Part II

Adapting to a New Reality—Strategies for Building Energy Design in a Changing Climate

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ABSTRACT

Building energy design is traditionally performed using retrogressive data sets (e.g., the past 30 years of weather data). The implied presumption has always been that this data will cycle back and forth around relatively static baseline averages. With increasing evidence that some level of climate change may be occurring, it is natural for building owners, developers, designers, and managers to question whether (and to what extent) these fundamental climate assumptions may be altered in future years. Depending on a building's locality, this could take the form of increasing or decreasing trends in seasonal average temperatures, daily maximum and minimum temperatures, relative humidity, barometric pressure, wind speed and direction, cloud cover, and total precipitation. These assumptions are crucial, because a typical building must remain habitable for 30 to 50 years (or longer) and provide its owner with the maximum possible return on a sizeable capital investment.

This article will demonstrate how building owners and developers can employ intelligent strategies to maximize energy efficiency while concurrently meeting building energy requirements and retaining significant flexibility to cope with potential variations in local climate. Data from existing buildings that currently exhibit outstanding energy performance (e.g., net zero energy buildings, Leadership in Energy and Environmental Design [LEED®] Gold- and Platinum-certified buildings, buildings with ENERGY STAR® ratings above 90) will be utilized to identify energy efficiency and renewable energy production technologies that can further improve energy performance and reduce risk. This

article will demonstrate that, by implementing these types of adaptive strategies, the building sector can more nimbly respond to potential climate variations.

FUNDAMENTAL PRINCIPLES TO ADDRESS THE THREAT OF POTENTIAL CLIMATE CHANGE IMPACTS

Part I of this article (in SPEE 32, No. 4) demonstrated that climate change could impact building energy use and peak loads in a positive or negative manner, depending on a facility's location, design, and other factors. It also introduced a series of five Fundamental Principles (FPs) (see Table 1) to provide project planners and designers with straightforward, concise, and easily remembered axioms which will guide them as the project evolves from the charrette stage to conception and then to detailed design. These FPs, together with the innovative technologies and methods that they encourage (or particularly innovative applications of existing technologies and methods), will contribute to the three central goals of reducing energy consumption, reducing peak load, and increasing adaptability to local climate fluctuations. This Part II article addresses the three remaining FPs, namely:

- FP 3: Leverage "force multipliers."
- FP 4: Build down as well as up, and inward as well as outward.
- FP 5: Create systems that augment energy savings through occupant behavior.

Numerous case histories are discussed to illustrate recent, real-world applications of these concepts. (Refer to Appendix A for examples.) In many cases, due to limited data and information, the discussion is based on claims made by the project owner, sponsor, or other key stakeholder (e.g., the design architect or engineer). In general, due to limited time, it was not possible to obtain an objective confirmation of the building performance (e.g., interviews of occupants, public officials, etc.). In addition, while total facility energy performance data were available for nearly all case histories, disaggregation of these data to examine the contributions of individual measures or innovations discussed herein is an ongoing challenge that could require either additional years of operation or an increased body of literature.

Table 1. Fundamental Principles for Adaptive Buildings

Fundamental Principle (FP) 1 – Treat the Building Envelope as a Dynamic Membrane Rather than a Static Barrier • FP 1.1 – Adaptive Architecture • FP 1.2 – Harmonization of Building Indoor and Outdoor Environments
FP 2 – Replace Construct-Operate Model with Continuous Construction Model
FP 3 – Leverage "Force Multipliers" • FP 3.1 – LEED®, ENERGY STAR®, and Other Green Rating Systems • FP 3.2 – Innovative Technologies and Strategies • FP 3.3 – Worker Productivity and Student Achievement • FP 3.4 – Project Location and Climate • FP 3.5 – Administrative Measures • FP 3.6 – Models Other than Whole Building Energy Simulation • FP 3.7 – "Free" or Low-cost Money • FP 3.8 – Submetering • FP 3.9 – Exponential Relationships
FP 4 – Build Down as Well as Up and Inward as Well as Outward
FP 5 – Create Systems that Augment Energy Savings through Occupant Behavior

LEVERAGE FORCE MULTIPLIERS (FP 3)

The United States military services frequently use the term *force multiplier* for strategic planning, which, literally defined, means, "a capability that, when added to and employed by a combat force, significantly increases the combat potential of that force and thus enhances the probability of successful mission accomplishment" [1]. When used in the context of this article, force multipliers refer to factors that either directly contribute to improved energy performance and/or provide other significant benefits that would not otherwise be realized. Consider the situation of a project that has the objectives of reducing total energy consumption, reducing peak demand, and having greater adaptability to cope with climate fluctuations, but where the return on investment or other key metrics are marginal. The ability to leverage one or more of the force multipliers discussed in the following pages could reinforce the building developer's decision to: (1) proceed with the project, and (2) maximize, to the extent practicable, the building's expected energy performance through the use of applicable technologies, strategies, and practices.

Leadership in Energy and Environmental Design (LEED®), Energy Star®, and Other Green Building Rating Systems (FP 3.1)

LEED®, ENERGY STAR®, and similar systems can be used as more than merely a rating system to accumulate points or ratings and showcase a project. In fact, they can in many situations form a valuable, fundamental design philosophy (i.e., a "road map") for addressing the challenge of attaining significant energy consumption reduction and other green initiatives [2]. The benefits have been demonstrated through multiple projects and in numerous aspects, as indicated by the following examples:

- **Cost Savings**. For its Toledo, Ohio, headquarters building, Owens Corning facility managers estimated that the LEED®–related measures implemented during construction directly resulted in operation and maintenance (O&M) cost savings of at least $100,000 per year [3].

- **Energy/Fossil Fuel Savings**. A research project demonstrated that a midrise office facility located in Washington, DC, that followed an energy strategy predicated upon achieving a high LEED® score could reduce its annual fossil fuel consumption by over 80% [2].

- **Space Leasing Revenue (Rental Rates)**. A study by the University of California Energy Institute (UCEI) [4] concluded that a sample of 1,360 buildings that had earned LEED® certification and/or met ENERGY STAR® labeling requirements, on average, commanded rental rates 3-6% higher than a control sample of buildings. (The study indicated an actual premium of 3% in actual per-square-foot rent and 6% in "effective rent," defined as the rent per square foot multiplied by the occupancy rate.)

- **Property Value**. The above-referenced UCEI study found that resale values of the sample of LEED® and ENERGY STAR® buildings increased by approximately 16% in comparison with the control sample.

LEED® is designed to be a relatively flexible system; for each individual facility or project, the project stakeholders must balance the desired level of certification with other key goals. The Lillis Business

Complex (Eugene, Oregon) had originally aimed to achieve certification at LEED® Gold level. However, another project priority was to maximize utilization of passive (stack effect-driven) natural ventilation on a nighttime purge cycle to reduce overall energy consumption. Because a substantial portion of the makeup air would thus be introduced through windows and/or without the use of fans, the project was unable to obtain LEED® for New Construction (LEED-NC®) (Version 2.2) Indoor Environmental Quality (IEQ) Credit 5, Indoor Chemical and Pollutant Source Control, which would have required conveying all intake air through filters meeting Minimum Efficiency Reporting Value (MERV) 13 filtration efficiency. This one point proved to be the difference between the LEED-NC® Silver and Gold certification levels; nonetheless, the project stakeholders were satisfied that key goals were attained and that a Silver certification was sufficient. Stated otherwise, the advantages offered in the relatively mild Pacific Northwest climate through natural ventilation and nighttime purging were too valuable to sacrifice for the higher certification level [5].

Like almost anything else, the LEED® system can be utilized as a progressive learning and advancement tool, specifically to improve the capabilities of those in the green buildings sector. The project architect for the Jewish Reconstructionist Center (Evanston, Illinois) attempted to produce a daylighting design that would result in at least 75% of the occupied spaces being daylit, in order to attain LEED-NC® IEQ Credit 8.1, Daylight and Views: Daylight 75% of Spaces (worth one point). The eventual design deemed optimum fell slightly short; based on the final, post-construction documentation submittal, approximately 71% of the occupied spaces would be daylit (in accordance with the LEED-NC® IEQ Credit 8.1 criteria). While the one point was not attained on this project, the architect realized the potential benefit of developing a targeted spreadsheet tool to:

(1) More accurately and proactively predict daylit areas during the design stage of the project

(2) Enable the project architect or lighting engineer to update those calculations during the construction stage (i.e., to verify that, notwithstanding any field changes, the credit would still be achieved)

This tool was reportedly used successfully on a subsequent project (the Barry School in Philadelphia, Pennsylvania—a LEED-NC® Gold-certified project) to generate a design that fulfilled the criteria for IEQ Credit 8.1. From a more holistic perspective, the goal of maximizing the LEED® score on one project led directly to development of a more advanced quantitation tool that has led to (and should continue to lead to) increased energy savings and other benefits from daylighting at newer facilities [6].

Innovative Technologies and Strategies (FP 3.2)

Innovation is usually at the core of progress, and its usage to aid the building industry's ability to respond to the threat of potential climate change is no exception. Innovative aspects that can produce noticeable benefits are: (1) creative use or modification of existing technologies, (2) willingness to experiment with new technologies, (3) sharing financial risk between tenant and owner, (4) using real-time data to improve control and performance, and (5) pioneering new applications for common materials. Applications of these traits are discussed in the following paragraphs. In addition, as the possibility of obstacles or distracting factors is often greater where innovative technologies or strategies are applied, one small but not insignificant example is discussed.

Creative Use or Modification of Existing Technologies

Building managers who wish to install renewable energy technologies are currently confronted with two problems: (1) the achievable scale and capacity are relatively small, and (2) the technologies are often not cost effective in these applications (e.g., paybacks commonly longer than 10 years). This means that any attempt to squeeze extra capacity from a renewable energy system can be worthwhile. At the Burns & McDonnell (B&M) headquarters building (Kansas City, Missouri), a total of 24 "bifacial" solar photovoltaic (PV) modules were installed, with a total peak load capacity of 5 kilowatts (kW). The rear surface (behind the PV panel) captures ambient light that is either transmitted through the panels (e.g., at panel joints) or reflected off nearby surfaces, thus maximizing overall potential power production, even though the total rated capacity of the PV systems is relatively small [7].

The Oregon Health & Sciences University Center for Health & Healing (Portland, Oregon) has also reportedly used a creative modification of an existing heating, ventilation, and air conditioning (HVAC) technology (displacement ventilation) to maximize energy performance. The patient examination rooms at the facility reportedly introduce a low-flow, cool air stream near the top of the interior walls and direct it downward in a "waterfall" type motion. The upward primary ventilation airflow is thereby cooled by convection, and exhaust vents for the stale, warmed air are provided at ceiling level. The facility operators claim that this innovative displacement ventilation configuration has: (1) resulted in an approximately 66% reduction in total fan energy consumption, and (2) eliminated any need for reheating the incoming air supply in order to maintain target dry bulb temperatures [8].

Willingness to Experiment with New Technologies

Pursuing innovative strategies can entail risk, but the reward side of the equation is also often increased and, furthermore, often offsets the corresponding risk over the long term. The electrical systems utilized at the 641 Avenue of the Americas Building, New York, New York (specifically, the 12,121 ft^2 space occupied by COOKFOX) incorporated a number of innovations:

- **Dimming Ballasts for Metal Halide Lighting**. This building featured one of the earliest known applications of electronic dimming ballasts in metal halide lighting fixtures in the U.S. According to the facility personnel, these fixtures are able to provide a suitable light supply for the occupants at approximately 50% of the original lumen levels (with corresponding energy savings). The initial reliability factor for these ballasts was less than desirable; specifically, 10 of the original 50 ballasts (20%) failed early and required replacement—an example of the risk described above. However, since that time, only six ballasts have failed in an approximate four-year period (i.e., a replacement rate of three every two years).

- **Centralized Master Switches**. Centralized master switch panels were installed, which enables the last employee leaving an area at night to shut off all lights. This feature was supplemented with conventional occupancy sensors in vestibules, restrooms, and closets.

- **Workstation Compact Fluorescent Lights**. Task lighting at individual workstations consists of 19 Watt (W) fluorescent light fixtures. These allow ambient (room-wide) lighting levels to be generally maintained between 20 and 25 foot-candles (fc), which results in an installed lighting power density of 1.03 W/ft^2 (approximately 25% below the corresponding ASHRAE 90.1-2004 maximum).

Based on the discussion above, it appears plausible that the risks undertaken by this project were well balanced by the rewards. A net positive outcome is never guaranteed; however, when faced with a changing climate, building developers may need to become more comfortable with leveraging innovation and tolerating the associated risk. As discussed in the following section, one means for mitigating risk, at least to some extent, is distributing it between the building owner and tenant(s) [9].

Sharing Financial Risk between Tenant(s) and Owner

In order to successfully implement technologies with moderate-to-lengthy payback periods at the B&M World Headquarters building (Kansas City, Missouri), the property owner (The James Campbell Company [TJCC]) and the lessee (B&M) developed a carefully crafted risk-sharing arrangement. B&M pays TJCC a flat fee for utilities, based on the square footage of space rented. This arrangement provides, in theory, little incentive for the property manager to invest in energy cost savings measures, unless the associated payback periods are very short. Therefore, a project-specific, investment-sharing, and risk-sharing agreement was negotiated, consisting of the following:

- TJCC paid for approximately $457,000 in energy efficiency measures, including condensing hot water boilers and lighting retrofits. The lighting retrofits had relatively rapid paybacks, ranging from 1.5 to 4 years.

- B&M paid for several projects with payback periods longer than four years but having significant environmental benefits, including the bifacial PV arrays (as described above) and the on-site stormwater management system (in total, approximately $1 million).

In addition, TJCC and B&M agreed to share the cost of other, longer-term payback measures, one being the installation of low-flow lavatory faucets, urinals, and toilets (overall payback period of 13.5 years) [7].

Using Real-time Data to Improve Control and Performance

Modern electronic controls have allowed buildings to effectively capture and automatically utilize real-time weather data to enhance building energy performance. Two such case histories are discussed below. Interestingly, both buildings have automation systems that utilize weather data during both occupied (daytime) and unoccupied (nighttime) hours to optimize the overall 24/7 energy performance.

The Mountain Equipment Co-op (MEC®) building (Montreal, Quebec, Canada), like many, operates using a BAS to control critical functions, including HVAC. It also features radiant floor heating and cooling systems. The BAS uses a predictive logic algorithm, based on weather forecast data downloaded from the internet each day, to "precharge" the building's radiant floor slabs in the morning, in accordance with seasonal requirements. While radiant systems can provide excellent heat transfer, one of their disadvantages can be longer response times to thermostat adjustments (compared with conventional hydronic or forced air systems). By pre-charging the slabs, the MEC® operators can more ably ensure that design comfort temperatures for staff and customers are attained during the first hour or two of morning operation. The use of daily weather data, combined with a modularized installation approach (similar to that discussed in Part I of this article) produced additional significant energy and cost dividends. The original design called for ten dual-stage modular ground source heat pump (GSHP) units, rated at 10 tons of refrigeration (tons R) each, but MEC® discovered that installing only eight of the ten GSHPs was sufficient to meet seasonal heating and cooling demand. In addition to the capital cost savings, the use of fewer operating stages (16 instead of 20) is anticipated to result in increased overall part-load efficiency (energy savings) and less cycling (reduced wear-and-tear on the equipment) [10].

At the Szencorp Building (Melbourne, Victoria, Australia), an onsite weather station is used to supply real-time outdoor temperature measurements to the BAS. These temperature data, combined with temperature measurements from sensors inside the occupied spaces, aid in maximizing the effective use of natural ventilation. The baseline settings are such that, if indoor temperatures are greater than 77°F, the BAS transmits signals to open certain vents and allow natural ventilation; however, if outdoor temperatures decrease below 66°F, the BAS closes specific vents to prevent overcooling the interior. In addition, a timer cycle has been input to the BAS for night purging; i.e., during off-hours, vents are opened to allow stack effect purging of indoor air (no fans used) that has been excessively warmed by solar fenestration; artificial lighting; occupants' latent and sensible heat; computers and other office equipment; and building electrical equipment (e.g., fan motors) [11].

Pioneering New Applications for Common Materials

At the B&M World Headquarters building (Kansas City, Missouri), ordinary fiber optic cables were used in a non-data transmission application, specifically as light tubes to increase daylight penetration to inner building areas [7]. While many facilities use larger-diameter, custom-designed light tubes to increase daylighting, the use of fiber optic cables on this project is intriguing because it: (1) provides an alternative usage for a commonly available material that can be volume purchased (reducing costs), and (2) enables on-site use of excess cabling that may be available after the building data systems are wired.

Near-term Obstacles

It is interesting to note that innovative technologies can produce near-term obstacles or drawbacks. One such example is the GSHPs for the MEC® building (Montreal, Quebec, Canada). The building owner wanted to procure GSHPs using the then most "ozone friendly" refrigerant available (R407c). However, no GSHPs rated for R407c were available for purchase in Canada or the United States. The GSHPs had to be imported from Europe, which resulted in two disadvantages: (1) additional shipping costs, and (2) a time delay and additional cost for undergoing the mandatory Canadian Standard Association (CSA) certification process. In the final analysis, these additional time delays and costs were not deterrents to implementing the original approach and realizing the benefits thereof [10].

Worker Productivity and Student Achievement (FP 3.3)

The evidence is already substantial and continues to accrue that green buildings can lead to considerable improvements in worker productivity or student achievement, as applicable. Personnel costs can range between \$200 and \$600/gross ft^2, giving building occupants significant motivation to maximize productivity [7]. Furthermore, productivity gains associated with new technologies can similarly be substantial; for example, worker productivity increases can account for 54% of the benefits from installing an underfloor air distribution (UFAD) system [12]. Similar improvements in student learning have been observed at various levels of schools, from primary school through college. Worker productivity or student achievement is a force multiplier because:

- The promise of this benefit, as proven at many facilities, encourages developers to build green projects (and the magnitude of potential benefits may further encourage them to aim for higher levels, e.g., LEED® Gold or Platinum rather than LEED® Silver).

- Higher productivity results in less energy expenditure per employee work hour and thus provides a reserve in energy consumption and peak demand, either for: (1) future expansion of operations, and/or (2) to cope with unpredictable changes in local climate.

As listed in Table 2, there is abundant evidence that green buildings can improve many factors relating to worker productivity, including increases in employees' actual or perceived productivity, reduced sick days and absenteeism, reduced turnover, and (in countries where measurable) reduced health care costs.

Design Process Must Consider Productivity or Student Achievement as a Vital Goal

There are numerous examples of remarkably self-evident design decisions instituted by facility architects and engineers that can contribute toward increased worker productivity or student achievement. At the Lundquist College of Business of the University of Oregon (located inside the Lillis Business Complex, Eugene, Oregon), classroom daylight is introduced through clerestory windows located behind the students, and the incident light is further deflected (softened) when it strikes angled panels in the ceiling assembly. The angled panels also divert light away from the front wall, which instructors use as a projection area for lecture materials (e.g., Powerpoint® presentations). This provides several concurrent benefits:

- A clearer view of the projection area and classroom presentations
- Less glare and/or shadowing on desk writing surfaces, enabling students to take better notes
- No need to darken the room for projector presentations, thus reducing potential for student fatigue [5]

Table 2. Examples of Reported Improvements in Worker Productivity in Green Buildings

Facility (Location)	"Green" Characteristics	Parameter	Results	Comments
Set of 154 office buildings in 10 large U.S. metropolitan areas; total of 755 tenant employees were surveyed[1]	Average ENERGY STAR® score of 83	Productivity (perceived)	55 percent of employees surveyed reported increase in personal productivity	Human impressions; not an objectively measurable parameter
		Sick days	Decrease in annual average sick days per employee of 2.88 days	Associated cost savings estimated at $5.00 per occupied ft^2 per year
PNC Financial Services Group Building (Pittsburgh, Pennsylvania)[2]	LEED® Silver-certified	Employee turnover	Decreased 50 percent below the typical level observed at other PNC facilities	None
Toyota North American Headquarters (Torrance, California) [2]	LEED® Gold-certified	Absenteeism	Decreased by 14 percent	None
500 Collins Street Building (Melbourne, Australia)[3]	5 Star rating, Green Star Rating system[4]	Billable hours	Increased by 7 percent	None
		Typing performance	Improved by 49 percent	Method of measuring performance increase was not specified
		Sick days	39 percent decrease in annual average sick days per employee	None
		Health care costs	44 percent reduction in average annual health care costs per employee	Greatest reduction observed among senior staff
Two Office Moves from non-LEED® to LEED®-Certified Facilities (Lansing, Michigan)[5]	One LEED® Platinum facility and one LEED® Gold facility	Mean productivity, as measured by additional productive work hours[6]	Increased by 38.98 hours per year	The survey sizes were 32 and 113 individuals, respectively

In the new Seattle City Hall building (Seattle, Washington), the west wall daylighting design uses a combination of exterior horizontal sunshades and interior light shelves to shield workstations near this wall from low-angle, late afternoon glare and solar heat gain [13]. At the Twenhofel Middle School (Independence, Kentucky), GSHP units were installed on vibration-isolated platforms above the corridors that separate classrooms, thus reducing noise levels inside the classrooms [14].

Augmenting Building Systems with O&M Practices and Extramural Factors

An emerging trend will be to approach employee wellness and productivity in a holistic and multifaceted manner that supplements green building technologies with O&M practices and "extramural" factors to maximize employee well-being and thence productivity. The VSP Vision Care building (Rancho Cordova, California) and its operator (VSP Vision Care) provide a case history that demonstrates these principles. The building was designed and constructed with significant attention to indoor air quality, including:

- Use of no- or low-volatile organic compound (VOC)-containing formulations in finishes and carpeting
- Upgrades to existing air filtration systems to achieve improved removal of dust, pollen, and other particulate matter
- Carbon dioxide (CO2) sensors that track indoor ambient concentrations and inform operators when to increase ventilation air to a zone(s) accordingly

However, these features are also supplemented and enhanced by O&M practices and extramural factors. Repairs and build-outs are also restricted to no- or low-VOC finishes and carpet, where available, and janitorial products (e.g., cleaning solutions) must meet certain "green" criteria. Extramural factors intended to boost employee productivity include: (1) an on-site cafeteria that serves fresh, organic, locally-grown foods; (2) available wellness counseling and nutrition education for employees; (3) an on-site exercise facility and subsidized membership dues for off-site fitness facilities; (4) company team sports; and (5) voluntary regular health and wellness evaluations by trained professionals.

Quantitative results can be interpreted to, at least in part, validate VSP's efforts. Between 2003 and 2008, the average annual employee sick-day rate decreased from 17 days to nine days. Without even considering productivity gains, i.e., on a labor cost basis alone, VSP estimated that the lower sick day rates resulted in an annual savings of approximately $840,000 [15].

Recruiting

It is also impossible to ignore the effect that green buildings have on recruitment of staff, particularly young professionals entering the workforce today. An October 2007 survey of recent graduates indicated that 92% would prefer working for an "environmentally friendly" company and that 80% were interested in a position that could "impact the environment in a positive way" [4].

Project Location and Climate (FP 3.4)

Project location can be a substantial advantage in terms of building energy load and total energy consumption. North American buildings located in the generally moderate temperature states and provinces west of the Rocky Mountains can often leverage extensive use of natural ventilation, chilled beams, and/or water-side economizers to reduce cooling load (and in some situations, even remove the need for chillers entirely [16]). On a smaller, but still significant level, a facility located within an urban heat island will, in many cases, have higher cooling loads (and thus consume greater energy) than an identical building in a rural or exurban setting, particularly because it cannot utilize nighttime cooling and purge ventilation to the same advantage.

However the project location is often a fixed parameter—i.e., the designer has no control over where it is sited. Even in those situations, developers and designers can exercise choices and implement strategies that take maximum advantage of local climate or terrain, i.e., using the local climate as an "ally" rather than an "opponent." Some examples include the following buildings:

- For the Twenhofel Middle School (Independence, Kentucky), an HVAC system using primarily GSHPs was selected, in part because GSHPs can provide cooling during winter warm spells [14].

- The U.S. Department of Homeland Security's Citizenship and Immigration Service facility (Omaha, Nebraska) was designed with an inner courtyard that provides a relaxation area for the occupants but simultaneously shields the eastern half of the building from strong, cold, northerly and northwesterly winds during the often-long Great Plaines winters [17].

- At the Stellar Commercial Building (Jacksonville, Florida), existing oak trees were retained to provide natural shading and, along with an on-site wetland, aid in combating the heat island effect [18].

The Heifer International Headquarters building (Little Rock, Arkansas) implemented a heat rejection system that is interesting for two reasons: (1) it conserves energy under today's conditions, and (2) it provides flexibility and adaptability in the event of potential climate change [19]. The cooling tower was designed with an approach temperature (T_a) of 3°F, as opposed to the more frequently used T_a of 5°F. The approach temperature is the difference between the entering water temperature to the cooling tower and the ambient wet bulb temperature (T_{wb}). (T_{wb} is the temperature that, for a given dry bulb temperature and relative humidity, represents the lowest temperature that could be attained by evaporative cooling alone.) This was accomplished in large part due to variable frequency drives (VFDs) on the cooling tower fan motors, which (Heifer International claims) have reduced energy consumption by 67% relative to the ASHRAE 90.1-2004 standard for axial fan cooling towers of 38.2 gallons per minute (gpm) of water per horsepower (hp) expended [20].

The 40% reduction in cooling tower T_a provides considerable fan energy savings under current climatic conditions, but there is another advantage it may supply. Consider the formula for approach temperature:

$$T_a = T_{in} - T_{wb}$$

where:

T_a = approach temperature
T_{in} = inlet water temperature
T_{wb} = wet bulb temperature.

Assuming the inlet temperature to the cooling tower remains relatively constant, as the approach temperature decreases, wet bulb temperature increases. As can be seen from the psychrometric chart [21], as dry bulb temperatures and relative humidity increases, in many cases, wet bulb temperatures also tend to increase. Therefore, a cooling tower equipped to operate optimally at higher wet bulb temperatures could be, in theory, more energy efficient in situations where the local climate exhibits an overall warming trend.

At times, measures must be both proactive and preventive. An example is found in the Normand-Maurice Building (Montreal, Quebec) [22]. Like many facilities, the architect included exterior wall fins to increase daylighting. However, in the eastern Canada climate, winter snowfall can be abundant; therefore, the fins had to be steeply sloped to allow snow to slough off. Where possible, the designer oriented the sloped fins to effectuate snow removal, but also to accumulate passive solar heat gain that could be transmitted to the building interior (while continuing to serve their original purpose, to increase daylighting).

Administrative Measures (FP 3.5)

Various non-engineering, administrative measures can be utilized to amplify the energy-saving effects of engineered systems. Several examples are provided below.

Procurement

The Plano Elementary School (Bowling Green, Kentucky) replaced 256 desktop computers and two servers with a completely internal wireless system and 180 laptop computers. The desktops consume between 150 and 175 W each, while the laptops consume only 25 to 50 W each. Therefore, if one assumes that all computers at the school are operating simultaneously, the total load reduction is in the range of 33 to 36 kW [23].

Standards and Codes

An interesting example, also from Kentucky, indicates how an installation's actual, demonstrated energy reduction performance can have a much wider influence at the policymaking level. The Twenhofel Middle School (Independence, Kentucky) was able to demonstrate required student achievement levels using a lighting system design that nominally supplies 40 foot-candles (FCs) rather than the Kentucky Department of Education (KDOE) then maximum allowable artificial lighting level of 50 FCs. This accomplishment impressed KDOE officials to the extent that the Department reduced the maximum level to 40 FCs for all future school construction projects [14]. As technology advances, the ability to lower the bar on standards and codes should continue to increase. As noted from this example, this can apply not only to organizations whose fundamental mission includes code development (ASHRAE, American Society of Mechanical Engineers [ASME], Underwriters' Laboratories [UL], etc.) but also to any organization such the KDOE which exercises influence over the buildings it designs, constructs, operates, or occupies.

Accountability and Tracking

The operator of the Skanska USA Building, Atlanta office (Atlanta, Georgia) conducts weekly third-party inspections to verify compliance with equipment and systems O&M plans [24]. This type of quality control (QC) activity is likely to increase as building tenants and stakeholders demand information regarding the actual, ongoing energy performance of a building. It can also be an excellent tool for facilities that seek to maintain their LEED® Existing Buildings Operation and Maintenance (LEED-EBOM®) certification, specifically with regard to:

- Energy and Atmosphere [EA] Prerequisite 2, Minimum Energy Efficiency Performance
- EA Credit 1, Optimize Energy Efficiency Performance
- EA Credit 3.1, Performance Measurement—Building Automation Systems
- EA Credit 3.2, Performance Measurement—System-level Metering
- EA Credit 6, Emissions Reduction Reporting [25]

At the 5 Houston Center building (Houston, Texas), tenants can enter work order requests for maintenance, repairs, or janitorial services through an online portal. This system aids in assuring that major repairs are not delayed and allows occupants to track the progress of their work order (and hold the building managers accountable if the problem[s] specified in the work order are not resolved) [26].

Models Other Than Whole Building Energy Simulation (FP 3.6)

Whole building energy simulation computer models (WBESMs) are almost a *de rigeur* feature of present-day building design practice (and will continue to be so). They are the best tool available for projecting building energy usage to a sufficiently granular level and testing various design scenarios in a quick, interactive manner. Furthermore, they are necessary for virtually any project applying for LEED® certification in order to meet the basic energy consumption reduction prerequisite and credits.

However, WBESMs do not have to be (and often should not be) the only building modeling tools employed on a project. In recent years, a powerful set of new modeling tools has emerged and begun to find widespread application. These include building information modeling (BIM), computational fluid dynamics (CFD), and daylighting design and configuration. This section will provide brief overviews of these modeling practices, some notes on some less-well-known models or model-like forms of analysis, and a cautionary note regarding overreliance on, or misapplication of, these modeling tools.

Building Information Modeling (BIM)

BIM is one of the most transformative developments in the building industry today, and enormous amounts have been written on this subject. This section will concentrate on one particularly striking example of how a contractor has embraced BIM as one of its core practices, and its rationale for the investments associated with this decision.

BIM Can be Both Preventive and Proactive

The most widely recognized major advantage of BIM is to eliminate "clashes" and other inefficiencies before they occur in the field. Examples of clashes would include piping runs that intersect when they are not supposed to, walls whose construction would result in subdividing design HVAC zones, electrical service that is required by equipment but does not show up on drawings (or shows up in the wrong location), etc. Unpredicted clashes result in construction change orders, which in turn cause increased costs and schedule slips. Clashes can be devastating to a project, particularly if the task affected by the clash is a critical path task, and more so if the project must be completed urgently. Change orders also have consequences and implications outside the immediate scope of completing the construction work, including some or all of the following:

- Potential loss of available specialized trade labor (i.e., individuals may be reassigned to competing projects while change orders are being reviewed and processed)

- Disappearance of available lay-down area for materials and equipment

- High inventory-storage costs for each day the project is delayed

- Liquidated damages assessed to the contractor or project developer, often assessed for each day of delay

- Pressure from local politicians or officials eager to see construction finished

One source estimates the average cost savings from using BIM to be between $3,372 and $5,934 per avoided clash [27]. Thus, where BIM can be effectively applied, cost savings can quickly accumulate, even when a relatively small number of clashes are avoided.

However, BIM can be utilized for more than just removal of the above-described negative events and consequences. The software may aid in identifying improvements during the design phase that might not ordinarily be noted. For one, BIM software allows all piping runs and ducts to be visualized, enabling a clever designer to lay out the most energy efficient and effective systems, including reducing/eliminating flow "choke points" (e.g., 90-degree elbows, rapid reductions in diameter and cross-sectional area, etc.). BIM can also aid in facilitating "what if"-type analyses, such as examining building performance for: (1) different building envelope configurations, materials, or systems; and (2) HVAC and electric equipment combinations, including the number and location of mechanical rooms. A WBESM can also provide this information; however, it cannot concomitantly ensure that clashes and other such problems are removed from the design. In the best case, BIM and WBESM software would be integrated to enable high-value design scenario testing. ASHRAE's Technical Committee 1.5, Computer Applications, has an active project investigating how interoperability between BIM and WBESM software products can be furthered [28]).

PCL Construction Case Studies

PCL Construction is a large construction contractor with 29 offices in Canada and the U.S. Through recent experience, PCL has come to believe so strongly in the advantages of BIM that it has created a substantial internal BIM capability. This has included hiring a corporate BIM "czar" and hiring and training BIM specialists within each district that the company serves. PCL also requires that an engineer, construction manager, or other specialist experienced with BIM software be a key member of the oversight and management team for virtually all of its projects.

BIM is applied to virtually all PCL projects, whether or not the architect and/or engineer has created a project-specific BIM model before PCL's involvement. In instances where the designer(s) have not produced a BIM model, PCL has found it to be worthwhile to create its own BIM model from scratch, with the foreknowledge that cost savings from clash avoidance or other hidden efficiencies will readily justify the effort and internal cost. The following two examples illustrate the benefits PCL believes it has realized from application of BIM:

- **Silverline Luxury Residences (Telluride, Colorado)**. Construction constraints associated with this project included its abutment against a steep hillside, proximity to the ski lift gondola, and sensitivity of neighboring property owners to excessive truck traffic. PCL used a "4D" BIM approach (three spatial dimensions with an integrated time schedule "fourth dimension") to develop an optimized excavation and shoring plan, which was sufficient for local zoning board approval. Moreover, the BIM model informed PCL that the total excavated soil volume in actuality would be approximately 79% greater than the preliminary estimate (179,000 cubic yards [yd^3] rather than 100,000 yd^3). Since the project was bid on a lump-sum basis, this additional excavation (and soil disposal) could have amounted to an approximately $3 million loss to PCL. Therefore, PCL stated that the modeling effort of approximately 560 person-hours and other associated costs were small in contrast to the benefits received and risks mitigated.

- **Memorial Hospital (Colorado Springs, Colorado)**. PCL believes that the use of BIM on this project avoided approximately 3,500 potential clashes, at least 500 of which could have resulted in significant schedule delays and/or negative cost impacts. Using the range of cost-per-clash values presented earlier, estimated avoided costs could have been in the range of $11.8 million to $20.8 million. PCL's BIM modeling "cost" was approximately 1,200 person-hours [29]. The source did not provide PCL's cost per person-hour. However, if one makes an assumption for average professional labor cost, including overhead and profit, of between $100 per hour and $150 per hour, the total modeling cost would have been between $120,000 and $180,000, approximately two orders of magnitude less than the avoided cost.

Computational Fluid Dynamics (CFD)

CFD is a computer modeling technique that is being employed with increasing frequency to optimize ventilation, heating, and cooling air delivery to indoor spaces. Formerly, CFD was only utilized for large, monumental buildings with immense, multi-story indoor open spaces, examples being the Grand Central Station reconstruction in New York City and the Steven F. Udvar-Hazy Center of the National Air and Space Museum in Chantilly, Virginia. However, as the CFD modeling software has become more affordable and processing speeds on ordinary personal computers have continued to increase rapidly, building designers are finding that CFD has both utility and affordability for buildings and spaces such as school libraries and auditoriums, parking garages, large office building, hotel atria, and health care facilities.

Airflow through an indoor space is governed by the Navier-Stokes and allied equations, which are non-linear partial differential equations. There are no explicit solutions to such equations, and they therefore must be solved numerically, with a computer being the only realistic means to perform the volume of calculations necessary to converge to a solution. CFD models operate by dividing the entire indoor volume of the space into a mesh of numerous tiny elements, typically several hundred thousands or millions of infinitesimal tetrahedrons. The joining points for these tetrahedrons are called *nodes*, and the Navier-Stokes and allied equations are solved at each node in the equation, starting with an initial estimate of boundary conditions. The model continues to calculate the parameters of interest until the comparative estimates for each node associated with each element are within an acceptably small error band. Parameters for indoor spaces that can be (and typically are) modeled using CFD include air velocity (from which volume flow rate can be easily derived), temperature, pressure, and concentrations of indoor air contaminants.

Specific applications for CFD in commercial and institutional buildings include:

- Determining the optimal configuration of supply diffusers and return grilles, which is critical when designing UFAD and displacement ventilation systems. Efficient usage of energy in UFAD and displacement ventilation systems relies on establishing a tightly focused “break line” at approximately 7 or 8 feet (ft) above floor level. Below the line, the zone is occupied and the air must be conditioned to the proper temperature (without drafts); above the line, energy is being wasted conditioning unoccupied space and possibly interfering with normal buoyant air patterns that would remove stale air from the occupied zone [30].

- Evaluating the concentrations of vehicle-produced carbon monoxide (CO) and other air pollutants in indoor parking garages, and ensuring that ventilation fans are adequately sized and located to reduce concentrations below U.S. Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) standards [31].

- Evaluating the flow patterns caused by wind currents along the outer walls of buildings and the resulting convective heat loss. Boundary layer problems such as this are difficult to conceptualize and solve without use of numerical techniques such as CFD. In certain climates, this phenomenon may be significant in understanding energy losses at the building perimeter and aiding in ensuring that seasonal space conditioning requirements (particularly indoor temperature) are maintained in those perimeter spaces.

- Optimizing flow patterns and evaluating corresponding space conditions in naturally ventilated buildings. Even in buildings that do not (or cannot) employ natural ventilation as the primary conditioning method due to climate extremes, there is still potential applicability—for example, in understanding airflow between the inner and outer walls of a double-wall façade of the type discussed in Part I of this article.

- Optimizing performance of renewable energy systems, including the: (1) size and geometry of wind turbine blades and orientation of the turbines themselves (which can in some units be rotated to optimize exposure to wind flow), and (2) removal of electrical resistance heat from the surfaces of PV panels and arrays [32].

- Evaluating the effectiveness of smoke removal/control exhaust fans to ensure conformance with applicable fire codes and allow for safe and orderly evacuation of occupants [33].

- For atria, ensuring that the atria themselves, but particularly spaces adjacent to the atrium on upper floors, receive plentiful daylight but not excess solar heat gain (by employing additional targeted ventilation or cooling sub-systems in those areas) [34].

- Optimizing the hot aisle/cool aisle configuration of data centers and meeting other data center ventilation challenges [35, 36].

CFD was utilized extensively in the design of the 153,000 ft^2, 140-office Kelley Engineering Center at Oregon State University (Corvallis, Oregon). The building design features a UFAD system with variable volume diffusers, radiant hot water heating, operable windows, and a four-story atrium that serves as a central air supply and return space and uses motorized air supply intakes and exhaust vents. Total building energy consumption is reportedly approximately 40% below a "conventional" building in the same ASHRAE climate zone. By virtue of being located in a moderate climate, the energy reduction measures have resulted in a building that reportedly does not require space heating or cooling for 90% of its yearly operating hours. (This value does not include energy consumed by a chiller that is dedicated to serve the computer room.) [37]

There remain several drawbacks related to the use of CFD modeling:

- While the cost of the software has become more affordable, it still requires considerable expertise on the part of the modeler to produce results that are accurate and realistic. It is true that more firms are gaining the expertise and offering these services, which in theory would reduce future costs; however, a building designer must take into account quality, experience, and reputation (in addition to cost) when selecting a modeler.

- Even though computer processing times have also decreased substantially, single modeling runs for even a moderately-sized, moderately complex space (e.g., a primary school auditorium) can require on the order of 40 to 50 hours [30]. Naturally, if model inputs must be adjusted and the model re-run (which is inevitably the case), it must be realized that CFD analyses for many applications cannot be completed at the last minute, or even "in a week or two."

Rather, the time required must be appropriately anticipated, and building owners and developers should be wary of any practitioners that promise to deliver finished product in such brief time frames.

- Thought and time must be allotted to presentation of model output and results. The iso-contour and other plots generated by CFD software can often be hazy, over-detailed, or difficult to interpret, especially for audiences unfamiliar with the models or procedures.

- CFD models will usually produce more accurate results in portions of the space where fully turbulent flow predominates and the bulk airflow is relatively undisturbed. At space boundaries (e.g., walls, partitions) near and around obstacles, and where there are localized fluctuations (e.g., combined latent and equipment loads, occupants frequently moving around the space), the potential for error (and the magnitude) will generally increase.

Daylighting Design and Configuration

If not properly designed, a daylighting system can cause: (1) worker discomfort and decreased productivity and/or (2) undesirable heat gain and significantly higher cooling energy costs. There is no effective "cookie cutter" approach for daylighting—each site demands a unique daylighting design. In addition, as window glazing area increases, there is usually a difficult tradeoff decision between energy savings from daylighting and increased energy cost associated with fenestration heat gain. Generally, the optimum glazing area to best promote daylighting while minimizing losses is a site-specific value(s) that must be derived through complex analysis and modeling [2].

For these reasons, designers are increasingly relying on computer models and/or three-dimensional scale model reproductions of spaces to predict lighting angles, intensities, penetration, and how all of these parameters may vary seasonally and diurnally. For two new school buildings in the Guilford County, North Carolina Schools District (Northern Guilford Middle School and Reedy Fork Elementary School), daylighting simulation software was used, concomitantly with a DOE-2 based WBESM, to optimize daylighting design and energy performance. The predicted lighting energy reductions for the two schools were 50% and 49%, respectively (as compared with the ASHRAE 90.1-

2004 lighting energy baseline), while ensuring a minimum light intensity of 50 FCs in classrooms, the library, and faculty offices for at least two-thirds of the school day. Expressed otherwise, the design classroom lighting level was 60 FCs; therefore, during the majority of the school day, only 10 FCs of artificial lighting had to be supplied [38].

For Rinker Hall at the University of Florida Gainesville Campus, designers used the SUPERLITE 2.0 daylight model [39] in conjunction with a DOE 2.1 WBESM to demonstrate that (curiously, unlike most locations) the building should be optimally oriented on a north-south rather than an east-west axis. At Gainesville's latitude, much of the daylight incident on a building's south face is "high angle" (greater than 75 degrees from the horizontal), which hinders significant penetration of daylight rays into the interior and also results in high average transmittance loss through the glazing. (Approximately 25% of daylight does not breach to the interior.) The high-angle daylight also carries a significant thermal load, which cannot be separated from the visible light component. Thus, by testing different daylighting/energy simulations, the architects demonstrated that reduced usage of southerly daylighting, combined with daylight from the other building faces and energy efficient artificial lighting, produced the building configuration with greatest energy and daylight benefits despite a less traditional north-south oriented footprint [40].

The emergence of daylighting software thus allows designers to challenge conventional assumptions (regarding, in this case, basic building orientation). Indeed, a baseline condition of east-west orientation settled upon at the charrette stage would have in this situation produced a less energy efficient building, with greater thermal loads in a sub-tropical climate, which would have overridden the incremental benefit of greater daylight received through the south-facing glazing.

Daylighting simulation software can also be utilized in a more innovative manner, such as to aid in design of naturally ventilated buildings. (Solar energy significantly influences air buoyancy and transport patterns.) At the Oregon Health & Science University Center for Health & Healing (Portland, Oregon), daylighting simulation and WBESM software packages were used conjunctively to optimize the location of sunshades (conventional application) and in the design of stairway towers as conduits for significant stack effect ventilation. These and other building design features together allowed the air conditioning system to be downsized by approximately 30 tons R, which (in addition to generating expected future energy savings) produced immediate benefits by allowing some budgeted funds initially allocated for air conditioning equipment to instead be used to purchase additional building-integrated photovoltaic (BIPV) panels [8].

Other Models and Tools

Models/tools do not necessarily need to consist of a computer program or software package into which one plugs numbers to retrieve a solution. For example, one engineering firm developed a set of three-dimensional fan curves, which add to the normally displayed parameters of pressure head and airflow the additional parameter of efficiency [41]. These curves highlight that there is a "ridge" on the three-dimensional surface where, for a given set of manufacturer fan curves, fan efficiency will be maximized. This information can be helpful to a design engineer trying to select a fan(s) for a given building or specific ASHRAE 90.1 climate zone.

Caution against Overuse or Misapplication of Computer Models

Notwithstanding the enormous potential benefits of computer models and commercial software packages (and the remarkable expansion of the universe of available tools year-to-year), models must be applied judiciously and simulate real-world conditions to within an acceptable range of accuracy. Modeling results can serve as a point of departure and "first cut" analysis, but they may need to be validated using physical methods (for example, constructing building scale models for daylighting analysis, as mentioned above) or against results from similar projects described in the literature or projects that the design architecture or engineering firm has already completed.

In order to complete modeling (whether optional or required) with expediency, simplifying assumption must always be made. For example, the modeler may assume that all lights are turned off at the end of a work day or shift (when in reality there is usually a staggered pattern of use), and electrical plug loads are often assumed to be a constant (e.g., a certain W/ft^2 value), which may not reflect the variations found throughout a typical building. Models are often also *single point in time* scenarios and can produce overoptimistic results that may not continue once the facility begins operating. For example, a California study of airside economizer performance indicated that 64% of the economizers in the sample had failed without the building operator's knowledge (and that due to the economizers being off-line, building energy usage increased by 10-20%). The overarching message is that, no matter how skillfully they are applied, models tend to idealize building operating conditions and performance, and a rigorous building O&M and data tracking program is always recommended to ensure that systems function optimally once installed [42].

Modeling of complex building systems is as much an art form as a science, and the application of technique and expertise becomes more critical as the models themselves become more complex. Given the same scenario, it is unlikely for two modelers (even experienced ones) to arrive at identical results, because their setup and simplifying assumptions will inevitably be affected by their own unique knowledge, experience, and intuition. Informed judgments based on these factors can be a significant asset to the success of a modeling effort and should not always be discouraged in favor of more rigid, standardized procedures. Instead, it is incumbent on the modeler to explain their decision-making and on the end-user of the data to become a more educated consumer of modeling services.

One common concern is that modelers may utilize optimal assumptions and input values for buildings that are seeking LEED® certification or to inflate the level of LEED® certification they are able to achieve (e.g., Gold or Platinum instead of Certified or Silver). The LEED-NC® process was not intended or designed to verify in the field whether a building can achieve its stated level of energy performance and thus the energy performance credits it claims on its application. As the number of buildings seeking certification increases exponentially, confirmation of such claims is becoming even more of a challenge. The emergence of additional rating systems such as LEED-EBOM® may address this problem by encouraging building owners to track performance and validate their initial energy performance projections [25].

Models and Real-world Results

While many if asked will relate stories where models have revealed their limitations (as elaborated upon above), there are also instances where facilities instead outperform the model's projections. This could be due to many factors, including conservative assumptions, inaccurate weather data, or the inability of currently available models to simulate to the required level of granularity the performance of certain equipment or systems. At the Newark Center for Health Sciences and

Technology at Ohlone College (San Jose, California), two 16-ft-diameter enthalpy wheels have been able to achieve greater air volume throughputs than originally assumed for the WBES modeling. This resulted in a wider temperature dead band and reduced cycling of the GSHP compressors, which is expected to decrease energy consumption and reduce wear-and-tear on the compressors over the long term [43].

The energy modelers engaged for the Jewish Reconstructionist Congregation (Evanston, Illinois) acknowledged that their models underestimated the actual energy performance of the building (57% below the ASHRAE 90.1-2004 baseline) and theorized that the WBESM software used at the time could not accurately model:

(1) The ability of the chiller system master controller to achieve energy savings by operating six chillers at part load and balancing them against building demand (rather than three chillers constantly operating at full load)

(2) Several of the specific energy conservation strategies employed, such as occupancy sensors, light tubes, displacement ventilation, and natural ventilation [6]

Newer WBESM software packages (e.g., EnergyPlus) and enhancements to existing models (e.g., ongoing improvements to eQUEST™ software [44] and increased sophistication of EnergyPlus user interface programs) are beginning to address several of the reported modeling shortcomings encountered on the Jewish Reconstructionist Congregation project.

Experience with new and emerging technologies is continuously revealing how models can be more effectively leveraged to assess future building performance. For a 376,000-ft^2 telephone call center in Kentucky, the engineers used CFD models to simulate performance of an HVAC system that relied significantly on UFAD and passive chilled beams (both relatively new technologies in U.S. buildings). During initial operation of the facility, return air temperatures were below those predicted, thus at times increasing reheat energy consumption. After further investigation, it was noted that the actual vertical temperature stratification gradient established by the UFAD system was less than that predicted by the CFD model. As a result, for chilled beam units in the vicinity of return air grilles, chilled air produced by the beams was being "fed back" into the space around the grille, thus causing the lower inlet temperatures to the grilles. Put otherwise, the stratification effect from the UFAD was insufficient to overcome the local circulation of excess chilled air near the grilles, thus causing the undesirable reheat. This situation was remedied by simply blanking off certain of the chilled beams, but it indicates room for continued improvement in CFD software and/or its application [45]. (It also clearly exemplifies how formidable it can sometimes be to balance interactions between multiple innovative, low-displacement flow HVAC technologies operating within a large building space).

"Free" or Low-cost Money (FP 3.7)

The availability of "free" or low-cost financing for project components can be a significant force multiplier and indeed determine whether a project incorporates certain specific green features or achieves the desired LEED® certification level or ENERGY STAR® score. In the green buildings arena, this kind of financing generally comes from two sources: (1) grants and low-interest loans, or (2) subsidized renewable energy projects. Occasionally, outright contributions are also part of the financing equation.

Grants and Low-interest Loans

The Owens Corning Headquarters building (Toledo, Ohio) is an example of a facility that leveraged a variety of available funding sources. The most substantial amount came from the Port Authority of Toledo, which: (1) provided the project site and a long-term lease to Owens Corning, and (2) issued $85 million in 20-year revenue bonds to finance construction of the building. Owens Corning also received several smaller allocations intended to bolster economic development in Toledo, including:

- A $5 million loan from the Northwest Ohio Bond Fund, with only $3.5 million required to be repaid over the first 20 years
- A $1 million grant from the state of Ohio
- A $10 million loan from the state of Ohio, with only $5 million required to be repaid over the first 20 years [3]

Other examples of grants and low-interest loans include:

- Ohlone College (San Jose, California) received a $2 million grant from the state of California to assist with construction of the Newark Center for Health Services and Technology [43].
- The Oregon Health & Science University Center for Health & Healing (Portland, Oregon) received a $1.5 million grant from the Energy Trust of Oregon [8].
- The Poudre School District (PSD) (Larimer County, Colorado) received $92,500 from the local utility (Xcel Energy) in energy modeling services and other incentives for implementing peak load reduction measures [46].
- The 641 Avenue of the Americas project received a low-interest loan from the New York State Energy Research and Development Authority (amount and terms confidential) [9].

Renewable Energy Projects

Financing or subsidization of renewable energy projects has occurred through a variety of mechanisms. The California Department of Education's Block 225 Building (Sacramento, California) received grants for installing (among other items), BIPVs totaling 330 kW in generating capacity [47]. For the Twenhofel Middle School (Independence, Kentucky), the electricity utility provider, Cinergy, Inc. (now part of Duke Energy) donated a $100,000 PV array with 22 kW of rated capacity [14]. The Sweetwater Creek State Park Visitor Center (Lithia Springs, Georgia) also received donated PV equipment valued at approximately $85,000, as well as a $20,000 grant from the Georgia Environmental Facilities Authority to purchase additional PV panels. The project designers estimated that these donations and grants offset overall project construction costs by approximately $10 per ft^2 [48].

Submetering (FP 3.8)

Submetering is rooted in the principle that as more information is made available to building owners, operators, and tenants, they will (in most cases) make wiser choices regarding their use of utilities. While most examples to date have involved submetering electricity (as evidenced by the case histories in Table 3), submetering of potable water, steam, and natural gas are also expected to become increasingly common.

Instruments that transmit information from submeters do not need to be flashy or sophisticated. At the Georgetown Mews Apartments (Queens, New York), the submeters installed in each apartment incorporate three "traffic light"-style light-emitting diode (LED) indicators, as well as a simple electrical usage data display. The red, yellow, and green lights indicate peak, shoulder, and off-peak periods, respectively, and activate accordingly to remind the resident which period is operative at any given time. The intended effect is to encourage the resident to reduce electricity usage during peak periods (and also shoulder periods, where possible) by:

(1) Modifying thermostat settings and occupying only one room during peak period

(2) Switching off non-essential loads during peak periods (e.g., opening window blinds instead of using lamps)

(3) Conducting non-time dependent energy-consuming activities (e.g., operating washing machines and dishwashers) during off-peak periods

To further encourage conservation during peak periods and shifting consumption to off-peak periods, electric use charges are modified by a multiplication factor of 2:1 for shoulder periods and 3:1 for peak periods [49,50].

For existing buildings and building campuses, installation of submetering systems does not necessarily involve a complete or costly rework of existing infrastructure. This was demonstrated at the College of New Jersey (Ewing, New Jersey). This campus contains approximately 50 buildings tied onto six main electrical feeders. New digital energy monitors were installed in each building and linked to the existing building automation and control system (BACS) using already in-place standard copper telephone wiring. Based on instantaneous load data provided by the submetering system, the BACS utilizes a load-shedding algorithm, which is based on apportionment of different loads into 12 load groups (150 to 200 kW each) and a predetermined strategy for shedding loads from lower priority load groups during peak or otherwise high demand conditions. Facility energy managers assert that during peak periods, total load drawn is generally between 500 and 900

Table 3. Examples of Submetering Projects and Results

Building(s) (Location)	Building Description	Utilities Monitored	Capital Cost of Submeters	Energy Savings[1]	Annual Cost Savings[1]	Simple Payback Period	Comments
Phoenix Plaza (Phoenix, Arizona)[2]	21-story; 800,000 ft^2 office building	Electricity	$75,000	Data not available	$200,000	4.5 months	Total of 80 metering points installed throughout the building
Georgetown Mews (Queens, New York)[3,4]	37 building, 930 unit, low-rise (two-story) garden apartment complex	Heating Hot Water and Electricity	$762,644	12.6% per year	$116,579	6.5 years (*at cost*); 4.0 years (*with incentive funding included*)	Estimated energy savings would likely be higher if some or all of the tenants of the 141 "non-shareholder" (rent-stabilized) apartments paid for electricity[5]
Bank of America Center (San Francisco, California)[6]	52-story, 2-million ft^2 office building	Electricity	Data not available	30% per year[6]	30%	Data not available	Allowed property operator to recover approximately $1 million per year in electricity charges from tenants[7]
College of New Jersey (Ewing, New Jersey)[8]	50-building, 2.5-million ft^2 (total) college campus	Electricity	$200,000	5 million kWh per year; 500 – 900 kW reduction in peak demand	$170,000 – $240,000	0.83 – 1.18 years	Submetering is performed at the building level (i.e., the central feeders going to each building, rather than portions of buildings such as floors). System utilizes an existing campus-wide copper-wire network (no additional network infrastructure had to be installed)
Park Plaza Condominiums (Pittsburgh, Pennsylvania)[9]	Nine-story, 120-unit, mixed-use building[10]	Electricity	$113,000	Data not available	$192,000	7 months	124 submeters in six MMU cabinets; Ethernet link to building engineer's master PC

Notes:

1. Submetering is often a vital element of a strategy to expose energy inefficiencies and enhance/optimize performance. However, the submeters themselves do not directly generate the energy and cost savings, unless they are part of a feedback control system that adjusts building operating parameters (e.g., temperature, lighting) in response to preset targets. In some situations, particularly residential properties, the occupants themselves are the core element of the feedback system, i.e., they are required to manually adjust thermostats or turn off lights before energy savings are produced.
2. Source: E-Mon, *Case Study, Phoenix Plaza, Phoenix, Arizona*, Energy User News Magazine, April 1998.
3. Sources:
   a. C.J. Ott, *Submetering and Georgetown Mews: Reducing Energy, Changing Behavior*, The Green Report, July/August 2008, pp.6-9.
   b. H.H. Hirschfeld, *Integration of Energy Management, Electrical Submetering, and Time Sensitive Pricing in a Large Residential Community Utilizing Wireless Communications*, presented at the World Energy Engineering Congress, Washington, DC, November 5, 2009.
4. Approximately $300,000 in incentive funding was provided by the New York State Energy Research and Development Authority (NYSERDA).
5. The non-shareholder (rent stabilized) apartments consumed over 50 percent more electricity than the shareholder apartments during the cooling season billing periods. Rent stabilization in New York City dates back to 1974, as a program to make affordable housing available within the New York Boroughs. It is similar, though not identical, to the original New York Rent Control Program instituted in 1943.
6. Source: D. Millstein, *A Cool Million Payoff*, Energy & Environmental Management, Second Quarter, 2001.
7. The baseline billing was derived from a nominal 3 W/ft^2; many tenants operated round-the-clock data centers and/or other computer systems, with UPS. Actual operations indicated significantly greater power intensity, due to heavy electricity consumption and associated cooling requirements from many tenants' computer systems and data centers. Thus, the realtor was, under the original lease agreements, not recovering much of the electricity cost associated with the building.
8. Sources:
   a. New Jersey Higher Education Partnership for Sustainability, *The College of New Jersey: Metering and Management for Energy Savings*, date unknown, downloaded June 22, 2010 (www.njheps.org/case-studies/energy/TCNJ.htm).
   b. Enerwise Global Technologies, *Client Background: The College of New Jersey, Ewing, New Jersey*, date unknown, downloaded on September 18, 2010 (www.enerwise.com/success_cnj.php).
9. Source: D. Millstein, *Property Manager Installs E-Mon® D-Mons® to Recover Owners' Electrical Costs in Lieu of Raising Monthly Maintenance Fees*, Case Study: Park Plaza Condominiums, E-Mon®, LLC, date unknown.
10. The ground floor contains offices and other commercial spaces, and the upper eight floors are residences.

ft^2 – square feet; kW – kilowatts; kWh – kilowatt-hours; MMU – master metering unit; PC – personal computer; W/ft^2 – Watts per square foot; UPS – uninterruptible power supply kW lower than before the submetering system was installed. Through extensive data collection, the submetering system has also aided in identifying energy-intensive buildings and developing plans for future energy conservation projects at those locations. Parameters include: (1) total kWh per ft^2 per building, (2) time and date of peak kW demand per building, (3) time and date of campus coincident peak kW demand, (4) total electricity consumption cost per building, and (5) peak kW data for each of the six electrical feeders, among others. Reports can be generated for daily, weekly, monthly, or user-defined periods [51].

Exponential Relationships (FP 3.9)

Fundamental physical laws or principles that follow exponential behavior can also serve as force multipliers for building energy consumption and peak demand savings. Two specific examples will be discussed in this section: (1) radiant heating and cooling, and (2) oversizing water pipe diameters.

Radiant Heating and Cooling

Unlike conduction and convection heating (the primary heat transfer mechanisms inherent in traditional HVAC technologies), which are linear with temperature differential, radiation heat transfer varies with the fourth power of temperature differential. Thus, in the most theoretical sense, to add or remove an equivalent amount of heat energy to conduction/convection heating, the temperature difference to transfer that amount of energy need only be the fourth root of the temperature differential (e.g., to establish a temperature gradient of 15°F would require a change in radiant slab temperature of only 2°F). This example is an oversimplification, but the capabilities of radiant heating have, in particular, been appreciated by mechanical designers for many years. As one example, infrared radiant heating devices in large, open, and expensive-to-heat spaces (bus garages, aerodromes, warehouses) have been commonly used because they warm the occupants (e.g., mechanics, stock desk clerks) adequately but do not expend excess energy on heating the large spaces in between work stations that are rarely occupied. Also, many such workers, sometimes after an adjustment period, come to appreciate that they are able to shed bulky clothing (performing their job more easily) and rely on consistent warmth from the device or system without being exposed to the drafts and air currents essential in conventional convection delivery heating. The concepts of radiant heating and radiant cooling (radiant heat flow in the reverse direction) are being observed with greater frequency outside of these specialized applications, although they normally occur as a component of a multi-technology HVAC design concept, as discussed below and seen in Table 4 (which details several radiant heating and cooling case histories).

One significant disadvantage of radiant heating and cooling systems is the time required overnight to bring the thermal mass of the slab to the required temperature for the following day and, in general, the slower response times of radiant systems to condition "calls" (e.g., thermostat adjustment in an individual zone). Often, the response time is measured in hours rather than minutes. Therefore, for example, not only may building occupants be uncomfortable when they first arrive to work on a winter morning, but "too cold" trouble calls cannot always be remedied quickly. The solution employed by some buildings (e.g., 31 Tannery Building, in Branchburg, New Jersey) is to maintain the radiant slab at a temperature slightly below the zone setpoint(s) and use auxiliary HVAC systems (in the case of 31 Tannery, a rooftop-mounted air handler) to supplement and balance the load in individual zones [52]. This maximizes the benefit of the radiant system (i.e., it is still covering the majority of the heating load) while:

(1) Ensuring that setpoint conditions are met throughout the day, including the early morning

(2) Minimizing the number of "too cold" or "too hot" trouble calls

(3) Allowing rapid and effective response to the few trouble calls that may arise

Another issue particular to radiant cooling system is condensation control. Condensation formation is a serious problem for any radiant cooling project because excess condensation will require drainage to prevent damage to building structural and electrical systems and to ensure that occupants do not experience any of the obvious problems caused by moisture condensing on exposed floors, walls, or ceilings. One strategy, used by the Normand-Maurice Building (Montreal, Quebec, Canada), is to supply dehumidified air through the ventilation system [22]. In general, there are several possible methods for achieving this, including: (1) slip-stream mixing inlet air with return air, (2)

Table 4. Examples of Radiant Heating and/or Cooling Systems

Building (Location)	Building Type	Heating	Cooling	Area of Building Covered by Radiant System	Circulation System	Heating and/or Cooling Source(s)	Comments
California Academy of Sciences (San Francisco, California)[1]	410,000 ft^2 museum and exhibition space	✓	✓	38,000 ft^2 portion of the main exhibition level	Approximately 100,000 ft of hePEX™ tubing inside the floor slab	Six 2 million BTUh gas-fired, condensing boilers Three 4 tons R centrifugal, vapor compression chillers	Projected annual reduction of approximately 10 percent in overall building energy consumption (mostly due to heating energy savings). Radiant system is piped to nine individual zones; can provide heating or cooling to different zones simultaneously as needed[2]
31 Tannery (Branchburg, New Jersey)[3]	41,500 ft^2 construction company headquarters building	✓		41,500 ft^2, approximately 63% of which is a vehicle maintenance shop and the remainder is office space	Approximately 47,500 ft of PEX tubing in the floor slabs, with 16 manifold headers, 146 loops, and 80 separate zones	One 14,000 BTUh, gas-fired, low-NO_x, condensing boiler	Radiant floor circulates 80°F water (100°F water during high heating demand periods). System capital cost was approximately $160,000 ($3.86 per ft^2 of floor space served)
Crystals, Mirage CityCenter™ (Las Vegas, Nevada)[4]	700,000 ft^2, three-story retail and entertainment complex	✓	✓	98,200 ft^2, including both "interior" (shops) and "exterior" (indoor plaza) spaces	98,200 ft of ⅝-inch hePEX™ tubing, installed in the floor slabs on either 6-inch or 9-inch centers	Not specified	Radiant heating and cooling are provided to the "exterior" areas; radiant cooling is provided only to the "interior" areas

Building (Location)	Building Type	Heating	Cooling	Area of Building Covered by Radiant System	Circulation System	Heating and/or Cooling Source(s)	Comments
Normand-Maurice Building (Montreal, Quebec)[5]	168,900 ft^2 office building for Canadian Government departments	✓	✓	Entire building	Piping is installed in the lower portion of 12 inch-thick floor slabs; provides heating/cooling to the story below; 12-inch spacing between tubing runs	GSHP, two air-cooled chillers, two boilers	During the cooling season, the radiant slab provides baseline cooling, with supplemental cooling from UFAD systems in the lower portion of each space. The main ventilation air supply is dehumidified, to ensure that water vapor does not condense on the undersides of the radiant slabs
Ballard Manor Retirement Home (Seattle, Washington)[6]	45,000 ft^2, five-story, 65-unit apartment complex	✓		Entire building	⅜-inch hePEX™ tubing, installed in the floor slab on either 6-inch or 9-inch centers	One 670,000 BTUh boiler	System is designed to operate at zone set point temperatures of between 75°F and 80°F at an outdoor design temperature of 27°F
Urban Outfitters Corporate Headquarters (Philadelphia, Pennsylvania)[7]	280,000 ft^2, offices, design studios, and support space	✓	✓	Central core space (square footage not specified)	25,000 ft of hePEX™ tubing, nine manifolds, three temperature averaging sensors	Chiller water loop delivering 38°F water Hot water loop delivering 200°F water (maximum)[8]	System is designed to circulate 115°F water through the hePEX™ tubing during the heating season and 52°F water during the cooling season

pre-heating inlet air, and (3) desiccant beds or wheels. The other most commonly used approach is to carefully control the circulating water temperature to preclude dew point conditions from occurring on the exterior side of the radiant slab.

As with any other heating or cooling technology, climate is a very important factor in determining whether radiant systems are feasible. However, where they are used, there are potentially large benefits other than just energy efficiency. Due to the ability to combine radiant chilled ceilings with natural ventilation and UFAD, the Pearl River Tower project (Guangzhou, Peoples' Republic of China, under construction) will not require an independent air conditioning system, which obviously represents sizeable savings in building infrastructure (i.e., fans, ductwork, chillers) and associated capital and O&M costs [53].

It was mentioned earlier that radiant heating and cooling often must be combined with conventional forced air HVAC systems. In the case of radiant cooling, one major reason for this is that radiant slabs provide sensible cooling only; latent heat (heat of evaporation, e.g., from occupants) must be handled via some other means. In the most fortuitous cases (e.g., the Pearl River Tower project) natural ventilation and/or down-sized displacement ventilation systems can be employed to provide makeup ventilation and manage the latent load. However, the majority of buildings, in the majority of climates, will require a hybrid-type HVAC design when radiant cooling is utilized.

Over-sizing Water Pipe Diameters

The flow of water in pipes at typical operating conditions for building systems is governed by the Hazen-Williams equation. Under this relationship, for a circular pipe, the friction loss (f) due to the roughness of the pipe interior surface is directly proportional to the pipe's length and the flow rate, and inversely proportional to the fifth power of the diameter, as follows:

$$f \propto LQ/d5$$

where:

f = friction loss due to pipe roughness, in feet of water head
L = pipe length, in feet
Q = flow rate, in gallons per minute (gpm)
d = interior diameter of the pipe, in inches

Note that the Hazen-Williams equation applies for turbulent flow conditions only, which can be safely assumed for water flowing through hydronic systems in buildings. This discussion does not include the losses due to fittings such as elbows, tees, equipment connections, etc., which can be substantial and often greater than the pipe roughness friction loss.

The implications on friction energy losses from moderately increasing the pipe size can therefore be remarkable [54, 55]. For example, a 25% increase in pipe diameter reduces friction loss due to roughness by approximately 66%. Therefore, under some circumstances, the energy savings from the reduced friction (i.e., smaller pumps and less pumping energy) may outpace the cost of installing slightly larger pipes. According to Lovins [55], pipe cost generally increases with cross-sectional area by an exponent of two based on diameter, in contrast to the friction energy savings, which increase with the fifth power of diameter.

Rumsey and Lovins also outline some interesting ideas for reducing the pipe loss due to fittings, which will not be addressed here, but are notable. For example, on the Oakland, California Museum condenser loop retrofit project, considerable use was made of 45-degree pipe junctions rather than the more historically used 90-degree junctions, reportedly saving approximately 69% in pumping energy consumption [55].

Reverse Force Multipliers

Unfortunately, there are also factors that could be characterized as *reverse force multipliers*, i.e., factors that can disproportionately compromise efforts to reduce energy consumption and peak demand. Two examples of this concept are purpose-related limitations and historical preservation restrictions.

The Sweetwater Creek Visitor Center (Lithia Springs, Georgia) is a repository for historical archives and as such requires specific baselines and tight bands on interior temperature and relative humidity. Designers considered natural ventilation but found it to be infeasible for maintaining the specified interior conditions. Nonetheless, the facility was able to incorporate several other energy efficiency measures, such as an enthalpy wheel energy recovery system, rooftop PVs, and ground contact (i.e., the structure is partially buried into a hillside) [48].

The Cambridge City Hall Annex (Cambridge, Massachusetts) includes approximately 8,000 ft^2 of rooftop-mounted PV panels. After reviewing the design, the Cambridge Historical District Oversight Com-mission issued a requirement that the PV panels not be visible from ground level. This necessitated two modifications to the original design: (1) a steel mounting structure above the existing roof, and (2) a completely horizontal (flat) orientation of all PV panels (rather than, for example, tilted toward the south) [56].

While reverse force multipliers often cannot be eliminated, they can be partially offset using alternate energy efficiency strategies, as described above for the Sweetwater Creek Visitor Center. Where they present more serious obstacles to project energy performance, alternatives such as relocating the project to a more favorable climate or site may merit consideration.

BUILD DOWN AS WELL AS UP, AND INWARD AS WELL AS OUTWARD (FP 4)

As climate fluctuates, the perimeter of the building becomes "ground zero" for possible energy inefficiencies. While there are obviously limits on how much contact with the exterior can be shielded, it is nonetheless a fact that many commercial and institutional buildings require separate perimeter space conditioning systems (i.e., in addition to the systems that condition the majority of the occupied space). These systems are often more mechanically intensive and can be wasteful of energy if required to maintain the perimeter spaces at a set temperature and relative humidity. In addition, if the exterior conditions fluctuate significantly, the required control systems may become more complex and/or the perimeter system may not be able in all circumstances to remain within the transformed design conditions, thus resulting in occupant discomfort. Furthermore, the interaction of perimeter HVAC systems with interior HVAC systems can pose problems. For example, if an interior UFAD system is (out of necessity) coupled with a perimeter variable air volume (VAV) system, the VAV system could set up thermal or airflow gradients at the zone boundaries, potentially interfering with the thermal stratification that the UFAD system must achieve in order to be effective and energy efficient.

Some facilities have begun to address this issue, where possible, by utilizing site terrain as a heat insulator and/or other design techniques to protect the building interior from outdoor weather fluctuations, while keeping any exposed perimeter areas as comfortable as possible. Several of these case histories are discussed in this section.

Build Down as Well as Up (FP 4.1)

As has been known throughout the ages, earth is an excellent insulating medium. Therefore, it is not unusual to observe building designers leveraging this principle, particularly where terrain is cooperative (e.g., partially building into the side-slopes of hills). As square footage of the building surface in contact with earth increases, the effect of outdoor weather conditions on building interior conditions is obviously diminished or eliminated. This principle mostly holds true; however, for example, if precipitation and resultant infiltration into the ground increases, the size and complexity of drainage systems (e.g., subsurface French drains) to cope with the increased water and prevent damage to the foundation could increase. This section describes several such projects, as follows:

- The site selected for construction of the new Kitsap County Administration building (Kitsap, Washington) contained a 54-ft change in elevation from south to north. Rather than view this as a deal breaker, the design team implemented a terraced design that supplies several advantages, including: (1) lower heating loads, (2) a narrower floor plate to increase daylighting coverage, (3) gravity drainage for rainwater harvesting, and (4) ability to include operable windows on each floor for optional natural ventilation [57].

- The Sweetwater Creek Visitor Center (Lithia Springs, Georgia) is also constructed into a hill, with approximately 1½ stories of earth contact on three sides (north, west, and east, with approximately 37% of the building footprint buried). Energy savings at this facility are further enhanced by a vegetated roof above the buried section [48]. Vegetated roofs can reduce daytime summer roof surface temperatures by 50°F or greater, and the heat flux through the roof (summer heat gain and winter heat loss) by as much as 40-50%, compared with a traditional built-up roof [58]. Vegetated roofs also commonly offer other benefits such as evapotranspiration of storm water, absorption of atmospheric CO_2, and contribution to urban heat island reduction.

- The Library of Congress' 415,000 ft^2 Packard Campus for Audiovisual Conservation (PCAVC) (Culpeper, Virginia) is similarly constructed, itself a retrofit of a former Federal Reserve Bank storage vault that abuts a large hill, which is partially topped by a vegetated roof [59].

Both the Sweetwater Creek Visitor Center and the PCAVC contain large, climate-controlled archival storage areas; hence, the temperature regulating effect of a partially buried structure is an additional advantage.

For buildings located on generally level sites, this strategy becomes more problematic, although there are still options. Mechanical rooms, computer server rooms, storage areas, support facilities, and parking garages can, and often are, constructed below the ground surface. The Szencorp Building (South Melbourne, Victoria, Australia) is one example of a facility in which the computer server rooms are located within a basement and all excess heat produced is rejected directly to the atmosphere (thus reducing the year-round building cooling load) [11].

A design concept that is becoming increasingly favored in Canada is earth tubes, which are usually horizontal ventilation conduits used to warm or cool airflow (and/or otherwise condition the air, e.g., dehumidify it) and thus reduce load on the building HVAC systems. Earth tubes leverage the same relatively consistent year-round temperature of the ground, as (for example) a GSHP well field does but on a smaller scale. These conduits can be capable of sizeable air throughput; for example, the earth tubes at the MEC® Building (Montreal, Quebec, Canada) process 6,000 cubic feet per minute (cfm) from dedicated outdoor air system (DOAS) air handlers and simultaneously up to 25,000 cfm of recirculated air from the building. The designer claims that the earth tubes have been important elements in enabling the use of the DOAS system, as well as radiant heating and cooling systems and displacement ventilation. As a result of the earth tubes and other system features (including use of GSHPs as the primary heating and cooling source and an enthalpy wheel for airside energy recovery), the building achieved monthly energy savings (compared with a Canadian Model National Energy Code for Buildings [MNECB] reference building) ranging from 75% during the coldest month (January) to 47% during the warmest month (July) [10]. This was based on 2006 data, the most recent available.

To prevent damage, earth tubes must be located beneath the frost line. However, this creates the potential for condensation formation.

This is an important design variable that must be considered. Earth tubes can just as readily be used in warmer climates, although the additional excavation, dewatering, long-term groundwater management, and other costs may not be as easily justified by energy cost savings. The growing popularity and anticipated potential increased application of earth tubes in colder climates is also reflected by the fact that the most recent version of EnergyPlus contains an earth tube analysis subroutine/module [60].

Build Inward as Well as Outward (FP 4.2)

Nearly all buildings will have some (or a great amount of) exposed perimeter façade, and most will require a perimeter heating and/or cooling system. However, there are emerging strategies for reducing the heat loss or gain through the façade and thus the size and energy consumption of perimeter HVAC systems. The most common approach is to provide, where possible, a thermal buffer zone between the locations of the outermost occupants and the building façade. For example, in the design for the Missouri Department of Natural Resources' new headquarters building, the HVAC engineer used CFD modeling to demonstrate the benefit of creating a 4.5-ft-wide perimeter buffer zone separated from the perimeter offices by a 5.5-ft-tall partition. The model's output demonstrated that while (at ASHRAE design conditions and a plenum supply temperature of 72°F) the perimeter buffer zone would be at 71.5°F (i.e., below comfort conditions), the perimeter offices would be maintained at 74.1°F, and the inner office spaces would be at 76.1°F. Thus, all occupied spaces would actually be above design conditions, and both the zone setpoint and plenum supply temperatures could possibly be reduced [61].

Space is almost always at a premium, and a buffer zone purely for energy savings purposes may often be unacceptable. However, a related strategy involves using the perimeter buffer for functions other than full-shift occupancy, i.e., almost as a transient space. This has been accomplished at the Jewish Reconstructionist Congregation (Evanston, Illinois). The South Ceremonial Staircase provides a (weather cooperating) daylit passageway intended to both allow normal traffic flow for worshipers, clergy, and staff, as well as opportunities for casual contact and conversation. The staircase was intentionally located on the south-facing wall to maximize available daylighting and create a thermal buffer against excessive summertime passive heating. Moreover, a simple "indoor climate control" system for the staircase has been constructed in order to: (1) prevent uncomfortably high temperatures, and (2) facilitate makeup fresh air flow. The system consists of an air intake on the first floor, an exhaust fan immediately below roof level on the third floor, and an outdoor temperature sensor. Thus, if outdoor temperatures exceed a specific setpoint, an upwards airflow through the open stairwell is induced to provide ventilation and prevent excessive heat buildup. (Note that this ventilation design operates in conjunction with the stack effect, allowing the exhaust fan's capacity and anticipated energy consumption to be reduced.) [6]

CREATE SYSTEMS THAT AUGMENT ENERGY SAVINGS THROUGH OCCUPANT BEHAVIOR (FP 5)

Companies are increasingly realizing that the human element is critical for successful programs to reduce energy consumption and peak demand. As such, many creative approaches are emerging, several of which are briefly summarized in this section.

Stakeholder Accountability and Participation

At McDonald's Corporation World Headquarters (Oak Brook, Illinois), a Six Sigma team was established in 2007. Several initiatives originating from this team have included:

- Installing motion sensors on lighting
- Installing approximately 350 temperature sensors that provide real-time data to the BAS
- Re-evaluation of HVAC demands and needs throughout the building, in some cases adjusting the setpoints for certain spaces (up or down, as applicable) by 2 to 4°F

Positive outcomes were first reported in the summer of 2008—facility managers claimed a $110,000 annual cost savings, compared with the equivalent cost of consuming energy at the facility's 2005 baseline rate [62].

Two Kentucky school districts (Warren County and Kenton County) have actively embraced the importance of the "human" contribution to sustained energy savings. In Warren County, one of the annual rating criteria for each school principal (along with student performance, safety, etc.) is energy efficiency and energy savings. In addition, the district hired a full-time energy subject matter expert to support and guide principals, custodial personnel, and other staff. Unannounced energy audits are also conducted at selected schools, usually at least one per week. The auditors make a snapshot evaluation of sources of energy loss and inefficiency, including: (1) building envelope deficiencies (e.g., damaged windows, garage doors left open), (2) HVAC equipment malfunctioning or not operating in proper design modes (e.g., setpoints off-base, excessive cycling), (3) unnecessary lighting, and (4) plug loads such as computers that can be disconnected while not in use [14, 23].

The Twenhofel Middle School (Independence, Kenton County, Kentucky) organizes an energy conservation competition between the sixth, seventh, and eighth grades every year. Students are encouraged to open window blinds to admit daylight and check that computer monitors are put into sleep mode when not being used. At another Kenton County school (James A. Caywood Elementary School, Edgewood, Kentucky), the students were given light meters and assigned to measure the daylight levels in each space, in order to gather data for future school designs. These data were in fact used in the lighting design of the Turkey Foot Middle School (Edgewood, Kentucky), which was able to achieve interior lighting levels comparable to the Caywood Elementary School, but with half the total glazing area [14].

Interfaces between Occupants and Building Systems

There are multiple examples of how building occupants are able to interact with critical building systems to adjust the indoor climate or lighting within their immediate work environment or obtain other crucial services. These include the following:

- At the McDonald's Corporation World Headquarters building (Oak Brook, Illinois), facility occupants can, through their computer workstations, request additional lighting from the BAS when working off-shift hours (e.g., evenings, weekends) [62]. The 5 Houston Center building (Houston, Texas) has a similar system, through which occupants can enter requests for after-hours HVAC and lighting into a central computer maintenance system. (The system also generates a monthly report on after-hours usage by each tenant, for billing purposes.) [26]

- Workstations at the Stellar Commercial Building (Jacksonville, Florida) feature “inboard” switching, which allows employees to temporarily override occupancy sensors if the sensors do not recognize the presence of the occupant(s) [18].

- The air handling unit (AHU) at the 641 Avenue of the Americas Building (New York, New York), which is normally idle during off-shift hours, is equipped with a manual override button. To discourage excess use or operation after the occupant(s) have departed, the AHU automatically shuts off every two hours (i.e., personnel must press the button every two hours to obtain air/heat/cooling) [9].

Interestingly, there are also buildings that do not wait for (or rely upon) occupant input—rather, the building systems guide occupants into undertaking behaviors that promote energy efficiency without their direct knowledge or realization. In the classrooms of the Lundquist Business College, University of Oregon campus at the Lillis Business Complex (Eugene, Oregon), the light switches (in addition to turning on the lights) automatically open fabric window shades. Once daylight begins to (and continues to) penetrate the classroom, the artificial lamps are dimmed or shut off completely, based on light measurements taken by photocells within the room. Moreover, occupancy sensors provide a redundant means of shutting the lamps completely off after, for example, a class has concluded and all participants have left the room [5].

Finally, there is also a potential role for education, particularly in residential settings. As mentioned previously, the simple traffic light-style submetering system at the Georgetown Mews Apartments (Queens, New York) contributed to documented electricity savings [49, 50]. In addition, at the Solaire Building (New York, New York), each incoming resident is provided with a building tour and information regarding how he/she can contribute to reducing building energy consumption. Building operators claim this has contributed, in part, to overall energy consumption approximately 24% below the equivalent New York State Energy Code residential building baseline [63].

CONCLUSIONS

The research presented in Parts I and II of this article has demonstrated the following:

- Many organizations are concerned about the possible effects of a variable climate on buildings, including potential global warming, and believe some sort of action/response will be required to help buildings becoming more adaptive.

- Preliminary climate modeling, using CC WorldWeatherGen® and EnergyPlus, indicate a wide variation of results with changing latitude within the Midwestern U.S. and south-central Canada. Under some circumstances, total energy use increases and under others it decreases; nonetheless, peak summer electric demand is projected to increase at all locations.

- Employing a set of five Fundamental Principles (FPs) can improve buildings' energy performance and dampen the impact of climate variations.

Numerous case studies were presented to illustrate application of the FPs. (Appendix A contains a partial list.)

The scope of this article did not include focusing on energy sourcing; however, there is an interesting example of just how strikingly the decision-making process for energy procurement could change for facilities in the immediate future. The Poudre School District (PSD) in Larimer County, Colorado operates four elementary schools, one middle school, one high school, and a Central Operations Office building. PSD, in addition to total energy consumption, uses total carbon emissions as a benchmark for selecting HVAC technologies. This necessarily involves simultaneous consideration of the mix of energy sources available in the local area. Specifically, 75% of the county's electricity is obtained from coal-fired generating plants; therefore, GSHPs and vapor compression chillers could (in theory) have a higher carbon footprint compared with natural gas-fired boilers. However, as discussed below, the results have borne out differently.

PSD performed an analysis of the total carbon footprints of its six school buildings for the combined fiscal years 2008 and 2009 and noted the following (see Table 5):

- The two schools that used indirect/direct evaporative cooling (via cooling towers) and natural gas boilers exhibited, on average, an approximately 19% lower carbon footprint (measured in pounds of CO_2, equivalent per square foot per year) than those using electric, air-cooled vapor compression chillers, ice thermal storage, and natural gas boilers.

- The one school (Kinard Middle School) using a GSHP outperformed all of the others (approximately 13% lower carbon footprint than the schools with evaporative cooling and approximately 30% lower than the schools with vapor compression chillers and ice thermal storage). This was observed notwithstanding the fact that approximately twice its energy supply was derived from coal-fired electricity rather than from natural gas (71% compared with

Table 5. Poudre School District, Larimer County, Colorado, Energy Intensities and Carbon Footprints[1]

Facility	Energy Consumption Intensity (kBTU/ft^2/yr)	Carbon Emissions (lb CO_2, equivalent/ft^2/yr)	Ratio of Electricity to Natural Gas Consumption
Central Operations Office[2]	19.0	9.8	100%
Zach Elementary School[3]	42.6	12.0	40%
Bacon Elementary School[3]	45.7	11.8	36%
Fossil Ridge High School[4]	40.9	12.3	50%
Kinard Middle School[5]	21.6	8.4	71%
Rice Elementary School[6]	41.5	9.8	27%
Bethke Elementary School[6]	41.7	9.9	29%

Notes:

1. Data are for the combined fiscal years 2008 and 2009. Source: Franconi, E., *Green Evolution, Case Study: Bethke Elementary School, Timnath, Colorado*, High Performing Buildings, Winter 2010, pp. 5 – 15.
2. HVAC system: DOAS, energy recovery, and GSHP.
3. HVAC system: VAV, air-cooled chiller, ice thermal storage, and natural gas boilers.
4. HVAC system: VAV, indirect/direct evaporative cooling, four-pipe fan coils, air-cooled chiller, ice thermal storage, and natural gas boilers.
5. HVAC system: DOAS, energy recovery, and GSHP.
6. HVAC system: VAV, indirect/direct evaporative cooling, cooling tower, and natural gas boilers.

kBTU/ft^2/yr – thousand British Thermal Units per square foot per year; CO_2 – carbon dioxide; HVAC – heating, ventilating, and air conditioning; DOAS – dedicated outdoor air supply system; GSHP – ground source heat pump; VAV – variable air volume; lb – pounds an average of 36% for the other schools). At Kinard Middle School, 94% of its carbon footprint was associated with electricity usage, and only 6% was associated with natural gas usage.

- The one all-electric building (the Central Operations Office, which uses a GSHP) was not the facility with the highest carbon footprint; in fact, its carbon footprint was almost identical to those of the two schools using indirect/direct cooling and natural gas boilers [46].

Naturally, these results are very tightly linked to local climate conditions, building envelope design, and available energy supplies and prices, among other factors. There is a strong probability that the results from another geography and school district would be different, perhaps considerably different. Site-specific analyses are always essential, and one cannot translate these results "as is" to other situations.

Carbon emissions/footprint would apparently be one of numerous project-specific criteria PSD would use to select HVAC systems on future school projects. What this case history clearly illustrates is the potential introduction of *carbon planning* into the building design process, which five or ten years ago probably would have been completely absent. It is one more example of how building designers, developers, owners, operators, and managers should expand their perspective and seek to drive technological innovation in order to produce high performing buildings that both limit their carbon emissions impact and are prepared to cope with potential local climate fluctuations.

A FINAL WORD ABOUT COST

From Appendix A, it is not difficult to discern that most high-performing buildings are not inexpensive to construct. Square footage costs for the subset of buildings listed therein generally range from \$140 per ft^2 to almost \$450 per ft^2. Many of these projects will recoup these costs within an acceptable payback period (or produce an acceptable return on investment [ROI]) as a result of energy cost savings or other factors (e.g., worker productivity). In other cases, there are additional factors beyond economics that prompted these facilities to be built using leading-edge, greening architectural designs, technologies, and systems. Evaluation of

ROI for such projects was beyond the scope of this article; however, the need will always exist to define project goals and objectives such that capital costs, O&M costs, and other issues are properly balanced. Each developer, owner, or operator will have unique requirements for a particular facility. The possibility of climate change introduces a new risk to the already large portfolio of risks, which includes occupancy levels, energy supplies and prices, cost of capital (i.e., financing), insurance costs, etc. Adaptive buildings provide a potential means for, if not completely alleviating those risks, at least partially mitigating them (analogous to smoothing out "spikes" on a graph). In addition, developers or owners of an adaptive building (based on the most innovative and cost effective technologies available to them) cannot easily be accused of not doing their part to aid in controlling: (1) tenants' costs, and (2) the other impacts weather can cause to a building that preclude its occupants from successfully and comfortably engaging in their intended activities.

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Appendix A
Examples of Case Histories Used in this Article (Part I)

Table A-1. Results of Climate Change and Whole Building Energy Simulation Modeling for the EnergyPlus Benchmark Primary School and Benchmark High School

Location (North Latitude)	Year	**Benchmark Primary School**			**Benchmark High School**		
		Total Annual Energy Consumption (mmBTU)	**Total Annual Energy Consumption (kBTU/GSF)**	**Annual Peak Electrical Load (kW)**	**Total Annual Energy Consumption (mmBTU)**	**Total Annual Energy Consumption (kBTU/GSF)**	**Annual Peak Electrical Load (kW)**
New Orleans, Louisiana (30 deg N, 0 min, 0 sec)	2010 (Baseline)	4,384	59.27	311.1	13,009	61.69	1,153
	2020	4,558	61.63	335.2	13,697	64.95	1,340
	2050	4,678	63.25	347.1	14,276	67.69	1,436
	2080	4.906	66.34	367.5	15,395	73.00	1,580
Memphis, Tennessee (35 deg N, 4 min, 12 sec)	2010 (Baseline)	4,712	63.71	329.0	14,285	67.74	1,226
	2020	4,803	64.94	350.9	14,576	69.12	1,307
	2050	4,854	65.64	369.0	14,791	70.13	1,392
	2080	4.987	67.43	399.8	15,279	72.45	1,630
St. Louis, Missouri (38 deg N, 45 min, 0 sec)	2010 (Baseline)	5,609	75.84	343.7	17,426	82.63	1,235
	2020	5,548	75.02	362.6	17,115	81.16	1,312
	2050	5,500	74.37	389.2	16,872	80.00	1,429
	2080	5,450	73.69	436.5	16,644	78.93	1,582
Chicago, Illinois (41 deg N, 58 min, 48 sec)	2010 (Baseline)	5,974	80.77	328.6	19,546	92.69	1,242
	2020	5,854	79.15	342.4	18,937	89.80	1,340
	2050	5,764	77.94	364.2	18,426	87.38	1,478
	2080	5,637	76.21	400.3	17,570	83.32	1,686
Minneapolis, Minnesota (44 deg N, 52 min, 48 sec)	2010 (Baseline)	6,998	94.62	321.2	23,110	109.58	1,076
	2020	6,707	90.68	330.6	22,107	104.83	1,212
	2050	6,510	88.02	352.5	21,459	101.75	1,340
	2080	6,201	83.84	382.2	20,135	95.48	1,550
Winnipeg, Manitoba (49 deg N, 54 min, 0 sec)	2010 (Baseline)	8,825	119.3	296.2	30,549	144.86	1,012
	2020	8,507	115.0	314.1	29,212	138.52	1,109
	2050	8,288	112.1	331.9	28,226	133.84	1,126
	2080	7,866	106.4	367.7	26,300	124.71	1,355

Table A-2. Results of Climate Change and Whole Building Energy Simulation Modeling for the EnergyPlus Benchmark Medium Office and Benchmark Large Office

Location (North Latitude)	Year	Benchmark Medium Office			Benchmark Large Office		
		Total Annual Energy Consumption (mmBTU)	Total Annual Energy Consumption (kBTU/GSF)	Annual Peak Electrical Load (kW)	Total Annual Energy Consumption (mmBTU)	Total Annual Energy Consumption (kBTU/GSF)	Annual Peak Electrical Load (kW)
New Orleans, Louisiana (30 deg N, 0 min, 0 sec)	2010 (Baseline)	2,227	41.53	208.2	20,191	40.50	1,686
	2020	2,305	42.97	223.2	20,865	41.85	1,766
	2050	2,367	44.14	232.4	21,452	43.03	1,822
	2080	2,476	46.17	246.8	22,452	45.03	1,918
Memphis, Tennessee (35 deg N, 4 min, 12 sec)	2010 (Baseline)	2,303	42.95	208.1	19,799	39.71	1,710
	2020	2,360	44.00	225.8	20,270	40.65	1,795
	2050	2,407	44.89	234.3	20,709	41.54	1,844
	2080	2,504	46.69	241.0	21,461	43.04	1,907
St. Louis, Missouri (38 deg N, 45 min, 0 sec)	2010 (Baseline)	2,469	46.05	226.1	20,333	40.78	1,867
	2020	2,472	46.10	247.5	20,586	41.29	1,926
	2050	2,494	46.50	258.7	20,846	41.81	1,850
	2080	2,551	47.57	280.7	21,257	42.63	1,899
Chicago, Illinois (41 deg N, 58 min, 48 sec)	2010 (Baseline)	2,650	49.42	188.0	21,683	43.49	1,628
	2020	2,624	48.93	200.5	21,728	43.58	1,727
	2050	2,625	48.95	212.8	21,860	43.84	1,810
	2080	2,641	49.24	238.3	22,147	44.42	1,941
Minneapolis, Minnesota (44 deg N, 52 min, 48 sec)	2010 (Baseline)	2,887	53.83	191.6	23,086	46.30	1,657
	2020	2,831	52.79	206.1	22,922	45.97	1,743
	2050	2,807	52.35	237.1	22,928	45.99	1,829
	2080	2,770	51.66	259.2	22,882	45.89	1,975
Winnipeg, Manitoba (49 deg N, 54 min, 0 sec)	2010 (Baseline)	3,431	63.97	180.1	26,911	53.98	1,609
	2020	3,348	62.43	191.3	26,620	53.39	1,689
	2050	3,298	61.50	220.3	26,508	53.17	1,773
	2080	3,199	59.65	252.7	26,008	52.16	1,911

Table A-3. Results of Climate Change and Whole Building Energy Simulation Modeling for the EnergyPlus Benchmark Midrise Apartment Building and Benchmark Large Hotel

		Benchmark Midrise Apartment Building			Benchmark Large Hotel		
Location (North Latitude)	**Year**	**Total Annual Energy Consumption (mmBTU)**	**Total Annual Energy Consumption (kBTU/GSF)**	**Annual Peak Electrical Load (kW)**	**Total Annual Energy Consumption (mmBTU)**	**Total Annual Energy Consumption (kBTU/GSF)**	**Annual Peak Electrical Load (kW)**
New Orleans, Louisiana (30 deg N, 0 min, 0 sec)	2010 (Baseline)	1,545	45.80	77.29	17,676	144.8	592.1
	2020	1,617	47.94	84.05	18,241	149.4	628.5
	2050	1,677	49.70	87.82	18,623	152.5	654.7
	2080	1,779	52.72	94.35	19,499	159.7	724.8
Memphis, Tennessee (35 deg N, 4 min, 12 sec)	2010 (Baseline)	1,540	45.64	79.53	17,433	142.8	563.1
	2020	1,587	47.02	86.80	17,758	145.4	621.2
	2050	1,630	48.30	91.43	18,088	148.1	659.6
	2080	1,710	50.67	100.6	18,692	153.1	719.7
St. Louis, Missouri (38 deg N, 45 min, 0 sec)	2010 (Baseline)	1,618	47.95	76.99	17,610	144.2	554.9
	2020	1,630	48.31	82.68	17,904	146.6	685.7
	2050	1,647	48.81	88.27	18,068	148.0	727.7
	2080	1,686	49.97	96.48	18,387	150.6	814.6
Chicago, Illinois (41 deg N, 58 min, 48 sec)	2010 (Baseline)	1,702	50.44	76.93	18,139	148.5	581.5
	2020	1,685	49.95	84.13	18,181	148.9	646.3
	2050	1,683	49.88	90.92	18,230	149.3	711.9
	2080	1,678	49.73	104.6	18,317	150.0	855.7
Minneapolis, Minnesota (44 deg N, 52 min, 48 sec)	2010 (Baseline)	1,831	54.26	80.22	18,911	154.9	617.4
	2020	1,793	53.13	87.68	18,864	154.5	672.9
	2050	1,784	52.88	95.61	18,886	154.7	741.0
	2080	1,758	52.09	110.9	18,853	154.4	883.4
Winnipeg, Manitoba (49 deg N, 54 min, 0 sec)	2010 (Baseline)	2,192	64.96	75.07	20,544	168.2	565.5
	2020	2,126	63.01	81.44	20,459	167.5	616.9
	2050	2,095	62.10	87.69	20,365	166.8	672.5
	2080	2,023	59.96	99.98	20,161	165.1	798.6

Appendix B—Examples of Case Histories Used in this Article (Part I, II)

Facility	Location	Square Footage	Primary Facility Use(s)	Sustainability Ratings or Scores			Capital Cost per Square Foot
				LEED®	ENERGY STAR®	Other	
Richard J. Klarchek Information Commons Building, Loyola University	Chicago, Illinois	70,500	Student/faculty digital library	Silver(a)	85.6(b)	NA	$397.16
Lavin-Bernick Student Center, Tulane University	New Orleans, Louisiana	148,000	University center	NA	Not specified	NA	$192.05
Manitoba Hydro Place	Winnipeg, Manitoba, Canada	698,000	Commercial office	NA	NA	NA	$398.28
Jewish Reconstructionist Congregation	Evanston, Illinois	31,600	Religious institution	Platinum (NC)	Not specified	NA	$231.01
Plano Elementary School	Bowling Green, Kentucky	81,147	Elementary school	NA	99	NA	$140.49
5 Houston Center Building	Houston, Texas	580,875	Office	NA	86	NA	Not specified

Notes:

(a) LEED® rating system was not specified, believed to be New Construction due to recent completion date.

(b) Maximum ENERGY STAR® score is 100 points.

NC – New Construction; NA – not applicable