rolled back to 2003. Some northeastern US states (including Maine, Maryland, Massachusetts, New Jersey, and New York) have adopted similar requirements (23).

However, the development of electric vehicle batteries has encountered several problems and barriers that are still difficult to overcome. In particular, the performance characteristics of all existing electric vehicle batteries (including leadacid, lithiummetaldisulfide, nickelcadmium, nickelmetal hydride, sodiumnickelchloride, sodiumsulfur, and zinc-air) fall short of the long-term goals set by the US Advanced Battery Consortium (*USABC*). The goals set by the USABC enable an electric vehicle to perform as closely to a conventional vehicle with battery recharging required after 200 to 400 miles. Moreover, electric vehicles (powered by batteries) have to be recharged from electric power stations that are typically supplied by generating facilities that most likely produce pollutants. Therefore, electric vehicles—powered by batteries—are not actually clean since they indirectly pollute. As an alternative to the battery, the fuel cell is emerging as a promising technology to power electric vehicles.

Batteries and fuel cells are similar since they both convert chemical energy into electricity with high efficiency and minimal maintenance cost (because they do not have any moving parts). However, unlike a battery that needs to be recharged or replaced, a fuel cell can generate electricity as long as the vehicle's tank contains fuel. The fuel cell generates electricity by converting molecular hydrogen and oxygen into water, justifying the term *clean technology*.

The principle of the fuel cell was first demonstrated over 150 years ago. In its simplest form, the fuel cell is constructed similar to a battery with two electrodes in an electrolyte medium, which serves to carry electrons

Table 14: Types of Fuel Cells

Fuel-cell name	Electrolyte	Fuel	Oxidant	Operating temperatures (°C)
PAFC	Phosphoric acid	Pure hydrogen	Clear air (without CO_2)	200
AFC	Alkaline	Pure hydrogen	Pure oxygen and water	60–120
SPFC	Solid polymer	Pure hydrogen	Pure oxygen	60–100
MCFC	Molten carbonate	Hydrocarbons	Air and oxygen	650
SOFC	Solid oxide	Any fuel	Air	900-1000

Source: Reference 6, With Permission.

released at one electrode (anode) to the other electrode (cathode). Typical fuel cells use hydrogen (derived from hydrocarbons) and oxygen (from air) to produce electrical power with other by-products (such as water, carbon dioxide, and heat). High efficiencies (up to 73%) can be achieved using fuel cells. Figure 15 illustrates the operation of a typical fuel cell. Table 16 summarizes various types of fuel cells that are under development. Each fuel-cell type is characterized by its electrolyte, fuel (source of hydrogen), oxidant (source of oxygen), and operating temperature range. The solid polymer type fuel cell (SPFC), or more commonly called polymer electrolyte membrane (*PEM*), is considered by almost all manufacturers around the world as the technology of choice for fuel-cell vehicles.

Summary

In this article, simple yet proven analysis procedures and technologies have been described to improve energy efficiency in three end-use sectors: buildings, industry, and transportation. If the energy management procedures are followed properly and if some of the energy conservation measures—briefly described here—are actually implemented, it is expected that huge savings in energy use can be achieved. The reduction in the energy use will benefit not only the individual facilities but the entire nation and our environment. The efficient use of energy will become increasingly vital to improve the environment and to increase the economic competitiveness.

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