Actual Energy Performance of Small Office and K-12 School Buildings Designed to Meet the 30% ASHRAE Advanced Energy Design Guides

Dennis Jones, PE,
Member ASHRAE

Susan Reilly, PE,
Member ASHRAE

Michelle Sadeghy, PE
Member ASHRAE

ABSTRACT

The purpose of Research Project RP1627 is to evaluate the effectiveness of 30% Advanced Energy Design Guidelines (AEDGs) for K-12 schools and small office buildings, determine the factors common to well and poorly performing buildings, and provide recommendations for how future AEDG can be made more effective. To determine the effectiveness of the 30% ASHRAE AEDG, Group14 collected utility data and developed weather-normalized Energy Utilization Indices (EUIs; site energy use per unit area per year) for a sample of small office and K-12 school buildings. These results are compared to the modeled ASHRAE Standard 90.1-1999 Baseline and 30% Savings EUIs from the AEDG Technical Support Documents. Small office buildings constructed per AEDG achieved an average 34% site energy EUI savings compared to average ASHRAE 90.1-1999 modeled code EUI. Average EUI savings of AEDG schools averaged 52% of the ASHRAE 90.1 AEDG baseline; however, non-AEDG schools averaged 34% EUI savings. On a source energy basis, schools with electric heating systems, such as heat pumps, produced minimal energy savings relative to schools constructed to code. Factors common to well performing buildings include an integrated design approach as outlined in the AEDG, good daylighting design, and an "Environmental Ethic" within the design team and the O&M personnel maintaining the building. Factors common to poorly performing AEDG buildings include failure to incorporate all required AEDG strategies, ineffectively applied AEDG strategies, and general design and commissioning issues. Recommendations include using a source energy basis for developing AEDG requirements, development of a digital performance estimating tool based on required AEDG strategies, including ability to stimate potential savings for each AEDG strategy, and clarifying requirements and strategy descriptions for selected AEDG strategies.

INTRODUCTION

ASHRAE developed the 30% Advanced Energy Design Guidelines (AEDG) for several building types to provide designers with a streamlined approach to incorporating energy efficiency. The 30% AEDGs (ASHRAE, 2008), (ASHRAE, 2004) present a set of prescriptive strategies for the design of a building that will provide at least 30% site energy savings, relative to a similar building meeting requirements of ASHRAE Standard 90.1-1999. Recommended strategies address the following areas of design: building envelope, fenestration, electric lighting systems, daylighting systems, heating, ventilation, and air-conditioning (HVAC) systems, and service water heating (SWH).

Study Objectives

- Compare Energy Utilization Indices (EUIs; site energy use per unit floor area per year) for a sample of small

Dennis Jones is a senior building engineer in the Denver, CO. **Sue Reilly** is a senior building engineer in the Denver, CO. **Michelle Sadeghy** is a building energy engineer in Denver, CO.

office and K-12 school buildings designed in accordance with the first (30%) ASHRAE AEDGs to the "baseline" modeled EUIs of small office and K-12 school buildings meeting the requirements of ASHRAE Standard 90.1-1999. EUIs for AEDG buildings are calculated from metered utility data, normalized for weather. The baseline EUIs were taken from the AEDG source documents, (Jarnagin, 2006)(Pless, 2007).

- Compare metered EUIs for schools and small offices constructed per AEDG requirements to "Code" buildings constructed to ASHRAE 90.1-1999 requirements.
- Perform site surveys of 10 AEDG buildings to determine the factors common to relatively well-performing buildings, as well as the factors common to relatively poorly-performing buildings.
- Provide recommendations for how future AEDGs for small office and K-12 school buildings could be made more effective in achieving better energy performance.

Data Regression and Normalization

Monthly utility data was collected for 50 buildings. Available site utility data ranged from 12 months to 7 years. Analysis indicated PV systems affect the accuracy of utility data correlation. Utility meter kWh iwas corrected by adding the monthly PV production, estimated by PVwatts, to the metered kWh used by the building. Utility data for each AEDG and Code building was regressed to the closest weather data site to determine separate EUIs for the energy use categories of natural gas space heating, natural gas DHW heating, electric cooling, electric heating, and base electric energy use including plug loads, most fans and pumps, lighting, and other miscellaneous equipment. Energy use for each category is normalized to the closest TMY-3 weather site using the regression coefficients, and summed to determine the building EUI. Normalization of monthly utility data to actual local weather data was performed using the ASHRAE Inverse Modeling Toolkit (IMT).

OVERALL EFFECTIVENESS OF AEDG

K12 Schools

Figure 1 compares site utility data EUIs for all schools with the ASHRAE 90.1-1999 Baseline EUI values for each school, which vary by school type and climate zone. Baseline EUIs vary by climate zone.

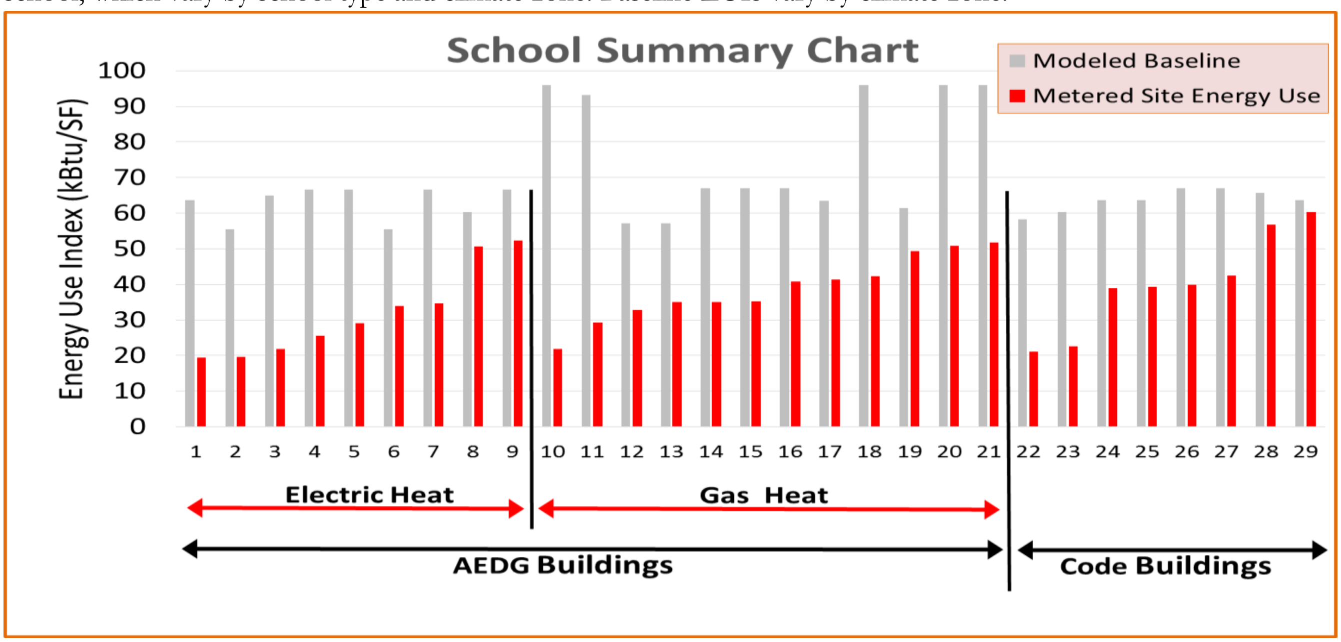

Figure 1 Metered EUIs for all schools.

Small Offices

Figure 2 presents site EUIs for all small offices in the study along with modeled baseline EUIs. Most AEDG small offices achieved 30% EUI savings. As can be seen, AEDG buildings use less energy than code buildings.

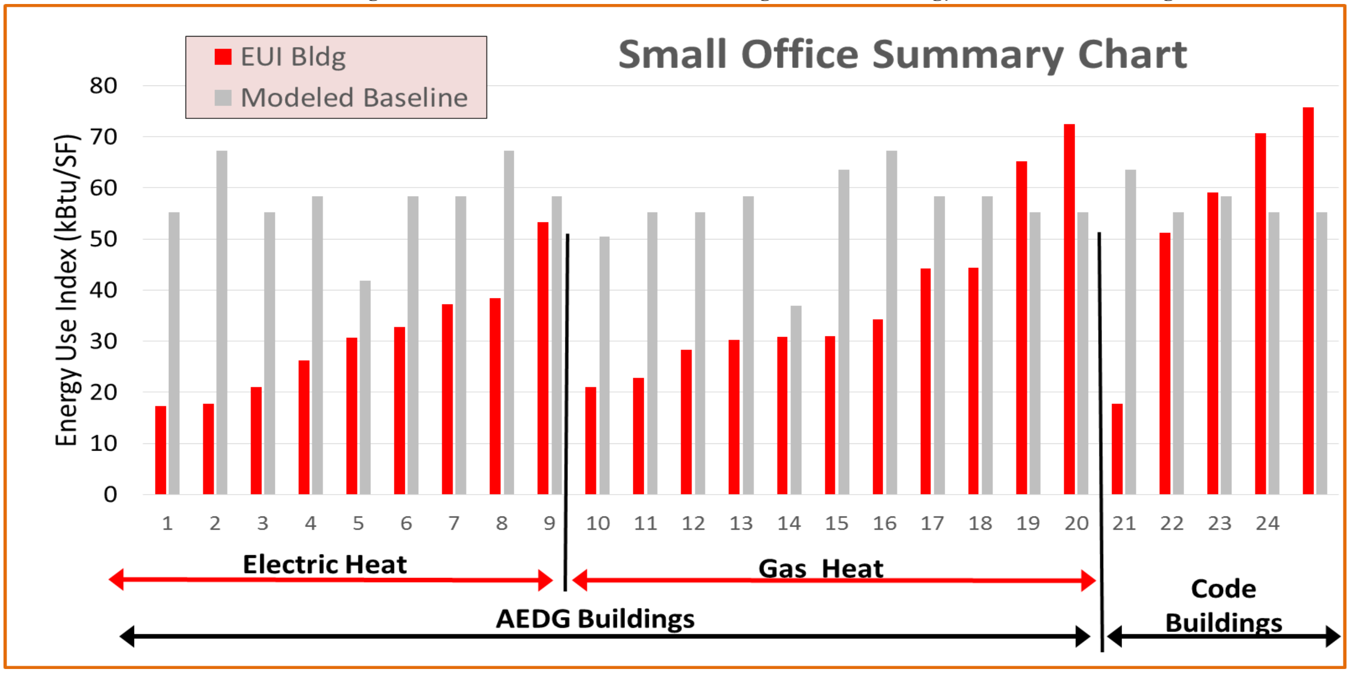

Figure 2 Metered EUI for all small offices.

Site vs Source Energy

Figure 3 indicates the site and source EUIs for the 29 schools in the study.

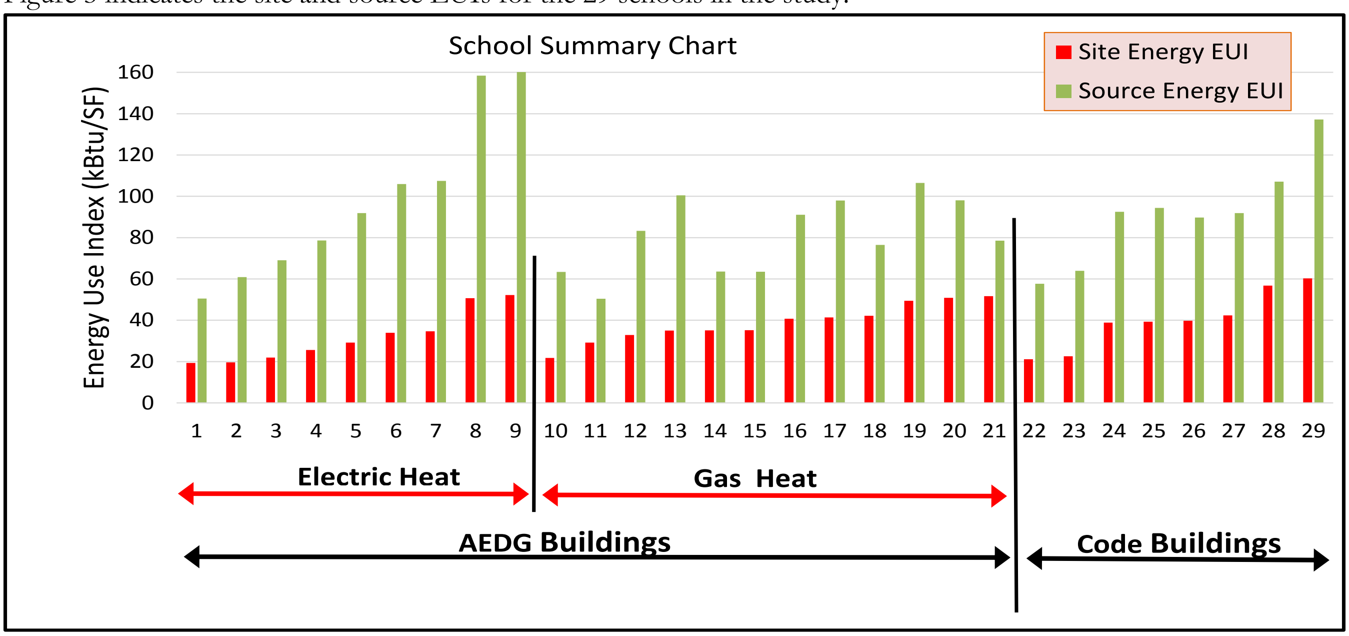

Figure 3 Comparison of site and source energy EUIs for schools.

Source energy calculation, used for Figure 3, followed the DOE methodology for Zero Energy Buildings (Torcellini, 2015), which specifies 3.15 and 1.09 multipliers for converting site energy to source energy for electricity and natural gas, respectively. A source energy basis accounts for the energy used to generate electricity off-site and to produce natural gas. As can be seen, schools with electric heat generally use more source energy than schools with natural gas heat. On a source energy basis, buildings with natural gas heat have significantly lower EUIs than buildings with electric heat. AEDG buildings with electric heat show minimal source energy savings over schools built to code. Table 1 summarizes average EUIs presented in the figures above.

Table 1 Site vs Source EUI for all Buildings

Building	School	School	School	School	Small Office	Small Office	Small Office	Small Office
Energy Use Index kBtu/sf/yr (watts/m2/yr)	Site EUI	Site Energy Savings	Source Energy	Source Energy Savings	Site EUI	Site Energy Savings	Source Energy	Source Energy Savings
AEDG - Electric Heat	32 (11)	55%	98 (33)	48%	31 (10)	46%	96 (32)	32%
AEDG - Gas Heat	36 (12)	48%	78 (26)	59%	39 (13)	32%	91 (30)	36%
Code Buildings	46 (15)	34%	102 (34)	46%	55 (18)	3%	134 (45)	5%
Modeled Baseline	70 (23)		189 (63)		57 (19)		141 (47)	

As can be seen:

- Site energy savngs for non-AEDG schools buildt to code is 34%, compared to the average modeled baseline. Further investigation indicated the assumed plug loads in the modeled baselines for schools (Pless, 2007) are unrealisticly high; exceeding the metered kWh for the entire building for several schools.
- AEDG schools have disappointing site energy savings at 48% to 55% when compared to metered data for code buildings, which had 34% energy savings.
- AEDG schools have minimal source energy saving when compared to metered data for code buildings; particularly for buildings with electric space heating systems. Geo-excahnge heat pumps were used for all electrically heated schools.
- Small offices performed as expected with code buildings slightly better than modeled baselines, and AEDG buildings in the 32 to 46% savings range on a site energy basis.
- AEDG small offices performed slightly better with gas heat on a source energy basis.

BUILDING ENERGY AND IEQ AUDITS

Building Audit Overview

Energy audits were completed on ten buildings, 5 schools and 5 small offices, with distribution over a range of climate zones. Audits were focused on the 5 best and 5 poorest paerforming AEDG buildings in the database. Audits included collection of monthly utility data, collection of design and operating documentation including construction plans and specifications, controls submittals, and other printed information. Site visits were condcted to evaluate the effectiveness of energy-using systems with regards to design, construction, and operation. Indoor environmental quality (IEQ) survey forms were completed by building occupants. The audits focused on compliance with each individual recommendation from the AEDGs and corrective action recommendations for system deficiencies uncovered during the audits. Separate energy audit reports for each building including AEDG summary tabulations documented finding for each building.

Well Performing Buildings – Common Factors

The best performing buildings in the study, School #1 and Small Office #1, are both owned by the same school district. These buildings have site EUIs of 19 and 17 kBtu/sf/yr, respectively; which have been maintained for the last 7 years. Factors relating to performance of these buildings included:

- **An Environmental Ethic** that includes administration, teachers, O&M personnel, and even students, who are constantly looking for ways to be greener, including energy efficiency. The same ethic guided the design of the school. Small Office #1, is designed and constructed for the school's facilities group, who maintains building systems in the schools.
- **An Integrated Design Approach** that brings all stakeholders together in design review and coordination meetings throughout the process to constantly brainstorm the optimal design for the building. Ideas like using the municipal water system for a heat sink for water source heat pumps were fully explored. The school district constantly experiments with various HVAC and other technologies; retaining ones that work well. Leading experts in specialty areas like energy modeling, electric lighting, and daylighting were part of the design team as were O&M personnel, teachers, and other stakeholders. Energy and IEQ goals were set early; daylighting was a major goal as were energy metrics. More important than the actual goals, the design team knew the district was serious about constructing a high performance school and office. LEED certification was not pursued. The design team was encouraged to offer to suggestions outside their field of expertise.
- **Daylighting** capable of fully lighting classrooms for most of the day, was a requirement from the start. In response, the architect oriented the great majority of classrooms to the north to eliminate direct beam penetration, a problem with the last school constructed. The daylighting requirement drove the architecture. Other schools and small offices with the best energy performance also had well-designed daylighting systems.
- **Comprehensive Commissioning** of daylighting and HVAC was required. Several months were required to achieve proper daylighting control.
- **Simple Lighting and HVAC Systems with Simple Control.** School #1 and Small Office #1 both use Ground Source Heat Pumps (GSHP) for zone conditioning and DOAS with heat recovery for ventilation. The system provides excellent energy performance on a site energy basis and is simple enough to be controlled with simple setback thermostats. In reality, controls are monitored and programmed by a building management system (BMS) with web access. Control sequences are simple, heat pumps are in heating or cooling or off, the DOAS fan is on or off based on the occupancy schedule, condenser loop pumps operate when any heat pump calls for heating or cooling. There are no economizer controls, variable speed fan control, duct static reset control, discharge air temperature reset control, or boiler or chiller controls. Any failure in GSHP equipment or control affects thermal comfort as well as energy, and is thus diagnosed and fixed quickly.

Similar characteristics were found in other well performing schools and small offices.

POORLY PERFORMING BUILDINGS – COMMON FACTORS

Common Deviations from the AEDGs

The site audits included an evaluation each recommended AEDG strategy for the appropriate climate zone. The following highlight deviations from the AEDG and offer a brief assessment:

- **Exterior Sun Control** using overhangs or external shading devices were seldom used in schools, but were used slightly more frequently for small offices. Our experience is that this requirement is often confused with daylighting related shading by AEDG users and we address this requirement in more detail later in the report. External window shading or roof overhangs are expensive, relative to their benefit in producing energy savings.
- **Average Window-to-Wall Ratio (WWR)** for vision and daylight glass combined is 18% as opposed to the 35% AEDG maximum value. School #1, which has excellent daylighting, has a WWR of 30%, but much of the added glass is daylighting glass. This report recommends a much lower AEDG WWR target, particularly for buildings not utilizing daylighting.
- **Daylight Harvesting** controls are a key strategy for many high-performance buildings and are required by code in some jurisdictions, but have historically been difficult to apply and maintain. Three of the four schools with daylighting controls specified in the plans, did not have operational daylighting control. A common problem was direct solar beam radiation through the window producing glare and subsequent use of internal wndow shades. In addition, daylighting controls were often not functional. Recommendations are offered in this report for better daylighting design, including daylighting controls.
- **Lighting Power Density (LPD)** recommended for daylit and non-daylit spaces is 1.20 and 1.10 watts/sf, respectively, for schools. Average LPD was 0.90 for the five schools, but only 0.65 for the two daylit schools. Low LPDs appear to be a byproduct of the daylighting design process, which requires considerably more attention to predicting illumination. This report provides recommendations for the combination of electric and natural lighting. For small offices, average LPD was 0.77, as compared to 0.90 recommended by the AEDG. Lighting technology is constantly advancing and the AEDGs struggle to keep up.
- **HVAC System Type.** The AEDGs provide little guidance on selection of the optimal type of HVAC system. The K12 30% AEDG recommends six different competing types of HVAC systems, but offers no indication of energy efficiency of recommended systems. The Small Office AEDG makes no recommendations as to HVAC system type. The AEDG source documents indicates a wide variation in building energy performance by HVAC system type. Six of the ten audited buildings utilized GSHP systems, which resulted in significantly lower site energy use, but high source energy use.
- **Ventilation.** DOAS with exhaust air heat recovery is used in all schools, including those with VAV systems. DOAS was ineffectively applied in 3 schools; problems included excessive fan energy, use of supplementary heating and cooling to deliver neutral temperature air to the zones, and excessive ventilation rates. The DOAS was found to be inoperable for one school, leaving only one school with a well performing DOAS system. For small offices, DOAS with heat recovery is used in 3 buildings. Demand controlled ventilation was not used at any audited schools, but is present in 2 small offices. This report recommends actions for improving ventilation guidance in AEDG.

General Design and Commissioning Issues Noted in Energy Audits

In addition to AEDG compliance issues noted above, the energy audits uncovered additional HVAC design and commissioning issues in the poorest performing buildings. These issues can be generally classified as:

- **Failure of the design to meet 100% of AEDG requirements.** No buildings were found to comply with all

AEDG requirements. The criteria used in this study for AEDG designation was compliance with 80% of AEDG strategies. The commissioning agent (CxA) is required to perform a design review, but may or may not verify compliance with AEDG strategies or energy codes.

- **Ineffective design.** Some design elements were found to be ineffective at saving energy; examples include daylighting controls near windows with inadequate architectural shading and with internal shade screens permanently deployed or heat recovery ventilators with excessive fan energy. The CxA design review should identify such issues, but the CxA may not have the energy expertise to identify all issues.
- **Ineffective control sequences** were found, two schools in climate zone 7 had DOAS discharge air temperatures locked in at 50°F (10°C). Some control strategies require energy consultants to evaluate.
- **Malfunctioning of controls.** CxAs excel at testing and verification of proper functioning of controls, and verifying proper operator training; but it is up to the owner or maintenance contractor to maintain proper control of HVAC and lighting systems.

The study verified that all audited buildings were commissioned, but did collect data on the commissioning scope or interview the CxA.

SUMMARY

The following summarize findings and recommendations of the study:

EUI Savings for buildings Designed and Constructed per AEDG Recommendations

- Small office buildings constructed per AEDG recommendations behaved as expected, saving an average of 30% to 46% site energy EUI savings over the AEDG baseline, while the average non-AEDG small office barely met code.
- Schools easily achieved the expected 30% site energy AEDG savings, including the Non-AEDG schools. Average EUI savings of AEDG schools averaged 50%, non-AEDG schools, averaged 37% EUI savings.
- Assumed plug loads for schools, used in modeling ASHRAE 90.1-1999 baseline EUIs are unrealistically high. The assumed plug EUIs from the K12 Technical Support document (Pless, 2007), exceeded the total metered electric EUI for 5 of the schools. It is recommended that AEDG baselines for schools be revised.
- On a source energy basis, which accounts for the fossil fuel energy required to generate electricity, AEDG schools with electric space heat saved little energy compared to non-AEDG schools built to code.

ADEG Strategies Recommended for Revision

The following AEDG strategies were found to be often poorly applied based on energy audits for 10 buildings. Strategies requiring revision in the climate-specific tables in Chapter 3 and AEDG strategy descriptions (Liu, 2010), (Pless, 2007) in Chapter 5 are listed below:

- **Daylighting** is an option for schools and is limited to skylights for small offices; daylight dimming controls are required within 15 feet of windows for both schools and small offices, regardless of the effectiveness of the daylighting design. We recommend strengthening AEDG requirements and strategy descritions to encourage more use of daylighting.
- **Dedicated outside Air Systems (DOAS)** with heat recovery were used in all audited schools, but not effectively applied in 3 of 5 schools. Ineffective applications included excessive fan energy and inefficient control of discharge air temperatures and ainti-frosting control. Similarly DOAS was applied to 3 small offices, but only one was found to be operating correctly. We recommend strengthening and reorganizing Chapter 5 strategy descriptions for DOAS systems to address fan energy and control.
- **Minimum ventilation airflow set points were excessive** for several buildings, one school had specified ventilation at 50 cfm/student. We recommend the AEDGs outline code required ventilation rates and

calculation procedures.

- **Maximum window-to-wall ratio (WWR)** for vision glass is recommended to be reduced from 35% to 20%; recommendations for daylight glass should remain the same. Average (WWR) for the 10 buildings audited by this study was 18% for schools and 21% for small offices.
- **VAV systems** are listed as an AEDG strategy, but the assumed design parameters used in modeling are not presented, most notably the required 20% turndown on VAV boxes. The VAV strategy in Chapter 5 should be strengthened to include all code requirements related to VAV systems and the further enhacements assumed by the AEDG developpers (Liu, 2010), (Pless, 2007) necessary to achieve AEDG savings targets.

AEDG Concept Recommendations

The following major AEDG concept modifications are recommended:

- AEDG schools with electric space heating systems, such as heat pumps, score high on a site energy basis, but have minimal source energy saving compared to non-AEDG code buildings. Source energy is more representative of greenhouse gas emissions and energy costs to the building owner. ASHRAE should settle on a consistent basis of savings for the AEDGs and other guidelines and standards, weighing the benefits and short comings of site energy, source energy, building energy costs, and GHG emissions.
- ASHRAE should address the problem of AEDGs becoming obsolete as ASHRAE Standard 90.1 (ASHRAE, 2013) requirements continue to evolve.
- Future AEDGs should seek to provide a digital performance estimating tool based on required AEDG strategies, including potential savings for each AEDG strategy.
- Reorganize Chapter 5 of the AEDGs to provide a more fundamental tutorial on high-performance HVAC and lighting system design.

REFERENCES

ASHRAE. (2008). *Advanced Energy Design Guide for K-12 School Buildings*. Atlanta.
ASHRAE. (2013). *ANSI/ASHRAE/IES Standard 90.1-2013: Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta.
Liu, B. (2010). *Technical Support Document: 50% Energy Savings for Small Office Buildings*.
Mumma, S. (2010). DOAS & Building Pressurization. *ASHRAE Journal*, 42.
Pless, S. (2007). *Technical Support Document: Development of the Advanced Energy Design Guide for K-12 Schools—30% Energy Savings*. Golden: National Renewable Energy Laboratory.
Torcellini, P. (2015). *A Common Definition for Zero Energy Buildings*. Department of Energy.
USGBC. (2009). *LEED 2009 for New Construction*.