Feasibility of ZNE by Building Type and Climate

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Zero net energy buildings are all the rage. California has the policy goal that all new low-rise residences be zero net energy (ZNE) by 2020 and that all new commercial buildings be ZNE by 2030. This is in line with the Architecture 2030 goals adopted by ASHRAE, the American Institute of Architects, and others. The New Buildings Institute and the International Living Building Institute maintain growing lists of verified ZNE buildings. ASHRAE's latest series of *Advanced Energy Design Guides* lays out what is needed to achieve ZNE for schools.

This article explores the feasibility of this goal for a range of building types and climate zones. It shows that the goal is feasible for most new commercial building construction, but that on-site ZNE is challenging for energy intensive buildings, tall buildings, and buildings on shaded sites. For these conditions, off-site renewable energy must be incorporated to achieve ZNE, and many options exist for doing this.

What's a ZNE Building?

The common definition of a ZNE building is one in which the sum of all energy that is delivered to the property is less than the sum of all energy that is exported from the property (*Figure 1*).[1] All energy that enters or leaves the property is included in the accounting: electricity, gas, chilled water, etc. Electricity used to charge vehicles that are used off-site is considered exported energy. The accounting is fairly simple for all-electric buildings, but a consistent currency must be used when buildings have multiple fuels delivered to the site. DOE recommends that source energy be used as the currency to account for multiple fuels.*

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Collector-to-Floor Area (CFA) Ratio

Photovoltaic (PV) panels are the most common on-site renewable energy system for ZNE buildings, although wind is another option for special sites. Since PV is most common, ZNE feasibility in this article is judged in terms of the ratio of collector area needed for each square foot

*Source energy accounts for losses that occur in the distribution, storage, and dispensing of primary fuels burned at the site. For secondary energy like electricity or chilled water, source energy accounts for the conversion losses at the plant as well as losses that occur during transmission and distribution.

FIGURE 1 ZNE definition. All energy that enters or leaves the property is included in the accounting: electricity, gas, chilled water, etc.[2]

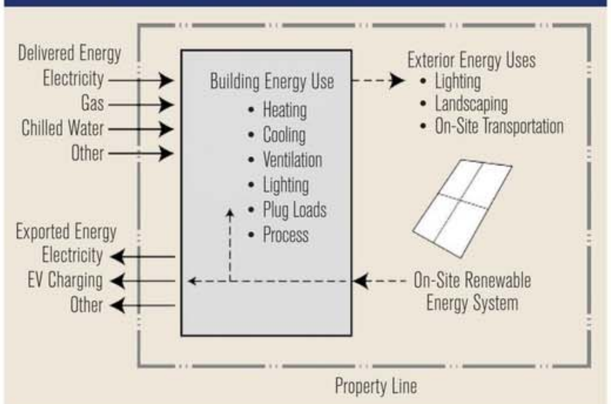
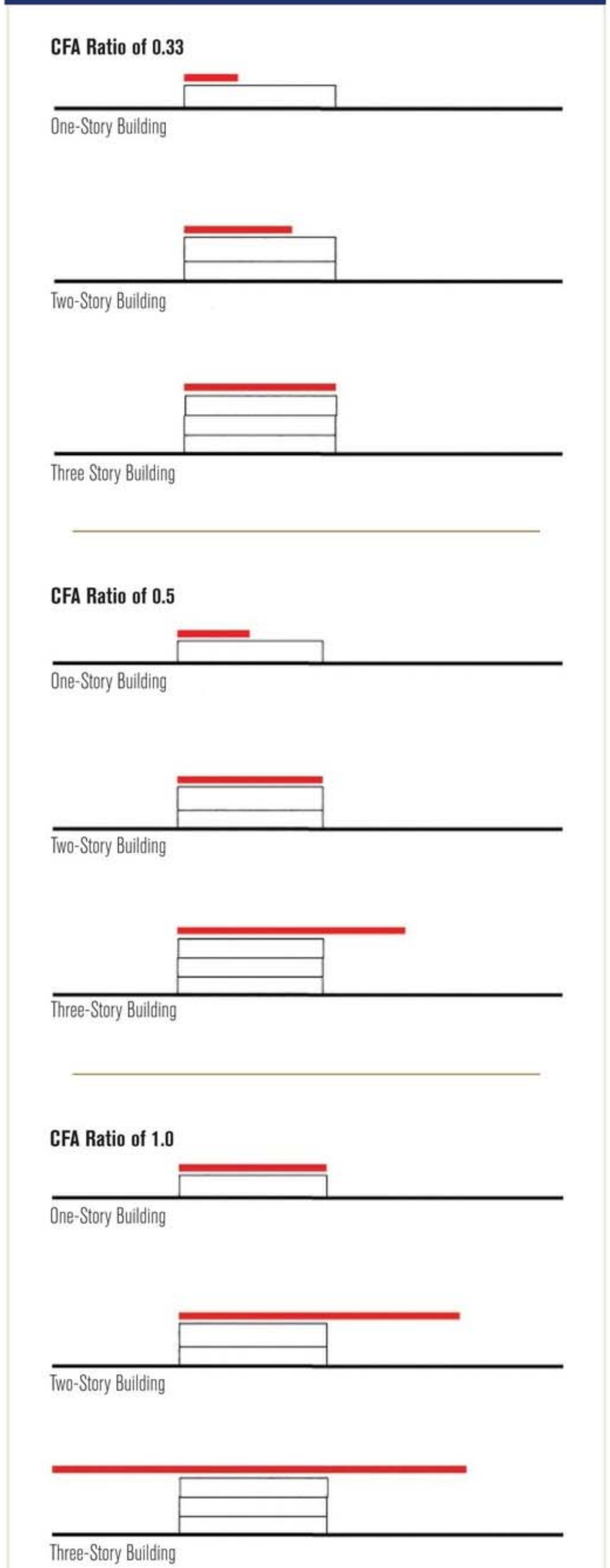


FIGURE 2 Example collector-to-floor area (CFA) ratios.



of conditioned floor area. This concept is illustrated in *Figure 2* for one-, two-, and three-story buildings.

ZNE is more feasible with lower CFA ratios (less collector area is needed per floor area) and more difficult with higher ratios. If it is possible to only place PV panels on the roof of the building, ZNE feasibility is limited by the height of the building. For urban building sites where the building footprint includes the entire site, it may be more useful to define on-site ZNE feasibility in terms of maximum floor area ratio (FAR). The FAR is the building floor area divided by the site area and is a common term used in planning codes and real estate. The maximum FAR is simply the reciprocal of the minimum CFA ratio.

$$\text{Maximum FAR} = \frac{1}{\text{Minimum CFA Ratio}}$$

Determination of the minimum CFA ratio or maximum FAR can be simplified as shown in the equation below:

$$\text{Minimum CFA Ratio} = \frac{\text{Energy Use Intensity}}{\text{Annual Renewable Energy Production}} = \frac{\text{kBtu/ft}^2_{\text{Building}} \cdot \text{yr}}{\text{kBtu/ft}^2_{\text{Collector}} \cdot \text{yr}} = \frac{\text{ft}^2_{\text{Collector}}}{\text{ft}^2_{\text{Building}}}$$

Based on this equation, you can see that as the EUI becomes smaller so does the minimum CFA ratio. Likewise, as the annual renewable energy production increases on a per square foot basis, the minimum CFA is reduced. Using this metric to evaluate ZNE feasibility, we just need to estimate how low we can get the EUI and how high we can push the annual renewable energy production. To be consistent with the DOE common definition for ZNE buildings, source energy should be used as the metric for both EUI and annual renewable energy production. However, in the analysis that follows, site energy is used for both EUI and renewable energy.†

Minimizing EUI

ASHRAE supported a recent modeling study that looked at the EUI that would be achieved with compliance with Standard 90.1-2013, but, more interestingly, the study estimated the maximum technical potential for reducing EUIs.[3] Sixteen building types and 17 climate zones were evaluated. For the estimate of maximum technical potential, all possible measures were included, whether they are currently cost-effective or not. Advanced building envelope systems, high efficacy lighting systems, effective controls, and super-efficient HVAC systems and equipment were all evaluated in a methodical manner.

The results of the study are shown in *Table 1* and *Table 2* in a simplified format. In these tables, both climate zones (*Figure 3*) and building types are consolidated. The EUIs that result from minimum compliance with Standard 90.1-2013 (*Table 1*) are about half of what is reported for turn-of-the-millennium buildings in the CBECS 2003 survey. (Standard 90.1-2016 reduces the EUIs even more.) The maximum technical potential EUIs (*Table 2*) are about half again lower than what results from minimum compliance with Standard 90.1-2013.

TABLE 1 Standard 90.1-2013 EUIs in kBtu/ft²·yr.

	PACIFIC COAST (3C, 4C)	WARM AND DRY (2B, 3B, 4B)	HOT AND HUMID (1A, 2A)	WARM AND HUMID (3A, 4A)	COLD AND DRY (5B, 6B)	COLD AND HUMID (5A, 6A, 7)	ARCTIC (8)
WAREHOUSES	16	15	12	17	20	26	33
OFFICES	22	31	33	32	31	34	41
RETAIL	35	49	48	50	53	59	81
SCHOOLS	35	46	49	47	48	50	68
APARTMENTS	35	48	48	51	53	61	76
OFFICES/DATA CENTER	62	69	71	70	72	77	88
HOTELS	57	75	80	78	77	83	100
HEALTH CARE	101	108	117	116	111	120	140
RESTAURANTS	360	431	414	471	513	574	759

TABLE 2 Maximum technical potential EUIs in kBtu/ft²·yr.

	PACIFIC COAST (3C, 4C)	WARM AND DRY (2B, 3B, 4B)	HOT AND HUMID (1A, 2A)	WARM AND HUMID (3A, 4A)	COLD AND DRY (5B, 6B)	COLD AND HUMID (5A, 6A, 7)	ARCTIC (8)
WAREHOUSES	6	6	5	6	7	8	7
OFFICES	8	10	11	11	11	11	12
RETAIL	13	18	18	17	18	19	27
SCHOOLS	16	21	23	22	21	23	26
APARTMENTS	24	30	29	31	32	34	35
OFFICES/DATA CENTER	43	47	47	44	47	46	47
HOTELS	40	49	49	51	51	54	58
HEALTH CARE	63	64	68	67	66	69	72
RESTAURANTS	265	323	324	336	343	353	377

Some building types represent a lot more construction activity than others, and the volume of construction in some climate zones is much greater. For instance, the warm and humid climate region represents more than a third of all construction activity. Likewise, hotels, health care, and restaurants have some of the highest EUIs, but fewer of these building types are being built. As part of its support for Standard 90.1, the U.S. Department of Energy and the national laboratories have estimated the construction weights by climate zone and building type. These are shown below in *Table 3* for the consolidated building classifications and climate regions.

The maximum technical potential EUIs can be combined with projections of construction activity as shown in *Figure 4*. In this graph, the most energy intensive building types (restaurants, health care and hotels) are shown on the right side, and the building types with the lowest EUIs (warehouses, offices, and retail) are shown on the left side. The vertical axis is the site EUI, and the area of each plateau represents the estimated

†For all-electric buildings, site energy and source energy will achieve the exact same result. For buildings that use both electricity and gas, source energy would elevate the importance of renewable energy production, resulting in lower CFA ratios.

construction activity for that building type and climate. The most energy-intensive climate regions are shown at the back of the graph (arctic and cold and humid), and the climates with the lowest EUIs are shown in the front. This one graph shows both maximum technical potential EUI and weights. The footprint of the graph represents total construction activity.

FIGURE 3 Consolidation of climate regions.[2]

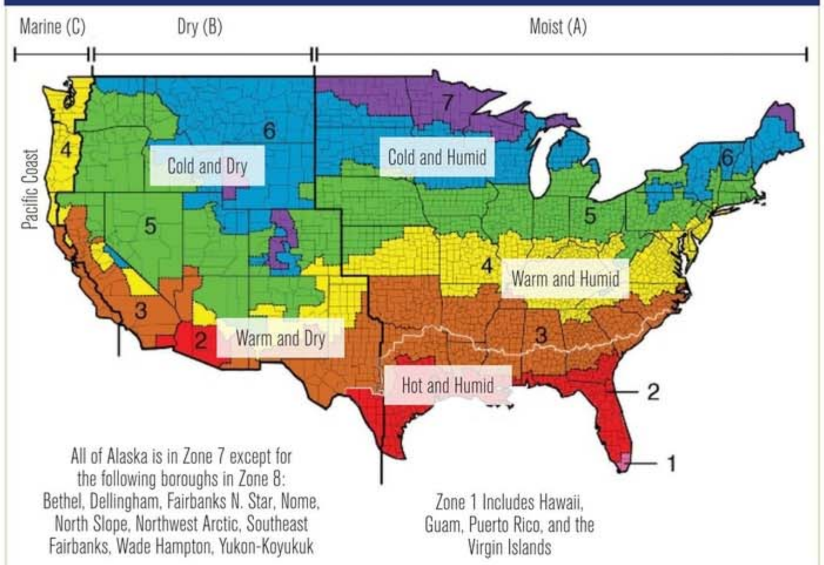


TABLE 3 Construction weights by building type and climate region.[4]

	PACIFIC COAST (3C, 4C)	WARM AND DRY (2B, 3B, 4B)	HOT AND HUMID (1A, 2A)	WARM AND HUMID (3A, 4A)	COLD AND DRY (5B, 6B)	COLD AND HUMID (5A, 6A, 7)	ARCTIC (8)	SUM
WAREHOUSES	0.0059	0.0295	0.0294	0.0541	0.0074	0.0409	0.0000	0.1671
OFFICES	0.0053	0.0185	0.0209	0.0386	0.0073	0.0258	0.0001	0.1166
RETAIL	0.0083	0.0278	0.0357	0.0696	0.0110	0.0567	0.0002	0.2092
SCHOOLS	0.0049	0.0175	0.0268	0.0575	0.0079	0.0388	0.0002	0.1535
APARTMENTS	0.0116	0.0179	0.0438	0.0568	0.0051	0.0276	0.0000	0.1629
OFFICES/DATA CENTER	0.0027	0.0035	0.0043	0.0158	0.0012	0.0059	0.0000	0.0333
HOTELS	0.0029	0.0112	0.0103	0.0218	0.0038	0.0168	0.0001	0.0668
HEALTH CARE	0.0039	0.0082	0.0112	0.0248	0.0049	0.0251	0.0000	0.0782
RESTAURANTS	0.0004	0.0017	0.0022	0.0043	0.0006	0.0034	0.0000	0.0125
SUM	0.0459	0.1358	0.1846	0.3431	0.0491	0.2409	0.0006	1.0000

Annual Renewable Energy Production

Annual renewable energy production can be calculated with a variety of tools. One of the more common tools is the PVWatts calculator, a free online tool supported by NREL.[5] You begin by choosing a weather file. For this study, the climate data is chosen for a representative city within each climate region. The tool also requires input for the size of the system at standard rating conditions, the module type (standard, premium, or thin film); the mounting system (fixed open rack, fixed roof mounted, or tracking); the system losses; and the azimuth and tilt of the collectors (when mounted in a fixed configuration).

For this analysis, all the defaults were accepted and performance for a standard PV panel was used. Production is calculated as the ratio of the annual production in kWh/yr divided by the rated size of the system in kW. You can also think of this as the full-time-equivalent operating hours per year for the system. *Table 4* shows example results for Atlanta, the representative city chosen for the warm and humid climate region. In this case, maximum annual production is for south orientation and a 30° tilt from the horizon. The table shows how performance falls off for other tilts and orientations. A similar analysis was performed for the seven climate regions shown in *Figure 3*.

While production on a per-square-foot-of-collector area basis is higher for a panel that is tilted toward the south (north in the southern hemisphere), the panels need to be spaced so they do not shade each other (*Figure 5*). If the goal is to maximize energy production for a given rooftop or site, as opposed to maximizing production for each collector, it is best to place the collectors in the same plane, even if the slope is near horizontal. This is the configuration used for the zero energy Bullitt

Center in Seattle and many other ZNE projects. For this reason, the energy production numbers for a horizontal orientation are used in this analysis.

The results (*Table 4* shows an example for Atlanta) can be converted to kBtu/ft²·yr (kWh/m²·yr) of annual production by assuming that 65 ft² (6 m²) of collector area are needed for each kW of standard test conditions (STC) rated capacity. This is typical of most monocrystalline solar collectors now on the market. The STC for rating collectors assumes insolation of 93 W/ft² (1,000 W/m²), normal incidence, and other standard conditions.

The results of this conversion are shown in *Table 5*. We now have the information we need to calculate the collector area needed for each square foot of floor area to achieve zero net energy.

FIGURE 4 Maximum technical potential EUI and construction activity.[2]

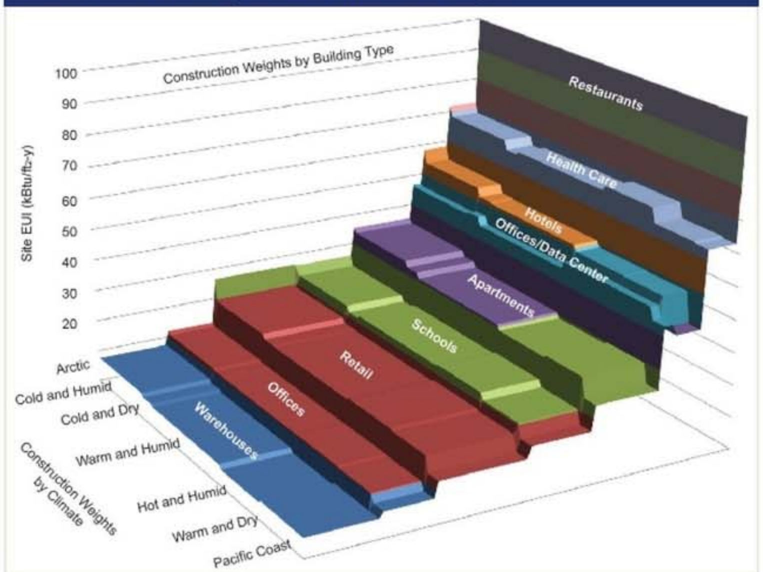


TABLE 4 Example results for Atlanta in kWh/yr per kW_{STC}.

	TILT						
ORIENTATION	0°	10°	20°	30°	40°	50°	60°
East	1,316	1,312	1,286	1,244	1,187	1,119	1,039
Southeast	1,316	1,368	1,410	1,412	1,386	1,333	1,255
South	1,316	1,404	1,457	1,475*	1,458	1,408	1,324
Southwest	1,316	1,374	1,402	1,401	1,370	1,316	1,237
West	1,316	1,306	1,274	1,227	1,166	1,096	1,018

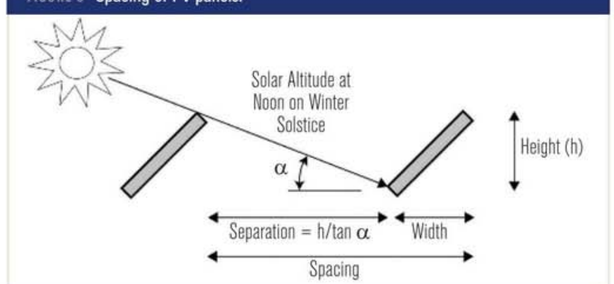
* This orientation and tilt results in the greatest production.

Note: Lighter shading indicates greater PV production. Darker shading indicates less PV production.

Results

Table 6 and *Table 7* show the CFA ratio needed to achieve ZNE for buildings that comply with Standard 90.1-2013 and for buildings designed to achieve maximum technical potential. The darkest shaded areas represent CFA ratios equal to or greater than 1.00 and represent the building types and climates for which ZNE will be most challenging. Even if these buildings are only one story, covering the roof with solar panels would not be enough to achieve ZNE. Unshaded areas represent building types and climates that are easiest, e.g., the CFA ratio is less than 0.25, and rooftop solar on four-story buildings could achieve ZNE. Restaurants are inherently energy intensive and are by far the most challenging building type of the ones discussed here, but the ASHRAE study cited earlier did not look at comprehensive ways to reduce energy for cooking, refrigeration, and ventilation in the commercial kitchens. Even with these measures considered, restaurants would remain a challenging building type.

FIGURE 5 Spacing of PV panels.[2]



Conclusion

ZNE is feasible for most new commercial construction (*Table 6* and *Table 7*) and for retrofitting many existing commercial buildings. The most challenging building type is restaurants, but they represent just over 1% of construction activity. Health care (representing about 8%) is also challenging, as are hotels (about 7%). The most challenging climate regions are the arctic and cold and humid areas. These areas have both higher EUIs and lower renewable energy production.

Tall buildings are also an obvious challenge. If the opportunity for renewable energy is limited to rooftop PV, the maximum number of stories for achieving ZNE can be calculated as the reciprocal of the CFA ratio shown in *Table 6* and *Table 7*. If an office building in the hot and humid climate region is designed to the maximum technical potential EUI, the maximum number of stories would be about six stories for ZNE feasibility (one divided by the CFA ratio of 0.15). But this assumes the entire roof can be covered with PV.

Wooded areas and urban environments also present challenges because of solar access. Yet urban areas have a smaller transportation impact because of location efficiency and have a lower infrastructure cost. The value of trees, more efficient transportation, and less infrastructure in urban areas often outweigh the benefits of suburban ZNE buildings.

Feasibility in this paper is based on rooftop solar, but a number of off-site renewable energy options exist that will enable challenging building types to achieve ZNE, including community solar and wholly owned off-site renewable energy systems. Opportunities also exist to pool buildings and apply the ZNE test to portfolios of buildings, campuses, and communities.

Note

The material in this article is adapted from *Design Professional's Guide to Zero Net Energy Buildings*.

References

1. DOE. 2015. "A Common Definition for Zero Energy Buildings." Prepared for the U.S. Department of Energy by the National Institute of Building Sciences.

2. Eley, C. 2016. *Design Professional's Guide to Zero Net Energy Buildings*. Washington, D.C.: Island Press.

3. Glazer, J. 2015, "Development of Maximum Technically Achievable Energy Targets for Commercial Buildings." ASHRAE Research Project RP-1651, Final Report.

4. Jarnagin, R., GK Bandyopadhyay. 2010. "Weighting Factors for the Commercial Building Prototypes Used in the Development of ANSI/ASHRAE/IESNA Standard 90.1-2010." PNNL-19116. Report prepared for U.S. Department of Energy by Pacific Northwest National Laboratory.

5. NREL. 2017. "PVWatts Calculator." National Renewable Energy Laboratory. http://tinyurl.com/lh7g843. ■

TABLE 5 Renewable energy production for each climate region. This is based on 65 ft² of collector area per kW of STC-rated capacity.

		Optimum Tilt		Horizontal Tilt	
Climate Region	Climate Zone	kWh/kW_{STC}	kBtu/ft²·yr	kWh/kW_{STC}	kBtu/ft²·yr
Pacific Coast	3C, 4C	1,582	83	1,378	72
Warm and Dry	2B, 3B, 4B	1,605	84	1,414	74
Hot and Humid	1A, 2A	1,462	77	1,359	71
Warm and Humid	3A, 4A	1,475	77	1,316	69
Cold and Dry	5B, 6B	1,589	83	1,311	69
Cold and Humid	5A, 6A, 7	1,304	68	1,138	60
Arctic	8	1,022	54	748	39

TABLE 6 Minimum CFA ratio needed for ZNE, compliance with Standard 90.1-2013.

	PACIFIC COAST	WARM AND DRY	HOT AND HUMID	WARM AND HUMID	COLD AND DRY	COLD AND HUMID	ARCTIC
Warehouses	0.22	0.21	0.17	0.24	0.28	0.44	0.84
Offices	0.30	0.42	0.46	0.46	0.45	0.56	1.04
Retail	0.49	0.66	0.67	0.72	0.77	0.98	2.07
Schools	0.48	0.62	0.68	0.69	0.69	0.84	1.72
Apartments	0.49	0.64	0.67	0.74	0.76	1.02	1.93
Offices/Data Center	0.85	0.94	0.99	1.02	1.05	1.29	2.25
Hotels	0.78	1.01	1.12	1.13	1.12	1.38	2.55
Health Care	1.40	1.45	1.64	1.68	1.61	2.01	3.57
Restaurants	4.97	5.80	5.81	6.82	7.46	9.60	19.34

The darkest shaded areas represent CFA ratios equal to or greater than 1.00 and represent the building types and climates for which ZNE will be most challenging.

TABLE 7 Minimum CFA ratio needed for ZNE, maximum technical potential.

	PACIFIC COAST	WARM AND DRY	HOT AND HUMID	WARM AND HUMID	COLD AND DRY	COLD AND HUMID	ARCTIC
Warehouses	0.08	0.08	0.07	0.09	0.10	0.13	0.19
Offices	0.11	0.14	0.15	0.15	0.15	0.18	0.30
Retail	0.18	0.24	0.25	0.25	0.26	0.32	0.67
Schools	0.22	0.28	0.32	0.32	0.31	0.38	0.66
Apartments	0.33	0.40	0.41	0.44	0.47	0.57	0.90
Offices/Data Center	0.59	0.63	0.66	0.64	0.68	0.77	1.19
Hotels	0.55	0.66	0.69	0.74	0.75	0.90	1.48
Health Care	0.87	0.86	0.96	0.96	0.95	1.15	1.83
Restaurants	3.66	4.35	4.53	4.87	4.99	5.91	9.61

The darkest shaded areas represent CFA ratios equal to or greater than 1.00 and represent the building types and climates for which ZNE will be most challenging.