FRAMING THE IMPACT OF BUILDING MASSING ON NET-ZERO ACHIEVABILITY

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ABSTRACT

This paper explores how massing may affect the achievability of net-zero energy use for commercial and institutional buildings. A detailed energy simulation tool that has daylighting and natural ventilation analyses capabilities is used in conjunction with a renewable systems analysis software to compare various massing alternatives. The Baseline building has a square footprint. The proposed alternatives are: (1) a rectangular parallelepiped building with an aspect ratio of three along the east-west orientation; (2) a rectangular parallelepiped building with an aspect ratio of three along the north-south; and (3) a pyramidal building. All buildings are a ten-floor office building, 100,000 ft^2 (9290 m^2) gross area, assumed located in Washington, D.C., with underground garage, 30% window-to-wall ratio, equally distributed fenestration, R-40 insulation in the exterior walls, and R-50 insulation in the roof. The HVAC system type is ground-source heat pump with dedicated outdoor air system, and the lighting and equipment power densities are respectively 0.5 and 0.75 W/ft^2 (5.4 and 8.1 W/m^2) for all cases. The buildings use a PV system on the roof and building integrated PV on the walls to try to achieve net-zero status.

The buildings achieve gross annual energy use indices of 22 to 24 $kBtu/ft^2$ (70 to 76 kWh/m^2), and PV production from the roof and walls was found to offset between 71% and 99% of the gross annual energy uses. That leads to net annual energy use indices of respectively 2.6 (8.2), 0.6 (2.0), 0.3 (1.0), and 6.9 $kBtu/ft^2$ (21.7 kWh/m^2) for the Baseline, the East-West alternative, the North-South alternative, and the Pyramidal alternative.

INTRODUCTION

There are limits on how low the gross annual energy consumption of a building can be reduced to. And achieving net-zero energy use status is very challenging for buildings where renewable energy production is limited, especially buildings located in a dense urban environment.

There are indeed several definitions of net-zero energy building (NZEB): for example, net-zero site energy building, net-zero source energy building, net-zero energy cost building. In the United States, the now revoked Executive Order 13514 – Federal Leadership in Environmental, Energy, and Economic Performance (which required federal agencies to implement high performance building design by, beginning in 2020 and thereafter, ensuring that all new Federal buildings that enter the planning process are designed to achieve net-zero status by 2030) defines a zero-net energy building as "a building that is designed, constructed, and operated to require a greatly reduced quantity of energy to operate, meet the balance of energy needs from sources of energy that do not produce greenhouse gases and therefore result in no net emissions of greenhouse gases and be economically viable" (EO 13514, 2009). In this paper, the definition of net-zero used is that of net-zero site energy as defined in Crawley et al. (2009): a NZEB produces at least as much renewable energy as it uses in a year, when accounted for at the site.

Mid- and high-rise buildings may not be able to achieve net-zero status if, as tends to happen in dense urban environments, only the roof is available for renewable energy production (Phillips et al., 2009). One of the potential solutions to the problem of achieving net-zero status in dense urban environments is by acting on the massing of the building. Massing impacts, among others, the performance of passive solar systems (such as shading devices and thermal mass) and active solar systems (such as rooftop photovoltaic panels, building integrated photovoltaics, and solar thermal), and the availability of daylighting and natural ventilation (Ourghi et al., 2007; AlAnzi et al, 2009; Granadeiro et al., 2013; Hemsath and Bandhosseini, 2015).

In this paper, various massing alternatives are compared to study net-zero status achievability with the choice of Washington D.C. as the location. The alternatives are: (i) a baseline building with a square footprint; (ii) a rectangular parallelepiped building with an aspect ratio of 3 along the east-west orientation; (iii) a rectangular parallelepiped building with an aspect ratio of 3 along the north-south orientation; and (iv) a pyramidal building.

METHODOLOGY

The modeling process follows two broad steps: gross annual energy use of the building (without renewable), and energy produced from photovoltaics.

Gross annual energy use

The gross annual energy use is modeled using the DOE-2-based building simulation program eQuest 3.65 (Hirsch, 2014).

The baseline and the three alternatives share common characteristics except their shapes. The baseline building was designed as a typical office building, with 10 floors, 13 ft (4 m) floor-to-floor height, and 9 ft (2.7 m) floor-to-ceiling height, with an underground parking garage. The gross-area, excluding the parking garage, is 100,000 ft^2 (9290 m^2). Zoning configuration is core-perimeter with 15-ft deep perimeter zones. Bulk occupancy is from 7 AM to 6 PM, with the HVAC fans operating continuously from 6 AM to 7 PM on weekdays; weekends are unoccupied with the HVAC fans off, except to maintain setback temperatures. The setpoints for cooling and heating are respectively 75°F/70°F (23.9°C/21.1°C), with setbacks of 84°F/62°F (28.9°C/16.7°C). The parking garage, with exhaust-supply fans providing the code-required 0.75 cfm/ft^2, is heated only, using electric unit heaters, with a setpoint of 60°F (15.6°C). The window-to-wall ratios are 30% on each façade. There are three elevators, 20 HP each, for a total of 45 kW. Exterior lighting load is assumed to equal 5.5 kW. Location is Washington D.C. (ASHRAE climate zone 4A – see Table 1).

Table 1
Design-days (ASHRAE, 2010)

HEATING DESIGN TEMP.	COOLING DESIGN TEMPERATURES		
	Dry-bulb	Range (Max – Min)	Wet-bulb
15°F (-9.4°C)	92°F (33.3°C)	20°F (11.1°C)	76°F (24.4°C)

The buildings were designed to minimize energy consumption with high performance envelope, high performance HVAC system, daylighting, and natural ventilation. Daylighting was modeled with continuous dimming (down to 20%) lighting controls for the fixtures, and an illuminance setpoint of 50 fc (538 lx). Natural ventilation assumed the Sherman-Grimsrud model in DOE-2, with a maximum number of 20 air changes per hour. Tables 2 to 9 describe the other characteristics of the buildings.

Figures 1 to 3 present three-dimensional views of the four building designs. The rectangular parallelepiped building with aspect ratio of 3 along the north-south orientation (Alternative 2) is simply a rotation of 90° of the rectangular parallelepiped building with aspect ratio of 3 along the east-west orientation. It is to be noted that the Pyramidal building has a larger footprint than the base building (138'x138' versus 100'x100') and one floor more, but keep the same window-to-wall ratio of 30% and the same gross area (excluding the underground parking garage) of 100,000 ft^2. The slope of the walls in the Pyramidal building was chosen to be 70° in this preliminary analysis. .

Energy produced from photovoltaics

A photovoltaic (PV) system installed on the roof alone may not provide the required energy to offset the normal consumption of the building. So, in addition to the roof system, Building Integrated Photovoltaics (BIPV) is used in the facades of the building.

Table 2
Properties of the constructions (Excludes the exterior air film)

ITEM	LAYERS (FROM EXTERIOR TO INTERIOR)	U-VALUE	R-VALUE
Exterior walls	Concrete 8 in. normal weight 140 lb/ft^3 | R-40 rigid insulation | Gypsum board 5/8 in. | Interior air film	0.022 Btu/h.ft^2.°F (0.125 W/m^2.K)	45.4 h.ft^2.°F/Btu (8.0 m^2.K/W)
Roof	R-50 continuous insulation | Metal deck | Interior air film	0.020 Btu/h.ft^2.°F (0.114 W/m^2.K)	50.0 h.ft^2.°F/Btu (8.8 m^2.K/W)
Floor over garage	R-30 continuous insulation | Concrete 6 in. normal weight 140 lb/ft^3 | Carpet + rubber pad | Interior air film	0.031 Btu/h.ft^2.°F (0.176 W/m^2.K)	32.2 h.ft^2.°F/Btu (5.7 m^2.K/W)

Table 3
Properties of the fenestration

TYPE	Triple pane, low-E, argon fill, insulated spacer
DOE-2 GLASS TYPE CODE	3623
U-VALUE (INCL. FRAME)	0.181 Btu/h.ft^2.°F (1.028 W/m^2.K)
SOLAR HEAT GAIN COEF.	0.47
VISIBLE TRANSMITTANCE	0.66

Table 4
Internal loads

<table>
<tr><th rowspan="2">SPACE TYPE</th><th colspan="3">OCCUPANCY</th></tr>
<tr><th>Area/ Person</th><th>People sensible heat gain</th><th>People latent heat gain</th></tr>
<tr><td>Office</td><td>200 ft^2 (18.6 m^2)</td><td>250 Btu/h.person (73.3 W/person)</td><td>200 Btu/h.person (58.6 W/person)</td></tr>
<tr><th colspan="3">LIGHTING</th><th rowspan="2">EQUIP. POWER DENSITY</th></tr>
<tr><th>POWER DENSITY</th><th>HEAT-TO-SPACE RATIO</th><th>RADIANT FRACTION</th></tr>
<tr><td>0.50 W/ft^2 (5.4 W/m^2)</td><td>1.00</td><td>0.67</td><td>0.75 W/ft^2 (8.1 W/m^2)</td></tr>
</table>

Table 5
Ventilation and infiltration

SPACE TYPE	VENTILATION	INFILTRATION/ FLOOR AREA
Perimeter	15 cfm/person (7.1 L/s.person)	0.045 cfm/ft^2 (0.228 L/s.m^2)
Core	15 cfm/person (7.1 L/s.person)	0.015 cfm/ft^2 (0.076 L/s.m^2)
Plenum	N/A	0.020 cfm/ft^2 (0.102 L/s.m^2)

Table 6
Domestic hot water system

SYSTEM TYPE	Recirculation
SUPPLY TEMPERATURE	140°F (60°C)
PUMP TYPE	One-speed, premium motor class
HEATER TYPE	Electric
PEAK FLOW RATE	0.82 gpm (0.05 L/s)
STORAGE TANK HEAT LOSS COEFFICIENT	5.00 Btu/h.°F (2.64 W/K)

Table 7
Ground-loop heat exchanger

COOLING DESIGN TEMP.	80°F (26.7°C)
HEATING DESIGN TEMP.	50°F (10.0°C)
DESIGN TEMP. CHANGE	10°F (5.6°C)
LOOP PUMP TYPE	Variable-speed, premium motor class
HEAT EXCH. CONFIG.	4x8
PIPE TYPE	Polyethylene
PIPE SIZE	1-1/4, schedule 80
BOREHOLE DEPTH	450 ft (137 m)
BOREHOLE DIAMETER	6.0 in. (0.152 m)
BOREHOLE SPACING	20.0 ft (6.1 m)
U-TB LEG SEPARATION	2.7 in. (0.069 m)
GROUT CONDUCTIVITY	0.75 Btu/h.ft.°F (1.30 W/m.K)
NUMBER OF IDENTICAL WELL FIELDS	6 (for a total of 192 boreholes)
FLUID TYPE	Propylene glycol, 10%
UNDISTURBED MEAN GROUND TEMP.	59°F (15°C)
GROUND THERMAL DIFFUSIVITY	0.037 ft^2/h (9.55x10^{-7} m^2/s)
GROUND THERMAL CONDUCTIVITY	1.27 Btu/h.ft.°F (2.20 W/m.K)
YEARS OF PREVIOUS OPERATION	20

Table 8
Dedicated outdoor air system

SYSTEM TYPE	Ground-source HP
DEMAND-CONTROLLED VENTILATION	Yes
OVERALL FAN EFFICIENCY	52%
COOLING EER	21.0
HEATING COP	4.1
HR DEVICE TYPE	Enthalpy wheel
HR CONFIGURATION	Counter flow
HEAT RECOVERY SENSIBLE EFFECTIVENESS	80%
HEAT RECOVERY LATENT EFFECTIVENESS	70%
HR POWER CONSUMPTION	0.085 W/cfm
HR CONTROL STRATEGY	Mixed-air T reset
HR CONTROL MECHANISM	Wheel speed modulation

Table 9
Zonal HVAC systems

SYSTEM TYPE	Ground-source heat pump
OVERALL FAN EFFICIENCY	52%
FAN TYPE	Variable speed
COOLING EER	21.0
HEATING COP	4.1
COOLING CAPACITY	Auto-sized
HEATING CAPACITY	Auto-sized

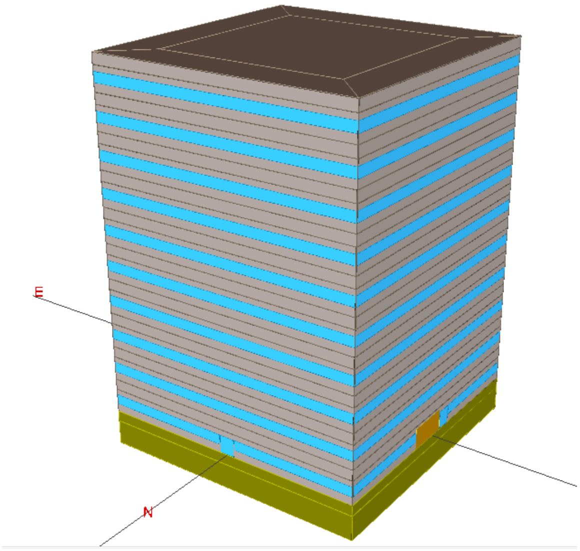

Figure 1 Three-D view of the baseline building

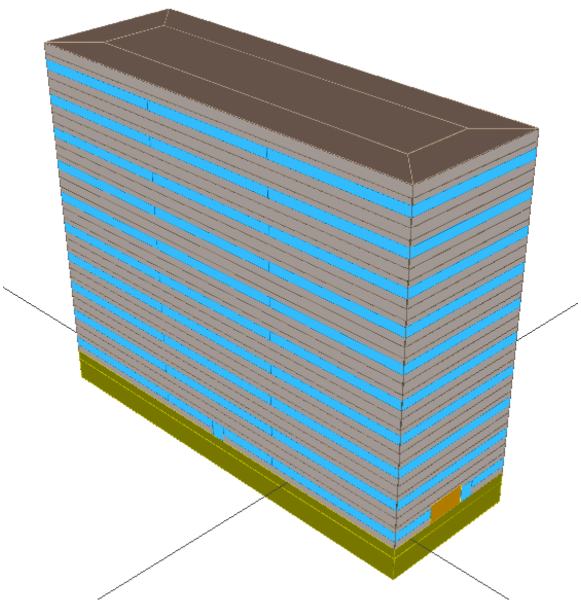

Figure 2 Three-D view of the rectangular parallelepiped building

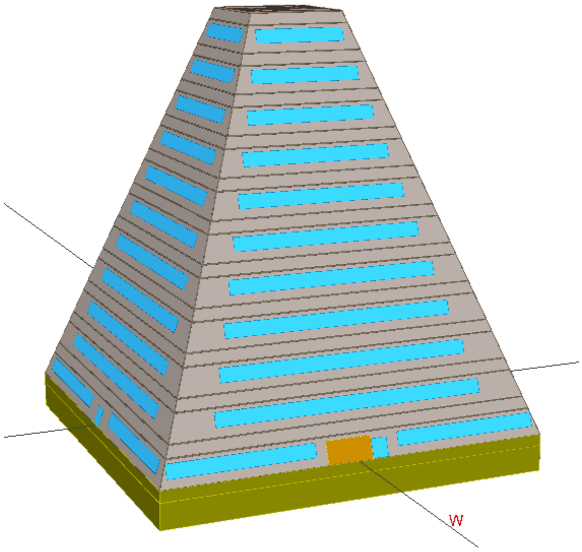

Figure 3 Three-D view of the pyramidal building

It is assumed that 80% of the roof is available for a PV system, and 60% of each façade is available for BIPV. The 20% loss in the roof accounts for various contingencies, including potential mechanical equipment in the roof. The 60% availability of the facades excludes the windows and other potential contingencies. Although there exist BIPV systems that are translucent and may be used as fenestration systems, the windows in our designs are assumed untouched by BIPV.

In the present study, it is assumed that conventional PV panels may also be used on the walls, and that the panels on the walls are sufficiently ventilated so that there is no drop in performance due to too high temperatures. The shading due to the PV systems on the roof and walls is not accounted for.

The renewable energy analysis software RETScreen 4 (NRCan, 2013) is used to model the PV systems in the Baseline building and alternatives. It is assumed that the panels installed on the roof and walls have a performance similar to the Samsung LPC241SM (Table 10).

Table 10
Samsung PV module LPC241SM performance at Standard Test Conditions (STC: irradiance 1000 W/m^2, air mass 1.5, and cell temperature 25°C) and at Nominal Operating Cell Temperature (NOCT: irradiance 800 W/m^2, air mass 1.5) (Samsung, 2015)

PARAMETER		STC	NOCT
Maximum power	Pmax (Wp)	241	194
Max. power voltage	Vmp (V)	30.1	30.3
Max. power current	Imp (A)	8.01	6.43
Open circuit voltage	Voc (V)	37.4	37.4
Short circuit current	Isc (A)	8.54	6.84

Each LPC241SM module has 60 cells of mono-crystalline silicon type, 1.6 m^2 frame area, and an efficiency of 15.06% at Standard Test Conditions (Samsung, 2015).

The inputs to the models of the PV systems are as follows:

- Slope: 38.9° for the roof system (corresponding to the latitude of D.C.), and 90° for the wall systems to the exception of the Pyramidal building where the wall systems have a slope of 70° (corresponding to the slope of the walls themselves).
- Inverter efficiency: 95%.
- Transformer losses: 3%.
- Miscellaneous losses: 18.5% (23.0% for the vertical walls). That percentage comes from the combination of the following losses (Vanek et al., 2012):
  - o mismatch of panels and inverter: 2%;
  - o losses in diodes and connections: 0.5%;
  - o resistance losses in direct current wiring: 2%;
  - o resistance losses in alternating current wiring:1%;
  - o soiling of the panel surface: 7.5%;
  - o shading: 5% (10% for the vertical walls);
  - o system availability: 2%.

The loss factor for shading includes shading from other row panels, but also shading due to other building elements, trees and other neighboring structures.

RESULTS AND DISCUSSIONS

Gross annual energy use

Table 11 shows the annual site energy consumptions of the buildings before inclusion of the energy production from the PV. Figures 4 to 7 show the shares of the various end-uses to the annual energy consumptions of the buildings.

Table 11
Energy Use Index (EUI) and Annual Energy Consumption (AEC) of the Baseline and alternatives

CASE	EUI		AEC
	kBtu/ft^2.yr	kWh/m^2.yr	(kWh/yr)
Baseline	22.8	71.8	667,544
East-West	22.5	71.1	660,729
North-South	23.4	73.8	685,734
Pyramidal	23.9	75.3	699,387

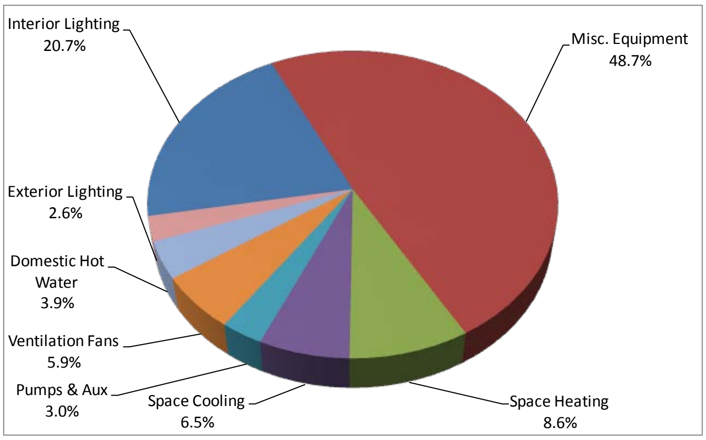

Figure 4 Proportion of each end-use to the gross annual energy use of the baseline building

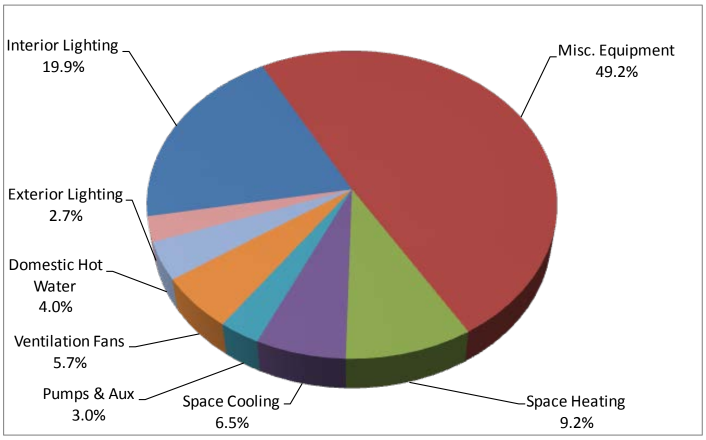

Figure 5 Proportion of each end-use to the gross annual energy use of the East-West alternative

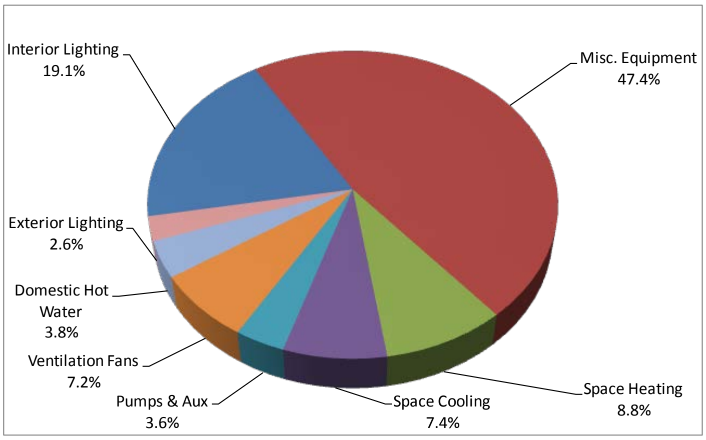

Figure 6 Proportion of each end-use to the gross annual energy use of the North-South alternative

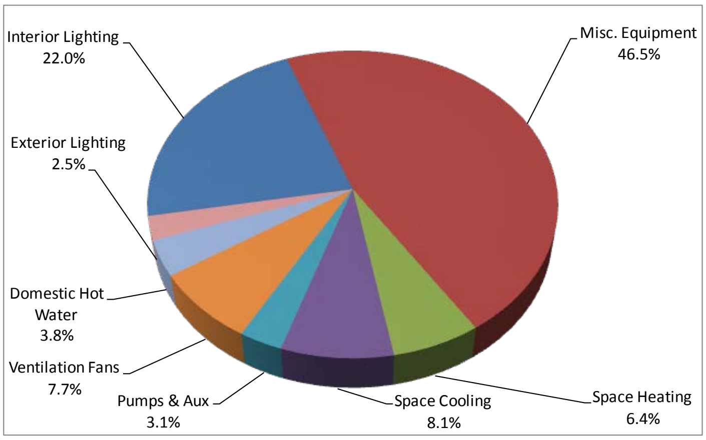

Figure 7 Proportion of each end-use to the gross annual energy use of the Pyramidal alternative

It is seen (Table 11) that the Baseline case achieves a very low Energy Use Index of only 22.8 kBtu/ft^2, which is about 70% lower than the Commercial Buildings Energy Consumption Survey (CBECS) average (EIA, 2015). As indicated earlier, that excellent EUI is mostly due to the inclusion of the high performance envelope, the relatively low LPD, the ground-source heat pump system, daylighting and natural ventilation. The separate contribution of daylighting to the performance of the Baseline building amounts to 6%, and the separate contribution of natural ventilation reaches 11%. Similar figures apply to the alternative designs.

Figure 4 reveals a relatively large share of equipment (almost 50%) in the total energy consumption of the Baseline. This is to be expected as a normal outcome for low-energy commercial buildings. It is also seen from this figure that interior lighting is the next big load (at about 20%), despite the relatively low LPD. That is the same picture with about the same proportions for the alternative building designs. This suggests that equipment and lighting are the next loads to target in order to lower the energy use of the buildings.

Among the alternatives to the Baseline, the East-West achieves the best energy performance, with a EUI slightly less than that of the Baseline. The two other alternatives come at EUI's higher than the Baseline, with the Pyramidal at about 5% more energy use than the Baseline. A direct comparison of the East-West alternative with the Baseline shows that the former achieves about 5% lower interior lighting energy use, with the other end-use consumption being basically the same in both. The Pyramidal building has higher lighting, space cooling, and ventilation fan energy uses than the Baseline.

Energy production from PV

The results of the PV analysis are summarized in Table 12. Focusing on the Baseline, it is observed that the production from the east and west facades are equal, production from the south façade is highest, and production from the north façade is the lowest among the four facades. The east and west facades produce 6% less energy than the south façade. And the north façade produces 36% less energy than the south façade. These results were expected. Extending the south façade to the detriment of the east and west exposures might be thought as a better alternative than a squared footprint. And that is confirmed by the results of the East-West alternative. However, since the north façade tends to produce lower energy, it impairs a longer south façade to a certain extent, and then making longer east and west facades (North-South alternative) better. This is probably valid up to a certain aspect ratio (the subject of later research). The Pyramidal building performs the worst. Its walls produce more energy than the Baseline walls, but it has a far smaller roof area.

Table 12
Energy production from PV per façade for the Baseline and its alternatives

	BASELINE (kWh)	**EAST-WEST (kWh)**
Roof	159,691	159,691
South wall	122,456	212,400
West wall	115,390	66,630
North wall	78,406	135,996
East wall	115,390	66,630
Total	**591,333**	**641,347**

	NORTH-SOUTH (kWh)	**PYRAMIDAL (kWh)**
Roof	159,691	18,241
South wall	70,710	138,864
West wall	200,150	127,975
North wall	45,274	84,480
East wall	200,150	127,975
Total	**675,975**	**497,535**

The total number of modules required for each design case is as follows:

- Baseline building: 464 modules on the roof, and 452 modules on each wall, for a total of 2272 modules (548 kW of capacity).
- East-West alternative: 464 modules on the roof, 784 modules each on the south and on the north walls, 261 modules each on the west and on the east walls, for a total of 2554 modules (616 kW of capacity).
- North-South alternative: 464 modules on the roof, 261 modules each on the south and on the north walls, 784 modules each on the west and on the east walls, for a total of 2554 modules (616 kW of capacity).
- Pyramidal building: 53 modules on the roof, and 437 modules on each wall, for a total of 1801 modules (434 kW of capacity).

It follows that the average PV production per module per year is for each case:

- Baseline building: 260 kWh;
- East-West alternative: 251 kWh;
- North-South alternative: 265 kWh;
- Pyramidal building: 276 kWh.

The Pyramidal building is so the most efficient in terms of PV energy generation.

Net energy consumption

The net energy uses (including PV production) are shown in Table 13. Among the buildings, the North-South alternative, with an Energy Use Index of only 0.3 kBtu/ft^2 per year, is the closest to net-zero status. The East-West alternative is the next best net performer, followed by the Baseline case. The Pyramidal building seems far from achieving net-zero status within the assumptions of this preliminary analysis.

Table 13
Net Energy Use Indices and Annual Energy Consumptions of the Baseline and alternatives

CASE	**NET EUI**		**NET AEC (kWh/yr)**
	kBtu/ft^2.yr	**kWh/m^2.yr**	
Baseline	2.6	8.2	76,211
East-West	0.6	2.0	19,382
North-South	0.3	1.0	9,759
Pyramidal	6.9	21.7	201,852

CONCLUSION

Hypothetical office building design alternatives in Washington D.C. were analyzed for their potential to achieve net-zero status, despite being mid- to high-rise in a dense urban environment setting. A baseline building, with a square footprint, was compared with three massing alternatives: (1) a rectangular parallelepiped building with an aspect ratio of 3 along the east-west orientation (East-West alternative); (2) a rectangular parallelepiped building with an aspect ratio of 3 along the north-south orientation (North-South alternative); and (3) a pyramidal building.

The buildings are designed with high performance envelope (R-40 in the exterior walls, R-50 in the roof, and triple glazing fenestration), high performance ground-source heat pump system, daylighting, and natural ventilation. Those high performance features in the designs show in the annual energy use indices, which are seen to be around 22 to 24 kBtu/ft^2 (70 to 76 kWh/m^2), resulting in about 70% savings over the CBECS 2003 average for that location for office buildings. The average contributions of the daylighting and natural ventilation to the performance of the buildings, when taken separately each, amount to 6% and 11% respectively.

It was seen that the different building designs could achieve energy production from PV systems installed on the roof and walls corresponding to offsets of 89%, 97%, 99%, and 71% of the gross annual energy consumption, respectively for the Baseline, the East-West alternative, the North-South alternative, and the Pyramidal alternative. Finally, with an annual Energy Use Index of only 0.3 $kBtu/ft^2$ (1.0 kWh/m^2), the North-South alternative is the closest to achieve net-zero status.

The Baseline and the East-West alternative are both close to net-zero status; but, the Pyramidal alternative is far from reaching that status. However, the Pyramidal building is the most efficient in terms of average PV energy production per module. In future research, the influence of different slopes of the walls in the Pyramidal building will be investigated, along with the impact of specific locations in the potential for achieving net-zero within dense urban environments.

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