ZNE vs. Comfort: A holistic look at high performance

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ABSTRACT

While energy use and energy generation are the primary performance metrics for Zero Net Energy (ZNE) buildings, it's important that resource use not overshadow the primary purpose of a building: to provide an adequate or even an enhancing environment for activities, whether human or machine, to operate. Our study measured the actual energy performance from July 1, 2014 - June 30, 2015 of four mixed mode ZNE component-built portable classrooms as well as two typically constructed (non-ZNE) portable classroom buildings. The goals of the study were to understand differences and interactions among energy use and indoor environmental quality. A total of 227 sensors were installed across all 6 buildings to measure system energy use, renewable electricity generation, thermal comfort, visual comfort and air quality. On average, the ZNE classrooms achieved 40% lower energy use intensity than their traditional classroom counterparts. When adjusting for comfort levels maintained during occupied hours, the ZNE classrooms provided a higher level of comfort. By tracking comfort delivered per unit of energy, building managers are better able to balance energy use and indoor environmental quality.

Introduction

The path toward high performance buildings has been advanced, in part, through initiatives that raise the performance expectations of buildings. Leadership in Energy and Environmental Design (LEED) and Zero Net Energy (ZNE) initiatives have grown in popularity despite having aggressive performance goals (USGBC 2016; NBI 2016). As part of both initiatives, early conversations bring awareness to the interdependencies between building occupants and supporting systems such as lighting, heating and ventilation. By highlighting co-benefits between needs of occupants and systems, the building community marches further down the path towards high performance buildings.

Indoor Environmental Quality (IEQ) provides the foundation to calculate energy demand that aims to be offset by ZNE design. IEQ focuses on providing an interior environment that is supportive of the productivity, health and well-being of the building occupants. The environmental factors that may concern building owners are:

- thermal comfort,
- indoor air quality,
- acoustic comfort and
- visual comfort.

In contrast, ZNE promotes mindful building design with significant effort on energy efficiency to produce a building with low energy requirements. ZNE buildings offset any remaining building energy requirements through on-site renewable energy generation (NIBS 2015). Ultimately, ZNE buildings aim for equal levels of energy consumption and on-site generation over the course of a year. In the event that renewable energy is insufficient to offset demand, grid electricity is supplemented. Most ZNE buildings are grid-connected rather than energy independent. Grid connectivity allows flexibility to import or export electricity (or fuels) when needed. Thus, a building can reach ZNE performance over the course of a year.

Today, common metrics used by portfolio building managers are often focused on energy or Indoor Environmental Quality (IEQ) and not their interaction. For example, total energy consumption (kWh) and energy use intensity (kBtu/sf or kWh/sf) at the building or system level are useful for performance benchmarking and trend analysis, but ignore the impact of provided energy on occupants. IEQ's metrics focus on the percentage of time within a threshold. For example, an indicator for acceptable indoor air quality is the percent of time carbon dioxide levels are below 1100 ppm (ASHRAE 2013b), independent of the energy required.

At first glance, ZNE and IEQ initiatives may appear to be at odds with each other: ZNE focuses on low energy consumption and IEQ focuses on ideal personal comfort conditions. As an extreme example, one could have a ZNE building with no lights such that people must use headlamps indoors after sunset. In this situation, the building would have low energy consumption, but the occupants would likely be uncomfortable. However, ZNE performance targets can be achieved while simultaneously meeting IEQ metrics by achieving high levels of building performance.

This paper aims at investigating the ZNE and IEQ connection by measuring energy and comfort in six Hawaiian portable classrooms. The classrooms are compared first on energy followed by comfort metrics. Furthermore, this project used "comfort efficiency" as a combination metric to promote the notion of occupant comfort to energy focused stakeholders. Our hope is that incorporating more combination metrics in projects will educate the building community on ZNE and IEQ synergies.

Case Study – Hawaii School District Portable Classrooms

Background

The Hawaii State Department of Education is unlike most other school districts in the United States in terms of size and quantity of its portable classrooms. Most school districts are delineated by city or county boundaries, but Hawaii has one school district across all eight main islands totaling over 250 schools. Of the 13,500 school districts (NCES 2013) in the United States, the vast majority have fewer than 20 schools (NCES 2009). Hawaii's schools are not alone in using portable classrooms, 30% of U.S. schools have at least one portable classroom (NCES 2012). The Hawaii State Department of Education averages approximately 7 portable classrooms per school (i.e. 1800 total portable classrooms) (A. Donnelly, Senior Strategist, MKThink, pers. comm. January 5, 2016).

Portable classrooms are intended to be used to overcome a short-term increase in student population as they are quick to deploy and cost approximately one-third the price of traditional brick and mortar classrooms (Drury and Mcclure 2014). Portables typically were not designed for high energy efficiency or good air quality. Despite short-term intentions, in practice many school districts, Hawaii included, do not remove their portable classrooms from use. For example, the Hawaii school district has portable classrooms from 1960 in current operation.

In Hawaii, the economics are favorable for ZNE and the need for IEQ is high. Hawaii has one of the highest electricity prices in the U.S. at $0.25-0.35/kWh (EIA 2015), and a culture that relies heavily on air conditioning to remove heat and humidity from interior spaces. Therefore, ZNE has risen in popularity because of the promising conditions for renewable energy and as a way to reduce energy costs. Balancing thermal comfort needs and energy costs for building managers in Hawaii is a challenge due, in part, to the large temperature and humidity differentials between the interior and exterior environments.

Project Description

The project scope encompassed measuring energy consumption, generation and indoor environmental quality across six similarly sized (840 sf to 1280 sf) portable classrooms within the Hawaii School District from July 1, 2014 - June 30, 2015 (Table 1). The portable classrooms were located on two different islands across three different elementary and middle schools. Four of the six classrooms were designed for ZNE while the remaining two were considered traditional (non-ZNE) portables (Table 1). Operating hours are defined as school hours from 8am to 2pm during the 185 school days in the study period.

Table 1: Classroom Asset Summary

	KW EAST	KW WEST	ILIMA	EWA P6	EWA P1	EWA D36
LOCATION	Lihu'e	Lihu'e	Ewa Beach	Ewa Beach	Ewa Beach	Ewa Beach
GRADE LEVEL	7-12	7-12	7-8	K-6	K-6	K-6
SIZE (NSF)	1280	1280	1280	1176	840	900
YEAR BUILT	2013	2013	2010	2010	1996	1960
AC TYPE	Underfloor air	Underfloor air	Underfloor air	None	Window	Central
PV TYPE(S)	Thin Film & Mono	Mono	Thin Film & Mono	Mono & Poly	N/A	N/A
PV CAPACITY (KW)	5.24	5.24	5.24	12.32	- -	- -
CATEGORY	ZNE	ZNE	ZNE	ZNE	Traditional	Traditional

Each classroom had sensors installed to measure energy consumption broken down by air conditioning, ceiling fans, internal lights, and external lights. The portables classrooms only used electricity. No natural gas or other fuels were direct energy sources to the classrooms. The photovoltaic (PV) generation was measured, but the PV types and system sizes varied (Table 1). The sensor sampling rate across all sensors was 5 minutes.

For this project, ZNE was defined as producing at least as much energy needed annually at the site boundary (NREL 2006). The ZNE-site definition was chosen for ease in communication to various stakeholders. After this project was underway, the broader ZNE community settled on ZNE-source as the common definition. Specifically, the Department of Energy defines a Zero Energy Building "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" (NIBS 2015). The key difference between site and source energy is that source energy includes upstream energy sources (e.g. extraction, processing and transport) required to deliver energy to a site. In practice, source energy is site energy multiplied by a conversion factor that takes into account the upstream impacts. (NIBS 2015).

The Hawaii Portables project scope measured three out of four Indoor Environmental Quality parameters. Thermal comfort was given the highest priority because the school district received a large quantity of hot and cold complaints. Thermal comfort was calculated using ASHRAE's Predicted Mean Vote (PMV) thermal comfort model (ASHRAE 2013a). The six factors within the PMV model include:

- indoor temperature,
- relative humidity,
- wind speed,
- mean radiant temperature,
- clothing value and
- metabolic rate.

A PMV score is calculated for each time interval resulting in a value between -3 (occupants feel too cold) to +3 (occupants feel too hot). If the PMV score is between +/- 0.5, then 80% of occupants should be comfortable (ASHRAE 2013a). Measurements of daylight availability and surface glare were used as indicators of visual comfort. To monitor student/teacher health, carbon dioxide levels were measured for indoor air quality. Acoustical comfort was not considered as a part of this study. Across all six classrooms, 227 sensors were installed to measure energy and IEQ parameters.

Results

On average, the four ZNE classrooms used 40% less energy per square foot during occupied hours. KW East, KW West and Ewa P6 had an average annual energy intensity of 1.2 kWh/sf (3.8 kBtu/sf), but Ilima with identical construction to KW East and KW West had over double the EUI at 3.4kWh/sf (10.7 kBtu/sf) (Energy Star 2013). Such a large energy use for Ilima was because the occupants chose to run the air conditioning system for the majority of the time irrespective of the outside conditions. For those portables with air conditioning (Table 1), the use of air conditioning consumed 44% to 92% of the energy use during occupied hours. The traditional (non-ZNE) classrooms of Ewa P1 and Ewa D36 had energy intensities of 3.4 kWh/sf (10.7 kBtu/sf) and 2.4 kWh/sf (7.5 kBtu/sf) respectively.

Three of four ZNE classrooms achieved net neutrality or better on an annual basis (Figure 1). While Ilima, KW East, and KW West had the same PV system size, Ilima had a higher Renewable Production Intensity likely due to higher solar radiation from being located at Ewa Beach instead of Lihu'e. Ewa P6's PV system was 2.3 times larger (12.32kW system capacity) than each of the other three systems (5.24kW of capacity) (Table 1). Ilima was the only classroom not to achieve ZNE on an annual basis because of the high energy use intensity.

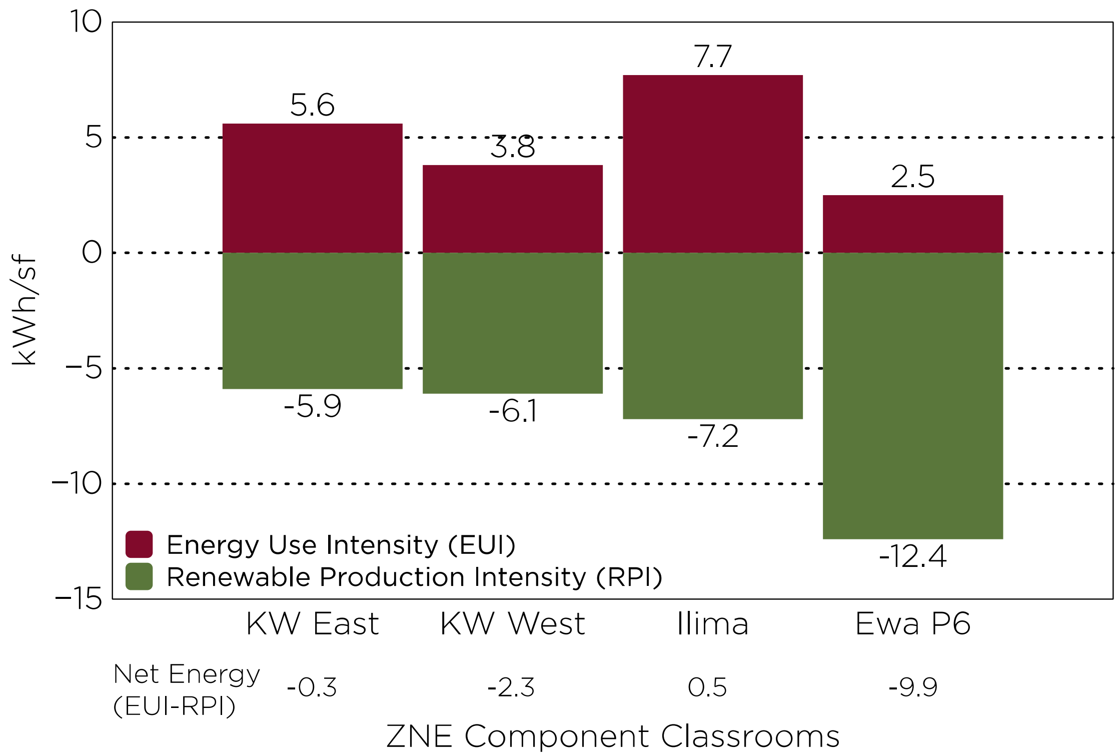

Figure 1: Renewable production intensity (RPI), classrooms energy use intensity (EUI) and net energy use intensity (EUI-RPI) (kWh/sf) for four ZNE Classrooms from July 1, 2014 to June 30, 2015

Of the three IEQ components, thermal comfort had the most variability across classrooms (Table 2). Ewa P6 had the least amount of time, 27%, within the calculated comfort range (ASHRAE 2013a) compared to 77% for Kawaikini West. Even among identical, adjacent classrooms of KW East and KW West, there was a 38% difference in time spent within acceptable comfort conditions. When classrooms were outside the ASHRAE thermal comfort range, typically the interior was too hot for occupants. Ilima was the exception, which used air conditioning to overcool the space. On average, the traditional classrooms had more thermally acceptable conditions than the ZNE classrooms (56% vs. 41% respectively) (Table 2). Possible explanations for lower thermal comfort values for ZNE classrooms include:

- lack of education for occupants on how to optimally operate the ZNE classroom,
- variations in thermal mass of the walls and roof, and
- occupant thermal comfort preferences.

Operationally, ZNE classrooms did not utilize night flushing to reduce interior temperature by natural convection from the cool night temperatures as intended. If night flushing were implemented, the amount of time within the thermal comfort range would likely increase. Additionally, 60% or more of HVAC operations in ZNE classrooms occurred during times not recommended in the high-performance operational guides. For the other two IEQ components, ZNE classrooms had 41% more time with acceptable air quality and 2% more time with acceptable lighting conditions compared to Traditional classrooms (Table 2).

Table 2: Percentage of time during school hours the classrooms were within each IEQ component threshold.

	ZNE					Traditional		
IEQ Component	KW East	KW West	Ilima	Ewa P6	Avg	Ewa P1	Ewa D36	Avg
Thermal Comfort	39	77	27	21	41	44	68	56
Air Quality	100	100	100	100	100	21	96	59
Visual Comfort	95	97	84	92	92	94	86	90
Overall IEQ	37	75	24	18	39	8	57	33

Combining all three IEQ components into an overall IEQ score (Eq. 1) provided a more complete perspective of the inside conditions. Therefore, an overall IEQ score represents the amount of time in which all three IEQ components are in compliance and occupants should be comfortable.

Eq. 1

$$Overall\ IEQ\ (\%) = 100\ x\ \left\{\frac{\sum_{x=1}^{x=N} \begin{cases} 1, & if\ all\ \begin{matrix} -0.5 \leq TC_x \leq 0.5 \\ AQ_x \leq 1100 \\ VC1_x > 5 \\ VC2_x < 5 \end{matrix} \\ 0, & else \end{cases}}{N}\right\}$$

Where:
N = number of time intervals
Tc = Thermal Comfort PMV (ASHRAE 2013a)
AQ= Air Quality (ppm)
VC1= Visual Comfort - daylight availability: illuminance (ft-cd)
VC2 = Visual Comfort - surface glare: illuminance ratio (wall ft-cd/surface ft-cd)

On average, ZNE classrooms performed only slightly better (6%) on overall IEQ than traditional classrooms mostly due to superior performance in Visual Comfort and Air quality (Table 2). While KW West had the highest IEQ score overall (75%), the other three ZNE classrooms had much lower IEQ scores.

While decisions based primarily on energy or IEQ are valuable, looking at both metrics simultaneously could lead to more holistic decision-making. One option to assist in comparative decision making is to plot IEQ and EUI on different axes in order to highlight the Pareto frontier (Figure 2). A decision maker could use Figure 2 to choose a specific EUI or IEQ level and then determine the best classroom given the constraints. For example, if a building owner aims for a minimum EUI threshold of 1.5 kWh/sf (4.7 kBtu/sf), then Kawaikini West provides the most comfort for that energy intensity. A drawback of Figure 2 is that depending on the results the most desirable classroom within a certain threshold might be difficult to discern by visual inspection. Furthermore, tracking classroom performance over time is not easy.

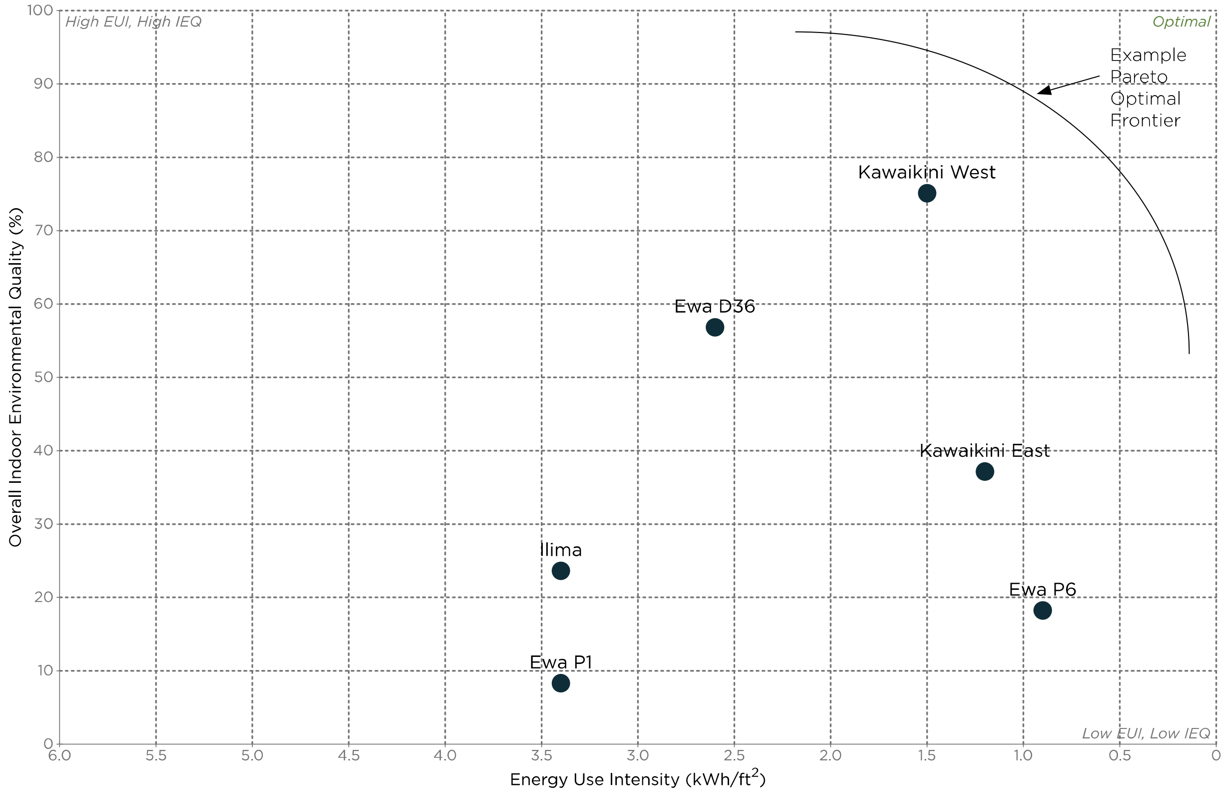

Figure 2: Energy use intensity (x-axis) compared with IEQ (y-axis) shown with an example of a pareto optimal curve. The pareto optimal curve is for illustration purposes and does not have any quantitative basis.

Another option to blend energy and IEQ but allowing for easier analysis over time is to compare these metrics as a ratio. Therefore, we proposed a *comfort efficiency* metric creating a ratio of delivered comfort to provided energy (Eq. 2).

Eq. 2 *Comfort Efficiency = Overall IEQ (Eq. 1) / Energy Use Intensity (kWh/sf).*

A higher comfort efficiency value is an indication of an efficient classroom that provides more comfort to the occupants from each unit of energy. Figure 3 shows the six classrooms' comfort efficiency score. KW West achieves the highest value at 50 and Ewa P1 has the lowest at 2. A decision maker could use the comfort efficiency metric for benchmarking and setting targets across their building stock over time.

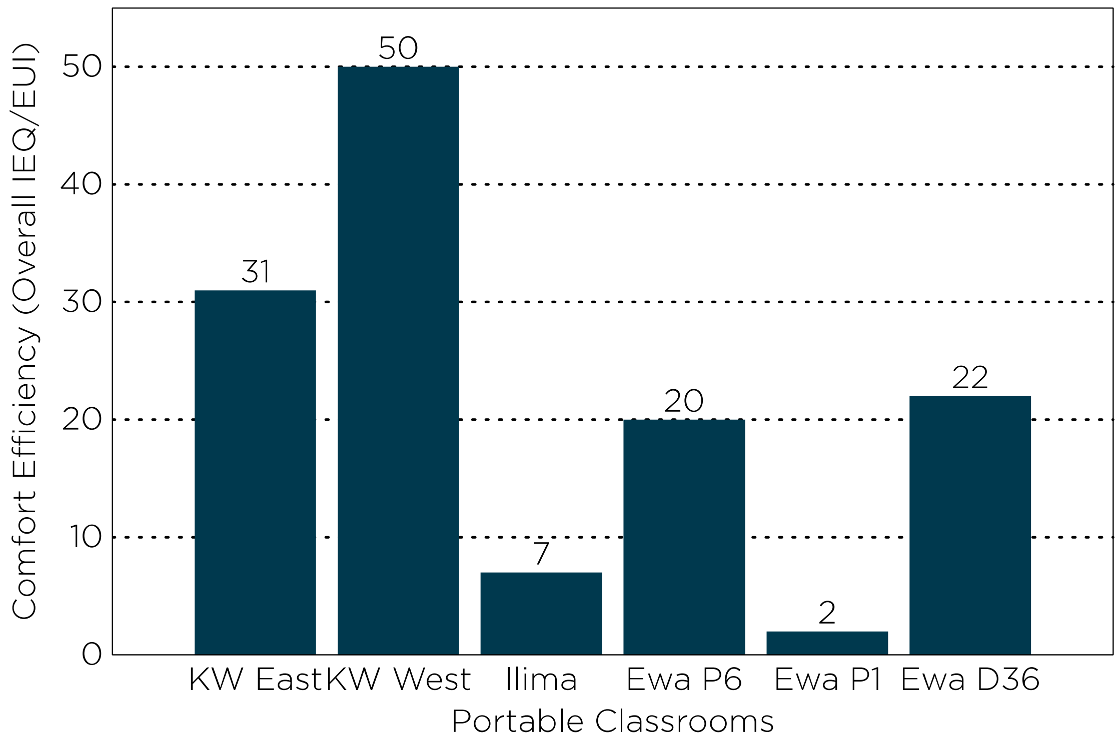

Figure 3: Comfort efficiency index of ZNE (i.e. KW East, KW West, Ilima, Ewa P6) and traditional portable classrooms (i.e. Ewa P1, Ewa D36). The comfort efficiency axis upper limit could increase significantly as it depends the EUI.

Discussion

Adapting to changing occupant comfort demands can consume significant amounts of energy. Therefore, the combination of Zero Net Energy and Indoor Environmental Quality metrics can provide a more holistic look into classrooms and, more broadly, buildings in general. Ideally, each ZNE project incorporates IEQ at some level and vice versa. Because these initiatives are often inversely related (e.g. requiring a high level of comfort at low energy cost), examining them in isolation could lead to less than ideal outcomes. For example, Ewa P6 has an excellent EUI but one of the lower IEQ scores (Figure 2). If a decision was made on EUI alone to purchase additional Ewa P6 portable classrooms (Figure 2), energy costs would be low but the facilities department may receive a lot of occupant compliants of being too hot or too cold. Therefore, blending metrics can lead to a clearer picture of synergies and facilitate conversations about preferences. Our hope is that using metrics and figures linking energy and IEQ would lead to more informed maintenance, retrofit and design decisions.

In this ZNE and IEQ portable classroom case study, we used both the Pareto frontier plot and the comfort efficiency metric to bring forward the connection between energy and IEQ with some success. While the project was initially focused on the energy and ZNE project aspects, these two figures (Figures 2 and 3) broaden the discussion into the IEQ dimension to more fully understand the interrelationships.

In our experience the comfort efficiency metric is the first to combine IEQ and energy. While comfort efficiency is only a ratio of IEQ and EUI, IEQ requires significant effort to calculate. First, unlike energy data that comes from regulated meters, IEQ data collection is disaggregated. Thermal comfort, visual comfort and air quality components all typically require different data collection methods (e.g. sensors, observations, surveys) which can be cumbersome. Second, IEQ's boundary is subjective so standardization across buildings is challenging. In this study, we chose three IEQ components, limited sub-components (e.g. only included carbon dioxide for Air Quality) and excluded acoustical comfort from the IEQ boundary. Based on the project scope, the IEQ component priorities are likely to change. At a minimum, we would recommend including Thermal Comfort. Third, current IEQ threshold values (e.g. PMV +/- 0.5) rely on defining comfort for occupants at steady state, but in reality comfort is dynamic and individualized making it hard to model. Despite all of these challenges, we suggest using the comfort efficiency metric as a starting point to communicate the connection between energy use and thermal comfort. We hope the comfort efficiency metric or some iteration would become a mainstay both in the ZNE and the building community at large.

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