Site layout planning and Sensitivity of Energy Performance

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Abstract. Buildings account for almost 40% of all U.S. energy use (REF). This has an impact on national energy security, the economic crisis, and the global environment. Provisions for local, state, and national building energy standards/codes exist to promote energy efficiency, making such codes a central part of the sustainable building movement. These efforts are advanced further by the building design and construction industry through passive design strategies, advanced construction techniques, and the application of renewable energy sources. This paper analyzes the sensitivity of energy use to variations in footprint aspect ratio and building orientation for high-rise office buildings. The energy analysis is performed using Autodesk Ecotect Analysis 2011 for four high-rise office buildings that have been modeled according to International Energy Conservation Code (IECC 2009). The outcome suggest that buildings built to current energy codes were barely sensitive to variations in footprint aspect ratio and building orientation (which is some of the passive design strategies) for high-rise office buildings.

Keywords: Site layout planning, Orientation, Passive solar gain, High-raise, Sustainable

1 INTRODUCTION

Global warming and climate change are major challenges facing the nation and the world. More than two thirds of the electricity energy and one third of the total energy in the US are used to heat, cool, and operate buildings (WBDG 2012), representing roughly 18% of all U.S. CO2 emissions in that year (EIA 2010). A reduction in building energy consumption will help to mitigate the energy security and climate change impacts of buildings. The reduction in energy use may translate to a financial savings that can be achieved through the development of new technologies (for the building's envelope, mechanical, and lighting systems) that save energy and reduce CO2 emissions. The benefit to the building owner is lower monthly utility expanses, and smaller less expensive HVAC equipment. Building energy codes are intended to promote energy efficiency (US department of energy 2012) by specifying minimum material, mechanical and construction standards.

An alternative approach is the use of passive systems that employ renewable energy sources. Passive systems avoid the need for heating or cooling through better design, construction, and operation. They utilize solar or wind energy to heat, cool, or light buildings. In the present study, we analyze the sensitivity of energy demand to two parameters of passive design related to building layout and site. The key parameters we investigate are building footprint aspect ratio and the building orientation and are considered important factors in passive design (Yeang 1999). Four high-rise office buildings (glazed curtain wall) with four different aspect ratios are thermally analyzed in four major Koppen climate zones: cool, temperate, arid, and tropical (Kottek et al. 2006). Energy demand is calculated for each model with respect to two opposing orientations (figure1). The four high-rise buildings are modeled to meet International Energy Conservation Code (IECC) 2009 requirements, which reference several American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standards, including Std. 90.1 for commercial building construction (IECC 2009).

Previous studies have shown potential for building site layout planning to play a positive role in influencing energy demand. For example, in *The Green Skyscraper* (1999), Kenneth Yeang suggests that in different climate zones the shape of the building footprint and the building orientation should be modified based on the climate zone in which the building is to be constructed. Walker (2009), shows that a building with simple shapes are typically more efficient to heat and cool than a building with irregular shapes, where the building with a simple shape has a smaller surface area and consequently less exposure to the sunlight, rain and wind. Therefore, it gains less heat in the summer and loses less heat in the winter. It also uses fewer construction materials and simplifies the length and complexity of the mechanical and plumbing systems that serve the building.

In the following sections we describe the analytical method and the primary variables that will be measured against energy use in the four modeled buildings. We then summarize the results for each of the thirty-six scenarios and present our conclusions.

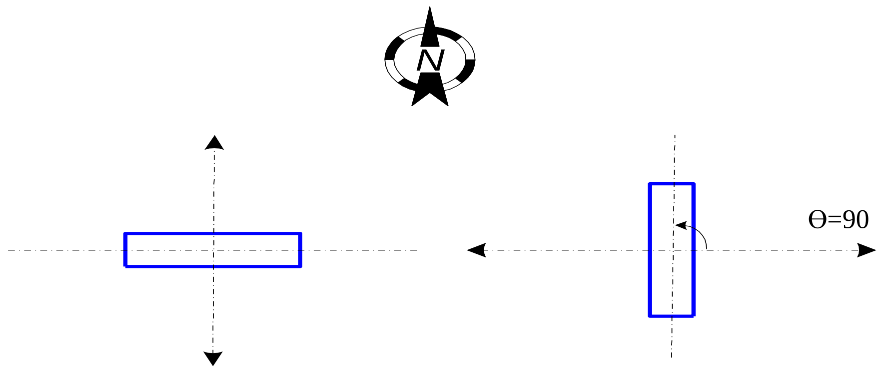
2 BUILDING MATERIALS AND METHOD

Four models of high-rise office buildings are considered in this study to evaluate the sensitivity of energy demands to variations in: (1) footprint aspect ratio (1:1, 1:2, 1:3, and 1:4), and (2) building orientation. Since our goal is to isolate the influence of building site layout planning on energy demand, all other buildings descriptors such as the square footage, number of stories, building height, and occupancy for the four buildings are held constant across all four buildings. Specifically, we treat the thermostat range, internal design conditions, occupancy, infiltration rate, and hours of operation as fixed control variables (table 1). The four buildings are 200 meters in height, 50 stories that are 4.0 m floor-to-floor height, with a total conditioned floor area of 135,000 square meters.

The primary material for the envelope is a glazed curtain wall, which comprises of double pane standard glass with 10% metal framing. The floors are composed of layers of 10mm ceramic tiles, 5mm screed, 100 mm normal concrete, insulation (as needed to meet the R-value specified for a climate according IECC 2009), 50 mm air gap, and 10 mm plaster underneath.

To simplify the thermal analysis, we have neglected the effect of surrounding buildings, in essence assuming that the buildings are erected on flat open ground and are aligned with the cardinal directions.

The four buildings are simulated in each of the four major climate zones (cool, temperate, arid, and tropical) and we have selected specific cities to represent each climate zone: Boston, Massachusetts for the cool zone, Sacramento, California for the temperate zone, Las Vegas, Nevada for the arid zone, and Honolulu, Hawaii for the tropical zone. Building envelope materials are selected for all four models to meet the requirements of thermal properties of IECC 2009, corresponding to each climate zone.

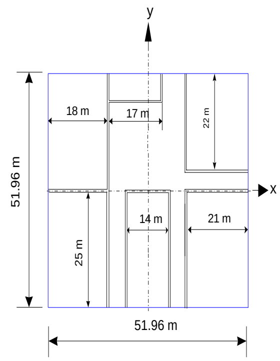


ϴ=0; N-S Orientation ϴ=90; E-W Orientation

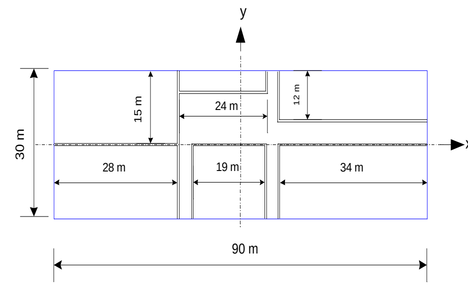
Fig. 1. building orientation considered in this study

Table 1. Thermal analysis conditions

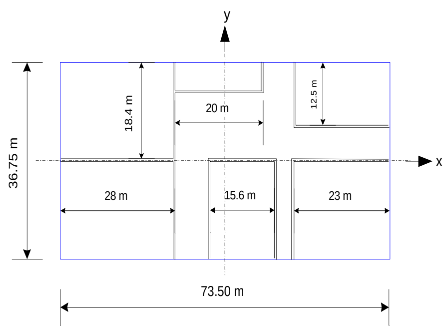
Parameters		**Values**
Active system		Full Air conditioning
Thermostat range		18 – 26 ^{o}C
Occupancy	People	12 m^2/person
	Activity	70 W/person
Internal design conditions	clothing	1 clothing/person
	Relative humidity	60%
	Air speed	0.5 m/s
	lighting level	300 lux
Infiltration	Air change rate	0.5 /hr
Internal heat gain		10 W/ m^2
Hours of operation		Schedule (8 am – 18 pm)



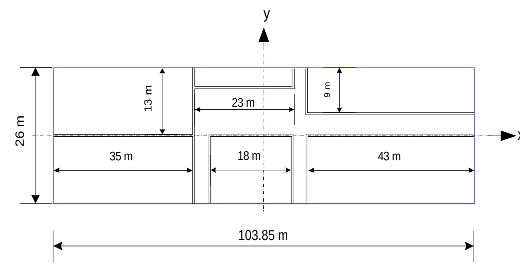
Plan view 1:1 configuration



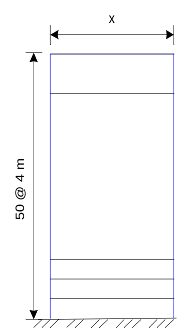
Plan view 1:3 configuration



Plan view 1:2 configuration



Plan view 1:4 configuration



Elevation

	Building's envelope thermal properties			
Climate / Element	Cool	Temperate	Arid	Tropical
Fenestration (Glazing wall with 10 % metal framing)	U=2.5	U=3.4		U=5.4
	SHGC=0.4	SHGC=0.25		
Roofs	R=3.7			R=2.7

U: U-value (W/m^2K)
SHGC Solar Heat Gain Coefficient
R: R-value (Km^2/W)

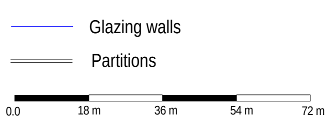


Fig. 2. building plan view and envelope thermal properties

3 ANALYTICAL APPROACH

Autodesk's Ecotect energy simulation package was used for the thermal analysis. Ecotect 2011 is a comprehensive concept-to-detail sustainable building design program; it is a popular program used by architects, as its modeling procedure is simple, easy to manipulate, and it consumes a reasonably short run time for large models. For this study, the building geometry was prepared in Revit 2010, and then imported as surfaces and rooms to Ecotect 2011. In Ecotect, thermal properties are assigned to the envelope. The basic material of an element (floor, roof, glazing wall, etc.) is assigned first, the thermal properties of element and the insulation is then applied according to specifications of IECC 2009. The next step is to assign a weather file that corresponds to the climatic zones selected for this study and to provide occupancy and scheduled usage data. Finally, the program calculates monthly and annual heating and cooling loads according to the prescribed conditions.

3.1 Thermal analysis

The thermal analysis involves examining each of the four models (1:1, 1:2, 1:3, and 1:4) in each of the four climatic zones (cool, temperate, arid, and tropical). For each climate zone, weather data (TMY files) for each city is loaded and the four models are tested under equivalent interior thermal and schedule conditions. That is, the only differences among the four runs in the same climate zone are the building width to length ratio (aspect ratio) for one orientation at a time. Ecotect calculates the overall heat gain/loss, and then based on Flat Comfort Bands Method (FCBM) the heating & cooling loads are calculated. FCBM sets upper and lower limits for comfort temperatures. If the internal zone temperature is either above or below the temperature limits for the prescribed comfort zone, then thermal environmental conditions are unacceptable to a majority of the occupants within that space. Factors that determine thermal environmental conditions are temperature, thermal radiation, humidity, air speed, and personal factors such as activity and clothing. Environmental factors are influenced by: 1) Direct solar gain, or radiant flow through transparent surfaces; 2) Internal (sensible) heat gain from lights, people, and equipment; 3) Conductive heat flow through opaque (envelope) elements; 4) Radiant flow through opaque (envelope) elements; 5) Ventilation and infiltration heat flow through cracks and openings; 6) Inter-zonal heat flow between adjacent zones, which for this analysis is negligible. Conductive and radiant flows through opaque elements are treated together and described as "Fabric" in Ecotect. Personal factors such as activity (metabolic rate) and clothing (insulation of clothing) are treated as constant for all building occupants.

In this study there are two main stages of the thermal analysis. The first stage is to find the sensitivity of the energy demand (heating and cooling loads) to the change of the surface area ratio (SAR), which relates to floor-plan aspect ratio:

$$\mathrm{SAR} = \frac{(\text{floor perimeter} \times \text{floor height})}{\text{floor plan area}}, \tag{1}$$

This analysis consists of thirty-two different simulation runs (of four models in two orientations in four climate zones = 4×2×4), where annual cooling and heating loads are calculated for each model. The results corresponding to the N-S orientation are provided in Table 2, and the difference in the total energy demand between the N-S and E-W orientations is not significant, as shown in Figure 3. Using the model of 1:4 aspect ratio as an example, the monthly and yearly energy demand ratios (EDR) for each of the four climate zones are shown in Table 3.

$$\mathrm{EDR} = \frac{\text{energy demand of East} - \text{West orientation}}{\text{energy demand of North} - \text{South orientation}}\,, \tag{2}$$

Also the passive solar heat gain ratio (PSHGR) of the 1:4 model is displayed in Figure 4. Moreover, the total heat gain and heat gain ratio (HGR) of the month of July are broken down into individual sources of direct (solar) gain, internal gain, fabric, and ventilation. Table 4 presents the percentage of each of these heat sources and how they vary by orientation.

The total energy demand for each orientation are not significantly different, even though the E-W oriented models have a much higher potential for passive solar heat gain. The next stage of the thermal analysis investigates why the differences in the energy demand are negligible. One possible reason maybe is because of the thermal properties of the IECC 2009 envelope. In the initial analysis, the glazing walls were modeled with U-factors and SHGC set according to the regional climate. These walls were subsequently modeled using single-pane glazing, which has inferior thermal properties (U=6.0 W/m^{2}K & SHGC=0.94). The simulation was run again to evaluate the total energy demand for each of the two orientations. The results of the new simulation runs show that buildings oriented E-W require 12% more energy than those oriented N-S, and that the passive solar heat gain in July is significantly increased.

4 RESULTS DISCUSSION

4.1 Demand sensitivity -- glazing walls built to code

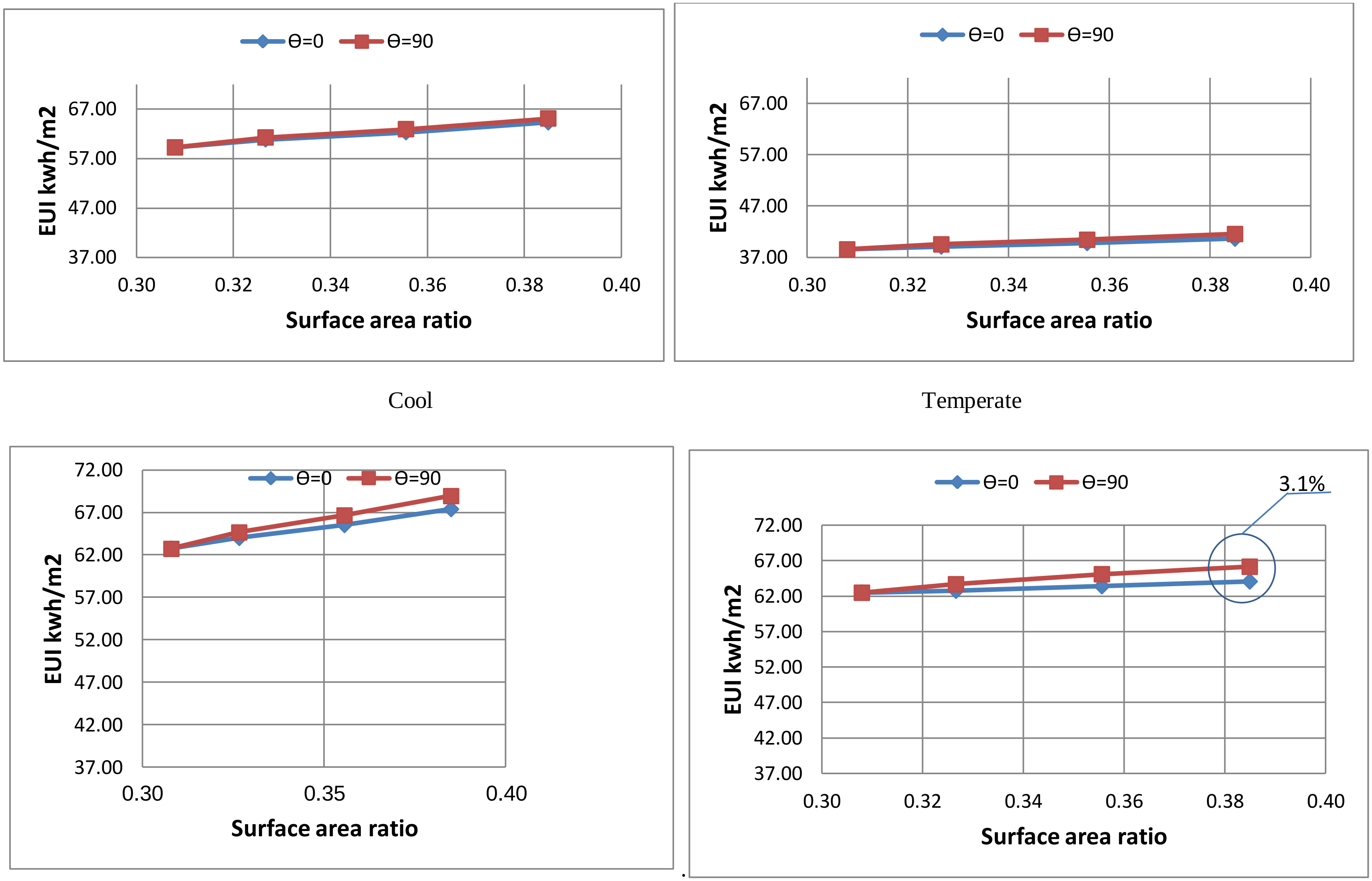
For each building in the climate zones of Cool, Temperate, and Arid, the change in energy demand is slightly significant, where by increasing the surface area (up to 20%), energy demand is increased by 5.1-7.9% (table 2) depending on the climate zone. In the tropical climate, however, the energy demand is insensitive to the variations in SAR, where the average increment percent is 0.4% and the total increase is 0.84%.

Of course, an increase in the surface area (SAR) is likely to lead to an increase in the materials used, may impact construction costs and embodied energy. Furthermore, increases in the surface area may result in an increase in the area exposed to wind pressure, which might lead to the need of a larger size of structural element, which also impact construction costs and embodied energy. The differences in the total energy demand for two building orientations (N-S & E-W) in each climate zone are nearly negligible (see figure 3). The horizontal axis represents the SAR corresponding to the four building's aspect ratios (1:1, 1:2, 1:3, and 1:4), while the vertical axis represent EUI.

Table 2. Energy demand verses SAR (N-S orientation)

Type / Climate	Width to length ratio - increase in SAR											
	1:1			1:2			1:3			1:4		
	H	C	EUI	H	C	EUI	H	C	EUI	H	C	EUI
	kwh/m^2			kwh/m^2			kwh/m2			kwh/m2		
Cool	49.8	9.4	59.2	51.9	9	60.9	53.6	8.7	62.3	55.9	8.4	64.3
Temperate	7.9	30.7	38.55	8.4	30.7	39.1	8.9	30.8	39.8	9.7	31	40.6
Arid	5.8	57	62.8	6.1	57.9	64.0	6.5	59	65.5	7	60.4	67.4
Tropical	0.0	62.5	62.5	0.0	62.75	62.75	0.0	63.4	63.4	0.0	64.1	64.1

EUI: Energy Use Intensity, H: heating, C:cooling



Cool Temperate

Arid Tropical

Fig. 3. Sensitivity of EUI to the change in surface area ratio

These small differences in EUI raise questions about the results presented in Figure 4, where the monthly breakdown shows solar heat gains and losses resulting from building oriented E-W are much greater than if the building were oriented N-S. The sources of total energy demand for the month of July are presented in Table 4, and it is clear that the influence of solar loads is small compared to internal, fabric, or ventilation loads. The amount of heat gain from passive sources represents 5-20% of the total heat gain. This is consistent for both orientations, and the effect is trivial compared to the total heat gain.

Table 3. Energy demand ratio (model of 1:4 aspect ratio)

Months	Energy demand ratio (EDR)			
	Cool	**Template**	**Arid**	**Tropical**
Jan	1.01	1.01	1.03	0.96
Feb	1.01	1.02	0.97	0.99
Mar	1.01	0.99	0.99	1.05
Apr	0.99	1.02	1.04	1.07
May	0.97	1.04	1.05	1.06
Jun	0.99	1.04	1.03	1.05
Jul	**1.011**	**1.034**	**1.026**	**1.055**
Aug	1.02	1.02	1.02	1.05
Sep	1.00	0.99	1.01	1.03
Oct	1.01	0.98	0.99	1.01
Nov	1.02	1.00	0.99	0.99
Dec	1.02	1.02	1.03	0.97
yearly	**1.01**	**1.02**	**1.02**	**1.03**

4.2 Demand sensitivity with non-code-compliant glazing on walls (model of 1:4 aspect ratio)

The second stage of thermal analysis is an investigation of the sensitivity of built-to-code glazing systems on passive solar heat gain, compared to single-pane glazing, which has poorer thermal properties.The outcome demonstrates that code requirements for glazing systems results in reductions in direct heat gain to become represent 5% rather than 24% of total heat gain(N-S),while become represent 8% rather than 34% of total heat gain(E-W), (Table 4 & Table 5 for arid climate). Code-built glazing also reduces total energy demand by 12%, which also explains why there is such a small effect from varying building orientation on monthly and yearly energy demand.

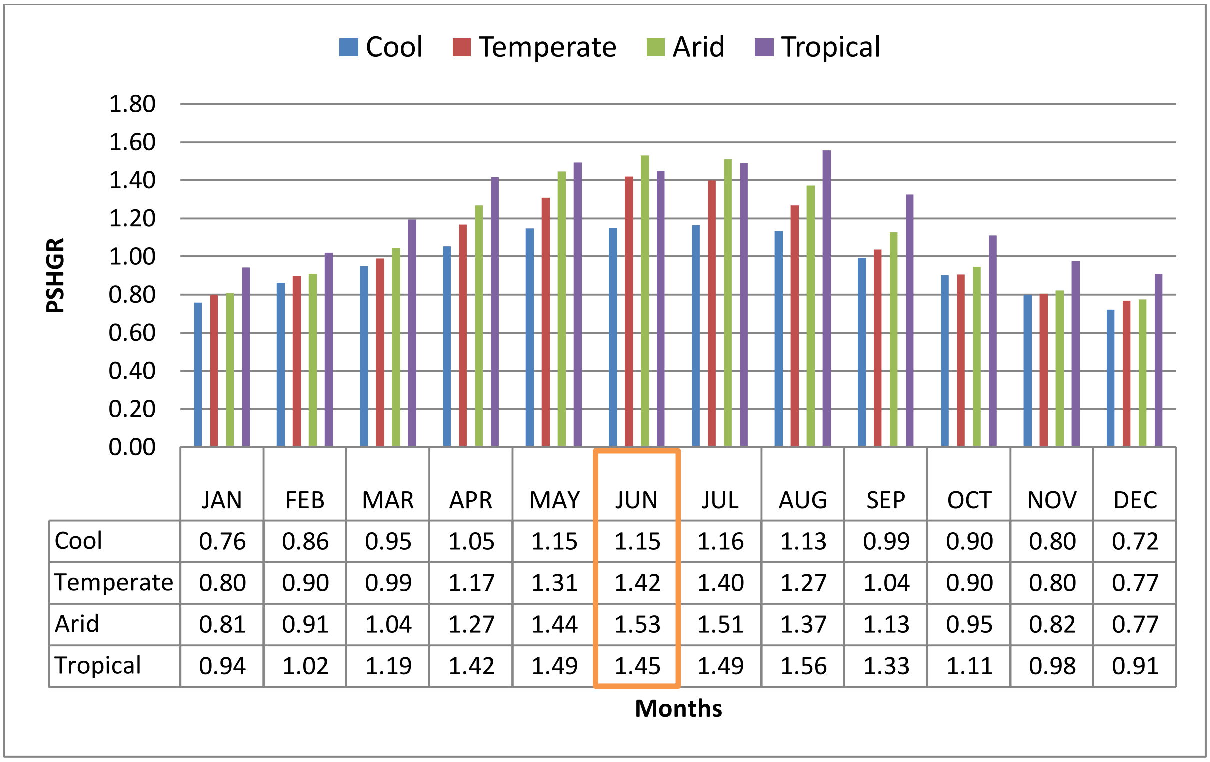


Fig. 4. monthly heat gain ratio (model of 1:4 aspect ratio)

Table 4. Sources of heat gain (Wh) in July- built to code envelope (model of 1:4 aspect ratio)

Climate	**Cool**					**Temperate**				
Orientation	**ϴ=0**		**ϴ=90**		July HGR	**ϴ=0**		**ϴ=90**		July HGR
Direct	1.1E+08	17%	1.3E+08	20%	**1.16**	1.1E+08	8%	1.5E+08	11%	**1.40**
Internal	5.1E+08	78%	5.1E+08	75%	1.00	5.1E+08	40%	5.1E+08	38%	1.00
Fabric	2.1E+07	3%	2.3E+07	3%	1.11	2.8E+08	22%	2.9E+08	22%	1.02
Ventilation	1.3E+07	2%	1.3E+07	2%	1.00	3.8E+08	30%	3.8E+08	29%	1.00
Total	6.573E+08		6.783E08		**1.032**	1.277E+9		1.325E+9		**1.038**
Climate	**Arid**					**Tropical**				
Orientation	**ϴ=0**		**ϴ=90**		July HGR	**ϴ=0**		**ϴ=90**		July HGR
Direct	1.1E+08	5%	1.6E+08	8%	**1.51**	9.9E+07	10%	1.5E+08	14%	**1.49**
Internal	5.1E+08	25%	5.1E+08	24%	1.00	5.1E+08	50%	5.1E+08	47%	1.00
Fabric	6.1E+08	30%	6.2E+08	29%	1.01	2.2E+08	21%	2.3E+08	21%	1.05
Ventilation	8.3E+08	40%	8.3E+08	39%	1.00	2.0E+08	19%	2.0E+08	18%	1.00
Total	2.068E+09		2.129E9		**1.03**	1.029E+9		1.087E+9		**1.057**

Table 5. Breakdown heat gain (Wh) in July in Arid climate – regular glass envelope (model of 1:4 aspect ratio)

	Heat gain (Wh)				**July HGR**
	Ɵ=0		**Ɵ=90**		
Direct	7.4E+08	24%	1.2E+09	34%	1.62
Internal	5.1E+08	16%	5.1E+08	14%	1.00
Fabric	1.0E+09	33%	1.0E+09	29%	1.01
Ventilation	8.3E+08	27%	8.3E+08	23%	1.00
Total	3.099E+09		3.564E+09		1.15

5 CONCLUSION

This paper examines four different building footprint aspect ratios in two different two orientations to investigate the sensitivity of site layout characteristics on the energy consumption of high-rise office buildings in four different climate regions. By simulating each building configuration using Autodesk's Ecotect, we can draw two major conclusions regarding building energy consumption:

For the buildings in Cool, Arid, and Temperate climate zones, the energy demand may be considered marginally sensitive to changes in surface area ratio (SAR). Increasing the envelope surface area by 20% leads to energy demand increases of 5.1-7.9% depending on the climate zone. The energy demand for buildings in the Tropical climate zone is insensitive to variations in SAR.

The energy performance of high-rise office buildings is not sensitive to the passive solar gain as long as the exterior envelopes are built to IECC 2009 requirements for thermal performance. This further emphasizes that site layout planning, specifically orientation, is not as important as other drivers in calculating total energy demand.

These findings suggest that high quality code-built envelope systems offer more flexibility to designers with regard to the building site planning (geometry, layout, and orientation) without creating negative impacts on total energy demand. On the other hand, this limits the possibility of maximizing the advantages of passive heat gain. And, because built to code buildings are not significantly sensitive to direct solar gain, it leaves little room for other passive design strategies for energy conservation such as shading devices, landscaping, and thermal mass.

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