Building Height and Net Zero

How High Can You Go?

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To determine whether the combination of building type, façade and site conditions permit a net zero energy building, screening level calculations must be done. For example, in a particular location, can a net zero energy building be one story? Two stories?

Using standard assumptions on internal gains, and a high performance building façade, the maximum height of a zero energy building in Abu Dhabi, UAE, is approximately two stories, according to modeling done by the authors. This presumes that the solar collector area is the same as the footprint of the building. If internal gains are aggressively reduced, then a three- to five-story, net zero energy building might be possible.

Net Zero

Many definitions of net zero exist,[1] and some buildings meeting one definition do not come close to meeting others. As a minimum, a net zero energy building must achieve an operating net zero energy demand. This means that the combination of all building energy demands must be offset by the energy harvested within the site or project. This is the lowest target level as it does not acknowledge the embodied energy in the building materials and construction, nor the quality of the energy produced.

When proposing a net zero energy building, a design team must make assumptions about the building and associated occupant energy use and the potential for energy harvesting at the building site. This information is not always readily apparent. In addition, the choice of building façade, mechanical systems and occupant behavior have significant impacts on whether a building can achieve a low enough energy use to match the energy produced on site.

This article illustrates how the combinations of building façade, daylighting, infiltration and other parameters can be adjusted to lower energy use for a hypothetical building in Abu Dhabi, UAE. This energy demand is then compared to the energy harvested on site within the same footprint of the building.

Different energy harvesting strategies are evaluated and the combination of these two analyses points to a maximum building height that can be designed while maintaining a net zero energy demand. A few key envelope design and renewable energy decisions may limit the maximum height of a building attempting to obtain net zero energy status.

Methodology

A building's energy consumption can be coarsely broken down into envelope needs, occupant needs and system efficiencies.

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Case	Case Description	Occupants (kWh/m²·yr)	Equipment (kWh/m²·yr)	Lighting (kWh/m²·yr)	Windows (kWh/m²·yr)	Walls (kWh/m²·yr)	Total (kWh/m²·yr)
Case 1	Façade and Gains,* No Shading Devices	6.7	23.4	32.2	31.9	2.4	96.5
Case 2	Façade and Gains,* 1 m Overhangs and Side Fins	6.7	23.4	32.2	17.8	3.0	83.0
Case 3	Façade and Gains,* 1.5 m Overhangs and Side Fins	6.7	23.4	32.2	15.1	3.0	80.4
Case 4	Gains,* Improved Glazing, No Shading Devices	6.7	23.4	32.2	23.0	2.8	88.0
Case 5	Gains,* Improved Glazing, 1 m Overhangs and Side Fins	6.7	23.4	32.2	13.3	3.2	78.8
Case 6	Gains,* Improved Glazing, 1.5 m Overhangs and Side Fins	6.7	23.4	32.2	11.4	3.2	76.9
Case 7	Internal Gains* Reduced by 25%, Improved Glazing, 1.5 m Overhangs and Side Fins	6.7	17.5	24.1	3.9	3.2	55.5
Case 8	Internal Gains* Reduced by 50%, Improved Glazing, 1.5 m Overhangs and Side Fins	6.7	11.7	16.1	3.9	3.2	41.6

*Standard 90.1-2004 recommendations.

Table 1: Annual gains (sensible only) by end-use energy consumption.

Envelope energy demands include sensible conduction and solar loads, along with latent and sensible infiltration load contributions. Occupant energy demands include the sensible and latent loads associated with the occupants, as well as the outside air requirements. For this work, lighting and equipment loads are presumed to be sensible loads only, although it is realistic to expect latent components from office and kitchen equipment, for example. Finally, building system efficiencies include installed mechanical component efficiencies, configuration and control strategies.

A net zero building always relies on a renewable energy contribution. This article focuses on technologies that can be closely integrated with the building design and fit within the building footprint. The contribution of solar energy harvested through photovoltaic cells and concentrating solar collectors are included in the parametric study. This strategy acknowledges that Abu Dhabi does not have viable, sustained wind energy potential.

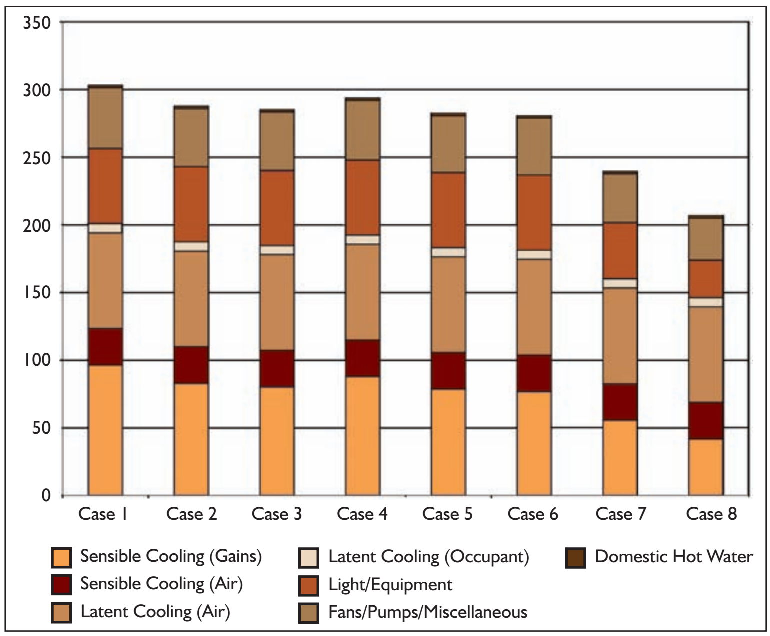

Figure 1: Total building cooling and thermal loads by end use (kWh/m²·yr).

Net zero energy demand, as discussed here, is based on a net zero annual energy requirement with no penalties for storage or temporary borrowing of energy from a district system. Additionally, it is assumed that the quality of the energy produced is equivalent to the need for this building: this implies equivalent value of low-grade hot water and electricity. These assumptions are baseline and permit an easier comparison of use and production. As a screening process, these assumptions are a reasonable start to show how much solar energy lands on a site versus that amount required to operate the building. However, the type of on-site energy production and its conversion efficiency is critical to the success of achieving a net zero energy building.

Building Energy Consumption

The first step in a screening level calculation is estimating the building's energy demand. For this purpose a whole-building energy model was created to predict building loads. Using a public and freely available software product, a simulation model of a typical office tower floor was created. A simple floor plan was modeled with a square footprint, 151 ft (46 m) wall length, and 13 ft (4 m) floor-to-ceiling height. A window-to-wall ratio of 30% was evenly distributed among all four exposures. The building envelope was initially modeled to represent ASHRAE Standard 90.1-2004 minimum requirements for a hot climate (ASHRAE Climate Type 4B). Initial estimates for internal gains were established using the Standard 90.1-2004 recommended energy densities and schedules for occupancy, lighting, and equipment/plug load gains. The modeled office building was simulated for a typical year in a representative hot climate using the Abu Dhabi IWEC weather data.[3]

The base model was simulated for eight scenarios representing the base case described previously, as well as cases with improved shading and glazing systems (*Table 1*). The results from these simulations are shown in *Table 1* and *Figure 1*.

For a large footprint office space, the gains to a space are dominated by windows (solar transmitted and thermally conducted), lighting, and equipment loads. When good solar shading practices are used, the window gains can be reduced significantly. However, the scheduled internal gains are maintained. This shows the importance of focusing on internal gain reduction, as well as façade improvements when targeting net zero energy design.

For example, if the equipment and lighting gains can be reduced by 25%, along with using good solar shading (Case 7), the annual gains are reduced to 5.16 kWh/ft$^2 \cdot$yr (55.5 kWh/m$^2 \cdot$yr). Aggressively conserving by 50% (Case 8) reduces the overall gains to 3.87 kWh/ft$^2 \cdot$yr (41.6 kWh/m$^2 \cdot$yr). Methods to reduce these gains can include energy-efficient lighting, lighting sensors (daylight and occupancy), ENERGY STAR equipment, and minimization of standby power loads.

From the information garnered from the model for internal gains, overall annual building energy consumption was established for each scenario. To do this, infiltration, ventilation and domestic hot-water (DHW) demands were estimated, assumed equal for each of the eight building scenarios, and added to the sensible cooling (occupants, window and wall demands) and plug loads (lighting + equipment) described previously. An infiltration rate assumption of 0.25 ach was used, as well as a ventilation rate as per Standard 90.1-2007 (5.30 cfm [2.5 L/s] per person and 0.64 cfm [0.3 L/s$\cdot$m^2]) to determine infiltration and ventilation loads.

For domestic hot-water calculations a supply of 1 gallon (3.7 L) per occupant per day, heated from 86°F [30°C] to a hot water supply temperature of 140°F (60°C) was used. Occupant density was assumed to be 276 ft^2 (25 m^2) per occupant. Finally, an equivalent total electrical building energy demand was calculated using a chiller COP of 5. This annual equivalent energy consumption is shown in *Figure 2*.

The results in this figure highlight that the energy impact of infiltration is approximately the same as that of a high performance façade (cooling). Further, the load contribution from outside air requirements for the occupants is of the same magnitude as the sum of plug and façade driven cooling loads.

Focusing on the façade as the exclusive driver of total building energy demand will not lead to a net zero energy building. When a high performance façade is selected that effectively reduces solar gain and infiltration loads, a significant load contribution from plug and lighting loads still must be addressed through optimization of daylight penetration, internal lighting controls and use of energy efficient appliances. This ultimately means that there is diminishing value from focusing on the façade, and that design teams must also concentrate on internal and latent loads.

Renewable Energy Harvesting

The available solar radiation in Abu Dhabi makes the harvesting of solar energy an obvious first choice for renewable energy production. With the relatively low average wind speeds for the region, wind energy typically may be less feasible in terms of likely lower power production for roof-mounted, micro wind turbines compared to solar energy for the same roof area.[2] In

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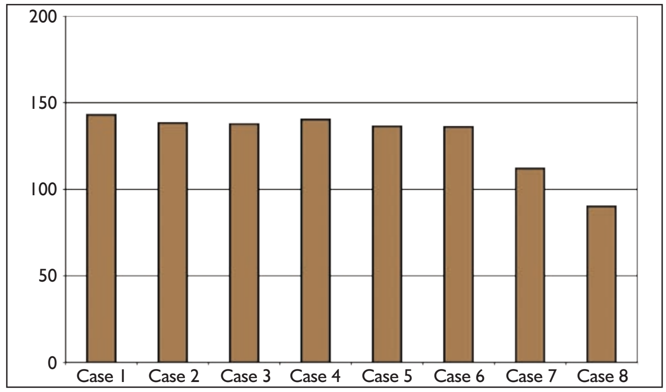

***Figure 2:** Total building energy demand (equivalent electrical [kWh/m² · yr]). The cases are described in* **Table 1.**

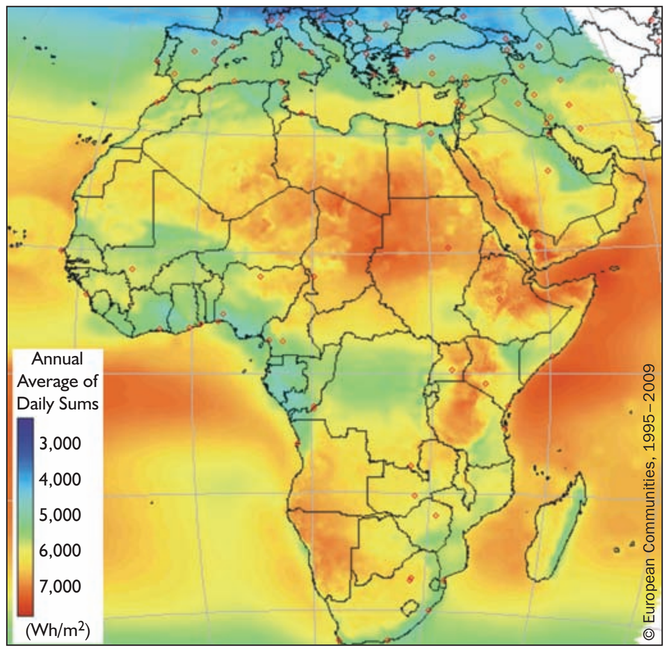

***Figure 3:** Annual average of available daily solar energy.*

this paper, a technology that can be simply integrated onto a given roof area was considered more appropriate.

Figure 3 shows the average daily solar irradiation for the region for a solar collector panel tilted towards the south at an angle of 24°. Typical daily and annual average available solar radiation for the region is of the order of 558 kWh/ft^2 (6,000 Wh/m^2) or 204 kWh/ft^2 (2,190 kWh/m^2), respectively, for a horizontal surface.

The authors used an HVAC systems modeling tool, coupled with the same IWEC[3] meteorology data used for the building energy simulations, to calculate the available solar energy for different surface orientations and solar tracking schemes. *Table 2* shows the results of the predicted solar radiation for different collector arrangements.

These calculations assume 100% collection efficiency and no inter-collector, or adjacent building, shading reductions to the annual power production. These calculations confirm the annual or daily average values reported previously and shown in *Figure 3*. *Table 2* also shows the beam radiation component incident on the same surfaces to identify the solar energy component avail-

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able to the concentrating solar renewable technologies discussed below.

A few available solar conversion technologies are discussed later to identify the range of conversion efficiencies. The intent of the discussion is not to comment on the cost implication, the suitability of the technology for a particular location or application or the finer details of what the system components should be to be feasible. It is meant as a general guidance towards practical limits for conversion efficiency.

	Annual Radiation Received (kWh/m²)	
Solar Collector	One Axis Tracking	No Tracking
Flat Plate, Horizontal	2,802	2,204
Flat Plate, 24° Tilt	2,934	2,364
Flat Plate, Horizontal, Direct Beam Radiation	2,088	1,590
Flat Plate, 24° Tilt, Direct Beam Radiation	2,199	1,723

Table 2: Available solar radiation on collector surface (100% efficient) from calculations.

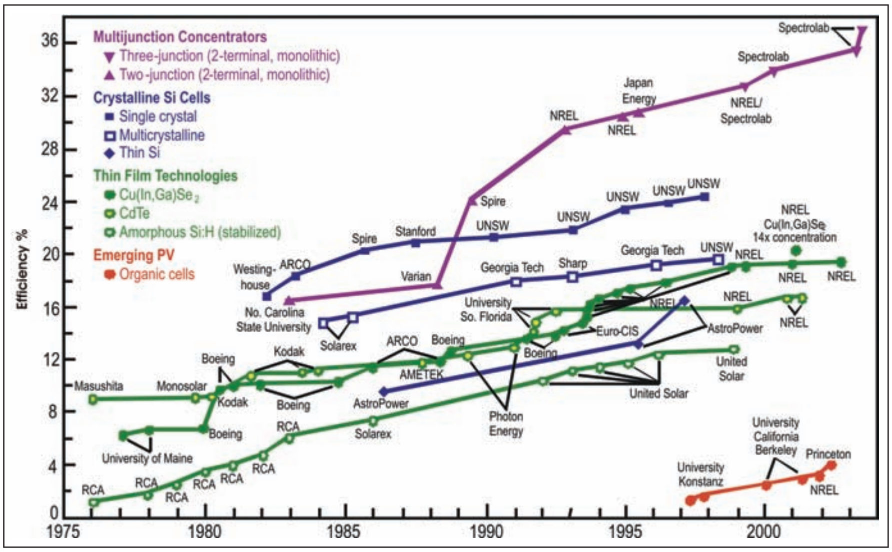

Figure 4: Photovoltaic cell conversion efficiencies improvement from 1975 through 2003.[4]

Photovoltaic (PV) Power Production

The conversion efficiency of the available solar energy into useful thermal or electric energy varies greatly between different commercially available technologies (*Figure 4*, for example, compares PV technologies[4]). Solar electricity production using multicrystalline silicone photovoltaic cells typically have efficiencies of between 16% and 20%; thin film technology, sometimes a more economical choice, may deliver efficiencies of around 10%.

Our approach here is focused on an early assessment of the likelihood of achieving net zero energy, regardless of cost but using available technology. For that reason a photovoltaic cell efficiency of 17% was chosen. The power production of these cells also deteriorates with increased outside temperature. The power degradation temperature coefficients for these cells are often quoted as approximately –0.3% to –0.4% per degree Kelvin. The actual surface temperature of the cell, that affects the conversion efficiency depends on the incident radiation, the local dry-bulb temperature and local wind speed, as well as wind exposure of the panels.[5]

Using local meteorological data for Abu Dhabi and a predicted cell temperature based on these local conditions,[5] the average panel collection efficiency may be reduced from 17% to 15%. For our calculation purposes a photovoltaic cell efficiency of 15% was used. A large portion of the roof area can be covered by photovoltaic cells with limited space made available for access for maintenance. For the present analysis a roof coverage factor of 75% was assumed.

Other photovoltaic modules are available with higher efficiencies, such as concentrating photovoltaic that use Fresnel lenses to concentrate incident radiation on smaller very high efficiency cells. These types of emerging technology devices are not considered for the present analysis.

Electricity can also be produced through a solar thermal cycle such as parabolic trough solar collector systems (producing heated oil or steam) or concentrating mirrors focusing radiation on a Stirling engine. Typically, the energy conversion efficiency for large scale systems (solar radiation to electricity) is 17% and 31% of parabolic trough and Stirling energy systems, respectively.

Parabolic trough solar collector systems can be roof mounted and connected to a trigeneration power generation system that converts high pressure steam to electricity using a steam turbine generator (*Figure 5*). The waste heat from the turbine (lower pressure hot steam) can be used in an absorption chiller system to produce chilled water with the remained of the waste heat (low pressure hot condensate) can be used for domestic hot-water production before being sent back to the collector array for reheating. These systems require tracking devices that continuously track the sun to focus the radiation on the collector absorber tube.

Considering that high pressure steam can be produced at a temperature of 608°F (320°C) and that the return temperature of the steam to the collector array would be approximately 212°F (100°C), a Carnot efficiency of approximately around 37% is expected. Actual steam turbine efficiency when coupled with a waste heat absorption system may be 14%.

Assuming that the thermal system losses and solar absorption (reflectivity) losses amount to 25% of the incident solar energy and that the absorption chiller system has a coefficient of performance (COP) of 1.4 and requires 20% of its rated power in

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electricity, it can be shown that the overall system efficiency is approximately 34% (solar energy to equivalent electricity). This assumes that the equivalent electrical energy required by a vapor compression chiller operates at a COP of 3.

For now, the balance of thermal power, electrical power and chilled water produced with such a system compared to the average office building energy demand splits (electricity and cooling) was not evaluated. The installation and collection surface of this system will likely be lower than that achievable by roof mounted photovoltaic to account for the tracking system, maintenance requirements and thermal system components. A roof coverage factor of 66% was assumed.

Table 3 summarizes the solar collector conversion efficiencies used for the assumed rooftop-mounted renewable energy systems that needs to match the building energy demand.

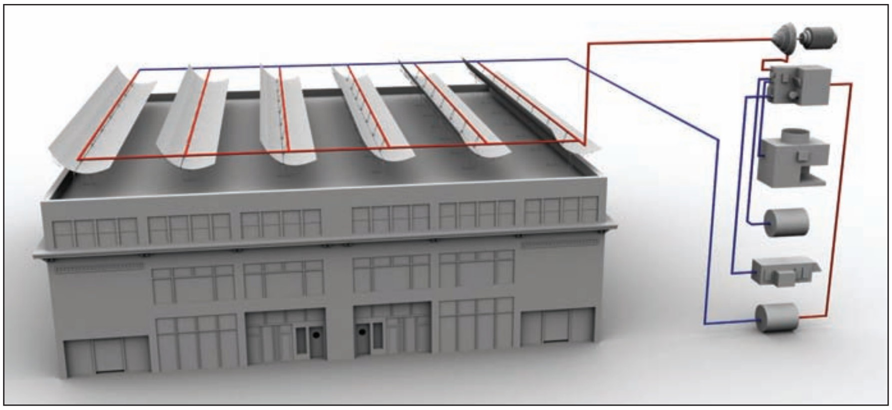

Figure 5: Parabolic trough solar collection system with steam turbine generator, absorption chiller and domestic hot-water heating.

Renewable Technology	Solar Conversion Efficiency	Roof Coverage Factor
Photovoltaic Cell	15%	0.75
Solar Thermal Parabolic Trough	34%	0.66

Table 3: Assumed renewable energy conversion efficiency.

	Building Energy Simulation Scenario (Option)							
Renewable Energy Used	1	2	3	4	5	6	7	8
Non-Tracking Photovoltaic	1.98	2.05	2.06	2.02	2.08	2.08	2.53	3.14
Tracking Photovoltaic	2.46	2.55	2.56	2.51	2.58	2.59	3.15	3.90
Concentrating Parabolic Trough Solar Collector (PTSC)	3.45	3.57	3.58	3.52	3.62	3.63	4.41	5.46

Table 4: Effective number of floors to match roof-mounted renewable energy production (solar).

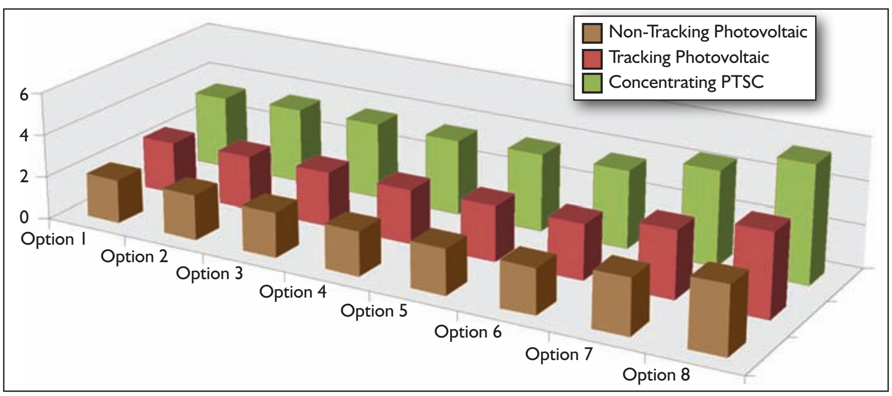

Figure 6: Effective number of floors to match roof mounted renewable energy production (solar).

Towards Zero Energy Building

The aim of the article is to illustrate the available building floor space that theoretically can be supported by a roof-mounted renewable energy (solar) technology. One way to simplify this is to describe the balance between available solar power and required building energy as the number of floors of the modeled building that can be stacked while still achieving net zero energy. This ultimately reduces the calculation to the ratio of annual available solar energy (kWh/m^2) per technology discussed and the modeled building scenario total energy demand (kWh/m^2). This ratio is number of floors allowed to achieve net zero energy on a site that can use all of its roof and building footprint to install a solar collection device that produces electricity or its equivalent.

Table 4 and *Figure 6* show the number of stories for the different building arrangements coupled with the three solar technologies discussed here. The results show that the maximum height for a building with a standard efficiency (Scenarios 1 through 6) is approximately between two and three stories. For the case with reduced internal gains (plug and lighting), the building height can go to four or five stories based on the assumptions used.

The calculations suggest that even in an area with high solar exposure and good solar energy production the maximum number of floors that can be supported, for the simulated cases Options 1 through 6, is two for typical photovoltaic production. The influence of the building façade has a significant influence on the solar gains transmitted into the building. However, selecting proper window-to-wall ratios, proper and ample shading for important well-exposed façades is not sufficient to create buildings that can support more than three stories with renewable energy.

Significant energy demands are attributed to the building lighting load, as well as the treatment of humid fresh air. If significant savings (25% or 50%) can be achieved in lowering

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these two components (simulation Options 7 and 8) then the building floor numbers that can be net zero energy increases to between four and five.

Summary

The results presented highlight a number of important conclusions:

- The façade can be responsible for approximately 25% to 30% of the sensible building loads in a hot climate. Meanwhile, occupant needs such as lighting, equipment and ventilation are a significant proportion of the total building energy demand. Focusing on the façade as a means to achieve a net zero energy design is not the best strategy. As important, is reducing the internal gains and latent loads.
- The height of a building that can achieve net zero design is two or three stories based on the topology presented here and the assumptions. A different building configuration will have different demand and generation levels.
- The climate of Abu Dhabi is hot and humid. Many other regions of the world have similar climates including other regions of the Middle East, Asia and North America. Therefore, the calculations are applicable to other areas. Although similar estimates are also possible for dryer and cooler parts of the world, the intent of this work is to focus on the effect of renewable energy selection in a very hot and humid climate.
- A number of assumptions were made that simplify the analysis and limit the applicability. However, for screening process, these assumptions provide a starting point to show how much solar energy lands on a site versus that which is required to operate the building. The reality of this analysis highlights that solar energy harvesting alone does not permit tall net zero energy buildings.

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