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Energy Modeling of a Supertall Building Using Simulated 600 m Weather File Data

Ali Irani, Luke Leung and Marzia Sedino†

Skidmore, Owings, & Merrill, LLP, 224 South Michigan Ave., Chicago, IL 60604 USA

Abstract

Assessing the energy performance of supertall buildings often does not consider variations in energy consumption due to the change of environmental conditions such as temperature, pressure, and wind speed associated with differing elevations. Some modelers account for these changing conditions by using a conventional temperature lapse rate, but not many studies confirm to the appropriateness of applying it to tall buildings. This paper presents and discusses simulated annual energy consumption results from a 600 m tall skyscraper floor plate located in Dubai, UAE, assessed using ground level weather data, a conventional temperature lapse rate of 6.5°C/km, and more accurate simulated 600 m weather data. A typical office floorplate, with ASHRAE 90.1-2010 standards and systems applied, was evaluated using the EnergyPlus engine through the OpenStudio graphical user interface. The results presented in this paper indicate that by using ground level weather data, energy consumption at the top of the building can be overestimated by upwards of 4%. Furthermore, by only using a lapse rate, heating energy is overestimated by up to 96% due to local weather phenomenon such as temperature inversion, which can only be conveyed using simulated weather data. In addition, sizing and energy consumption of fans, which are dependent both on wind and atmospheric pressure, are not accurately captured using a temperature lapse rate. These results show that that it is important, with the ever increasing construction of supertall buildings, to be able to account for variations in climatic conditions along the height of the building. Adequately modeling these conditions using simulated weather data will help designers and engineers correctly size mechanical systems, potentially decreasing overall building energy consumption, and ensuring that these systems are able to provide the necessary indoor conditions to maintain occupant comfort levels.

Keywords: Energy modeling, Microclimate, Simulated weather, Lapse rate, Supertall buildings

1. Introduction

With the ever increasing pace in the construction of supertall buildings around the world, robust and rigorous methods are required to accurately convey overall energy consumption and building system performance of these buildings. Of particular interest is the variation in energy usage associated with building height. Climatic conditions including temperature, air density, and wind speed vary by elevation and have a direct impact on building cooling and heating load, in addition to fan performance.

While some energy modelers use temperature lapse rates to account for these climactic changes, the applicability of lapse rates is highly climate and season specific and using a linear function such as 6.5°C/km cannot convey local microclimatic conditions such as temperature inversion. The best way to accurately represent climate at different building heights is to measure them, where possible. Short of actual measurements, building a computational climate model can be a better approximation. Duncan Phillips, et al., at Rowan Williams Davis & Irwin Inc. (RWDI) have developed a robust climate model methodology to generate annual climate data at various elevations using a combination of recorded weather data and complex atmospheric modeling [1]. It is expected that simulated weather data will be increasingly used in energy modeling for supertall skyscrapers.

This paper presents a comparison of the conventional lapse rate with the simulated weather data for Dubai, a hot and humid desert climate. The paper will provide an overview of climate profiles, look at existing research on energy modeling for tall buildings, develop a standard model for assessing building energy performance, and present the findings of the investigation.

2. Climate Profile

2.1. Temperature Lapse Rate

The conventional temperature lapse rate of 6.5°C/km is based on the methodology outlined in the ASHRAE Fundamentals Handbook [2]. It is based on an average, standard atmosphere which will likely not occur during many hours in Dubai. Furthermore, this lapse rate cannot account for microclimatic phenomena such as tempera-

†Corresponding author: Marzia Sedino
Tel: +1 (312)360-4072
E-mail: marzia.sedino@som.com

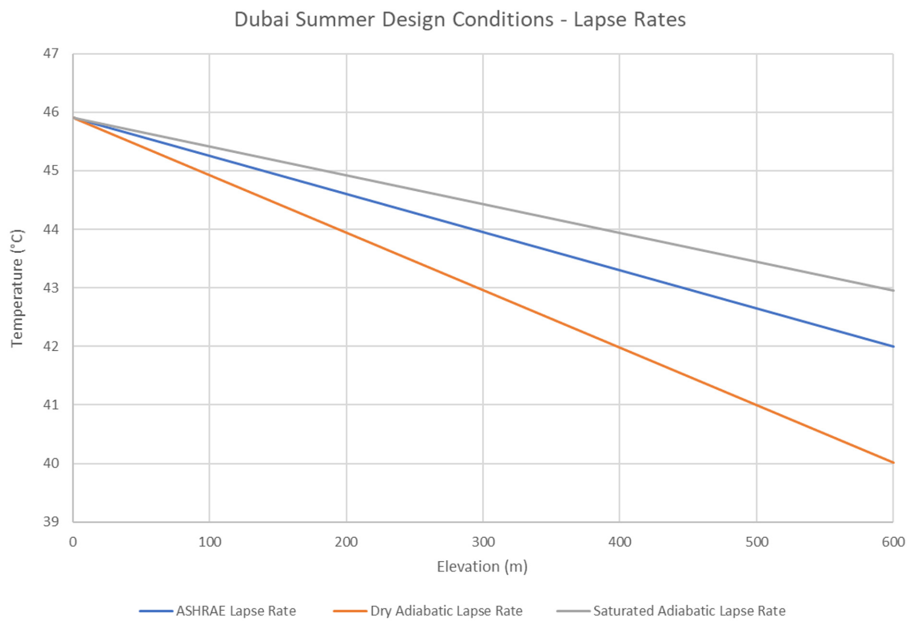

Figure 1. Three different lapse rates for Dubai summer design conditions.

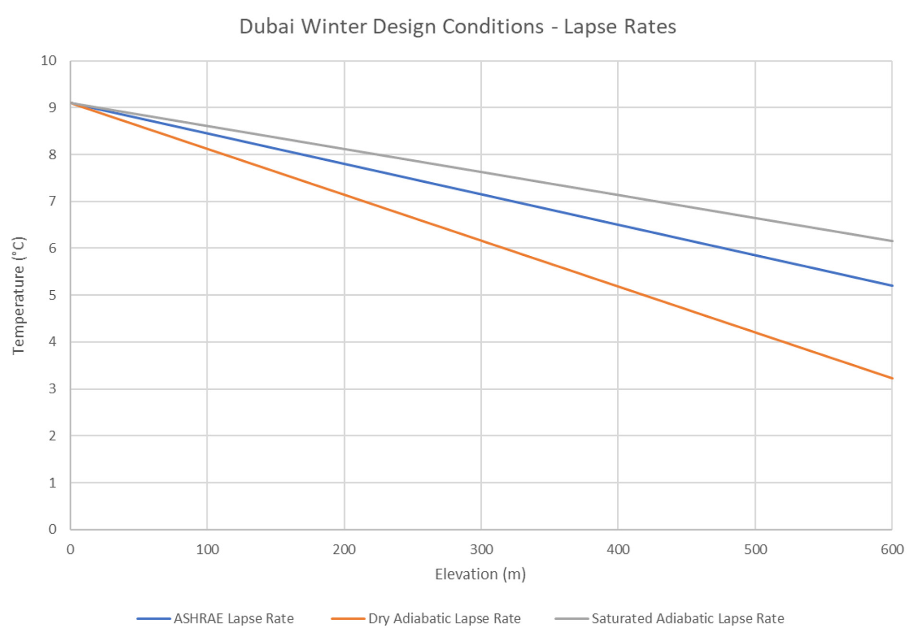

Figure 2. Three different lapse rates for Dubai winter design conditions.

ture inversion, when the temperature is higher at a given elevation than at ground level. Temperature inversion occurs commonly in the winter season in Dubai.

The dry adiabatic temperature lapse rate (DALR) is another method used to account for temperature change due to elevation. When air contains little to no water, there is minimal chance of condensation and a rate of 9.8°C/km can be assumed. Conversely, the saturated adiabatic temperature lapse rate (SALR) considers conditions when the air contains high amounts of water and minimal heat transfer occurs across the air. In this scenario, a rate of 5.5°C/km is used [3].

The summer design temperature for Dubai, at ground level, is 45.9°C and the winter design temperature is 9.1°C. The following graphs summarize the trends associated with each lapse rate for summer and winter design conditions.

In the summer design conditions, the simulated weather file indicates a temperature of 39.1°C at 600m which is relatively close to that predicted by the DALR method, but not close to the conventional lapse rate estimation.

Table 1. Comparison of Lapse Rate Methods and Simulated Weather Data for Dubai Design Conditions

	Ground Level	ASHRAE	DALR	SALR	Simulated Data
Summer Conditions	45.9°C	42.0°C	40.0°C	42.6°C	39.1°C
Winter Conditions	9.1°C	5.3°C	3.2°C	5.8°C	10.1°C

Conversely, none of the lapse rate methods can account for temperature inversion. The simulated weather file, however does consider this local weather phenomenon and indicates a temperature of 10.1°C at 600m. This comparison is summarized in Table 1.

Evidently while the lapse rate may be adequate for certain climates, they certainly do not have universal application especially given extreme climates and localized weather phenomena. The simulated weather data, however can account for climate specific conditions and thus presents a more robust and accurate way of accounting for temperature variation by elevation.

2.2. Air Pressure

Air pressure varies by elevation and the relationship can be captured by the following Eq. (1).

$$p = 101325 \times (1 - 2.25577 \times 10^{-5} h)^{5.2552}$$

where h is elevation in meters.

This function exists in an almost linear regime for elevations close to sea level. Since air pressure is also tied to humidity and temperature, the relationship is often simplified to use a constant temperature or a conventional lapse rate.

2.3. Air Density

Likewise, air density decreases with elevation. It is tied to atmospheric pressure and temperature. Here again, the conventional lapse rate can be used as a first order approximation. The formula is represented in Eq. (2).

$$\rho = \frac{p}{R_{specific} \times T}$$

where p is absolute pressure (Pa), T is absolute temperature (K), and $R_{specific}$ is the specific gas constant for dry air (287.058 J/kgK).

Given a certain elevation, the energy simulation engine, EnergyPlus can account for decreasing air density by performing its own calculation. Air density is a critical factor in the sizing of fans as it determines fan static pressure and will have an impact on the mass flow rate of the system.

2.4. Wind Speed

Wind speed increases with elevation and its magnitude depends on a wide range of factors such as terrain roughness and density. Increased wind speed on the building façade increases the convection coefficient, and ultimately heat transfer from inside the building to outside. Infiltration is also impacted by increasing wind speed [3].

A wind speed profile has been generated for Dubai and indicates the non-linear nature of wind speed increase, see Fig. (3). Given baseline weather data and elevation, EnergyPlus is able to approximate wind speeds at a given height.

3. Review of Existing Research

Multiple researchers have developed methodologies to

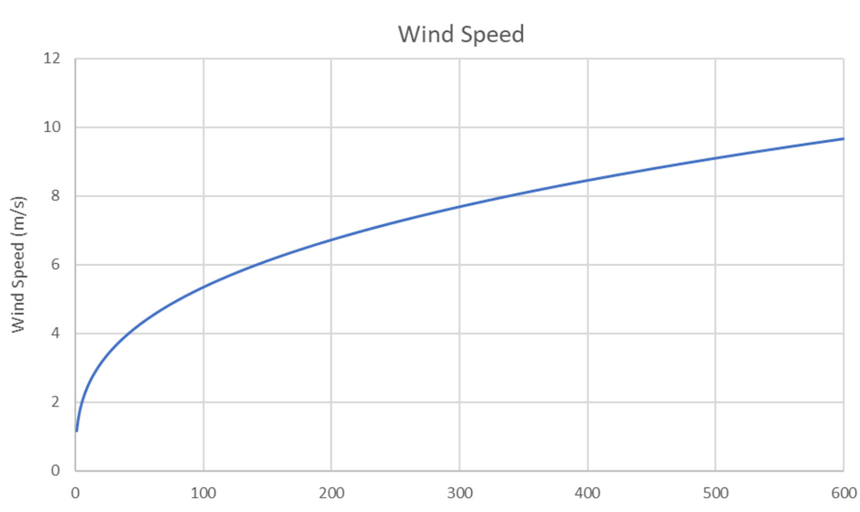

Figure 3. Wind speed variation by elevation.

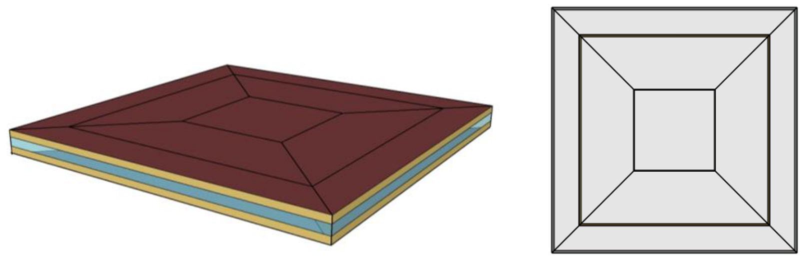

Figure 4. Typical floor axonometric view and plan indicating zonal distribution and window to wall ratio.

assess the energy consumption of supertall buildings. Ellis and Torcellini have analyzed the variation of energy consumption along a building's height, focusing on the 541m Freedom Tower (1 WTC) in New York [4]. The results indicate a decrease in energy consumption (2.4% decrease in cooling energy) at higher levels due to a greater wind speed and cooler outside air temperatures. The building is essentially cooling dominated given the high internal heat gains associated with an office program. Of course, given the dense urban context of the building, the effect of shade from surrounding buildings, which vary by orientation and height, cannot be discounted. The study used a conventional temperature lapse rate of 6.5°C/km to account for temperatures at the top of the tower.

Saroglu et al. similarly looked at the energy consumption of skyscrapers of various heights in Tel Aviv [5]. Given the Mediterranean climate of the city, the simulated buildings are all cooling dominated. A noticeable decrease in cooling energy (6% reduction) was observed, as was an increase in heating energy for a 100m building. The reduction in cooling energy use is further evident when considering a building height of 400m (26% reduction in cooling energy). A conventional temperature lapse rate of 6.5°C/km was again used. The authors also attributed significant energy reductions due to the increased wind speeds, and the corresponding increased heat transfer through the building envelope.

Finally, Lotfabadi simulated the energy consumption of the 164m tall Tehran International Tower in Tehran [5]. Given the residential program and the colder winter temperatures in Tehran, the simulated model showed both cooling and heating loads. The results of the model indicate a 2.4% total reduction in energy consumption due to decreased temperatures only – estimated using a 8.0°C/km temperature lapse rate. The paper also looked at the independent effects of increased wind speed and increased solar insolation and a found a combined 32% energy consumption reduction.

Evidently while current research has begun to look at the effect of elevation on energy consumption and have noted a defined decrease in cooling energy and increase in heating energy, the modeling efforts only consider linear temperature lapse rates and thereby do not consider local microclimatic conditions.

4. Methodology

In order to assess the relative impact of conventional temperature lapse rates versus a simulated weather file on the energy consumption of a building, an energy model for a typical office floor in Dubai was developed and evaluated.

4.1. Simulation Overview

A typical office floor was assessed using the EnergyPlus energy simulation engine (Version 8.8.0). The OpenStudio graphical user interface was used to define system properties while the geometric definitions were input using the 3D modeling software SketchUp.

4.2. Geometric Inputs

A typical office floor geometry was generated in SketchUp. The square floorplan building is 45 m × 45 m with a square core of 15 m × 15 m (see Fig. 4). The floor to ceiling height was 3m and no return air plenums were modeled. A 40% window to wall ratio was considered for all facades, in compliance with ASHRAE 90.1-2010 standards. The model is divided into 4 exterior zones, with a depth of 5m. There are 4 interior zones, and one core zone. The program for the core is defined as storage space while the remaining 8 zones are treated as open office program. The model is aligned so that the facades all align with their respective cardinal direction.

Standard ASHRAE 90.1 – 2010 values for Climate Zone 1A were used to define the building envelope including glazing SHGC and U-Value. The roof and floor of the building were considered to be adiabatic surfaces to neglect the effect of direct radiative solar gains and heat transfer through conduction. This is a fair assumption – only the top and bottom floors of a tower would have horizontally exposed surfaces, while the other floors would only have an exposed façade. While the model includes physical interior partitions between zones, the defined material has a very high thermal conductivity, ensuring adequately representative conductive heat transfer between thermal zones.

4.3. System Inputs

Internal loads and HVAC system definitions were ass-

Table 2. Internal Gains and Occupancy Density

	Open Office Zone Program	Core Zone Program
People (person/m^2)	5	1
Lights (W/m^2)	11	7
Equipment (W/m^2)	15	5

igned for the model using the OpenStudio graphical user interface. The building internal heat gains are based on ASHRAE baselines and best practice values for office spaces, see Table 2.

The typical office floor model is served by a VAV system with hot water reheat coils (System 7 in the ASHRAE 90.1-2010 Appendix G standard). The single duct VAV system has reheat coils in terminal boxes. One central AHU provides cold supply air (12.8 °C to each thermal zone). Return air is delivered to the same AHU. One supply fan (1000 Pa pressure rise with 60% fan efficiency) and one return fan (500 Pa pressure rise with 60% fan efficiency) are included in the model. The model does not include an outside air economizer. Outside air ventilation requirements are set based on ASHRAE 62.1-2010 standards. A central natural gas hot water boiler provides hot water to the main heating coil in the AHU and the reheat coils in each VAV terminal box. An electric, centrifugal chiller provides chilled water to the main cooling coil in the AHU. A dedicated condenser water loop connects the chiller to a two-speed cooling tower. Each hydronic water loop has its own pump with a pump head corresponding to a typical high-rise construction.

The cooling setpoint for the office zones is 24°C while the heating setpoint is 21°C. 3°C setback temperatures are considered. Occupancy and equipment usage schedules are roughly based on a conventional office schedule. The air conditioning system is active from 6:00 AM to 10:00 PM on weekdays.

4.4. Climate Inputs

Three different weather files (all .epw file formats) are used to simulate full length year annual energy consumption. The weather files include data for 8,760 hours.

Case 1

- A ground level weather file taken from Dubai International Airport. This a standard Typical Meteorological Year (TMY) weather file.

Case 2

- Modified ground level weather file with decreased air pressure (94400 Pa constant for all hours of the year – corresponding to an elevation of 600 m) and a conventional temperature lapse of 6.5°C/km. In this case, the model elevation was set to 600m using EnergyPlus, in order to account for changes in wind speed and air density as outlined in Section 2.

Case 3

- Simulated weather file at 600 m for Dubai developed by RWDI [1]. A brief overview of the development of this weather file is given in Section 1.

5. Results and Discussion

The results of the annual energy model analysis for the typical office floor considering all three cases are summarized in Table 3.

The results indicate that there is a defined reduction in overall energy consumption associated with an increase in elevation.

Even though the conventional lapse does not account for temperature inversion, since the building is cooling dominated (because of climate and program), the lapse rate does indeed provide an adequate estimate for the decrease in cooling energy. The simulated weather file scenario shows a cooling energy decrease of 16% while case 2, which uses only the lapse rate, indicates a decrease of almost 19%. However, only in case 3, with a simulated weather file, are we able to see the decrease in heating energy we would expect due to temperature inversion. In case 2, the heating energy is overestimated close to 100%. These trends match closely with the analysis of the design temperatures seen in Section 2.

The reduced cooling load in case 2 also accounts for a decrease in pumping energy of 1.3%. A similar trend can be seen for the pumping energy in case 3, albeit the savings are smaller at 0.9% due to a smaller reduction in

Table 3. Energy End Use Distribution and Totals by Climate Inputs

End Use	Case 1	Case 2	Percent Change	Case 3	Percent Change
Heating (kWh)	414	764	84.6%	367	–11.4%
Cooling (kWh)	98,950	80,366	–18.8%	82,741	–16.4%
Lighting (kWh)	88,230	88,230	0.0%	88,230	0.0%
Equipment (kWh)	148,824	148,824	0.0%	148,824	0.0%
Fan (kWh)	28,731	28,600	–0.5%	29,664	3.2%
Pump (kWh)	27,283	26,939	–1.3%	27,025	–0.9%
Heat Rejection (kWh)	18,516	18,250	–1.4%	18,519	0.0%
Area (m^2)	2,025	2,025		2,025	
Total (kWh)	410,948	391,973		395,370	
EUI (kWh/m^2)	202.9	193.5	–4.6%	195.2	–3.8%

overall cooling energy.

Air density directly affects fan energy consumption. To achieve the same mass flow rate, the fans will expend more energy to move a greater volume of the less dense air at 600m. This can clearly be seen in case 3, which shows a 3.2% increase in fan energy. However, in case 2, the greater reduction in cooling energy balances out this increased fan energy, and we see an overall decrease of 0.5%. The simulated weather file also better accounts for the reduced atmospheric pressure and air density, as compared to the constant value used for case 2.

Finally, the energy models used for both case 2 and case 3, assume that the cooling tower is located at 600 m. Like the AHU supply and return fans, the fan located in the cooling tower will have to work harder to achieve the same mass flow rate, given the less dense air at 600 m. However, we would also expect the energy consumption of the heat rejection equipment to decrease, given the reduced cooling energy. Hence, for case 2, we see a reduction of 1.4%. There is no reduction for case 3, since the reduced cooling energy and increased cooling tower fan energy balance out.

6. Conclusion

The results of this investigation indicates that while conventional temperature lapse rates are adequate for certain seasons and potentially different climates, simulated weather files provide the most accurate way of representing actual atmospheric conditions in an energy model. Changes in elevation will most often lead to a decreased energy consumption due to cooler temperatures at higher elevations – the precise decrease will ultimately depend on the analytical or computational model used to generate those temperatures. The results also indicate that local weather phenomenon such as temperature inversion can lead to a decrease in heating energy – this behavior can only be captured through the use of simulated weather data. Other end uses such as fan energy are directly affected by elevation as well.

Using simulated weather data, in lieu of conventional temperature lapse rates, is an effective way to account for microclimatic conditions that will affect the energy consumption of supertall buildings. It is incredibly important to consider elevation when designing, sizing, and selecting components of buildings to ensure central plant equipment such as chillers and boilers are not oversized and that equipment such as fans are able to maintain the airflow requirements necessary to ensure setpoints and occupant comfort.

References

[1] Phillips, D. (2012 June). *Meteorological Data in a Humid Climate at Grade and 1970ft /600m*, ASHRAE Annual Conference, Houston, TX.

[2] ASHRAE. (2005). Fundamentals Handbook 2005. ASHRAE, USA.

[3] Leung, L., & Weismantle, P. (2008). How Supertall Buildings Can Benefit From Height. *CTBUH 2008 8th World Congress*, Dubai, CTBUH.

[4] Ellis, P.G. & Torcellini, P.A. (2005). Simulating Tall Buildings Using Energy Plus, *Ninth International Building Performance Simulation Association Conference and Exhibition,* Montreal, IBPSA.

[5] Saroglou, T., Meir, I.A., & Theodosiou, T. (2017). Quantifying Energy Consumption in Skyscrapers of Various Heights. *Procedia Environmental Sciences*, *38*, pp. 314-321.

[6] Lotfabadi, P. (2013). High-rise buildings and environmental factors. *Renewable and Sustainable Energy Reviews*, *38*, pp. 285-295.