CENTRE FOR RENEWABLE ENERGY SOURCES

ENERGY AUDIT GUIDE

PART B: SYSTEM RETROFITS FOR ENERGY EFFICIENCY

COMMUNITY INITIATIVE

ADAPT

European Committee
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The present edition constitutes part of a series of three Technical Guides published by the Centre for Renewable Energy Sources (CRES) regarding the Energy Audit procedure in buildings and in industry. The aim of these publications is to comprise a useful and practical tool for Engineers and other scientists that are going to be occupied in the field of Energy Auditing.

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The Training Department of CRES was responsible for the implementation of the project, with the scientific support of the Energy Policy & Programming and Supervision & Execution of Energy Programming Departments of CRES. Dr. Ch. Malamatenios, who is the Head of CRES Training Dept, coordinated the project that was realised during the 1998-2000 period.

The transnational partnership was completed by the French organisation ARMINES - Centre d' Energetique, whose colleagues contributed in many ways to the proper dispatch of the project, thus retaining its European dimension, as well as to the preparation of a part of these Guides. More specifically for this Guide, parts of Chapters 2, 3, 4, 5 and 6 have been reproduced, after relevant elaboration, from the texts produced by ARMINES - Centre d' Energetique in the frame of the present project. The original texts are also included in the book: Krarti, M., 2000, "Energy Audit for Buildings, Engineering Approach", CRC Press LCC, whose author (Pr. M. Krarti, University of Colorado at Boulder) worked in the project on behalf of partner ARMINES - Centre d' Energetique. For this reason, copy of any portion of these Chapters is prohibited without the permission of CRES, the author and CRC Press LCC.

CONTENTS

1. GENERAL CONSIDERATIONS REGARDING AN ENERGY AUDIT

In new or retrofit energy conservation building design, innovation should be encouraged. However, any innovation will fail no matter how beneficial from the energy conservation point of view it is, if it cannot be easily integrated into conventional construction practices and conform to the established owner-user preferences, financing methods, building codes and standards. Though the same procedures and information are used whether designing for energy conservation or not, significantly greater care and effort is necessary for energy-saving measures.

Special attention must be given to the following:
- Overall values of the heat transfer coefficient U for walls, floors, roofs and glass.
- Maximum percent of fenestration (glass) area.
- Building orientation in respect to fenestration exposure.
- Hours of operation of each space and area on workdays, weekends and holidays.
- System efficiencies at full load and at partial loads.
- Ability to control, reset, start/stop and reduce loads.
- Heat recovery and heat storage.
- Electrical motor efficiencies.

Whether it is a new or retrofit project, reduction in one or more of the following general categories is required to reduce the energy consumed:
- Hours of system operation.
- Air-conditioning loads.
- Lighting loads.
- Off-peak loads.

Demand limiting and electric loads shifting to off-peak periods generally do not reduce the total energy required for the facility. They do reduce peak electric load and therefore the utility or co-generation plant energy requirement. Of all the above energy-reduction items it is the hours of operation that will usually have the most significant impact on energy conservation. In another way, the energy consumption of an inefficient mechanical, plumbing, electrical system that is turned off when not needed will generally be less than that of the most efficient system that is unnecessarily left on.

Of all energy conservation factors, the major one, which determines the annual energy consumption of a facility, is the way that the facility is used. This is more important than the type or capacity of the refrigeration systems, chillers and processes and the amount of glass or insulation or lighting. It is therefore essential, if not mandatory, for the auditor to have a definitive work schedule for each activity to be performed in the facility before energy conservation options can be considered.

This schedule is part of the project design program and should include the following items for each space and area:
- A detailed description of the work being performed.
- The type of energy producing/consuming equipment.
- The number of working staff or personnel by shifts for weekdays, Saturdays, Sundays and holidays.
- The percent of equipment operating in a given hour and the average percent of full capacity for all the equipment by shifts for weekdays, weekends and holidays. If this information is not available, then the percentage of each operating piece of equipment maximum capacity for each hour of each shift for weekdays, weekends and holidays is required.

Finally, it has to be remembered that, the purpose of the typical energy audit is threefold:
- to learn how much energy is being used annually and for what purpose,
- to identify areas of potential energy saving (cooling reclamation) and areas of energy waste, and
- to obtain data required to prepare plans and specifications to reduce, reclaim, or eliminate the waste identified in the audit.

It is a general practice to set priorities for the recommendations of the energy audit, starting with the most cost-effective options and progressing down to the least cost-effective ones. Before proposing or making any modifications to a particular system, the system engineer should carefully study all possible effects these modifications will have on the total facility. For instance, a reduction in energy usage for one or more subsystems may actually result in an increase in the total facility energy consumption.

2. BUILDING ENVELOPE ENERGY AUDIT

2.1. Introduction

Typically, architects design the envelope of a structure to respond to several considerations, including structural and aesthetics. Before the oil crisis of 1973, the energy efficiency of the envelope components was rarely considered as an important factor in the design of a building. Since then, several standards and regulations have been developed to improve the energy efficiency of various building envelope components. For energy retrofit analysis, it is helpful to determine if the building was constructed or modified to meet certain energy-efficiency standards. If it is the case, retrofitting of the building envelope may not be cost-effective, especially for high-rise commercial buildings.

However, improvements to building envelope can be cost-effective if the building was built without any concern for energy efficiency, such as the structures constructed with no insulation provided in the walls or roofs. Moreover, the building envelope retrofit must be performed after careful assessment of the building thermal loads. For instance, in low-rise buildings (residential and small commercial buildings or warehouses) the envelope transmission losses and infiltration loads are dominant, while the internal loads are typically low. In high-rise commercial, industrial and institutional facilities, the internal heat gains due to equipment, lighting and people are typically dominant and the transmission loads affect only the perimeter spaces.

The accurate assessment of the energy savings incurred by building envelope retrofits generally requires detailed hourly simulation programs, since the heat transfer in buildings is complex and involves several mechanisms. In the following, only simplified calculation methods are presented to estimate the energy savings for selected improvements of building envelope commonly proposed to improve not only the energy efficiency of the building but also the thermal comfort of its occupants and the structural integrity of its shell.

2.2. Simplified calculation tools for building envelope audits

To determine the cost-effectiveness of any energy conservation measure for the building envelope, the energy use savings have to be estimated. In this section, a general calculation procedure based on the degree days method is provided with some recommendations to determine the values of the parameters required to perform the energy use savings.

2.2.1. Degree-days method

The degree-days method provides an estimation of the heating and cooling loads of a building due to transmission losses through the envelope and any solar and internal heat gains. This method is based on steady-state analysis of the heat balance across the boundaries of the building, which is typically subject to several heat flows including conduction, infiltration, solar and internal gains, as illustrated in figure 2.1.

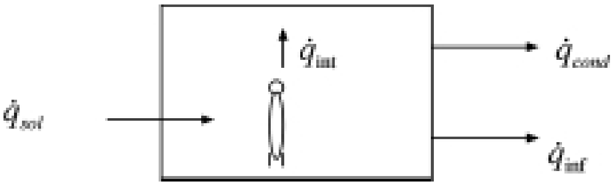


Figure 2.1. A simplified heat balance model for a building

The net heat loss or heat gain at any instant is determined applying a heat balance (i.e., first law of thermodynamics) to the building. Thus, for the calculation of the heating load, the instantaneous heat balance provides:

$$\dot q_H = BLC.(T_i - T_o) - \dot q_g \tag{2.1}$$

where T_i and T_o stand for the condition space and outdoor temperatures respectively,$\dot q_g$ is the net heat gains due to solar radiation ($\dot q_{sol}$), internal gains (people, lights and equipment) ($\dot q_{int}$) and, in some cases, due to the ground losses ($\dot q_{grd}$), if they are significant: $\dot q_g = \dot q_{sol} + \dot q_{int} - \dot q_{grd}$. Finnaly, *BLC* is the building load coefficient, modified to include the effects of both transmission and infiltration losses. The *BLC* for any building can be calculated as:

$$BLC = \sum_{j=1}^{N_E} U_{T,j}.A_j + \dot m_{\inf}.c_{p,a} \tag{2.2}$$

Equation (2.1) can be rearranged to introduce the building balance temperature *(T_b):*

$$\dot q_H = BLC.\left[(T_i - \frac{q_g}{BLC}) - T_o\right] = BLC.(T_b - T_o) \tag{2.3}$$

Therefore, the balance temperature adjusts the interior temperature set-point *(T_i)* by the amount of temperature increase due to a reduction in the heating load, resulting from the internal gains. Before the oil crisis, the transmission and infiltration losses were significant (high *BLC* value relative to the internal gains). It is estimated that the net internal gains contributes to about $3^{o}C$ in most buildings. Thus, the balance temperature is assumed to be $18^{o}C$ for all buildings.

By integrating the instantaneous heating load over the heating season, the total building-heating load can be determined. Note that only the positive values of $\dot q_H$ are considered in the integration. In practice, summing averages over short time intervals (one hour or one day) approximates the integration. If daily averages are used, the heating load is estimated as:

$$Q_H = 24.\sum_{i=1}^{N_H} \dot q^{+}_{H,i} = 24.BLC.\sum_{i=1}^{N_H} (T_b - T_{o,i})^{+} \tag{2.4}$$

The sum is performed over the number of days in the heating season N_H.

From Eq. (2.4), the heating degree-days (DD_H) can be defined as a function of only the outdoor temperatures and the balance temperature, as follows:

$$DD_H(T_b) = \sum_{i=1}^{N_H} (T_b - T_{o,i})^{+} \tag{2.5}$$

Then, the total energy use (E_H) to meet the heating load of the building can be estimated, by assuming a constant efficiency of the heating equipment over the heating season (several manufacturers provide the annual fuel use efficiency rating for their boilers or furnaces), as:

$$E_H = \frac{Q_H}{\eta_H} = \frac{24.BLC.DD_H(T_b)}{\eta_H} \tag{2.6}$$

Moreover, the degree-days method stated by Eq. (2.6) can also be applied to determine the cooling load, by estimating the cooling season degree-days (DD_C) using an equation similar to Eq. (2.5):

$$DD_C(T_b) = \sum_{i=1}^{N_C} (T_{o,i} - T_b)^{+} \tag{2.7}$$

where N_C is the number of days in the cooling season.

The degree-days method provides remarkable accurate estimation of the annual heating energy use, especially for buildings dominated by losses through the building envelope, including infiltration or ventilation. On the other hand, this method is not as accurate for calculating the cooling loads due to several factors, including effects of building thermal mass that delays the action of internal gains, mild outdoor summer temperatures, resulting in large errors in the estimation of the cooling degree days, and the large variation in infiltration or ventilation rates as occupants open windows or economizer cycles are used.

2.2.2. Estimation of the energy use savings

When an energy conservation measure is performed to improve the efficiency of the building envelope (for instance by adding thermal insulation to a roof or by reducing the air leakage area for the building envelope), the *BLC* is reduced. Assuming no changes in the indoor temperature set-point and in the internal gains within the building, the heating balance temperature actually decrease due to the envelope retrofit, as can be concluded from its definition illustrated by Eq. (2.3). Therefore, the envelope retrofit reduces the heating load and the energy use, since both the *BLC* and the $DD_H(T_b)$ are reduced. The energy use savings due to the retrofit can be generally calculated as:

$$\Delta E_{H,R} = \frac{24\cdot\left(BLC_E\cdot DD_H\left(T_{b,E}\right) - BLC_R\cdot DD_H\left(T_{b,R}\right)\right)}{\eta_H} \tag{2.8}$$

The efficiency of the heating system is assumed to remain the same before (index *E*) and after (index *R*) the retrofit. This is generally the case, unless the heating system is replaced or retrofitted. In many applications, the variation caused by the retrofit of the balance temperature is quite small. Thus, the degree-days (DD_H) can be considered constant before and after the retrofit, so that the energy use savings can be estimated more easily using the following equation:

$$\Delta E_{H,R} = \frac{24 \cdot \left(BLC_E - BLC_R\right) \cdot DD_H\left(T_{b,E}\right)}{\eta_H} \qquad (2.9)$$

Note that when only one element of the building envelope is retrofitted (for instance the roof), the difference (BLC_E-BLC_R) is equivalent to the difference in the roof $U \cdot A$ values before and after the retrofit (i.e., $U \cdot A_{roof,E}$-$U \cdot A_{roof,R}$). To use either Eq. (2.8) or (2.9), it is clear that the auditor needs to estimate the heating degree-days and the existing overall building load. Some recommendations on how to calculate these two parameters are summarized below.

2.2.3. Estimation of the building BLC

The *BLC* can he estimated using two approaches as briefly described below. Depending on the data available, the auditor should select the appropriate approach:

1. Direct Calculation: The auditor should have all the data (through the architectural drawings or from observation during a site walk-through) needed to estimate the R- or U-values of all the building envelope components and their relevant surface areas. References are available to provide the R-value of various construction layers commonly used in buildings (ASHRAE 1997, CSTB Refs). In addition, the auditor should estimate the infiltration/ventilation rates either by rules of thumb or by direct measurement. With all these, *BLC* can be calculated using Eq. (2.2).
2. Indirect Estimation: In this method, the auditor can rely on the utility energy use (monthly data are sufficient for this purpose) and its correlation with the outdoor temperature to provide an accurate estimation of the *BLC*. This method is similar to the PRISM method (Fels 1986). It must be noted that the outdoor temperature should be averaged over the same periods that the utility data are available.

2.2.4. Estimation of the Degree-days

Data for heating degree days can be found in various sources, especially the degree days for the balance temperature of 18°C. Table 2.1 presents the values of DD_H (18°C) calculated over one year for 14 representative locations of various climate zones in Greece and France.

Table 2.1. Heating degree days for selected locations in Greece and France

Location (Greece)	DD_H (18°C) over one year	Location (France)	DD_H (18°C) over one year
Athens	1100	Embrun	3087
Heraklion	782	Bourg-St Maurice	3426
Thessalonica	1725	Besanson	2995
Ierapetra	674	St Quentin	3085
Ioannina	2065	Le Bourget (Paris)	2758
Kalamata	983	Lyon	2656
Corfu	1185	Marignane (Marseille)	1760
Komotini	1926	Bordeaux	2205
Larissa	1855	Toulouse	2205
Milos	1142	Toulon	1376
Skyros	1157	La Rochelle	2179
Mytilini	1297	Nantes	2413
Patras	1124	Deauville	2961
Chios	1150	Ouessant	2314

2.3. Selected retrofits for the building envelope

Generally, energy efficiency improvements in the building envelope are expensive, since labour intensive modifications are typically involved (e.g. addition of thermal insulation and replacement of windows). Thus, the payback periods of most building envelope retrofits are rather long, but they can still be justified for reasons other than energy efficiency, such as the increase in occupants' thermal comfort or reduction of moisture condensation to avoid structural damages. However, there are cases where building envelope retrofits can be justified based solely on improvement in energy efficiency. Some of these measures are discussed in this section with examples to illustrate how the energy savings and the payback period are calculated.

2.3.1. Insulation of poorly insulated building envelope components

When an element of the building envelope is not insulated or poorly insulated, it may be cost-effective to add insulation in order to reduce transmission losses. Although the calculation of the energy savings due to such retrofit may require a detailed simulation tool to account for the effects of the building thermal mass and/or the HVAC system, Eq. (2.8) or (2.9) can be used to determine the energy savings during the heating season. If the building is both heated and cooled, the total energy savings due to adding insulation can be estimated by summing the energy savings due to a reduction in heating and those due to a decrease (or increase) in cooling.

Example 2.1: A *machine shop has 500m^2 metal frame roof that is non-insulated. Determine the payback period of adding insulation (R=2.0°C·m^2/W). The building is electrically heated with a cost of electricity \$0.07/kWh. The machine shop is located in Paris (Le Bourget) and operates 24 hours/day, 7 days/Week throughout the heating season. Assume that the installed cost of the insulation is \$15/m^2*

Solution: Based on ASHRAE handbook, the existing *U*-value for a metal frame roof is about 1.44 W/m^2·°C. To determine the energy savings due to the addition of insulation, it will be assumed that the annual heating degree-days before and after the retrofit remained unchanged and are close to 18°C. Using Eq. (2.9), with the retrofitted roof *U*-value to be 0.37 W/m^2·°C and heating system efficiency set to be unity (electrical system), the energy savings are calculated to be:

*ÄE = 24 * 500 m^2 * [(1 .44 - 0.37) W/m^2 °C] * 2758°C.day/yr = 35,413 kWh/yr*

Thus, the payback period for adding insulation on the roof can be estimated to be:

$$Payback = \frac{500m^2 * 15\$/m^2}{35{,}413kWh/yr * 0.07\$/kWh} = 3.0\,years$$

Therefore, the addition of insulation seems to be cost-effective and further analysis is warranted to determine more precisely the cost-effectiveness of this measure.

2.3.2. Windows improvements

Windows improvements, such as installation of high-performance windows, window films and coatings, or storm windows can save energy through reductions in the building heating and cooling thermal loads. Improvements in windows can impact both the thermal transmission and the solar heat gains. In addition, energy-efficient windows create more comfortable environments with evenly distributed temperatures and quality lighting.

Energy-efficiency improvements can be made to all the components of a window assembly including:

- insulating the spacers between glass panes to reduce conduction heat transfer,
- installing multiple coating or film layers to reduce heat transfer by radiation,
- inserting argon or krypton gas in the space between the panes can decrease the convection heat transfer,
- providing exterior shading devices can reduce the solar radiation transmission to the occupied space.

To determine accurately the annual energy performance of window retrofits, dynamic hourly modelling techniques are generally needed, since fenestration can impact the building thermal loads through several mechanisms. However, the simplified calculation method based on Eq. (2.8) to account for both heating and cooling savings can be used to provide a preliminary assessment of the cost-effectiveness of window retrofits.

Example 2.2: *A window upgrade is considered for an apartment building from double-pane metal frame windows (U_E=4.61 W/m$^{2.o}$C) to double-pane with low-e film and wood frame windows (U_R=2.02 W/m$^{2.o}$C). The total window area to be retrofitted is 200 m^2. The building is located in Nantes and is conditioned 24 hours/day, 7days/ week throughout the heating season. Electric baseboard provides heating while a window AC provides cooling.*

Solution: To determine the energy savings due to the window upgrade, it will be assumed that the annual heating and cooling degree days before and after the retrofit remain unchanged (this assumption is justified by the fact that the window contribution to the *BLC* is relatively small) and are respectively DD_H= 2244^{o}C-day/yr and DD_C= 255^{o}C-day/yr. The energy savings during heating are calculated to be:

$$\text{ÄE} = 24 * 200\ m^2 * [(4.61 - 2.02)\ W / m^2\ {}^oC] * 2244\ {}^oC.day/yr = 27{,}897\ kWh/yr$$

If an *EER* (energy efficiency ratio) value of 8.0 is assumed for the AC system, the energy savings for cooling are estimated as follows:

$$\text{ÄÅ} = \frac{24 * 200m^2 * [(4.61 - 2.02) W/m^2\ {}^0C] * 255^0C \cdot day/yr}{8.0} = 396kWh/yr$$

Therefore, the total energy savings due to upgrading the windows is 28,293 kWh, which corresponds to about $2,829 when electricity cost is $0.10/kWh. The cost of replacing tile windows is rather high (it is estimated to be $150/m^2 for this project). The payback period of the window retrofit can be estimated to be:

$$Payback = \frac{200m^2 * 150\$ / m^2}{28{,}293kWh / yr * 0.10\$ / kWh} = 10.4 years$$

Thus, the window upgrade is not cost-effective, when the estimation is based only on thermal performance. The investment on new windows may be however justifiable based on other factors, such as increase in comfort within the space.

2.3.3. Reduction of air-infiltration

In several low-rise facilities, the thermal loads due to air infiltration can be significant. It is estimated that for well-insulated residential buildings, infiltration can contribute up to 40% to the total building-heating load. Tuluca et al. (1997) reported that measurements in eight US office buildings found average air leakage rates of 0.1 to 0.5 air changes per hour (ACH). These air infiltrations accounted for an estimated 10 to 25% of the peak-heating load. Two measurement techniques can be used to evaluate the existing amount of infiltrating air, namely the blower and the tracer gas technique, as is described in Chapter 3.5.7 of the “Energy Auditing Guide - Part A”.

While several studies exist to evaluate the leakage distribution for residential buildings, very little work is available for commercial or industrial ones. However, some results indicate that the envelope air tightness levels for commercial buildings are similar to those in typical houses. In particular, it was found that leaks in walls (frames of windows, electrical outlets, plumbing penetrations) constitute the major sources of air leakage to both residential and commercial buildings. Other sources of air leakage identified for large buildings are through internal partitions (such as elevator and service shafts) and exterior doors (especially for retail stores).

To improve the air tightness of the building envelope several methods and techniques are available including:

i. Caulking: Several types of caulking (urethane, latex, polyvinyl, etc.) can be applied to seal various leaks, such as those around the window and door frames, and any wall penetrations, such as holes for water pipes.
ii. Weather Stripping: By applying foam rubber with adhesive backing, windows and doors can be air sealed.
iii. Landscaping: This is a rather long term project and consists of planting shrubs or trees around the building to reduce the wind effects and air infiltration.
iv. Air Retarders: They consist of one or more air-impermeable components that can be applied around the building exterior shell to form a continuous wrap around the building walls. There are several AR types such as liquid -applied bituminous, liquid-applied rubber, sheet bituminous and sheet plastic. The AR membranes can be applied to impede the vapour movement through the building envelope and thus act as retarders. Unless they are part of an overall building envelope retrofit, these systems are typically expensive to install for existing buildings.

To assess the energy savings due to a reduction in air infiltration, Eq. (2.8) or (2.9) can be used. Whenever available, the degree days $IDD_H(T_b)$ determined specifically to calculate infiltration loads can be used, instead of the conventional temperature based degree days $DD_H(T_b)$. The infiltration heating degree-days for the balance temperature are defined as follows:

$$IDD_H(T_b) = \sum_{i=1}^{N_H} \frac{\dot{V}}{\dot{V}_{ref}} (T_b - T_{o,i})^+ \qquad (2.10)$$

with $\dot{V}/\dot{V}_{ref}$ calculated as:

$$\dot{V}/\dot{V}_{ref} = \sqrt{\rho/2 \cdot \Delta P} \cdot (f_s . \Delta T + f_w . v_w^2)^{1/2} \qquad (2.11)$$

ÄT is the indoor-outdoor temperature difference, v_w is the period average wind speed, while f_s and f_w are the stack and wind coefficients, respectively.

Moreover, $\dot{V}_{ref}$ is the reference volume air rate through the building at a pressure difference (between indoors and outdoors) of 4 Pa. The radicand in Eq. (2.11) provides an estimate of the equivalent area of holes in the building envelope through which air leaks can occur. However, the conventional degree-days (which basically ignore the effects of weather on the variation of the infiltration rate) provide generally good estimation of the energy savings incurred from a reduction in air infiltration.

<u>Example 2.3</u>: *Consider a heated manufacturing shop with a total conditioned volume of 1000 m^3. A measurement of the air leakage characteristics of the shop showed an infiltration rate of 1.5 ACH. Determine the energy savings due to caulking and weather-stripping improvements of the exterior envelope of the facility to reduce air infiltration by half. Assume the shop is located in Lyon and is heated by a gas-fired boiler with a seasonal efficiency of 80%.*

Solution: To determine the energy savings, it will be assumed that the annual heating degree-days before and after the retrofit remain unchanged and are close to 18°C. The existing air infiltration has an equivalent *UA*-value of $UA_{inf}=\dot{m}c_{p,a}=500$ W/°C. Using Eq. (2.9) with the new air infiltration equivalent *UA*-value equal to 250 W/°C and the heating system efficiency set to be 80% (gas-fired boiler), the energy savings are calculated to be:

$$\Delta E = \frac{24}{0.80}\cdot\left[(500-250)W/{}^{o}C\right]*2656{}^{o}C\cdot day/yr = 19{,}920 kWh/yr$$

The cost of caulking and weather-stripping is estimated to be about $1,500 (if only material costs are included). For a gas price of $0.05/kWh, the payback period for reducing the infiltration rate can be estimated to be:

$$Payback = \frac{\$1{,}500}{19{,}920 kWh/yr * 0.05\$/kWh} = 1.5\, years$$

Therefore, based only on the energy savings, the caulking and weather-stripping can be justified.

3. ENERGY RETROFIT OF ELECTRIC SYSTEMS

3.1. Introduction

In most buildings and industrial facilities, electric systems consume a significant part of the total energy use. Motors, lighting and HVAC systems are the major equipment that consumes electric energy. In commercial buildings, the electrical energy use due to office equipment, such as computers and printers, is becoming important in the last decade. Table 3.1 compares the part of electricity consumption in three sectors (residential, commercial and industrial) for the US, France and Greece.

Table 3.1. Percentage share of electricity in the total energy use in three sectors for US^1, France^2 and Greece^3

SECTOR	*US*	*FRANCE*	*GREECE*
Residential buildings	61%	52%	26%
Commercial buildings	52%	68%	79%
Industrial facilities	12%	52%	33%

1. Office of Technology Assessment (1995).
2. Electricité de France (1997).
3. "Greece - National Energy Balance for 1998", Ministry of Development.

In the following sections, measures to reduce the electrical energy use of various systems are presented and discussed. Moreover, where needed, a brief review of basic characteristics of an electric system is provided to highlight the major issues that an auditor needs to consider when retrofitting an electric system.

3.2. Power factor improvement

The reactive power has to be supplied by the utility even though it is not actually registered by the power meter (as real power used). The magnitude of this reactive power increases as the power factor decreases. To account for the loss of energy due to the reactive power, most utilities have established rate structures that penalize any user that has low power factor. Therefore, significant savings in the utility costs can be achieved by improving the power factor. This improvement can be obtained by adding a set of capacitors to the entire electrical system (figure 3.1).

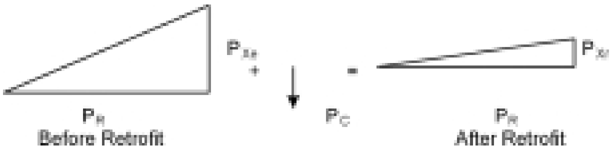


Figure 3.1. Effect of adding capacitors on the power triangle of the electrical system

The size of these capacitors (P_C) is typically measured in KVAR (the same unit as the reactive power) and can be determined, as shown in figure 3.1, using the power triangle analysis:

$$\begin{aligned} P_C &= P_{Xe} - P_{Xr} = P_R.(\tan\phi_e - \tan\phi_r) = \\ &= P_R.\left[\tan(\cos^{-1} pf_e) - \tan(\cos^{-1} pf_r)\right] \end{aligned} \tag{3.1}$$

where P_R stands for the real power (measured in kW), while P_{Xe} and P_{Xr} stand for the reactive power before and after the retrofit, respectively. The last equity resulted using the values of power factor before and after the retrofit.

The calculations of the cost savings due to power factor improvement depend on the utility rate structure. In most of the rate structures, one of three options summarized below is used to assess the penalty for low power factor. Basic calculation procedures are typically needed to estimate the annual cost savings in the utility bills:

1. <u>Modified Billing Demand</u>: In this case, the demand charges are increased in proportion with the fraction by which the power factor is less than a threshold value. The size for the capacitors should be selected so the system power factor reaches at least the set threshold value.
2. <u>Reactive Power Charges</u>: Charges for reactive power demand are included as part of the utility bills. In this option, the size of the capacitors should be ideally determined to eliminate this reactive power (so that the power factor is unity).
3. <u>Total Power Charges</u>: This rate is similar to the rate described above, but the charges are set for the building/facility total power. Again, the capacitors should be sized so that the power factor is equal to unity.

3.3. Electrical motor retrofits

3.3.1. Replacement with energy-efficient motors

There are basically two types of electric motors used in buildings and industrial facilities: induction motors and synchronous motors. Induction motors are the more common type, accounting for 90% of the existing motor horsepower. Both types use a motionless stator and a spinning rotor to convert electrical energy into mechanical power. One main difference between the two motor types is how the rotor field is produced. In an induction motor, the rotating stator magnetic field induces a current, thus a magnetic field, in the rotor windings that are typically of the squirrel-cage type.

Since its magnetic field is induced, the rotor cannot rotate as the stator field (if the rotor spins with the same speed as the stator magnetic field, no current can be induced in the rotor since effectively the stator magnetic field remains unchanged relative to the rotor). The difference between the rotor speed and the stator magnetic field rotation is called the slip factor. In a synchronous motor, the rotor field is produced by application of direct current through the rotor windings. Therefore, the rotor spins at the same speed as the rotating magnetic field of the stator and thus the rotor and the stator magnetic field are synchronous in their speed.

Because of its construction characteristics, the induction motor is basically an inductive load and thus have a lagging power factor, while the synchronous motor can be set so it has a leading power factor (i.e., acts like a capacitor). Therefore, it is important to remember that a synchronous motor can be installed to both provide mechanical power and improve the power factor of a set of induction motors. This option may be more cost-effective than just adding a bank of capacitors.

One parameter is typically important to identify an electric motor during full-load operation, the conversion efficiency of the motor (ç). This efficiency expresses the mechanical power as a fraction of the real electric power consumed by the motor: $ç_{Ì} = Ñ_{Ì}/Ñ_{R}$. Due to various losses (friction, core losses due to the alternating of the magnetic field and resistive losses through the windings), the motor efficiency has typical values ranging from 75% to 95%, depending on the size of the motor. In the above definition, P_M stands for the mechanical power output of the motor, expressed in kW or horsepower (HP), which is the most important factor in selecting a motor.

Table 3.2. Typical motor efficiencies (adapted from Hoshide, 1994)

MOTOR MECHANICAL POWER OUTPUT kW (HP)	AVERAGE NOMINAL EFFICIENCY FOR STANDARD-EFFICIENCY MOTOR	AVERAGE NOMINAL EFFICIENCY FOR PREMIUM-EFFICIENCY MOTOR
0.75 (1.0)	0.730	0.830
1.12 (1.5)	0.750	0.830
1.50 (2.0)	0.770	0.830
2.25 (3.0)	0.800	0.865
3.73 (5.0)	0.820	0.876
5.60 (7.5)	0.840	0.885
7.46 (10)	0.850	0.896
11.20 (15)	0.860	0.910
14.92 (20)	0.875	0.916
18.65 (25)	0.880	0.926
22.38 (30)	0.885	0.928
29.84 (40)	0.895	0.930
37.30 (50)	0.900	0.932
44.76 (60)	0.905	0.933
55.95 (75)	0.910	0.935
74.60 (100)	0.915	0.940
93.25 (125)	0.920	0.942
111.9 (150)	0.925	0.946
149.2 (200)	0.930	0.953

Based on their efficiency, motors are classified into two categories: standard-efficiency and high/premium-efficiency motors. The energy-efficient motors are 2 to 10 percentage points more efficient than standard-efficiency ones, depending on the size. In table 3.2, the average efficiencies for both standard and energy-efficient motors that are currently commercially available are summarized. The improved efficiency of the high/premium-motors is mainly due to better design with use of better materials to reduce losses, which however comes with a higher price (about 10 to 30% more than standard-efficiency motors). This fact partially explains why only one-fifth of the motors sold in the US are energy-efficient.

3.3.2. Energy savings calculations

There are three methods to calculate the energy savings due to energy-efficient motor replacement. These three methods are outlined below:

Method 1: *Simplified Method*

This method has been and is still being used by most energy engineers to determine the energy and cost savings incurred by motor replacement. Inherently to this method, two assumptions are made, namely that the motor is fully loaded, and that the change in motor speed is neglected.

The electric power savings due to the motor replacement is computed as follows:

$$\Delta P_R = P_M \cdot \left(\frac{1}{\eta_E} - \frac{1}{\eta_R} \right) \qquad (3.2)$$

where P_M is the mechanical power output of the motor, $ç_{Å}$ is the design (full-load) efficiency of the existing motor (before retrofit) and $ç_R$ is the design efficiency of the energy-efficient motor (after retrofit). The electric energy savings incurred from the motor replacement are:

$$\Delta kWh = \Delta P_R . N_h . LF_M \qquad (3.3)$$

where, N_h is the number of hours per year during which the motor is operating and LF_M is the load factor of the motor's operation during one year.

Method 2: *Mechanical Power Rating Method*

In this method, the electrical peak demand of the existing motor is assumed to be proportional to its average mechanical power output:

$$P_{R,E} = \frac{P_M}{\eta_{op,E}} . LF_M . PDF_M \qquad (3.4)$$

where:

- $ç_{op,E}$ is the motor efficiency at the operating average part-load conditions. To obtain this value, the efficiency curve for the motor can be used. If the efficiency curve for the specific existing motor is not available, a generic curve can be used.
- $LF_{M,E}$ is the load factor of the existing motor, that is the ratio of the average operating load of the existing motor and its rated mechanical power. In most applications, the motor is oversized and operates at less its capacity.
- $PDF_{M,E}$ is the peak demand factor, representing the fraction of typical motor load that occurs at the time of the building peak demand. In most applications, $PDF_{M,E}$ can be assumed to be unity, since the motors often contribute to the total peak demand of the building.

Since the mechanical load does not change after installing an energy-efficient motor, it is possible to consider a smaller motor with a capacity $P_{M,R}$ if the existing motor is oversized with a rating of $P_{M,E}$. In this case, the smaller energy-efficient motor can operate at a higher load factor than the existing motor. The new load factor of the energy-efficient motor can be calculated as follows:

$$LF_R = LF_E \cdot \frac{P_{M,R}}{P_{M,E}} \tag{3.5}$$

The energy-efficient motors often operate at higher speeds than the standard motors they replace, since they have lower internal losses. This higher speed actually has a negative impact, since it reduces the effective efficiency of the energy-efficient motor by a factor called the slip penalty. If $ù_{ì,Å}$ and $ù_{M,R}$ are the rotation speeds of the existing motor and of the energy-efficient one, the slip penalty factor is defined as:

$$SLIP_P = \left(\frac{\omega_{M,R}}{\omega_{M,E}} \right)^3 \tag{3.6}$$

Using a similar to Eq. (3.4) relation, the peak electrical demand for the retrofitted motor (e.g. energy-efficient motor) can be determined:

$$P_{R,R} = \frac{P_{M,R}}{\eta_{op,R}} .LF_{M,R} .PDF_{M,R} .SLIP_P \tag{3.7}$$

The electrical power savings due to the motor replacement can now be estimated as:

$$\Delta P_R = P_{R,E} - P_{R,R} \tag{3.8}$$

The electric energy savings can be calculated again using Eq. (3.3).

Method 3: *Field Measurement Method*

In this method, the motor electrical power demand is measured directly on-site. Typically, current (I_M), voltage (V_M), power factor (pf_M) readings are recorded for the motor to be retrofitted. For three-phase motors (common in industrial facilities and in most HVAC systems for commercial buildings), the electrical power used by the existing motor can be either directly measured or calculated from current, voltage and power factor readings as follows:

$$P_{R,E} = \sqrt{3} .V_M .I_M .pf_M \tag{3.9}$$

The load factor of the existing motor can be estimated by the ratio of the measured current over the nameplate full-load current (I_{FL}), as:

$$LF_{M,E} = \frac{I_M}{I_{FL}} \tag{3.10}$$

Eq. (3.10) was proved to be much more accurate for the estimation of the motor load ratio than an approach based on the ratio of the motor speeds (i.e. measured speed over nominally rated speed). It should be noted that, Eq. (3.10) is recommended for load ratios that are above 50%, since for these load ratios a typical motor draws electrical current that is proportional to the imposed load. The methodology for the calculation of the electrical power and energy savings is the same as described for the Mechanical Power Rating Method using Eq. (3.5) through Eq. (3.8).

3.4. Energy-efficient lighting

3.4.1. Introduction

Lighting accounts for a significant portion of the energy use in commercial buildings. In office buildings, for instance, 30% to 50% of the electricity consumption is used to provide lighting. In addition, heat generated by lighting contributes to the thermal load to be removed by the cooling equipment. Energy retrofits of lighting equipment are typically very cost-effective, with payback periods of less than 2 years in most applications.

To better understand the retrofit measures that need to be considered in order to improve the energy-efficiency of lighting systems, a simple estimation of the total electrical energy use due to lighting can be provided by Eq. (3.11):

$$kWh_{Lit} = \sum_{j=1}^{J} N_{Lum,j} .WR_{Lum,j} .N_{h,j} \tag{3.11}$$

where $N_{Lum,j}$ is the number of lighting luminaries of type *j* in the building to be retrofitted (a luminary consists of the complete set of ballast, electric wiring, housing and lamps), $WR_{Lum,j}$ is the wattage rating for each luminaries of type *j* (the energy use due to both the lamps and ballast should be accounted for in this rating), $N_{h,j}$ is the number of hours per year when the luminaries of type *j* are operating.

There are three options to reduce the energy use due to lighting, including:

a) Reduction of the wattage rating for the luminaries including both the lighting sources (lamps) and the power transforming devices (ballasts), therefore decreasing the term $WR_{Lum,j}$ in Eq. (3.11). In the last decade, technological advances such as compact fluorescent lamps and electronic ballasts have increased the energy efficiency of lighting systems.

b) Reduction of the lighting systems time of use through lighting controls, therefore decreasing the term $N_{h,j}$ in Eq. (3.11). Automatic controls have been developed to decrease the use of a lighting system, so illumination is provided only during times when it is needed. Energy-efficient lighting controls include the occupancy sensing systems and light dimming controls through the use of day lighting.

c) Reduction of the number of luminaries, therefore decreasing the term $N_{Lum,j}$ in Eq. (3.11). This goal can be achieved only in cases where de-lamping is possible due to over-illumination.

Herein, only measures related to the general actions described in items (a) and (b) are discussed. To estimate the energy savings due to any retrofit measure for the lighting system, Eq. (3.11) can be used. The energy use due to lighting has to be calculated before and after the retrofit and the difference between the two estimated energy uses represents the energy savings. In the following, examples of lighting retrofit are presented, together with calculations of the resulting energy savings.

3.4.2. Energy-efficient lighting systems

Improvements in the energy-efficiency of lighting systems have provided several opportunities to reduce electrical energy use in buildings. In this section, the potential of high efficiency fluorescent lamps, compact fluorescent lamps, compact halogen lamps and electronic ballasts is discussed. First a brief description is provided for the factors that an auditor should consider for achieving and maintaining an acceptable quality and level of comfort for the lighting system. Secondly, the design and operation concepts are summarized for each available lighting technology. Then, the energy savings that can be expected from retrofitting existing lighting systems using any of the new technologies are estimated and discussed.

Typically, three factors determine the proper level of light for a particular space, including: age of the occupants, speed and accuracy requirements and background contrast (depending on the task being performed). It is a common misconception to consider that over-lighting a space provides higher visual quality. Indeed, it has been shown that over-lighting can actually reduce the illuminance quality and the visual comfort level within a space, in addition to wasting energy. Thus, it is important when upgrading a lighting system to determine and maintain the adequate illuminance level, as recommended by the appropriate standards. In table 3.3 the lighting levels recommended for various activities and applications in selected countries, based on the most recent illuminance standards, are summarized.

High Efficiency Fluorescent Lamps:

Fluorescent lamps are the most commonly used lighting systems in commercial buildings. In the US, fluorescent lamps illuminate 71% of the commercial space. Their relatively high efficacy, diffuse light distribution and long operating life are the reasons for their popularity. A fluorescent lamp generally consists of a glass tube with a pair of electrodes at each end. The tube is filled at very low pressure with a mixture of inert gases (primarily argon) and liquid mercury. When the lamp is turned on, an electric arc is established between the electrodes. The mercury vaporizes and radiates in the ultraviolet spectrum. This ultraviolet radiation excites a phosphorous coating on the inner surface of the tube that emits visible light.

High-efficiency fluorescent lamps use a krypton-argon mixture, which increases the efficacy output by 10 to 20% from a typical efficacy of 70 to about 80 lumens/Watt. Improvements in phosphorous coating can further increase the efficacy to 100 lumens/Watt. On the other hand, the handling and the disposal of fluorescent lamps is highly controversial due to the fact that mercury inside the lamps can be toxic and hazardous to the environment. A new technology is being tested to replace the mercury with sulphur to generate the radiation that excites the phosphorous coating of the fluorescent lamps. The sulphur lamps are not hazardous and would present an environmental advantage to the mercury-containing fluorescent lamps.

The fluorescent lamps come in various shapes, diameters, lengths, and ratings. A common labelling used for the fluorescent lamps is *F.S.W.C.-T.D,* where:

- *F* stands for the fluorescent lamp.
- *S* refers to the style of the lamp. If the glass tube is circular, then the letter C is used. If the tube is straight, no letter is provided.
- *W* is the nominal wattage rating of the lamp (being 4, 5, 8, 12, 15, 30, 32, etc.).
- *C* indicates the colour of the light emitted by the lamp: W for White, CW for Cool White and BL for Black Light.
- *T* refers to tubular bulb.
- *D* indicates the diameter of the tube in eighths of one inch (1/8in = 3.15mm) and is for instance 12 (D =1.5in = 38mm) for the older and less energy efficient lamps and 8 (D =1.0in = 31.5mm) for more recent and energy efficient lamps.

Thus, F40CW-T12 designates a fluorescent lamp that has a straight tube, uses 40 W electric power, provides cool white colour, and is tubular with 38 mm (1.5 inches) in diameter. Among the most common retrofit in lighting systems is the upgrade of the conventional 40W T12 fluorescent lamps to more energy efficient lamps, such as 32W T8 lamps.

Compact Fluorescent Lamps (CFL):

These lamps are miniaturized fluorescent lamps with small diameter and shorter length. The compact lamps are less efficient than full size fluorescent lamps with only 35 to 55 lumens/ Watt. However, they are more energy efficient and has longer life than incandescent lamps. Currently, compact fluorescent lamps are being heavily promoted as energy savings alternatives to incandescent lamps, even though they may have some drawbacks. In addition to their high cost, compact fluorescent lamps are cooler and thus provide less pleasing contrast than incandescent lamps.

Table 3.3. Recommended lighting levels for various applications in selected countries
(in Lux maintained on horizontal surfaces)

APPLICATION	FRANCE AEF (92&93)	GERMANY DIN5035 (90)	JAPAN JIS (89)	US/CANADA IESNA (93)
Offices				
General	425	500	300-750	200-500
Reading Tasks	425	500	300-750	200-500
Drafting (detailed)	850	750	750-1500	1000-2000
Classrooms				
General	325	300-500	200-750	200-500
Chalkboards	425	300-500	300-1500	500-1000
Retail Stores				
General	100-1000	300	150-750	200-500
Tasks/till Areas	425	500	750-1000	200-500
Hospitals				
Common Areas	100	100-300	-	-
Patient Rooms	50-100	1000	150-300	100-200
Manufacturing				
Fine Knitting	850	750	750-1500	1000-2000
Electronics	625-1750	100-1500	1500-300	1000-2000

Compact Halogen Lamps:

The compact halogen lamps are adapted for use as direct replacements for standard incandescent lamps. They are more energy-efficient, produce whiter light and last longer than incandescent lamps. Indeed, incandescent lamps convert typically only 15% of their electrical energy input into visible light, since 75% is emitted as infrared radiation and the filament uses 10% as it burns off. In halogen lamps, the filament is encased inside a quartz tube that is contained in a glass bulb. A selective coating on the exterior surface of the quartz tube allows visible radiation to pass through but reflects the infrared radiation back to the filament. This recycled infrared radiation permits the filament to maintain its operating temperatures with 30% less electrical power input. The halogen lamps can be dimmed and present no power quality or compatibility concerns, as can be the case for the compact fluorescent lamps.

Electronic Ballasts:

Ballasts are integral parts to fluorescent luminaries, since they provide the voltage level required to start the electric arc and regulate the intensity of the arc. Before the development of electronic ballasts in early 1980's, only magnetic or "core and coil" ones were used to operate fluorescent lamps. While the frequency of the electrical current is kept at 50 Hz (or 60 Hz in US) by the magnetic ballasts, electronic ballasts use solid-state technology to produce high-frequency (20 - 60 MHz) current, which increases the energy-efficiency of the fluorescent luminaries since the light is cycling more quickly and appear brighter. When used with high-efficiency lamps (i.e., T8), electronic ballasts can achieve 95 lumens/Watt, as opposed to 70 lumens/ Watt for conventional magnetic ballasts. It should be mentioned, however, that efficient magnetic ballasts could achieve similar lumen/Watt ratios as electronic ballasts.

Other advantages that electronic ballasts have relative to their magnetic counterparts include:

- Higher power factor. The power factor of electronic ballasts is typically in the 0.9 to 0.98 range. Meanwhile, the conventional magnetic ballasts have low power factor (less than 0.80) unless a capacitor is added, as discussed in section 3.2.
- Less flicker problems. Since the magnetic ballasts operate at 50 Hz current, they cycle the electric arc about 120 times per second. As a result, flicker may be perceptible, especially if the lamp is old during normal operation or when the lamp is dimmed to less than 50% capacity. However, electronic ballasts cycle the electric arc several thousands of times per second and flicker problems are avoided, even when the lamps are dimmed to as low as 5% of capacity.
- Less noise problems. The magnetic ballasts use electric coils and generate audible hum, which can increase with age. Such noise is eliminated by the solid-state components of the electronic ballasts.

3.4.3. Lighting controls

As illustrated by Eq. (3.11), energy savings can be achieved by not operating at full capacity the lighting system in cases when illumination becomes unnecessary. The control of the lighting system operation can be achieved by several means, including manual on/off and dimming switches, occupancy sensing systems, and automatic dimming systems using day-lighting controls.

While manual switching and/or dimming can achieve energy savings, the results are typically unpredictable since they depend on the occupant behaviour. Scheduled lighting controls provide a more efficient approach to energy savings, but can also be affected by the frequent adjustments from occupants. Only automatic light switching and dimming systems can respond in real-time to changes in occupancy and climatic changes. Some of the automatic controls available for lighting systems are briefly discussed below.

Occupancy Sensors:

Occupancy sensors save energy by automatically turning off the lights in spaces that are not occupied. Generally, occupancy sensors are suitable for most lighting control applications and should be considered for lighting retrofits. It is important to properly specify and install the occupancy sensors to provide reliable lighting during periods of occupancy. Indeed, most failed occupancy sensor installations result from inadequate product selection and improper placement. In particular, the auditor should select the proper motion sensing technology used in occupancy sensors.

Two types of motion sensing technologies are currently available in the market:

i. *Infrared sensors*, which register the infrared radiation emitted by various surfaces in the space including the human body. When the controller connected to the infrared sensors receives a sustained change in the thermal signature of the environment (as is the case when an occupant moves), it turns the lights on. The lights are kept on until the recorded changes in temperature are not significant. The infrared sensors operate adequately only if they are in direct line-of-sight with the occupants and must be used in smaller enclosed spaces with regular shapes and without partitions.

ii. *Ultrasound sensors* operate on a sonar principle, like the submarines and airport radars, emitting a high frequency sound (25-40 kHz) that is beyond the hearing range of humans. This sound is reflected by the surfaces in a space (including furniture and occupants) and is sensed by a receiver. When people move inside the space, the pattern of sound wave changes. The lights remain on until no movement is detected for a preset period of time (e.g., 5 min.). Unlike infrared radiation, obstacles do not easily block sound waves. However, these sensors may not operate properly in large spaces that tend to produce weak echoes.

Based on a study by EPRI, table 3.4 provides typical energy savings to be expected from occupancy sensor retrofits. As shown in the table, significant energy savings can be achieved in spaces where occupancy is intermittent, such as conference rooms, rest rooms, storage areas and warehouses.

Table 3.4. Energy savings potential with occupancy sensor retrofits

SPACE APPLICATION	RANGE OF ENERGY SAVINGS
Offices (Private)	25-50 %
Offices (Open Space)	20-25 %
Rest Rooms	30-75 %
Conference Rooms	45-65 %
Corridors	30-40 %
Storage Areas	45-65 %
Warehouses	50-75 %

Light Dimming Systems:

Dimming controls allow the variation of the intensity of lighting system output based on natural light level, manual adjustments and occupancy. Smooth and uninterrupted decrease in the light output is defined as a continuous dimming, as opposed to stepped dimming in which the lamp output is decreased in stages by preset amounts. The auditor, using relevant computer software to accurately estimate the energy savings from dimming systems that use natural light controls, can predict the percentage of time when natural light is sufficient to meet all lighting needs.

3.5. Power quality

3.5.1. Introduction

Under ideal conditions, the electrical current and voltage vary as a sine function of time. However, problems in the utility generation/distribution system, such as voltage drops, spikes or transients, can cause fluctuations in electricity that can reduce the life of electrical equipment, including motors and lighting systems. Moreover, latterly an increasing number of electrical devices operating on the system can cause distortion of the current and/or voltage sine waveform leading to poor power quality, which can waste energy and harm both electrical distribution and devices operating on the systems. Therefore, it is important the energy auditor to be aware of these problems and take steps in improving the power quality of the electrical systems.

3.5.2. Total harmonic distortion

The power quality can be defined as the extend to which an electrical system distorts the voltage or current sine waveform, which is the ideal power quality for an electrical system, often referred to as the fundamental harmonic. When the power is distorted due, for instance, to electronic ballasts (which change the frequency of the electricity supplied to the lighting systems), several harmonics need to be used in addition to the fundamental harmonic to represent the voltage or current time-variation.

Highly distorted waveforms contain numerous harmonics. While the even harmonics (second, fourth, etc.) tend to cancel each other effects, the odd harmonics (third, fifth, etc.) have their peaks coincide and significantly increase the distortion effects. To quantify the level of distortion for voltage and current a dimensionless number, referred to as the total harmonic distortion (*THD*), is determined through a Fourier series analysis of the voltage and current waveforms and is respectively defined as:

$$THD_V = \sqrt{\sum_{k=1}^{N_V} V_k^2 \Big/ V_1^2} \qquad THD_I = \sqrt{\sum_{k=1}^{N_V} I_k^2 \Big/ I_1^2} \qquad (3.12)$$

Table 3.5 displays current *THD* for selected lighting and office equipment loads. Generally, it is found that devices with high current *THD* contribute to voltage *THD* in proportion to their share to the total building electrical load. Therefore, the auditor should first consider the higher-wattage devices to reduce the voltage *THD* for the entire building/facility, this way determining which devices to correct first in order to improve the power quality of the overall electric system. Typically, harmonic filters are added to electrical devices to reduce the current *THD* values. In the example that follows, a simple calculation procedure that an auditor can follow to assess the impact of an electrical device on the current *THD* is presented.

Table 3.5. Typical power quality characteristics (power factor and current THD) for selected electrical loads (adapted from NLPIP, 1995)

ELECTRICAL LOAD	REAL POWER USED (W)	POWER FACTOR	CURRENT THD (%)
Incandescent Lighting Systems			
100-W incandescent lamp	101	1.0	1
Compact fluorescent lighting systems			
13-W lamp w/ magnetic ballast	16	0.54	13
13-W lamp w/ electronic ballast	13	0.50	153
Full-size fluorescent lighting systems (2 lamps per ballast)			
T12 40-W lamp w/ magnetic ballast	87	0.98	17
T12 40-W lamp w/ electronic ballast	72	0.99	5
T10 40-W lamp w/ magnetic ballast	93	0.98	22
T10 40-W lamp w/ electronic ballast	75	0.99	5
T8 32-W lamp w/ electronic ballast	63	0.98	6
High-intensity discharge lighting systems			
400-W high-pressure sodium lamp w/ magnetic ballast	425	0.99	14
400-W metal halide lamp w/ magnetic ballast	450	0.94	19
Office equipment			
Desktop computer w/o monitor	33	0.56	139
Colour monitor for desktop computer	49	0.56	138
Laser printer (in standby mode)	29	0.40	224
Laser printer (printing)	799	0.98	15
External fax/modem	5	0.73	47

Example: *Assess the impact on the current THD of a building of two devices: the 13-W compact fluorescent lamp (CFL) with electronic ballast and the laser printer while printing. Use the data from Table 3.5.*

Solution: Both devices have an RMS voltage of 120 V (i.e., V_{rms} = 120 V); their RMS current can be determined using the real power used and the power factor given in Table 3.5 and the following equation:

$$I_{rms} = \frac{P_R}{V_{rms} \cdot pf}$$

The above equation gives an RMS current of 0.22 A for the CFL and 6.79 A for the printer. These values are the RMS of each device's fundamental current waveform and can be used in the *THD* equation [Eq (3.16)], to estimate the total harmonic current of each device:

$$I_{tot} = I_{rms}.THD_I$$

The resultant values of 0.33 A for the CFL and 1.02 A for the printer show that, although the printer has relatively low current *THD* (15%), the actual distortion current produced by the printer is more than three times that of the CFL, because the printer uses more power.

IEEE (1992) recommends a maximum allowable voltage *THD* of 5% at the building service entrance (where the utility distribution system is connected to the building electrical system). Verderber et al. (1993) showed that the voltage *THD* reaches the 5% limit when about 50% of the building electrical load has a current *THD* of 55% or when 25% of the building electrical load has a current *THD* of 115%.

When the electrical device has a power factor of unity (pf=1), there is little or no current *THD*, since the device has only a resistive load and effectively converts input current and voltage into useful electric power. Thus, the power factor and the current *THD* are interrelated and both define the characteristics of the power quality. As indicated in table 3.5, the lighting systems with electronic ballast have typically high power factor and low current *THD*. This good power quality is achieved using capacitors to reduce the phase lag between the current and voltage (to improve the power factor) and filters to reduce harmonics (to increase the current *THD* value).

The problems that have been reported due to poor power quality include:

i. Overload of neutral conductors in three-phase with four wires. In a system with no *THD*, the neutral wire carries no current if the system is well balanced. However, when the current *THD* becomes significant, the currents due to the odd harmonics do not cancel each other and rather add up on the neutral wire that can overheat and cause a fire hazard.
ii. Reduction in the life of transformers and capacitors. This effect is mostly caused by distortion in the voltage.
iii. Interference with communication systems. Electrical devices that operate with high frequencies, such as electronic ballasts (operating at frequencies ranging from 20 to 40 kHz), can interfere and disturb the operation of communication systems, such radios, phones and energy management systems (EMS).

3.6. Selected examples for electric measures to save energy use

3.6.1. Power factor correction - Calculation of the capacitor size

Background: To reduce the penalty of low power factor imposed by the utility, a set of capacitors can be installed in parallel to the electrical system. The benefits of increasing the power factor can only be determined for each specific case since the calculation of the cost savings depends closely on the utility rate. In this calculation sheet, only the size in kVAR of the capacitors is determined so that the power factor can be increased from the existing value to the minimum required by the utility in order to incurs no penalty. With this size, the cost of the capacitors and thus the cost-effectiveness of improving the power factor can be calculated.

Required Data:

- pf_e: existing power factor (this information can be directly measured or taken from the utility bills),
- pf_r: power factor to be achieved after the retrofit (this value is defined by the utility rate structure),
- P_R: real power used by the electrical system at peak conditions (this information is provided by the utility bills).

Calculation Procedure: The size of one capacitor or a bank of capacitors in kVAR is determined as: $P_C=P_R\cdot[\tan(\cos^{-1}pf_e)-\tan(\cos^{-1}pf_r)]$

Calculation Example:

Problem: *Consider a building with a total real power demand of 500 kW and a power factor of* pf_e*=0.70. Determine the required size of a set of capacitors to be installed in parallel at the building service entrance so that the power factor becomes* pf_r*=0.90.*

Solution: The size in kVAR of the capacitor is:

$$P_C=500\cdot[\tan(\cos^{-1}0.70) - \tan(\cos^{-1}0.90)]=268\text{kVAR}$$

Thus, a capacitor of 275 kVAR will be adequate.

3.6.2. Install High Efficacy Lamps - Calculation of energy savings

Background: The high efficacy tubes introduced herein represent the next generation of high efficiency fluorescent lamps and are currently available in the market. These lamps consume 40 Watts, but have several advantages over the ~40 Watt lamps currently used. The initial lighting intensity of these bulbs is rated at 3,300-3,700 lumens, which is about 780-1,180 lumens greater than that of the existing lamps, resulting in about 15-17% greater light output, due primarily to a narrower tube body and special phosphor blends. Also the initial lumen level is maintained for a longer period with these lamps. The colour rendition (a measure of "usable" light output) is also significantly greater for these lamps. Moreover, the improved efficacy lamps typically have a longer life than the existing ones (rated at 24,000-30,000 hours at 3 hrs. per start, as compared with 20,000 hours rating). These lamps can be used in all standard 4-foot fixtures with no modifications.

Required Data:

- WR_E: Wattage rating for existing luminaries,
- WR_R: Wattage rating for energy-efficient luminaries,
- N_{lum}: Number of luminaries,
- N_h: Number of operating hours of luminaries per year.

Calculation Procedure: The energy saving in kWh is determined as follows:

$$\Delta kWh = N_{lum} \cdot (WR_E - WR_R) \cdot N_h \cdot \frac{1}{1000}$$

4. UPGRADE OF CENTRAL HEATING SYSTEMS

4.1. Introduction

According to a survey reported by the US Energy Information Administration (EIA, 1997), four types of heating systems are used extensively in US commercial bu~~ilding~~s including boilers, packaged heating units, individual space heaters and/or furnaces. Boilers are the main equipment used by percentage of total heated buildings, since they provide heating to almost 33% of the total heated floor-space of US commercial buildings.

However, boilers are used in only 15% of heated commercial buildings, significantly less than furnaces, which are used in more than 42% of US commercial buildings. This difference in usage stems from the fact that the boilers are typically used in larger buildings, while furnaces are used in smaller ones. Of the existing boilers in US commercial buildings 65% are gas-fired, 28% oil-fired, and only 7% are electric. The average combustion efficiency of the existing boilers is in the range of 65 to 75%. New energy-efficient gas or oil-fired boilers can be in the range of 85 to 95%.

4.2. Basic combustion principles and fuel types

Fuels used in boilers consist of hydrocarbons including alkynes (C_nH_{2n-2}) such as the acetylene (n=2), alkenes (C_nH_{2n}) such as the ethylene (n=2), alkanes (C_nH_{2n+2}) such as the octane (n=8). A typical combustion reaction involves an atom of carbon with two atoms of oxygen with a generation of heat, which is known as the heating value (*HV*) of a fuel. Typically, the heating value is given when the fuel is dry, while the moisture reduces the heating value according to the relation: $HV=HV_{dry}\cdot(1-M)$, with *M* the moisture content of the fuel. It should be noted that the heating value of a fuel increases with its carbon content.

Liquid or distillate fuels are generally graded in different categories depending on its properties. For fuel oils, there are 6 different grades depending on the viscosity. Table 4.1 provides the heating values and common usage of 5 oil fuels commonly sold in the US. Fuel oil No 3 has now been incorporated as part of fuel oil No 2. Similar grades are used for diesel fuels with diesel No 1 used for high-speed engines and diesel No 2 used for industrial applications and heavy cars.

4.3. Boiler configurations and components

Typically, boilers have several parts including an insulated jacket, a burner, a mechanical draft system, tubes and chambers for combustion gases, tubes and chambers for water or steam circulation, and controls. There are several factors that influence the design of boilers including fuel characteristics, firing method, steam pressure, and heating capacity. However, commercial and industrial boilers can be divided into two basic groups: fire-tube or water-tube, depending on the relative location of the hot combustion gases and the fluid being heated within the boiler. In the following sections, a brief description of the boiler and burner types is provided.

4.3.1. Boiler types

Most commercial boilers are manufactured of steel. Some smaller-size boilers are made up of cast iron. The steel boilers transfer combustion heat to the fluid using an assembly of tubes, which can be either water-tubes or fire-tubes.

Fire-tube Boilers: In these boilers, the hot combustion products flow through tubes submerged in the boiler water. To increase the contact surface area between the hot gases and the water, 2 to 4 passes are used for the tubes. The multi-passes tubes increase the efficiency of the boiler but require greater fan power. Due to economics, the highest capacity of fire-tube boilers is currently in the 10,000 kg of steam per hour at an operating pressure of 16 atm (250 psi). The fire-tube boilers are generally simple to install and maintain. Moreover, they have the ability to meet sudden and wide load fluctuations with only small pressure changes.

Water-tube Boilers: In these boilers, the water flows inside tubes surrounded by flue combustion gases. The density variation between cold feed water and the hot water/ steam mixture in the riser generally maintain the water flow. The water-tube boilers are classified in several groups depending on the shape, and drum location, capacity and number. The size of water-tube boilers can be as small as 400 kg of steam per hour and as large as 1000 MW. The largest industrial boilers provide about 250,000 kg of steam per hour.

Cast-iron Boilers: These boilers are used in small installations (below 1 MWh) where long service life is important. They are made up of pre-cast sections and thus are more readily field assembled than steel boilers. At similar capacities, the cast-iron boilers are typically more expensive than fire-tube or water-tube boilers.

4.3.2. Firing systems

The firing system of a boiler depends on the fuel used. The characteristics of the firing system for each fuel type are summarized below.

Gas-fired units: Natural gas is the simplest fuel to burn since it mixes easily with combustion air supply. Gas is generally intro-

Table 4.1: Heating value and specific gravity of oil fuels used in the US

Oil Grade	Specific Gravity	Heating Value kWh/litre (MBtu/gal)	Applications
No 1	0.805	9.7 (134)	For vaporizing pot-type burners
No 2	0.850	10.4 (139)	For general purpose domestic heating
No 3	0.903	10.9 (145)	For burners without preheating
No 5	0.933	11.1 (148)	Requires preheating to 75-95 °C
No 6	0.965	11.3 (151)	Requires preheating to 95-115 °C

duced at the burner through several orifices providing jets of natural gas that mix rapidly with the combustion air supply. There is a wide range of burner designs depending on the orientation, the number and the location of the orifices. As part of routine tune-up and maintenance of gas-fired boilers, it is important to inspect gas injection orifices to check that all the passages are unobstructed. In addition, it is important to identify and replace any burned off or missing burner parts.

Oil-fired units: Oil fuels need some form of preparation and treatment before final delivery to the burner. The preparation of the oil fuels may include the following:

- Use of strainers and filters to clean the oil fuel and remove any deposit or solid foreign material.
- Add flow line pre-heaters to deliver the fuel oil with a proper viscosity.
- Use atomizers to deliver the fuel oil in small droplets before mixing with the combustion air supply. A gun fitted with a tip having several orifices that can produce fine spray can carry out the atomisation of the fuel oil. Moreover, oil cups that spin the oil into a fine mist are also used on small boiler units.

During tune-up of central heating systems, it is important to check that the burner is adequate for the boiler unit. In particular, it is important to verify that the atomizer has the proper design, size and location. In addition, the oil-tip orifices should be cleaned and inspected for any damages to ensure proper oil-spray pattern.

Coal-fired units*:* Some central heating systems use coal as the primary fuel to fire the burner. The efficiency of such systems depends on the firing system, the type of boiler or furnace and the ash characteristics of the coal. Some units are equipped with ash re-injection systems that allow collected ash, containing some unburned carbon, to be redelivered into the burner. There are two main coal-firing systems:

a) Pulverized coal fired systems that pulverize, dry, classify and transport the coal to the burner's incoming air supply. The pulverized coal fired systems are generally considered to be economical for units with large capacities (more than 100,000 kg of steam per hour).

b) Coal stoker units that have bed combustion on the boiler grate through which the combustion air is supplied. There are currently several stoker-firing methods used in industrial applications, such as underfed, overfed and spreader. Both underfed and overfed firing methods require the coal to be transported directly to the bed combustion and usually respond slowly to sudden load variations. The spreader stokers burn partially the coal in suspension before transporting it to the grate, while they can burn a wide range of fuels including waste products.

4.3.3. Boiler thermal efficiency

As is already mentioned, combustion is a chemical reaction of carbon and oxygen atoms that produces heat. The oxygen comes from the air supplied to the burner that fires the boiler, which also contains nitrogen that is useless to the combustion process. A specific amount of air is needed to ideally complete the combustion of the fuel. This amount of air is typically referred to as the stoichiometric air. However, in actual combustion reactions, more air than this ideal amount is needed to totally complete the combustion of fuel.

The main challenge to ensure optimal operating conditions for boilers is to provide the proper excess air for the fuel combustion. It is generally agreed that 10% excess air provides the optimum air to fuel ratio for complete combustion. Too much excess air causes higher stack losses and requires more fuel to raise ambient air to stack temperatures. On the other hand, incomplete combustion occurs if insufficient air is supplied, and the flame temperature is reduced.

The overall boiler thermal efficiency is defined as the ratio of the heat output (E_{out}) over the heat input (E_{in}):

$$\eta_b = \frac{E_{out}}{E_{in}} \tag{4.1}$$

The overall efficiency accounts for the combustion efficiency, the stack loss and the heat losses from the outside surfaces of the boiler. The combustion efficiency refers to the effectiveness of the burner to provide the optimum fuel/air ratio for complete fuel combustion.

To determine the overall boiler thermal efficiency, some measurements are required. The most common test used for boilers is the flue gas analysis using an Orsat apparatus to determine the percentage by volume of CO_2, CO, O_2 and N_2 in the combustion gases leaving the stack. Based on the flue gas composition and temperature, some adjustments can be made to tune-up the boiler to get the best air-to-fuel ratio in order to improve the boiler efficiency.

The following general rules can be used to adjust the operation of the boiler:

- *Stack temperature*: The lower the stack temperature, the more efficient is the combustion. High flue gas temperatures indicate that there is no good heat transfer between the hot combustion gases and water. The chambers and the tubes within the boiler should be cleaned to remove any soot, deposit and fouling that may reduce the heat transfer. However, the stack temperature should not be too low to avoid water condensation along the stack. The condensed water mixes with sulphur and can cause corrosion of the stack. Table 4.2 provides the minimum stack temperature for common fuel types to avoid corrosion problems.
- *CO_2 level*: The higher this level, the more efficient is the combustion. The low limits acceptable for CO_2 level is 10% for gas fired boilers and 14% for oil fired boilers. If the CO_2 levels are lower than these limits, the combustion is most likely incomplete. The air-to-fuel ratio should be adjusted to provide more excess air.
- *CO level*: No CO should be present in the flue gas. Indeed, any presence of CO indicates that the combustion reaction is incomplete, thus there is not enough excess air. The presence of CO in the flue gas can be detected by the presence of smoke that leads to soot deposit in the boiler tubes and chambers.
- *O_2 level*: The lower the O_2 level, the more efficient is the combustion. High level of O_2 is an indication of too much excess air. The high limit acceptable for O_2 level is 10%. When greater levels are found, the excess air should be reduced.

Table 4.2: Minimum exit flue gas temperatures to avoid stack corrosion

Fuel type used by the boiler	Temperature Limit (°C)
Fuel Oil	200
Bituminous Coal	150
Natural gas	105

When the excess air is not adequate, the following boiler adjustments can be used:

1. Operate the boiler for a specific firing rate and put the combustion controls on.
2. After stable operation, take a complete set of measurements (composition and temperature of the stack flue gas).
3. Increase the excess air by 1 to 2% and take a new set of measurements (after reaching stable boiler operating conditions).
4. Decrease the excess air in small steps until a minimum excess O_2 condition is reached (i.e., when the combustion is incomplete and a noticeable CO level –above 400 ppm- can be detected in the flue gas). Take measurements following each change (allow the boiler to reach stable operating conditions).
5. Plot the measured data to determine the variation of CO level as a function of the percent of O_2 in the flue gas. Typically, a margin in excess O_2 ranging from 0.5 to 2% O_2 above the minimum value is used.
6. Reset the burner controls to maintain the excess O_2 within the margin established in step 5.
7. Repeat steps 1 through 6 for various firing rates to be met in the boiler operation. It is recommended the tests to be performed from higher to lower firing rates.

The new operating controls should be closely monitored for a sufficient length of time (one to two months) to ensure proper operation of the boiler. Monographs are available to determine the overall boiler efficiency based on measurements of flue gas composition and temperature. One of these monographs applies to both gas- and oil-fired boilers and is shown in Appendix. Example 4.1 illustrates how the monographs can be used to determine the boiler efficiency.

Example 4.1: *A flue gas analysis of an oil fuel fired boiler indicates that the CO_2 content is 11% with a gas flue temperature of 343°C. Determine the overall thermal efficiency of the boiler.*

Solution: From the monograph of Appendix, the combustion occurs with an excess air of 38% and excess O_2 of 6%. The overall boiler thermal efficiency is about 78%.

4.4. Boiler efficiency improvements

There are several measures by which the boiler efficiency of an existing heating plant can be improved, providing savings in the fuel use by the plant. Among these measures are:

- The tuning-up of the existing boiler.
- The replacement of the existing boiler with a high efficiency boiler.
- The use of modular boilers.

To calculate the savings in fuel use (*ÄFU)* related to the change in the boiler efficiency, the following equation could be used:

$$\Delta FU = \frac{\eta_{eff} - \eta_{std}}{\eta_{eff}}.FU_{std} \qquad (4.2)$$

where ς_{std}, ς_{eff} are the old and new efficiency of the boiler respectively and FU_{std} is the fuel consumption before any retrofit of the boiler system. It is therefore important to estimate both the old and the new overall thermal efficiency of the boiler in order to estimate the energy savings. The following sections provide a detailed description of the various boiler improvement measures, with some estimation of their impact.

4.4.1. Existing boiler tune-up

The boiler thermal efficiency can be estimated analysing the flue gas composition and temperature, using the monograph of Appendix. If the efficiency is found to be low due to inappropriate excess air, the boiler can be adjusted and its efficiency improved, as described in the step-by-step procedure of the previous section. For this, some instrumentation is needed, such as a gas flue analyser and a temperature measurement device. Example 4.2 illustrates how the cost-effectiveness of a boiler tune-up can be evaluated.

Example 4.2: The boiler of example 4.1 uses 1,500,000 litres of fuel oil per year. Instrumentation for the adjustment of the boiler operation so its excess O_2 to be only 3% is purchased at a cost of $20,000. Determine the payback of the equipment if the cost of fuel oil is $0.20/litre.

Solution: From example 4.1, the existing boiler has excess O_2 of 6% and the overall boiler thermal efficiency is about 78% (i.e., $n_{std}=0.78$). After the boiler tune-up, the excess O_2 is 3%. Using the monograph of Appendix, the new boiler efficiency can be determined from the flue gas temperature (343°C) and the excess O_2 (3%). It is found to be $n_{eff}=84\%=0.84$. Using eq. (4.2), the fuel savings can be calculated:

$$\Delta FU = \frac{0.84 - 0.78}{0.84} \cdot 1{,}500{,}000 = 107{,}140\, litre / yr$$

Therefore, the simple payback period for the instrumentation is:

$$SBP = \frac{\$20{,}000}{107{,}140\ litre / yr\ *\ \$0.20 / litre} \approx 1.0\, year$$

Other measures that can be considered to increase the overall efficiency of the boiler are summarized below:

- Installation of turbulators in the fire-tubes to create more turbulence, thus increasing the heat transfer between the hot combustion gas and the water. The improvement in boiler efficiency can be determined by measuring the stack flue gas temperature, which should decrease when the turbulators are installed. As a rule of thumb, a 2.5% increase in the boiler efficiency is expected for each 50°C decrease in the stack flue gas temperature.
- Insulation of the boiler's jacket to reduce the heat loss. The improvement of the boiler efficiency depends on the surface temperature.
- Installation of soot-blowers to remove boiler tube deposits that reduce the heat transfer between the hot combustion gas and the water. The improvement in the boiler efficiency depends on the flue gas temperature.
- Use of economizers to transfer energy from stack flue gases to incoming feed-water. The stack temperature should not be lowered below the limits provided in table 4.2 to avoid corrosion problems. As a rule of thumb, a 1% increase in the boiler efficiency is expected for each 5°C increase in the feed-water temperature.
- Use of air pre-heaters to transfer energy from stack flue gases to combustion air. The stack temperature should not be lower than the values provided in table 4.2.

The stack flue gas heat recovery equipment (i.e., air pre-heaters and economizers) is typically the most cost-effective auxiliary equipment that can be added to improve the overall thermal efficiency of the boiler system.

4.4.2. High efficiency boilers

Manufacturers continue to improve both the combustion and the overall efficiencies of boilers. Currently, commercially sized units can achieve over 95% combustion efficiency. For conventional boilers, anything over 85% is traditionally considered efficient. One of the most innovative combustion technologies currently available in the market is the gas-fired pulse-combustion boilers. This technology was introduced in the early 1980s for residential water heaters and is now available in several commercial-size boilers, for both space heating and hot water heating.

Pulse-combustion boilers operate essentially like internal combustion engines. Air and gas are introduced in a sealed combustion chamber in carefully measured amounts. This mixture is then ignited by a spark plug and, when completely burned, is expelled through an exhaust pipe. Almost all the heat from the combustion is used to heat the water in the boiler. Indeed, the exhaust gases have only a relatively low temperature of about 50ºC. Once the combustion chamber is full heated, successive air/fuel mixtures or “pulses” ignite spontaneously (without need of electrical spark). Thus, no fuel-consuming burner or standing pilot light is required.

When pulse boilers operate, they extract latent heat from the combustion products by condensing the flue gas. Therefore, the boiler efficiency is increased and the flue gas is left with low water vapour content, thus avoiding the corrosion problems at the stack. The efficiency of the pulse-combustion boilers can reach 95 to 99%. When combined with other high-performance elements for heat transfer, the overall thermal efficiency of the heating system can attain 90%. In addition, these boilers can reach operating temperatures in as little as one-half the time of conventional boilers, while they are typically producing lower emissions.

4.4.3. Modular boilers

Almost all heating systems are most efficient when they operate at full capacity. Improvements in peak-load efficiency result in lower fuel use. However, the reduction in the fuel use is not necessarily proportional to the improvement in the heating system efficiency. Indeed, peak loads occur rarely in heating installations. Therefore, the boiler is most often operating under part-load conditions. Some boilers may be forced to operate in an on/off cycling mode, which is an inefficient mode of operation. Indeed, the boiler loses heat through the flue to the ambient space when it cycles off. Moreover, the water in the distribution pipes cools down.

All these losses have to be made up again when the boiler restarts. If the boiler capacity is much higher than the load, the cycling can be frequent and losses mount significantly, reducing the seasonal efficiency of the heating system. Instead of operating the boiler in an on/off mode, controls using step-firing rates (high/low/off) or modulating firing rates (from 100% to 15%) can be specified. Another effective measure to avoid cycling the boilers is to install a group of smaller or "modular" boilers.

In a modular heating plant, one boiler is first operated to meet small heating loads. Then, as the load increases, new boilers are fired and enter on-line to gradually increase the capacity of the heating system. Similarly, as the load decreases, the boilers are taken off-line one by one. Pre-assembled modular boiler packages of various sizes are offered, ranging from approximately 50 kWh to 1 MWh. However, individual units can be piped and wired together in the field to form an efficient modular heating system. Moreover, modular boilers allow more flexibility in the use of space, since they can be transported through doors that cannot accommodate a large boiler. Thus, modular boiler can be located in confined spaces.

Modular boiler plants are suitable for applications with widely varying heating, steam and hot water loads, such as hotels, schools or high-rise buildings. The modular boilers can increase the overall seasonal efficiency of the heating system by 15 to 30%. For instance, a 5000 m^2 shopping mall in Iowa, with more than 16 stores and food service area, was retrofitted with 12 modular boilers of 40 kWh capacity each. According to the system manufacturer, the heating cost savings is about 33% relative to a conventional gas fuelled boiler.

5. ENERGY IMPROVEMENTS OF COOLING SYSTEMS

5.1. Introduction

In general, cooling systems are widely used in industrial cooling, food retail and air conditioning applications. According to a survey reported by the US Energy Information Administration (EIA, 1997), several types of cooling systems are used in US commercial buildings including: packaged air-conditioning units, central chillers, individual air-conditioners, heat pumps, district chilled water, evaporative coolers. From all these, the packaged AC units are the main equipment used, both in terms of percentage of total cooled buildings (42%) and of the total cooled floor-space (55%). On the other hand, central chillers are used in only 4% of conditioned commercial buildings, but cool 27% of the floor area.

This difference in usage stems from the fact that central chillers are typically used in larger buildings, while packaged AC units are used in smaller ones. An extensive research in Japan on cooling plant systems in office buildings has shown that 48% of the energy used is due to the air-conditioning. From this 48%, the energy losses account for 28% and only the rest 20% corresponds to the true production of the necessary cooling amount, also resulting in the increase of pollution rates released in the environment. In the following, a brief description of commonly used cooling systems and their typical energy efficiencies is provided, as well as some common measures to improve their energy efficiency are discussed.

5.2. Basic cooling principles

A typical cooling system consists of several components, including a compressor, a condenser, an expansion device, an evaporator and auxiliary equipment. Figure 5.1 illustrates a simple chilling system, where the compressor is driven by a motor.

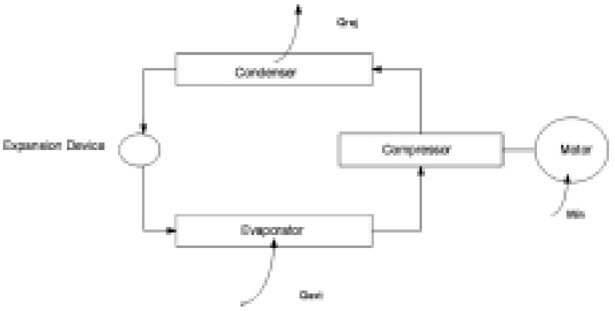


Figure 5.1. Typical cooling system driven by an electrical motor

Note that the chilling (or heat extraction) occurs at the evaporator, while the condenser does the heat rejection. Both the evaporator and the condenser are heat exchangers. At the evaporator, heat is extracted by the refrigerant from water that is circulated through cooling coils of an air-handling unit. At the condenser, heat is extracted from the refrigerant and rejected to the ambient air (air cooled condensers) or water (water cooled condensers, connected to cooling towers).

The Coefficient of Performance *(COP)* characterizes the energy efficiency of a cooling system and is defined as the ratio of the heat extracted divided by the energy input required. In case of an electrically driven cooling system, as the one shown in figure 5.1, the *COP* can be expressed as: $COP=Q_{ext}/W_{in}$. Both Q_{ext} and W_{in} should be expressed in the same unit (i.e., W or kW), so that *COP* to be dimensionless. Most manufacturers provide the *COP* of their systems for full load conditions.

The maximum theoretical value of *COP* corresponds to the ideal Carnot cycle, which consists of isentropic compression and expansion and isothermal evaporation and condensation. In real cooling systems, the Carnot cycle cannot be achieved because of the irreversible losses in the compression and expansion of the refrigerant, the pressure losses in the lines and the heat losses in the rejection and absorption processes. However, it is useful to compare the *COP* of an actual cooling system to that of the Carnot cycle operating between the same temperatures to determine the potential of any energy efficiency improvements in the design of cooling units.

The *COP* of an ideal Carnot cycle can be expressed in terms of the absolute temperature of the evaporator (T_C - the lowest temperature in the cycle) and the condenser (T_H - the highest temperature in the cycle) as follows:

$$COP_{Carnot}=\frac{T_C}{T_H-T_C} \qquad (5.1)$$

Using the ARI standard 550/590 (1998) rated conditions for water chillers ($T_H=308$ K and $T_C=280$ K), the COP_{Carnot} is calculated to be 9.88. Currently, the most energy efficient centrifugal chiller has a *COP* of about 7.0 (70% of the ideal Carnot cycle).

The capacity of cooling systems is expressed in kW and is defined in terms of the maximum amount of heat that can be extracted. Cooling systems manufacturers use tons to provide their capacity (1 ton is about 3.516 kW) and kW/ton to express their energy efficiency. In addition, the energy efficiency of the electrically powered cooling systems can be expressed with the energy efficiency ratio *(EER),* which is defined as the ratio of the heat extracted (in Btu/h) over the energy input required (in Watts). Therefore, the relation between *EER* and *COP* is: $EER=3.413\cdot COP$.

The above stands only for US, since in Europe the *EER* is defined to be exactly the same as the *COP.* However, the adopted European standard EN814 (CENELEC, 1997) specifies that the term *COP* should be used for only heating mode operation of heat pumps. Otherwise, the standard requires the use of the term *EER* to rate the energy efficiency of air conditioners and heat pumps. ARI standard 550/590 allows rating the energy efficiency of water chilling systems using the vapour compression cycle by one of the three parameters: *COP, EER* or kW/ton.

Since cooling systems operate often under part-load conditions throughout the year, other efficiency coefficients have been proposed in an attempt to provide a better estimation of the cooling units energy performance over a wide range of operating conditions. Two such parameters are commonly used, the seasonal energy efficiency ratio *(SEER)* and the integrated part load value *(IPLV).* ARI 550/590 standard defines the *IPLV* using the relation: $IPLV = 0.01xA + 0.42xB + 0.45xC + 0.12xD$, with A the *COP* (or *EER)* at 100% load, B at 75%, C at 50% and D at 25% load.

5.3. Types of cooling systems

As already mentioned, several types of cooling systems are currently available for space air conditioning, the most common of which can be grouped into two major categories: unitary AC systems and chillers.

5.3.1. Unitary AC systems

These systems are typically factory-assembled units to provide either cooling only or both cooling and heating, and include packaged AC units, individual air conditioners, residential type AC units and heat pumps. Compared to chillers, the unitary AC systems have lower life span and lower energy efficiency. They are typically installed in small commercial buildings (less than three floors) including small office buildings, retail spaces and classrooms.

The packaged AC units are compact cooling systems encased in cabinets, including:

- *Rooftop Systems*, typically located in the roof. For commercial buildings, these units are available in the range of 17 to 70 kW, even though custom-built units can have capacities up to 350 kW. For residential buildings, capacities between 3 and 7 kW are common. Most units are equipped with a heating system (a built-in gas furnace, an electric resistance, etc.) to provide both cooling and heating.
- *Vertical Packaged Systems*, which are typically designed for indoor installation. Most systems have water-cooled condensers.
- *Split Packaged Systems* have typically air cooled condenser and compressor installed outdoors and the evaporator installed in an indoor air-handling unit.

Heat pumps can be used for both cooling and heating by simply reversing the refrigeration flow through the unit. The heat sink (or source) for the heat pump can be air, water or ground. For commercial and industrial applications, air-to-air heat pumps have capacities up to 90 kW, while hydronic heat pumps can have higher cooling capacities. Ground-coupled heat pumps are still small and are mostly suitable for residential applications.

5.3.2. Central chillers

In large buildings, central chillers are used to cool water for space air conditioning. Electric motors, hot water or steam, fossil fuel engines or turbines can power central chillers. Description of the various types of central chillers is provided below.

Electric Chillers: These chillers use mechanical vapour compression cycle. There are currently three major types of electric chillers available in the market, according to the type of the compressor they use:

- *Centrifugal compressors* use rotating impellers to increase the refrigerant gas pressure and temperature. Chillers with centrifugal compressors have capacities in the range of 300 to 25000 kW. For capacities above 4500 kW, the centrifugal compressors are typically field erected.
- *Reciprocating compressors* use pistons to raise the pressure and the temperature of refrigerant gases. Two or more compressors can be used under part-load conditions to achieve higher operating efficiencies. Capacities of 35 to 700 kW are typical for chillers with reciprocating compressors.

- *Rotary compressors* use revolving motions to increase refrigerant gas pressure. One of the most ingenious rotary compressors is the scroll one, while the most conventional are the screw compressors, which have several configurations. The capacity of the rotary chillers can range from 3 to 1750 kW.

Engine-driven Chillers: Like electrically driven ones, these chillers use reciprocating, rotary or centrifugal compressors to provide mechanical refrigeration, which can be powered by turbines or gas-fired engines. Engine-driven chillers can have capacities up to 15000 kW, but have usually a high first cost.

Absorption Chillers: They operate using a concentration-dilution cycle to change the energy level of refrigerant (water) by using lithium bromide to alternately absorb heat at low temperatures and reject heat at high temperatures. A typical absorption chiller includes an evaporator, a concentrator, a condenser and one absorber. These chillers can be direct fired (using natural gas or fuel oil) or indirect fired:

- *Direct-fired absorption chillers* can be cost-effective when the price of natural gas is low and are available in the market in two types: single-effect and double-effect. Some of them can be used to produce both chilled and hot water, known as chillers/heaters, and can be cost-effective especially when heating needs exist during the cooling season (i.e., in buildings with large service hot water needs). Capacities ranging from 100 to 5000 kW are available for direct-fired chillers.
- *Indirect-fired absorption chillers* operate with steam (with pressure as low as 15 psig) or hot water (with temperature as low as 140ºC) from a boiler, a district heating network, an industrial process, etc. Small absorption chillers using solar energy have been developed and analysed. Cooling capacities from 15 to 425 kW are available, even though typical sizes range from 200 to 5000 kW. Double-effect chillers can be considered only for high temperature hot water and steam, or with hot industrial waste gases.

5.4. Energy conservation measures

5.4.1. Relations used

To reduce the energy use of cooling systems, the energy efficiency of the equipment has to be improved for both full and part load conditions. In general, the improvement of cooling systems energy efficiency can be achieved by one of the following ways:

- Replacing the existing cooling systems by other more energy efficient.
- Improving the existing operating controls of the cooling systems.
- With the use of alternative cooling systems.

The energy savings from a cooling system retrofit can be estimated using the simplified but general expression:

$$\Delta E_C = \left(\frac{\dot{Q}_C . N_{h,C} . LF_C}{SEER} \right)_e - \left(\frac{\dot{Q}_C . N_{h,C} . LF_C}{SEER} \right)_r \qquad (5.2)$$

The indices *e* and *r* indicate the values of the parameters before and after retrofitting the cooling unit, *SEER* is the seasonal efficiency ratio of the unit, $\dot{Q}_C$ is the rated capacity of the system, $N_{h,C}$ is the number of equivalent cooling full-load hours, and LF_C is the rated load factor (the ratio of the peak-cooling load experienced over the rated capacity of the equipment), that compensates for over-sizing the cooling unit.

It should be noted that the units for both $\dot{Q}_C$ and *SEER* have to be consistent, that is if *SEER* has no dimension (for Europe), $\dot{Q}_C$ has to be expressed in kW. When the only effect of the retrofit is improved energy efficiency of the cooling system, so that only the *SEER* is changed, the energy savings can be calculated as:

$$\Delta E_C = \dot{Q}_C . N_{h,C} . LF_C . \left(\frac{1}{SEER_e} - \frac{1}{SEER_r} \right) \qquad (5.3)$$

In the following, some common energy saving measures related to cooling systems are described, with some calculation examples of the resulting energy use savings.

5.4.2. Chiller replacement

It can be cost-effective to replace an existing chiller by a new and more efficient one. In recent years, significant improvements in the overall efficiency of mechanical chillers have been achieved by the introduction of two-compressor chillers, variable-speed centrifugal chillers, and scroll compressor chillers. A brief description of these configurations is presented below, with an estimation of their energy efficiency:

- Multiple compressor chillers can be reciprocating, screw or centrifugal, with capacities in the range of 100 to 7000 kW. They are energy efficient especially when operating under part load conditions. Some studies indicate that chillers equipped with multiple compressors can save up to 25% of the cooling energy use compared to single-compressor chillers (Tuluca, 1997).
- Variable-speed compressor chillers are in general centrifugal and operate with variable head pressure using variable speed motors, therefore working best when their cooling load is most of the time below the peak. Their typical capacity is in the range of 500 to 2500 kW. It is reported that chillers with variable speed compressors can reduce the cooling energy use by almost 50% (Tuluca, 1997).
- The scroll compressor is a rotary compression unit with two primary components, a fixed scroll and an orbiting scroll, both needed to compress and increase the pressure of the refrigerant. The scroll compressors are more energy efficient than the centrifugal ones since the heat loss between the discharge and the suction gases is reduced. The *COP* of the scroll chillers exceeds 3.2.

The following example illustrates a sample of calculations used to determine the cost-effectiveness of replacing an existing chiller with a high-energy efficient one.

Example 5.1: *An existing chiller with a capacity of 800 kW and an average seasonal COP of 3.5 is to be replaced by a new chiller with the same capacity but with an average seasonal COP of 4.5. Determine the simple payback period of the chiller replacement if the cost of electricity is $0.07/ kWh and the cost differential of the new chiller is $15,000. Assume that the number of equivalent full-load hours for the chiller is 1000 per year, both before and after the replacement.*

Solution: In this example, the energy use savings can be calculated using Eq. (5.3) with $SEER_e = 3.5$, $SEER_r = 4.5$, $N_{h,C} = 1000$ and $\dot{Q}_C = 800$ kW ($LF_C = 1.0$, assuming that the chiller is sized correctly):

$$\Delta E_C = 800 kW * 1000 hrs/yr * 1.0 *$$
$$* \left(\frac{1}{3.5} - \frac{1}{4.5} \right) = 50{,}800 kWh/yr$$

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

$$SPB = \frac{\$15{,}000}{50{,}800 kWh/yr * \$0.07/kWh} = 4.2 years$$

A Life Cycle Cost analysis may be required to determine if the investment in a high-energy efficiency chiller is really warranted.

In some cases, only some parts of the cooling system may need to be replaced. Indeed, by the end of 1995 norms have been enacted that phased out the production and use of CFCs (including R-11 and R-12), after their implication in the depletion of the earth's ozone layer. Since CFCs have been extensively used as refrigerants in air-conditioning and refrigeration equipment, their existing stocks have been reduced significantly and become expensive. Therefore, replacement and conversion of CFC chillers to operate with non-CFC refrigerants are becoming attractive options.

Thus, if the existing chiller is relatively new (less than 10 years old), it may not be cost-effective to replace it entirely with a new non-CFC one. Just the conversion of the chiller to operate with non-CFCs may probably be the most economical option. However, the non-CFC refrigerants (e.g. R-134a and R-717) may reduce the chiller cooling capacity due to their inherent properties. Fortunately, this loss in energy efficiency can be limited by upgrading some components of the cooling system, including the impellers, orifice plates and gaskets, even the compressors.

In some cases, the conversion with upgrade may actually improve the chiller performance. Some of the strategies that can be used to improve the efficiency of existing chillers include:

- Increment of the evaporator and the condenser surface area for more effective heat transfer.
- Improvements in the compressor efficiency and control.
- Enlargement of the internal refrigerant pipes for lower friction.
- Ozonation of the condenser water to avoid scaling and biological contamination.

Over-sizing is another problem that may warrant the replacement of cooling systems. Indeed, several existing chillers have a capacity that is significantly higher than their peak-cooling load and operate exclusively under part load conditions, with reduced efficiency and thus increased operating and maintenance costs. When the oversized chillers are more than 10 years old, it may be cost-effective to replace them with smaller and more energy efficient ones, operating with non-CFC refrigerants.

5.4.3. Chiller control improvement

Before replacing an existing chiller, it is recommended to consider alternative cooling systems or simple operating measures to improve its energy performance. Some common and proven alternative cooling systems are presented later on. Other measures involve the use of automatic controls to:

- supply chilled water at the highest temperature that meets the cooling load,
- decrease the condenser water supply temperature (for water-cooled condensers) when the outside air wet-bulb temperature is reduced.

Indeed, chiller performance depends not only on the cooling load but also on the chilled water supply temperature and the condenser water temperature. The Carnot efficiency (Eq. 5.1) shows that the *COP* increases when the condenser temperature (T_H) is reduced or when the evaporator temperature (T_C) is increased. For typical water chillers, figure 5.2 is used to evaluate the improvement in the *COP* of a chiller when the leaving water temperature is increased, while figure 5.3 is used to estimate the effect of reducing the condenser water temperature on the *COP* of the system.

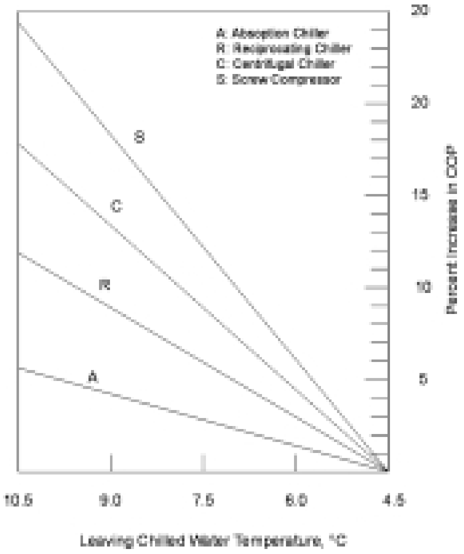


Figure 5.2. Effect of leaving chilled water temperature on the chiller COP

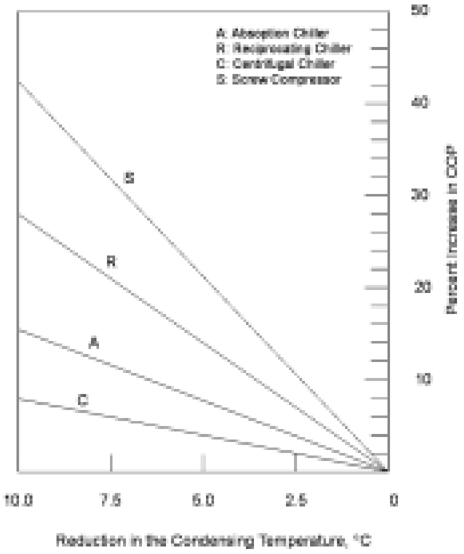


Figure 5.3. Effect of the condensing temperature on the chiller COP

Example 5.2: *A centrifugal chiller with a capacity of 500 kW and average seasonal COP of 4.0 operates with a leaving chilled temperature of 4.5ºC. Determine the cost savings incurred by installing an automatic controller that allows the leaving water temperature to be set on average 2.5ºC higher. The number of equivalent full-load hours for the chiller is 1500 per year and the electricity cost is $0.07/kWh.*

Solution: Using figure 5.2, the increase in the *COP* for a centrifugal chiller due to increasing the leaving chilled water temperature from 4.5ºC to 7.0ºC is about 8%. The energy use savings can be calculated using Eq. (5.3) with $SEER_e = 4.0$, $SEER_r =$ 4.0x1.08 $= 4.32$, $N_{h,C} = 1500$ and $\dot{Q}_C = 500$ kW ($LF_C = 1.0$, assuming that the chiller is sized correctly):

$$\Delta E_C = 500kW * 1500hrs/yr * 1.0 * \left(\frac{1}{4.0} - \frac{1}{4.32}\right) = 13{,}890 kWh/yr$$

Therefore, the energy cost saving is $970.

5.4.4. Alternative cooling systems

There are various alternative systems and technologies that can be used to reduce (even eliminate) the cooling loads on the existing cooling systems. Among them are:

- Waterside economizers, that can be used when the outdoor conditions are favourable. Instead of operating the chillers to provide air conditioning, water can be cooled by using only cooling towers and circulated directly to the coils, either through the normal chilled water circuit or through heat exchangers.
- Evaporative cooling is a well-established technique that uses water sprays or wetted media to cool supply air, allowing temperatures to approach the wet-bulb temperature of the ambient air. Direct evaporative cooling humidifies the air supply when its temperature is reduced, while indirect evaporative cooling is performed via air-to-air heat exchangers with no humidity addition, and is less effective and more expensive than the direct one. In addition to some energy use (electric energy to power fans), both methods consume a significant amount of water. Evaporative cooling can be used to reduce the load for a conventional air-conditioning system in climates with dry conditions, either throughout the year or during limited periods. The average *COP* of evaporative cooling systems can be in the range of 10 to 20, depending on the climate (Huang, 1991).
- Desiccant cooling is a reverse evaporative cooling, since the air temperature is increased but its humidity is reduced. The dried air is then cooled using heat exchangers in contact with ambient air. Finally, the air is further cooled using evaporative cooling. A source of heat is needed to regenerate the desiccant after it has absorbed water from the air. Desiccant cooling has been used mostly in industrial applications and is less commonly used in the commercial sector.
- Sub-cooling of the refrigerant increases typically the cooling capacity and can decrease the compressor power, thus increasing the overall efficiency of the cooling system. It requires the addition of a heat exchanger to decrease the enthalpy of the refrigerant entering the evaporator, resulting in an increase in the cooling capacity. There are currently three common sub-cooling technologies:
  - ➢ one that uses suction-line heat exchanger of the vapour compression system as a heat sink,
  - ➢ the second one involves a second mechanically driven vapour compression cycle coupled with the main cycle using a sub-cooling heat exchanger located downstream from the condenser, and
  - ➢ the third technology requires an external heat sink, such as a small cooling tower or ground source water loop.

  Refrigerant sub-cooling has long been used in low and medium temperature refrigeration systems. Currently, some manufacturers of packaged and split-system for air conditioners and heat pumps are using sub-cooling devices in their systems using alternative refrigerants (such as R-134a).

6. HVAC SYSTEMS RETROFIT

6.1. Introduction

The Heating, Ventilating and Air-Conditioning (HVAC) systems maintain and control air temperature and humidity levels to provide an adequate indoor environment for people activity or for processing goods. The cost of operating an HVAC system can be significant in commercial buildings and in some industrial facilities. In the US, it is estimated that the energy used to operate the HVAC systems represents about 50% of the total electrical energy use in a typical commercial building (EIA, 1994). It is therefore important for the auditors to recognize some of the characteristics of the HVAC systems and determine if any retrofits can be recommended to improve their energy consumption.

6.2. Types of HVAC systems

A basic HVAC air distribution system consists of an air-handling unit (AHU) with the following components, as shown in figure 6.1:

- Dampers to control the amount of air to be distributed by the system, including: outside air (OA), return air (RA), exhaust air (EA) and supply air (SA) dampers.
- Preheat coil, in case that outside air is too cold, to avoid any freezing problems.
- Filter to clear the air from any dirt.
- Cooling coils that chill the supply air to meet the necessary cooling loads.
- Humidifiers to add moisture to the supply air in case that humidity control is provided to one or more conditioned spaces.
- A duct network, where the air is channelled to various locations and spaces.

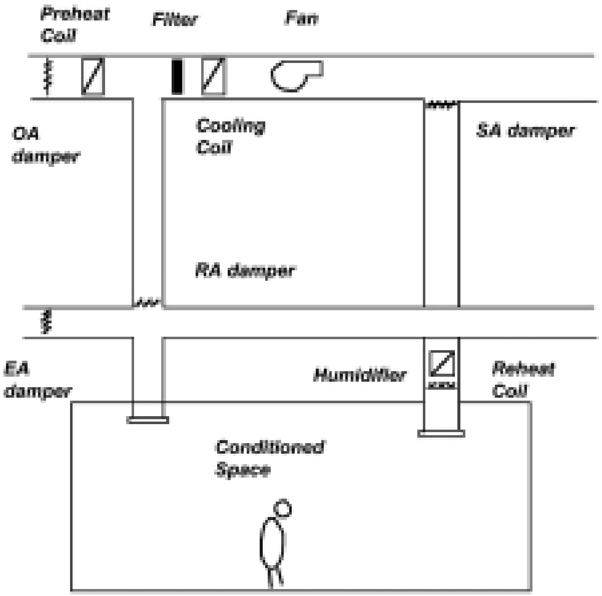


Figure 6.1. Typical Air Handling Unit (AHU) for an air HVAC system

Each of the above listed components can come in several types and styles, and their integration constitute the HVAC system for mainly distributing conditioned air. Two main categories of central HVAC systems can be distinguished:

Constant Air Volume (CAV) systems, which provide a constant amount of supply air, conditioned at proper temperature to meet the thermal loads in each space based on a thermostat setting. Either mixing cooled air with heated or bypassed air or directly reheating cooled air is used to control the supply air temperature, this way wasting energy because of the mixing and/or reheat, especially under partial load conditions. Among the CAV systems commonly used to condition existing buildings are:

a) CAV with terminal reheat systems, which require the circulated air to be cooled to meet design thermal loads. If partial thermal load conditions occur, reheat of pre-cooled air is required.

b) CAV systems with terminal reheat in interior spaces and perimeter induction or fan-coil units. For these systems, the energy waste is reduced at the perimeter spaces, since a large portion of the air supplied to the perimeter spaces is re-circulated within each space by either induction or fan-coil units.
c) All-air induction systems with perimeter reheat. The induction units accept varying amounts of warm return air to mix with primary air for temperature control. The energy waste due to reheat is small for these systems. However, extensive static pressure control is required at the terminals.
d) CAV double duct systems, which have a cold air duct and a hot air duct. Mixing cold air with hot air proportionally to meet the thermal load of the space controls the supply air temperature. Energy waste occurs during partial thermal load conditions when mixing is needed.

Variable Air Volume (VAV) systems, which provide a variable amount of supply air, conditioned at a constant temperature to meet the thermal loads in each space based on thermostat setting. The air volume is controlled using outlet dampers, inlet vanes and variable speed drives. Only cooled air is supplied at the central AHU while reheat is provided in each space depending on the thermal load. VAV systems waste significantly less energy than the CAV ones. The most commonly used types are:

a) VAV systems with terminal reheat, which reduce the amount of air supplied as the cooling load lowers until a preset minimum volume is reached. At this limit, reheat is provided to the supply air to meet the thermal load. Because of this volume reduction, reheat energy waste is significantly reduced relative to the CAV systems with terminal reheat.
b) VAV systems with perimeter heating units, providing only cooling since heating is performed by other systems, such as hot water baseboard units. The heating units are controlled by outside air temperature, since the perimeter-heating load is function of the transmission losses.
c) VAV double duct systems, which have cold air and hot air ducts and operate in a similar way to VAV systems with terminal reheat. As the cooling load decreases, only cold air is supplied until a preset minimum volume is reached. At this limit, the hot air is mixed with the cold air stream.

Summarizing, VAV systems are more energy efficient than the CAV ones, since they minimize reheat energy waste. Retrofitting existing CAV systems to VAV constitutes a common and, generally, cost-effective energy conservation measure for HVACs. However, energy savings can be also considered even if the existing system is a VAV. The potential for energy savings in HVAC systems depends on several factors, including their design, the method of operation and their maintenance.

Generally, energy can be conserved in HVAC systems applying one or several of the measures listed below:

- Operation of the HVAC systems only when needed. For instance, there is no need to provide ventilation during unoccupied periods.
- Elimination of overcooling and overheating of the conditioned spaces to improve comfort levels and avoid energy waste.
- Reduction of reheat, since it wastes energy.
- Provision of free cooling and heating whenever possible using economizer cycles or heat recovery systems to eliminate the need for mechanical air-conditioning.
- Reduction of the amount of air delivered by the HVAC systems by reducing the supply air and, especially, the make-up and exhaust air.

In the following sections, selected energy conservation measures are described, starting from measures specific to each component of an AHU to conversion of a CAV system to a VAV one.

6.3. Ventilation

The energy required to condition ventilation air can be significant in both commercial buildings, where it is used to provide fresh air to occupants, and industrial facilities, used to control the level of dust, gases, fumes or vapours, especially in locations with extreme weather conditions. The auditor should estimate the existing volume of fresh air and compare this estimation to the amount of ventilation air required by the appropriate standards and codes.

Excess in air ventilation should be reduced if it can lead to increases in heating and/or cooling loads. Some energy conservation measures related to ventilation are described in this section. However, in some climates and periods of the year or day, providing more air ventilation can be beneficial and may actually reduce cooling and heating loads through the use of air-side economizer cycles. The potential of energy savings attributed to economizers is also described below.

6.3.1. Reduced ventilation air

The auditor should first estimate the existing level of ventilation air brought by the mechanical system (rather than by natural means, such as infiltration through the building envelope). The tracer gas technique can be used to determine the amount of fresh air entering a room, which however cannot differentiate between the air coming from the mechanical system to that from infiltration. Several techniques are currently available to measure the flow of air through ducts, which are summarized in Chapter 3 of the "Energy Audit Guide - Part A". It should be noted that, all these techniques are relatively expensive and are generally difficult to set up in existing systems.

To have an estimation of ventilation air provided by the HVAC system, an enthalpy balance technique can be used, for which the temperature must be measured at three locations in the duct system: before the outdoor air damper (for outdoor air temperature, T_{oa}), in the return duct (for return air temperature, T_{ra}) and in the mixing plenum area (for mixing air temperature, T_{ma}). The outside air fraction X_{oa} (ratio of ventilation air over the total supply air) is then estimated by: $T_{ma}=X_{oa}\cdot T_{oa}+(1-X_{oa})\cdot T_{ra}$.

The amount of ventilation $\dot{V}_{oa}$ can be determined under design conditions using the capacity of the air handling unit ($\dot{V}_{des}$), as:

$$\dot{V}_{oa} = X_{oa}.\dot{V}_{des} = \left(\frac{T_{ra}-T_{ma}}{T_{ra}-T_{oa}}\right)\dot{V}_{des} \qquad (6.1)$$

The accuracy of the estimation for the ventilation air using Eq. (6.1) is reduced as the difference between the return air and outside air temperatures is small. Thus, it is recommended for the auditor to perform the measurements when the outdoor temperatures are extremes (i.e.; during heating or cooling seasons).

Once the existing ventilation air is estimated, it has to be compared to the ventilation requirements by the applicable standards. The following table 6.1 summarizes some of the 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 ventilation that meet the below listed minimum standard requirements.

Table 6.1. Typical ventilation rate requirements for selected spaces in buildings

Type of area	Ventilation air flow (m^3/h per person)
Rooms	17-26
Toilets	51-85
Corridor	12-17
Public areas	17-26
Meeting rooms	34-51
Public toilets	34-43
Dining room	26-34
Bar	68-85
Kitchen	60

Further reductions in outdoor air can be obtained using demand ventilation controls for supplying outside air only during periods when there is need for fresh air. A popular approach for demand ventilation is the monitoring of CO_2 concentration level within the spaces. CO_2 is considered as a good indicator of pollutants generated by occupants and construction materials. The outside air damper position is controlled to maintain a CO_2 set point within the space.

The energy savings due to reduction in the ventilation air can be attributed to lower heating and cooling loads required to condition outdoor air. The instantaneous heating and cooling savings can be estimated using respectively Eq. (6.2) and (6.3):

$$\Delta e_H = \rho_a.c_{P,a}.(\dot{V}_{oa,E} - \dot{V}_{oa,R}).(T_i - T_o) \tag{6.2}$$

and,

$$\Delta e_C = \rho_a.(\dot{V}_{oa,E} - \dot{V}_{oa,R}).(h_o - h_i) \tag{6.3}$$

with $\dot{V}_{oa,E}$ and $\dot{V}_{oa,R}$ the ventilation air rates before and after retrofit respectively, $ñ_á$ and $c_{P,á}$ the density and the specific heat of air, T_i and T_o the air temperatures of respectively the indoor space and outdoor ambient during winter, and h_i and h_o the air enthalpies of the indoor space and the outdoor ambient during summer respectively.

It should be noted that the humidity control is not typically performed during winter, thus the latent energy is neglected, as indicated in Eq. (6.2). To determine the total energy use savings due to ventilation air reduction, the annual savings in heating and cooling loads have to be estimated. Without using detailed energy simulations, these savings can be calculated applying Eq. (6.2) and (6.3) for various bin temperatures and then summing the changes in the thermal loads over all the bins.

Taking into account the energy efficiency of the heating and cooling equipment, the energy use savings due to a reduction in the ventilation air can be estimated, for both winter and summer, as illustrated in Eq. (6.4) and (6.5) respectively:

$$\Delta kWh_H = \frac{3.6 * \sum_{k=1}^{N_{bin}} N_{h,k}.\Delta e_{H,k}}{\eta_H} \tag{6.4}$$

and,

$$\Delta kWh_C = \frac{3.6 * \sum_{k=1}^{N_{bin}} N_{h,k}.\Delta e_{C,k}}{EER_C} \tag{6.5}$$

where $N_{h,k}$ is the number of hours in bin k, EER_C the average seasonal efficiency ratio of the cooling system and $ç_Ç$ the average seasonal efficiency of the heating system. When an air-side economizer is present, the summation in both Eq. (6.4) and (6.5) should be performed for only the bin temperatures for which the outside air damper is set at its minimum position.

The calculations of the energy use savings can be simplified if the air density is assumed to be constant and if the HVAC system has a year-round operation. Under these conditions, the energy savings due to heating can be estimated as follows:

$$\Delta kWh_H = \frac{3.6 * \rho_a.c_{p,a}.N_h.(\dot{V}_{oa,E} - \dot{V}_{oa,R}).(T_i - \bar{T}_o)}{\eta_H} \tag{6.6}$$

with N_h the total number of hours in the heating season (if ventilation is not provided during all hours, N_h can be adjusted to include only occupied hours assuming that the average outdoor air temperature does not vary significantly with this adjustment) and $\bar{T}_o$ the average outdoor air temperature during the heating season. In the case of cooling, a simplified form of Eq. (6.5) can be obtained with the introduction of a seasonal cooling load ($ÄÇ_C$) to condition a reference amount of outdoor air (such as 1000 m^3/h), which depends on the climate and the indoor temperature setting:

$$\Delta kWh_C = \frac{3.6 * \rho_a.N_h.(\dot{V}_{oa,E} - \dot{V}_{oa,R}).\Delta H_C}{EER_C} \tag{6.7}$$

Other measures that can reduce the ventilation air through HVAC systems include:

1. The reduction of the leakage through the outside air damper, especially when this is set to be closed. The change in the ventilation air can be calculated using the leakage percentage. The low leakage dampers can restrict leakage to less than 1%, while the standards can allow 5% up to 10% leakage when closed.
2. The elimination of ventilation during unoccupied periods or when it is not needed.

The calculations of the energy savings for the above listed measures follow the same methods illustrated by equations (6.2) through (6.7).

It should be noted that, when the ventilation air is reduced, the amount of exhaust air should also be adjusted. Otherwise, a negative static pressure can be obtained in the building (since more air is exhausted than introduced to the building). Several problems can occur because of the negative pressure within the building including:

- Difficulty in opening exterior doors and windows.
- Draft can be felt at the perimeter of the building since outside cold air is drawn near the windows and doors.
- Accumulation of fumes, odours, dirt, and dust is increased since exhaust fans cannot operate at rated capacity under negative pressure.
- Combustion efficiency of boilers and ovens can decrease, if this equipment depends on natural draft to operate properly.

6.3.2. Air-side economizers

When the outdoor air conditions are favourable, excess ventilation air can actually be used to condition the building, thus reducing the cooling energy use for the HVAC system. There are typically two ways to determine the switchover point and decide when it is better to use more than the minimum required amount of the outdoor air to cool a building: one based on dry-bulb temperatures and another one on enthalpies, known respectively as temperature and enthalpy air-side economizers, which are briefly described below. Then, the operation of the HVAC system is said to be on an economizer cycle.

<u>Temperature Economizer Cycle</u>: In this cycle, the outside air intake damper opens beyond the minimum position whenever the outside air temperature is colder than the return air temperature. However, when the outdoor air temperature is either too cold or too hot, the outside air intake damper is set back to its minimum position. Therefore, there are outdoor air temperature limits beyond which the economizer cycle should not operate, which are respectively called economizer low temperature and high temperature limits, as illustrated in figure 6.2.

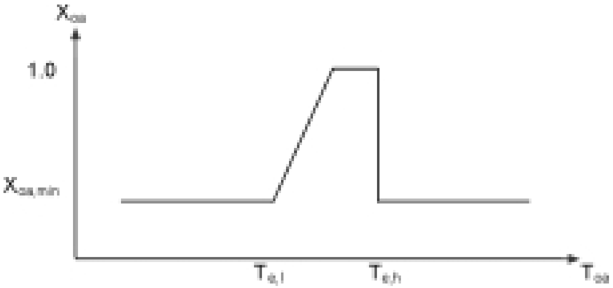


Figure 6.2. Economizer temperature limits

While the economizer high temperature limit is typically set to be the same as the return air temperature, the economizer low temperature limit should be determined as a function of the conditions of both the return and supply air. There is no need to introduce more than the required amount (i.e., for ventilation purposes) of outdoor air if it has more heat content than the return air.

<u>Enthalpy Economizer Cycle</u>: This cycle is similar to the temperature-based one, except that the enthalpy of the air streams is used instead of the temperature. Thus, two parameters are typically measured for each air stream in order to estimate its enthalpy (e.g. dry and wet bulb temperatures). This is why the enthalpy economizers are less common, since they are more expensive to implement and less robust to use, even though they may achieve greater savings if properly operated.

6.4. Indoor temperature controls

The indoor temperature settings during both heating and cooling seasons have significant impacts on the thermal comfort within the occupied spaces and on the energy use of the HVAC systems. It is therefore important for the auditor to assess the existing indoor air temperature controls within the facility to evaluate the potential for reducing energy use and/or improving indoor thermal comfort without any substantial initial investment.

There are four options for adjustments of the indoor temperature setting that can save heating and/or cooling energy:

1. Eliminating overcooling by increasing the cooling set-point during the summer.
2. Eliminating overheating by reducing the heating set-point during the winter.
3. Preventing simultaneous heating and cooling operation for the HVAC system by separating heating and cooling set-points.
4. Reducing heating and/or cooling requirements during unoccupied hours by setting back set-point temperature during heating and setting up the set-point temperature (or letting the indoor temperature float) during cooling.

The calculations of the energy use savings for these measures are based on the degree-days, as outlined earlier. It should be noted that some of the above listed measures could actually increase the energy use if they are not adequately implemented. For instance, when the indoor temperature is set lower during the winter, the interior spaces may require more energy since they need to be cooled rather than heated. Similarly, the setting of the indoor temperature higher can lead to an increase in the reheat energy use for the zones with reheat elements.

6.5. Upgrade of Fan systems

6.5.1. Introduction

Fans are used in several HVAC systems to distribute air throughout the buildings, in particular to move conditioned air from central air handling units to heat or cool various zones within a building. According to a survey reported by the US Energy Information Administration (EIA, 1997), the energy use for fans represents about 25% of the total electrical energy use in a typical building. Thus, a reduction in the operation of fan systems can provide significant energy savings.

In a typical AHU, fans create the pressure required to move air through ducts, coils, filters, and any other obstacles within the duct system. Two types of fans are used: centrifugal and vane-axial. The centrifugal fan consists of a rotating wheel, known as "impeller", mounted in the centre of a round housing. The impeller is driven by an electric motor through a belt drive. The vane-axial fan includes a cylindrical housing with the impeller mounted inside along the axis of the housing. The impeller of an axial fan has blades mounted around a central hub similar to an airplane propeller.

Typically, axial fans are more efficient than centrifugal fans, but are more expensive since they are difficult to construct. Currently, the centrifugal fans are significantly more common in existing HVAC systems. There are several energy conservation measures that help reduce the energy use of fan systems. Some of these measures are described in this section. A brief review of basic laws that characterize the fan operation is first provided.

6.5.2. Principles of Fan operation

To characterize the operation of a fan several parameters need to be determined, including the electrical energy input required in kW (or Hp), the maximum amount of air it can move in lit/s (or cfm) for a total pressure or static pressure differential (*ÄÑ*$_t$ or *ÄÑ*$_s$), and the fan efficiency. The electrical energy input required for a fan is calculated as a function of the airflow, the pressure differential and its efficiency using a simple relationship. If the total pressure is used, the electrical energy input is:

$$kW_{fan} = \frac{\dot{V}_f . \Delta P_t}{\eta_{f,t}} \tag{6.8}$$

while if the static pressure is available, then Eq. (6.9) should be used:

$$kW_{fan} = \frac{\dot{V}_f . \Delta P_s}{\eta_{f,s}} \tag{6.9}$$

To measure the total pressure of the fan, a Pitot tube can be used in two locations within the duct that houses the fan, at the inlet and outlet of the fan respectively. Then, the fan total pressure is simply found by taking the difference of the above two measured quantities. From the fan laws it can be noted that, by reducing the amount of air to be moved by the fan the required electricity input is reduced significantly. For instance, a 50% reduction in the volume of air results in a 87.5% reduction in fan energy use. These facts hint clearly to the advantage of using variable air volume fan systems compared to constant volume ones.

6.5.3. Size adjustment

A recent study has shown that 60% of buildings fan systems are oversized by at least 10%. By reducing the size of these fans to the required capacity, it is estimated that average savings of 50% can be achieved in energy use of fan systems. Even more savings can be expected if the fan size adjustment is implemented with other measures related to fan systems, such as energy-efficient motors, energy-efficient belts and variable speed drives.

The size adjustment of fans can be implemented for both CAV and VAV systems. In addition to energy savings, the benefits of using the proper fan size include:

- Better comfort, since if the fan system is oversized more air than needed may be supplied to the zones, which may reduce the comfort of the occupants.
- Longer equipment life, since an oversized fan equipped with variable speed drive operates at low capacities. This mode of operation can reduce the useful life of motors and other equipment.

To determine if a fan system is oversized, some in-site measurements can be made, depending on the type of the HVAC system. For CAV systems, the measurement of supply fan static pressure is generally sufficient to assess whether or not the fan has the right size. To ensure that the static pressure of the main supply fan is measured when the system is operating close to its design capacity, the testing should be made during hot and humid days, while all dampers and vanes should be fully open during the tests. If the measured static pressure is larger than the design one, that is normally provided in the building mechanical drawings, the fan supplies too much air and is most probably oversized.

For VAV systems, three methods can be used to determine if the fan system is oversized including:

a) Measurement of the electric current drawn by the fan motor. If this is lower than 75% of the full-load amperage rating (obtained directly on the motor's nameplate or from the operations and maintenance manual), then the fan is oversized.
b) Check of the position of fan control vanes and dampers. If the vanes or dampers are closed more than 20%, the fan is oversized.
c) Measurement of the static pressure for the main supply fan. If the measured static pressure is larger than the set-point, the fan system is oversized.

If it is clear that the fan system is oversized, one or a combination of the following measures can be used for its size adjustment:

a) Installation of a larger pulley to reduce the speed of the existing fan. This way, not only the flow of air moved through the duct is proportionally reduced, but also the energy use of the fan system is reduced significantly. For instance, a 20% reduction in fan's speed will reduce its energy consumption by 50%.
b) Replacement of the existing oversized motor by a smaller energy-efficient one that matches the peak load. This will obviously reduce the energy use of the fan system. For instance, replacing a 50 kW standard motor with a 35 kW energy-efficient one will reduce the energy use of the fan system by about one third.
c) Adjustment of the static pressure setting (only for VAV systems). By reducing the static pressure set-point to a level enough to maintain indoor comfort, the energy use by the fan system will be reduced. For instance, a VAV system operating at a static pressure of 6 inches of water can be reduced in some cases to 4 inches without loss of thermal comfort. This 33% reduction of static pressure will achieve about 45% of energy savings in the fan system operation.

It is important to analyse the performance of the entire HVAC system with any of the measures described above to ensure effective adjustment of the fan size. Indeed, changes to the fan system can affect the operation and/or control of other components of the HVAC system.

7. ENERGY CONSERVATION MEASURES IN INDUSTRIAL PROCESSES

7.1. Introduction

The main objective of energy conservation measures is to improve the industrial companies' ability to make the correct decision in matters regarding the reduction of their energy consumption, the efficient use of energy and the pollution prevention. Special attention has been paid to the industrial sector, since an important segment of energy is consumed there in high temperature industrial units (furnaces, kilns, ovens) during energy intensive production processes.

The concept of energy savings is characterized by the effort to rationalize the use of energy through the adoption of innovative technologies. A variety of strategies have been developed in order to initiate energy savings, such as the recovery of waste heat, the avoidance of waste heat, the development of machinery and equipment for lower energy consumption, e.g. in the ceramics industry. There, most of the developments have been focused on improving the energy efficiency of the kiln, which is the most energy intensive part of the ceramic plant.

7.2. Important technologies

The technologies that can improve an industry's energy performance are divided into two groups: cross-sector technologies and sector specific technologies. Many of the cross-sector technologies could benefit from further development, demonstration or dissemination at a wider level, in order to overcome market barriers. The following table 7.1 presents important issues associated with each of the selected cross-sector technologies.

As far as the sector specific technologies are concerned, some examples of energy intensive industries and of key issues concerning energy opportunities are as follows:

- The oil industry is a major energy consumer but provides important opportunities for energy savings through the introduction of new techniques for production (e.g. 4D-seismic, time-lapse seismic techniques) and decommissioning processes.
- The chemical industry provides many opportunities for using the cross-sector energy saving technologies; specifically, energy savings can be obtained by optimizing the steam crackers.

Table 7.1. Cross-sector technologies (Ref. 28)

TECHNOLOGY	CURRENT STATUS	LONG-TERM SAVINGS (%)
Separation processes	Further development of materials and systems needed	5 – 30
Process control and energy management	Relatively mature, but needs further dissemination and improved sensors to facilitate automation	5 – 10
Process integration and process intensification	Further demonstrations needed, especially to open up new markets in batch processes	5 – 25
Refrigeration	Further dissemination needed to promote more efficient and environmentally acceptable systems	5 –10
Heat pumps, transformers and organic Rankine cycle	Further development needed to reduce costs and promote applications in new markets	3 – 8
High-temperature CHP	Further demonstrations and dissemination needed to reduce costs and open up new markets	8 – 15
Combustion techniques	Further development of emission controls needed, together with demonstrations and promotion	5 – 30
Adjustable-speed drivers	Further dissemination to stimulate uptake of existing units and demonstration to promote new markets and reduce costs needed	10 - 20

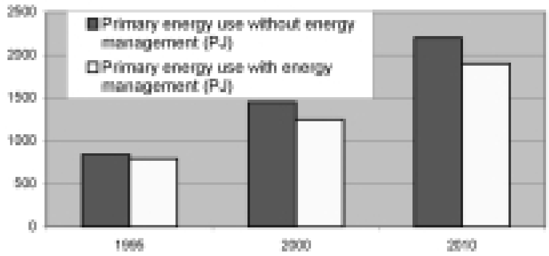
- The steel industry is a major energy consumer and there are substantial opportunities for energy savings through the introduction of new technologies for smelt reduction and for near net shape casting.
- The pulp and paper industry offers key opportunities for energy savings through the following sector specific processes: black liquor gasification, impulse drying and condensing belt drying.

7.3. Energy conservation measures

7.3.1. Process control and energy management technologies

Process control and energy management constitute an important element in the total quality system of industries. Sophisticated sensors and control systems can be used in order to generate energy savings. Other substantial benefits include improved product quality, lower emissions and reduced raw material costs. Energy management involves buying energy supplies at the lowest price and implementing practical measures to save energy. Some of these measures are, for example, switching off equipment when not required and preventive maintenance.

Energy management systems allow industries to improve their performance through better control strategies. Typical investment costs for an energy management system vary from 0.5-40 ECU per GJ of saved energy. In industrial applications, the payback period ranges from less than a year to four years. The lifetime of such a system depends on the working life of the equipment for which it is used; on average this is 15 years. The following graph shows the predicted total energy savings from energy management systems in EU countries relative to industrial energy consumption in 1990. High rates of growth are predicted for process control equipment for monitoring temperature, flow, moisture content, chemical composition and machine conditioning.



Graph 7.1. Predicted total energy savings from energy management systems (Ref. 28)

7.3.2. Process integration and intensification techniques

Process integration is a management/design tool used to optimize energy resources in process plant employing conventional technologies. On the other hand, process intensification involves making fundamental changes to processing technologies to produce improved product quality and energy efficiency.

Process integration is a well-known technique used for continuous processes, especially in chemical industry, oil refining, food and drink industry (table 7.2). The most common integration tool is the pinch analysis that involves the use of heat exchanger networks in order to optimize heat energy by linking hot and cold processes streams in the most thermodynamically advantageous way.

The use of process intensification leads to energy, capital, environmental and safety benefits through fundamental reductions in plant size (often by a factor of three to four). Smaller, innovative heat exchanger designs employing ceramic, polymeric or other novel systems can be used to achieve cost-effective heat transfer. Both techniques offer potential energy savings and waste minimization.

Table 7.2. Estimated potential energy savings and payback from the application of process integration in industrial sectors (Ref. 28)

SECTOR	PROCESS/APPLICATION	IDENTIFIED SAVINGS (%)	TYPICAL PAYBACK PERIOD (YEARS)
Oil refining	Crude distillation	12	1
Chemical	Aromatics	10	1
	Tar-based chemicals	15	1
	Sulfur-based chemicals	42	1
Food and drink	Brewery	21	1
	Distillery	24	3
	Beverages	21	2

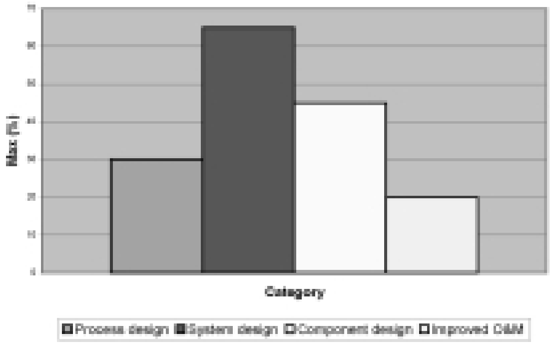
7.3.3. Refrigeration technologies

The use of refrigeration is increasing over the years mainly because of the higher living standards. Refrigeration is the major user of electricity across EU countries and the withdrawal of Chlorofluorocarbon-based systems, as a result of environmental agreements, offers the opportunity to seek the most energy efficient solutions to replace them.

Refrigeration in industry is mainly carried out by means of compression cooling and, in some cases, by absorption cooling. Changes in the process design will allow components to be designed with energy savings taken into account (e.g. the development of super heat pumps with high COPs). Additional savings can be achieved by optimizing cold airflow distribution in stores, which can also reduce product losses. Furthermore, the use of alternative working fluids (as opposed to common working fluids for compression heat pumps), such as halogen refrigerant mixtures, and natural refrigerants, such as air and CO_2, will offer energy savings of 2-20%.

Absorption refrigeration offers considerable energy savings when it is driven by waste heat. When it is used in conjunction with a CHP unit, it can result in increasing the viability of the CHP plant by providing a productive use for the heat, especially over summer periods. As it was mentioned above, component design is a crucial area for achieving energy savings. There is a scope for improving all its aspects, including developing more efficient condensers and evaporators, expansion valves, motor drives and fan controls.

Furthermore, energy savings can also be achieved by improving the energy management related to control systems, air purge and defrost cycles, as well as maintenance issues. The energy savings achieved by process design, system design, component design and improved operation and maintenance (O&M) techniques are illustrated in the graph below.



Graph 7.2. Energy savings by category (Ref. 28)

7.3.4. Heat pumps, heat transformers and organic Rankine cycle technologies

The waste heat from power generation and industrial processes can be used in such a way that it can save energy and costs. The energy conversion technologies that can exploit this source of waste heat include heat pumps, heat transformers and the organic Rankine cycle (ORC). Heat pumps and heat transformers transfer heat from a cooler object or space to a warmer one. This process enables low-grade waste heat to be re-used at a higher temperature, suitable for another process.

In the closed vapor compression, heat evaporates a liquid that is then compressed and releases more heat when it condenses. In the semi-closed vapor compression, steam from a process is captured, compressed and then transferred to another process, by a heat exchanger. Mechanical vapor compression (MVR) systems can be considered as open-loop heat pumps. On the other hand, ORC operates at lower temperatures, as opposed to heat transformers, using organic compounds instead of steam (as shown in table 7.3).

The primary energy savings that can be gained by applying the above-mentioned technologies range from 2% to 90%, depending on the selected technology. The largest potential for energy savings is achieved by high temperature heat pumps of more than 130ºC. Heat pumps have potential in industrial waste heat recovery from steam production and heating processes and in industries which use relatively large amounts of hot water and low pressure steam produced by boilers, e.g. pulp and paper, chemicals and textiles. For this technology, the primary energy savings can reach the value of 50%.

Mechanical vapor compression (MVR) systems are suitable for the dairy sector and have been proved successful in Europe's chemicals industry. Energy savings of 50 to 90% can be achieved by applying MVR systems. Heat transformers have the potential to recover heat from water-cooling systems and are particularly used in the steel production process. Energy savings can be as high as 90%. Finally, the ORC technology can be used to improve efficiency in power stations and for the recovery of geothermal and solar heat. This technology offers low value energy savings of 2%.

7.3.5. High temperature combined heat and power technologies

This is a highly efficient technology for producing energy, offering considerable savings. CHP systems have been employed in a wide range of industrial processes. Industries that most commonly use these systems are chemicals, food and drink, paper, ceramics and bricks. In some industrial sub-sectors, e.g. minerals processing, petrochemicals, bricks and ceramics, use is made of direct heat in the range of 300ºC – 800ºC from CHP systems. However, the potential for this type of application is

Table 7.3. Technologies that utilize waste heat (Ref. 28)

TECHNOLOGY	PRINCIPLE	TEMPERATURE RANGE
Heat pumps (closed vapor compression)	Heat evaporates a liquid that is then re-compressed and transferred to a process by a heat exchanger	High temperature heat pumps >130°C
Heat pumps: MVR	Steam from a process is captured, compressed and then transferred to another process by a heat exchanger	High temperature heat pumps >130°C
Heat transformer	Heat is passed to an absorber/desorber combination	About 150°C
ORC	Heat expands to a spin turbine that drives a generator	70 – 200°C

much greater and could also be developed for other high temperature industries, such as glass, metals and iron and steel.

Another technology used in high temperature combined heat and power is the re-powering of CHP that provides an option where the furnace does not need to be modified, but the combustion air in the furnace is supplied by a gas turbine. The gas turbine can deliver up to 20% of the furnace heat and the exhaust gases still contain a considerable amount of oxygen, which can be used as combustion air for the furnace. Long-term savings, relative to conventional furnaces, are 30%.

The replacement of the existing furnace of the CHP plant, in conjunction with the deliverance of the total heat demand of the furnace by the CHP plant, will offer greater potential for energy savings. This is because the radiative heat transfer from the gas turbine is much less than that from combustion gases.

7.3.6. Combustion techniques and technologies

Developments in combustion techniques/burner technology have allowed the creation of a range of energy efficiency burners. The heat using burners are used in high temperature industry sectors throughout EU countries, such as the iron and steel, glass, brick and tiles, non-ferrous metals and foundries. The process of pre-heating the air used by the burner for combustion offers potential for greater energy efficiency. This can be done through the use of either recuperators or regenerators.

Recuperator is a heat exchanger that extracts heat from the burner's waste gases to heat the combustion air coming into the burner. Burners with recuperators can achieve energy savings of 30%, compared to cold air burners. On the other hand, regenerative burners work in pairs. One of them burns the fuel while the second one stores heat from the waste gases in a porous ceramic bed. Around 85% of waste heat can be recovered in this way, raising the combustion air to temperatures only 150ºC less than the furnace temperature and thus achieving fuel savings in excess of 50% compared to cold air burners.

7.3.7. Adjustable-speed drivers

The use of adjustable-speed drivers (ASDs) offers numerous advantages to drive systems' energy efficiency. They can offer the potential for higher efficiencies, lower operating costs, easier control and minimal maintenance. The most frequently used type of adjustable-speed drivers is the frequency controlled ASDs offering the greatest advantages. They consist of two types: direct and indirect inverters. The first ones convert frequency and voltage in one step, whereas the latter use an intermediary DC link. Some of the savings that ASDs have offered in various projects in Canada, Norway, UK, USA and Netherlands, are shown in Table 7.4.

Table 7.4. Savings due to ASDs (Ref. 28)

SECTOR	APPLICATION	SAVINGS (%)
Metals	Reheating furnace	50
	Fume cleaning	37
Pulp and Paper	Stock transfer pump	65
	Paper pulpier	13
Chemicals and plastics	Cooling water pumps	12 – 30
	Stirrer batch vessel	52
	Boiler fan	63
Food and Drink	Refrigeration	45

7.4. Key technologies used in some energy intensive industries

The cross-sector and sector specific technologies used for improving industry's energy performance have been presented previously. However, a range of energy efficient technologies, processes and developments has also been used in order to reduce energy consumption in energy intensive industries, as well as to promote efficient use of energy and pollution abatement. Some of these achievements are presented in the following paragraphs.

7.4.1. Ceramics industry

The following presented technologies have been focused on improving the energy efficiency of the kiln, which is the most energy intensive part of the ceramic plant.

<u>Preparation of raw materials:</u>

- *Dry grinding and granulation*: In this process, energy savings are resulted from the reduction of the amount of water to be evaporated. Energy and operating costs are much lower than those of wet process. In addition, this process can result in a specific consumption of 2.5 times less than that of wet grinding and spray-drying. Lower manpower, maintenance and investment costs compared to those of wet process, are some of the supplementary advantages.
- *Continuous wet grinding*: This process gives higher slip density and therefore higher energy savings of up to 35% in the subsequent spray-drying phase.
- *Variable frequency inverter installation*: With this process, the grinding cycle can be optimized and reductions between 15-25% both in grinding times and energy consumption are possible.

<u>Drying process:</u>

- *Optimizations of the re-circulation of drying air*: Energy savings result through the control of relative humidity, temperature and flow rate of the process air.
- *Utilization of waste heat*: This technology uses heat exchanging systems at the tunnel kiln cooling zones. A conservative estimation for the potential energy savings in drying through the use of waste heat recovery for each sub-sector is as follows: tiles 10%, sanitary-ware 30%, tableware 50%.
- *Single-layer horizontal roller dryers*: Reducing the drying time to 10 minutes, they offer energy savings of about 20-40% compared to traditional drying methods.
- *Airless drying system*: Steam is used as heat transfer medium, which reduces the drying time and the thermal energy use by 20-50%.

7.4.2. Cement industry

Some of the specific energy efficient technologies used are:

- *Roller mills*: They are used in dry process plants and can result in a total electrical power consumption of 10-15% lower than in a ball mill system.
- *Suspension pre-heater kilns*: These are vertical devices that consume about 3.6 GJ/t, as opposed to long dry kilns (without pre-heater) consuming about 4.5 GJ/t.
- *Pre-calciner*: This is a fuel burner located in the lower part of the pre-heater, where it provides additional heat.
- *High efficiency separators*: These separators have led to increases in mill output of 15% and reductions in specific power use of 8%.
- *Roller press*: This device also leads to higher output and lower specific power consumption of 20%.

- *Variable speed fan drivers*: These fan drivers lead to significant electrical power savings by controlling the air or gas flow, generated by large fans.
- *High efficiency electric motors*: They give a payback period of about 2 years.

7.4.3. Iron and steel industry

Iron and steel plants require large amounts of heat and mechanical work for their operation. In order to reduce the overall energy consumption, the energy that flows in the plant must be well known and understood. Some of the energy efficient technologies used are the following:

- *Thin scrap casting*: It offers energy savings of more than 1-5 GJ/t over the conventional route and since flat products represent about 60% of output in the EU, significant opportunities are available.
- *Energy optimizing process*: It combines simple scrap pre-heating utilizing off gases, together with oxygen and coal injection into a liquid iron bath. This process offers considerable savings by incorporating scrap pre-heating. Additionally, it offers environmental benefits in terms of reduced electricity and reduced greenhouse gases.
- *Corex plant*: This process involves lump ore reduction or sinter to 90% iron. It is estimated that energy savings are 10%-15% that of the conventional blast furnace route.
- *Top gas pressure recovery turbine*: This is one of the most effective energy saving technologies allowing for the high top pressure operation of blast furnaces (up to 2.5 atmospheres) to be reduced to that of the gas boiler with the generation of electricity.
- *Hot stove waste heat recovery*: Through this process, the residual sensible heat comes from the hot stove gases and used for pre-heating both combustion air and flue gas. Energy savings are of 0.08 GJ/tpi.
- *High temperature scrap pre-heating*: The low temperature pre-heaters have caused environmental problems in Europe and are now being replaced by high temperature pre-heaters allowing for energy savings between 0.1-0.3 GJ/tcs.
- *Secondary refining via ladle metallurgy*: It uses a high-powered electric furnace giving energy savings equivalent to 0.05 GJ/tcs.
- *Self recuperative and regenerative burners*: They have a significant effect on energy use in re-heating furnaces and offer potential savings in the region of 65% representing between 0.3-0.7 GJ/tcs.
- *Hot direct rolling*: It involves transferring of hot semi-finished products to a hot mill without undertaking intermediate re-heating. Potential energy savings can be up to 2GJ/tcs.
- *Hot charging*: It involves transferring the stock as rapidly as possible to the re-heating furnace and minimizing the cool-down period. Energy savings of 0.5-1.2 GJ/tcs are possible.
- *Combined cycle power plant*: It gives higher energy efficiency and results in energy savings in the range of 0.5 GJ/tcs.

APPENDIX
COMBUSTION SYSTEM EFFICIENCY METHODOLOGY

Test data

Stack temp: ______________°C (1)
Combustion air temp: ______________°C (2)
%O_2 in flue gas: ______________% (3)
%CO in flue gas: ______________% (4)
Excess air (determined by the diagram A.1): ______________% (5)
Dry flue gas loss (determined by the diagram A.2): ______________% (6)
Hydrogen loss (determined by the diagram A.3): ______________% (7)
Radiation loss (determined by the diagram A.5): ______________% (8)
Carbon monoxide loss (determined by the diagram A.4): ______________% (9)
Unaccounted for loss (usually 1%): ______________% (10)

TOTAL LOSSES:
(Sum of (6) to (10)):______________% (11)
EFFICIENCY = 100 – (11)
= __________%

Note: The diagrams provided below were reproduced from the manual: “Combustion”, *Energy Management Series No 5 for Industry, Commerce and Institutions*, Ministry of Supply and Services, Canada, 1989.

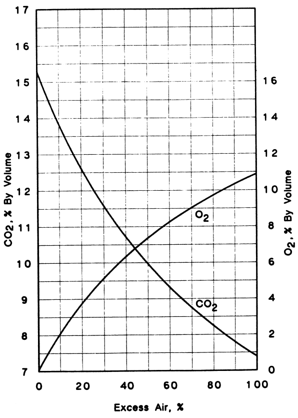


Diagram A.1.
Excess air determination

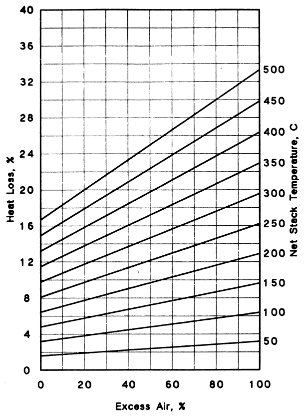


Diagram A.2.
Dry flue gas losses

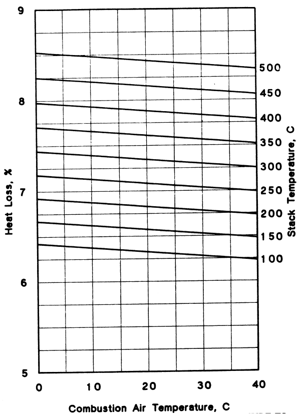


Diagram A.3.
Hydrogen losses

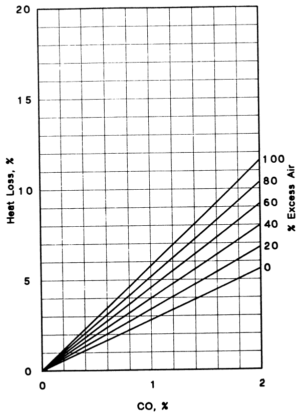
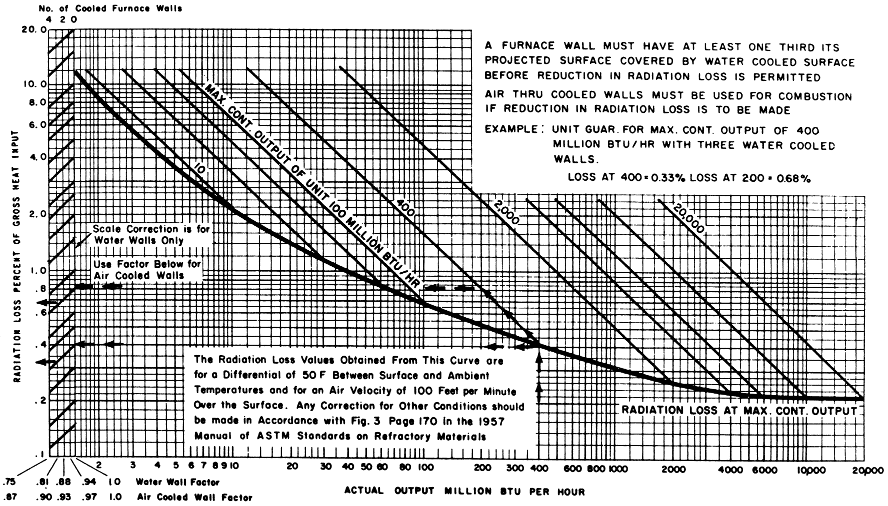


Diagram A.4.
CO losses

RADIATION HEAT LOSS FROM BOILER WALLS



A FURNACE WALL MUST HAVE AT LEAST ONE THIRD ITS PROJECTED SURFACE COVERED BY WATER COOLED SURFACE BEFORE REDUCTION IN RADIATION LOSS IS PERMITTED

AIR THRU COOLED WALLS MUST BE USED FOR COMBUSTION IF REDUCTION IN RADIATION LOSS IS TO BE MADE

EXAMPLE: UNIT GUAR. FOR MAX. CONT. OUTPUT OF 400 MILLION BTU/HR WITH THREE WATER COOLED WALLS.
LOSS AT 400 = 0.33% LOSS AT 200 = 0.68%

The Radiation Loss Values Obtained From This Curve are for a Differential of 50 F Between Surface and Ambient Temperatures and for an Air Velocity of 100 Feet per Minute Over the Surface. Any Correction for Other Conditions should be made in Accordance with Fig. 3 Page 170 in the 1957 Manual of ASTM Standards on Refractory Materials

Diagram A.5. Radiation losses

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