A SYSTEM-ORIENTED ASSESSMENT OF ELECTRICITY USE AND EFFICIENCY IN PUMPING AND AIR-HANDLING

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ABSTRACT

Pumping and air-handling account for 30% to 40% of global electricity use. A good understanding of the potential for efficiency improvements in these systems is needed for planning least-cost supply of electricity services. We illustrate the importance of a systems perspective to understanding the full potential for efficiency improvements in pumping and air-handling. Few previous studies estimating potential savings take this perspective. Emphasis tends to be given to modifications to individual system components.

We include a review of the status and development of efficient component technologies (e.g. pumps, fans, motors, variable speed drives, etc.). We also illustrate the importance of system design and operating considerations. New computer software that incorporate economic considerations are important tools for reaching "optimal" system designs.

Based on our own analyses and a review of detailed studies of measured and estimated electricity savings, we conclude that 50% to 75% savings are probably cost-effective in many applications. A key to identifying such savings is thorough and creative examination of individual systems rather than considering generic conservation opportunities (e.g. energy efficient motors) across a broad range of applications. Synergistic effects from conservation measures in pumping and air-handling, and from other conservation measures resulting in, for example, reduced flow rates, are also important to consider.

We discuss a number of barriers to achieving higher efficiency in practice. Future electricity costs are heavily discounted by many users and favour investments with low initial cost. Discount rates used for evaluating new electricity supply are typically much lower. Innovative conservation programs (e.g. undertaken by utilities) can help reconcile the different economic perspectives and capture more of the savings potential. To date, however, most of them have been focussed on components (e.g. motors) rather than system-wide improvements. Programs that encourage system-wide modifications are more likely to lead to the large electricity savings which appear technically and economically feasible.

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1. INTRODUCTION

Pumping and air handling account for a large portion of total global electricity consumption. Pumps in the United States have been estimated to account for 43% of all electricity used in motors, or 24% of national electricity consumption [1]. In Sweden, air-handling consumes perhaps 10% of all electricity.[1] More precise estimates of pumping and air-handling electricity use are available at the individual factory or building level, based on detailed measurements and surveys. In two kraft pulp mills in Sweden, pumping and air-handling were measured to account for 41-46% and 14-20% of total mill electricity consumption, respectively [5]. Energy audits in the US on a variety of commercial and multi-family residential buildings indicate that air-handling can account for 30% to 50% of total building electricity use (Fig. 1).

Improved efficiencies of pumping and air-handling systems could have an important impact on current and future electricity needs. How much can efficiencies be improved cost-effectively? Most efforts to answer this question have focussed on the use of energy-efficient motors and variable speed drives [6,7,8,9]. With the exception of Baldwin's work [10], few studies have effectively addressed the potential for reducing electricity use in pumping and air-handling through system-wide modifications.

We present here detailed systems analyses and economic assessments of pumping and air-handling and draw on recent measurement-based case studies to illustrate the importance of a variety of systems considerations in addition to motors and drives: other components in the system, interactions between the components, the system design process, potential process changes that would reduce the need for the service provided by the system, and others. We also discuss some important barriers to

[1] This is our estimate of electricity use in air-handling, excluding that used for heating and cooling within air-handling systems. It is based on: (a) 5% of national electricity use in Sweden for air-handling in the buildings and light manufacturing sectors [2] (which appears consistent with estimated electricity use in air-handling in the commercial sector of the US--10% [3] to 18% [4] of sectoral electricity use or 2.5 to 4.5% of national consumption); and (b) 5% of national electricity consumption in the energy-intensive process industries, obtained by extrapolating a measurement-based estimate for pulp and paper mills in Sweden [5].

improving system efficiencies in practice.

Our work is motivated by the scarcity of systems-oriented studies on pumping and air-handling that provide useful data and analyses for individuals with relatively broad energy planning and analysis responsibilities, e.g. electricity conservation program leaders at utilities and in government, industrial managers responsible for energy, and other energy analysts. Our analysis here draws partly on the first volume of a recently initiated publication designed for such users, ***The Technology Menu for Efficient End Use of Energy*** [11].[2] The Menu is designed as a "first-stop" source of technical and cost data and analysis relating to a wide variety of existing and advanced energy end-use technologies. Each 10-page entry in the Menu is authored by experts and peer reviewed before publication to insure a consistently high quality of information.

2. REVIEW OF PREVIOUS STUDIES

Comprehensive assessments of pumping and air-handling electricity use and efficiency for planning purposes are sparse in the literature. The majority of relevant studies focus on electric motors and variable speed drives, understandably so, since electric motors are the single largest electricity consuming device in the world, and saving electricity through speed control has been facilitated by the rapid evolution of power electronics. To help put our own analyses in context, we begin by reviewing previous estimates of the technical potential for saving electricity in motor-drive systems generally, including some estimates for pumping and air-handling.

One of the earliest efforts to quantify electricity use in motors and pumps [1] is still widely quoted in the literature today. The overall objectives of the work were to

[2] In particular, we draw on the following entries in the Menu volume entitled **Movement of Material** : "Air-Handling Systems" and "Fans" by J.B. Graham, "Ducting" by R.J. Tsal and H.F. Behls, "Piping" by N.P. Cheremisinoff, and "Liquid Pumping Systems," "Electric Motors," Adjustable Speed Drives," and "Pumps," by L.J. Nilsson and E.D. Larson.

develop standard motor and pump classifications and to evaluate the practicability and likely effects of implementing minimum efficiency standards. The study estimates the technically achievable efficiency improvement (cost-effectiveness considerations aside) of the motor and pump populations existing in the United States in the mid-1970s. The improvement estimates ranged from 18% for motors smaller than 1 kW to 0.3% for motors larger than 94 kW.[3] For pumps, the range was from 50% improvement for units smaller than 1 kW to 2% for pumps larger than 94 kW. The electricity use-weighted savings potential across all sizes was estimated to be 2.3% for motors and 4.2% for pumps (Table 1). The study noted that because the effects of pump wear with use could not be quantified, the pump savings estimate was probably conservative. In addition, little effort was made to assess pump oversizing, except to note that an estimated additional savings potential of 10% could be achieved if all throttling losses could be reduced in pumping systems (20% average savings applicable to half the current pumping electricity use). This estimate was based on "many knowledgeable, sources," but no additional substantiation was provided since analysis of throttling losses was considered outside the scope of the study.

The principal objective of a 1981 study [7] was to examine the potential energy savings and economic benefits from the use of advanced power conditioning and controls, including variable speed drives (VSDs). The report provides a thorough review of the development and status of power semi-conductor devices, but estimates of potential electricity savings with VSDs appear less thorough. For industrial pumping, the study estimates that 20 to 25% savings are technically achievable on average where throttling can be eliminated, based on the estimate in [1] discussed in the previous paragraph. This is combined with an unsubstantiated estimate that 60% of industrial pumping installations are suitable for VSDs, which gives an overall technical savings

[3] These estimates are consistent with findings of a more recent study [6] focussing on energy efficient motors in Canada.

Table 1. Estimates of possible electricity savings in motor-drive applications, including pumping and air-handling.[a]

Study author	*Percentage Savings*
#1. US Department of Energy [1]	
Savings as % of existing electricity use in indicated applications in the USA	
Energy-efficient motors (EEMs)	2.3%
Improved efficiency pumps	4.2%
All throttling losses in pumping systems (e.g. using VSDs)	10%
#2. Stanford Research Institute [7][b]	
VSD savings as % of existing electricity use in indicated applications in the USA	
In industrial pumping systems	12-15%
In industrial blowers and fans	15-18%
In pumps in commercial central refrigeration systems	25%
In fans in commercial central refrigeration systems	30-35%
#3. Rocky Mountain Institute [8][c]	
Total drivepower savings as % of current motor electricity use in the USA	28-60%
Of which:[d]	
EEMs	7-10%
Electrical tuneups	1-13%
Controls	12-24%
Mechanical tuneups	2-5%
Indirect effects	5-8%
VSD savings as % of total sector drivepower:[e]	
Residential	18-28%
Commercial	16-31%
Industrial	10-23%
Electric utility	21-45%
#4. Barakat & Chamberlin, Inc. [13]	
Total savings in commercial sector ventilation in the USA	30-50%
Total savings in industrial motor drives in the USA	29-45%
#5. Norgaard, et al. [14]	
Optimization of pumping systems in Denmark	70%
Optimization of ventilation systems in all sectors in Denmark	85%

(a) All estimates shown here include consideration of both the savings potential in applications where savings are possible and the number of such applications. For example, see note (b).

(b) The industrial pumping estimate assumes 20-25% savings on average in installations where throttling occurs (based on the USDOE [1] estimate discussed in the text) and that 60% of all pumping installations are throttled. The number for blowers and fans is based on 30-35% average savings where throttling occurs and throttling in 50% of all applications. Virtually all central refrigeration system fans and pumps are assumed suitable for VSDs, with the indicated average savings percentages.

(c) Estimates include all end-uses, not only pumps and fans.

(d) The EEM estimate includes motor rewinds and correcting oversizing. Electrical tuneups include, for example, phase balancing, correcting power factors, improving local power quality and voltage stability, and reducing in-plant distribution losses. Controls include variable speed drives, power factor controllers, idle-off savings and compressor-only fast-controller savings. Mechanical tuneups include, for example, using improved belts, gears, bearings, lubricants, and cooling, cleaning and maintenance practices. Indirect effects include, for example, reduced resistance losses in distribution wiring and HVAC savings from reduced internal heat gains to buildings.

(e) The VSD savings percentages are higher than those shown for "controls," because the former are estimated assuming no other improvements. If other improvements were made, the scope for savings using VSDs would be reduced.

potential of 12 to 15% (Table 1).[4] For pumps and fans in commercial central refrigeration systems and for industrial blowers and fans the estimated savings potentials (Table 1) are also presented without substantial supporting data or analysis.

To date, perhaps the most comprehensive and up-to-date review of drivepower technology and potential electricity savings is a 419-page publication prepared at the Rocky Mountain Institute [8]. Based on a variety of literature sources, the study's authors estimate the technical savings potential in the US of retrofitting VSDs and energy-efficient motors (EEMs) and by electrical and mechanical tune-ups. The savings from retrofitting EEMs is estimated to be 7 to 10% of current electricity use in motors. Control modifications, including use of VSDs, are estimated to save 12 to 24%. VSD savings by sector were also estimated, as shown in Table 1. (Specific estimates for pumping and air handling are not presented in [8].) The total US retrofit drivepower savings potential (considering the motor and drive only) is estimated to range from 28% to 60% of current electricity use in motors. The study also estimates the average cost of saving electricity to be 0.5 ± 0.15 cents per kWh. Despite the relatively high savings potentials estimated, the report concludes that potential savings in motor-driven systems (including downstream components) are probably larger than the savings in the drivetrain itself.

Two other studies consider a broader system perspective. In a recent study [13], the maximum technical potential savings (all end-use equipment replaced overnight with best available technology) are estimated for all electricity uses in the US in the year 2000 (Table 1, #4). For the industrial sector, the achievable savings are estimated to range from 29 to 45%, using only EEMs and VSDs. For the commercial sector, ventilation electricity use is estimated to be reducible by 30 to 50% through a variety of system modifications (use of variable air volume systems, low-friction air distribution

[4] A recent major energy conservation assessment [12] further propagates the USDOE [1] estimate by estimating potential savings from VSD use in the industrial sector to be 22.5%, based on [7].

designs, EEMs, VSDs, heating, cooling and lighting efficiency improvements, and proper operation and maintenance). No economic constraints were considered. The study indicates that the savings estimates are based on an extensive review of literature sources. Aside from a bibliography, however, no specific supporting data or analyses are given in the report.

A second systems study [14] presents a theoretical analysis of how potential system-wide modifications could reduce pumping and air-handling electricity use in Denmark. The analysis includes some reduction of flow rates, which arise as a synergistic benefit from other conservation measures. Nationally, 70% and 85% savings are estimated to be technically achievable in the long term (20-50 years) in pumping and ventilation, respectively (Table 1, #5). For ventilation, average savings of 96% in commercial sector applications, 84% in the industrial sector, and 55% in the residential sector are estimated. Economics are not considered explicitly in the study. However, all modifications are assessed as beneficial with respect to the environment, energy security and societal economics, and only commercially available technologies were considered.

Three observations about Table 1 seem particularly worth noting. The studies that include some consideration of improvements in addition to EEMs and VSDs (#3,#4,#5) report much higher total drivepower savings potential, indicating the importance of a broader systems perspective. Among studies taking a systems perspective, there is a wide range in savings estimates, reflecting the dearth of data from which to develop reliable estimates. Finally, only one of the studies (#3) provides a quantitative estimate of the cost of saving electricity (a remarkably low average of 0.35 to 0.65 cents per kWh saved). The scarcity of cost estimates also reflects a lack of data.

3. ASSESSING COST EFFECTIVENESS

The level of electricity saving that is cost-effective in practice will vary with the economic criteria applied. As background for subsequent cost comparisons in which we consider different economic perspectives, therefore, we discuss cost-effectiveness measures and discount rates.

3.1. Analytical Measures

We refer to four cost-effectiveness measures in this paper: (1) simple payback; (2) net present value or life-cycle cost, (3) internal rate of return, and (4) cost-of-saved-electricity.[5] In general we consider only capital and electricity costs associated with an investment. Our calculations assume that costs other than these, as well as benefits, both of which are often difficult to quantify, are the same for two alternative investments providing the same energy service.

Probably the most widely used measure is the simple payback time (SP)--the initial capital expenditure divided by the anticipated electricity cost savings in the first year. The SP involves no discounting of future cash flows or consideration of energy price changes beyond the first year.

A measure that does consider future cash flows and energy costs is the life-cycle cost (LCC) or net present value (NPV)--the sum of all cash flows associated with an investment over its lifetime. The levelized or annualized-LCC is an equivalent comparative measure. Calculating the LCC or NPV requires specification of a discount rate and future energy prices.

A measure related to the LCC and more commonly used in industrial practice is the internal rate of return (IRR). The IRR is the discount rate that causes the LCC to be zero, i.e. at which the discounted savings in electricity costs equal the required

[5] See [15] for detailed explanation of how we calculate each.

capital outlay.

The cost-of-saved-electricity (CSE) is calculated as the annualized non-electricity portion of the life-cycle costs divided by the anticipated annual electricity savings. The result has units of dollars per kWh saved. The CSE is typically used to compare the cost of an energy-efficiency investment against the cost of additional electricity supply.

Each of the four measures are useful in different situations. The SP is the simplest to calculate. It is often used in industry investment decisions, particularly for smaller projects, and is relied on heavily for initial screening of projects [16]. Companies typically demand a SP of less than 3 years for smaller investments and investments aimed solely at cost reduction, including those in energy efficiency. Unlike the SP, the NPV takes into account the value of money over time and expectations of future energy prices. This measure is not widely used in industry, however, because it does not account for capital constraints [17]: in considering two competing investments, the one with the highest present value, i.e., that which will generate the largest absolute return, could be chosen if there were no constraints on capital availability. The use of SP, IRR or CSE implicitly reflects such capital constraints and the resulting priority demand for high percentage returns rather than high absolute returns. In general, the economic ranking of alternative investments can differ depending on the economic indicator used.

3.2. The Discount Rate

The discount rate is an important parameter in assessing the cost-effectiveness of conservation investments since it determines how future cash flows (or energy savings) are valued. The discount rate can be regarded as the opportunity cost of capital, i.e. the cost for borrowing capital or the rate of return on the best alternative investment. Alternatively the discount rate can correspond to a required rate of return on capital--a "hurdle" rate of return.

Discount, or hurdle rates used in industry vary widely--10% to 40% [17] or higher [16]. In industry, the particular hurdle rate used is typically determined by corporate policy and access to capital. Based on a detailed survey of 400 energy related projects at 15 large industrial firms in the US, Ross [16] distinguishes between firms that strictly ration capital and those with more flexible budgeting practices. For the rationing firms, investment hurdle rates are in the range of 35-60% (in current dollars) for small projects (up to $1 million), 25-40% for medium-sized projects ($1-10 million), and 15-25% on large projects (over $10 million). For the flexible-budgeting firms, the hurdle rate for projects of any size is essentially the cost of capital to the firm (14-17%). Many firms require higher rates of return on non product-related, discretionary investments, such as in energy efficiency. Typical payback times of 1 to 3 years for investments in energy efficiency are reported [17,18,19], corresponding implicitly to discount rates of about 100-30%. Rates of return typically demanded (explicitly or implicitly) on conservation investments in the commercial and residential sectors are commonly higher than in the industrial sector [20,21].

For utility investments in new electricity supply, a real discount rate in the range of 4-6% is common for utilities in industrialized countries [22,23] and 10-15% in developing countries (e.g. see [24,25]). These relatively low discount rates reflect the long-term average cost of capital to electric utilities.

In subsequent analyses we use a 6% real discount rate to represent a social or electric utility perspective and 20% for the private or industrial perspective.

4. COMPONENT TECHNOLOGIES

As background for subsequent discussion of system design and operation, we review here the major component technologies in pumping and air-handling systems. We give brief technology overviews and some cost-effectiveness calculations.

4.1. Electric Motors

Electric motors account for an estimated 50% of all electricity use in industrialized countries [8] and 60-70% of industrial electricity use [4]. The most widely used type is the induction motor. Others include synchronous, universal, and direct current motors. Induction motors can be single or polyphase and are available in sizes from megawatts down to fractions of a watt. The majority of motors are small, but the majority of motor electricity use is in larger units [1,26].

Efficiencies of standard polyphase induction motors vary from about 70-75% for a 1-kW motor to about 92% for a 150-kW motor and up to 95% for 200-kWs and larger (Fig. 2). A number of manufacturers market energy-efficient motors (EEMs) [27], as defined by the National Electrical Manufacturers Association (NEMA) in the US. EEMs have efficiencies 5-10 percentage points higher than standard motors in small sizes and 2-3 percentage points higher in larger sizes. The price premium on EEMs also varies with motor size (Fig. 2). Maintenance costs on EEMs are generally no greater than for standard motors and may be lower: some data suggest longer lifetimes for insulation and lubricants due to lower operating temperatures [28].

Although motors are considered a relatively mature technology, continued development of advanced materials [10] and design tools (e.g. CAD/CAM) can be expected to help improve motor efficiencies further. For example, the use of permanent magnets (PMs) instead of rotor windings results in lower rotor losses, offering the possibility of achieving higher efficiencies [10,29,30,31] (Fig. 2) and greater compactness. To date, PM motors have been used mostly in small power and special applications. With the development of new magnetic materials, applications for PM motors can be expected to grow to include larger sizes. Incorporating superconducting (SC) materials into a motor could, in theory, reduce losses by 1/3 to 2/3 [32]. However, the time frame for developing SC motors is much longer than for the other materials discussed here.

In new applications or where existing motors have finished their useful life, EEMs will often provide cost-effective electricity savings, even where annual operating hours are relatively short or electricity prices are relatively low. This is illustrated in Fig. 3 by the cost-of-saved-electricity calculated for different motor sizes (based on Fig. 2) for 6% and 20% discount rates and for 3000 and 5000 annual operating hours.

4.2. Variable Speed Drives

The use of variable speed drives permits continuous regulation of shaft or motor speed. This alternative to throttling for partial load operation leads to electricity savings, since input power to many pumps and fans varies with the cube of flow, while flow varies directly with speed. Speed regulation can be classified as: mechanical (e.g. gearboxes and adjustable pulleys), hydraulic (controlling slip between input and output shafts), or electronic. In general, mechanical drives have limited performance, and their bulk makes them unsuitable for many retrofits. The traditional bulkiness of hydraulic drives and high losses at low speeds also restrict their use.[6]

Electronic variable speed drives are growing rapidly in popularity since they can be controlled more precisely, have higher efficiencies, require less maintenance and are becoming less costly. Direct current (DC) motors are commonly used in industrial applications for speed control where simplicity and a high degree of precision are important. Their wider use is restricted by safety, reliability and maintenance concerns (all associated primarily with mechanical commutation) and relatively high cost. Because of the limitations of DC systems much effort has been focussed on the development of AC systems.

Rapid advances in semiconductor technology and microelectronics have made AC variable speed drives (VSDs) increasingly more attractive during the last decade. AC drives can be used with both induction and synchronous motors and are relatively

[6] There is some development work ongoing on compact hydraulic couplings that require no more space than the coupling on the motor shaft [33].

easily retrofitted since they do not have to be placed close to the motor. Most AC drives vary speed by controlling the frequency of input power to the motor.

A variety of VSD designs are available for different applications [8,9,34]. Efficiencies of VSDs are high (90-98%) at full and partial load, but tend to drop at light load. Aside from energy savings, VSDs offer benefits such as longer equipment life due to smoother starting, less noise and wear, and better control. Research is ongoing in the areas of electronic switching devices and microelectronics-based control methods that promise improved performance of VSDs and expanded ranges of application [34].

VSD equipment and installation costs vary over a wide range depending on the specific requirements of the application. Estimated 1986 list prices are shown in Fig. 4a. The cost of VSD components today are estimated to be 7-12% lower than in 1988 [35], primarily as a result of increased production volumes and technological developments. Actual purchase prices are lower than list prices since VSDs are nearly always discounted [9]. Fig. 4b compares estimated 1986 list prices against estimated 1990 as-purchased prices. Further cost reduction seems likely. For example, work on integration of the control and power electronics into the same chip promises reduced production costs for low-power VSDs.

The overall economics of VSD use are very case-specific. The percentage electricity savings, annual operating hours, and assumed discount rate are all important parameters in determining cost-effectiveness. This is illustrated in Fig. 5, which shows the percentage electricity savings required to achieve a cost-of-saved-electricity of 5 cents/kWh with different sized VSDs (using cost data from Fig. 4), assuming 4000 to 8000 operating hours.

4.3. Pumps

Our discussion of pumps focusses on the most common type, the centrifugal pump. Three-quarters of all pumps in the US are estimated to be of this type and to account for 90% of all power consumed in pumping [1].

Energy losses during pumping lead to heating of the fluid and the pump itself (Fig. 6). Design-point efficiencies of centrifugal pumps range from less than 50% for small pumps up to 85% or higher for large pumps. Improving pump efficiencies has not been a high priority among pump manufacturers, particulary with smaller pumps, reflecting a general lack of customer concern about high efficiency. Reliability, price and a tendency to stick to one supplier to minimize spare parts inventories and simplify maintenance have been more important to customers [1].

There appears to be some potential for improving average pump efficiencies, however. More precise manufacturing methods producing smoother impeller-blade and casing surfaces could yield efficiency improvements of 50% in pumps smaller than 1 kW [1,36] and 2% in pumps larger than 94 kW [1]. In addition, higher shaft speeds, leading to higher specific speed,[7] can improve efficiency in low-specific-speed centrifugal pumps by several percentage points [37]. Simply selecting pumps more carefully can provide a large difference in efficiency. For example, Fig. 7 shows pump efficiency versus specific speed for a sample of small (< 8 kW) pumps sold in Sweden. (The spread in efficiencies is similar to that found with larger samplings [1].) The two highlighted pumps are identical except for an 8 percentage point efficiency difference [38]. The difference in list price for the two pumps is $15 (about 1%).

This example also suggests that there currently may be little correlation between purchase price and efficiency. Except in a few industries, users may not fully appreciate the importance of the energy costs of operating pumps, so vendors are not motivated to differentiate models by efficiency. Greater user interest in efficiency would probably lead to more such differentiation and to a closer correlation between

[7] Specific speed (N_s) is a correlating parameter which combines flow ($Q, m^3/s$), outlet pressure head (H, m) and rotational speed (N, rpm) into a single number: $N_s = (N*Q^{0.5})/H^{0.75}$. Generally, higher specific speed gives higher efficiency.

price and efficiency. One study [1] estimates that a 20% increase in pump production cost would produce a 10 percentage point efficiency improvement in small pumps (< 4 kW) and up to a 2-3 percentage point improvement in larger pumps (> 40 kW). For many pump applications, a 20% higher cost would be paid back rapidly assuming such efficiency gains.

4.4. Piping and Fittings

A large fraction of the electricity input to a pumping system is typically needed to overcome hydraulic resistances due to pipes and fittings. The magnitude of the resistances depends on fluid properties, dynamics of the operation and the physical characteristics of the equipment. The first two of these factors are important, but relatively process-specific, so we focus here on the latter.

In a straight section of pipe, pressure loss is related to pipe diameter and surface roughness. Energy use is proportional to pressure drop. For turbulent flows, the pressure drop varies inversely with the fifth power of diameter. Thus, for a given volume flow rate, energy requirements will fall significantly with increasing pipe diameter. Of course, larger diameter piping is more costly per unit length. This implied cost trade-off is discussed further in Section 5.1.

The relative surface roughness[8] of the piping affects friction losses and thus pumping energy requirements. For a 5-cm diameter pipe, a relative roughness of 0.001 corresponds to commercial steel. Cast iron pipe has a relative roughness of 0.005, corresponding to more than a 50% higher pumping energy use to overcome pressure loss. Deposit buildup (fouling) can increase wall roughness and reduce the effective diameter with time.

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[8] The relative roughness of a pipe is calculated by dividing the absolute roughness (a characteristic of the pipe material and method of manufacture) by the pipe diameter (see [39]). This measure is then used to determine an empirical friction factor used to calculate pressure loss.

Hydraulic resistances in valves, bends and fittings also contribute to friction losses. The head loss in valves and bends is directly proportional to empirically-determined loss coefficients, the magnitudes of which vary substantially depending on design and function. For example, a 90° smooth bend has a loss coefficient that can vary by a factor of 2 depending on the relation between bend radius and pipe diameter. For a fully open ball valve it can vary by a factor of 4 depending on the design [40]. Thus, careful selection of piping components, and attention to interactions between them that can generate additional pressure losses [41], can help reduce pumping energy demand.

4.5. Fans

Fans are major energy users within air-handling systems. For example, in ventilation systems, typically 20-25% of the electrical energy input is lost in the fan itself (Fig. 8). The principles of operation are similar to those of pumps. They are characterized by fan performance curves which refer to particular fans operating at fixed speeds (see Fig. 9). A simple set of fan laws are used to calculate the characteristics of a fan operating at other than its rated speed.[9]

Two basic categories of fans are centrifugal and axial fans. The former category includes airfoil, backwardly-curved blade fans and forwardly-curved blade fans, which are used for general heating, ventilating and air-conditioning (HVAC) applications. These fans can generally be used interchangeably. The other centrifugal fans (i.e.

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[9] The performance of geometrically similar fans of other sizes or the same fan operating at other speeds can be calculated from the fan laws:

(1) $TE_c = TE_b$

(2) $Q_c = Q_b * (D_c/D_b)^3 * (N_c/N_b)$

(3) $TP_c = TP_b * (D_c/D_b)^2 * (N_c/N_b)^2 * (d_c/d_b)$

(4) $P_c = P_b * (D_c/D_b)^5 * (N_c/N_b)^3 * (d_c/d_b)$

where TE is total efficiency, Q is flow rate, D is wheel diameter, N is fan rotational speed, TP is total pressure at the fan outlet, P is input power, d is gas density, and subscripts b and c refer to base and calculated quantities, respectively. For a given fan and fluid, Equations 1, 2, and 3 would be simplified, since wheel diameter and gas density would be constant.

radial, modified radial and pressure blower fans) are typically used in heavy-duty industrial applications, for example where foreign materials pass directly through the wheel. Vaneaxial and tubeaxial fans are used in general HVAC applications as well as more specialized applications like exhaust systems and drying ovens. Vaneaxial fans have straightening vanes downstream of the wheel which result in a less turbulent, more uniform discharge air distribution than with tubeaxial fans. Propeller fans are typically used for low pressure applications as, for example, moving air without ductwork through a wall.

Peak efficiencies range from 60-83% for centrifugal fans and 45-85% for axial fans, depending on the specific design (Table 2). The best fan efficiencies have not changed much over the last decade. The elimination of small imperfections imparted during the production process, e.g. sharp edges and rough seams, could improve fan efficiency by 1 or 2 percentage points, but would involve much higher production costs [42]. Fan users generally place a higher premium on lower cost than high efficiency. Under these market conditions research and development work on fans is largely aimed at reducing production costs, not on improving efficiency. Efficiency may nevertheless be improved by better installation and system-design practices, so that the performance of installed fans comes closer to design ratings [42].

It is difficult to present reliable cost data for fans since the price paid by installers is typically given on a job-by-job basis. In general, retail fan prices increase with efficiency. For example, the price of backwardly-curved blade fans in Sweden has been estimated to be about 15% higher than for forwardly-curved blade fans [43]. The modest extra cost would buy a significant increase (10 to 20 percentage points) in efficiency (Table 2). Such an investment would probably be cost-effective in all but very short annual operating-time applications.

Table 2. Estimated maximum peak efficiencies for different fan designs [42].

	Peak Efficiency Range
Centrifugal Fans	
Backwardly curved/inclined	79-83
Airfoil	79-83
Modified radial	72-79
Radial	69-75
Pressure blower	58-68
Forwardly curved	60-65
Axial Fans	
Vaneaxial	78-85
Tubeaxial	67-72
Propeller	45-50

4.6. Ducting

The majority of energy used in ventilation systems goes to overcome losses arising from friction between the air and the duct walls and from changes in direction and/or flow area due to dampers, bends, filters, inlets, outlets etc. (Fig. 8). In a typical duct system, the majority of losses occur through the latter elements [2].

The pressure loss in straight ducts and through flow disturbances (bends, dampers, etc.) is proportional to the inverse of the diameter raised to the fifth power and to the fourth power, respectively. Since the power required to overcome pressure losses is directly proportional to the pressure loss, power input falls dramatically with increasing diameter. Thus, simply choosing one standard-size larger duct diameter can produce large reductions in energy requirements. Also, the pressure loss in a round duct is lower than in a rectangular duct with the same cross sectional area.

Duct surface roughness also affects pressure losses. The absolute roughness of a smooth aluminum duct is 15 times less than for a fiberglass duct. The energy requirement for the fiberglass duct would be nearly twice that for the aluminum duct.

Careful selection of bends, fittings, and other flow disturbances can help greatly reduce ducting losses. For example [44], the pressure loss in a smooth 90° turn (elbow) in a rectangular duct is about half of that for a mitered elbow. By adding a splitting vane in the smooth elbow, the pressure loss would be 25 times lower than in the mitered elbow.

The economics of alternative ducting designs are discussed in Section 5.2.

5. PUMPING AND AIR-HANDLING SYSTEMS

Combining the components discussed in Section 4 into pumping or air-handling systems optimized for efficiency is a complex task. The details of specific applications are important, and typically a large number of trade-offs are involved. Computer programs can often facilitate the analysis. We present some simplified analyses to illustrate the impact of key technical and economic parameters on system performance and lifecycle costs.

5.1. Pumping systems

Typically much less than half of the electricity input to a pumping system is converted into useful movement of the fluid (Fig. 10). Inefficiencies in the pump and motor/drive and friction from piping and fittings account for the balance. The main components of a typical pumping system -- pump, motor/drive, piping and valves -- have been reviewed earlier. Here we concentrate on understanding system design considerations, including the interactions among these components and how overall system efficiency can be improved.

Head-flow curves

Pumping system electricity use and savings potential can be understood in terms of basic design and operating principles derived from head-flow curves. Fig. 11 shows a set of such curves for a variable-flow variable-pressure pumping system equipment layout (Fig. 12)[10] using a centrifugal pump. The pump curve shows for a fixed speed the possible operating points defined in terms of volume flow rate, discharge pressure, and corresponding efficiency. The system curve indicates how the required head (pressure) at the pump outlet increases with flow due to increasing downstream friction in the system.[11] The actual operating point of the pump is identified by the intersection of the pump and system curves.

Traditionally a throttle valve is used to change the operating point. Fig. 11 illustrates how the system curve shifts with throttling to create the "throttled operating point." The pump continues to operate at the same rotational speed (100% speed curve), but it operates less efficiently. Input power requirements are somewhat reduced.[12]

In most pumping applications, the throttle valve will be partially closed most of the time, e.g. where the pump is oversized for the application or when flow requirements change continuously with time (Fig. 13a). In these cases, controlling flow by changing the speed of the pump or modifying the impeller, instead of throttling, can reduce electricity use substantially. Changing the pump speed or trimming the impeller moves the pump curve so that it intersects the unthrottled system curve at the desired new operating point (Fig. 11). The difference between the throttled operating point and the new operating point represents the throttling losses, or the potential savings. The pump efficiency can be higher at the reduced speed point than at the throttled point, providing a synergistic benefit.

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[10] The variable-flow variable-pressure system is the most common of three general types of pumping systems. The others are constant-flow variable-pressure and variable-flow constant-pressure [45].

[11] For turbulent flow the fricitional pressure drop is proportional to the square of the volume flow rate. The system curve in Fig. 11 indicates a pressure head of 12.5 m of water at zero flow. This represents the static head due either to an elevation change in the particular system used to construct this figure, or in a fixed static head requirement for proper system control.

[12] Power input is calculated as the product of pressure (kPa) and flow (m^3/s) divided by pump efficiency.

Fixed-Flow Systems

In the original design of many constant-flow pumping systems, the pump and motor are oversized relative to the actual pumping need in order to hedge against uncertainties in predicting required flow rates, system friction losses, future pipe fouling, future process changes and the like [10,46]. Once installed, the pump output is then throttled to achieve the desired operating point.

A simple exercise based on the pumping system described by Fig. 11 can help illustrate the potential for improving the efficiency of such fixed-flow systems. Assuming reasonable component efficiencies, a typical overall efficiency of the system when operating at the "throttled operating point" might be 16%, e.g. see [47] and Table 3 (base case). The largest losses arise through the pump and piping and from throttling. A few percent of the base-case electricity input could be saved by using an energy-efficient motor or a more efficient pump (Table 3).

Much larger savings are possible by eliminating the throttling loss. Savings would be about 1/3 of input electricity (Table 3). This can be achieved by installing a smaller pump, a new impeller, or by trimming the existing impeller. If the full existing capacity is needed, e.g. for meeting peak demand, a multi-speed motor or VSD could be used.

About 60% of input electricity could be saved by increasing pipe diameter by 25% in addition to implementing the improvements discussed above (Table 3). The system characteristics would be altered significantly in this case (Fig. 11), enabling a smaller motor and pump could be used.

The modifications considered in Table 3 could be made as retrofits or designed into new applications. The discussions in Section 4 relating to the economics of improved motors, pumps, and VSDs give a rough guide as to the expected cost-effectiveness of these measures, depending on operating hours, electricity costs, and economic parameters. In the case of reducing throttling losses, if a smaller pump or a

Table 3. Hypothetical energy savings with indicated efficiency improvements to a fixed-speed pumping system (adapted from [10]).

Component	Base[a]	---------- MODIFICATIONS INVOLVING ---------				
		Motor[b]	Pump[c]	VSD[d]	ALL[e]	+ Pipe[f]
Speed Change	--	--	--	95	95	95
Electric Motor	92	94.5	92	91	93.5	93.5
Pump	77	77	80	79	82	82
Throttle Valve	66	66	66	--	--	--
Piping	35	35	35	35	35	56
Total Efficiency (%)	16.4	16.8	17.0	23.9	25.5	40.8
Percent electricity saved over base-case		2.4	3.5	31.4	35.7	59.8

(a) The base-case pumping system is assumed to be that indicated in Fig. 11, operating at approximately 80% flow (at the point designated "throttled operating point"). The flow and head at the operating point are approximately 86 m^3/s and 60 m, respectively. A 75 kW motor is required. Motor and pump efficiencies are assumed based on [27] and [38]. Piping efficiency is assumed to be the ratio of static pressure at zero flow to total head less valve losses [10]. Losses in the motor and pump shaft coupling are neglected.

(b) Based on [27] for an energy efficient motor.

(c) Based on [38].

(d) Based on [10,34], assuming use of a VSD, which eliminates the throttling valve. The motor efficiency is assumed to be reduced compared to the base case due to VSD harmonics. With the VSD, the pump is assumed to operate closer to its optimum efficiency, so pump efficiency is better than in the base case.

(e) Assumes use of a VSD and improved pump and motor. Motor efficiency is reduced 1 percentage point due to VSD harmonics.

(f) The pipe diameter is assumed to be increased by 25%. In this case, a smaller capacity motor, pump, and VSD (about 45 kW) could be used compared to the 75-kW base case. We have assumed pump and motor efficiencies for the 45-kW units would be the same as for the 75-kW unit.

new impeller could be used rather than a VSD, the economics would be more favorable. The cost for a new impeller might be roughly 20% of the cost for a VSD [18]. Trimming the existing impellers would be less costly still.

The especially large potential savings shown in Table 3 from piping modifications warrants some additional discussion. Modifications to existing piping have been recommended for some situations [48]. Major retrofits might often be complex, though not necessarily uneconomic. Because of the large potential electricity savings, the evaluation of alternative piping arrangements is routinely undertaken for new industrial designs. The final design of a piping system is typically arrived at by a trial-and-error analysis of the trade-off between energy and capital costs for different pipe sizes and materials. The specific application puts some constraints on the analysis, e.g. design flow rates, choice of pipe material, peak capacity requirements, need for backup pumps, etc. The calculation usually yields an "optimum" pipe diameter, which minimizes some economic criterion. Various design procedures have been developed to calculate this diameter [40,49,50].

A number of cost-related factors can be included in the analysis: capital costs for pipe, pump, motor, drives, valves and support structure and required return on investment, taxes, insurance, etc. Which considerations are actually included in practice depends on the accounting conventions of the firm and the degree of complexity involved in a more complete analysis. The calculated "optimum" diameter (and associated electricity use) can depend on which costs are included. In many cases, the analysis is arbitrarily limited to consideration of only the pipe capital costs and operating and maintenance costs [39].

Table 4 shows illustrative results for an optimum-diameter calculation for a variable-flow water piping application in Sweden. Electricity use varies by a factor of 10 with a doubling of pipe diameter (150 mm to 300 mm). If only piping and electricity costs are included in the analysis, then the lifecycle costs are at a minimum for a pipe diameter of 200 mm (Fig. 14a). If pump/motor costs are also included, the optimum diameter shifts to 250 mm (Fig. 14b), and electricity used is halved.

The cost of electricity and discount rate assumed for the calculation are also important. Fig. 14c shows the total lifecycle piping-plus-electricity cost for electricity at 3.5 to 6.5 cents/kWh. The optimum diameter increases with the electricity price, as expected. Also, with a fixed electricity price of 3.5 cents/kWh, decreasing the discount rate from 20% to 6% moves the optimum pipe diameter from 200 to 250 mm (Fig. 14d).

Table 4. Input data for the optimum pipe diameter calculation summarized in Fig. 14.[a]

Pipe diameter (mm) ----->	125	150	200	250	300	350	400	500
Friction loss (m)[b]	204	77	20	6.5	2.8	1.8	0.9	0.3
Total head (m)[c]	299	118	36	17	11	10	8.6	7.7
Maximum power (kW)	377	148	46	21	14	12	11	10
Electricity use (MWh/yr)[d]	2056	809	251	114	78	67	59	53
Equipment capital costs (10^3 $)[e]								
Piping	37	48	72	98	132	159	208	277
Motor and Pump	188	74	23	10	7.1	6.2	5.4	4.9
TOTAL	225	122	95	108	139	165	213	282

(a) From [33] for pumping water over a distance of 500 meters with flow rates varying from 20-90 liters per second.

(b) For 90 l/s flow, assuming piping with absolute roughness of 0.2 mm and the sum of loss coefficients due to fittings, bends, etc. of 8.

(c) Includes elevation change of 6 meters and friction losses adjusted from the 90 l/s values for variable flow.

(d) Assuming 6500 operating hours per year, throttle flow control, and motor/pump efficiency of 70%.

(e) The pump/motor costs include reserve units and their associated plumbing. The reserve equipment accounts for 60% of the indicated pump/motor cost. Costs were converted from 1988 Swedish kronor (SEK) to US dollars using an exchange rate of 6.5 SEK/$.

It is interesting to note that for all cases in Fig. 14 the diameter which minimizes lifecycle cost shifts with changing assumptions, but the lifecycle cost curve is relatively flat in the region of the minimum (between 200 and 300 mm). Since electricity consumption over this range varies by more than a factor of three, if electricity conservation were an important design criterion, the larger diameter could be chosen with virtually no effect on lifecycle cost.

Variable-Flow Systems

In a second category of pumping applications, required flow rates vary with time. In these applications, substantial electricity savings are often possible by continously adjusting pump speed using a VSD rather than a throttle valve. The actual electricity savings at any operating point can be determined from head-flow curves for the system and pump and efficiency curves for the motor/drive system. Fig. 11 can be used to illustrate the magnitude of possible savings.

The 100% speed curve in Fig. 11 refers to a pump rated at 75 kW to pump a maximum of 108 liters/sec through a pressure head of 55 m. The calculated electricity requirement for different flow rates with throttling or VSD control is shown in Fig. 15. With throttled operation, the input power falls modestly with reduced flow, because the effect of flow reduction is greater than the combined effects of outlet pressure rise and pump efficiency decrease (see footnote 12).

The lower curves in Fig. 15 assume pipe diameter is increased by 25%. The input power falls to about half at 100% load compared to the case with the smaller diameter pipe. Applying the duty cycle shown in Fig. 13a to the input power requirements calculated in Fig. 15 would result in electricity savings from VSD operation of 41% and 37% for the systems with the larger and smaller piping, respectively.

Conservation supply-cost curves are shown in Fig. 16 for this illustrative case. When no piping modifications are made, the efficient motor and pump would provide a small portion of the savings at the lowest cost (Fig. 16a). The VSD would provide most of the savings at higher cost. The total electricity savings in this case, about 150 MWh/year, is about 44% of the original system's electricity use. Using a 25% larger pipe diameter would save the largest amount of electricity and would also lower the capital costs for the motor, pump and VSD, since smaller units could be used. The costs for the piping change have not been assessed here, since they would be highly dependent on the specifics of the application. The piping change also reduces the scope (and slightly raises the cost) for electricity savings through use of the VSD and efficient motor and pump (Fig. 16b). Overall, the changes considered here would save nearly 2/3 of the electricity used in the original system.

5.2. Air-Handling Systems

The design of a particular air-handling system and how it is operated affect the amount of electricity it consumes to meet a certain air-handling service. Of course, the absolute demand for delivered air also impacts energy use. A number of factors not directly associated with the air-handling system determine the demand for delivered air: internal heat gains, level of insulation, required air changes per hour, etc. In seeking to reduce air-handling energy use, overlooking such factors in favor of improved component efficiencies will in many cases lead to underestimates of the possible electricity savings. We focus here on system design and operation. Section 6 includes one case study showing the importance of indirect factors.

Fan and System Curves

Fan and system curves are similar to those used to characterize pumps and pumping systems. A fan will operate at highest efficiency within a limited range of volume flow and corresponding delivery pressure (Fig. 9). System curves show the pressure/volume-flow relationship for the system (Fig. 17), including the effects of ducting, dampers, and other resistances. For best efficiency, the fan is selected so that the system curve intersects the fan curve in the region of peak efficiency.

Fixed-Flow Systems

In constant-flow air-handling applications the improvements that can be made to overall energy efficiency are similar to those for fixed-flow pumping, e.g. appropriately sized and more efficient fans and motors. In applications involving significant ducting of the flow, e.g. as in building ventilation systems, the largest potential for savings is in ducting modifications.

The opportunities for cost-effective ducting system modification are obviously greatest for new construction. Popular traditional design methods, including equal friction and static regain [51], provide engineers with expedient tools for design. However, since using these methods involves some engineering judgment and extensive manual calculation and recalculation, an air distribution system designed by different engineers typically results in different duct sizes, costs, and overall system energy demands [52]. A number of computerized optimization methods are now being developed to improve the design process. Among the most useful of these methods appears to be the T-Method, which can be used to design duct systems such that lifecycle costs are minimized [53,54,55]. Unlike traditional design methods, the T-Method balances pressures throughout the system by simulating duct size changes rather than use of less efficient devices like dampers. It also considers economic criteria, which traditional methods do not.

Table 5 shows results of T-Method and equal-friction method design calculations for alternative duct materials and electricity prices for a hypothetical ducting system of approximately 185 meters total length. Using the T-method, a different level of electricity use and duct surface area results for each combination of electricity price and duct material cost. Differences in lifecycle cost for the equal-friction designs in Table 5 are due only to changes in the electricity price and unit cost of ducting--not different duct surface areas or electricity use. Table 5 suggests that cost-effective electricity savings of 20% to 40% might typically be achieved over systems designed using traditional methods, when electricity prices are 2 to 8 cents/kWh. Savings as high as 60% are technically feasible, but would be cost-effective only with higher electricity prices.

Variable-Flow Systems

Many large industrial applications have variable flow demands (e.g. boiler fans), as do many heating, ventilating and air-conditioning systems for large commercial and/or residential buildings (Fig. 13b). In these cases, the flow control method used

Table 5. Lifecycle costs of T-Method and equal-friction method designs for a hypothetical ducting system, assuming different electricity prices and duct materials [54]. The indicated cost savings are for the T-Method design relative to the equal-friction design.

Electricity Price ($/kWh)	Duct material & installed cost ($/m^2)	Lifecycle cost (10^3 \$)[a]		Lifecycle cost savings (%)		
		Equal-F.	*T-Method*	*Total*	*Capital*	*Elect.*
11.88	Spiral (33)	30.9	16.2	48	-9	57
11.88	Stainless (128)	50.9	40.0	21	-5	26
8.52	Galvanized steel (41)	25.7	16.3	37	-9	46
7.26	Insulated galv. (55)	26.3	19.1	27	-7	35
4.83	Aluminum (43)	18.8	14.2	25	-6	31
2.40	Spiral (33)	11.9	9.8	18	-3	20
2.03	Spiral (33)	11.1	9.4	16	-1	17
2.03	Stainless (128)	31.1	27.3	12	17	-4
1.89	Spiral (3)	10.8	9.2	15	0	15

(a) The calculations assume a 6% discount rate, 3.1% real escalation in electricity price, 10-year amortization, fan efficiency of 75% (operating) and 85% (peak), and motor efficiency of 80%.

can be among the most important factors affecting energy use [56]. This is illustrated by a comparison of flow controlled by an outlet damper and by fan speed variation. These cover the least to most efficient control options. An important intermediate to these is the use of variable inlet vanes (VIVs), which throttle flow more efficiently than outlet dampers.

Outlet dampers are analogous to throttling valves in pumping systems. Changing the damper position creates a new system curve (Fig. 18a). Since the fan operates at a constant speed independent of damper position, the change in input power follows the original fan characteristics. Fan efficiency moves sharply away from its peak. Changing fan speed creates a new fan curve (Fig. 18b). Since fan efficiency remains approximately constant when fan speed is changed and input power requirements change with the cube of flow, this is far more efficient than damper control. When permanent speed changes are required, e.g. for after-installation adjustments in a constant-flow application, speed change is usually accomplished by changing pulley sizes. In variable-flow installations, variable speed drives can be used.

Heating, ventilating, and air-conditioning (HVAC) systems for buildings are important applications where flow control can save electricity. Two major categories of HVAC systems are constant-air-volume (CAV) and variable-air-volume (VAV). In a CAV system, the volume of air supplied to a space is kept constant and its temperature is raised or lowered to meet changes in heating and cooling demand in the space. In a VAV system, the volume of air supplied to a space is varied to follow load changes in the space. A VAV system can require as little as half the electricity of a CAV system to meet the same space conditioning demand [57]. How much less electricity is needed depends largely on the flow control method used.

6. SAVING ELECTRICITY IN PUMPING AND AIR-HANDLING

We now discuss a number of detailed studies of measured or estimated electricity savings illustrating the practical realization of a number of the efficiency improvement possibilities discussed in previous sections of this paper. We have organized this section around issues chosen to highlight the importance of a systems approach to identifying the full efficiency improvement potential in specific pumping and air-handling applications.

6.1. Variable Speed Control and Efficient Motors

The potential for saving electricity cost-effectively using energy efficient motors and/or variable speed drives has been widely noted [7,8,9,10,58], but there have been relatively few measurements made to identify potential applications compared to the overall installed capacity of pumping and air-handling systems. Many more measurement-based studies like the few we describe here are needed to fully understand the extent to which such savings levels can be generalized.

Measurements on four boiler fans at a pulp and paper mill in Sweden [59] indicated a total savings potential of 50% by replacing variable-inlet-vane (VIV) control with VSD control, at an average cost-of-saved-electricity of 1.7-3.0 cents/kWh (Table 6). Because of the variable load on the existing fans, they were operating at relatively low energy-use-weighted efficiencies--ranging from 27 to 43%. The study also indicated a 12% savings could be achieved at a CSE of 1.3-2.3 cents/kWh by replacing existing damper control on four drying-hood circulating fans with variable-inlet vane control. With VSD control the savings would be 20% at a CSE of 2.5-4.4 cents/kWh.

In another study, detailed measurements were made to determine the savings from converting two VAV air-handling systems from VIV to VSD control in a 12,000 m^2 commercial office building in New Jersey, USA [60]. The building VAV systems operate approximately 3000 hours per year. Electricity consumption was measured for several months before and after retrofitting VSDs to the four fans in the VAV system (106 kW total capacity). The resulting annual savings were 35% of pre-retrofit consumption. The calculated cost-of-saved-electricity (CSE) (assuming a 15-yr lifetime) was 3.4 cents/kWh for a 6% discount rate and 7.1 cents/kWh for a 20% discount rate. If the building were one with longer annual operating hours (e.g. a hospital--8760 hours), the CSE would be 1.4-2.9 cents/kWh.

Another study of a VSD retrofit to a boiler fan at an automobile manufacturing facility in the United States indicated cost-effective annual electricity savings in excess of 60% [61]. At another facility, VSD control of a machining-coolant pump was estimated to reduce pumping power requirements by over 50%.

Energy-efficient motors (EEMs) provide relatively modest percentage electricity savings. Because of the long operating hours typical of many motors, however, the savings can be cost-effective. In one study of improving electrical efficiency in the pulp and paper industry in the Northwestern United States, where electricity prices are relatively low, it was estimated that the installation of EEMs would account for nearly 3/4 of the electricity savings found to be cost-effective [19]. (The EEMs would have a

Table 6. Measured fan data and potential electricity savings at a pulp and paper mill in Wargoen, Sweden [59].

	Rated Size (kW)	Existing System's Electricity Use (MWh/yr)	Existing System's Fan Eff.[a] (%)	Retrofit Investment Cost[b] (10^3 US$)	Electricity Savings (MWh/yr)	Cost-of-Saved Electricity (cents/kWh)[c] for discount rate of (6%)	(20%)
Boiler Fans				*Replace VIV with VSD control*			
Fan #1	34	53	27.3	22.5	33 (62%)	9.3	16.3
Fan #2	65	358	43.2	24.6	154 (43%)	2.2	3.8
Fan #3	135	818	37.8	35.4	412 (50%)	1.2	2.0
Fan #4	139	630	38.8	35.4	339 (54%)	1.4	2.5
TOTALS	**373**	**1859**	**38.9**	**117.9**	**938 (50%)**	**1.7**	**3.0**
Drying Hood Fans				*Replace damper with VIV control*			
(Four identical fans)							
#1,#2,#3,#4	123	916	61.7	10.8	111 (12%)	1.3	2.3
TOTALS	**492**	**3664**	**61.7**	**43.2**	**444 (12%)**	**1.3**	**2.3**

(a) Measured average operating efficiency.

(b) Includes equipment, installation, and 20% contingency. Assumes exchange rate of 6.5 Swedish kronor per US dollar.

(c) Assuming a 10-year economic lifetime.

cost-of-saved-electricity ranging from 1.5-2.7 cents/kWh for a 6% discount rate or 2.6-4.7 cents/kWh for a 20% discount rate.) These electricity savings would represent about 3% of the industry's total electricity use in the region. Another study estimated total potential savings from use of EEMs in industry generally to be 1-2% of current use [61].

6.2. Components Other than Motors and Drives

Our analysis in Sections 4 and 5 indicates that attention to system components other than motors and drives and to system design considerations can be very important in identifying energy savings. Some recent measurements confirm this.

Table 7. Measured electricity savings potential in pumping in Sweden and Finland [62]. See also Table 8.

	FINLAND	SWEDEN
Number of pumps investigated[a]	53	31
Pulp and paper industry	75%	85%
Chemical industry	20%	--
District heating & other water pumping	5%	15%
Total installed capacity (kW)	4,680	2,600
Potential electricity savings (kW)	1,024 (22%)	1,244 (48%)

(a) All are centrifugal pumps ranging in size from 23 kW to 1673 kW.

In one study, detailed measurements were made of the performance of 84 large pump systems in Sweden and Finland [62]. The measurements identified a total savings potential of 22% in the Finnish systems and nearly 50% in the Swedish systems (Table 7). The large inter-country difference was due to different selection criteria: 30% of the pumps in Finland were analyzed for reasons other than electricity savings; only pumps with potential electricity savings were analyzed in Sweden. The measurements indicated that wear alone had reduced the average efficiency of all the pumps by 14 percentage points from the original average rated efficiency. Seven additional inefficiencies were also identified, the most important of which was pump oversizing (Table 8). The primary recommendations to eliminate the inefficiencies consisted of pump or impeller changes (Table 8). The installation of a VSD generated the major part of the savings for only 15% of the cases. The use of energy efficient motors was evidently not considered.

Similar results were obtained in measurements at an integrated pulp and paper mill in Sweden [18]. In 3/4 of the pumping systems that were singled out for detailed

Table 8. Inefficiencies identified in 84 pumps in Sweden and Finland and primary recommended improvements [62]. See also Table 7.

INEFFICIENCIES IDENTIFIED	Percent of Systems
Oversized pump	23
Undersized pump	6
Cavitation	6
Very uneconomical bypass regulation	6
Excessive air in material (pulp) being pumped	6
Large deposits built up in the system	3
Unnecessary pump	3
RECOMMENDED ACTIONS	
Replace pump[a]	38
Replace or modify impeller	28
Install VSD	15
Replace coupling	4
Make adjustment in process	1
Decrease pump speed	1
Replace motor	1
No change	13

(a) The percentage of pump replacements is larger than the number of oversized and undersized pumps combined due to replacements of worn pumps. Recommended action refers to the measure accounting for the largest fraction of the savings, although combined measures are common.

study, modifications to the pump (replacement or trimming impeller) were recommended to save electricity (Table 9). The measured efficiencies of the pumps ranged from 10.7% to 82%, with an energy-use-weighted average of 52%, indicating a large potential for improvement.

Other recent studies support the finding that fan electricity use in existing installations is higher than required, primarily as a result of oversizing and operation outside of the peak efficiency range. Measurements on eight 1-2 kW forwardly-curved blade fans in 6 residential buildings in Sweden showed that the efficiency of the fan/motor assembly ranged from 15% to 57% with an energy-use-weighted average of 34% [63]. The findings agree with measured efficiencies of ten fans of similar sizes in Danish schools--fan/motor efficiencies ranged from 15% to 35%, with an average of 25% [64]. The Swedish study also found that heat-exchanger sizes recommended in vendor

Table 9. Electricity savings potential estimated for 12 pumps based on measurements at a pulp and paper factory in Wargoen, Sweden [18].

Pump application and capacity (kW)	Recommended Investments[a] M	P	TI	VSD	Investment Cost (10^3\$)[b]	Annual Savings (MWh/yr)	Cost-of-Saved-Elect.[c] (cents per kWh saved) for discount rate of 6%	20%
Raw-water intake (119)	x	x			44.3	475 (50%)	1.3	2.2
Cleaning water (380)		x		x	86.2	550 (18%)	2.1	3.7
Tank drainage (69)				x	29.2	216 (42%)	1.8	3.2
Bleached sulfate pulp (36)		x			8.9	43 (31%)	2.8	4.9
Return water (101)	x	x		x	85.8	610 (68%)	1.9	3.4
Warm water filtration (54)	x	x			19.1	192 (40%)	1.4	2.4
Mixing (184)	x		x		32.3	331 (23%)	1.3	2.3
Fresh water supply (59)	x	x			14.9	414 (82%)	0.5	0.9
Effluent (28)	x	x			13.1	130 (57%)	1.4	2.4
Paper machine water (28)				x	13.4	162 (79%)	1.1	2.0
Mixing tank (26)				x	13.4	153 (78%)	1.2	2.1
Waste water (52)			x		5.2	200 (48%)	0.4	0.6
TOTALS					**2378**	**3478 (38%)[d]**	**1.4**	**2.5**

(a) M = replace motor, P = replace pump, TI = trim pump impeller, VSD = install variable speed drive.

(b) Original costs in Swedish kronor (SEK) converted using 6.5 SEK per US dollar.

(c) Assuming 10 year lifetime.

(d) The savings represent 26% of the electricity used by a total of 32 pumps which were originally selected for this study. Detailed savings estimates were made only for those listed in this table.

catalogs for ventilation systems resulted in suboptimal designs. Selecting heat-exchangers one or two standard sizes larger would give less than a three-year simple payback as a result of the decreased pressure drop.

6.3. Oversizing

Oversizing of pumps and fans is pervasive (e.g. see Table 8). It generally results from the application of large safety factors during the design process. Factors in excess of 30% are not uncommon. A design factor of 1.25 is typically applied to pump size to account for uncertainties in pressure drop calculations alone [39]. Additional oversizing often enters into a design, e.g. to account for future buildup of deposits on duct or pipe walls or for changes that might occur in the process, or as a result of choosing the "next biggest" pump or fan from a vendor's catalog [10]. In general, oversizing is practiced because the increased capital and operating costs are considered worthwhile compared to the risk of future problems that might arise from insufficient capacity or compared to the additional engineering effort required to size a system nearer to its required operating size. Computer-based design tools and simulation that better predict system operation could help reduce the use of excessively large safety margins. Routinely making cost-effective after-installation modifications could also lead to major energy savings. For example, pump impellers could be trimmed once actual process pumping requirements are clearly established.

6.4. Synergistic Interactions

The electricity savings from a combined set of efficiency measures can be larger than the sum of the savings from each individual measure. This is illustrated by a case study analysis of a 40,000 m^2, 26-level office building in Southern California [56]. Air handling currently accounts for 20% of the building's electricity use. Lighting accounts for 50%. A detailed building audit indicated that a CAV to VAV conversion of the air-handling system was feasible and that significantly reduced lighting electricity use could be achieved by slightly reducing the high degree of over-lighting in the building and replacing existing ballasts and flourescent lamps with more energy-efficient models. The lighting changes would have the added benefit of reducing the load on the air-conditioning system since less waste heat would be generated.

A detailed building simulation was undertaken to determine the potential electricity savings from the lighting and CAV-to-VAV modifications. Two possible flow control strategies were investigated: variable inlet vanes and variable speed drives. Most of the fans in the system were originally installed with variable inlet vanes which were fixed in place after fine-tuning the flows in the new system. The VIV control option would involve adding automatic control to these inlet vanes. The alternative strategy would be to install variable-speed drives to control fan speed.

Table 10 summarizes the estimated electricity use in the existing building and after assumed retrofits to the lighting and air-handling systems. Lighting electricity use would fall by some 30%. Air-handling electricity use would fall by some 60% if VIV control were used. It would fall by 75% if the more efficient variable-speed drive option were used. Other electricity demands (for chillers, pumps, cooling towers, etc.) would also fall with the retrofits (by 25%) by installing a direct digital control system to operate essentially all equipment in the building at optimal efficiency. In the best case, total building electricity use would be reduced by 40%. For discount rates of 6% and 20%, the cost-of-saved-electricity would be about 3 cents/kWh and 5.5 cents/kWh, respectively, for both the lighting and air-handling modifications (Table 10).

Another illustration of a synergistic interaction can be found in work relating to the 12,000 m^2 commercial building [60] referred to in Section 6.1. The original VIV air-handling system operated so as to maintain the static pressure at a particular point in the duct at a fixed level. This insured that no zone of the building was "starved" for air under worst-case operating conditions. Under normal operating conditions, a much lower static pressure set point could be used. This would lower duct losses, but would not have a major impact on electricity use in a VIV system [60]. In contrast, with VSD control, savings in duct losses translate directly into electricity savings. In this study, the electricity savings with a 40% reduced static pressure set point (from 0.62 to 0.37 kPa) were increased by 2/3 over the savings from the VSD use without change of the set point (57% versus 35% of pre-retrofit consumption). In practice, the lower set point could result in sub-minimum flow rates at times, and daily adjustment to avoid this might be impractical. In this case, a direct digital control (DDC) or comparably sophisticated system would have to replace the existing pneumatic one. DDC installation as a retrofit was deemed not cost-effective in the study, but a 2.5 year

Table 10. Summary of estimated electricity use and cost-of-saved-electricity for alternative air-handling and lighting retrofits to an existing 40,000 m^2 commercial office building in Southern California [56].[a]

ELECTRICITY USE (MWh/yr)	*CAV system* Existing building	*VAV systems using* Variable inlet vane	Variable speed drive	**COST-OF-SAVED-ELECTRICITY (cents per kWh)**[e]	*For discount rates* (% per year) **6**	**20**
Air Handling[b]	1507	603	378	*Lighting only*	2.9	5.1
Lighting[c]	3546	2482	2482	*Air-Handling*[f]		
				Variable inlet vane	3.1	5.4
Other[d]	2001	1483	1483	Variable speed drive	3.3	5.8
Total	7054	4568	4343	**Overall average**	3.2	5.5

(a) The building consists of a 26-level portion with 31,000 m^2 of floor area and an 8-level portion with 9,000 m^2 of floor area. Both portions are supplied by common chiller and boiler plants.

(b) The total rated power of the existing fans (14 supply fans, 4 return fans) is 425 kW, ranging in size from 7.5 to 75 kW.

(c) In the improved-efficiency systems, 16,400 existing 40-W flourescent lamps and 8,200 conventional ballasts are replaced by 34-W lamps and energy-efficient ballasts. The result is a reduction in power drawn per 2-lamp, 1-ballast set from 94 W to 59 W. Since the building is highly overlit, the 15% lower light output from these lamps is acceptable. Electricity use by incandescent lights and office equipment (which is included under the lighting category) remains the same for each case.

(d) In the improved-efficiency cases, a microprocessor-based Direct Digital Control (DDC) system will control essentially all electricity-using equipment in the building. The resulting better control strategies, together with the reduced lighting load, lead to less electricity use by chillers, cooling towers, and pumps.

(e) Assuming an amortization period of 10 years. The estimated capital expenditures are $227,000 for the lighting retrofits, $328,677 for the VIV air-handling retrofits, and $403,100 for the VSD retrofits. Both the VIV and VSD costs include a direct digital control system for the building.

(f) The assumed electricity savings are 1,422 MWh/yr and 1,647 MWh/yr for the VIV and VSD cases, respectively (sum of savings due to "Air Handling" and "Other").

payback was estimated for selection of a DDC system in place of a pneumatic one for a new building.

6.5. Looking for Efficiency Improvements

Some excellent retrofit opportunities for improving pumping and air-handling system efficiencies are reported in the literature, but the total number identified to date is small compared to the total installed capacity. Many more measurements are needed to better understand the extent to which previous findings can be generalized. Looking at generic savings possibilities (e.g. energy-efficient motors) is generally unsatisfactory, however. Larger savings potentials are likely to be found when process specific measurements, analyses, and changes are considered [65].

A related factor is the level of effort expended in looking for savings. A comparison of three studies in the pulp and paper industry illustrates this.

Based on the measurements summarized in Table 7, the authors of that study [62] estimate that 30% of electricity used in pumps larger than 50 kW can be saved cost-effectively in the pulp and paper industry, not considering energy-efficient motors. This estimate is consistent with that presented in [18] based on the measurements summarized in Table 9: cost-effective savings were estimated to range from 26-38% for pumps larger than 30 kW. A recently completed analysis indicates that pumping accounts for 41-46% of all electricity used in a typical kraft pulp mill in Sweden [5]. Since pumps larger than 50 kW account for approximately 2/3 of pumping electricity use in such mills [46,62] a 30% savings potential translates to a total of some 8-9% of the total electricity use.

A substantially different result was found in another study of electricity use in the pulp and paper industry in the Northwestern United States, where electricity prices are relatively low and comparable to those in Sweden and Finland. The total cost-effective electricity savings potential for all efficiency improvements (including lighting, solids conveying, and motor drive) was estimated to be about 9% of the industry's electricity use, although only 4% savings were actually identified in the audits [19]. Measures related to pumping system improvement, excluding installation of energy-efficient motors, accounted for less than one-tenth of these savings. Thus, from this study, it would appear that pumping system improvements could save less than 1% of the industry's total electricity consumption.

Since the Scandinavian pulp and paper industry is acknowledged to be the most energy efficient globally [48], a greater savings potential could be expected outside of Scandinavia. However, the savings estimate for the Northwestern US is an order of magnitude lower than the estimates made for Scandinavia. The difference is probably due largely to how focussed the efforts were to identify savings. The Scandinavian studies targeted pumping systems alone, while that for the Northwestern US considered all electrical uses, which limited the effort expended to identify pumping system opportunities. For example, little effort was made to estimate the savings from replacing oversized pumps.[13] The potential savings are probably large, as we have discussed previously.

6.6. Ancillary Benefits

Ancillary (non-electricity-saving) benefits from investments that save electricity are often important in determining whether an energy-efficiency improvement is actually instituted [61]. In some cases such benefits are relatively easy to quanitify. For example, a VSD control installed on a boiler fan can reduce fan electricity use and also lead to reduced boiler fuel consumption through more efficient boiler operation [61,66]. In many cases, however, ancillary benefits are difficult to quantify in economic terms, which can complicate an assessment of the cost-effectiveness of an efficiency investment. Price and Ross [61] describe the replacement of a fixed-flow machining-coolant system with a variable flow one in an automobile assembly plant. The variable flow system permitted reduced coolant flow velocities to the workpiece. This reduced the tendency for the coolant to form a mist coming off the workpiece. The ancillary benefits included reduced ventilation requirements and lower cleaning costs.

[13] This point is acknowlegded by the authors [19]: "While only one oversized pump application was analyzed, it is believed that this instance by no means exhausts the savings potential from this energy conservation measure... (which) has a very favorable payout."

6.7. New vs. Retrofit Opportunities

There appear to be many opportunities for retrofit electric efficiency improvements in pumping and air handling systems, as discussed above. The cost-effective potential for introducing efficiency improvements in new designs is at least as large since some major electricity saving options (e.g. piping or ducting size and/or system layout) are more readily implemented in new designs. In the longer term, more fundamental changes that emphasize reducing the need for pumping and air-handling services could further reduce electricity use. The scope for such reductions is very large. For example, most industrial processes have no or only very small net thermodynamic requirements in principle [67]. Fundamental process change and energy efficiency in new air-handling and pumping systems are especially relevant for developing countries, where infrastructure building is still in early stages [68].

7. BARRIERS TO MORE EFFICIENT ELECTRICITY USE

There is a large potential for reducing pumping and air-handling electricity use, as we have shown. A substantial part of these savings are available at today's electricity prices. Only a small fraction of the potential savings have been realized in practice, however. We discuss six categories of barriers to achieving more of the potential and some ideas that are being tried for overcoming these. The discussion is relevant to electricity conservation generally.

One barrier is the low priority of energy efficiency for many users, since energy costs are generally a small fraction of their operating costs. Electricity costs in an office building may be \$2-4 per m^2 per year, compared to \$2000-4000/m^2-year for salaries. In the industrial sector, energy efficiency improvements may generally improve cash flow marginally, but do little to affect product quality or market share [16], which are generally of greater concern.

A related barrier is the lack of awareness among users about the costs and performance of energy-efficient equipment [6]. There is generally a high cost associated with obtaining information and doing the necessary engineering, particularly with smaller projects [16]. Also, some users have negative misconceptions about the performance and costs of more efficient equipment and are reluctant to take perceived risks on "new" technology. Industrial users are concerned with reliability of equipment and the ability to replace a failed unit quickly. They will typically replace a piece of equipment with an identical model, which encourages distributors to stock these rather than energy-efficient units that may sit in inventory for long periods [6].

A third barrier is the misplaced-incentives or "tenant-landlord" problem--a landlord purchases energy using equipment for a building and the tenant pays the operating costs. The tenant's and landlord's interests are at odds, since higher efficiency often means higher capital cost. More generally, the "tenant-landlord" problem can involve equipment specification by architecture/engineering firms or sales to original equipment manufacturers (who use motors, pumps, fans, etc. in the products they sell) and building developers. A large number of pumps and motors sold in the US fall into this category [1]. The purchaser or designer has some interest in offering low overall capital costs for systems to end users and not much interest in energy efficiency. Another illustration of the tenant-landlord problem is the separate management of capital and operating budgets in many industries. Increased operating funds to pay higher energy costs are generally easier to secure than additional funds for a capital investment.

One of the most serious barriers to improved energy efficiency are the stiffer economic criteria generally applied on the user's side of the electric meter compared to the utility's side. The differential in discount rates--we have used 6% and 20% in this paper to reflect the different perspectives--will favor investments in new supply rather than in more efficient electricity use. (See Section 3.2 for a discussion of discount rates used in practice.) In several utility-sponsored conservation studies the potential savings from the utility economic perspective are five times higher than from industry's perspective [18,19,59,69]. Higher discount rates for assessing energy conservation projects in industry (and other sectors) are typically justified on the basis of a number of factors [6,16,19]: project lifetimes may be shorter due to product and/or process changes or obsolescense of technology; difficulties of raising investment capital; management priorities (e.g. market impacts of investments are typically given higher priority than cost reductions); uncertainty about the adequacy of the supporting engineering analysis that identified the savings (particularly for small projects). Counter-balancing considerations include ancillary benefits of an energy efficiency investment which are often difficult to quantify, e.g. lower costs for environmental compliance, better process control, or improved working environment.

The discount rate differential is compounded by artificially low electricity prices to many users, particularly large industrial ones. The marginal cost for electricity production is relatively high in many parts of the world. But prices to many users are based on the much lower average cost of production (e.g. see [70]). The largest users often receive preferential rates through favorable long-term contracts and/or tax exemptions. Furthermore, long-term external costs of producing and using electricity (national energy security, environmental damage, etc.) are not reflected in electricity prices.

A sixth barrier is the tendency of both end users and conservation program designers to focus on component retrofits. As we have discussed previously, much of the potential for saving electricity lies in system modifications. The structure of many utility conservation programs has not allowed capturing available systems savings [71]. For example, most rebate programs are directed toward single components like motors. Industrial end users might typically implement component efficiency investments in order of decreasing internal rate of return. This can lead to "cream skimming," whereby an investment made on the basis of high IRR excludes the possibility of achieving much greater electricity savings by a combination of system-wide investments.

A variety of approaches are being tried to overcome market barriers to greater electric efficiency. Sending appropriate electricity price signals through marginal-cost and/or other pricing strategies is a necessary but not sufficient condition for realizing greater efficiency improvements. Standards and/or regulations concerning new commercial and residential sector construction and new electricity using equipment can help deal with issues such as the "tenant-landlord" problem [72]. Other approaches involve a changing role for electric utilities from suppliers of electricity to suppliers of energy services [73]. Utilities are increasingly adopting least-cost planning strategies [74], the objective of which is to evaluate all feasible "demand-side" resources on an equal economic basis (e.g. same discount rate) with supply alternatives. Investments are then made in the order of least cost per kWh saved or supplied. There are ongoing efforts to provide better information regarding technical options for improving efficiency to help overcome users' lack of awareness regarding efficiency [8,11,75]. Creative electric utility programs have in some cases helped to close the "payback gap"--the large differential in discount rates between electricity users and suppliers. For example, some utilities offer loans, rebates or other incentives for efficiency investments [74]. Some utilities have entered into "demand-side bidding," whereby they request owners of buildings or industries or independent energy service companies to propose electricity conservation projects. The utility pays the winning bidder for "saved electricity" resulting from implementation of their proposal [74,76]. Utility, government, or corporate energy efficiency programs emphasizing a systems perspective are favorable to component-focussed efforts, but few have been undertaken [71]. Designing and implementing programs to capture systems benefits offers a challenge, particularly in the heterogeneous industrial sector.

8. CONCLUSIONS

Pumping and air-handling are major electricity consuming activities in the world, e.g. accounting for 30-40% of electricity use in industrialized countries. Improving the efficiency of these tasks could thus play an important role in reducing future electricity supply needs. To facilitate conservation planning at utilities, industrial sites, and elsewhere, the magnitude of potential efficiency improvements must be well understood. Our analysis suggests that the potential for saving electricity in pumping and air-handling is much greater than has generally been appreciated to date.

Most efforts to assess energy efficiency improvement potentials for planning purposes have focussed on generic component modifications--primarily use of energy efficient motors (EEMs) and variable speed drives (VSDs)--across a broad spectrum of end uses, e.g. all motor-drive applications in a particular sector, all industrial pumping applications, all commercial ventilation, etc. The case studies we have cited in this paper indicate that when individual systems are thoroughly and creatively examined, much larger cost-effective savings can often be identified than suggested by such generic assessments. For many pumping and air-handling applications, achieving cost-effective retrofit or new-installation savings of 50 to 75% over existing stock averages does not seem overly optimistic.

New applications provide the greatest opportunity for savings, often at little or no additional capital cost. We illustrated this by showing that alternative pipe diameters for the same application will change the lifecycle cost of the system very little in the region of the minimum lifecycle cost, but would result in very different levels of electricity consumption. Thus, major electricity savings could be achieved at essentially no increase in lifecycle cost. In the longer term fundamental changes in industrial processes or building designs could lead to very low energy use in new applications.

Major retrofit savings also exist, but much more field effort is needed to assess what fraction of installed kilowatts are amenable to the large savings we have discussed in this paper. Capturing savings on a widespread basis will require measurements and demonstrations in a wide variety of specific applications. The cases we have discussed in this paper should provide encouragement to others pursuing such efforts. If savings are larger in specific cases than suggested by most broad studies (such as discussed in section 2) the economics are also likely to be better than generally believed. To facilitate the search for savings, it would be helpful to standardize procedures and techniques for measuring and monitoring equipment performance and energy use. The implementation of utility or government programs that encourage creative examination of systems, rather than replacement of components alone, would also help.

Aside from the need for demonstrations, there are other, largely institutional impediments to achieving improved efficiencies in practice. One of the most important barriers is the difference in economic perspectives between end-users making the efficiency investment decisions and electric utilities making decisions about new supply investments. The cost-effective electricity savings potential is much greater assuming utility discount rates. Aggressive programs to reconcile the two economic perspectives, as initiated in California late in 1990 [77], can help capture more of the electricity savings potential.

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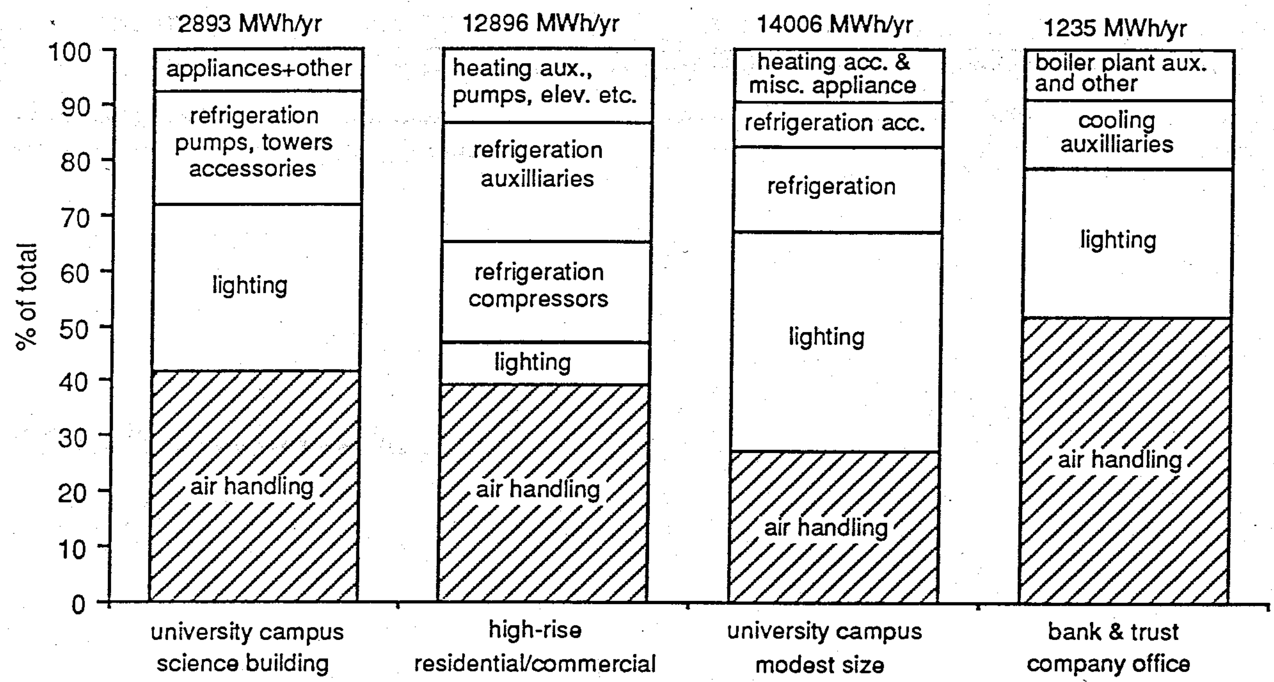

Fig. 1 Estimated annual electricity consumption by end-use in some commercial and residential buildings in the Midwestern USA [78].

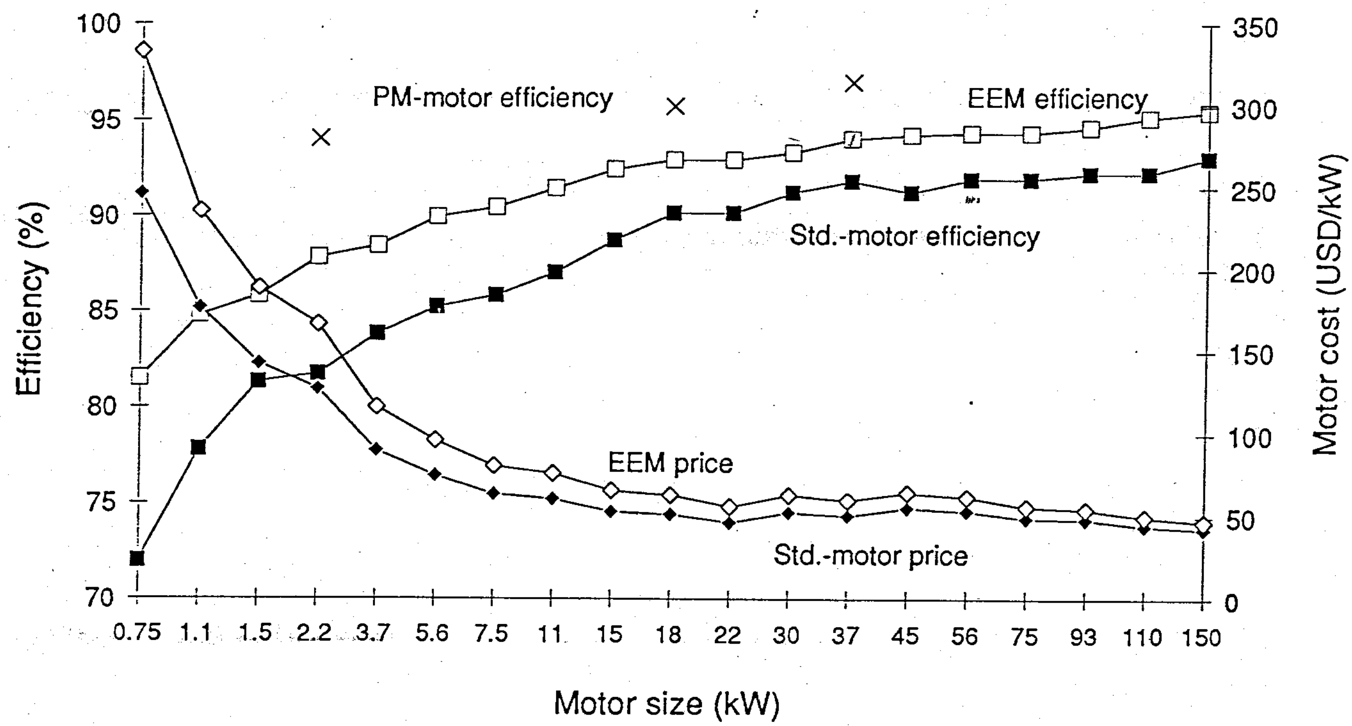

Fig. 2. Full load efficiencies and wholesale prices of standard and energy-efficient 3-phase motors in Canada as a function of rated output capacity [6]. Also shown are reported efficiencies of permanent magnet motors [29,30,31].

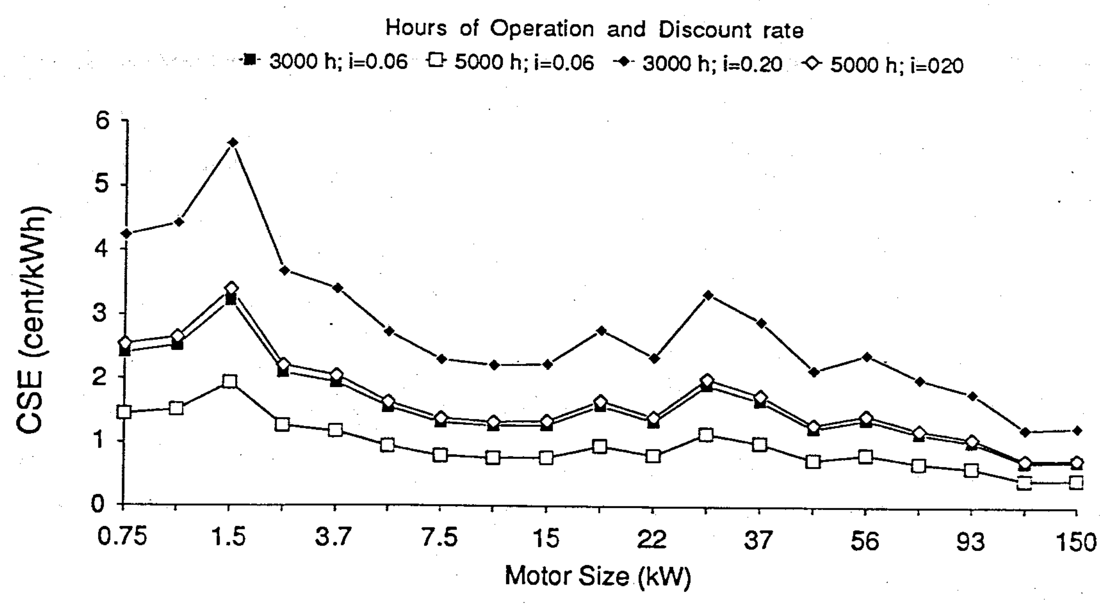

Fig. 3. Calculated cost-of-saved-electricity for new investments in energy-efficient motors versus standard motors. Motor costs and performance are from Fig. 2. A 10-year economic lifetime is used in all cases.

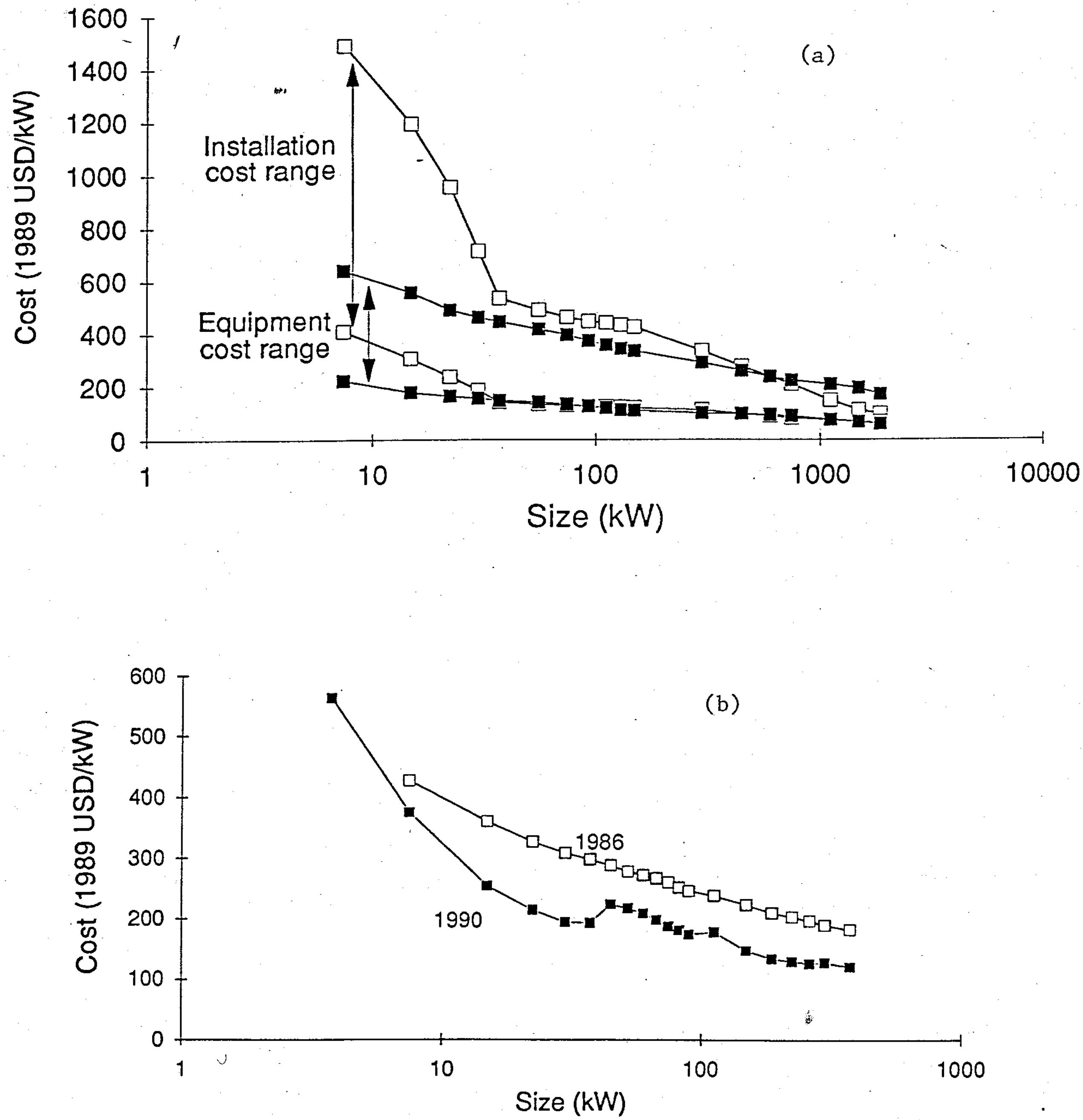

Fig. 4. (a) Estimated equipment list prices and installation costs for VSDs in 1986 [79]. The equipment cost range spans ±50% of the average cost of a large sampling of commercial units. The installation cost range reflects variations in labor rates, extra equipment features included, etc. (b) Variable speed drive list prices in 1986 and as-purchased prices in 1990. The upper curve is the average of the equipment prices shown in Fig. 4a. The lower curve is from [9].

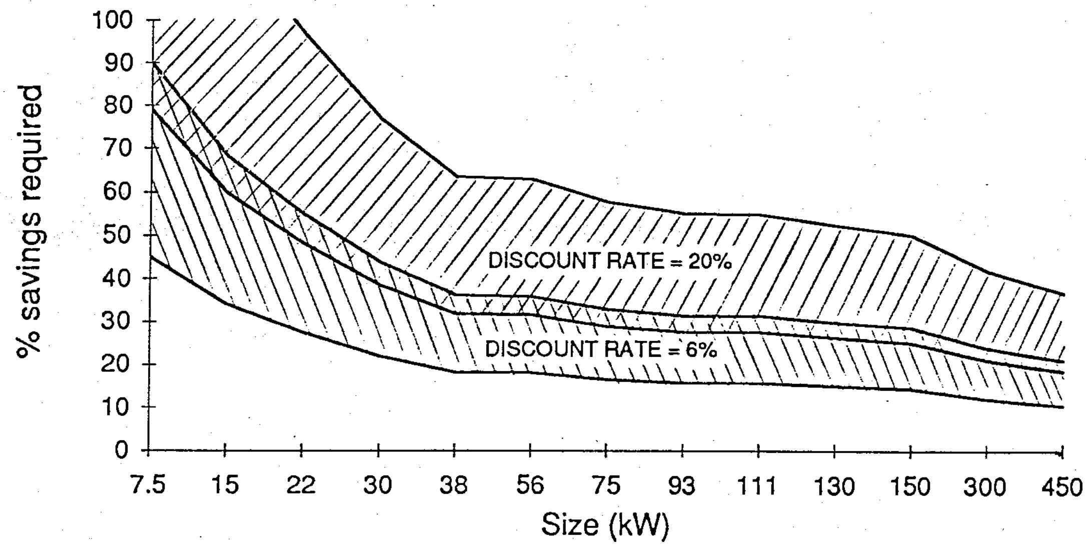

Fig. 5. Required percentage electricity savings with VSDs to achieve a cost-of-saved-electricity of 5 cents per kWh for 4000 (upper border of each shaded region) to 8000 (lower border) annual operating hours for discount rates of 6% and 20%. Equipment costs are from the lower curve in Fig. 4b. Installation costs are the averages shown of those in Fig. 4a. A ten-year equipment life is assumed.

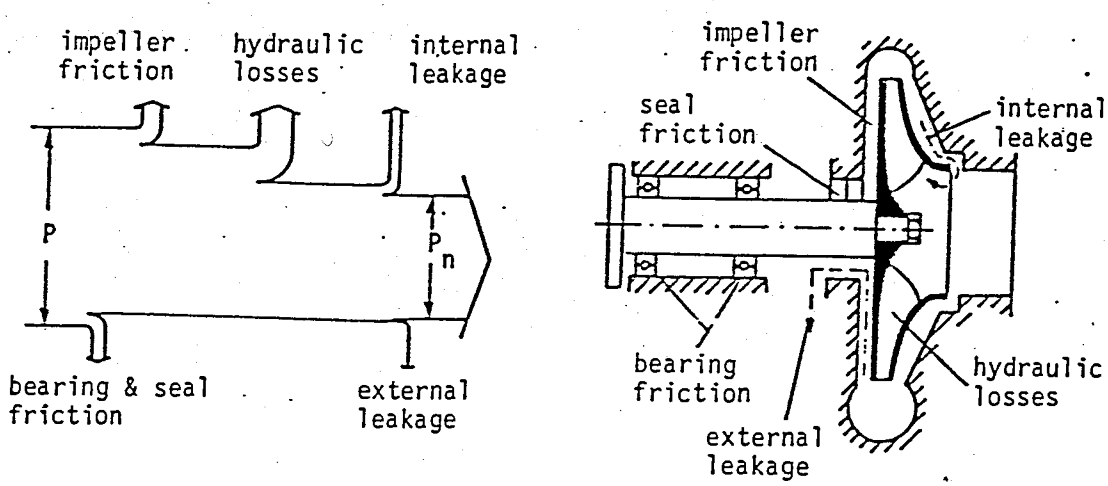

Fig. 6. Estimated energy balance for a typical centrifugal pump [80].

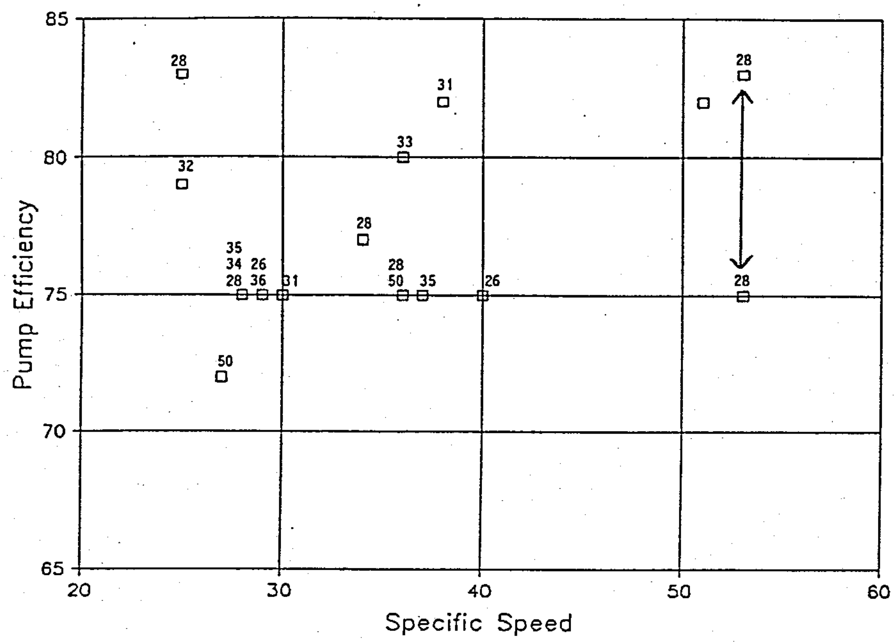

Fig. 7. Design-point pump efficiencies versus specific speed (defined in footnote 7) for a sampling of 4 to 7.5 kW pumps on the Swedish market [38]. The small numbers indicate design-point flow in liters per second. The two highlighted units can provide essentially identical duty.

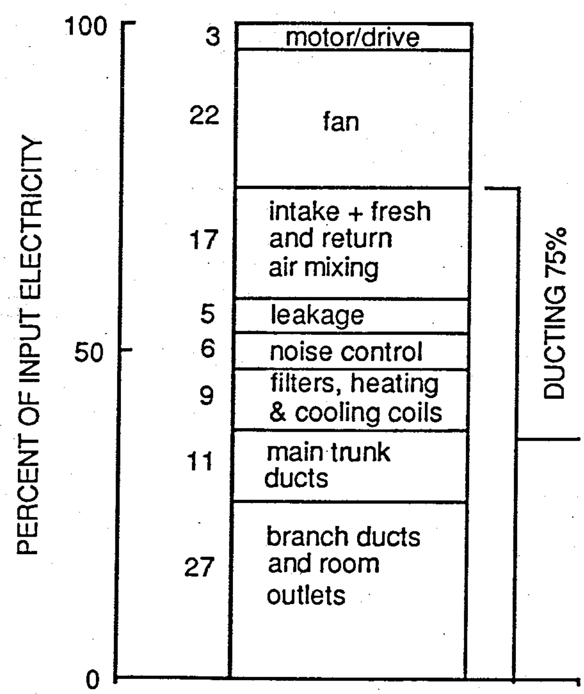

Fig. 8. Estimated accounting of electricity use by component in an air-handling system, excluding that for heating and cooling, for a typical air-conditioned multi-level commercial office building in the United States [56].

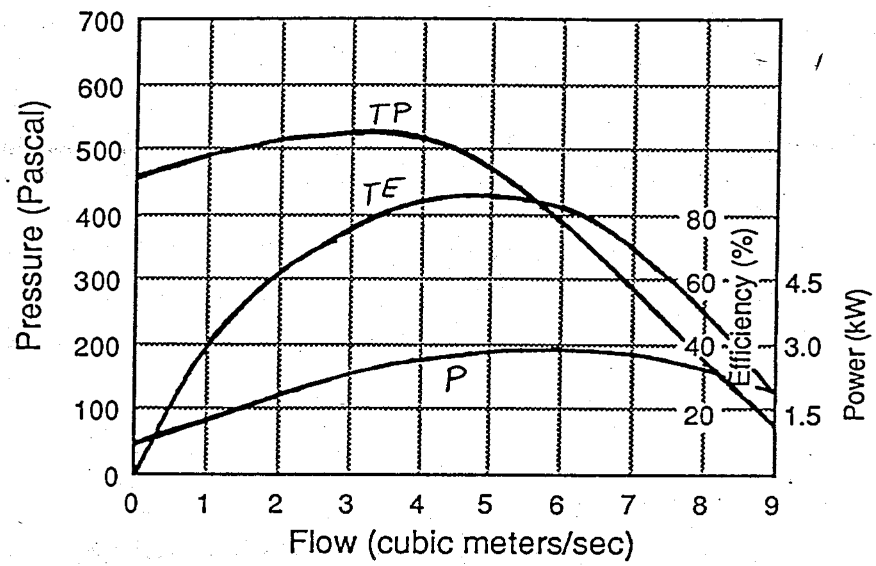

Fig. 9. Typical performance curves for a centrifugal fan [42]. TP is the pressure at the fan outlet, P is input power, and TE is the fan efficiency.

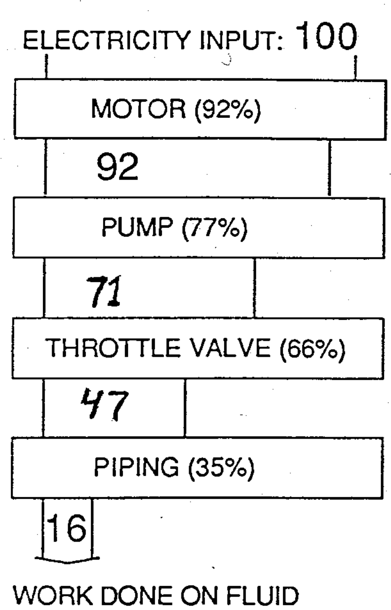

Fig. 10. Pumping system energy balance (based on the base case in Table 3). The overall efficiency of 16% is typical for many pumping systems [41,47].

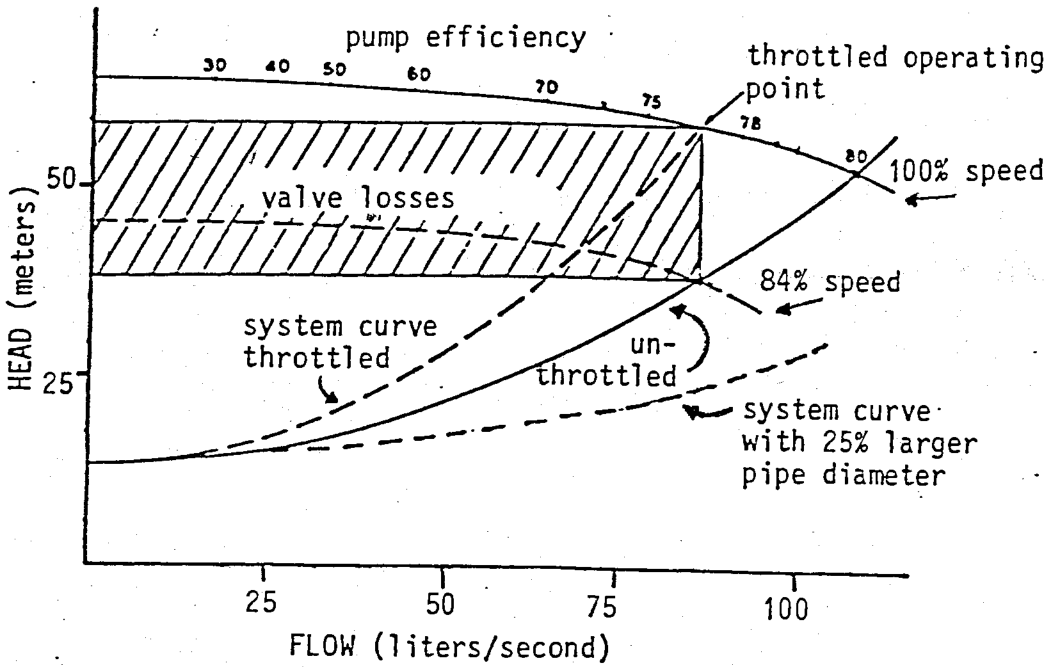

Fig. 11. Head-flow curves for a variable-flow, variable-pressure pumping system (see Fig. 12) showing throttled versus reduced speed operation and the effect of reducing piping losses by increasing pipe diameter (adapted from [45] and [10]). With the increased pipe diameter a 45 kW motor/pump would be sufficient, compared to a 75 kW unit in the original system.

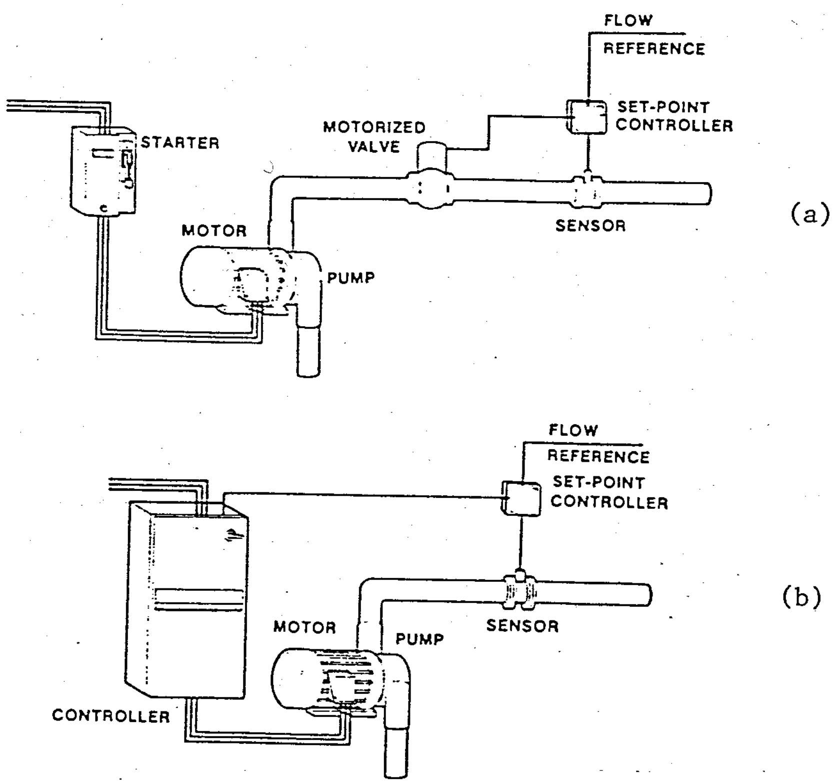

Fig. 12. Equipment configuration for a variable-flow variable-pressure pumping system [45] with (a) throttle control, and (b) VSD control.

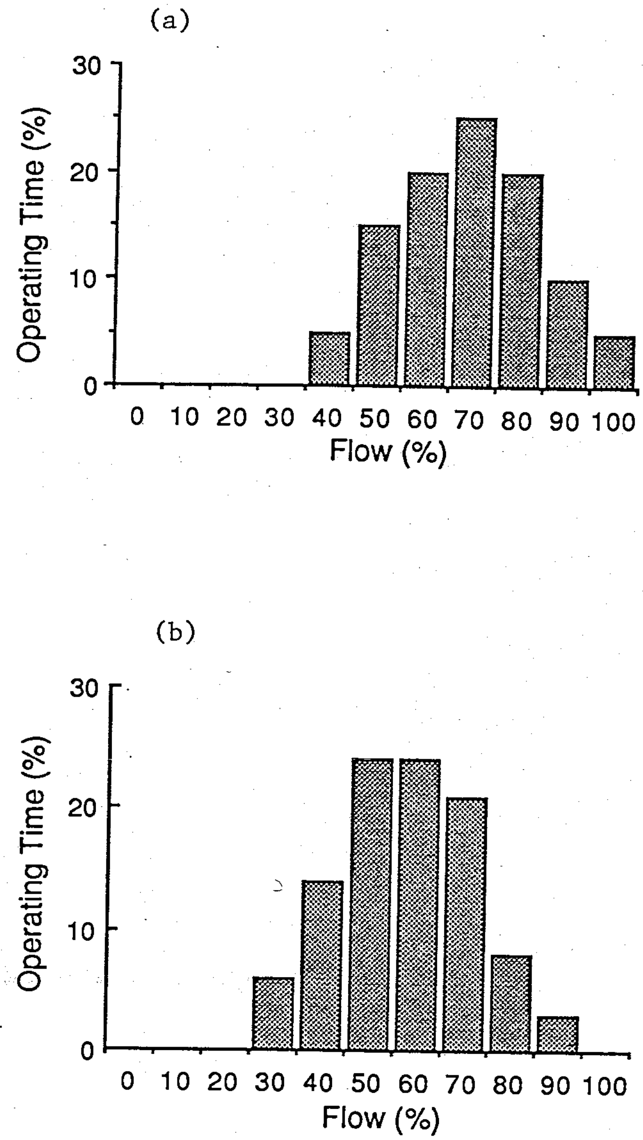

Fig. 13. Characteristic duty cycles for (a) a variable-flow pumping application [45] and (b) a supply fan used in a variable-air-volume air handling system for a commercial office building [60].

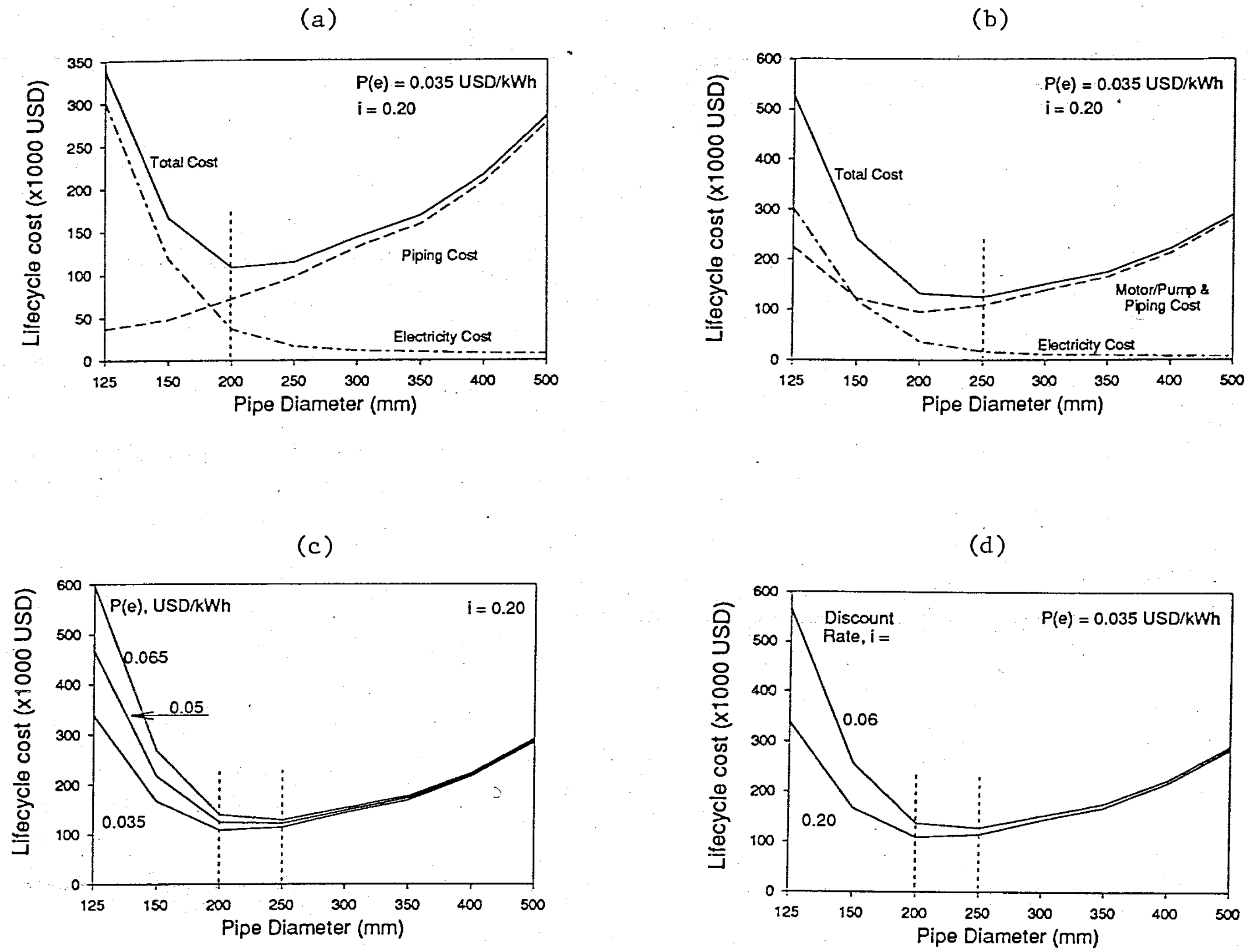

Fig. 14. Lifecycle cost (LCC) as a function of pipe diameter for a pumping application (see Table 4) for the indicated electricity prices and discount rates (assuming a 10-year lifetime), adapted from [39]. The graphs show how the diameter giving the minimum LCC shifts depending on the assumptions used: (a) capital cost includes only that for piping; (b) capital costs include those for the motor and pump in addition to pipe; (c) effect of electricity price assuming capital cost for piping only; (d) effect of discount rate assuming capital cost for piping only.

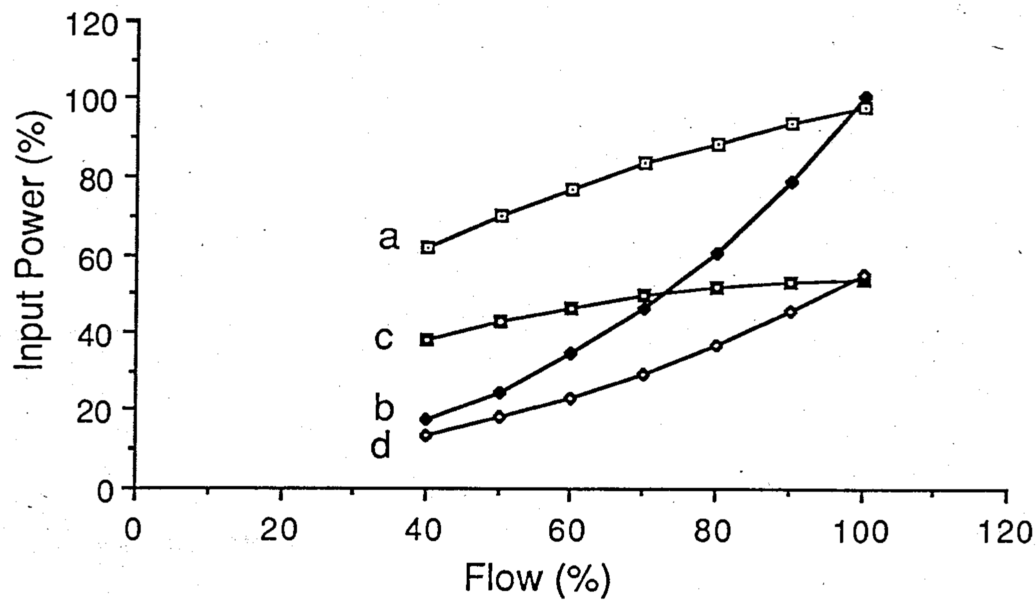

Fig. 15. Calculated input power requirements for reduced flow operation of a variable-flow variable-pressure pumping system (see Fig. 12) based on Fig. 11 [81]. Curve (a) represents throttle control (corresponding to "throttled system curve" in Fig. 11), and curve (b) represents the same system with VSD control. Curves (c) and (d) are analogous to (a) and (b) for the system with 25% larger pipe diameter (note that a smaller pump and motor could be used in this case).

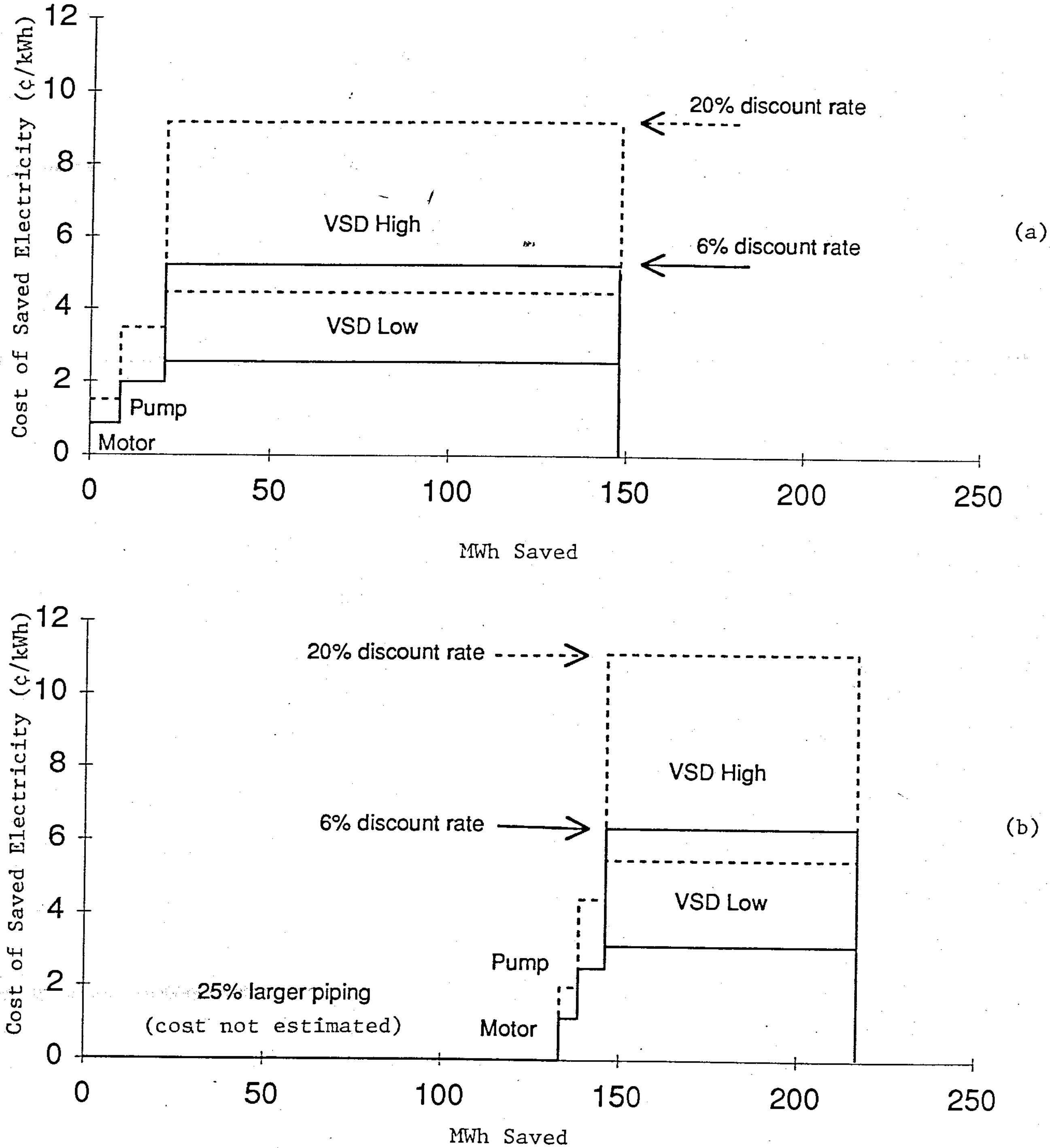

Fig. 16. Pumping electricity conservation-supply curves showing potential electricity savings and costs of saved electricity for the variable-flow application described by Table 3 and Fig. 11, with the duty cycle and input power requirements as shown in Fig. 13a and 15, respectively. Graph (a) assumes no modifications are made to the piping, in which case a 75-kW motor is required. Graph (b) assumes 25% larger diameter piping, in which case a 45-kW motor can be used. The extra costs for the more efficient motors are from Fig. 2. The extra cost for more efficient pumps is assumed to be 20% of the cost for a standard pump, based on [1]. Standard pumps are assumed to cost $9000 for the 75-kW unit [18] and $7220 for a 45-kW unit. VSD equipment costs are from the lower curve in Fig. 4b. These are combined with the high and low installation costs from Fig. 4a to give the two cost-of-saved-electricity estimates here. Costs for larger diameter piping were not estimated. The calculations assume 5000 operating hours per year and 10-year equipment lifetime.

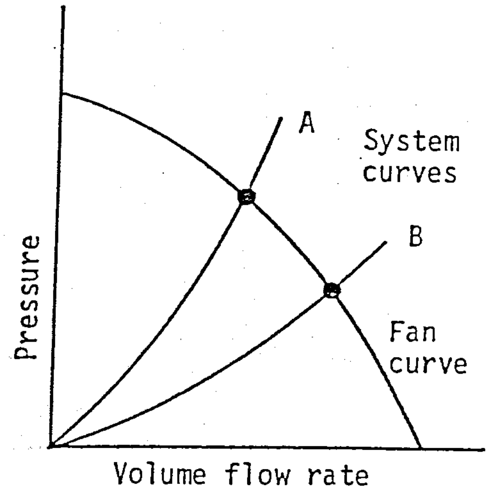

Fig. 17. Schematic centrifugal fan and system curves [56].

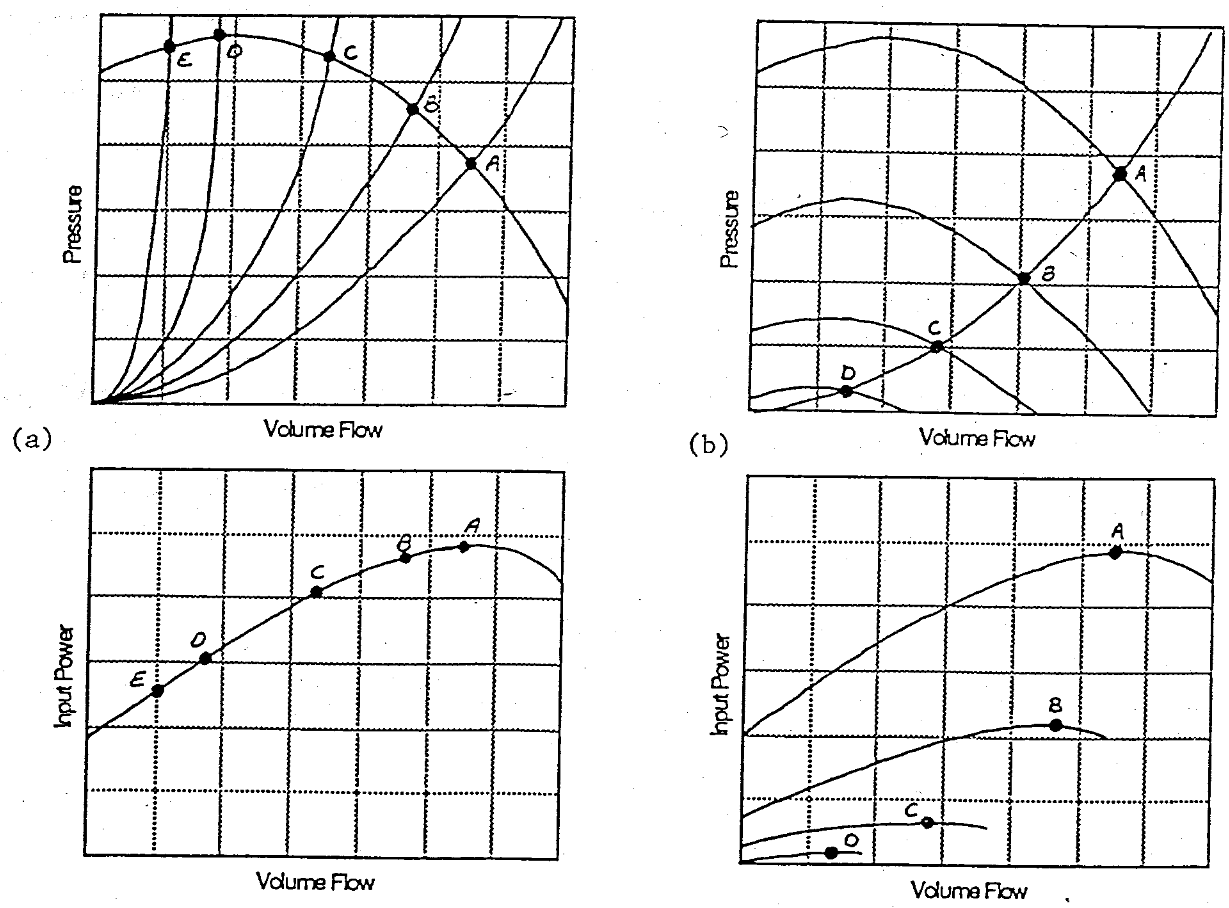

Fig. 18. Two flow control options in air-handling [56]: (a) outlet damper--different system curves correspond to alternative damper settings and (b) speed control--different fan curves correspond to different fan speeds.