Energy Savings Through Treating Buildings as Systems

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ABSTRACT

Much of the analysis of the potential to save energy and reduce emissions of greenhouse gases in the buildings sector has focused on the energy savings that can be achieved through incremental improvements in the efficiency of individual energy-using devices (motors, fans, pumps, boilers, chillers) but without changing the way in which they are put together as systems. However, much larger savings are possible through changes in building systems, and further, these savings can be achieved at much smaller incremental investment cost and sometimes at lower first cost. This paper will focus on the savings that can be achieved through a systems approach to buildings. The systems approach begins with a consideration of building shape and form and the specification of a high-performance envelope so as to minimize heating and cooling loads. This leads to a number of synergies that further reduce energy requirements, such as permitting cooler temperatures for distributing heat and warmer temperatures for distributing coldness (which leads to greater efficiency in the operation of heating and cooling equipment), the use of displacement ventilation (which reduces ventilation energy requirements), and chilled-ceiling cooling (which improves the efficiency of chillers). Use of warmer temperatures for cooling also permits greater use of ambient air or direct use of cooling towers for cooling, giving yet further cooling-energy savings. Separation of cooling from dehumidification functions permits use of solar thermal energy in desiccant dehumidification and cooling systems. In desiccant dehumidification systems without the use of solar energy, efficiencies of individual components do not appear to be any better than that of conventional vapour-compression systems, but overall system efficiency can be much better. Altogether, heating and cooling loads in new buildings can be readily reduced by a factor of three to four, and sometimes more, compared to current practice in most jurisdictions of the world. With regard to lighting, system-level considerations (layout, controls, sensors, placement of sensors, daylighting) are at least as important as the efficiencies of individual devices. Finally, the building occupants are part of the building energy system, and are an important consideration with regard to operable windows and fans, use of an adaptive thermal comfort standard, demand-controlled ventilation, the operating strategy with passive and hybrid passive/mechanical ventilation systems, and occupancy sensors for lighting systems.

KEYWORDS

Integrated design, energy efficiency, buildings as systems

INTRODUCTION

In keeping with the theme of the IAQVEC series of conferences – the integrated approach to the design and operation of buildings – I have chosen in this paper to present some of the key findings in the chapter on buildings in the most recent IPCC assessment report (Levine et al. 2007), in which I served as a lead author, within the theme of “system versus device efficiencies”. “Devices” are individual pieces of energy-using equipment, such as fans, motors, pumps, air

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conditioners or chillers, boilers, heat exchangers, and electrical lighting lamps and luminaries, while “systems” refers to how the devices are put together and function. Given the interest of this conference in air quality, I will highlight areas in which energy use can be simultaneously reduced and indoor air quality improved through a systems approach to the design of buildings. Extensive justification and references supporting the summary presented below can be found in Harvey (2006).

SYSTEM-LEVEL CONSIDERATIONS

Building Form, Orientation, Thermal Mass, and Envelope

In climates cold enough to require winter heating, a high performance envelope – consisting of high (but optimized) levels of insulation, high-performance windows, and minimal uncontrolled air leakage – can readily reduce heating energy requirements by a factor of four compared to current practice. Window performance can be chosen so as to permit elimination of perimeter heating on the coldest winter days, down to temperatures of -40ºC (see Figure 1) and also to serve as a net heat source over the course of the heating season (due to passive solar gains exceeding heat losses). The elimination of perimeter heating in turn reduces costs and amplifies the savings in heating energy use by shifting the warmest temperatures away from the window area. Compact building designs, with a low surface:volume ratio, can also significantly reduce heat loss.

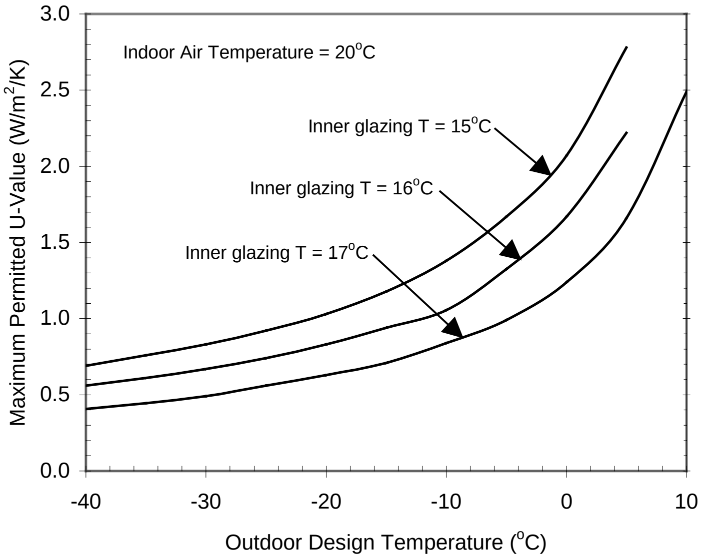

Figure 1. Window U-value below which perimeter heating is not needed as a function of the minimum expected winter outdoor temperature and of the minimum permitted temperature of the innermost glazing surface. Source: Harvey and Siddall (in preparation).

In hot climates, or during the summers in moderate climates, cooling requirements can be significantly reduced through judicious building orientation so as to provide some self-shading and to minimize the surface area (in particular, the glazed area) exposed to the hot afternoon sun. Cooling loads can also be reduced through the use of high-albedo surfaces, external insulation (to reduce inward conductive heat transfer from building surfaces, which can become substantially warmer than the air temperature), windows with low solar heat gain (0.25 being about the lowest available), and through use of features such as atria and stairwells in a way so as to facilitate passive ventilation and cooling. In hot-dry climates, thermal mass in combination with the above features and night ventilation can significantly reduce cooling requirements, while in hot-humid climate, a more open building form with less thermal mass is more appropriate.

In residential construction, careful application of a continuous impermeable barrier can reduce rates of air leakage by a factor of 5-10 compared to standard practice. A mechanical ventilation system is then required that circulates fresh outdoor air through the building. Up to 95% of the available heat in the warm exhaust air can be transferred to the cold incoming air in winter using a heat exchanger. Air leakage is more difficult to measure and control in commercial buildings, but can nevertheless be greatly reduced through simple measures that are part of a higher overall quality of construction. Improving the air tightness of commercial buildings is essential to the proper operation of low-energy ventilation and cooling techniques, such as displacement and passive ventilation (discussed below), as well as directly reducing winter heat loss and summer heat gain and infiltration of moisture.

The net result of careful attention to building form, orientation, and thermal mass, and the implementation of a high-performance envelope, is to reduce winter heating requirements by a factor of 4-10 and summer cooling requirements by a factor of 2-4 in most jurisdictions and climates. None of these savings require advanced technologies; rather, they depend strongly on human factors such as the design process and the skill and care displayed during construction.

Passive Ventilation

In the absence of ventilation, the interior air temperature in a building will rise considerably above the outside air temperature, such that the building is quite uncomfortable even when the outside temperature is pleasant. As the ventilation rate increases, the interior temperature will approach the outside temperature. At the same time that the real interior air temperature decreases, the *perceived* temperature will decrease further due to the greater ability of moving air to remove heat from a warmer body. Finally, with natural ventilation, the *acceptable* air temperature increases due to enhanced psychological adaptation to warmer conditions compared to buildings with mechanical ventilation.

Passive ventilation can be achieved through building designs that permit cross-ventilation and create wind suction; or that exploit the “stack” effect (the natural tendency of warm air to rise) through solar chimneys, stairwells, and atria; or that make use of air-flow windows, double-skin façades, and cool towers. In this case, the building and indeed its interaction with surrounding buildings through the outside airflow, has to be understood and designed as an integrated fluid-dynamic and thermal system. Passive ventilation not only reduces energy use, but can improve air quality (if the outdoor air is not overly polluted!) and gives people what they generally want.

Minimizing HVAC energy use through separation of functions

There are a number of changes in the design of HVAC (Heating, Ventilation, and Air Conditioning) systems that can achieve dramatic savings in the amount of energy used for heating, cooling, and ventilation, even with no improvement in the efficiencies of individual devices. Two key principles are:

(1) To separate the ventilation from the heating and cooling functions by using chilled or hot water for temperature control, and circulating only the volume of air needed for ventilation at any given time (demand-controlled ventilation). This saves energy because it takes about 25 times less energy to deliver a given amount of heat or coldness by circulating water than by circulating air, and airflow requirements for ventilation are far less than what is normally needed for temperature control. Thus, shifting temperature control from air circulation to a hydronic system allows a sharp reduction in airflow and an associated large savings in fan+pump energy. Furthermore, indoor air quality is improved because, once the airflow rate is reduced to that needed for ventilation alone, the air will of necessity be passed through the building only once before it is vented to the outside.

(2) To separate cooling from dehumidification functions through the use of desiccant dehumidification. This avoids the need to overchill and then reheat air for humidity control, which in itself will save energy. This savings is compounded by the fact that the chiller can operate with a warmer evaporator and hence a higher COP (Coefficient of Performance, the ratio of heat removed to energy used). Even larger savings will occur if solar thermal energy is used to recharge the desiccant (this also turns out to be a more effective way of using solar energy for air conditioning than solar-powered absorption chillers). Air quality problems associated with moist evaporators are eliminated too.

With regard to ventilation, efforts should be made to minimize the ventilation airflow without compromising air quality. This can be done in two ways: (1) through the use of displacement ventilation, which entails supplying slightly cool air over a broad region at floor level, such that it rises and displaces the pre-existing air as it is warmed by internal heat sources; and (2) through demand-controlled ventilation. Displacement ventilation allows a reduction of airflow by at least a factor of two while improving indoor air quality; inasmuch as fan energy varies almost with the airflow to the third power, this translates into a factor of 6-7 reduction in fan energy use. With demand-controlled ventilation, airflow changes with changing building occupancy (as determined, for example, with CO_2 sensors). This alone can save 20 to 30% of total HVAC energy use (Brandemuehl and Braun 1999). Demand-controlled ventilation is possible only if the heating/cooling function of airflow has been eliminated through use of a separate hydronic system for heating and cooling.

Having adopted a once-through, displacement ventilation system, yet further energy savings are possible because heat that is picked up from the ceiling area (from electric lights, or daylight that is bounced off the ceiling as part of a daylighting system) is directly routed to the outside. In a conventional HVAC system, where 80% or so of the internal air is recirculated through the building on each circuit, this heat has to be removed by the chillers. For office buildings in Chicago, about 1/3 of the total heat load on the chillers can be avoided with once-through displacement ventilation (Loudermilk, 1999).

The natural complement to displacement ventilation is chilled ceiling (CC) cooling, in which cooling water at 16-20ºC is circulated through large ceiling panels. There are a number of energy-saving synergies with CC cooling:

- the room temperature can be 2 K warmer with the same perceived temperature, which will reduce heat gains due to conduction and leakage through the building envelope; and
- by providing cooling at 16-20ºC, the chiller efficiency will be much larger or the chiller can be bypassed altogether if the cooling-tower water is used for chilling (as discussed below).

However, if a CC ceiling is combined with an otherwise conventional system, both of these energy savings can be lost. In particular,

- if dehumidification is accomplished by over-cooling the ventilation air and then reheating it, more energy will be needed for reheating because the ventilation air is supplied at a warmer temperature in a CC system;
- if ice thermal storage is being used, then the COP benefit of a warmer chilled-water temperature and the greater opportunity for directly cooling the chilling water using the cooling tower is lost, because initial cooling down to freezing occurs whether a CC or all-air system is used.

Thus, the magnitude (and even the sign) of the change in energy use from a given design change can depend on the other parts of the system.

Moisture can be transferred from the incoming air to the dry outgoing air in a mechanical ventilation system using passive or active desiccant wheels. Both consist of a rotating drum that contains a solid desiccant and rotates from the incoming airflow (picking up moisture) to the outgoing airflow (releasing moisture) and back. In a passive desiccant wheel, the dryness of the outgoing airflow is the driving force for driving moisture from the desiccant. In an active desiccant wheel, supplemental heating of the outgoing air stream is used to assist in driving moisture from the desiccant. The combination of active desiccant wheels with conventional (electric vapour-compression) cooling systems reduces electricity use both by shifting some of the cooling load (the latent portion) to the desiccant wheel, which in turn can be regenerated using solar thermal energy, and by permitting a lower chiller evaporator temperature and hence greater chiller COP. Total energy savings in cooling and dehumidification can vary from as little as 6% to almost 50%, depending on the way the components of the system are put together, and up to 75% if solar thermal energy is used to regenerate the desiccant (Mumma and Shank 2001; Fischer et al. 2002; Niu et al. 2002). The combination of desiccant wheels with evaporative cooling and sensible heat exchangers permits purely evaporative cooling and dehumidification, eliminating the need for electric chillers altogether. In effect, desiccant systems extend the applicability of evaporative cooling into the hot-humid regions of the world, where it otherwise cannot be used.

An interesting synergy between different system components arises from the fact that the COP of a solid-desiccant cooling system increases with increasing initial temperature and humidity even though the regeneration temperature must be increased in order to produce the same final temperature and humidity (this is explained in Harvey 2006, Box 6.5). An important corollary is that the COP will be lower if the desiccant cycle is applied to outside air that has been mixed with recirculated indoor air (as in most conventional systems). This is another factor in favour of dedicated outdoor air supplies, but these require supplemental hydronic heating and cooling so as to avoid excessively large ventilation airflows.

With regard to indoor air quality, a significant advantage of desiccant systems is that dehumidification is accomplished without saturation, thereby eliminating the potential for the growth of mould and bacteria and associated health hazards (in most HVAC systems, the cooling coil will be wet 90% or more of the time). As well, the growth of mould and bacteria on the cooling coil increases the resistance to airflow (thereby increasing fan energy use) and decreases the effectiveness of heat exchange (thereby increasing the energy use by the compressor), although these energy impacts are not well quantified. Mould and bacterial growth are normally constrained through acid cleaning (which is not completely effective) or through the use of UV radiation (which consumes further energy).

Synergies between building envelopes and heating and cooling systems

During the heating season, a high-performance building envelope reduces the total heat loss but also the maximum rate at which heat is loss. This in turn reduces the rate at which heat must be supplied by ventilation air or radiators. As the rate of heat supply depends on the difference between the radiator temperature and ambient air, this in turns permits lower radiator temperatures, which in turn means that hot water for heating can be supplied at a lower temperature. This in turn leads to more efficient operation of boilers and especially of heat pumps. The lowest distribution temperatures can be achieved through floor radiant heating systems; in new, thermally-tight buildings in cold climates, a distribution temperature of 30-35°C can be used, compared to a typical supply temperature of 70-90°C used in Europe. For an outside temperature of 0°C, reducing the distribution temperature from 70°C to 30°C doubles the heat pump COP.

Similarly, during the cooling season, a reduction in cooling loads means that radiator coils (or chilled-ceiling panels) do not need to be as cold, which in turn means that the cooling water in hydronic systems can be supplied at a warmer temperature. With chilled ceiling panels, cooling water can be supplied at 16-20°C (warmer at smaller cooling loads) instead of the usual 5-7°C used in fan-coil systems. This in turn leads to more efficient operation of chillers (COPs up to 1.0-3.0 larger), as the evaporator can be set to a warmer temperature. Further savings are possible because now cooling water supplied to the chiller condenser from the cooling tower (in buildings with water-cooled rather than air-cooled chillers) will more often be cold enough to be directly used for cooling purposes, bypassing the chiller altogether (this is referred to as water-side free-cooling). Assuming the chilling water to be supplied at 18°C, a cooling tower could directly meet cooling requirements 97% of the time in Dublin and 67% of the time in Milan according to Costelloe and Finn (2003). If chilling water at 20°C is adequate, then evaporative cooling in a cooling tower is sufficient 99% of the time in Dublin and 78% of the time in Milan.

Lighting Systems

Lighting systems provide another example where system-level considerations and especially human behaviour can often provide larger savings than are possible through improved energy-using lamps and ballasts, even though the potential energy savings from these is often a factor of two or more (depending on the baseline). The basic tool of contemporary lighting design seems to be the rectangular grid, with lighting layout usually guided by non-lighting considerations such as the spacing of ceiling tiles rather than actual lighting needs. System-level considerations involve: a mix of task and ambient lighting (lower background lighting levels, with individually-controlled, greater levels of lighting when and where it is needed); incorporation of daylighting with light sensors, occupancy sensors, and dimmable electric lighting so that electric lighting levels can actually be varied according to the sunlight contribution and automatically turned off when a space is unoccupied; and wiring of lighting controls to coincide with zones having different degrees of daylighting.

Building form and glazing area can significantly affect the extent to which daylighting can replace electric lighting, but this also has implications for heating and cooling loads. Thus, lighting energy use should not be analyzed in isolation, but as part of an optimized system of overall energy use. Computer algorithms to automatically control adjustable shading devices can be designed to minimize the sum of lighting plus cooling energy use for a given building, occupancy schedule, and climate. If only the amount of daylight needed for a given task is allowed to enter a building, cooling energy requirements will be reduced compared to the use of electric lighting, adding to the energy savings from reduced electric lighting loads. Peak electrical and cooling loads are also reduced, allowing downsizing of cooling systems and electrical transformers, and reducing costs.

It appears that most people require less light at night and on cloudy days, because of less window glare but also because requirements are conditioned in part by expectations (Torcellini et al. 2004). This parallels the finding that the acceptable temperature range depends in part on expectations, which vary with outside conditions. An added benefit of task/ambient lighting, then, is that it allows the lighting level to be adjusted to changing preferences, as well as to differences between users.

Recirculation-loop domestic hot-water systems

Recirculation-loop (RL) domestic hot-water systems provide another example of dramatic energy savings that can be achieved at the system level, with no change in the efficiency of individual devices (hot-water boilers and pumps in this case). In RL systems, water is heated and stored in a central tank, continuously circulated through a closed loop to all the points of use, and consumed as needed. This keeps the hot-water pipes warm, so that hot water is instantly available when the faucet is opened. Apart from convenience, this avoids wasting hot water by running the faucet until the pipes have warmed sufficiently to deliver hot water to the faucet. Since the purpose of recirculation is to keep the pipes warm, the required flow can be reduced by insulating the pipes well. Since pumping power varies with the flow rate to the third power, dramatic reductions in pump energy use are possible along with reduced heat loss. However, even with well-insulated piping, piping heat losses can constitute 40% to more than 50% of the total hot-water load (Goldner 1999; Lutz et al. 2002). An alternative is point-of-use water (POU) heaters, in which water heaters are located at or very close to the point of use.

Hiller et al. (2002) monitored the energy use in a new (1997 opening) school in Tennessee using an RL system serving six points of use, and again after it was converted to a POU system with three water heaters and short piping. An impressive 91% savings in total (pump+water heater) energy use was achieved. The POU water heaters were operated continuously, but it is estimated that they could have been shut down at night, on weekends, and during school holidays, with a further energy savings of 40% (bringing the total savings to 94.3%).

Humans as part of the energy-using system

Humans are a critical part of the building energy systems, especially where passive ventilation and daylighting are part of the building, and with regard to the control of HVAC systems. In particular, adoption of an adaptive thermal comfort standard – in which the indoor temperature is allowed to vary with the outdoor temperature – can save substantial amounts of energy. Fortunately, it turns out that the indoor temperature perceived as “comfortable” increases with increasing outdoor temperature. Thus, buildings do not need to be cooled to as low a temperature on the hottest days of the year as on other days. Furthermore, a large body of evidence indicates that the temperature and humidity set-points in general are significantly lower than necessary (de Dear and Brager 1998; Fountain et al. 1999). Increasing the thermostat from 24°C to 28°C in summer will reduce annual cooling energy use by more than a factor of three for a typical office building in Zurich and by more than a factor of two in Rome (Jaboyedoff et al. 2004), while increasing the thermostat setting from 23°C to 27°C for night-time air conditioning of bedrooms in apartments in Hong Kong reduces cooling energy use by a factor of 2-3 (Lin and Deng 2004).

INCREMENTAL COST OF HIGH-PERFORMANCE BUILDINGS

By treating buildings as systems, and focusing on system-level efficiencies (while not neglecting the efficiency, proper sizing, and commissioning of individual energy-using devices), dramatic savings of energy use can be achieved, often while improving indoor air quality, and often at lower first cost. Some examples, discussed more fully in Harvey (2006), are

- Commercial buildings in Vancouver with radiant-slab heating and cooling and high-performance windows have a first cost about 10% less than conventional buildings and require 45% less annual energy use.
- HVAC systems using chilled ceiling panels and dedicated outdoor air supply with sensible and latent heat exchangers cost the same or slightly less than the conventional system, while reducing energy use by 30% in the US (Mumma 2001).
- A recently-completed science building at Concordia University, Montreal, with offices, classrooms, and 250 fume hoods, achieved a 45% reduction in energy use while increasing the total building cost by only 2.3%, resulting in a payback time of 19 months (Lemire and Charneux 2005).
- The cost premium for buildings meeting the LEED Silver standard and saving on average 30% of the normal energy use is 2.11%, while for buildings meeting the LEED Gold standard and saving on average 48% cost only 1.82% more on average (some of the extra costs in this example are due to incorporation on non-energy features) (Kats et al 2003).
- Measured performance on 10 buildings in the German *Solar optimized building – SolarBau* programme achieved the programme target of 100 kWh/m^2/yr total energy use, compared to 300-600 kWh/m^2/yr for typical German and Swiss office buildings (Wagner et al. 2004). Additional costs are reported to be comparable to the difference in cost between alternative standards for interior finishings.
- A new 16-storey building at the Oregon Health and Science University is expected to achieve an energy savings of 60% relative to the ASHRAE 90.1-1999 building code, with a net first-cost savings of about \$3.5 million out of an original budget of \$145.4 million and operating cost savings of \$600,000 per year (Interface Engineering 2005).

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