Natural History Museum and Swiss Re Office Building in London were built a century apart, but both use natural ventilation and daylighting.

Sustainability In Cold Climates

By Shahrokh Farzam, P. Eng., Member ASHRAE; and **Giuliano Todesco,** Member ASHRAE

During the last five years, ASHRAE has significantly addressed sustainability and energy efficiency in buildings with the ultimate goal to develop net zero energy buildings by 2020 or 2030.[1,2] Activities have included continued updates of ANSI/ASHRAE/IESNA Standard 90.1; development of *Advanced Energy Design Guides* (AEDGs) designed to provide performance improvements of 30% beyond Standard 90.1; and more recently, development of ASHRAE/USGBC/IES Standard 189.1, *Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings,* which is being published this month. These goals have also been recently confirmed as part of the U.S. government's strategic energy plan.[3]

The American Institute of Architects (AIA) proposed and passed comparable targets in 2006 after the architect Ed Mazria set in motion The 2030 Challenge. This initiative calls for architects to design all new buildings to use 50% less energy than current practice and progressively increase the performance towards carbon neutral energy designs by 2030.

In the same year, the European Union (EU) passed legislation that mandates large improvements in the energy perfor-

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mance of existing and new buildings to meet the EU's Kyoto commitment within 10 years. Buildings account for one-third of energy use in the EU.[4,5]

These efforts clearly indicate a rapid market transformation and mark a move towards a second generation of high performance designs, envisioned to achieve a 50% or better improvement over current design practice with the ultimate goal to reach Zero Energy Building (ZEB) designs as early as 2020. However, current design standards must be strengthened significantly before the industry can reliably achieve designs that are 50% better than current practice. A recently released report compiling the performance of 121 LEED projects found the average performance to be only 28% better than Standard 90.1-1999.[6]

This article describes the design approaches and technologies required to achieve high performance, low energy designs suited to cold climates that are 50% better than Standard 90.1-2007. The article also provides a comparison of design standards and presents potential reductions in energy use based on a DOE 2.1E energy model of a hypothetical mid-rise office building located in Chicago.

High Performance Construction and Integrated Design

High performance low energy designs that are able to achieve a reduction in energy use greater than 50% more than Standard 90.1-2007 require minimal heating and cooling loads plus minimal internal heat gains via low lighting power density (LPD) designs and maximum use of natural lighting. Such low energy designs also require higher reliance on weather integration, passive design techniques, alternate HVAC designs such as displacement ventilation (DV) or dedicated outdoor air systems (DOAS) and use of best-in-class technologies to meet the reduced loads. By necessity, low energy designs also require renewable technologies to achieve further reductions in energy use.

Integrated design process (IDP) has emerged as an approach to design low energy buildings. IDP was originally described by Amory Lovins in 1992 as a whole building design approach that focuses on load minimization, meeting the load with most efficient technologies, efficient operation and commissioning.[7] This design approach allows the designer to take advantage of synergies that exist between building elements and allow maximization of energy savings while minimizing incremental costs via equipment trade-offs.[8] During the last 15 years, this approach has been validated in high performance construction programs from electric utilities in the U.S. and Canada.[9] It is also described in the LEED-NC Reference Guide introductory section that lists design features typically present in sustainable buildings. These include good thermal performance to reduce heating and cooling loads, optimized architectural designs for free heating, cooling, ventilation and lighting and use of smaller and more efficient HVAC and lighting systems.

More recently, the International Energy Annex (IEA) 49, "Low Exergy Systems for High Performance Buildings and Communities," described a similar design strategy. Its documentation describes a three-step approach that includes minimization of the building energy demand with good levels of thermal insulation, use of renewable energy sources to the maximum extent possible and using fossil fuel as efficiently as possible to meet the remaining energy demand.[10]

The building industry has embraced the drive towards high performance construction and continues to push design concepts with recent trends that embrace load minimization, passive designs and a return to design approaches used in the past.

An example of this return to the design approaches used in the past is illustrated by two buildings located in London that were built a century apart. The Natural History Museum relies on a natural ventilation design via the use of fresh air inlets located at ground level plus six towers to ventilate the building via natural convection. Professor Jeffrey Cook from Arizona State University stated that: "The design of the ventilation system is an example of forgotten knowledge that addresses today's interest in passive and low energy systems."[11]

Swiss Re office building in London was built 123 years later. It is a 40-story, 450,000 ft² (41 806 m²) office building and a striking example of modern day, high performance buildings that incorporates a hybrid ventilation system that relies on natural ventilation and a displacement ventilation system when weather conditions do not allow sufficient air exchange. It also features 100% daylighting using light wells, plus other leading edge energy efficiency features.

Other architectural techniques reintroduced in modern sustainable construction are passive cooling technologies including operable windows, wind-induced cross-ventilation and solar or thermal chimneys. These technologies were used in past building construction such as the well-known Flatiron building in New York City, and they are increasingly used in passively ventilated new construction.

Design Standards and Performance Levels

Achieving a performance improvement greater than 50% through load minimization of conventional designs and use of "best-of-class" equipment is extremely difficult as attested by the few examples that exist. The majority of the high performance buildings constructed in the last 15 years achieved improvements of 25% to 50% with an upper level of approximately 60%.[10] This is because in a typical commercial building the HVAC and lighting end uses account for approximately 80% of the total building energy use, while commercial food preparation, commercial refrigeration, office equipment, and vertical transportation account for the balance. Energy reductions in these end uses are not as easily achieved.[12] As a result, further savings in HVAC and lighting become increasingly more difficult.

Figures 1a and *1b* provide a breakdown of energy use by end use of typical commercial buildings in heating dominated regions in the U.S. and Canada.[12,13] As shown, space heating is the largest end use accounting for 30% to 50% of the total energy use. Lighting is the second largest end-use in buildings in the U.S. and the third largest end-use in buildings in Canada.

In addition, lighting contributes indirectly to the space cooling energy use.

Combined, these three end-uses account for 62% to 68% of the total energy use by commercial buildings and as a result, a high performance low energy design needs to address the components and technologies that will impact these end-uses.

Standard 90.1 is increasingly defining higher levels of thermal performance and lower lighting power densities. As shown in *Table 1*, succeeding versions of Standard 90.1 offer increasingly higher levels of thermal performance. The values shown are the maximum U-values for buildings in Zone 5 with heating degree days from 5,400 to 7,200. The European Union under the Energy Performance Building Directive (EPBD) proposed in 2004 thermal performance levels that are significantly higher than those of Standard 90.1-2007.[14]

Similarly, Standard 90.1 continues to define increasingly lower lighting power densities (LPDs) made possible with improvements in performance of fluorescent lighting coupled with better understanding of the physiology of the human eye and the importance of lighting color. As shown in *Table 2*, LPD levels have decreased by approximately 20% to 30% between the 2001 and 2007 versions of the standard.

The reductions shown in *Table 2* have been possible due to the increase in the efficacy of fluorescent lighting systems from approximately 65 lumens/watt for standard F34 T12 lamps with electromagnetic ballasts to 100 lumens/watt for high performance T8 lamps with extra efficient instant start ballasts.[15]

Improvements have also occurred with lamp phosphors and the quality and color of fluorescent lighting. Spectrally enhanced fluorescent lamps produce light that is closer to daylight and allow further reductions in the connected lighting loads. This results in a potential further drop in the LPD beyond what can be achieved from the improvement in the lighting efficacy alone. LPDs as low as 0.75 W/ft^2 (8 W/m^2) in office environments are possible now with the best fluorescent technologies, while providing good illuminance levels and ongoing research by the U.S. Department of Energy (DOE), supports these LPD levels.[16]

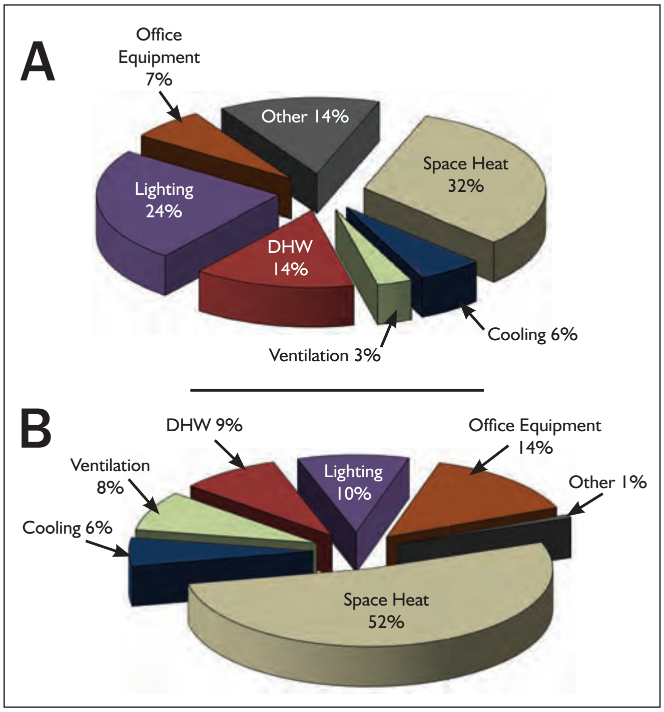

Figure 1a (top): 1995 Commercial Buildings Energy Consumption Survey (CBECS). Table 2A, p 35.8, **2003 ASHRAE Handbook—HVAC Applications.** *Energy intensities of commercial buildings in a climate zone with 2,200 to 3,055 HDD. Figure 1b (bottom):* **Energy Use Data Handbook,** *August 2006, Natural Resources Canada (NRCan). Values shown are based on the total energy use by end-use for the entire commercial sector divided by the total floor area (pp. 48–49).*

High performance construction projects are routinely achieving these levels and the use of daylighting controls applied to the building perimeter can help lower the "in use" LPD even more. One example is the recently completed renovation of the Exelon Corporation 200,000 ft^2 (18 581 m^2) headquarters in Chicago. The design earned a LEED CI Platinum certification and achieved a low "in use" LPD of 0.6 W/ft^2 (6.5 W/m^2).[17]

Still lower LPDs will be possible as white LED lighting efficacies continue to increase beyond the level of the best fluorescent systems. Recently, one manufacturer of LED lighting reported efficacies of 129 lumens/watt in the laboratory for a cool white LED light. Researchers believe that LED can achieve efficacies of 150 to 200 lumens/watt and these performance levels can potentially lower LPDs further.[18]

The performance improvement of cooling equipment, heating equipment and fan power use outlined by the different versions of Standard 90.1 are less than the improvements achieved in envelope thermal performance and connected lighting loads. The performance guidelines of large tonnage centrifugal chillers, natural gas boilers and the fan power limitations defined in various versions of Standards 90.1 are shown in *Table 3*. The full load performance requirement and integrated part load value (IPLV) for centrifugal chillers in the range of 300 to 600 tons have not changed since Standard 90.1-2001, yet manufacturers of cooling equipment have continued to improve equipment performance. Best-in-class products capable of IPLV levels in the range of 0.45 to 0.5 kW/ton (1.58 to 1.76 kW/kW) at AHRI standard conditions are available in the market. Similarly, fan power limitations and boiler efficiency have not changed.

Future Performance Levels and Technologies

High performance designs able to achieve energy savings above 50% will require performance levels beyond those outlined in the preceding section. *Table 4* show the performance improvements that can be achieved with different envelope, lighting and HVAC equipment performance levels based on a hypothetical building located in Chicago.

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Building Element	Standard 90.1–2001	Standard 90.1–2004	Standard 90.1–2007	U.K. (EPBD)*
Roof Above Deck U-Value (R)	0.063 (R15.8)	0.063 (R15.8)	0.048 (R21)	0.023 to 0.035 (R28 to R43)
Mass Wall U-Value (R)	0.123 (R8.1)	0.123 (R8.1)	0.09 (R11.1)	0.035 to 0.048 (R21 to R28)
Glass U-Value (R)	0.57 (R1.75) Double 6/12/6	0.57 (R1.75) Double 6/12/6	0.35 (R2.85)	0.227 to 0.31 (R3.2 to R4.4)
Glazing SHGC	0.49	0.39	0.40	

*EPBD is the Energy Performance of Buildings Directive published by the European Commission in January 2004. This directive requires member states to set minimum energy performance standards for new and existing buildings for EU countries to meet their commitment to the Kyoto Protocol by 2015.

Table 1: Evolution of thermal performance levels in building design standards for Zone 5 (HDD from 5,400 to 7,200; U-Values in Btu/h·ft²·°F).

Building Type	Standard 90.1–2001	Standard 90.1–2004	Standard 90.1–2007	Best Designs	Future*
Office	1.3	1.0	1.0	0.65 to 0.7	0.45 to 0.5
School	1.5	1.2	1.2	–	–
Retail	1.9	1.5	1.5	–	–

*This value is extrapolated using an efficacy of 150 lumens/watt that could be possible with future LED lighting.

Table 2: Evolution of LPDs from three versions of Standard 90.1 and best achievable performance levels (building area method values in W/ft²).

Component	Standard 90.1–2001	Standard 90.1–2004	Standard 90.1–2007
Cooling Equipment kW/ton (IPLV)* (300 to 600 ton)	(0.55)	0.58 (0.55)	0.58 (0.55)
Heating Equipment (300,000 to 2.5 million Btu/h)	80% *Ec*†	80% *Ec*	80% *Ec*
Fan Power Limitations (>20,000 cfm) Constant Volume	1.1 hp/1,000 cfm	1.1 hp/1,000 cfm	1.1 hp/1,000 cfm
Fan Power Limitations (>20,000 cfm) Variable Volume	1.5 hp/1,000 cfm	1.5 hp/1,000 cfm	1.5 hp/1,000 cfm

*Cooling equipment IPLV is at 44°F leaving chilled water and 85°F entering cold water temperatures and condenser flow of 3 gpm/ton. †*Ec* means combustion efficiency.

Table 3: Equipment performance improvement from three versions of Standard 90.1.

Table 4 shows the effect on the size of the heating load and annual natural gas energy use from various levels of thermal insulation. The building assumes a 100,000 ft² (9290 m²) total building area and a floor plate dimension of 100 ft × 200 ft (30.5 m × 61 m). The building envelope is a curtain wall system with a window-to-wall ratio (WWR) of 0.35.

The design heat loss was calculated using the equation shown in *Table 4* and the annual natural gas use was calculated with DOE 2.1E. As shown, a low energy design with an R4 high performance glazing system can achieve a reduction in the design heat loss of 31% compared to the Standard 90.1 reference building. The size of the heating plant is reduced by 18%. The annual natural gas use, which includes domestic hot water, is reduced by approximately 42%.

The suggested energy performance of the low energy design would result in a natural gas intensity of 15 kBtu/ft²·yr (174 MJ/m²·yr). Although this performance improvement is good, it is not sufficient for low energy designs that aim at performance levels of 60% below Standard 90.1.

Adding heat recovery to preheat outside air using building exhaust, plus condensing boilers for space heating and DHW, could lower the overall heating plant requirements and annual natural gas use by 39% and 49% respectively. This option would exhibit a very low natural gas energy intensity of 13 kBtu/ft²·yr (151 MJ/m²·yr).

While it is possible to increase the thermal performance of the building envelope further, and there are new materials with high levels of thermal resistance such as vacuum insulated panels (VIPs) and transparent insulation materials (TIM),[19] other approaches are emerging to achieve low space heating energy use that focus on the heat loss and heat gain through the building envelope.

Scenarios	Roof		Wall		Window		Design Heat Loss		Ventilation Load Btu/h	Heating Plant Size		Natural Gas Use	
	U-Value	R	U-Value	R	U-Value	R	Btu/h	Savings		Btu/h Input	Savings	Therms/ year	Savings
Standard 90.1 - 2007	0.0480	20.8	0.0900	11.1	0.3500	2.86	697,080	–	479,520	1,434,878	–	26,446	–
Improved Design	0.0333	30.0	0.0417	24.0	0.3500	2.86	591,679	**15.1%**	479,520	1,306,341	9.0%	16,839	**36.3%**
Low Energy Design	0.0286	35.0	0.0357	28.0	0.2500	4.00	481,085	**31.0%**	479,520	1,171,469	18.4%	15,414	**41.7%**
Low Energy Design +HR +Condensing Boiler	0.0286	35.0	0.0357	28.0	0.2500	4.00	481,085	**31.0%**	234,965	873,231	39.1%	13,351	**49.5%**

- Design heat loss calculated as follows:
  - Indoor temperature of 70°F and OA winter design of –4°F (Climate Data, *2001 ASHRAE Handbook—Fundamentals*, Chapter 27, at Chicago Meigs Field)
  - Infiltration heat loss based on 0.05 cfm/ft² wall area
  - Design Heat Loss $(Q) = U_r A_r (T_i - T_d) + U_w A_w (T_i - T_d) + U_{wi} A_{wi} (T_i - T_d) + \text{Inf. A } 1.08 (T_i - T_d)$
- The ventilation load is based on 250 ft/person and 15 cfm/person
- The heating plant size based on an 82% thermal efficiency (*Et*)
- The annual natural gas was calculated with DOE 2.1E
- The annual natural gas use includes 5,730 therms for DHW or 5.8 kBtu/ft²·yr

***Table 4:** Impact of varying thermal performance levels on design heat loss and annual natural gas use for a five-story, 100,000 ft² office in Chicago with a 100 × 200 ft footprint and a WWR of 0.35 (U-Values in Btu/h·ft²·°F).*

Studies show high performance glazing systems are a net heat source during heating season in most climates. This can be true for double-skin façades (DSF).[20] A properly designed DSF can operate as an energy positive envelope and achieve large heating energy savings relative to what is expected from only its thermal performance since the two façades can act as a passive solar collector.

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This technology has been used mostly in Europe due to the stringent building codes that require fully daylit building interiors while maintaining good thermal performance of the building envelope. DSFs meet these criteria, work well with natural and hybrid ventilation designs and can minimize the excess heat gain in the summer via operable louvers.

This technology is, in theory, superior to a conventional high performance building envelope. However, the limited design knowledge, the lack of analytical tools that can model the complex thermal behavior and an incomplete understanding of how the technology works is producing designs that exhibit mixed performance results.[21,22] Two successful DSF designs include the Daimler Building in Berlin built in 1996 and the Deutsche Post in Bonn, Germany, built in 2003.[4,23] The Daimler building is reported to use 30% less energy for space heating than a naturally ventilated German office building and exhibits a whole building energy intensity 24 kBtu/ft^2·yr (271 MJ/m^2·yr), which is a very low intensity considering that Berlin has similar heating degree-days as Chicago.

From an electricity use standpoint, the low energy design could achieve potential savings as high as 59% using technologies and design approaches that include best-in-class fluorescent lighting design with a low LPD of 0.6 W/ft^2 (6.4 W/m^2), daylighting controls, best-in-class cooling plants and alternate HVAC designs such as DOAS and chilled ceiling system.

At the end-use level, cooling energy use of the low energy design is 40% lower thanks to the efficient lighting design and use of the latest generation of variable speed, frictionless, centrifugal chiller that can achieve an IPLV of 0.45 and a full load performance of 0.5 kW/ton (1.75 kW/kW). The plant size requirement based on the coincident peak cooling load predicted by the DOE 2.1E model is reduced from 160 tons to 120 tons (563 kW to 422 kW), a 25% reduction.

The DOAS design can achieve fan power and energy savings of as much as 70% based on total airflows of 0.2 cfm/ft^2 (1 L/s·m^2) compared to the reference design of 1 cfm/ft^2 (5 L/s·m^2) since DOAS are designed to only deliver ventilation air.[24,25]

As shown in *Table 5*, total predicted energy savings relative to a Standard 90.1-2007 building are estimated to be approximately 54%. This value drops to ~46% for the entire building with the inclusion of plug loads. While this level of savings does not look impressive relative to industry goals, energy intensities below the predicted values of 30 kBtu/ft^2·yr (349 MJ/m^2·yr) are difficult to achieve. As an example, the best levels of energy performance from a sample of 120 LEED projects recently analyzed were in the range of 25 kBtu/ft^2·yr (284 MJ/m^2·yr) and examples of high performance designs exten-

Scenarios	LPD W/ft²	Cooling IPLV kW/ton	Electrical Energy				Natural Gas Therms/yr	Total Energy		Building Energy	
			Lighting kWh/yr	Cooling kWh/yr	Fans kWh/yr	Savings		kWh/yr	Savings	kBtu/ft²·yr	Savings
Standard 90.1 - 2007	1.00	0.55	311,344	113,038	207,410	–	26,446	1,406,653	**–**	55	**–**
Improved Design	0.77	0.50	240,584	79,947	200,086	17.6%	16,839	1,013,995	**27.9%**	41	**24.0%**
Low Energy Design	0.60	0.50	169,820	79,947	200,086	28.8%	15,414	901,479	**35.9%**	38	**30.9%**
Low Energy Design (DOAS)	0.60	0.45	135,876	62,593	60,026	59.1%	13,351	649,676	**53.8%**	31	**46.4%**
DOAS + Photovoltaics	0.60	0.45	135,876	62,593	60,026	74.9%	13,351	549,676	**60.9%**	27	**52.5%**

Table 5: Potential improvement in electrical and natural gas energy use in Chicago.

sively monitored by the National Renewable Energy Laboratory (NREL) have achieved performance levels of 25 to 30 kBtu/ft²·yr (284 to 349 MJ/m²·yr).[6,26]

The addition of renewable technologies such as photovoltaic (PV) collectors on the roof can reduce the electrical energy use by as much as 175,000 kWh/year and lower peak demand by more than 100 kW. This is based on a PV collector with a peak power production of 10 W/ft² (107 W/m²) and annual production of 43 kBtu/ft²·yr (488 MJ/m²·yr) for a Chicago location and 65% roof coverage.[27] As shown in *Table 5* total energy savings increase to 61% and 53% with inclusion of plug loads.

The next generation of high performance construction will need to have significantly improved building envelopes, extremely low lighting power densities and HVAC design technologies that minimize the fan energy use such as DV or DOAS designs. For the designs to achieve savings beyond 50% relative to Standard 90.1-2007, they will need to integrate renewable technologies such as photovoltaics, which at present can only provide small incremental savings.

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