The Roof Space Battle: PV vs Skylights and Other Technologies in Net-Zero Energy Capable Facilities

Mohamed Tatari, Gregory Raffio, John Seryak and Peter Kleinhenz, Go Sustainable Energy LLC

ABSTRACT

In a net zero energy (NZE) facility the roof is an important source for energy savings and production. A project can utilize passive solar design, reflective roof surfaces, a green roof, skylights, and/or renewable energy generation. In a NZE design, the roof must contribute either significant energy savings or energy generation. In particular, two uses of the roof space are directly tied to energy; skylights to reduce lighting energy and photo-voltaics (PV) to produce renewable energy. However, when it comes to implementing these technologies in energy efficient or NZE projects, competition for roof space occurs.

This paper highlights the importance of proper calculations in choosing technology for best utilization of roof space in a NZE building and presents the main factors. First, this paper introduces the common energy efficiency technologies competing for roof space and their potential to contribute to NZE and conflict with one another. Next, the NZE path is chosen and a metric for NZE evaluation is introduced. Finally, sample scenarios for PV generation and skylight savings are analyzed and PV's impact is favored. The findings demonstrate that PV produces more net energy than skylights save.

Background

In 2011, our team performed a NZE campus study of the Akron Zoo (Raffio et al. 2012). This campus, like most, has limited area on roof spaces and over parking lots to install PV. Our analysis concluded that all available south-facing and flat roof area must be utilized for PV generation if the campus were to be able to achieve NZE.

Once the "PV Energy Budget"[1] was determined, the campus was incapable of achieving NZE without deep energy efficiency retrofits. Deep efficiency means efficiency measures that are typically not analyzed in traditional retrofit scenarios due to their long paybacks, such as skylights and expensive HVAC renovations to ultra-high efficiency systems.

For example, in an administrative office area of the Akron Zoo with a flat roof, skylights offered lighting savings potential. However, the team concluded that in a NZE scenario, the skylights would reduce available roof area by more than their own foot-print and the potential electricity generation from solar panels would be reduced more than the skylight savings. This paper explores this topic further and to offer general guidelines for applying energy efficiency or generation technologies that reside on a roof.

---

[1] The PV Energy Budget is the amount of energy that a facility or campus can generate, not a monetary budget.

Introduction

NZE facilities are presented with two major constraints: the financial budget and the mathematical achievement of NZE. Like every project, up-front budget, ongoing lifecycle cost analysis, and financing provide the framework for turning a concept into reality. As technology such as high-efficiency lighting, building envelope components, and renewable energy continue to drop in price (Feldman et al. 2012), we speculate that NZE will become more achievable within typical project budgets or as project teams perform robust lifecycle cost analysis. Thus, this paper does not attempt to address financial constraints or other project logistics such as a facility's structural ability to install heavy equipment on a roof, etc.

This paper does not address financial budget. It does, for the first time, define the EGER Quotient as a NZE evaluation technique in a later section. The EGER Quotient is used to compare all the technologies that could occupy a rooftop and determine their impact on a NZE project. After comparing each technology and its potential, we simplified our analysis to the two most promising technologies: PV and skylights.

Roof Space Technologies

A design team has many tools to impact a facility's energy use, environmental impact, and occupant comfort. Of these tools, there are many that compete for roof space instead of a traditional asphalt or highly-absorbent roof. For example, a roof may be occupied by obstacles such as exhaust fans, HVAC equipment, hatches, plumbing stacks, architectural features, et cetera. The goal of this section is to portray the strengths and weaknesses of alternate technologies such as green roofs, highly reflective roofs, skylights, solar thermal, and PV.

In this paper, we reference the energy end-use breakdown in Figure 1. This breakdown is for commercial buildings and does not represent residential or industrial. This is not the only source of commercial energy use breakdown that can be found. In fact, each subset of commercial buildings will have a different end-use breakdown. Regardless, this breakdown does enable the NZE community to analyze and sanity-check technologies and their potential impact.

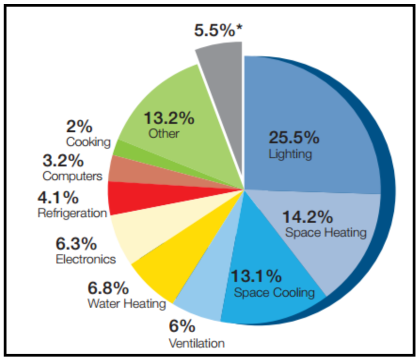

Figure 1. Commercial buildings energy end-use breakdown (DOE 2008).

Green Roofs

Roofs may be covered with soil and vegetation to create a green roof. Thermodynamically, green roofs have lower solar absorptivity than black roofs. They add thermal mass, which reduces peak cooling and heating loads, and allows evaporation from the vegetation, which cools the roof. Green roofs also greatly assist in sustainable storm water design by storing and evaporating rain water, which decreases peak discharge and can reduce a site's storm water infrastructure. Green roofs may also create a pleasant space for building occupants, especially in urban environments where garden and lawn space is limited or in hospital environments for private healing gardens. Finally, green roofs can reduce heat island effects caused by the density of buildings in urban areas.

While green roofs offer a wide array of sustainability benefits, they have a very minimal impact on total energy consumption. The R-value of dry soil is about 0.09 m^2-K/W (Becker and Wang 2011), which equates to an imperial R-value of approximately R-0.51/inch. Comparatively, one inch of rigid insulation is about R5 per inch, which is roughly the equivalent of 10 inches of soil. While there are other factors to consider, this leads to the basic conclusion that a facility can achieve more savings from insulation than a green roof, thus leaving the roof-space open for a more energy dense technology for production or savings.

High Solar Reflectance Index (SRI)

Surfaces with a high SRI contribute less than dark surfaces to heat island effects and also help reduce heat load to a facility. While this is advantageous for cooling dominated climates, in moderate and heating dominated climates, this creates a trade-off between reduced cooling energy use in the summer and increased heating energy use in the winter.

According to Rosenfeld, white roofs have great potential for facility energy savings due to their impact on the heat island effect and reducing HVAC energy consumption. Thus, the exposed roof area should at least be a white roof in cooling dominated climates to assist in achieving NZE. However, the question of total white roof energy impact is still valid. If a white roof is capable of reducing cooling energy by 20% (Akbari and Rosenfeld 2008), and cooling energy comprises about 15% of total energy consumption (Figure 1), a white roof has a multiplicative savings potential of:

Savings Potential = 15% consumption x 20% savings = 3% total savings

The total savings potential of a high SRI roof should increase in more highly cooling dominated climates. However, these technologies still only offer low overall savings for the facility. Thus, as technologies compete on a NZE roof, a white roof cannot provide the energy savings needed to be a preferred technology for the roof. This is not to say that a white roof should still not be employed in tandem with other technologies. For example, a white roof with PV and / or skylights is a marriage of technologies that could provide great impact.

Solar Thermal

Solar thermal energy is collected in a variety of ways and, in commercial applications, is typically used to produce either domestic hot water or hot water for heating systems. Respectively, these represent about 7% and 14% of total commercial energy consumption (Figure 1). Solar thermal has the potential to reduce these consumptions by up to 60% and 25% respectively (Goetzler, Guernsey, and Droesch 2014). Thus, the cumulative impact of solar thermal could achieve savings of:

$$\text{Solar thermal generation} = 7\% \times 60\% + 14\% \times 25\% \approx 7.7\%$$

Solar thermal can generate more energy per unit area than PV. However, the energy may not be fully utilized since seasonal production peaks in the summer while peak heating needs occur in the winter. All of the electricity produced by a grid-tied PV system is captured and used. Thus, since solar thermal can only save up to about 7% of a facility's energy, before considering energy efficiency to reduce this number further, solar thermal is not a high priority for roof space. There may be many scenarios where installing a small solar thermal system will be a better use of a small portion of a facility's roof, only if it offsets a minor amount of PV. Alternately, these two system types may be better to compare from an economic perspective before the final decision is made.

Skylights

A skylight is used to admit daylight into a space. Skylights coupled with proper daylight harvesting controls result in reduction of interior lighting energy consumption. While skylights have heating and/or cooling energy penalty, lighting energy savings is dominant, assuming a proper skylight to floor ratio (SFR), which is optimally 4% (Lawrence and Roth 2008). Besides energy savings, skylights are desirable for aesthetic reasons and allow natural light to create a more comfortable and natural working environment for occupants.

Lighting is the largest component of commercial building energy consumption at 26% (Figure 1). The annual lighting savings in spaces with skylights ranges from 35% to 55% (Lawrence and Roth 2008). Even using the lower estimate of 35% reduction, skylights have a potential to reduce total consumption as:

$$\text{Low-estimate savings} = 26\% \text{ total consumption} \times 35\% \text{ savings} \approx 9\% \text{ total savings}$$

Thus, skylights combined with daylight harvesting controls can deliver significant energy savings (9% - 26%). They can also co-exist with other technologies such as PV, solar thermal and white roof. Skylights thus remain a major contender for roof space in a NZE facility.

Photovoltaics (PV)

PV systems come in a variety of shapes and types, but they all generate electricity when exposed to sunlight. Most PV systems are installed with a number of symmetric circuits of PV panels to mitigate how shading reduces the overall system output. Most ideally, PV is a generation technology and is not tied to total facility consumption and could theoretically produce up to 100% of a facility's total energy needs.

Later in this document, the analysis shows that PV production on 1,000 ft^2 of a Columbus, Ohio rooftop can annually produce 15,787 kWh. Thus, the annual generation energy intensity would be:

$$PV\ Production = 15{,}787\ kWh/year \times 3.413\ kBtu/kWh\ /\ 1{,}000\ ft^2 = 53.8\ kBtu/ft^2/year$$

This could allow a single-story building to achieve NZE if it has an equivalent EUI. For a two-story building, the EUI would need to be 26.9 $kBtu/ft^2$/year for NZE. According to NBI's database of NZE buildings, all verified NZE office facilities have a total EUI between 13 and 33 $kBtu/ft^2$/year with an average of 19 $kBtu/ft^2$/year (Cortese, Higgins, and Hewitt 2014), which is less than 1/3 of the national office EUI average. Thus, PV has the generation potential to truly deliver NZE to a highly energy-efficient site.

Technology Summary

Of all the technologies that compete for roof space, PV is by far the most advantageous in a strict energy comparison. However, PV and other technologies can co-exist. For example, the space in between PV panels or skylights can easily be a highly-reflective roof. A green roof doesn't offer enough savings to truly consider and solar thermal is very application specific. However, thus far PV and skylights seem to offer the greatest potential for a NZE building.

Net Zero Energy (NZE)

There are four definitions of NZE as defined by the National Renewable Energy Laboratory: source, site, cost, and emissions (Pless and Torcellini 2010). The NZE community continues to discuss the merit and application of each definition. This paper assumes a goal of net zero site energy, where a facility/campus produces at least as much energy as it uses in a year using on-site renewable energy sources.

When a facility is characterized as NZE, it does not mean only "net-zero electricity". Consumption of natural gas or other on-site fossil fuels must be included in the NZE equation. We posit that a site that continues to consume natural gas cannot be net-zero source or site energy. It may only be considered net-zero cost or emissions. These are admirable paths, but are not the focus of this paper and cannot produce a truly zero-carbon, fully-renewable energy infrastructure. Thus, all natural gas equipment must be converted to electric equipment or be eliminated. This effectively increases annual electricity consumption, which requires additional generation or efficiency to offset (Raffio et al. 2012).[2] Alternately, a project could choose a different net-zero energy definition, such as net-zero emissions, and over produce electricity to offset the natural gas emissions. This is not the path considered in this publication.

---

[2] At the 2012 ACEEE Summer Study, gas conversion was discussed in many presentations and informal sessions. The NZE community is divided on this issue and debate surrounding it is vital to the field's advancement. This paper does not address both sides of the argument with the level of thoroughness required.

The EGER Quotient[3]

This paper introduces and defines the EGER Quotient as a unit-less quotient that is the ratio of energy generated and the energy requirements of facilities or equipment within the same defined boundary. Due to its unit-less nature, the EGER Quotient may be utilized to analyze projects with any of the four net-zero energy definitions. It may be written as follows:

$$\frac{EG}{ER} = \frac{Energy\ Generation\ Potential}{Energy\ Required}$$

EG is defined as the renewable energy generation potential within a boundary over a year-long period in which NZE is to be analyzed. This grouping can be as small as a single building or even as large as an entire city. As the numerator of the EGER Quotient, increasing EG also increases the EGER Quotient. The summarized components of EG are limitless in theory, but can be written as:

$$EG = \sum All\ Renewable\ Energy\ Generation\ Potential$$

In a NZE world, all energy generation must come from renewable energy sources. Thus, summarized components of EG include but are not limited to renewable energy sources such as PV (roof, parking structure or ground-mounted), wind, micro-hydro, or other renewable sources.

ER is defined as the actual or theoretical energy consumption requirements within the boundary. In design, ER can be determined with calculations or energy modeling. In a retrofit, historical energy consumption may suffice as ER or may be used to determine a target ER for NZE. As the denominator of the EGER Quotient, a reduced ER inversely increases the total value. Simply, the summarized components of ER are also limitless in theory, but are written as:

$$ER = \sum Energy\ Consumption$$

Summarized components of ER include all energy end uses within the boundary such as HVAC, lighting, equipment, production, domestic hot water, etc. Depending on the boundary to which the EGER Quotient is applied, this list may become quite extensive or may remain relatively simple.

The EGER Quotient is a powerful tool that may be used to define the presence or potential of NZE. An EGER Quotient greater than or equal to 1 is a facility that has achieved or is designed with the potential to achieve NZE. If the EGER Quotient is less than 1, NZE has either not yet been achieved or the current design is not capable of NZE. Further, even without

---

[3] The EGER Quotient is defined for the first time in this publication. The staff of Go Sustainable Energy has created this quotient in an attempt to standardize the measurement of NZE performance. While the staff of Go Sustainable Energy intend to publish a stand-alone piece solely about the EGER Quotient, this publication required a preliminary "unveiling".

actual installation of renewable energy, the EGER Quotient can be used to design a project in which future more cost-effective renewable energy can be seamlessly installed to achieve NZE.

The Path to an EGER Quotient ≥ 1

The New Buildings Institute (NBI) has published a wealth of knowledge in their 2012 and 2014 "Getting to Zero" Status updates (NBI 2012). According to the 2014 update (Cortese, Higgins, and Hewitt 2014), the average annual energy use index (EUI) for all NZE-verified offices is 19 kBtu/ft^2, which is over 75% below the national average. The stark contrast between the national average energy consumption and this current NZE average suggests a cost-achievable path to NZE is through an extremely low ER.

In the literature, EG may be referred to as the "solar budget" since, for the vast majority of urban buildings, the roof is the only feasible location for renewable energy. Vast parking lots and ready access to a valuable wind resource is a luxury that most sites do not have. Thus, for the majority of facilities the rooftop will be the main location of renewable energy generation.

Case Study: PV Generation Analysis

The NZE community must consider which of the competing roof technologies should be employed. A 10,000 ft^2 square roof space is selected for this study and is shown in Figure 2. This size is well within the NBI range of verified NZE facilities (Cortese, Higgins, and Hewitt 2014). Next, a basic PV system[4] is drawn on the roof, leaving spacing for aisle-access and a walkway around the perimeter.

Based on an optimal skylight-to-floor ratio (SFR) of 4% (Lawrence and Roth 2008), an array of skylights representing between 2% - 5%[5] SFR is overlaid on the roof and only over-lapping PV panels are removed. Approximately 1,000 ft^2 of PV is impacted through the addition of skylights, which is approximately 14 kW of panels[6], resulting in an equivalent of 10% of the roof area in PV panels being offset[7]. Thus, in our analysis below, as we vary SFR percentage and the energy savings increase, "equivalent" PV production remains constant.

---

[4] Typical PV module is 5 feet by 3 feet to estimate the roof area impacted by the skylights.

[5] ASHRAE 90.1-2007 sets an upper SFR of 5%

[6] PV impacted (kW) = 1,000 ft2 x (0.3048 m/1ft)2 x 15% efficiency x 1 kW/m2 ≈ 14 kW

[7] The analysis team chose the original grid size (5 skylights by 5 skylights) and changed the size of the skylights to affect between 2% and 5% of the roof. Thus, the full range of skylight SFR options all offset 10% of the roof PV area. We know that with more deliberate design, a team could decrease the amount of PV offset by a smaller skylights area, which could impact the results of this study to some effect. The scope of this paper is not to perform an optimization study, but to compare the order of magnitude of generation that PV offers a facility vs the level of savings provided by skylights.

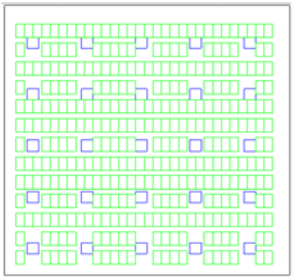

Figure 2. Sample roof layout.

Table 1 summarizes the PVWatts (2014) results for the annual solar energy production of the 14 kW PV that would be replaced by skylights. The PV was modeled with a south azimuth and a 30 degree tilt in the two representative cities. The skylights must save more energy than these offset PV installations in order to be beneficial to the EGER Quotient. We reiterate that in the analysis we conservatively removed as few PV panels as possible to minimize the reduction in EG that occurs. It is possible that, in an actual design of a PV array, additional panels would need to be removed due to circuitry symmetry, wiring logistics, or other reasons, which would require the skylights to overcome a greater challenge.

Table 1. Solar AC energy production loss from installing skylights

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Columbus, OH	913	951	1,438	1,515	1,634	1,683	1,673	1,634	1,469	1,332	826	719	15,787
Phoenix, AZ	1,596	1,578	1,916	2,133	2,133	2,001	1,956	2,009	1,969	1,849	1,700	1,593	22,433

Case Study: Skylight Savings Analysis

The skylight analysis uses SkyCalc (2006). SkyCalc is an excel spreadsheet tool provided by Energy Design Resources and designed by Heschong Mahone Group. SkyCalc uses hourly data of a typical weather year to calculate lighting and HVAC energy savings across a range of SFR to help determine the optimum strategy for achieving the maximum savings. Findings from a detailed study about skylights are also used in this analysis (Lawrence and Roth 2008).

Skylight savings and PV production are directly tied to the climate zone as solar radiation varies by region. The United States is divided into six major climate zones, 1 to 6, with three subdivisions for humidity level, A, B, and C. Commercial buildings may be categorized in a wide variety of space types, each with its own operating hours and lighting power density (LPD) in watts/ft^2 per ASHRAE 90.1 (2007). In this study, we compare retail and office space with "code-compliant" and efficient LPDs in Columbus, Ohio (zone 5A) and Phoenix, Arizona (zone 3B). This offers us eight scenarios with variable operating hours, LPD, and solar exposure where other building characteristics could be held constant.

In this analysis we use the LPD density defined by ASHRAE 90.1-2007 standards, which are 1.1 for office spaces and 1.7 for retail spaces. IESNA also defines the acceptable minimum lighting level for an office, as 30 foot-candles (fc) and 50 fc for retail (IESNA 2000). To achieve a reduced ER, a NZE building must reduce its interior lighting consumption. This can be achieved partially through reduced LPD in design. Thus, we also consider a reduced LPD scenario for the office (0.6) and for retail (1.2)

The physical and thermal properties of a skylight significantly impact the amount of light transmitted to the space and on the facility's HVAC energy consumption. These properties include solar heat gain coefficient (SHGC), thermal conductance (U-factor), and visible transmittance (VT). Optimizing these properties can reduce the cooling and heating losses, especially in heating or cooling dominant zones. Space temperature set-points, type of HVAC equipment, and HVAC efficiency also determine the magnitude of these losses. Based on the previous choice of net-zero site energy, and since there is no renewable source of natural gas, the facilities in this analysis utilize all electric heating and cooling through electric heat pumps. This allows all the heating and cooling impact from the skylight to manifest as electrical energy rather than as natural gas for a direct comparison with daylight harvesting savings.

ASHRAE 90.1-2007 dictates a VT of 0.66 and a U-value of 0.69 in both case-study locations with a SHGC of 0.39 in Columbus and 0.19 in Phoenix (ASHRAE 90.1). This analysis uses the ASHRAE VT and SHGC values and enhances the skylight with a U-value of 0.5, assuming these characteristics would be more typical of a low ER building.

The following two figures show the SkyCalc analysis results for a 10,000 ft2 office space and retail space. The graphs represent the annual total electricity savings from skylights across a range of SFRs. Each location is presented with two LPD scenarios.

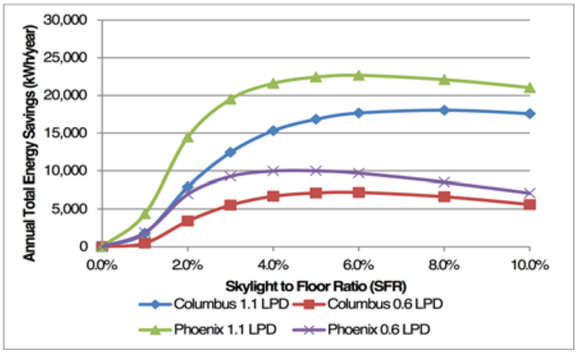

Figure 3. Skylight total savings for office.

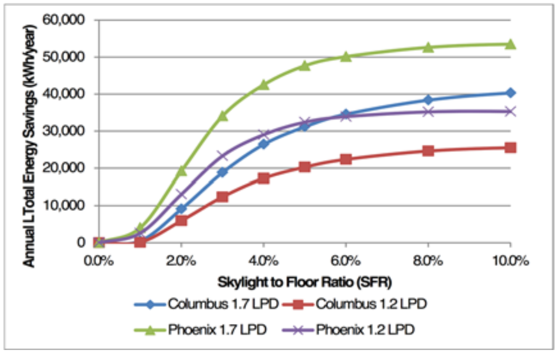

Figure 4. Skylight total savings for retail.

In the next two figures, we present the skylight total electricity savings for an office in each location vs the PV generation offset by the presence of skylights. Note again that based on a simply symmetrical layout of skylights, the amount of offset PV is relatively the same at 2% SFR to 5% SFR. The data shows that PV, in general, generates more energy in the area offset than skylight save. Thus far, when assumptions have been made, they have favored the presence of skylights. Thus, even though at 5% SFR, an argument could be made that skylights save more energy than the PV generation offset, the PV generation offset is highly conservative and may actually be higher.

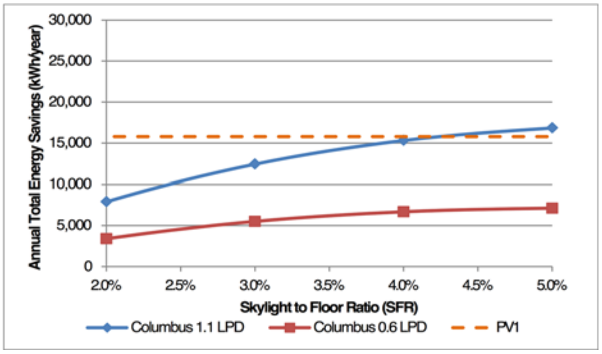

Figure 5. Columbus skylights vs PV – office space.

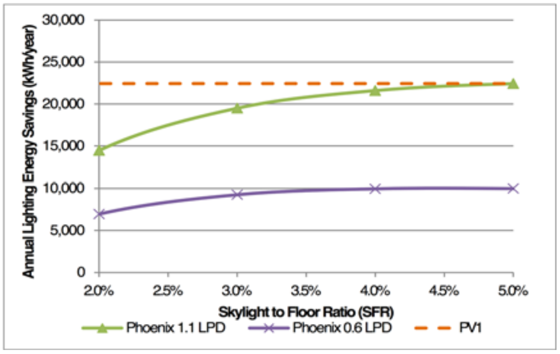

Figure 6. Phoenix skylights vs PV – office Space.

In the next two figures, we present the skylight total electricity savings for retail in each location vs the PV generation offset by the presence of skylights. An additional PV generation offset line has been added to the retail graph. As stated above for the office space, assumptions have been made to favor skylights. The data shows that skylights actually save more energy than PV generates in the PV1 scenario. However, PV2 has been added to show the effect if twice the PV area were to be affected by the presence of skylights. In this case, PV would generate more energy in the area offset than skylights save. Thus, retail spaces are much more likely candidates for successful integration of both skylights and PV together on a roof space due to their higher starting LPD and additional operating hours.

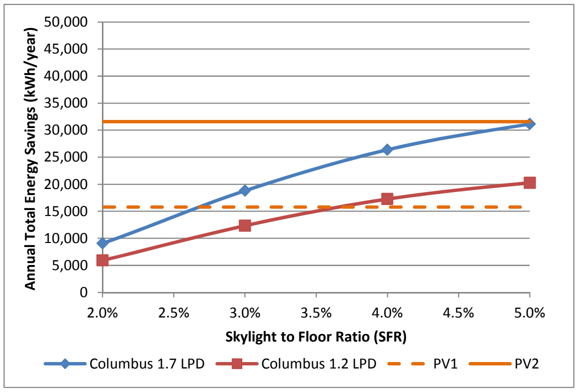

Figure 7. Columbus skylights vs PV – retail space.

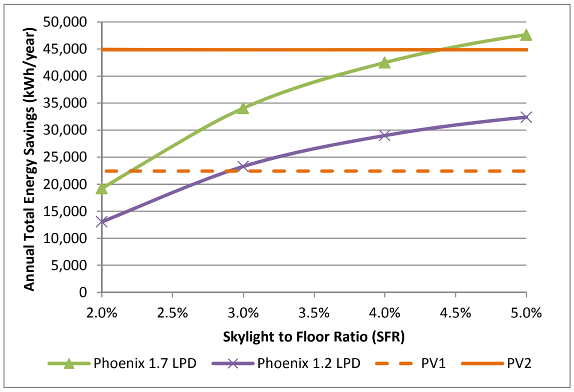

Figure 8. Phoenix skylights vs PV – retail space.

Design Optimization of Skylight Impact on PV

Previous sections have explained that a SFR of 2-5% removes an equivalent of about 10% or greater of potential PV generation. With PV and skylight layout as a prime consideration, a design team could theoretically greatly reduce the impacted area of PV when installing skylights. The theoretical limit of this reduction would be the equivalent skylight area. For example, in this paper's Columbus office space, where skylights have the least chance of success in Figure 5, reducing the impacted PV area to 5% allows a number of skylight configurations to actually save enough energy to justify the offset in PV installed.

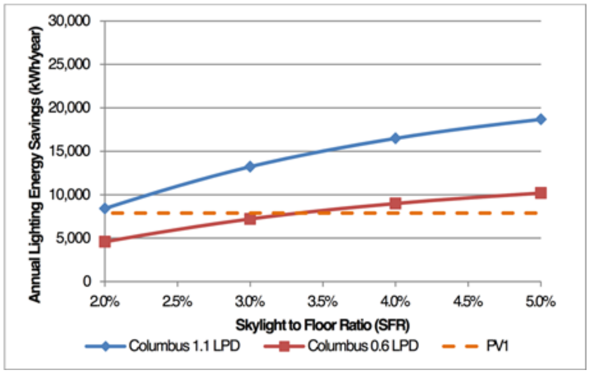

Figure 9. Skylights vs PV with optimization.

Conclusions

The literature shows that most existing NZE buildings have very low energy requirements. This suggests the need for deep energy efficiency features, such as skylights. However, most NZE buildings are likely to have PV installations on the roof, and thus skylights would offset some of the rooftop PV.

Our analysis considered two distinct climate areas and two building use types, to determine if skylights saved more energy than the displaced PV produced. We found that in simple design scenarios of an office space, they did not while in a simple design of a retail space, the results could be mixed. It is generally more advantageous to keep PV on the roof in lieu of skylights. We also considered a scenario in which the amount of displaced PV is perfectly equal to the square-footage of the installed skylights. In such an optimally designed case, the results are still mixed, with PV still at an almost obvious advantage. Because most NZE buildings likely will be designed with a lower LPD, this suggests skylights would only be favored over PV with a well-designed, custom layout.

This analysis could be extended to optimize the dozens of input variables for the range of building types in the US. However, the space types and climate zones are a reasonable representation of a large amount of commercial spaces in urban areas. Hence, it is reasonable to adopt a general NZE design guideline to not install skylights, and maximize rooftop PV potential, unless a custom analysis for this building overturns this assumption.

References

Akbari, H. and A. H. Rosenfeld. 2008. *White roofs cool the world, directly offset CO2 and delay global warming*. Heat Island Group at Lawrence Berkeley National Laboratory. Research Highlights. https://sites.google.com/a/lbl.gov/cool-white-planet/home/background-materials

ASHRAE 90.1 (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2007. *Energy Standard for Buildings Except Low-Rise Residential Buildings.* ANSI/ASHRAE/IESNA Standard 90.1-2007. ASHRAE.

Becker, D., and D. Wang. 2011. *Green Roof Heat Transfer and Thermal Performance Analysis.* Carnegie Mellon University. http://www.cmu.edu/environment/campus-green-design/green-roofs/documents/heat-transfer-and-thermal-performance-analysis.pdf

Cortese, A., C. Higgins, and D. Hewitt. 2014. *2014 Getting to Zero Status Update: A look at the projects, policies and programs driving zero net energy performance in commercial buildings.* nbi (new buildings institute). http://newbuildings.org/sites/default/files/2014_Getting_to_Zero_Update.pdf

DOE (U.S. Department of Energy, Energy Efficiency and Renewable Energy). 2008. *Energy Efficiency Trends in Residential and Commercial Buildings.* http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf

Feldman, D., G. Barbose, R. Margolis, R. Wiser, N. Darghouth, and A. Goodrich. 2012. *Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections.* SunShot, U.S. Department of Energy. http://www.nrel.gov/docs/fy13osti/56776.pdf

Goetzler, W., M. Guernsey, and M. Droesch. 2014. *Research & Development Needs for Building-Integrated Solar Technologies.* U.S. DOE, Building Technologies Program. http://energy.gov/sites/prod/files/2014/02/f7/BIST_TechnicalReport_January2014_0.pdf

IESNA (Illuminating Engineering Society of North America). 2000. *Illuminating Engineering Society of North America Lighting Handbook: Reference and Application, Ninth Edition*.

Lawrence, T., and K. W. Roth. 2008. *Commercial Building Toplighting: Energy Saving Potential and Potential Paths Forward*. U.S. DOE, Building Technologies Program. http://apps1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/toplighting_final_report.pdf

NBI (new buildings institute). 2012. *Getting to Zero 2012 Status Update: A First Look at the Costs and Features of Zero Energy Commercial Buildings.* NBI.

Pless, S., and P. Torcellini. 2010. *Net-Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options.* National Renewable Energy Laboratory.

Raffio, G., C. Mento, J. Seryak, P. Kleinhenz, C. Schreier, M. Tatari, and F. Sever. 2012. *Feasibility Study for a Net-Zero Energy Campus Retrofit.* 2012 ACEEE Summer Study on Energy Efficiency in Buildings.

Seryak, J., G. Mertz, and G. Raffio. 2011. *The Path to Net-Zero Energy Manufacturing.* 2011 ACEEE Summer Study on Energy Efficiency in Industry.

SkyCalc. Version 3.0 http://energydesignresources.com/resources/software-tools/skycalc.aspx

PVWatts. 2014. From NREL (National Renewable Energy Laboratory). http://pvwatts.nrel.gov/