Saving energy with

Energy-Efficient HVAC Systems in Commercial Buildings

Maxi Brochure 04

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CENTRE FOR THE ANALYSIS AND DISSEMINATION OF DEMONSTRATED ENERGY TECHNOLOGIES

CADDET
Centre for the Analysis and Dissemination of Demonstrated Energy Technologies - was founded in 1988. In 1993 CADDET was expanded and now has two branches: CADDET Energy Efficiency and CADDET Renewable Energy. This brochure is a bi-annual publication issued by CADDET Energy Efficiency in Sittard, the Netherlands.

OECD (Organisation for Economic Cooperation and Development)
IEA (International Energy Agency)
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Summary

Approximately a third of all energy used in OECD countries is consumed in non-industrial buildings such as offices and homes. Of this, a considerable proportion is used in space heating and cooling. As buildings become more thermally efficient, energy losses arising from ventilation and air distribution are predicted to become the dominant cause of heating and cooling loss in buildings of the next century. However, since ventilation is essential to good indoor health and comfort, there is a limit to the amount by which it may be reduced as a means of achieving further energy efficiency. As a consequence, innovation in ventilation technology must be regarded as an essential challenge to future energy conservation development.

When implementing energy efficiency measures in a building, either during the design process of a new building or during the planning stage of the renovation of an existing one, it is essential that a proper methodology is applied. Such a methodology must give the user clear indications of whether or not planned measures or designs really will be efficient or if they will affect other parts of the energy system in a building in such a way that the overall saving effects become insignificant, or even become negative. Single subsystems should not be optimised if the result is the deterioration of the total function of all subsystems.

In this Maxi Brochure such a methodology is presented. It describes how a building can be divided into finer and finer levels of complexity and analysed on each level, beginning with looking at the building as a whole. Special emphasis has been put on the heating, ventilating and air-conditioning (HVAC) system. The presentation is meant to give the reader an understanding of how the methodology can be used, rather than a complete detailed description of all parts. The reader who requires a more thorough presentation is advised to read the CADDET Energy Efficiency Analysis Report No. 15 *Learning from Experiences with Energy Efficient HVAC Systems in Office Buildings.*

Energy Consumption in Commercial Buildings

The use of energy in the commercial buildings sector represents a large proportion of the total energy consumption in all CADDET member countries. In Sweden, for example, the use of electricity in the commercial buildings sector is 53% (1992) of the electricity used in the entire building sector, while the use of heat is 27 % [1]. A further division into end-use in the commercial buildings sector shows a great variance between commercial buildings of different categories (hospitals, libraries, offices, etc.). In Figure 1 such a division is shown for a Swedish and a British office building.

Looking separately at each specific category of commercial buildings and comparing the buildings within each category, gives valuable information and good guidance about the energy end-use for a specific building in comparison to the entire building stock. Figure 2 shows the different energy end-uses in a typical and a 'Good Practice' Office (an air-conditioned office building), in the United Kingdom [2].

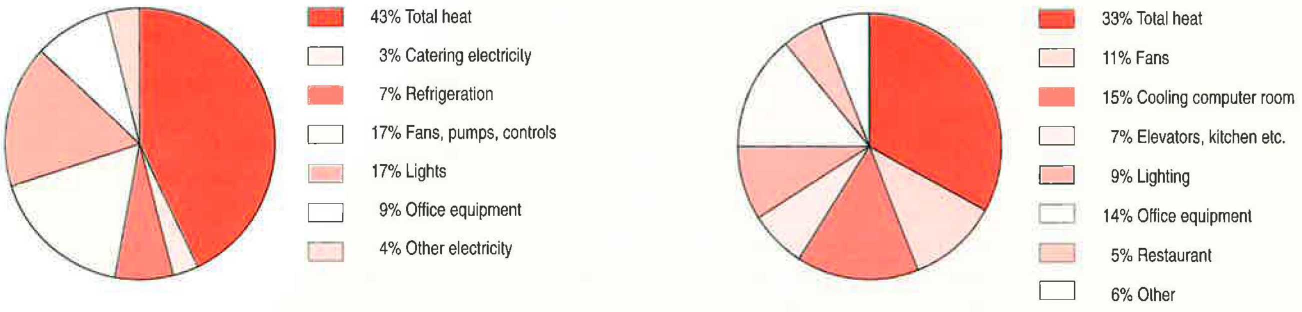


Figure 1: Division of energy end-use for a Swedish (left) and a British (right) office building.

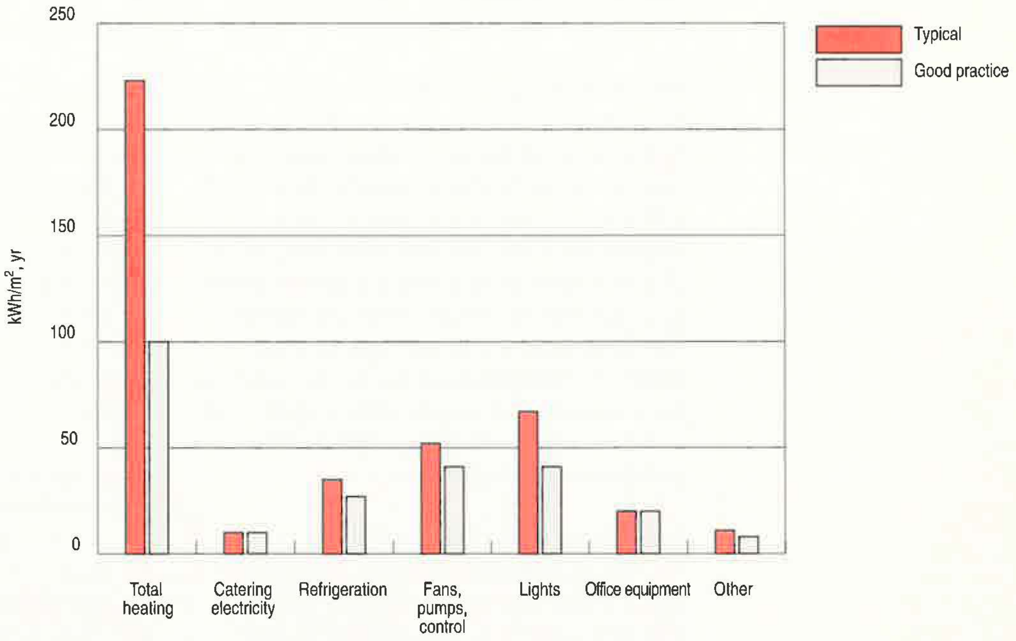


Figure 2: Comparison between a typical British office building and a so-called 'Good Practice' Office Building.

Methodology to Attain Energy-Efficient Buildings

This brochure focuses on a methodology for planning and designing energy-efficient buildings. Although the way of thinking presented is valid both for the building technology-related parts of the building, i.e. the building envelope and the building structure, and for the HVAC systems, the focus here is on the latter. The reason for this is that energy efficiency-related issues form a natural part of the planning process when designing and rating these systems and their components.

One of the two basic components of the methodology is the introduction of a selection of energy-related ratios, *Energy Performance Ratios*, which characterise how specific parts of the building, or specific technical systems within the building, influence the overall energy end-use of the building as a whole. By doing this, the incorporation of a systematic move towards energy efficiency as a routine in the design process is facilitated. However, a prerequisite is that the energy performance ratios can be quantified so that they can be used as targets to be aimed for in the design process.

Hence the second of the two basic components, called *Energy Targets*, are formed to give guidance when quantifying the energy performance ratios. These energy targets are basically predetermined numbers at which the energy performance ratios are to be aimed.

Energy efficiency is simply a question of achieving low energy end-use by efficient utilisation of materials and technology without compromising the primary system objectives. If a building or a technical system within a building has a low need for energy then, subject to certain constraints, the building or the system is energy-efficient. The primary constraints are that measures must be reasonable (e.g. cost effective) in comparison to the energy conservation obtained and that basic requirements, such as the indoor thermal climate or indoor air quality, are not compromised.

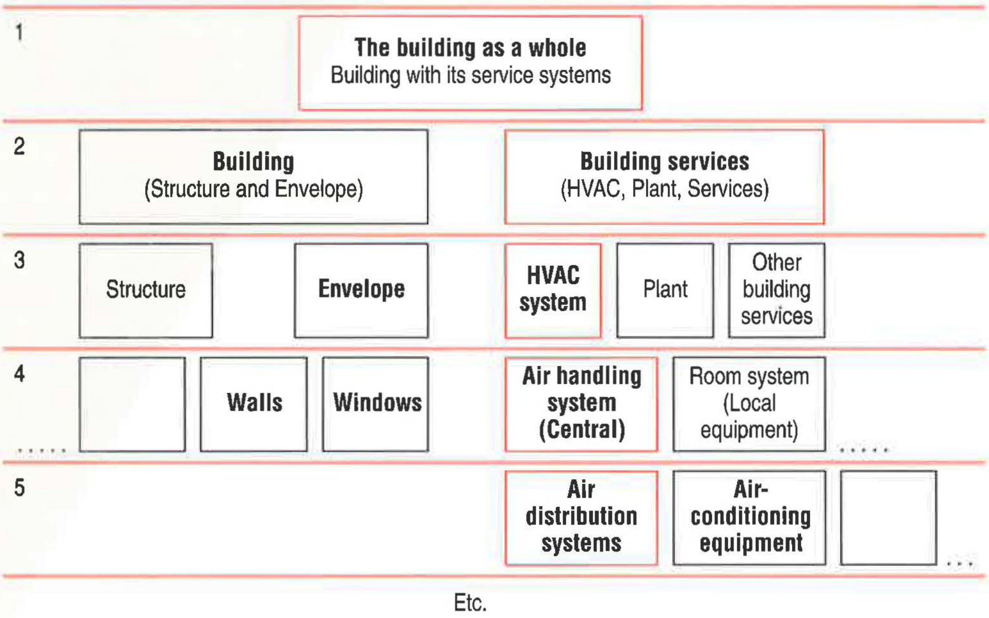
At the planning stage of new buildings or retrofitting of existing buildings, a prerequisite for achieving high energy efficiency is that the resources involved in the measures taken are seriously weighed against the energy conservation gained. In practice, both the resources utilised to obtain certain energy conservation and the achieved energy conservation itself can be quantified in economic terms. Therefore established economic models can be utilised for the assessment of resources and energy gains. Marginal-cost analyses have proven to be most appropriate for this purpose [3].

An assessment of resources sacrificed to conserve energy and the energy gained is, of course, meaningful only if the assumptions made about resources needed and energy saved are realistic. From an energy point of view, a building is quite a complex system. A particular measure taken for energy conservation might influence the building, and the energy end-use of the building, in several ways. This influence, and hence the real energy conservation, might be difficult to foresee without analysing the effect of the measure taken on the energy end-use of the building in question as a whole. Therefore, assumptions about energy conservation gained by a particular energy conservation measure must include not only the conservation potential of the measure itself, but also its influence on the total need for energy when the building is in normal use. This is not only a fundamental prerequisite for obtaining real energy efficiency, but also a prerequisite for achieving energy efficiency in reality.

Consequently, decisions about measures and rating of measures for improved energy efficiency must be based on the energy end-use of the building as a whole. This is achieved by dividing the building, from an energy end-use point of view, into characteristic system parts. The principle is to define the building parts or the technical systems in the building, on different levels, starting from the highest level of complexity, i. e. the building as a whole. This division is schematically shown in Figure 3.

It is possible to select the levels and make the divisions in such a way that parts which may interact from an energy point of view occur at the same level. Thus, when an energy conservation measure is taken within one of the building parts or technical systems, the results must

Figure 3: An example of the division of a building into several levels and systems.



always be examined to see whether any of the building parts or systems on the same level are influenced. Interactions typically occur with systems on the levels above that which is being studied, particularly with regard to the HVAC system. The importance of this examination increases with the complexity of the building in question. The more complex the building, the greater is the risk of sub-optimisation in the building design. However, by correctly defining these levels and placing each building or system component at the appropriate level, this risk is decreased.

Only if it is obvious, and shown beyond any doubt that a certain planned measure is, from an energy end-use point of view, completely isolated from any other part or system of the building, and that the measure has no side-effects on the total energy end-use of the building, can the planned measure be handled individually, i.e. without considering the effects on the building as a whole. Energy conservation measures on the building envelope are typical examples of instances when attention must be paid to the effects of the energy use of the building as a whole. This might seem self-evident but often the building envelope is optimised only with regard to the heat energy losses, without analysing the interaction with the HVAC system.

Energy Performance Ratios

Figure 4 gives an overview of the main characteristic parts of an HVAC system and connected energy performance ratios to be used when analysing such a system with its plant and subsystems. The energy performance ratios are divided into those suitable for design work and those suitable for audit and commissioning. In each case the ratio has to be expressed with respect to a physically measurable quantity. Depending on the specific part, this can either be in the form of a floor area (preferably the floor area of the thermally conditioned or 'treated' space) or the maximum measured air flow rate (as indicated in Figure 4).

Referring back to Figure 3, the energy related to levels 1 and 2 (i.e. the building as a whole and services levels) is both electrical and thermal. As the energy costs relate to the purchased thermal energy supplied to the building (e.g. to boilers) this represents the most relevant energy to use on this level. At the HVAC system and its subsystems levels, the most relevant energy is the electrical energy used by the air and water distribution systems, and the heating and cooling energy used by the equipment. On the other hand, at the air distribution system level, only the electrical energy used by the fans is of interest.

When designing a commercial building and its HVAC system, it is natural to start by defining the relevant standards or requirements for indoor thermal climate, indoor air quality and lighting levels etc. Based on this need, one or more possible HVAC system types should be selected. Each HVAC system and its subsystems can then be designed and rated, followed by the HVAC system plant.

The following section gives details of the energy targets for five different levels (in accordance with Figure 3), which can be found in codes and standards.

		ENERGY RATIO DESIGN	PERFORMANCE RATIO AUDIT & COMMISSIONING
BUILDING & HVAC SYSTEM AND PLANT	Annual Electrical and Thermal Energy:	$\frac{\text{kWh/year}}{\text{m}^2\text{ or m}^3\text{ or kW Cooling load}}$	$\frac{\text{kWh/year}}{\text{m}^2\text{ or m}^3}$
HVAC SYSTEM AND PLANT	Annual Electrical and Thermal Energy:	$\frac{\text{kWh/year}}{\text{kW Cooling load or kW Heating load}}$	$\frac{\text{kWh/year}}{\text{m}^2}$
HVAC SYSTEM	Annual Electrical, Heating and Cooling Energy:	$\frac{\text{kWh/year}}{\text{kW Cooling load}}$	$\frac{\text{kWh/year}}{\text{m}^2}$
AIR HANDLING SYSTEM	Annual Electrical, Heating and Cooling Energy:	$\frac{\text{kWh/year}}{\text{m}^3/\text{s}}$	$\frac{\text{kWh/year}}{\text{m}^3/\text{s}}$
AIR DISTRIBUTION SYSTEM	Specific Electrical Fan Power:	$\frac{\text{kW}}{\text{m}^3/\text{s}}$	$\frac{\text{kW}}{\text{m}^3/\text{s}}$

Figure 4: Summary of the main energy performance ratios to use during analysis.

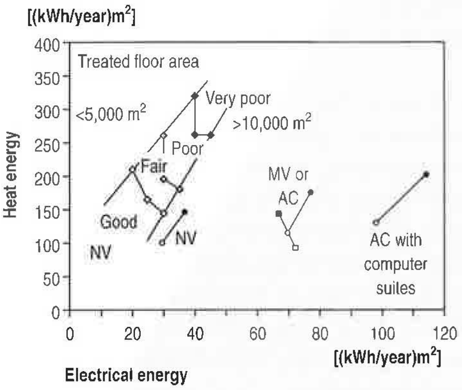
Energy Targets

▼ BUILDING, HVAC SYSTEM AND PLANT AS A WHOLE

This is the highest level in the system hierarchy. At this level the HVAC system with its plant, i.e. equipment for cooling and heating supply, must be seen together with the other building services systems, and the building-related parts, as a whole. The other building services systems include the electrical supply system, lighting, service hot water, etc. The building-related parts are the building structure, building envelope, etc.

Some energy codes and standards have requirements for the maximum annual energy use of the building as a whole. Two of these are the Swiss Building Code [4], and the British CIBSE Building Energy Code Part 4 [5]. The Norwegian Key Number File [6], and the British Consumption Guide for Offices [2], contain recommended energy yardsticks in the form of annual energy use of the entire building.

Figure 5: Maximum allowed and good practice annual electrical and thermal energy use for existing office buildings according to the Swiss Building Code, the British CIBSE Building Energy Code Part 4, and energy yardsticks from the Norwegian Key Number File. The numbers are recalculated to treated floor area according to factors in [2].



Key: Figure 5 & 6

Switzerland
● Maximal allowed annual energy use
○ Good practice annual energy use
Norway
■ Typical annual energy use
□ Good practice annual energy use
United Kingdom
◆; ◇; ◇ Naturally ventilated offices built < 1980 (Figure 5)
◇ Good practice annual energy use (Figure 6)

NV: Naturally ventilated
MV: Mechanically ventilated
AC: Air-conditioned

Related to treated floor area

Figure 6: Maximum allowed and good practice annual electrical and thermal energy use in new office buildings according to the Swiss Building Code, and energy yardsticks from the Norwegian Key-Number File and the British Energy Consumption Guide.

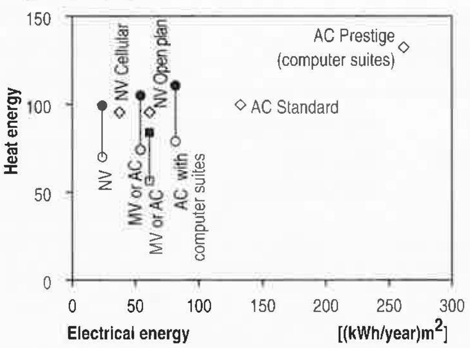


Figure 5 shows the maximum allowed annual electrical and thermal energy use, as well as what is achievable with good practice for existing office buildings, from three of these codes and standards.

The British numbers apply only to existing naturally ventilated office buildings built before 1980. As Figure 5 shows, these buildings have a much higher annual thermal energy use than the Swiss buildings, whereas the annual electrical use is of the same order. The Norwegian values represent buildings from about 1955 to 1970.

For new office buildings the Swiss Building Code also has maximum allowed annual energy usage as well as good practice values. Energy yardsticks for new office buildings are given in the Norwegian Key Number File as well as in the British Energy Consumption Guide. Figure 6 shows the values of the annual thermal energy use and the annual electrical energy use.

Calculation of annual energy costs for the HVAC system and its subsystems can generally be done by hand, although this may sometimes be time consuming. Only when analysing the HVAC system and the building as a whole, are computer-based building simulation programs needed. This is particularly valid when studying the economic impact of time-ofuse electricity rates. The selection of an appropriate design tool is very important. The analysis of all the complex interactions between the building and the HVAC system, as well as the impact of the combination of energy conservation measures on the building envelope, lighting system and HVAC system, normally requires a sophisticated computerised building simulation program. This should calculate temperatures, loads etc. hourly, either for all hours during the year or for typical days for each month. These types of programs are very complex, particularly the input data which tends to become very extensive, thus requiring an experienced user. Good advice for those using complex building simulation programs can be found in Guidelines for Energy Simulation of Commercial Buildings [7]. However, since at the early design stage not much is known of either the building design or the schedules for the use of lighting, miscellaneous equipment etc., the use of a simple design tool is, therefore, more appropriate.

▼ HVAC SYSTEM AND PLANT

Boilers

For boilers in commercial buildings the Swiss Building Code [4] assumes seasonal ratings as shown in Table 1. The ASHRAE Standard 90.1-1989 [8] has the same minimum seasonal rating, effective from 1 January 1992. It states that for gas-fired boilers larger than ≈90 kW, the minimum and maximum steady-state rating capacities are also 80%, whereas for oil-fired boilers they are 83%.

Table 1: Seasonal ratings for boilers according to the Swiss Building Code and the ASHRAE Standard 90.1-1989.

TYPE OF COMMERCIAL BUILDING	SWISS BUILDING CODE SIA 380/1	ASHRAE STANDARD 90.1-1989
Existing - minimum	80%	
Existing - good practice	85%	
New - minimum	80%	80%
New - good practice	90%	

Refrigerant Water Chillers and Air Conditioners

Standards and building codes for refrigerant air conditioners and water chillers have stated minimum requirements since the 70s. This is for both the standard rated coefficient of performance (COP) and the annual seasonal performance factor (SPF), sometimes called the integrated part load value (IPLV). However, as these characteristics are measured in well-defined conditions in accordance with several national standards, requirements from different countries may not be directly comparable. As an example, Figure 7 shows the requirements of COP and SPF in the more recent ASHRAE Standard 90.1-1989.

Table 2: Maximum allowed specific pump power (SPP) recalculated from the CIBSE Building Energy Code Part 1 and the ASHRAE Standard 90.1-1989.

TYPE OF WATER DISTRIBUTION CIRCUIT	CIBSE BUILDING ENERGY CODE, PART 1 SPP [KW/(L/S)]	ASHRAE STANDARD 90.1-1989 SPP [KW/(L/S)]
Hot water heating	1.16	0.30
Chilled water	0.93	0.30
Condensing water	0.47	0.35

A unitary air conditioner is built into the air-handling unit and is usually of the direct expansion (DX) type, whereas refrigerant water chillers deliver chilled water from a central plant, and a special condensing water circuit transfers the condenser heat to a cooling tower or air-cooled water cooler. Electricity use of unitary air conditioners normally includes the electricity for condenser fans, whereas for water chillers, only the electricity to the compressor is included. Hence, the design characteristics of these two types of cooling supply equipment give quite large differences in the minimum requirements of the COP and SPF.

Table 2 shows the maximum allowed specific pump power (SPP) for different types of water distribution circuits recalculated from the CIBSE Code and the ASHRAE Standard.

The values in Table 2 indicate that the CIBSE Code from 1977 gives an SPP of ≈1 kW/(l/s) for hot water heating and chilled water circuits and an SPP of ≈0.5 kW/(l/s) for condensing water circuits. The more recent ASHRAE Standard has increased the requirements to ≈0.3 for all types of water circuits. These numbers give a reasonable magnitude of the energy management ratio SPP to use when designing water distribution systems.

▼ HVAC SYSTEM

Annual energy targets for typical and good practice office buildings taken from Norwegian [6] and British guides [2] are given below. For the British data, the annual total heating energy use accounted for in EEO has been decreased with the normal service hot water annual energy use according to [2b]. Figure 8 shows the annual electricity use per treated floor area for the fans, pumps, chillers, controls, etc., and the annual energy use for space and ventilation air heating.

Figure 7: Minimum requirements, effective from 1 January 1992, on the coefficient of performance (COP) and seasonal performance factor (SPF) for unitary air conditioners and refrigerant water chillers according to ASHRAE Standard 90.1-1989. Standard testing conditions.

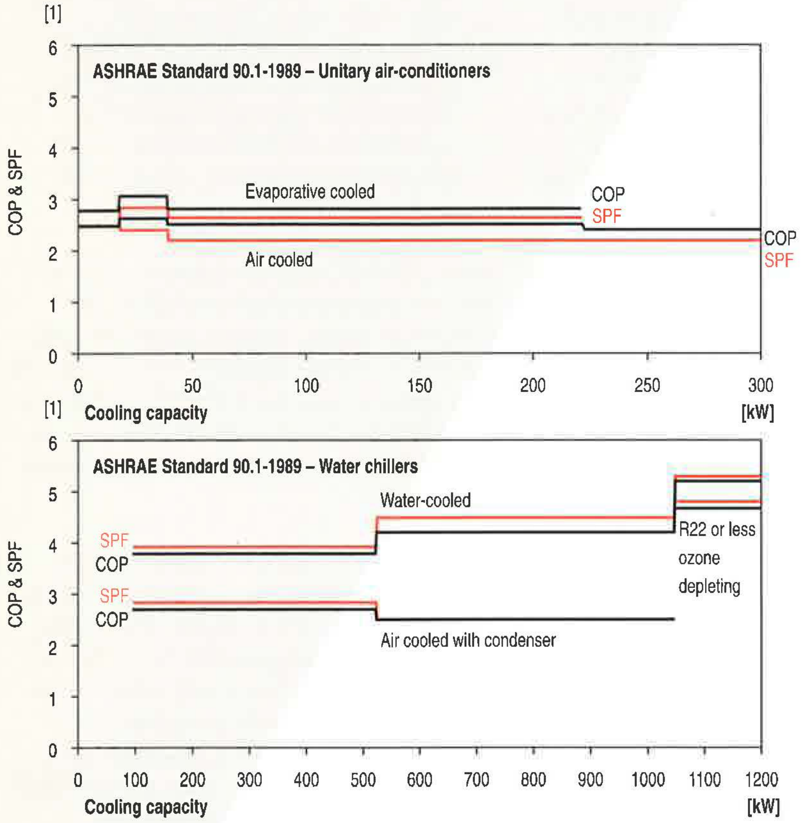
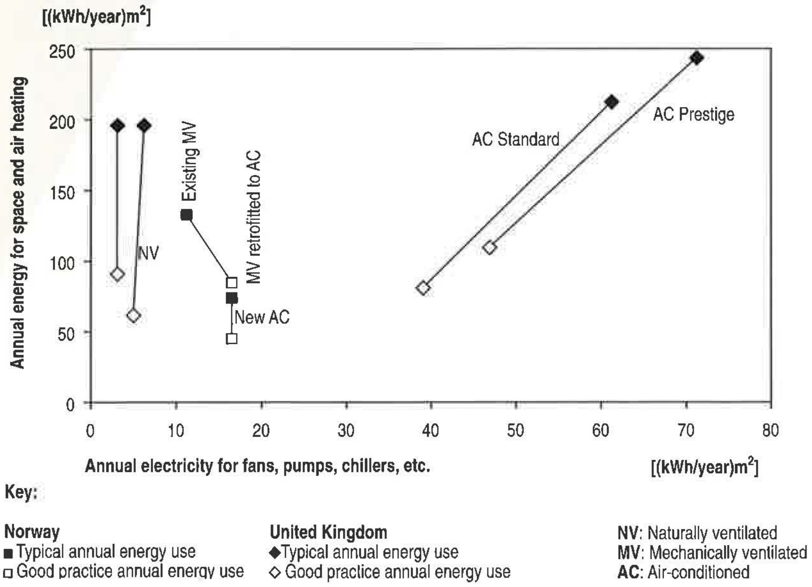


Figure 8: Annual electrical energy use for fans, pumps, chillers, controls, etc., and annual heat energy use for space and ventilation air heating for typical and good practice office buildings in Norway and the United Kingdom.



AIR HANDLING SYSTEM

Air Flow Rate Control

Present codes or standards do not state any requirements on the utilisation time or the utilisation factor. However, the requirements of ASHRAE Standard 90.1-1989 on the specific fan power (SFP) for a VAV system and a CAV system can be recalculated to give a utilisation factor. If the same run time is assumed, the requirements in the ASHRAE Standard 90.1-1989 give a utilisation factor of v= 0.64 for a VAV system.

Air-to-Air Heat Recovery Equipment

Certain building codes have requirements for some kind of air-to-air heat recovery. An example is the Swedish building code [9], which requires that at least 50% of the annual energy needed to heat the supply air is provided via heat recovery from the exhaust air. To ensure this in practice, a design temperature efficiency of 60% of the air-to-air heat recovery equipment is proposed.

Given the traditional American air-handling system layout, the US standards, as well as the British Building Energy Code, concentrate the requirements on the possibility of obtaining a large ambient air-flow-rate fraction in order to utilise free cooling by outdoor air.

The ASHRAE Standard 90-1975 [10], as well as the British CIBSE Building Energy Code Part I [11], require that each fan system (>2.4 m³/s for Standard 90) be designed to use up to 100% of the supply air-flow rate for cooling with outdoor air automatically, whenever its use will result in a lower use of new energy. In the more recent ASHRAE Standard 90.1-1989 the requirements have been changed so that fan systems larger than 2.8 m³/s shall have a temperature or enthalpy air-economiser system which is capable of automatically modulating the outdoor air, and return air dampers to provide up to 85% of the design supply air-flow rate as outdoor air for cooling.

▼ AIR DISTRIBUTION SYSTEM

The lowest level of complexity deals with the air-distribution system. However, regardless of the type of air-conditioning system, the air distribution network is a major component of the HVAC system. In all air systems, as well as in air-water systems based on induction units, fans in the central air-handling unit represent a dominant electrical energy end-use. Even in fan-coil systems, the fans in the room equipment may use a large amount of electricity as they often run non-stop throughout the year, providing both heating and cooling of the air-conditioning equipment.

Examples of two fairly recent standards containing the maximum allowed specific fan power for the air-distribution system are the American ASHRAE/IES Standard 90.1-1989 for new non-residential buildings, and the Scandinavian voluntary *Guidelines for Classification or Air Distribution Systems* [12].

In codes and standards there are two ways of stating the maximum allowed SFP for different types of air-distribution systems, such as constant air volume rate (CAV) or variable air volume rate (VAV) systems, respectively:

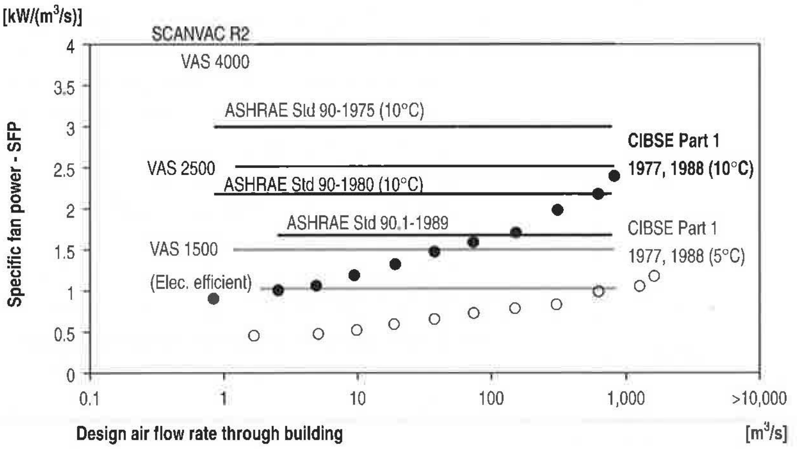
1. SFP refers to design conditions (air-flow rates), as in the American standard. A VAV system can then be allowed to have a higher SFP energy target than a CAV system and still use the same amount of annual electrical fan energy;
2. SFP refers to conditions (air-flow rates) that ideally reflect the average annual conditions, as in the Scandinavian guidelines or the British code. In the former, the same SFP energy target is given for a CAV system at an air-flow rate of 80% of the design. This condition also agrees with the conditions in the British code for a VAV system with a minimum airflow rate of 20% of the design.

In the ASHRAE Standard numeric values of SFP as a prediction criterion are given. As mentioned, design conditions should be used and different values applied to CAV systems and VAV systems respectively. The SFP is defined as the sum of the design power for all fans in the air-distribution systems over the design supply air-flow rate.

The voluntary Scandinavian guidelines have three different ventilation and air-conditioning system (VAS) classes specifying, among other things, different energy targets for the SFP. In addition, there is an "electrically efficient" sub-class within the class with the lowest SFP. Besides the SFP, the VAS denotations can be extended to include, for example, the utilisation factor v or the specific fan energy (SFE). Primarily included in the VAS classes are, principally, requirements for measurability and adjustability, cleanability and airtightness. As mentioned, for CAV systems design conditions should be used, while for VAV systems the SFP should be calculated at an air-flow rate of 80% of the design airflow rate. The air-flow rate used should be the air flow through the building, which in Scandinavian countries is normally the exhaust air-flow rate.

Figure 9 shows a comparison between the requirements of the SFP for a CAV system in the Scandinavian Guidelines and the British Code, as well as in the ASHRAE Standards of various dates. In the British Code, and in the ASHRAE Standards from 1975 to 1980, the so-called Air Transport Factor has been recalculated to an SFP utilising a temperature difference between the supply air and the room air of 10°C and 5°C respectively.

Figure 9: Maximum allowed SFP for CAV systems according to the British CIBSE Building Energy Code Part 1, three versions of the American ASHRAE Standard 90, and the Scandinavian SCANVAC Guidelines R2 (VAS-classes). For the CIBSE Code and the ASHRAE Standards from 1975 and 1980 the so-called Air Transport Factor is recalculated to an SFP, assuming a temperature difference between the supply air and the indoor air of 10°C and 5°C respectively.



Demonstration Projects

AU

Installation of variable frequency drives on air-handling unit fan motors at Royal Darwin Hospital, Australia [13]

An investigation of the chilled water-based air-conditioning system serving the hospital highlighted the large energy cost savings associated with controlling the fan speed on five large air-handling units (AHUs) in the Main Ward Block. All five AHUs are operated 24 hours per day.

At the time of the investigation internal temperature and humidity conditions within the Ward Block were maintained by modulating the chilled water control valve on each AHU in accordance with the highest demand for cooling as signalled by room temperature sensors. Reheat was provided to zones requiring less cooling. Reheat energy was provided in the form of hot water generated by steam calorifiers.

Each AHU also incorporated a humidity sensor in the return air stream to override the temperature sensors should the mean relative humidity rise. Over-cooling and re-heating can be avoided while maintaining humidity control if the air quantity over the cooling coil of each AHU is reduced as the sensible cooling load on the space reduces. This was achieved by installing variable frequency drives (VFDs) on each supply and return air fan motor within each AHU.

Variable frequency drives were installed on eight fan motors with electrical ratings ranging from 7.5 to 45 kW. Total mains duty was measured at 157.5 kW.

Adding VFDs to the supply fan motors of each AHU necessitated varying the return and outside air quantities to maintain space pressurisation. To achieve this, the return air fan speed and the outside air dampers were modulated in response to the same signal controlling the supply fan motor speed. Pressure transducers were also used to ensure positive pressurisation.

A direct digital control (DDC) system was supplied to provide enhanced control of each AHU. Also included in the project were new temperature sensors in each zone, electrical surge diverters for each VFD and software within the DDC to allow rolling starts and automatic restarts of fans after power failures common to the area. Outside air-monitoring devices were installed which enabled the accurate measurement and control of fresh air to each AHU. The speed of each VFD was limited by the DDC to a minimum of 50 % of full speed.

In 1994, control of the air-handling units was integrated into a new building management system installed throughout the hospital.

The variable frequency drives have been in continuous service for periods ranging from three to five years. Reliability of each drive has been excellent. At commissioning a number of malfunctions occurred through lightening-induced electrical surges. This problem has been rectified through installation of surge diverters.

Theoretical analysis of the project indicated that at average heat load conditions, fan speed would be reduced by 42%. Performance monitoring has shown an average reduction in fan speed ranging from 34% to 40%.

The total cost of the project was AUD 119,932.

Direct electricity cost savings resulting from reduced fan electrical load are estimated at AUD 129,000 per annum. Diesel fuel cost savings associated with eliminating reheat are estimated at AUD 181,000 per annum. A further saving estimated at AUD 140,000 per annum resulted from raising room conditions by 1°C.

All savings calculations are based on the 1989 electricity tariff rate and diesel fuel contract price. The electricity tariff rate has since increased by 12.3%.

UK

Variable speed drives on the circulating pumps of an airconditioning system [14]

The air-conditioning system in Terminal B at Manchester Airport, UK, originally comprised 10 chilled water circuits which were served by pumps providing a fixed volume of chilled water irrespective of actual demand. Diverter valves located at each air-handling unit controlled the amount of chilled water used and the excess was bypassed directly to the return leg of each circuit. This case study demonstrates the energy savings which were achieved when frequency inverters were installed to regulate the speed of each pump and thus optimise the chilled water supply to meet the cooling demand of each circuit. The new equipment operated well and maintained a sufficient supply of chilled water despite the extreme temperatures experienced in 1990. In addition to the direct savings made, the effectiveness of the air-conditioning system was improved.

The system comprises a centralised chilling plant with four chillers: one rated at 875 kW and three at 1,750 kW. The smallest chiller is sufficient to meet the load for 7,000 hours/year. The operating pattern of the chillers is computer controlled by the building energy management system. Each chilled water circuit has two pumps - one on duty and one on standby. Outputs range from 2.2 kW to 37 kW, depending on circuit duty, to give a total installed motor rating of 128 kW. Inverters were fitted to nine of the duty pump motors and integrated with the computer control system.

Total energy savings of 2,750 GJ/year were achieved. These were attributable to reduced consumption of the chilled water circulating pumps and the condenser cooling water pump, and to reduced chiller operation.

Total project costs amounted to GBP 49,600. Total energy savings were worth GBP 26,800/year, giving a payback period of 1.9 years. The marginal cost of electricity was valued at 3.5/kWh, which is typical for large users with electricity contracts. For other users, savings may be even greater.

US

New HVAC system for bank operations centre [15]

The HVAC system for a bank operations centre near Detroit, Michigan, USA, was designed and built for reliability and future replacement. The system also had to be easy to expand and maintain. The major emphasis, though, was to design and build an energy-efficient system for a building that would be economical to operate, yet maintain employee comfort.

There are glycol chilled water coils within two centrifugal electric chillers for the building air-handling systems with multiple air handlers that are connected to the supply duct header. The low temperature air is distributed by fans to provide constant air motion for comfort and enhanced air quality. During off-peak utility rate periods, both chillers run fully loaded making ice, which improves chiller efficiency. Only one chiller is allowed to run during peak periods. In the winter, free cooling associated with the ice thermal storage provides the required cooling.

Various speeds are available for all air-handling supply and return fans to meet the conditions of the building. The unit reduces the primary air-flow portion of the constant volume support flow when the temperature in a room begins to fall. Heating requirements are met by hot water coils in the box discharge. A computerised control system decides whether to use ice, chiller, free cooling or a combination of these based upon economy and energy efficiency.

The major mechanical system comprises two 2,042 kW centrifugal electric chillers; 19,000 kWh of thermal storage system consisting of 37 modular tanks; two 1,962 kW low pressure gas-fired boilers; 24 computer room air-conditioning units, and 10 air-handling units.

The chiller plant uses a partial storage approach. Ice thermal storage results in a lower chilled water supply temperature. This allows a lower temperature air supply design. Changing the design of the supply air temperature from 12.8°C to 10°C reduced the required supply air quantity from 180 to 165 m^3/s. This in turn lowered the electrical demand by 130 kW.

The chiller/ice storage system has a total annual cost saving of USD 230,000 compared to conventional HVAC systems. For cooling alone, it is projected that USD 52,752 will be saved annually and as there are no extra building costs involved in this project, there is an immediate payback.

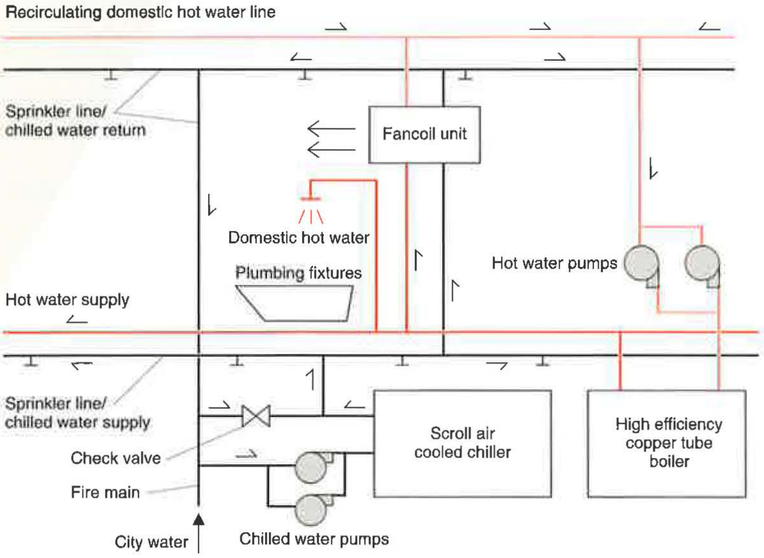
US

Motel HVAC system design incorporates novel combination of technologies to achieve energy savings [16]

An energy study was commissioned by the local electric utility, Montana Power Company, and the Great Falls Days Inn owner to find a cost-effective alternative to through-the-wall air-conditioners with electric heat.

Exterior of Great Falls Days Inn.

Figure 10: Integrated piping system schematic.



The concept used is termed the integrated piping system and combines HVAC and fire sprinkler systems by using the same pipes for both purposes (see Figure 10). Because the integrated piping system is a patented design, an engineering firm interested in using this design on their products should obtain licencing information from HVAC systems, Whitehall, Montana, USA. The integrated piping system is a four-pipe fan-coil system.

The National Fire Code specifically outlines a procedure for utilising the fire sprinkler lines for air-conditioning purposes. As long as all the components connected to the sprinkler lines are rated for the water pressures used in the sprinkler lines, and as long as the system is engineered so that it does not curtail the ability to respond to a fire, it is acceptable by the Fire Code. When a fire causes one of the sprinkler heads to activate, the flow sensor in the incoming water main will be tripped and will activate the fire alarm. The same flow sensor is also interconnected to the chilled water circulating pump and will cause the pumps to be turned off.

All components connected to the domestic water system are compatible with and rated for use with domestic water. This requires the use of bronze pumps, copper tube boilers, and fan-coil units with lead-free fittings and solder.

Utility data indicates that the energy saving for the first year was 74%. In addition, Montana Power Company was able to reduce its peak winter electricity load by 167 kW.

The Montana Power Company provided the motel developer with a USD 40,000 cash incentive to upgrade to the integrated piping system. The total cost of upgrading the facility was around USD 80,000, which left a net cost to the owner of USD 40,000.

The actual net saving in energy costs for the first year was approximately USD 12,000. When combined with maintenance savings of USD 1,950, this yields a 2.9 year payback.

HVAC system using ventilation window and automatic blinds [17]

The TEPCO office building in Tokyo.

A new window system, a ventilation window with an automatic slat-angle control blind, was developed and introduced into the TEPCO Higashi-Murayama Building, Tokyo, Japan. This was constructed as a model building having a heat storage HVAC System designed to provide "energy saving consistent with comfort". The ventilation window consists of double window panes and a slatted blind fitted between the panes. The structure exhausts indoor air, after it has passed between the panes and cooled the blind. The angle of the blind's slats are automatically adjusted in response to the sun's incident angle (see Figure 11).

The new window system improved indoor climate in perimeter zones whilst simultaneously reducing air-conditioning loads. It made use of an all-air HVAC system without the necessity of perimeter air-conditioning units. Taking advantage of this all-air system the thermal storage capacity was doubled without enlargement of storage tanks. This resulted in the reduction of the installed capacity of the HVAC system and savings of energy consumption.

Primary energy consumption for HVAC was 27% less than that of an ordinary office building, saving total electric power costs by 35%. Around 70% of the electric power used by the air-conditioning system is supplied by nighttime power, which is 1/4 of the cost of daytime power.

The building (total floor area: about 10,000 m²) has an air-conditioning system consisting of two air source heat pump/chillers, one with heat recovery, and an air-cooled chiller for year-round cooling. Each is rated at 59 kW. In addition there is a 400 m³ chilled water tank and a 200 m³ hot water tank as thermal storage facilities. The COP of the system is 2.75.

The incremental cost of the windows to include the new blind system was about JPY 17 million, but the costs of HVAC equipment were reduced by JPY 27 million because perimeter air-conditioning units were not needed. A saving of JPY 10 million was made on the initial investment for the overall system. The electricity cost for the whole building in 1990 was JPY 41.5 million. This compares to an estimated JPY 63.55 million for an ordinary office building of the same type, which does not have any energy-saving measures. The advanced HVAC system, together with the new windows, reduced the annual HVAC running costs by JPY 22.05 million - a 35% cut in the total power costs and a saving of JPY 10 million on the initial investment.

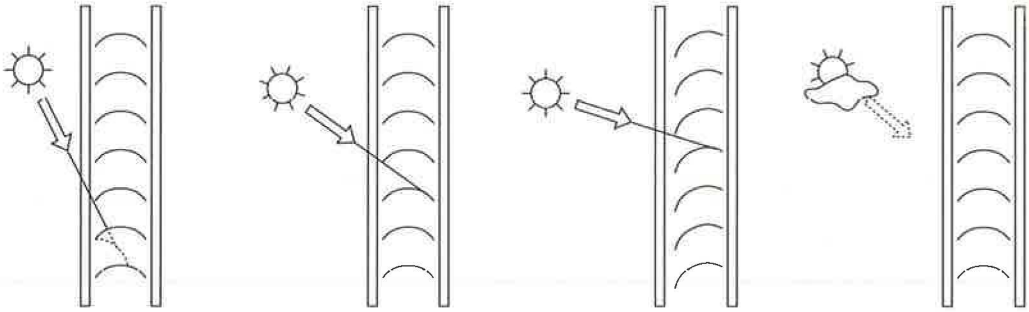


Figure 11: Solar shading by controlling slat angles.

US

Medical centre benefits from utility rebate programme [18]

Dartmouth Hitchcock Medical Center.

The overall design and construction goal of the Dartmouth Hitchcock Medical Center, Lebanon, New Hampshire, USA, was to provide a system that would be energy efficient, provide optimum comfort levels for the occupants, meet code requirements, and maintain system reliability while remaining within budgetary constraints.

Many alternative HVAC systems were evaluated using life cycle cost analyses before determining that a remote central plant would be the preferred option. Summaries of some of the main energy-efficient technologies used are outlined below:

Thermal storage

The central energy plant incorporates an ice storage system comprising 36 ice tanks interconnected to an ice-making chiller. Ice is made during off-peak hours, shifting an estimated 7,600 kW of demand from peak to off-peak periods.

Controls

All HVAC systems at the medical centre are controlled via a direct digital control (DDC) system.

Variable speed drives

Chilled water is distributed to each building within the medical centre in varying quantities adjusted according to the cooling load. Variable speed drives control the three secondary chilled water pumps.

Exhaust system

A variable air volume supply and exhaust tracking system is installed in the research laboratories.

Heat recovery

Heat is recovered from the exhaust airstream via central heat recovery units using glycol recovery coils. The glycol/water mixture is then pumped to the preheating coil of the main supply air-handling unit.

Motors

Energy-efficient motors are used throughout the medical centre complex.

Combining all of these energy-efficient technologies into one state-of-the-art facility has resulted in exceptional savings. Annual energy costs are estimated to be between USD 500,000 and USD 600,000 less than they would have been, had a conventional facility been built. This translates into annual energy savings of 5 to 7.2 million kWh. Peak demand was reduced by an estimated 1,000 to 1,200 kW. The cost of the high energyefficient equipment was about USD 1.5 million. Granite State Electric Company's Design 2000 programme awarded the facility USD 709,000 in rebates. With rebates, the payback for this added efficiency was approximately 1.4 years. Granite State Electric's ratepayers benefit as well because it is more cost effective for the utility to subsidise a portion of the costs of energy-efficiency measures, than it is to build or expand power generating facilities.

Auckland Hospital, New Zealand [19]

The Auckland Hospital Main Building air-handling system has been upgraded in an effort to increase energy efficiency. This has involved the re-balancing of air-flow rates, and installation of an adjustable speed drive for one of the supply air fans.

Energy consumption was not a high priority concern when the air-handling system in the hospital main building was designed and installed around 1973. The original supply fans had been fitted with two-speed motors, which were time-switch controlled to run at maximum speed during the day and at two-thirds of maximum speed during the night. The choice of speeds was very arbitrary and may not have been ideal.

The chosen solution has been the installation of an adjustable speed drive controller for one of the fans. The speed is regulated so as to maintain a constant static pressure within the supply ductwork. The existing controls for the fan were modified so that it would operate at the maximum speed necessary during the day. At night, when the building air quality requirements could be met by one fan alone, the time-switch would switch the fan off completely. During the day this fan now operates at a speed lower than it's previous maximum speed with a resultant energy saving.

In addition, it was apparent that energy was being wasted by heating and cooling large volumes of air to excessively high and low temperatures. The actual space demands were re-evaluated and the volumes of warmed/cooled air have been re-balanced to suit these demands.

The project was monitored for three weeks and the estimated annual energy usage is given in Table 3.

The costs, as shown in Table 4, are based on an electricity price of NZD 0.074 per kWh and a steam price of NZD 0.032 per kWh. The costs to supply and install the variable speed fan drive were NZD 23,900, resulting in a simple payback period of 4 years.

Table 3: Estimated annual energy usage.

	Fans MWH$_{\text{ELEC}}$	Cooling coils MWH$_{\text{THERMAL}}$	eating coils MWH$_{\text{THERMAL}}$
Two constant speed fans	485	3,505	255
Variable speed/constant speed fan	511	3,211	234
Savings	-26	294	21

Table 4: Operation costs.

	Total operation cost NZD/yr
Two constant speed fans	131,000
Variable speed/constant speed fan	124,980
Savings	6,020

Conclusions

The thermal conditioning of spaces accounts for a substantial proportion of the energy consumed in commercial buildings. As a consequence there is enormous scope for reducing energy demand by good design and operation of HVAC systems. In recent times, improvements have become possible as a result of the availability of building energy management systems. Through a network of sensors they are able to monitor the building environment and adapt system operations to meet demand. Such an approach may also be expected to result in capital savings by enabling a reduction in plant size. Careful effort at the design stage almost always results in an immediate cost benefit or, at the very least, a rapid payback period. Benefits are applicable to both new buildings and the retrofitting of existing buildings. In all instances, the primary goal is to ensure a healthy environment in which energy efficiency is balanced against the need to provide optimum indoor air quality and comfort.

For designs to be effective, the various HVAC components, as well as the building itself, must be considered as a coupled system in which each element invariably has an impact on the performance of those adjacent to it. Good design, therefore, must focus on the entire system and on its interaction with the building and its occupants. It must also equate energy-efficiency returns against such factors as capital expenditure, life cycle parameters, maintenance needs and operational costs. The quality of the building envelope also has a significant impact, since an excessively leaky structure will almost certainly destroy the intended performance of HVAC systems. To aid design and to assist in evaluating the interaction between parameters, a variety of analytical tools are available. These range from relatively simple design tools to complex computer-based simulation programs. In practice, the initial stages of design are usually evaluated with simple tools, while the more complex techniques are reserved for special applications.

Several countries have produced energy codes and standards to give guidance on maximum allowed and good practice energy use covering both electrical and thermal energy loads. These provide essential reference levels against which design and operational performance should be judged. In some countries, standards also cover the use of heat recovery systems, conditions for supply air cooling and fan power performance where fan power, especially, often represents a dominant component of electrical use.

Operational patterns frequently take into account electricity tariffs and are optimised to avoid peak load penalties and to take advantage of nighttime electricity rates. This forms an essential part of achieving operational cost efficiency. The challenge is to ensure that cost optimised solutions also deliver improved energy efficiency and can be modified to adapt to tariff changes.

Individual buildings are unique in terms of location, size, occupancy density, operational needs and exposure to outdoor climate. For this reason design solutions must be individually tailored to ensure maximum energy efficiency. The demonstration examples highlighted provide innovative examples of energy-efficient strategies that may be readily adapted to suit individual requirements.

Glossary

HVAC
Heating, Ventilating and Air-Conditioning.

Energy Performance Ratios
Energy-related ratios that characterise how specific parts of the building or specific technical systems in the building influence the overall energy end-use of the building as a whole.

Energy Targets
Predetermined target numbers, at which the Energy Performance Ratios are to be aimed.

COP
Coefficient Of Performance, normally used to describe the momentary performance of heat pumps and chillers.

SPF
Seasonal Performance Factor, normally used to describe the annual performance of heat pumps and chillers.

SPP
Specific Pump Power, a measure showing how much power a pump uses to keep up a liquid flow of 1 litre per second, [kW/(l/s)].

SFP
Specific Fan Power, a measure showing how much power a fan uses to keep up an air flow of 1 m^3/s, [kW/(l/s)].

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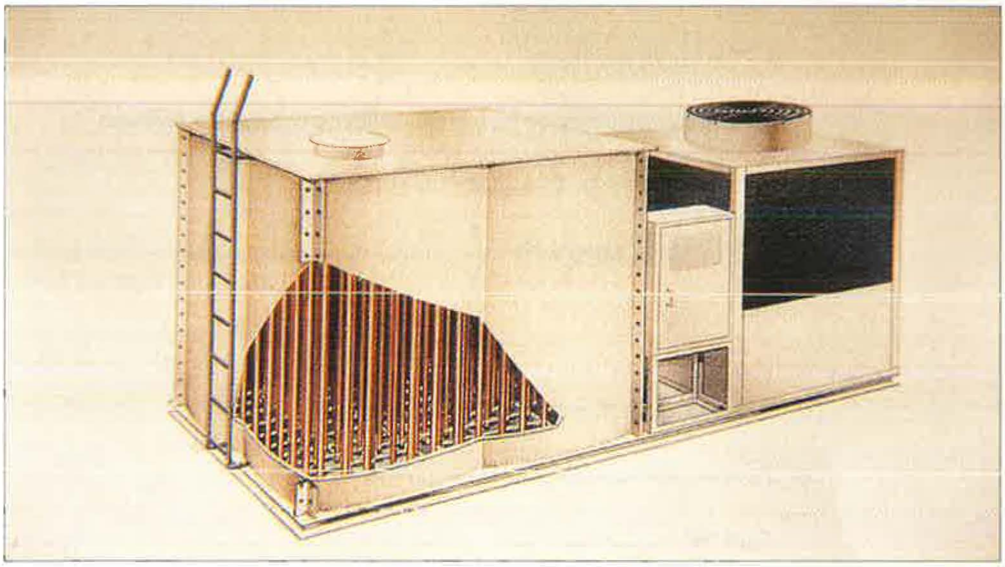

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