

Climate Effects on Tall, Supertall and Megatall Buildings in India

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Abstract

The design of tall buildings has historically relied on ground measurements for climate data. In some cases, the climate information at grade has been extrapolated upwards. However, as buildings have become taller the need for elevation specific meteorological data is becoming more important. The climate conditions at 100m above grade are not the same as 600 m. Over the height of the building, the pressure between the buildings and environment will become huge enough to cause a large impact on the functionality of these buildings, even on the building façade directly. Therefore, architects and engineers should pay sufficient attention to this phenomenon and ensure the function and operation of the building.

Rarely does the design of upper level of the building capitalize on this phenomenon. Furthermore, wind, temperature and pressure conditions at the top of a tall building are considerably different; therefore façade leakage rates and the buildings stack effect must be carefully assessed. If sufficient data is known about this difference, it can be incorporated to optimize the overall building design.

This novel paper explores the nuances of the ambient climate on tall buildings and the effects on the building's performance.

Keywords: Energy efficiency, Stack effect, Building codes, Energy consumption, Facades, Tall buildings, Design processes.

Introduction

This paper presents several years of studies and designs of 600 m plus buildings around the world. *For clarity, this paper will only concentrate on one location, viz. Delhi.* For simplicity, a 600 m building would have three sections: offices, residential and a hotel. It is the intention that the data presented in this paper will be readily available for architects and engineers in the near future.

We know that outside temperature decreases over the height of the building in both summer and winter; also, the wind speed

About the Author

Peter Simmonds has been involved in the design of buildings around the world for more than 35 years and has authored the new ASHRAE Design Guide for Tall, Mega Tall and Super Tall Building Systems. He has authored or co-authored more than 60 technical papers, articles and books. He is a member of several ASHRAE Technical Committees, viz. TC 2.1 Thermal Comfort and Human Physiology, TC 6.5 Radiant Heating and Cooling, TC 6.9 Thermal Storage, TC 9.12 Tall Buildings and Standard 55. He is a Consultant to Standard 62.1, serves on the Standards Committee and is President of the College of Fellows. He teaches Graduate and Post Graduate Architectural students at the University of Southern California, is an ASHRAE Distinguished Lecturer, and has been awarded the ASHRAE Distinguished Service and Exceptional Service awards.

increases and air density decreases. But how do these phenomena affect building designs?

Background

Many papers have been written on climate effects and stack effects on buildings (Philips 2014, Simmonds 2013). Very little information has been made available regarding the vertical climatic effects on a building's heating and cooling loads and infiltration. How will these effects, affect the performance of the building?

- The 2012 IECC includes a number of requirements related to air sealing. The analysis will be based on Section 502.4.1.2.3 – Building Test. This section requires an air leakage test of the completed building having a leakage rate of not more than 2.0 L/s-m² at 75 Pa (0.40 cfm/ft² at 0.3" w.g.).
- A report by PNNL, "Infiltration Modeling Guidelines for Commercial Building Energy Analysis," reported information from the Envelope Subcommittee of ASHRAE SSPC90.1. This committee had also been investigating the possibility of including an air sealing requirement in Standard 90.1. The Envelope Subcommittee recommended a value of 1.8 cfm/ft² at 0.3" w.g. as the baseline leakage rate (the "before" case). PNNL reported that this rate corresponds to the base infiltration rate used in the DOE Benchmark buildings.

Here we have two different recommendations:

- 0.40 cfm/ft² at 0.3" w.g. (2.0 L/s-m² at 75 Pa)
- 1.8 cfm/ft² at 0.3" w.g. (9.0 L/s-m² at 75 Pa)

Traditionally a building's façade would contribute about 50% of the total heating and cooling load. However, in today's world we are striving for net zero designs and energy codes also require base case models to have only 40% glazing in a façade.

This paper identifies base case energy consumption of a 600 m building against a proposed design having 60-80% glazing in a façade.

Design of energy efficient buildings is the quickest way to reduce energy consumption. The skin of the building acts as a barrier between the indoor environment and the outdoor environment. The thermal performance of a building depends upon the façade design to a large extent, ranking second to the local climatic characteristics.

For a given location or latitude, assuming that the climatic factors and the local parameters such as acclimatization levels do not vary, the interaction of the architectural parameters such as orientation of building, type of glazing on the windows, shading devices, etc. and the climatic parameters such as intensity of solar radiation, wind speed, etc. are deduced to the main factors on which the calculations depend.

Hypothetical Building

The building is 800 m (2700 ft) tall and has 197 floors. Each floor is identical with a length of 267 ft and a width of 80 ft; the gross floor area = 21,360 sft and the net floor area = 14,952 sft.

From ASHRAE 90.1, the recommended window-to-wall ratio for the base case model is 40%; if we assume a 14 ft. floor-to-floor height, the glazing would be 5'6" high.

For this study, we are also looking at the impact of a fully glazed building. We are assuming the glazing can be 9' high and therefore the percentage of glazing = 65% of the façade.

ASHRAE 90.1 also recommends the Solar Heat Gain Coefficient (SHGC) for the base case glass = 0.25.

The building will be orientated with the longest sides facing east-west.

Generating Climate Data at Upper Elevations

The design of tall buildings has historically relied on ground measurements for climate data. In some cases, the climate information at grade has been extrapolated upwards. However, as buildings have become taller, the need for elevation-specific meteorological data is becoming more important. This is especially relevant when the balance between sustainability and cost depends on good climate data to size the right HVAC equipment. The climate at 100 m above grade is not the same as 600 m. However, rarely does the design of the upper level of the building capitalize on that difference. Further, wind conditions at the top of a tall building are different. If sufficient data is known about this difference, it can be incorporated into the design.

Climatic Data

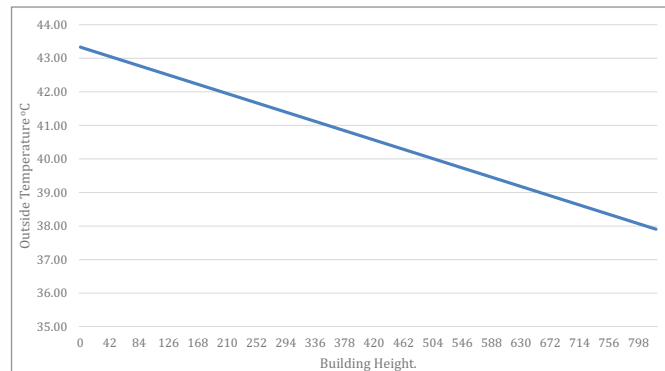


Figure 1: Variation in outside DB temperature as a function of the building height, during the summer, for Delhi

For summer design conditions, the outside dry bulb temperature decreases by about 5K over the height of an 800m tall building. This is shown in Figure 1.

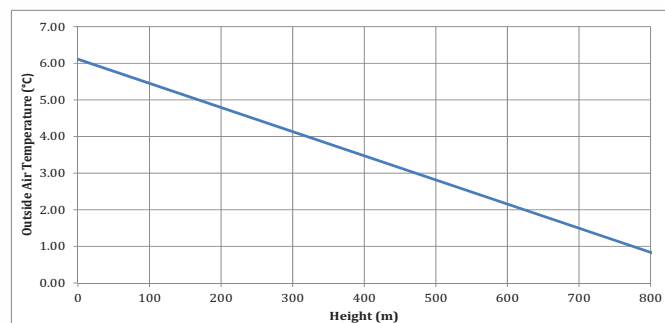


Figure 2: Variation in outside DB temperature as a function of the building height, during the winter, for Delhi

Figure 2 shows the winter scenario where the outside temperature further decreases over the height of the building. Traditional heat loss calculations would assume the winter design outside temperature would exist over the height of the building.

The alarming finding from Figure 2 is that the outside temperature at some 800 m (2700 ft) is very close to the freezing point of water. This information is vital to designers, contractors and operators. Who would have thought freeze protection may be required for a megatall building in Delhi?

For this article we are looking at the following alternatives:

- Base case, ASHRAE 90.1, 40% glass, SHGC=0.25
- Option 1 ASHRAE 90.1, 65% glass, SHGC=0.25
- Option 1 ASHRAE 90.1, 65% glass, SHGC=0.18

The base case is required to, as the term says, be the base case for minimum compliance for ASHRAE 90.1 and to set the precedence.

Table 1: Typical steady state cooling load calculation for the first 100 m of an 800 m hypothetical building

SUMMER		Energy Code				
Height	m ²	U value	Outside temperature	Inside temperature	ΔT	Energy
0-100 m		W/m ² . K	C	C	K	W
North Elevation - wall	1,935	0.504	43	25	18	17,558
South Elevation - wall	1,935	0.504	43	25	18	17,558
East Elevation - wall	1,935	0.504	43	25	18	17,558
West Elevation - wall	1,935	0.504	43	25	18	17,558
North Elevation - glass	1,290	3.25	43	25	18	75,479
South Elevation - glass	1,290	3.25	43	25	18	75,479
East Elevation - glass	1,290	3.25	43	25	18	75,479
West Elevation - glass	1,290	3.25	43	25	18	75,479
						372,147

Height	Area	SHGC	Solar	Energy
0-100 m	m ²		W/m ²	W
North Elevation - glass	1,290	0.25	223	71,931
South Elevation - glass	1,290	0.25	316	101,929
East Elevation - glass	1,290	0.25	564	181,924
West Elevation - glass	1,290	0.25	564	181,924
				554,070

From Figure 1 and 2 we can see the decrease in ambient temperature as the building height increases. Table 1 shows a steady state cooling load for a 100 m section of an 800 m building. The cooling load is calculated per m² of floor area.

Previously, most traditional load calculations would assume that during the summer the outside temperature over the whole height of the building would be a constant 43°C and that the calculated load of 22.55 W/m² would be the same over the height of the building. However, as the outside temperature reduces over the height of the building, the cooling load for each floor is different. Table 2 shows the difference in cooling loads per 100 m sections over the height of the building. For this article we have divided the building height into 8 sections for clarity; our actual calculations would be for each of the 190 floors.

Table 2: Comparison of heat gain calculations for 100m sections of an 800 m megatall building

Building section	90.1 2013	40% glass, SHGC = 0.25	60% glass, SHGC = 0.25
	W/m ² (floor area)	W/m ² (floor area)	W/m ² (floor area)
0 - 100m	22.55	31.44	28.33
100 m – 200 m	21.96	30.66	27.55
200 m – 300 m	21.43	29.94	26.83
300 m – 400 m	20.87	29.19	26.08
400 m – 500 m	20.31	28.43	25.33
500 m – 600 m	19.77	27.72	24.61

A traditional heat gain calculation across the building skin using $Q=U*A*\Delta T$ would amount to a heat gain of 22.5 W/m² building. Table 2 shows, when using a variable outside temperature, the heat gain varies from 22.55 at low level to 19.77 W/m² at the top of the 800 m building.

Table 3: Total cooling per floor area for the base case, option 1 and option 2 for 100 m sections of a hypothetical 800 m building

Base Case:						
	0 – 100 m	100 – 200 m	200 – 300 m	300 – 400 m	400 – 500 m	500 – 600 m
	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²
Envelope	22.55	21.96	21.43	20.87	20.31	19.77
People	7	7	7	7	7	7
Lights	12	12	12	12	12	12
Equipment	20	20	20	20	20	20
Total	61.55	60.96	60.43	59.87	59.31	58.77
Option 1:						
	0 – 100 m	100 – 200 m	200 – 300 m	300 – 400 m	400 – 500 m	500 – 600 m
	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²
Envelope	31.44	30.66	29.94	29.19	28.43	27.72
People	7	7	7	7	7	7
Lights	12	12	12	12	12	12
Equipment	20	20	20	20	20	20
Total	70.44	69.66	68.94	68.19	67.43	66.72
Option 2:						
	0 – 100 m	100 – 200 m	200 – 300 m	300 – 400 m	400 – 500 m	500 – 600 m
	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²
Envelope	28.33	27.55	26.83	26.08	25.33	24.61
People	7	7	7	7	7	7
Lights	12	12	12	12	12	12
Equipment	20	20	20	20	20	20
Total	67.33	66.55	65.83	65.08	64.33	63.61

For a base case scenario, where the varying outside temperature is not taken into consideration, the building's cooling load would be 61.55 W/m² for the whole building. When utilizing the reduction in outside temperature the cooling load will vary from 61.55 W/m² to 58.77 W/m².

For option 1, where the glass area is 65% of the façade, the cooling load will vary from 70.44 W/m² to 66.72 W/m².

For option 2, where the glass area is 65% of the façade and SHGC = 0.18, the cooling load will vary from 67.33 W/m² to 63.61 W/m².

Approaching Net Zero

There is a modern trend in building design and that is using realistic lighting and equipment loads in spaces to reduce the building's overall energy consumption. For a modern-day building design (net zero) we use a lighting power density of 4 W/m² when using LED lighting, compared to traditional lighting at 12 W/m². A net zero equipment (plug loads) has a power density of 6 W/m² compared to a traditional load of 20 W/m².

Table 4: Total cooling per floor area for the base case, option 1 and option 2 for 100 m sections of a hypothetical 800 m net zero building

Base Case Net Zero:					
	0 – 100 m	100 – 200 m	200 – 300 m	300 – 400 m	400 – 500 m
	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²
Envelope	22.55	21.96	21.43	20.87	20.31
People	7	7	7	7	7
Lights	4	4	4	4	4
Equipment	6	6	6	6	6
Total	39.55	38.96	38.43	37.87	37.31
Option 1 Net Zero:					
	0 – 100 m	100 – 200 m	200 – 300 m	300 – 400 m	400 – 500 m
	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²
Envelope	31.44	30.66	29.94	29.19	28.43
People	7	7	7	7	7
Lights	4	4	4	4	4
Equipment	6	6	6	6	6
Total	48.44	47.66	46.94	46.19	45.43
Option 2 Net Zero:					
	0 – 100 m	100 – 200 m	200 – 300 m	300 – 400 m	400 – 500 m
	W/m ²	W/m ²	W/m ²	W/m ²	W/m ²
Envelope	28.33	27.55	26.83	26.08	25.33
People	7	7	7	7	7
Lights	4	4	4	4	4
Equipment	6	6	6	6	6
Total	45.33	44.55	43.83	43.08	42.33

For the net zero base case scenario, where the varying outside temperature is not taken into consideration, the buildings cooling load would be 39.55 W/m² for the whole building. When utilizing the reduction in outside temperature, the cooling load will vary from 39.55 W/m² to 37.31 W/m².

For option 1, where the glass area is 65% of the façade, the cooling load will vary from 48.44 W/m² to 45.43 W/m².

For option 2, where the glass area is 65% of the façade and SHGC = 0.18, the cooling load will vary from 45.33 W/m² to 42.33 W/m².

Table 3 and 4 show the predicted cooling loads per floor of our hypothetical building. By using the outside temperature for the different heights, the cooling load is reduced. When using net zero lighting and equipment loads the predicted cooling loads are reduced even further.

We also express the efficiency of the building and its systems as Energy Use Intensity (EUI), as this really identifies how efficient the building is. The EUI calculated for this article includes all lighting, equipment loads, occupants, HVAC equipment, elevators and escalators, exterior lighting and car park ventilation and lighting.

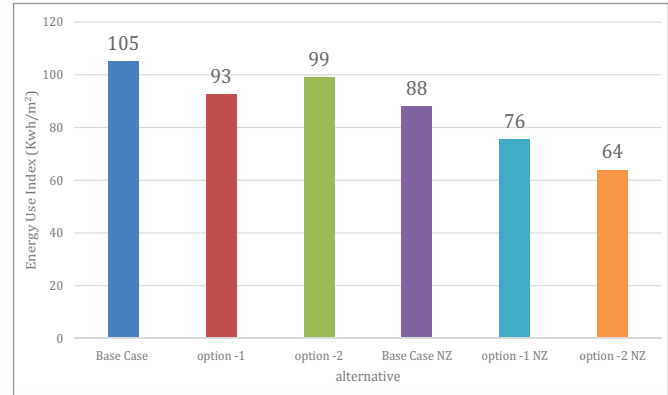


Figure 3: Energy Use Intensity (EUI) of the alternatives studied; the NZ alternatives have net zero lighting and equipment loads

For a modern-day building design (net zero) using a lighting power density of 4 W/m² and a plug load power density of 6 W/m², with 65% glazing in the façade and variable ambient temperature over the height of the building, the total load can be reduced from 26,799 kWh to 19,274 kWh, which is a 28% reduction.

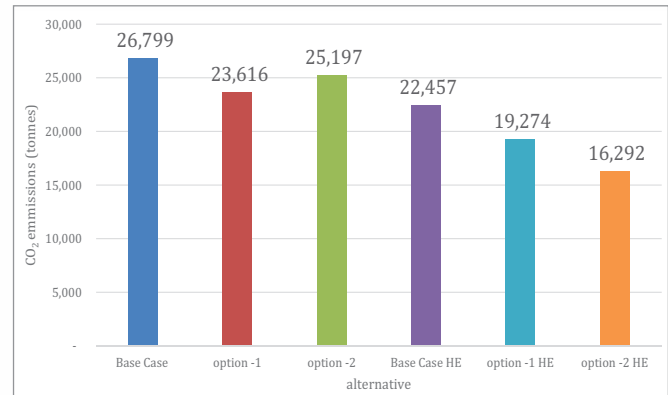


Figure 4: CO₂ emissions of the alternatives studied

The energy consumption glazing alternatives are as follows:

1. Base Case, consumes 26,799 kWh of electrical energy.
2. Option 1 alternative consumes 23,616 kWh, which is 3,183 kWh than the Base Case.
3. Option 2 alternative consumes 25,197 kWh, which is 1,602 kWh less than the Base Case.
4. Base Case Net Zero alternative consumes 22,457 kWh, which is 4,342 kWh less than the Base Case.
5. Option 1 Net Zero alternative consumes 19,274 kWh, which is 7,525 kWh less than the Base Case.
6. Option 2 Net Zero alternative consumes 16,292 kWh, which is 10,507 kWh less than the Base Case.

The overall potential saving from the Option 2 Net Zero alternative is 39%.

The Effect of a Net Zero Design on the Envelope Load

Base Case

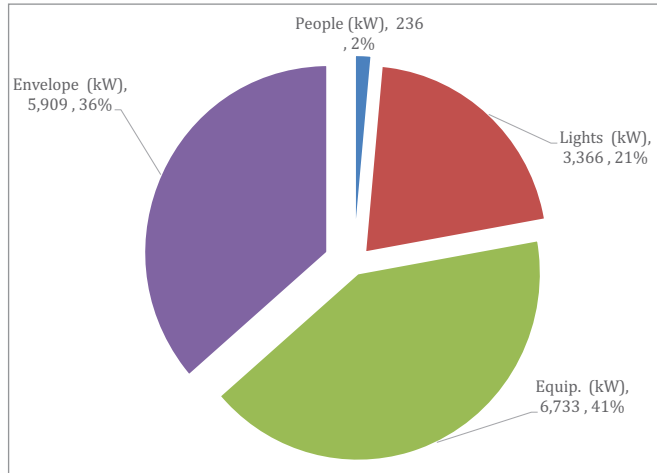


Figure 5: Breakdown of space loads for a building with 65% glass in the façade; the calculations were made using constant outside temperature.

The envelope load of 5,909 kW is 36% of the total load = 16,244 kW.

The envelope load is 13 BTU/h/sft and the total load is 25.24 BTU/h/sft (floor area).

Option 2 Net Zero

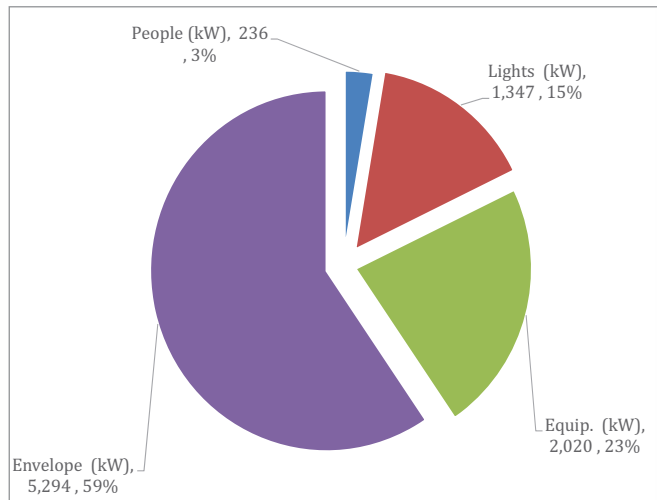


Figure 6: Breakdown of space loads for a building with 65% glass in the façade; the calculations were made using variable outside temperature.

The envelope load of 5,294 kW is 59% of the total load = 8,896 kW.

The Option 2 Net Zero alternative has an energy consumption of 8,896 kW, which is 7,348 kW less than the Base Case 16,244 kW. So, in reducing the overall energy consumption, which is the goal of a net zero design, the percentage of total energy consumption

due to the façade is now 59% of the total load and, therefore, the façade design becomes even more critical.

This is also helpful for selection of a suitable HVAC system for the building, as the conditioning system must be capable of providing a variable cooling load.

Infiltration Load

As building height increases, wind speed also increases. The increase in wind speed over the vertical height of the building can be calculated from weather data.

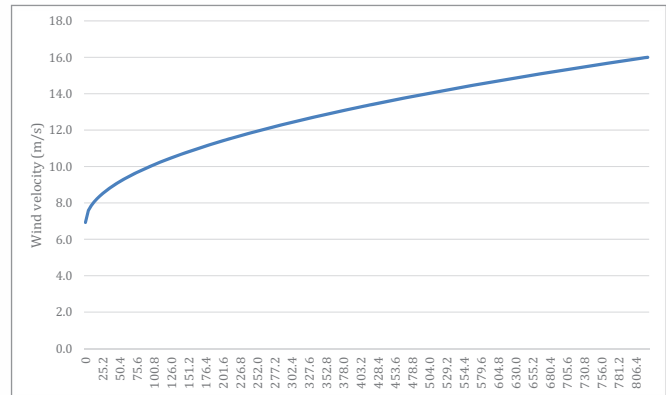


Figure 7: Increase of wind speed in relation to the building height

The wind speed at ground level is given at 18 mph and this is extrapolated upwards. For a 2,000 ft megatall building, the wind speed at the top of the building is some 35 mph.

Using the following façade leakage rates:

- 2.0 L/s-m² at 75 Pa, and
- 9.0 L/s-m² at 75 Pa,

it is possible to convert mph to pressure and then calculate the leakage associated with that pressure. This is shown in Figure 7.

The pressure of 75 Pa is about 16 mph wind speed.

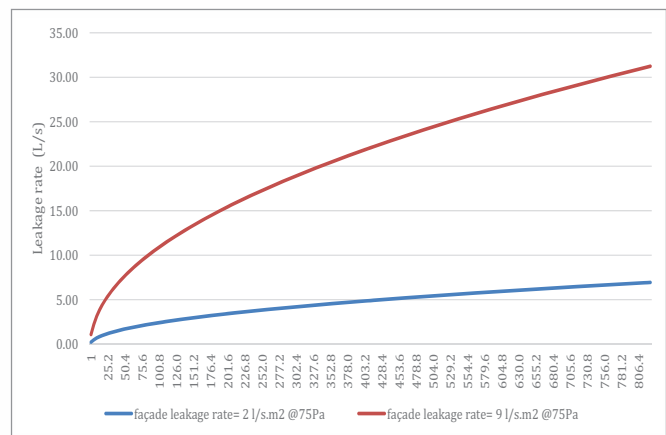


Figure 8: Equivalent leakage rates calculated from the wind speed in cfm/sft of façade area

Figure 8 shows the calculated leakage rates for an 800 m megatall building façade, calculated for 2.0 L/s-m² at 75 Pa and 9.0 L/s-m² at 75 Pa, so at about 100 m for a façade specified at 2.0

L/s-m² leakage, the actual leakage based on the exterior pressure is some 2L/s.m² façade area, and at 800 m the façade leakage rate is about 6 L/s.m² area. For higher leakage rate specifications, the calculated leakage rates are extremely high.

Why is this important?

1. The actual outside air infiltration will be much higher than specified; who will be responsible for the increase in infiltration?
2. To what pressure should the façade be tested?
3. What outside air infiltration rate has been included in the heating and cooling load calculations?

Conclusion and Future Work

The results clearly show that when calculating heating and cooling loads for tall, supertall and megatall buildings, the actual outside temperature differentials at different building heights need to be incorporated into the calculations.

At present, there are no commercially available load calculation programs that use a variable outside temperature in the calculations.

This paper shows how the variable outside temperature can be used when calculating a building's heating and cooling loads in a spreadsheet. These hand calculations should be recommended for tall, supertall and megatall buildings.

It is of course essential that vertical weather data be made available for such calculations.

For cooling loads, with floor to ceiling glazing (about 65%), the SHGC of the glazing needs to be reduced in order for the heat gain to be no more than the base case glazing (40%).

For heating loads, with floor to ceiling glazing (about 65%), the U value of the glazing needs to be reduced in order for the heat loss to be no more than the base case glazing (40%).

The façade air infiltration rate specified by the architect should be appropriate for the overall height of the building.

Due to the revised internal heat gains for lighting and plug loads, the overall energy consumption is reduced but the percentage of the total load related to the façade is increased. Typical present-day numbers are 50 to 70% of a building's total load.

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