

Simulating Tall Buildings Using EnergyPlus

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SIMULATING TALL BUILDINGS USING ENERGYPLUS

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ABSTRACT

Tall buildings pose unique challenges for simulation software and modelers. Environmental factors such as air temperature and wind speed change with altitude. The urban environment imposes additional environmental factors because of shading and reflections from surrounding buildings. The large scale of tall buildings can result in excessive input data and prohibitive run times.

EnergyPlus was used to compare the energy impacts of several environmental factors that vary with altitude. Results showed that environmental factors have a significant effect on the annual total building cooling and heating energy. The accuracy of using multipliers to reduce input data was also studied. Even simulating a single floor with a multiplier can give accurate results for an entire building, as long as the floor is near midheight.

INTRODUCTION

The energy analysis of most buildings is easily handled by many simulation programs. Tall buildings, however, pose unique challenges for software and modelers. The ASHRAE Technical Committee for Tall Buildings defines *tall buildings* as those higher than 91 m (Ross 2004). Because the atmosphere changes with altitude, tall buildings can experience significant differences in environmental factors between the ground floor and the top floor. These include differences in air temperature, barometric pressure, and wind speed. The urban environment imposes additional environmental factors because of shading and reflections from surrounding buildings. These environmental factors create a microclimate that can vary from floor to floor of a tall building.

Besides environmental factors, the large scale of a tall building is a challenge because it can result in excessive input data and prohibitive run times. In addition, tall buildings have specialized heating, ventilation, and air-conditioning (HVAC) systems that are difficult to model with existing programs.

Recently, the authors used EnergyPlus to model the proposed design of the Freedom Tower, a 70-floor office building to be constructed in Lower Manhattan as part of the World Trade Center reconstruction project. At 284 m at the top of the highest occupied floor, the proposed Freedom Tower is more than three times taller than the ASHRAE definition of a *tall building*. Densely packed with skyscrapers, Lower Manhattan is the archetype of all urban environments. As a *very* tall building in a *very* urban environment, the Freedom Tower provides an ideal case study for exploring the simulation challenges of tall buildings.

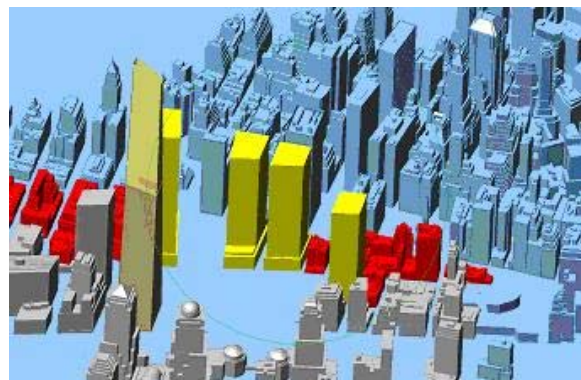


Figure 1 AutoCAD model of the Freedom Tower site and Lower Manhattan

EnergyPlus is a whole-building energy simulation program capable of handling some of the unique challenges of tall buildings (Crawley et al. 2004). For this study, a custom research version of EnergyPlus was developed based on version 1.2.2.

CHALLENGES OF TALL BUILDINGS

Atmosphere

All buildings are located in the troposphere, the lowest layer of the atmosphere. The troposphere extends from sea level to an altitude of 11 km. Throughout the troposphere, air temperature decreases almost linearly with altitude at a rate of approximately 1°C per 150 m. Barometric pressure decreases more slowly. Wind speed, on the other hand, increases with altitude.

Table 1 illustrates the atmospheric differences between the ground floor and the top floor of the Freedom Tower, at an altitude of 284 m. The values for air temperature and barometric pressure are taken from the *U.S. Standard Atmosphere* (1976). They are reference values for a given altitude and are independent of climate and seasonal differences.

Wind speeds in Table 1 are extrapolated from the annual average wind speed of 5.19 m/s for the TMY2 weather file for Central Park in New York City. The relationship between wind speed and altitude is described in Chapter 16 of the *Handbook of Fundamentals* (ASHRAE 2001). The wind speed measured at a meteorological station is extrapolated to other altitudes with the equation:

$$V_z = V_{met} \left(\frac{\delta_{met}}{z_{met}} \right)^{a_{met}} \left(\frac{z}{\delta} \right)^a \quad (1)$$

where V_z is the wind speed at altitude z . The variables a and δ are coefficients that depend on terrain roughness. The variables V_{met} , z_{met} , a_{met} , and δ_{met} correspond to conditions at the meteorological station. For the TMY2 weather file, the wind speeds are assumed to be measured at a meteorological station in an open field at a standard altitude of 10 m above the ground.

Buildings interact with the atmosphere through convective heat transfer between the outside air and the exterior surfaces of the building envelope, and through the exchange of air between the outside and inside of the building via infiltration.

EnergyPlus calculates heat transfer caused by exterior convection with the fundamental equation:

$$Q_c = h_{c,ext} A (T_{surf} - T_{air}) \quad (2)$$

where Q_c is the convective heat transfer rate, $h_{c,ext}$ is the exterior convection coefficient, A is the surface area, T_{surf} is the exterior surface temperature, and T_{air} is the outside air temperature. Because EnergyPlus version 1.2.2 does not account for temperature change with altitude, T_{air} is simply the air temperature from the weather file.

EnergyPlus offers several algorithms for calculating the exterior convection coefficient, $h_{c,ext}$. All depend on the local wind speed at the building surface. The default algorithm in EnergyPlus, labeled "ASHRAE Detailed", splits the coefficient into forced convection and natural convection components.

$$h_c = h_f + h_n \quad (3)$$

The forced convection component is based on a correlation by Sparrow (1979):

$$h_f = 2.537 W_f R_f \left(\frac{P V_z}{A} \right)^{1/2} \quad (4)$$

W_f is a wind direction modifier equal to 1.0 for windward surfaces and 0.5 for leeward surfaces. Leeward is defined as greater than 100° from normal incidence of the wind. R_f is a surface roughness multiplier. P is the surface perimeter length. A is the surface area. V_z is the local wind speed at the surface. EnergyPlus uses Equation 1 to calculate V_z at the altitude of the surface centroid.

The natural convection component is based on correlations found in Walton (1983). For upward heat flow,

$$h_n = 9.482 \frac{(|T_{surf} - T_{air}|)^{1/3}}{7.238 - |\cos \phi|} \quad (5)$$

or for downward heat flow,

$$h_n = 1.810 \frac{(|T_{surf} - T_{air}|)^{1/3}}{1.382 + |\cos \phi|} \quad (6)$$

where T_{surf} is the exterior surface temperature, T_{air} is the outside air temperature, and ϕ is the surface tilt. The two equations are equivalent for vertical surfaces.

In EnergyPlus, the heat transfer caused by infiltration air is calculated by the equation:

$$Q_{inf} = \dot{m} C_p (T_{zone} - T_{air}) \quad (7)$$

where \dot{m} is the mass flow rate of infiltration air, C_p is the specific heat of air, T_{zone} is the zone air temperature, and T_{air} is the outside air temperature from the weather file. The user schedules the mass flow rate in the input file.

Because the outside air temperature, T_{air} , appears twice in the calculation of exterior convective heat transfer (Equation 2 and Equation 5 or 6), and in the infiltration calculation (Equation 7), the *U.S. Standard Atmosphere* model for air temperature was added to the custom research version of EnergyPlus. According to the *U.S. Standard Atmosphere*, the relationship between air

temperature and altitude in a given layer of the atmosphere is:

$$T_z = T_b + L(H_z - H_b) \quad (8)$$

where T_z is the air temperature at altitude z . T_b is the air temperature at ground level. The variable L is the temperature gradient, equal to -6.5 K/km in the troposphere. The geopotential altitude, H_z , is:

$$H_z = \frac{Ez}{(E + z)} \quad (9)$$

where E is 6,356 km, the radius of the Earth. H_b is an offset equal to zero for the troposphere.

No special changes were made in the research version of EnergyPlus to account for variation in barometric pressure with altitude. By default, EnergyPlus does not calculate pressure-based air flow or pressure-based HVAC system performance. However, pressure-based air flow, such as natural ventilation, can be simulated via the pressure-based solver module, COMIS. With additional inputs for COMIS, EnergyPlus will calculate pressure differences caused by altitude and simulate the resulting air flow. Unfortunately, COMIS cannot yet be combined in conjunction with a forced-air HVAC system, so its utility for simulating tall buildings is somewhat limited.

Urban Environment

The center of the modern metropolis imposes special environmental factors on all buildings there. From one direction, the surrounding tall buildings cast many shadows; some completely eclipse other buildings. From the other direction, the mirror-like surfaces of highly-glazed buildings can flash brilliant reflections. Streets lined with tall buildings form urban canyons that can block or channel the wind, creating artificial wind patterns. Massive amounts of concrete and pavement contribute to the heat island effect and increase the local air temperature.

Like atmosphere, urban environmental factors vary with altitude. The lower floors of a building, for instance, often receive more shading than the upper floors. The upper floors may, in fact, never receive shading.

EnergyPlus uses three-dimensional coordinates to define all building and shading surfaces. The effects of shading from surrounding buildings are accurately computed using detailed surface geometry. Shading surfaces block both direct solar

radiation and diffuse sky radiation. They can also cast shadows on the ground, which reduce the ground-reflected radiation. Reductions in incident radiation caused by shading affect both solar heat gain and daylighting.

To model reflections, shading surfaces are assigned reflective properties. Glazed and unglazed portions of the surface are given different reflectances. The glazed portion creates specular reflections; the unglazed portion creates diffuse reflections. EnergyPlus uses a simple ray-tracing method to account for reflections in both the solar heat gain calculation and the daylighting model (UIUC, LBNL 2005).

EnergyPlus does not simulate the effects of the urban environment on local wind patterns and air temperatures. Wind speed, wind direction, and air temperature are read from the weather file. Using TMY2 weather files, however, can be problematic because the data typically come from meteorological stations at airports and military bases, sites far from the effects of the urban environment. In the best case, measured weather data from a location in the urban center at or near the actual site could be used.

Large Scale

The large scale of tall buildings means that many thermal zones may be required to fully simulate the building. If each floor is modeled with four perimeter zones, a core zone, and a plenum zone, a 70-floor building would require 420 zones. The disadvantages of so many zones are very large input files and long simulation run times.

Common practice, of course, is to select and simulate only a few floors. The results are multiplied by a factor to arrive at an estimate for the entire building. Like other simulation programs, EnergyPlus has a built-in multiplier for this purpose.

One problem with multipliers is that they may reduce the accuracy of the overall results. Because multipliers do not capture the variations of environmental factors from floor to floor, the floors that are to be explicitly modeled must be chosen carefully to ensure that they are representative.

HVAC Systems

Tall buildings have specialized HVAC systems. Often central air handling units temper outside air to serve separate air-conditioning systems on each floor. HVAC systems must also compensate for

pressurization problems caused by the stack effect and provide additional energy to push air and water up to higher floors.

EnergyPlus has a very flexible input format for describing HVAC systems. Each system component—fan, pump, cooling coil—is defined as an individual object. Objects are connected in loops in much the same way that the actual components are connected by networks of ductwork and piping.

Despite the flexibility of EnergyPlus, it is not currently possible to describe a central system that serves a number of subloops, such as a central outside air handling unit that serves separate floors. The alternative, which is also often adopted by DOE-2 users, is to simulate each floor as a separate air loop, each with its own outside air handling unit. The fan performance curves for each loop are modified to include the additional fan energy of the central station fans. A similar approach can be taken with other components, such as preheat coils, in the outside air stream.

EnergyPlus does not automatically take into account the stack effect and additional energy of moving air and water to higher altitudes, because it does not perform a pressure-based HVAC simulation. These effects can perhaps be approximated by using different performance curves for fans and pumps on different floors.

SIMULATION

To investigate some of the challenges of tall buildings, simulation was used to explicitly model every floor of the proposed Freedom Tower design. Annual energy intensity was compared on each floor to determine the energy impacts of several important environmental factors that vary with altitude:

- Air temperature
- Wind speed
- Shading
- Reflection

A series of simulations was performed to characterize the impact of each environmental factor in isolation and in full combination.

Floor-by-floor results were also analyzed to assess the accuracy of using multipliers to reduce model input and simulation run times. Multiplied results for various combinations of multipliers and

explicitly modeled floors were compared to the fully simulated building results.

For the simulations, the custom research version of EnergyPlus allowed each environmental factor to be isolated. As described above, the research version added variation of air temperature with altitude for exterior convection and infiltration calculations. Since variation of wind speed with altitude is the default assumption in EnergyPlus, the research version allowed this feature to be disabled to test the other environmental factors. Shading and reflection were controlled with standard input options. Although shading and reflection both use the same shading surfaces, the reflective properties can be easily turned off to test shading alone. Conversely, shading can be turned off by setting the surface transmittance to 1.0. This makes the surface transparent, yet keeps the reflective properties intact to test reflection alone.

The EnergyPlus model of the Freedom Tower design is described in detail here.

Freedom Tower

The crown jewel of the World Trade Center reconstruction is the Freedom Tower. This proposed building rises to a height of 541 m with 70 occupied floors and more than 240,000 m² of commercial space. The project involves several organizations, including architects (Skidmore, Owings & Merrill), mechanical engineers (Jaros, Baum & Bolles), and researchers (NREL, LBNL). A unique feature of the project is that all have agreed to use EnergyPlus as the energy simulation tool.

The authors' role in the project was to develop the simulation input for the EnergyPlus model. This involved envelope geometry and constructions, internal gains, schedules, shading surfaces, and the HVAC system. Two EnergyPlus models were developed. One represented the baseline model as prescribed by the ASHRAE Standard 90.1-2001 energy cost budget method. The other represented the proposed model that was designed to reduce energy use and costs.

To help create an accurate shading model, Skidmore, Owings & Merrill provided a detailed AutoCAD model of Lower Manhattan, shown in Figure 1. Because the AutoCAD model contained an immense number of surfaces, it was analyzed to determine which neighboring building surfaces were important for the shading model. A method was then developed to extract measurements from

the AutoCAD model. These were in turn used to create EnergyPlus shading surfaces.

For the simulations at hand, a modified version of the ASHRAE 90.1 baseline model was selected for all runs. The ASHRAE standard prescribed all the building envelope properties. Temperature setpoints, infiltration levels, and schedules for lights, equipment, and occupants were preserved from the original baseline model. For faster run times, the HVAC system input was replaced with the simple "purchased air" option that calculates cooling and heating load energy without taking into account equipment efficiency or performance. Reflective properties, which assumed a 50% glazing fraction for the surrounding buildings, were added to the shading surfaces. The weather file was the TMY2 for Central Park in New York City.

The original input file modeled only the commercial office space on the middle floors 8 through 65. To fully explore the effects of altitude starting at the ground floor, the entire building geometry input was shifted down to start at floor 1. The total number of floors was also rounded to 60 to allow for even multipliers. Despite the change in altitude, the ground and top floors are still modeled as middle floors with no special boundary conditions for the ground or roof.

Equivalent Square Tower

Most tall buildings have rectangular floor plans that are identical across many floors. The Freedom Tower, on the other hand, has an unusual parallelogram-shaped floor plan that is slightly different on every floor. No two floors are alike because the floor area decreases with altitude and two of the walls change orientation.

Because variations in floor plan were expected to skew the annual energy results (even after they were normalized by floor area), an equivalent square model of the Freedom Tower was also developed. The equivalent square tower has the same number of floors and same total building floor area as the Freedom Tower but with a square floor plan. All other inputs for the two towers are identical.

Ultimately, the equivalent square tower is a better representation of typical tall buildings. The square floor plan also makes the model more suitable for the use of multipliers. The original Freedom Tower design was simulated, nonetheless, to show the effect of its unique design on annual energy results and the accuracy of multipliers.

RESULTS

Like most office buildings, analysis showed that lights and equipment (receptacle loads) for the Freedom Tower model constitute more than half of the total annual end-use energy. To more easily discern the impact of the environmental factors on building energy, annual cooling and heating energy, instead of total annual energy, was chosen as the dependent variable for all simulation runs.

Analysis also showed that the Freedom Tower requires year-round cooling and very little heating. The annual cooling and heating energy is therefore primarily cooling energy. An elimination parametric analysis showed that the cooling loads are largely driven by internal heat gains caused by lights, equipment, and occupants.

The results for annual cooling and heating energy intensity for the equivalent square tower and the Freedom Tower are shown in Figures 2 and 3. The impacts of each environmental factor on total building cooling and heating energy are shown in Tables 2 and 3. Analysis of error caused by the use of multipliers is shown in Table 4.

The maximum differences in annual cooling and heating energy between any two floors in the building are 4% and 45% for the equivalent square tower and the Freedom Tower, respectively.

DISCUSSION

For the equivalent square tower model, the results for temperature and wind show the expected decrease in annual cooling energy with altitude. The cooler outside air temperature and greater wind speeds help reduce the required cooling energy. It is noteworthy that the effect of air temperature exceeds the effect of wind at roughly midheight of the tower and then continues to significantly surpass it at higher altitudes.

Shading substantially reduces the cooling load at lower altitudes because even short buildings provide some shade. The effect of shading declines somewhat with higher altitudes as the view is cleared of shorter buildings. The somewhat irregular shape of the shading curve in Figure 2 is indicative of the random distribution of surrounding buildings.

The effect of reflection is perhaps nonintuitive because one might expect reflections to increase the incident radiation on the building and therefore increase the cooling load and cooling energy. The explanation is that the glazed portions of

surrounding buildings only provide a full reflection of the solar beam when the alignment of building geometry and solar angles is nearly perfect, a rare condition. The rest of the time the glazing reflects nothing. The unglazed portion does, however, provide diffuse reflections. The net annual effect of the glazed and unglazed portions is apparently to provide less reflected radiation than the sky and ground radiation that it blocks.

The combined result of all environmental factors is an irregular shape that is surprisingly flat, considering that multiple effects work in different directions.

For the Freedom Tower model, the results are similar to the equivalent square tower, but show a distinct skew. Even in the case with no environmental factors, the annual cooling and heating energy intensity still varies with altitude, despite being normalized by floor area. This result is explained by the changing orientation of two of the walls with altitude.

Both towers show about the same reduction in total building annual cooling and heating energy of approximately 13% when no environmental factors are compared to all factors combined. Shading has the largest individual effect.

For the equivalent square tower, the error in total building cooling and heating energy caused by multipliers is surprising. Despite the various altitude effects, even simulating just one floor with a multiplier of 60 results in less than 1% error when compared to explicitly simulating every floor of the tower. The maximum difference in annual energy intensity between any two floors, however, is as much as 4%. Although a multiplier of 60 accurately estimates the annual *total* building cooling and heating energy, it predicts the annual energy for any single floor less accurately. This result has potential implications for HVAC equipment sizing.

The Freedom Tower also achieves less than 1% error when just one floor is simulated with a multiplier of 60. The maximum difference in annual energy intensity between any two floors is about 7%.

The reason both the equivalent square tower and the Freedom Tower are successfully modeled with a multiplier of 60 is that all the environmental factors, individually and in combination, are roughly linearly related to altitude after about the sixth floor. As long as a floor near midheight is selected, that floor will closely approximate the average of all the effects over the entire building.

CONCLUSION

Simulations of the Freedom Tower model and equivalent square tower model have shown that environmental factors that vary with altitude have a significant effect on the annual total building cooling and heating energy. The equivalent square tower has been especially useful in characterizing the trends caused by individual environmental factors.

An analysis of multipliers has demonstrated that even simulating a single floor with a multiplier can give accurate annual energy results for an entire building, as long as the floor to be simulated is near midheight. Although accurate for the building as a whole, the results may not accurately predict the performance of a specific floor.

As the simulation tool for this study, EnergyPlus has proven capable of simulating some of the unique challenges of tall buildings, including variation in wind speed with altitude and variations in urban environmental factors with altitude. The program has also demonstrated that it is robust enough, if necessary, to simulate as many as 360 zones and 3,180 surfaces in a single input file.

Results have indicated that the energy impact of variation in air temperature with altitude is at least as significant as variation in wind speed. The *U.S. Standard Atmosphere* model for air temperature should clearly be developed into a standard feature of EnergyPlus.

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*Table 1
Atmospheric variables at two different altitudes above ground level*

VARIABLE	1.5 METERS	284 METERS	ABSOLUTE DIFF	PERCENT DIFF
Air Temperature	15°C	13.15°C	1.85°C	12.3%
Barometric Pressure	101,325 Pa	97,960 Pa	3,365 Pa	3.3%
Wind Speed	2.46 m/s	7.75 m/s	5.29 m/s	215%

*Table 2
Impact on annual cooling and heating energy by environmental factor for the equivalent square tower*

ENV. FACTOR	TOTAL ENERGY [GJ]	ABSOLUTE DIFF [GJ]	PERCENT DIFF
None	65,711	-	-
Temperature	63,989	1,722	2.62%
Wind	64,188	1,523	2.32%
Shading	59,776	5,935	9.03%
Reflection	64,331	1,381	2.10%
Combined	57,249	8,462	12.88%

*Table 3
Impact on annual cooling and heating energy by environmental factor for the Freedom Tower*

ENV. FACTOR	TOTAL ENERGY [GJ]	ABSOLUTE DIFF [GJ]	PERCENT DIFF
None	65,753	-	-
Temperature	64,158	1,595	2.43%
Wind	64,272	1,482	2.25%
Shading	59,667	6,087	9.26%
Reflection	64,060	1,694	2.58%
Combined	57,119	8,634	13.13%

*Table 4
Error in annual cooling and heating energy attributed to multipliers*

MULTIPLIER	SQUARE TOWER (% ERROR)	FREEDOM TOWER (% ERROR)
60 Floors x 1	0%	0%
12 Floors x 5	0.004%	0.005%
6 Floors x 10	-0.04%	0.47%
3 Floors x 20	-0.22%	0.17%
2 Floors x 30	-0.15%	0.17%
1 Floor x 60	-0.69%	-0.47%

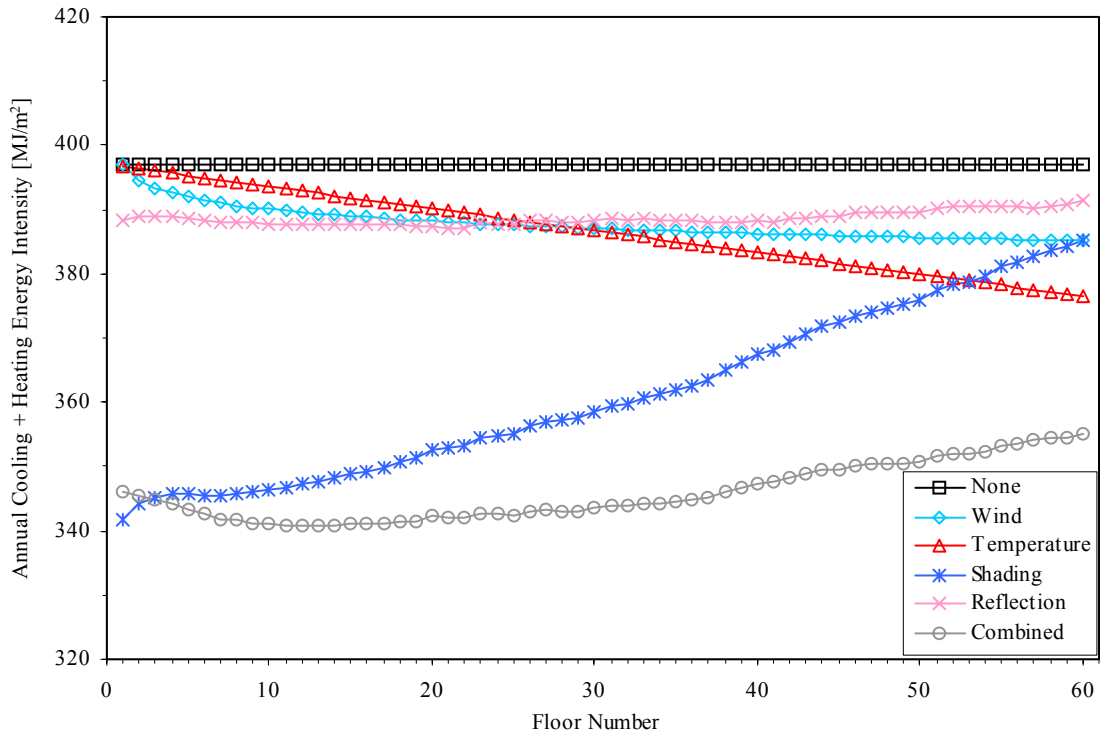


Figure 2 Annual cooling and heating energy intensity variation with altitude for the equivalent square tower

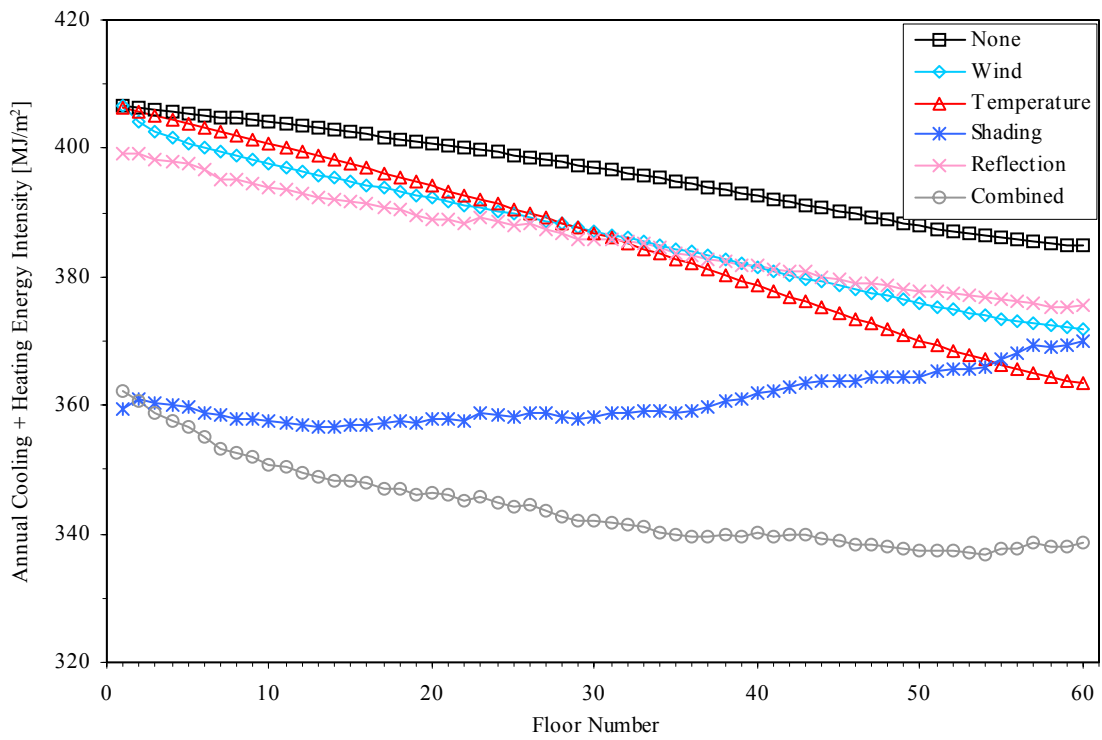


Figure 3 Annual cooling and heating energy intensity variation with altitude for the Freedom Tower

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