CHAPTER 35

SUSTAINABILITY

THE Brundtland Commission of the United Nations (UN 1987) stated that development of the built environment is sustainable "…if it meets the needs of the present without compromising the ability of future generations to meet their own needs." Given the profound impact of buildings on the environment, the work of HVAC&R design engineers is inextricably linked to sustainability. The engineering sector has seminal influence on building performance, and HVAC&R designers' work is inherently related to overall sustainability in buildings.

HVAC&R engineering design on projects concerned with performance and sustainability requires understanding of and involvement with more than just HVAC, including projected energy and water demands, stormwater runoff generation, waste generation, and air quality impacts. This chapter is intended to provide key information and identify reference sources for further resources on

- Defining the energy, water, and other resource-consuming aspects of projects
- Quantifying the relative environmental impacts of competing design alternatives

These aspects of sustainability are addressed with respect to energy and water conservation, greenhouse gas and air quality impacts, and other impacts of buildings, such as stormwater runoff and potable water use.

The need to address sustainability in the built environment is being accelerated by external pressures such as environmental and resource concerns, rising energy prices, indoor environmental quality, global warming, and energy security. While economies transition from carbon-based to other forms of more sustainable energy, engineers will be challenged to meet an ever-increasing tide of regulation and demand.

DEFINITION

Sustainability has been defined in the *ASHRAE GreenGuide* (ASHRAE 2006a), in general terms, as "providing for the needs of the present without detracting from the ability to fulfill the needs of the future," a definition very similar to that developed in 1987 by the United Nations' Brundtland Commission (UN 1987). Others have defined sustainability as "the concept of maximizing the effectiveness of resource use while minimizing the impact of that use on the environment" (ASHRAE 2006b) and an environment in which ". . . an equilibrium . . . exists between human society and stable ecosystems" (Townsend 2006).

Sustaining (i.e., keeping up or prolonging) those elements on which humankind's existence and that of the planet depend, such as energy, the environment, and health, are worthy goals.

CHARACTERISTICS OF SUSTAINABILITY

Sustainability Addresses the Future

Sustainability is focused on the distant future (e.g., 30 to 50 years). Any actions taken under the name of sustainability must address the impact of present actions on conditions likely to prevail in that future time frame.

In designing the built environment, the emphasis has often been on the present or the near future, usually in the form of capital- or first-cost impact. As is apparent when life-cycle costing analysis is applied, capital cost assumes less importance the longer the future period under consideration.

This emphasis on the distant future can differentiate sustainable design from **green design**. Whereas green design addresses many of the same characteristics as sustainable design, it may also emphasize near-term impacts such as indoor environmental quality, operation and maintenance features, and meeting current client needs. Thus, green design may focus more on the immediate future (i.e., starting when the building is first constructed and then occupied). Sustainable design is of paramount importance to the global environment in the long-term while still incorporating features of green design that focus on the present and near future.

Sustainability Has Many Contributors

Sustainability is not just about energy, carbon emissions, pollution, waste disposal, or population growth. Although these are central ideas in thinking about sustainability, it is an oversimplification to think that addressing one factor, or even any one set of factors, can result in a sustainable future for the planet.

It is likewise a mistake to think that HVAC&R design practitioners, by themselves and just through activities within their purview, can create a sustainable result. To be sure, their activities can *contribute* to sustainability by creating a sustainable building, development, or other related project. But they cannot *by themselves* create global sustainability. Such an endeavor depends on many outside factors that cannot be controlled by HVAC&R engineers; however, they should make their fair-share contribution to sustainability in all their endeavors, and encourage other individuals and entities to do the same.

Sustainability Is Comprehensive

Sustainability has no borders or limits. A good faith effort to make a project sustainable does not mean that sustainability will be achieved globally. A superb design job on a building with sustainability as a goal will probably not contribute much to the global situation if a significant number of other buildings are not so designed, or if the transportation sector makes an inadequate contribution, or if only a few regions of the world do their fair share toward making the planet sustainable. A truly sustainable outcome thus depends on efforts in all sectors the world around.

Technology Plays Only a Partial Role

It may well be that in due time technology will have the theoretical *capability*, if diligently applied, to create a sustainable future for

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the planet and humankind. Having the capability to apply technology, however, does not guarantee that it will be applied; that must come from attitude or mindset. As with all things related to comprehensive change, there must be the *will.*

For example, automobile companies have the technical capability to make cars that are much more efficient, to the extent that some developed countries now dependent on imported oil could be self-sufficient. But that is not the case, perhaps because there is a lack of demand or because car companies are not required to build them. The technology is available, but the will is not there; motivation is absent.

Similarly, HVAC&R designers know how to design buildings that are much more energy efficient than they have been in the past, but such buildings are still relatively rare. ASHRAE's long-standing guidance in designing energy efficient—and now green and sustainable—buildings, along with the motivation provided by the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED®) Green Building Rating System™ and the American Institute of Architects' (AIA) commitment to stringent energy efficiency goals, have pointed the way technologically for the built environment and related industries to make their fair-share contribution to sustainability.

There is little ASHRAE, within its technological purview, can do directly about other, nontechnological barriers. It can, however, set a good example in its area of expertise and can also encourage and inspire other sectors to do their part to move towards sustainability.

FACTORS IMPACTING SUSTAINABILITY

The major factors impacting global sustainability are the following:

- Population growth
- Food supply
- Disease control and amelioration
- Energy resource availability
- Material resource availability and management
- Fresh water supply, both potable and nonpotable
- Effective and efficient usage practices for energy resources and water
- Air and water pollution
- Solid and liquid waste disposal
- Land use

The preceding are only broad categories, yet they encompass many subsidiary factors that have received public attention recently. For instance, climate change/global warming, carbon emissions, acid rain, deforestation, transportation, and watershed management are important factors as well. However, each of these can be viewed as a subset of one or more of the listed major areas.

PRIMARY HVAC&R CONSIDERATIONS IN SUSTAINABLE DESIGN

The main areas falling within an HVAC&R designer's (and ASHRAE's) purview on most projects are those dealing with energy and water use, material resources, air and water pollution, and solid waste disposal. Although HVAC&R professionals' expertise may impact issues such as land use and food supply on certain specialized projects, these more typically fall under the purview of other professionals and their organizations.

Energy Resource Availability

Although conventional energy resources and their availability largely fall beyond the scope of HVAC&R designers' work, an understanding of these topics is often required for participation in project discussions or utility programs relating to projects. Chapter 34 has more information on energy resources.

Some **renewable** energy resources, in contrast with traditional energy and fuels, are ubiquitous by nature and are thus available on many building sites. **Wind** and **solar** energy are widely distributed (if not always continuously available) on almost any site for use in active or passive ways. High-level (high-temperature) **geothermal** energy is only present at limited sites, and may thus be unavailable as a direct energy source on a multitude of relevant projects. Low-level geothermal, on the other hand, is dependent on the nearly constant temperature of the near-surface earth and thus can be used on almost any project if other factors align in its favor.

Designers should be familiar with the characteristics of common traditional (nonrenewable) energy resources (natural gas, heating oil, electricity) from the standpoint of their use in the relevant application. Designers are typically very familiar with the relative per-unit cost as it affects the operating cost of the building being designed. Other energy characteristics traditionally taken into account by the designer might also include ease of handling and use, cleanliness, emissions produced, and local availability, because these also have a direct effect on design and installation. Until recently, designers have not had reason to consider an energy resource's characteristics beyond the site line of the project at hand.

However, recent public focus on the impacts of building energy use on the environment has changed that approach. Designers now must consider a resource's broader characteristics that may affect the regional, national and global environment, such as its origin (domestic or foreign), future availability, emissions characteristics, broad economics, and social acceptability. Though responsible designers may not be able to do much about such factors, they should be aware of them; indeed, that awareness may affect decisions within the designer's control.

For instance, familiarity with an energy resource's emissions characteristics, whether at the well head, mine mouth, or generating station, may influence the designer to make the building more energy efficient, or provide the designer with arguments to convince the owner that energy-saving features in the building would be worth additional capital cost. Furthermore, as owners and developers of buildings become more aware of sustainability factors, designers must stay informed of the latest information and impacts.

One way to reduce a project's use of nonrenewable energy, beyond energy-efficient design itself, is to replace such energy use with renewable energy. Designers should develop familiarity with how projects might incorporate and benefit from renewable energy. Many kinds of passive design features can take advantage of naturally occurring energy.

Increasingly common examples of nonpassive approaches are solar systems, whether photovoltaic (electricity-generating) or solar thermal (hot-fluid generating). Low-level geothermal systems take advantage of naturally occurring and widely distributed earth-embedded energy. Wind systems are increasingly applied to supplement electric power grids, and are also sometimes incorporated on a smaller scale into on-site or distributed generation approaches.

Some large power users, such as municipalities or large industries, require that a minimum percentage of power they purchase be from renewable sources. Also, renewable portfolio standards are being imposed on electric utility companies by regulators.

Fresh Water Supply

HVAC&R systems can impact potable and nonpotable water supplies both directly and indirectly. First, some building systems use potable water, for example in evaporative cooling towers. Second, some building systems can discharge treated water or other waste streams with contaminants of concern that can impact local watersheds and water supplies. Indirect impacts include the use of water by utilities for electricity generation.

Effective and Efficient Use of Energy Resources and Water

This area is where HVAC&R engineers can have a profound impact on achieving sustainability goals. Impacts of building consumption can be at least partially mitigated through overall system performance improvement, as well as through increased use of on-site renewable energy and certain off-site energy resources. See the section on Designing for Effective Energy Resource Use for more information on addressing energy efficiency in the design process.

Building systems' water use can be reduced by reusing clean water from on-site, such as condensate drain water, or by using less potable water. For example, hybrid cooling towers can operate as water-to-air heat exchangers when run dry, and can operate their water sprays for additional evaporative capacity only when conditions require. In process control and refrigeration systems, similar opportunities exist. For more information on water use, the USGBC's LEED rating systems each include a section on water efficiency and provide guidance on controlling water use in buildings.

Discharge from building systems can be reduced through careful design, proper sequences and control, choice of lower impact chemical treatment regimes, or nonchemical water treatment. These techniques may not eliminate chemical treatment in all applications, but it can be substantially reduced.

Material Resource Availability and Management

Designers do not typically focus on embodied impacts of their systems design. For example, within the LEED framework, building systems under the purview of HVAC&R designers are currently excluded from credits for locally procured building materials and resources. However, the same concepts can be applied in selection and procurement of HVAC&R system components. For example, recycled steel content in system components could be required to be stated in HVAC&R product submittals. In some areas, locally assembled or manufactured components may be available that can reduce transportation impacts.

Air, Noise, and Water Pollution

HVAC&R systems and equipment can interact with both local and global environments. On a local scale, HVAC&R systems interact with the environment in ways such as acoustical noise generated by heat rejecting equipment (e.g., condensing units, cooling tower). Occasionally, this may require the addition of special barriers to prevent sound migration from the site, as shown in Figure 1.

Local impacts of combustion from on-site heat or electricity generation can be mitigated to an extent through careful consideration of the location of sources (emitters) with respect to nearby receptors, including outdoor air intakes and residences or other buildings with operable windows.

On a larger scale, air and water pollution occurs indirectly through the consumption of energy to operate building systems. This occurs in generating the electricity (whether from fossil fuel, nuclear, or hydroelectric resources), steam, or hot water for building heating or cooling. In this sense, improved efficiency is an approach to partial mitigation.

Solid and Liquid Waste Disposal

The solid waste disposal burden from installation and operations of building systems can be substantially reduced. Competing alternatives can be assessed through life cycle analysis. For example, an air-cooled unitary system with a shorter service life than a costlier water-cooled alternative could, over the course of the building's life, increase the solid waste burden when it is discarded.

An example of an HVAC&R design impacting liquid waste disposal is using glycol to protect coils from freezing, where the glycol must be eliminated in summer to provide required capacity. Because reusing glycol is not a common practice, such a design would likely result in an annual glycol discharge.

Fig. 1 Cooling Tower Noise Barrier
(Courtesy Neil Moiseev)

In many locations, water quality regulations and agencies essentially limit or prohibit liquid waste disposal. Other approaches to pursue in reducing liquid waste disposal are discussed in the section on Effective and Efficient Use of Energy Resources and Water.

FACTORS DRIVING SUSTAINABILITY INTO DESIGN PRACTICE

HVAC&R designers face many challenges as they assimilate sustainability into their engineering practices. These challenges include climate change, a fast-changing regulatory and legal environment, and evolving standards of care. New tools, technologies, and approaches are required for well-prepared HVAC&R engineers. The challenges and the responses are creating new opportunities, just as changing project processes are allowing or requiring engineers to participate in projects in new ways.

Climate Change

In addition to their causal role (IPCC 2007), energy systems are exposed to significant vulnerabilities resulting from climate change. Increased volatility in weather profoundly affects HVAC&R practice. Historical weather data and extremes may inadequately describe conditions faced by a project built today, even over a modest lifespan for a building.

In 2001, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) (www.ipcc.ch) to study and report on the scientific issues, potential impacts and mitigation methods associated with climate change. A series of publications were produced that discuss the possible outcomes and interventions required to mitigate the impacts of anthropogenic emissions.

Responsible designers are concerned with two dimensions of climate change: not only *what* they can do to reduce their designs' contribution, but also *whether* and *how* their designs should anticipate the future. It is the first that is the focus of this chapter and a majority of the available information on sustainable design. Warming trends currently occurring have been quantified with certainty. As a result, historical weather data may not be the best source for load calculations. Depending on the rate of change, anticipating future weather may become more significant in its impact on the climate control of building systems.

Regulatory Environment

The global community has responded to two major environmental issues during the past two decades. In the late 1980s, the Montreal Protocol (UNEP 2003) regulated the manufacture and trade of refrigerants which had been shown to damage the stratosphere and the troposphere by depleting atmospheric ozone. The effect on the HVAC&R industry was to require research and investment in alternative materials to those that had become the mainstays of the industry (Figure 2).

Next came the much more controversial issue of greenhouse gas emissions (and their potential for causing global warming) in the early 1990s. In response to these threats, many countries have signed and accepted the Kyoto Protocol (UNFCCC 1998), which places limits on these emissions.

Both the underlying science and the regulation of greenhouse gas emissions, primarily concerning (but not limited to) carbon dioxide (CO_2), have been embroiled in politics. A consensus has finally been expressed from within the scientific community, which has spurred political and regulatory action. The Fourth Assessment Report of the World Meteorological Organization's International Panel for Climate Change (IPCC 2007) cites widespread consensus from hundreds of scientists worldwide that rising CO_2 levels are primarily attributable to human factors as well as being responsible for warming of the lower atmosphere and associated major impact on the environment and societies.

An emissions trading program for CO_2 equivalents, already in place in the European Union, has started in the United States. Such a program will change the way of thinking for engineers and industry as new opportunities and challenges emerge. For example, a rigorous measurement and verification approach could quantify reduced building energy use and allow building owners to monetize the associated carbon reduction.

Evolving Standards of Care

Litigation relating to sustainability and global climate issues has increased. For example, a consortium of states successfully sued to force the U.S. Environmental Protection Agency (EPA) to consider CO_2 a pollutant that is harming the environment and thus take measures to regulate its emissions. This ruling is one of several developments in the continued and broadened response to CO_2 emissions by society at large. Building design and construction industries are already being impacted.

In the United States, some states have adopted carbon legislation, such as California's Global Warming Solutions Act of 2006. There and elsewhere, environmental impact reports are increasingly addressing not only local and immediate pollutant impacts, such as stormwater run-off, but greenhouse gas emissions as well.

Changing Design Process

Even in jurisdictions without regulatory change, change is happening in the HVAC&R industry. Today's engineer can contribute value to projects that include sustainability goals, using some of the many resources and approaches cited in this chapter.

ASHRAE, in partnership with the Illuminating Engineering Society of North America (IESNA) and the USGBC, has begun developing *Standard* 189 for high-performance green buildings, which intends to call for a determination of annual CO_2 equivalent emissions in addition to overall energy savings and other requirements. The component of such emissions from electricity use depends on the mix of fuels used to generate the electricity. In addition to regional variations, the overall fuel mix is projected to change, as shown in Figure 3.

Emissions considerations alone are not the only driver for design decision-making. Energy price pressures continue to mount. Examples of recent pressures include

- Antiquated electric transmission and distribution infrastructure
- Power plants being forced to become cleaner and more efficient, expediting closure of cheap, dirty generators
- Mandates imposed on utilities to provide more renewable energy to customers
- Influence of commodities trading markets on spot and future prices
- Constrained natural gas reserves and growth in demand continuing to increase volatility in the natural gas market
- Global warming, through environmental pressures to reduce carbon emissions in the face of increased demand for electricity, and infrastructure damage from more frequent storms

These and other pressures are changing project teams and their work, which are being asked to

- Incorporate sustainable design guidance and rating systems into their work
- Add a variety of new team members who bring additional expertise to address sustainability
- Gather quantitative data related to energy, water, greenhouse gas emissions, etc.
- Use new analysis tools to help maximize sustainability

Opportunities relating to sustainability for the well prepared engineer are growing. The increased focus on sustainability in the built

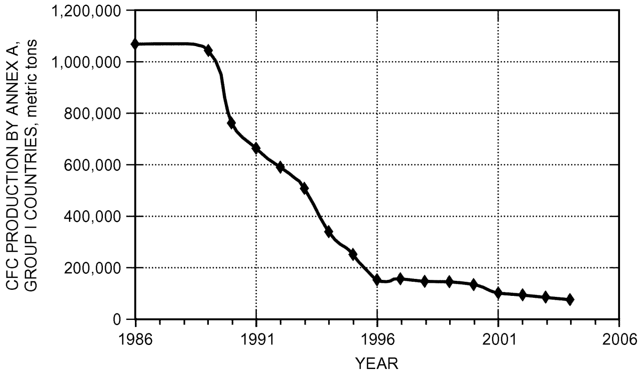

Fig. 2 Effect of Montreal Protocol on Global Chlorofluorocarbon (CFC) Production

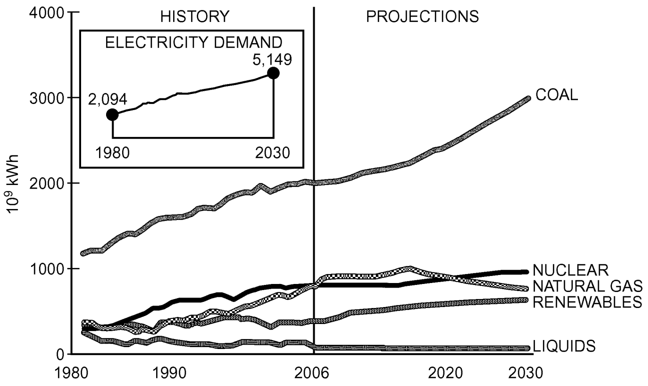

Fig. 3 Electricity Generation by Fuel, 1980–2030
(EIA 2008)

environment allows for more integrated, effective, and efficient ways to meet the nexus between environment, economy, and regulation. The challenge for the industry is how quickly it can adapt to these new opportunities and grow in an increasingly regulated environment. At the very least, the standard of care for engineers must be tracked and implemented to manage liability. Sustainability can provide an avenue for engineers and others to increase market share while exceeding current regulatory constraints and anticipating future regulations. More details on design considerations are provided in the section on Designing for Effective Energy Resource Use.

Integrating sustainability into HVAC&R system design can result in built environments that respect the greater environment and provide safe and comfortable indoor environments. The three occurrences of the letter *i* in *sustainability* can be thought of as representing key concepts in sustainable design: *interactive*, *iterative*, and *integrated*. Design processes that require greater interaction between team members and more iterative analysis to improve design solutions can be undertaken by teams through what has become known as integrated design.

Sustainability is inherently multidisciplinary. Recognizing this, teams often assemble a broad array of experts in a collaborative, interdisciplinary approach to achieve the highest levels of sustainability possible. This integrated design approach is addressed in Chapter 57 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Other Opportunities

In addition to designing HVAC&R systems, engineers may increasingly be called upon to help address issues ranging from transportation to irrigation to on-site renewable energy. The approach to sustainable design alternatives opens the door for creativity and innovation in the design process. Rather than taking a "one-size-fits-all" approach to design, engineers can provide a range of available solutions and facilitate flexible implementation. Often, engineers will be asked to develop and evaluate measures based on economic and environmental performance. Success may require design iterations to achieve the desired performance.

DESIGNING FOR EFFECTIVE ENERGY RESOURCE USE

Most energy used in buildings is from nonrenewable resources, the cost of which historically has not considered replenishment or environmental impact. Thus, consideration of energy use in design has been based primarily on economic advantages, which are weighted to encourage more rather than less use.

As resources become less readily available and more exotic, and replenishable sources are investigated, the need to operate buildings effectively using less energy becomes paramount. Extensive study since the mid-1970s has shown that building energy use can be significantly reduced by applying the fundamental principles discussed in the following sections.

Energy Ethic: Resource Conservation Design Principles

The basic approach to energy-efficient design is reducing loads (power), improving transport systems, and providing efficient components and "intelligent" controls. Important design concepts include understanding the relationship between energy and power, maintaining simplicity, using self-imposed budgets, and applying energy-smart design practices.

Energy and Power

From an economic standpoint, more energy-efficient systems need not be more expensive than less efficient systems. Quite the opposite is true because of the simple relationship between energy and power, in which power is simply the time rate of energy use (or, conversely, energy is power times time). Power terms such as horsepower, ton of refrigeration, Btu per hour, or kilowatt are used in expressing the size of a motor, chiller, boiler, or transformer, respectively. Generally, the smaller the equipment, the less it costs. Other things being equal, as smaller equipment operates over time, it consumes less energy. Thus, in designing for energy efficiency, the first objective is always to reduce the power required to the bare minimum necessary to provide the desired performance, starting with the building's heating and cooling loads (a power term, in Btu/h and continuing with the various systems and subsystems.

Simplicity

Complex designs to save energy seldom function in the manner intended unless the systems are continually managed and operated by technically skilled individuals. Experience has shown that long-term, energy-efficient performance with a complex system is seldom achievable. Further, when complex systems are operated by minimally skilled individuals, both energy efficiency and performance suffer. Most techniques discussed in this chapter can be implemented with great simplicity.

Self-Imposed Budgets

Just as an engineer must work to a cost budget with most designs, self-imposed power budgets can be similarly helpful in achieving energy-efficient design. The series of Advanced Energy Design Guides from ASHRAE are a source for guidance on achievable design budgets. For example, the following are possible categories of power budgets for a mid-rise office building:

• Installed lighting (overall)	W/ft^2
• Space sensible cooling	Btu/h·ft^2
• Space heating load	Btu/h·ft^2
• Electric power (overall)	W/ft^2
• Thermal power (overall)	Btu/h·ft^2
• Hydronic system head	ft of water
• Water chiller (water-cooled)	kW/ton
• Chilled-water system auxiliaries	kW/ton
• Unitary air-conditioning systems	kW/ton
• Annual electric energy	kWh/ft^2·yr
• Annual thermal energy	Btu/ft^2·yr·°F·day

As the building and systems are designed, all decisions become interactive as each subsystem's power or energy performance is continually compared to the budget.

Design Process for Energy-Efficient Projects

Consider energy efficiency at the beginning of the building design process, because energy-efficient features are most easily and effectively incorporated at that time. Seek the active participation of all members of the design team, including the owner, architect, engineer, and often the contractor, early in the design process. Consider building attributes such as building function, form, orientation, window/wall ratio, and HVAC system types early in the process, because each has major energy implications. Identify meaningful energy performance benchmarks suited to the project, and set project-specific goals. Energy benchmarks for a sample project are shown in Table 1. Consider energy resources, on-site energy sources, and use of renewable energy, credits, or carbon offsets to mitigate environmental impacts of energy use.

Address a building's energy requirements in the following sequence:

1. **Minimize the impact of the building's functional requirements** by analyzing how the building relates to its external environment. Advocate changes in building form, aspect ratio, and other attributes that reduce, redistribute, or delay (shift) loads. The load calculation should be interactive so that the effect of those factors can be seen immediately.
2. **Minimize loads** by analyzing external and internal loads imposed on the building energy-using subsystems, both for

peak- and part-load conditions. Design for efficient and effective operation off-peak, where the majority of operating hours and energy use typically occurs.

3. **Maximize subsystem efficiency** by analyzing the diversified energy and power requirements of each energy-using subsystem serving the building's functional requirements. Consider static and dynamic efficiencies of energy conversion and energy transport subsystems, and consider opportunities to reclaim, redistribute, and store energy for later use.
4. **Study alternative ways to integrate subsystems** into the building by considering both power and time components of energy use. Identify, evaluate, and design each of these components to control overall design energy consumption. Consider the following when integrating major building subsystems:
   - Address more than one problem at a time when developing design solutions, and make maximum use of the building's advantageous features (e.g., windows, structural mass).
   - Examine design solutions that consider time (i.e., when energy use occurs), because sufficient energy may already be present from the environment (e.g., solar heat, night cooling) or from internal equipment (e.g., lights, computers) but available at times different from when needed. Active (e.g., heat pumps with water tanks) and passive (e.g., building mass) storage techniques may need to be considered.
   - Examine design solutions that consider the anticipated use of space. For example, in large but relatively unoccupied spaces, consider task or zone lighting. Consider transporting excess energy (light and heat) from locations of production and availability to locations of need instead of purchasing additional energy.
   - Never reject waste energy at temperatures usable for space conditioning or other practical purposes without calculating the economic benefit of energy recovery or treatment for reuse.
   - Consider or advocate design solutions that provide more comfortable surface temperatures or increase the availability of controlled daylight in buildings where human occupancy is a primary function.
   - Use easily understood design solutions, because they have a greater probability of use by building operators and occupants.
   - Where the functional requirements of a building are likely to change over time, design the installed environmental system to adapt to meet anticipated changes and to provide flexibility in meeting future changes in use, occupancy, or other functions.
   - Develop energy performance benchmarks, metrics, and targets that will allow building owners and operators to better realize the design intent. Differentiate between peak loads for system design and selection and lower operating loads that determine actual energy use.

Building Energy Use Elements

Envelope.

Control thermal conductivity by using insulation (including movable insulation), thermal mass, and/or phase-change thermal storage at levels that minimize net heating and cooling loads on a time-integrated (annual) basis.

- Minimize unintentional or uncontrolled thermal bridges, and include them in energy-related calculations because they can radically alter building envelope conductivity. Examples include wall studs, balconies, ledges, and extensions of building slabs.
- Minimize infiltration so that it approaches zero. (An exception is when infiltration provides the sole means of ventilation, such as in small residential units.) This minimizes fan energy consumption in pressurized buildings during occupied periods and minimizes heat loss (or unwanted heat gain, in warm climates) during unoccupied periods. In warm, humid climates, a tight envelope also improves indoor air quality. Reduce infiltration through design details that enhance the fit and integrity of building envelope joints in ways that may be readily achieved during construction (e.g., caulking, weatherstripping, vestibule doors, and/or revolving doors), with construction meeting accepted specifications.
- Consider operable windows to allow occupant-controlled ventilation. This requires careful design of the building's mechanical system to minimize unnecessary HVAC energy consumption, and building operators and occupants should be cautioned about improper use of operable windows. CIBSE (2005) provides comprehensive design considerations for natural ventilation.
- Strive to maintain occupant radiant comfort regardless of whether the building envelope is designed to be a static or dynamic membrane. Design opaque surfaces so that average inside surface temperatures remain within 5°F of room temperature in the coldest anticipated weather (i.e., winter design conditions) and so that the coldest inside surface remains within 25°F of room temperature (but always above the indoor dew point). In a building with time-varying internal heat generation, consider thermal mass for controlling radiant comfort. In the perimeter zone, thermal mass is more effective when it is positioned inside the envelope's insulation.

Table 1 Example Benchmark and Energy Targets for University Research Laboratory

	Gross	Lit/ Conditioned
Building area, ft^2	**170,000**	**110,500**

Electric	**Electricity for Lighting**	**Electricity for Ventilation (Fans)**	**Electricity for In-Building Pumps**	**Electricity for Plug Loads**	**Electricity for Unidentified Loads**	**Total Electricity**	**Cogenerated Electricity**	**NGrid Electricity**
Design load, W/ft^2 gross	0.52	0.50	0.60	0.97	—	2.60	—	
Peak demand, W/ft^2 gross	0.42	0.50	0.42	0.73	0.00016	2.07	—	
Peak demand, kW (Projected submetered peak)	71	85	72	124	20	372	—	
Annual consumption, kWh/yr (Projected submetered reading)	218,154	346,598	191,245	891,503	175,200	1,823,000	966,000	857,000
Annual use index goal, kWh/yr	1.28	2.04	1.12	5.24	1.03	10.72		
Annual use index goal, site Btu/ft^2 gross·yr	4378	6956	3838	17,893	3516	36,583		
Annual use index, kWh/ft^2 gross·yr*	2.51 to 3.32	4.48 to 6.88	included elsewhere	4.39 to 5.67	NA	14.74 to 17.91		
Annual use index, site Btu/ft^2 gross·yr*	8564	15,286	—	14,979	—	50,293 to 61,109		

*From Labs21 program of U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE). See http://www.epa.gov/lab21gov/index.htm.

- Effective control of solar radiation is critical to energy-efficient design because of the high level of internal heat production already present in most commercial buildings. In some climates, lighting energy consumption savings from daylighting techniques can be greater than the heating and cooling energy penalties that result from additional glazed surface area required, if the building envelope is properly designed for daylighting and lighting controls are installed and used. (In other climates, there may not be net savings.) Daylighting designs are most effective if direct solar beam radiation is not allowed to cause glare in building spaces.
- Design transparent parts of the building envelope to prevent solar radiant gain above that necessary for effective daylighting and solar heating. On south-facing facades (in the northern hemisphere), using low shading coefficients is generally not as effective as external physical shading devices in achieving this balance. Consider low-emissivity, high-visible-transmittance glazings for effective control of radiant heat gains and losses. For shading control, judicious use of vegetation may block excess gain year-round or seasonally, depending on the plant species chosen.

Lighting.

Lighting is both a major energy end use in commercial buildings (especially office buildings) and a major contributor to internal loads by increasing cooling loads and decreasing heating loads. Design should meet both the lighting functional criteria of the space and minimize energy use. IESNA (2000) recommends illuminance levels for visual tasks and surrounding lighted areas. Principles of energy-conserving design within that context include the following:

- Energy use is determined by the lighting load (demand power) and its duration of use (time). Minimize actual demand load rather than just apparent connected load. Control the load rather than just area switching, if switching may adversely affect the quality of the luminous environment.
- Consider daylighting with proper controls to reduce costs of electric lighting. Design should be sensitive to window glare, sudden changes in luminances, and general user acceptance of daylighting controls. Carefully select window treatment (blinds, drapes, and shades) and glazing to control direct solar penetration and luminance extremes while maintaining the view and daylight penetration.
- Design the lighting system so that illumination required for tasks is primarily limited to the location of the task and comes from a direction that minimizes direct glare and veiling reflections on the task. When the design is based on nonuniform illuminance, walls should be a light to medium color or illuminated to provide visual comfort. In densely occupied work spaces, uniform distribution of general lighting may be most appropriate. Where necessary, provide supplementary task illumination. General ambient illumination should not be lower than a third of the luminance required for the task, to help maintain visually comfortable luminance ratios.
- Use local task lighting to accommodate needs for higher lighting levels because of task visual difficulty, glare, intermittently changing requirements, or individual visual differences (poor or aging eyesight).
- Group similar activities so that high illuminance or special lighting for particular tasks can be localized in certain rooms or areas, and so that less-efficient fixtures required for critical glare control do not have to be installed uniformly when they are only required sparsely.
- Use lighting controls throughout so lighting is available when and where it is needed, but not wasted when tasks are less critical or spaces are not fully occupied. Also consider user acceptance of control strategies to maximize energy saving.
- Limit use of lower-efficiency lamps (e.g., incandescent) to applications where their color, lumens, or distribution characteristics cannot be duplicated by other sources. Limit use of extended-service incandescent lamps to applications where fixtures are difficult to reach and/or maintenance costs for replacing lamps would be excessive.
- Carry lighting design through the rest of the building's interior design. Reduced light absorption may be achieved by using lighter finishes, particularly on ceilings, walls, and partitions.

Other Loads.

- Minimize thermal impact of equipment and appliances on HVAC systems by using hoods, radiation shields, or other confining techniques, and by using controls to turn off equipment when not needed. Where practical, locate major heat-generating equipment where it can balance other heat losses. Computer centers or kitchen areas usually have separate, dedicated HVAC equipment. In addition, consider heat recovery for this equipment.
- Use storage techniques to level or distribute loads that vary on a time or spatial basis to allow operation of a device at maximum (often full-load) efficiency.

HVAC System Design.

- Consider separate HVAC systems to serve areas expected to operate on widely differing operating schedules or design conditions. For instance, systems serving office areas should generally be separate from those serving retail areas.
- Arrange systems so that spaces with relatively constant, weather-independent loads are served by systems separate from those serving perimeter spaces. Areas with special temperature or humidity requirements (e.g., computer rooms) should be served by systems separate from those serving areas that require comfort heating and cooling only. Alternatively, provide these areas with supplementary or auxiliary systems.
- Sequence the supply of zone cooling and heating to prevent simultaneous operation of heating and cooling systems for the same space, to the extent possible. Where this is not possible because of ventilation, humidity control, or air circulation requirements, reduce air quantities as much as possible before incorporating reheating, recooling, or mixing hot and cold airstreams. For example, if reheat is needed to dehumidify and prevent overcooling, *only* ventilation air needs to be treated, not the entire recirculated air quantity. Finally, reset supply air temperature up to the extent possible to reduce reheating, recooling, or mixing losses.
- Provide controls to allow operation in occupied and unoccupied modes. In the occupied mode, controls may provide for a gradually changing control point as system demands change from cooling to heating. In the unoccupied mode, ventilation and exhaust systems should be shut off if possible, and comfort heating and cooling systems should be shut off except to maintain space conditions ready for the next occupancy cycle.
- In geographical areas where diurnal temperature swings and humidity levels permit, consider judicious coupling of air distribution and building structural mass to allow nighttime cooling to reduce the requirement for daytime mechanical cooling.
- High ventilation rates, where required for special applications, can impose enormous heating and cooling loads on HVAC equipment. In these cases, consider recirculating filtered and cleaned air to the extent possible, rather than 100% outside air. Also, consider preheating outside air with reclaimed heat from other sources.

HVAC Equipment Selection.

- To allow HVAC equipment operation at the highest efficiencies, match conversion devices to load increments, and sequence the operation of modules. Oversized or large-scale systems should never serve small seasonal loads (e.g., a large heating boiler serving a summer-service water-heated load). Include specific low-load units and auxiliaries where prolonged use at minimal capacities is expected.

- Select the most efficient (or highest-COP) equipment practical at both design and reduced capacity (part-load) operating conditions.
- When selecting large-power devices such as chillers (including their auxiliary energy burdens), economic analysis of the complete life-cycle costs should be used. See Chapter 36 of the 2007 *ASHRAE Handbook—HVAC Applications* for more information on detailed economic analysis.
- Keep fluid temperatures for heating equipment devices as low as practical and for cooling equipment as high as practical, while still meeting loads and minimizing flow quantities.

Energy Transport Systems.

Energy should be transported as efficiently as possible. The following options are listed in order of efficiency, from the lowest energy transport burden (most efficient) to the highest (least efficient):

1. Electric wire or fuel pipe
2. Two-phase fluid pipe (steam or refrigerant)
3. Single-phase liquid/fluid pipe (water, glycol, etc.)
4. Air duct

Select a distribution system that complements other parameters such as control strategies, storage capabilities, conversion efficiency, and utilization efficiency.

The following specific design techniques may be applied to thermal energy transport systems:

Steam Systems.

- Include provisions for seasonal or non-use shutdown.
- Minimize venting of steam and ingestion of air, with design directed toward full-vapor performance.
- Avoid subcooling, if practical.
- Return condensate to boilers or source devices at the highest possible temperature.

Hydronic Systems.

- Minimize flow quantity by designing for the maximum practical temperature range.
- Vary flow quantity with load where possible.
- Design for the lowest practical pressure rise (or drop).
- Provide *operating* and *idle* control modes.
- When locating equipment, identify the critical pressure path and size runs for the minimum reasonable pressure drop.

Air Systems.

- Minimize airflow by careful load analysis and an effective distribution system. If the application allows, supply air quantity should vary with sensible load (i.e., VAV systems). Hold the fan pressure requirement to the lowest practical value and avoid using fan pressure as a source for control power.
- Provide *normal* and *idle* control modes for fan and psychrometric systems.
- Keep duct runs as short as possible, and keep runs on the critical pressure path sized for minimum practical pressure drop.

Power Distribution.

- Size transformers and generating units as closely as possible to the actual anticipated load (i.e., avoid oversizing to minimize fixed thermal losses).
- Consider distribution of electric power at the highest practical voltage and load selection at the maximum power factor consistent with safety.
- Consider tenant submetering in commercial and multifamily buildings as a cost-effective energy conservation measure. (A large portion of energy use in tenant facilities occurs simply because there is no economic incentive to conserve.)

Domestic Hot-Water Systems.

- Choose shower heads that provide and maintain user comfort and energy savings. They should not have removable flow-restricting inserts to meet flow limitation requirements.
- Consider point-of-use water heaters where their use will reduce energy consumption and annual energy cost.
- Consider using storage to facilitate heat recovery when the heat to be recovered is out of phase with the demand for hot water or when energy use for water heating can be shifted to take advantage of off-peak rates.

Controls.

Well-designed digital control provides information to managers and operators as well as to the data processor that serves as the intelligent controller. Include the energy-saving concepts discussed previously throughout the operating sequences and control logic. However, energy conservation should not be sought at the expense of inadequate performance; in a well-designed system, these two parameters are compatible. See Chapter 7 of this volume and Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* for more information on controls.

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