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Towards energy efficient skyscrapers

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ABSTRACT

As of 2007 more than half of the world's population is living in urban areas (a figure expected to rise to 60% by 2030). Thus, the liveability of the high-density city is gradually becoming a central point of focus and concern. A successful skyscraper model of urban planning could provide the possibility to increase city-space vertically as opposed to the current continuous expansion outward, which has obvious environmental consequences. However, skyscraper development, as well as all other new construction and gradually the older building stock, has to comply with current strict regulations on building energy efficiency. Contemporary high-rise examples do not present a sustainable solution to an increasing population or as models of prosperity, as they are linked to high-energy demand, environmental and social imbalances.

This paper looks at design strategies towards promoting skyscraper energy efficiency by considering a climatically responsive design, where orientation, the thermal properties of the building envelope and the effect of altitude, become the main design tools. Initial simulations were performed for a residential and an office reference structure 100 m high. Different scenarios were implemented for gradually upgrading the building envelope and studying its relationship with the changing microclimate with altitude (wind speed increase and dry bulb temperature drop) between ground and top level. The advanced envelope was then simulated to up to 400 m high (120 stories high), and heating and cooling loads were compared in relation to different building heights and uses.

EnergyPlus is used as the main simulation tool as it accounts for wind speed increase and dry bulb temperature drop with height. The location chosen is Tel Aviv, Israel, a city already growing upwards and expected to have a significant increase in skyscraper construction in the coming years. The results of the simulations performed present the base upon which further design strategies can be implemented towards reducing the environmental impact of this challenging building type.

1. Introduction

World population is growing at a very fast pace and this affects the growth and density of the urban environments, with cities like Hong Kong and Mumbai having densities of 20,000 people/km^2, compared to London's 5,100 and New York's 1,750 people/km^2 [1]. As of 2007 more than half of the world's population lives in urban areas, a figure expected to rise to 60% by 2030 [2]. This makes the livability of high-density city a central point of interest and concern. Thus, it is possible to predict that high-density urban environments will soon be the norm and will dictate an increase in building demand. The increase in population, migration towards the cities, and the advancing industrialization have promoted the typology of the skyscraper as an important high-density living solution to the already dense urban centres of many of the world's megacities.

According to a research report by the Council of Tall Buildings and Urban Habitat (CTBUH), skyscrapers 200 m high and more around the world until 2015, were located as follows: China (348), South Korea (48), Rest of Asia (140), Australia (27), Europe (37), Middle East (120), USA (169) [3]. In addition, skyscraper construction is gradually spreading beyond the limits of megacities, cities whose population exceeds 10 million people, with places like Tel Aviv, in the already dense centre of Israel, changing their planning policies to allow for future skyscraper construction. Fig. 1 shows current skyscraper construction in Tel Aviv. In view of the number of skyscrapers that are being built across the world annually and are in planning for the near future, the typology of the skyscraper as a positive addition within the urban fabric calls for further research

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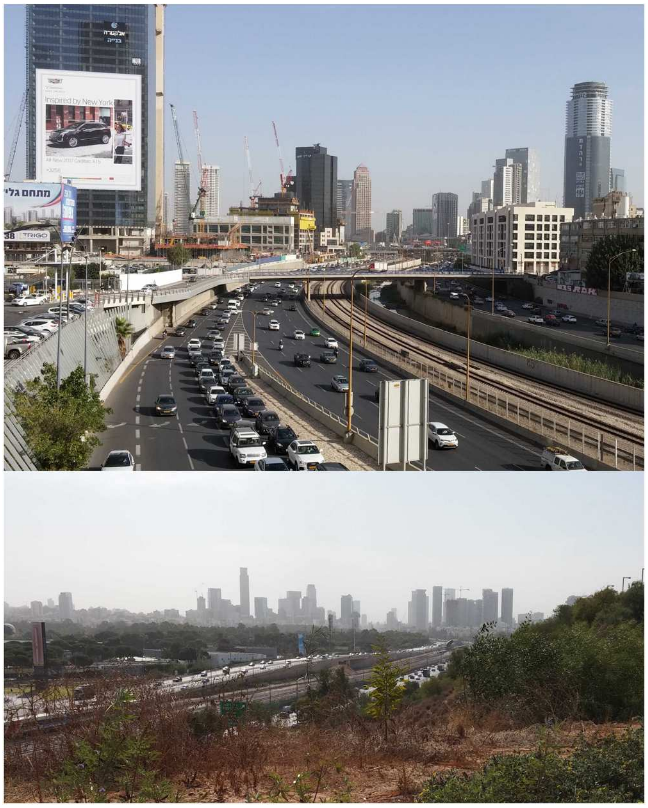

Fig. 1. Tel Aviv – Ramat Gan high-rise development looking north (above) and the same conurbation high-rise skyline looking south (below) (I.A. Meir, 2017).

and experimentation. This paper considers the skyscraper as an urban phenomenon closely related to city living and investigates design strategies towards reducing its energy consumption levels.

When considering the construction of a skyscraper within a dense urban fabric, initial drawbacks come from an economic point of view. The increased construction costs of typical high-rise buildings are approximately 40% higher in comparison with the typical low-rise ones (e.g. 1–6 floors high). In addition, regarding typical floor area efficiencies, gross internal area (GIA) for low-rise is between 68%-75%, while for the high-rise 60%-70% [4]. Net internal area is also smaller in high-rise buildings, as more area is used by plant and risers. The result is a 15%-25% of the high-rise floor area being taken over by circulation alone. In addition, a skyscraper consumes higher amounts of Operational Energy (OE) due to its large-scale volume compared to low-rise development. A main reason for the higher energy consumption is the energy used by elevators, which is often negligible in low- and medium-rise construction. It is estimated that depending on height and program, elevators can consume from 5 to 25% of the total energy consumed in tall buildings. This is due to the higher travel distances and the faster speeds used [5–7]. High-rise buildings, also consume large portions of pumping energy to distribute potable, fire extinguishing, heating and cooling water at higher altitudes [8].

However, skyscraper total energy consumption is affected by both internal and external conditions, like the surrounding built environment. Since 2009 the New York City requests from all buildings with gross areas greater than 50,000 ft^2 (4,645 m^2) to publicly release their energy consumption data. The height of the buildings is not included in the reports, but the number of floors is, which provides a good indication of height. Leung and Ray in their study on the energy consumption of tall buildings, collected energy benchmarking data of office buildings, with at least 80% of their total area used as office space [5]. This eliminated possible discrepancies created by different building uses. 706 buildings were studied. Results show the difference in energy consumption between buildings of 9 to >50 floors, measured in energy usage intensity (kBtu/m^2/year). The analysis revealed that lower buildings consume less energy on average than taller buildings. Results show a steady increase in energy use intensity (EUI) between 1 and 29 floors, with a rapid escalation at 30–39 floors, after which a plateau is reached for tall building construction. An important consideration in the EUI escalation between the 30th and 39th floor and the EUI balance that followed, is that buildings of that height to date, are mostly exposed to the sky, and don't experience wind or sun shading from other structures. So, the total EUI of a skyscraper is dependent on the density of the urban fabric around it, and is affected by parameters like mean radiant loss (small/high sky view factors), effect of relative low/high wind speeds on infiltration, and solar shading.

A comparative study on the environmental impact of a super tall building down to suburban homes, with all 9 prototypes housing 2000 residential units, created an overview of the advantages/disadvantages in relation to land use, energy loads, transportation and life cycle carbon emissions for each typology. For example, high carbon emissions of infrastructure reflected land use, and were related to low-rise development, while high carbon emissions of individual buildings were relative to the increasing height of buildings, with the super tall community having the highest embodied carbon than the other typologies. In terms of the total energy use intensity (EUI), it was revealed that the higher the building the better it performs, however, their overall energy consumption is greater than that of the low-rise ones, due to the added loads of water pumps, and elevators [9].

In recent years there have been a number of built skyscrapers aiming at achieving energy efficiency. A good example of a tower showing the complexities of sustainable high-rise construction is 'The Bank of America' by Cook + Fox Architects in New York, completed in 2010. The building received 'Core and Shell' LEED Platinum certification from the US Green Building Council, the highest level of LEED certification, as well as a number of other distinguished awards, like 'Best Tall Building Award – Americas' presented by the CTBUH, the American Institute of Steel Construction 2010 IDEAS award, and more. Bank of America has approximately 47,000 m^2 of office floor, including trading offices and data centres, housing nearly 10,000 occupants a day. The tower's sophisticated sustainable features include a greywater recycling system, recycled materials (fly ash concrete), floor-by-floor individual air handling units, on-site cogeneration plant, waste heat adsorption chilling, and more. However, in 2013 New York City released a public report of the tower's operations, as part of their 'OneNYC Green Buildings & Energy Efficiency' goal to reduce emissions, which revealed that Bank of America in 2012 had a site energy use intensity (EUI) of 665 kWh/m2/year, higher than any comparably sized office building in Manhattan [10,11].

This high EUI revealed a gap between what LEED as a certification procedure is able to achieve regarding the environmental performance of the structure as a whole, and the building's actual energy performance after occupation. So, even though LEED as a green rating tool is able to address broader issues of sustainability and promote green technologies, the issue of energy efficiency is still questionable. An important issue in the total energy consumption of the tower not taken into consideration, going beyond design strategies and specifications used, is the building's use, which is mainly characterized by high computing and other energy requirements, in turn affected by the occupants' activities and behaviour [12–14].

Nevertheless, the issue of high-energy demands, environmental and social imbalances, is a general observation on 20th century's architecture, which is characterized by a deviation from climatic considerations and reliance on mechanical means for the building's operation, a consideration that does not apply only to the typology of the skyscraper. However, skyscrapers are very large buildings and their impact on the urban fabric is substantial. Today, the building sector is the most energy intensive sector accounting for almost 50% of greenhouse gas (GHG) emissions. These are produced from the Embodied Energy (EE) used in the process of raw material extraction and processing, as well as the building process and, mostly, from the Operational Energy (OE) used mainly for heating, cooling and lighting. However, emissions produced from the OE form the largest source of building-related GHG emissions that is approximately 80–90% of the whole related energy use, according to UNEP SBCI [15]. So, in the process towards reducing GHG emissions, an important parameter is to enhance the energy efficiency of buildings.

One way towards achieving energy efficiency in buildings is energy benchmarking that acts as an important tool towards performance improvement. Energy performance of one building is measured in comparison with other similar buildings or simulations of reference models, and conclusions are drawn on the efficiency of its performance. However, the level of transparency that is offered in cities like New York and Seattle, for example, or even in counties like Singapore, does not apply to most of the world today. As a result, buildings and more specifically high-rise ones, that albeit may portray advanced environmental strategies and a high rank in green certification, could be still consuming high amounts of energy. This lack of information becomes especially problematic in the understanding of how a challenging building type like a skyscraper operates, towards quantifying its energy performance and forming a body of successful green-design guidelines in high-rise construction.

In 2009, High Performing Buildings (HPB) commenting on 'energy consumption reporting for buildings' published a report [16], claiming that calculating the EUI of a building is as simple as summing the total energy used and dividing it by the floor area to obtain the building's EUI (usually expressed in kBtu/ft^2/year or kWh/m^2/year). This figure can then be compared with the EUI that was estimated with the use of thermal simulations during the design process, a procedure that applied for most of the buildings highlighted in HPB [17,18]. However, buildings are using significantly more energy than predicted. One reason for these discrepancies could be the lack of sufficient information input in the simulations in regards to the use of equipment, or specific information on the building's users and their use of it. So, in the process of minimizing the energy variations between the design and operation stages of a building, an advanced level of feedback between the existing building stock and the proposed buildings becomes critical [19].

However, given the difficulties discussed above to accurately estimate EUI, especially post-occupancy, special attention should be paid to the building's design process, and more specifically, to the design of the building envelope. The fabric of the building acts as a mediator between indoor and outdoor conditions, and has a considerable impact on energy consumption. By forming a climatically responsive design where the building envelope interacts appropriately with the ambient climatic conditions, it is possible to take advantage of passive heating and cooling techniques [20–23]. This, in effect, can minimize the OE of buildings. This research considers a climatically responsive design in skyscraper construction that takes into consideration four main variables: first, a design strategy according to the building's immediate environment (orientation, prevailing winds); second, the thermal properties of the building envelope; third, the effect of height on energy performance; and fourth, the internal heat gains of the building (e.g. residential vs. office building).

This paper, which is part of a wider research on the energy efficiency of a skyscraper, studies the heating and cooling needs of two 100 m tall reference models, residential and office, by advancing the structures thermally step by step, and studying energy consumption for the ground and top floors. The thermally advanced structure of each building use is then simulated for taller buildings, of approximately 200m, 300m and 400m, and energy consumption is compared between different building heights and different uses. The changes in energy consumption between the successive heights present information on the relationship between the building envelope and its microclimate, in relation to height above ground. The models are located in Tel Aviv, Israel, a city whose Municipality's Planning and Construction Committee issued the 2025 city master plan that supports new sky-rise development. The study of skyscraper construction in the Mediterranean climate of Tel Aviv will be relevant for other Mediterranean cities, as well as other Middle Eastern cities, that undergo similar processes of rapid densification [24]. EnergyPlus is used as the main simulation engine that implements the height variable for simulating wind acceleration and temperature decrease with height, both of which are important aspects of this research. Ecotect Analysis is used for the design of optimum shading devices according to orientation. Indoor thermal comfort conditions are calculated in line with ASHRAE Standard 55 and the local weather files.

2. Achieving energy efficiency in skyscrapers

2.1. Complexities that arise with building height increase

The process of studying as challenging a building type as a skyscraper, involves forming a holistic understanding of the issues that this building type instigates, as well as what makes it exceptional. This procedure in effect creates the basis upon which changes towards the sustainable future of the skyscraper can occur. The main feature of the skyscraper is essentially its height. A tall structure poses a number of design considerations, two critical ones being the overshadowing of adjacent open spaces and buildings, and the relationship of the structure with local wind patterns.

The incorporation of a solar envelope as a zoning device, is a way to assure urban solar access for all buildings in order to enjoy 'adequate sunlight' and to produce passive, low-energy architecture [25,26]. For example, solar envelope regulations between two or more adjacent buildings, imply that the volume of one informs the design and volume of the other, meaning that shadows are cast in a way that all buildings enjoy 'adequate sunlight' for the design of passive and low-energy architecture; the characteristics of the solar envelope are relevant to land size, shape, as well as the climate and microclimate of the location [27]. An environmental approach for designing an urban block, is to establish a relationship between the sun-path and the urban form, in a way that has a direct effect on the energy efficiency of buildings (passive/active systems), and improves comfort conditions for pedestrians [28–31].

Many cities around the world have set specific regulations for ensuring solar rights; examples are New York, San Francisco and Tel Aviv. In Tel Aviv, which is the focus of this paper, a solar insolation conscious design was implemented for the design of the new business district [32], and a housing block in central Tel Aviv [28]. The desired result is proper insolation and ventilation for all neighboring buildings. For the design of the new business district, the solar envelope that was created determined the maximum allowed heights of the high-rise buildings, in relation to the adjacent residential neighborhood. Such studies are formed either with the use of wind tunnel models, or with the use of Computational Fluid Dynamics (CFD) simulations tools.

The large-scale volume of the skyscraper may also affect a city's natural ventilation potential, so additional design considerations need to be made on the building's shape and height. In Hong Kong,

Table 1
Wind Speed Profile Coefficients air layer thickness δ and exponent α (ASHRAE Fundamentals 2005).

Terrain Category	Description	Exponent α	Layer Thickness δ, m
1	Large city centres, in which at least 50% of buildings are higher than 21 m, over a distance of at least 2000 m upwind	0.33	460
2	Urban, suburban, wooded areas, and other areas with closely spaced obstructions compared to or larger than single-family dwellings (over a distance of at least 2000 m upwind)	0.22	370
3	Open terrain with scattered obstacles generally less than 10 m height, including flat open country typical of meteorological station surroundings	0.14	270
4	Flat, unobstructed areas exposed to wind flowing over a large water body (no more than 500 m inland)	0.10	210

high-rise beachfront construction is a leading example of what is known as the 'wall effect' where skyscrapers along the coast block the ingress of sea breezes. This phenomenon enhances poor city air quality and the Urban Heat Island (UHI) effect, due to compromised natural ventilation rates [33]. Ng, commenting on building density along the coast of Hong Kong that has negative implications on fresh air intake within the city fabric, suggests the inclusion of an Air Ventilation Assessment (AVA) as part of the planning application [34]. There are a number of scientific studies on the urban wind environment [35–38]. A study made on ventilation strategies and air change rates in high-rise compact areas revealed that variations between low-to-medium and high-rise structures improved ventilation by increasing vertical mean airflow [39].

The effect of wind on the skyscraper's structure also needs careful consideration. Its shape and volume have to take into account the wind loads imposed on the structure. When a strong wind hits the building, it is pushed up, down and around the sides, creating what is known as the 'downdraught effect' and 'channeling effect'. One design solution to this problem, is the use of various types of dampers along the envelope, as well as varying the structure's cross section with height in order to 'confuse' the wind and make the vortices lose their coherence [40]. Such effects can have very significant negative microclimatic outcomes. Thus, The City of London Corporation prompted for an Environmental Impact Assessment (EIA) as part of Planning Application, after concerns on strong winds and radiation reflection around the "Walkie Talkie" tower in the Square Mile.

According to information published by the CTBUH, the following steps become vital when determining wind loads. These are the wind speed and direction in the building's location, the influence of the terrain, the aerodynamics of the building and influence from nearby structures, and the building's wind-induced response and aero-elastic properties. In regards to the criteria used to assess the relationship between the building and the wind, CTBUH advises that a wind tunnel test may be appropriate if any of the following are applicable: a building is over 120m. tall, its height is greater than four times its width, the lower frequency movement of the building is less than 0.25 Hz [41], or the reduced air velocity at extreme conditions is greater than 5; absolute value may be calculated with the following relationship:

$$U/(f_1 b_{av})$$

Where:

U, is the mean hourly wind velocity at the top of the building

f_1, is the lowest natural frequency of the building

b_{av}, is the average width of building

CTBUH states that the above wind studies should be used as guidelines and not substitute building codes on wind speeds, but rather the two procedures should be treated as two separate processes with their results compared [42].

Increased wind speeds on high altitudes necessitate the increased use of materials in order to strengthen the structural system of the skyscraper [43,44]. This was especially valid in 20th century tall building construction due to wind loads and the non-advanced structural analysis techniques of the time. Today, a whole new range of structural systems characterizes high-rise buildings that eliminate height restrictions. Super tall buildings, like the Petronas Towers and Taipei 101, use the method of outrigger-and-core systems, where belt trusses or mega-columns are employed at the perimeter, creating big openings for windows on the facades. The use of diagrid node connections or megabrace can be seen as the next step to tall building construction that allows for complete elimination of vertical columns and the design of even taller structures [45].

Freeing parts of the façade from structural burdens has given rise to a new set of possibilities of innovative façade technology that, combined with HVAC systems, may aim for energy efficiency and indoor thermal comfort. Their combined design properties may reduce both initial and operating costs, as well as opt for higher system performance altogether [46]. This is a step forward in the design of the skyscraper as a more climatically responsive building where the façade and the mechanical systems can be designed to complement each other.

2.2. Environmental variables that influence energy consumption in skyscrapers

A building interacts with its environment through the envelope (walls, roof, windows, projections) and more specifically through the thermal properties of the materials chosen: by conduction through the opaque envelope materials, by convection as the result of wind or pressure-driven air movement, and by radiation as radiant heat transfer primarily from the sun through fenestration. In high-rise buildings the microclimate changes with altitude above ground, i.e., building height, more specifically, wind speed increases, while dry bulb temperature decreases. As a result it becomes essential to calculate the effect of these changing environmental variables on tall buildings, with a focus on energy performance.

The typical height of meteorological station anemometers is 10 m above ground, a height that does not relate to high-rise construction. For calculating wind speed at higher altitudes, ASHRAE [47] in Chapter 24: Air Flow Around Buildings uses the following equation to calculate the hourly average wind speed U_H of an uninterrupted wind approaching a building in its local terrain:

$$U_{H=}U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{\alpha}$$

Where:

U_H – hourly average wind speed

U_{met} – height above ground

α_{met} and δ_{met} can be calculated from Table 1

Dry bulb temperature drops with altitude. The built environment is located within the troposphere, where dry bulb temperature decreases with height at an almost linear rate, of approximately 1 °C per 150 m [48]. Since high-rise buildings today exceed the height of 150m, it becomes important to take into consideration the decrease in temperature and the increase in wind speed with altitude, and their effects on energy consumption. The following studies verify this.

Simulations on the annual energy usage of a stand-alone tower of 60 stories high using EnergyPlus, revealed that the effect of wind speed change was dominant for the first 10 floors. Higher up, at floor 25, the effect due to drop of air temperature caught up and was almost equal with the effect of wind speed, while from floor 25 and higher the effect of air temperature was overriding [49]. Two other studies on the effect of the changing microclimate with height in high-rise construction are Lotfabadi's study on the 164 m high residential 'Tehran's International Tower', in Iran [50], and Ellis and Torcellini's work on the 386 m high office 'Freedom Tower' in New York City [51].

In Tehran's tower [50], a 2.4% reduction in cooling energy during summer was achieved as a result of the decreased temperature in relation to height, while during winter the envelope's 4.2m^2 windows located within a 1.2 m deep recess, allow low angle winter sun to heat the premises, thus achieving energy efficiency all year round. In Freedom Tower [51], a dry bulb temperature difference of approximately 1.85 °C was observed between the elevations of 1.5 m to 284 m high, while wind accelerated from 2.46 m/s to 7.75 m/s. This decreased the energy consumption for cooling (summer) of the upper floors by 2.4%, while in regards to annual EUI a 9% net increase was found for cooling and heating due to the decreased shading at upper levels from other buildings. The lack of shading devices in the Freedom Tower, a curtain wall glass-and-steel envelope building, in combination with the building's high internal heat gains, advances considerably its cooling requirements, with the EUI of the tower mainly referring to cooling.

The above studies show that the total EUI of a structure depends on a number of variables, with the main ones being: climatic conditions, location of the building (open plane/dense city centre), the design of the envelope, the building height, and internal heat gains. The effect of the changing microclimate with height may become a positive asset in the building's energy efficiency all year round, if all the above variables are taken into consideration.

3. Research methodology

This paper studies the energy consumption of two 100 m tall reference structures, a residential and an office one, located in Tel Aviv, Israel, with the use of thermal simulations. The aim of the simulations is to study the effect of the changing microclimate with height on the energy performance of the structure. In the design process orientation and the building envelope become important tools towards achieving energy efficiency. The simulation engine used is EnergyPlus, which includes a variable in its calculations that estimates wind acceleration with height according to ASHRAE [47], and air temperature drop by elevation, while energy consumption is calculated in relation to indoor thermal comfort standards [52]. Within this comfort zone the acceptable temperature range according to the Predicted Mean Vote (PMV) model by Fanger, for winter, lies between 20 and 23 °C, and between 23 and 26 °C for the summer [53].

The effect of weather conditions, both on an individual's physiological and psychological level, seems to be very important even though it is not included in the PMV variables [54]. De Dear's analysis of the ASHRAE database [55] found that people were much more tolerant to the thermal variations of naturally ventilated buildings (NV) than those of centrally conditioned ones (AC) [56]. Nevertheless, a building could be operating in both modes during a year. It is worth noting that changes of weather have a time lag before affecting indoor comfort temperatures and that this depends on the thermal inertia of the building. However, the effect of natural ventilation in high-rise energy efficiency is not considered at this stage.

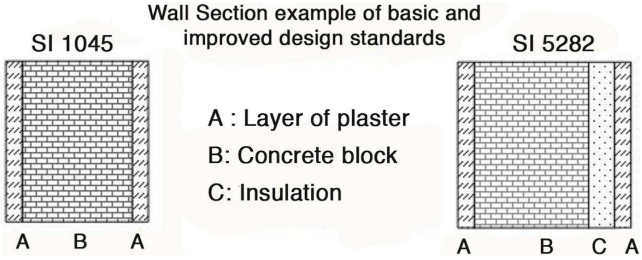

Fig. 2. External wall sections representing reference model (left – SI 1045 r = 0.40 m2 deg.C/Watt U = 2.5 W/m2 °C) and improved building (right – SI 5282) as defined in Table 11.

Simulations are performed for seven envelope scenarios for the residential structure and six for the office one, on ground and top floors. The design of the base reference structures meets the mandatory Israel Building Insulation Standard (SI 1045) and is then upgraded gradually to meet the voluntary Energy Rating in Buildings Standard (SI 5282), which is one of the basic requirements in the Sustainable Construction Standard (SI 5281) (Fig. 2) [57,58]. The final two scenarios test the effect of shading devices on energy performance (balconies and fixed shading). The effects of shading devices on building energy performance, with climate as a factor for best performance, have been investigated in a number of studies [59–61]. The advances of the building envelope for both building uses are shown in Table 2. The thermally advanced envelope (G for residential and F for offices) is then simulated at higher altitudes (of approximately 200 m, 300 m and 400 m high) in order to gain a better understanding of the effects of wind acceleration and air temperature drop with altitude on energy consumption. The reference models at this stage are theoretical and no in-depth study on the durability of the shading devices is made for the higher altitudes.

3.1. Building simulation data

The location chosen for the simulations is Tel Aviv; as a result, the Tel Aviv typical meteorological year (TMY2–new data) annual weather file is used in the simulations. In addition, design considerations regarding thermal properties of materials and windows ratio were considered for climatic zone A in Israel (coastal plan, with a hot and humid climate – Table 3). The proposed location for the tower is within an urban environment, yet no other structures were included in its proximity during the initial simulations presented here. Heating and cooling loads are calculated with EnergyPlus 'Ideal Loads Air System' mechanism. This is an ideal HVAC system that supplies cooling or heating air to a zone in sufficient quantity to meet the zone demands in accordance with heating and cooling schedules.

Both reference models are designed according to CTBUH typical tall building characteristics based on their wide database of built projects [62]. In the residential tower the ground level floor-to-floor height is assumed to be 4.65m, with a typical floor being 3.1 m high. Every 30 stories there is a mechanical floor of 4.65 m high and the roof mechanical level is estimated at 6.2 m high. As a result, a residential tower approximately 100 m tall has 30 usable stories $[4.65\text{m} + (30 \times 3.1\text{m}) + 4.65\text{m} + 6.2\text{ m} = 108.5\text{m}]$ (Fig. 3a). Similarly, a residential tower approximately 200 m high has 60 stories of usable space and is 206.15 m tall, a 300 m high tower has 90 stories and is 303.80 m tall, and a 400 m high has 120 stories of usable space and is 401.45 m tall.

The design of the office tower in accordance with CTBUH standards is somewhat different. The ground level floor-to-floor height

Table 2
Scenarios for upgrading the building envelope for the residential and office reference models.

RESIDENTIAL	OFFICE
A. Plain RC structure with double clear glass glazing 6 mm/13 mm air-gap, infiltration 0.9ACH	A. RC structure with 15 mm of extruded polystyrene insulation, double Low-E Tinted glazing 6 mm/13 mm air, infiltration 0.6ACH, WWR 15% per zone
B. Addition of 15 mm of extruded polystyrene insulation	B. Increase of WWR from 15% per zone to 35%
C. Replacement of double-glazing with double Low-E Tinted glazing, 6 mm/13 mm air, infiltration 0.6ACH	C. Increase of WWR from 35% per zone to 85%
D. WFR according to SI 5282 (Table 11)	D. Change from 4 thermal zones to open plan layout
E. Implement U-value of walls for residential according to SI 5282 (Table 11)	E. Implement U-value of walls and WFR for offices according to SI 5282 (Table 11)
F. Addition of balconies	F. Addition of shading devices
G. Addition of shading devices	

Table 3
Climate data for the 4 major climate zones in Israel.

Climate zones in Israel according to SI 1045			
Climate Zones	Meteorological Station Location	Winter (°C) (January) min / max	Summer (°C) (July) min / max
Zone A Coastal strip zone	Beit-Dagan	7.8 / 18.2	22.3 / 31.5
Zone B Costal plane and low country zone	Beer-Sheva	7.1 / 17.7	21.3 / 34.7
Zone C Mountain zone	Jerusalem	6.9 / 12.8	20.2 / 30.0
Zone D Jordan valley and the desert zone	Eilat	10.4 / 21.3	27.3 / 40.4

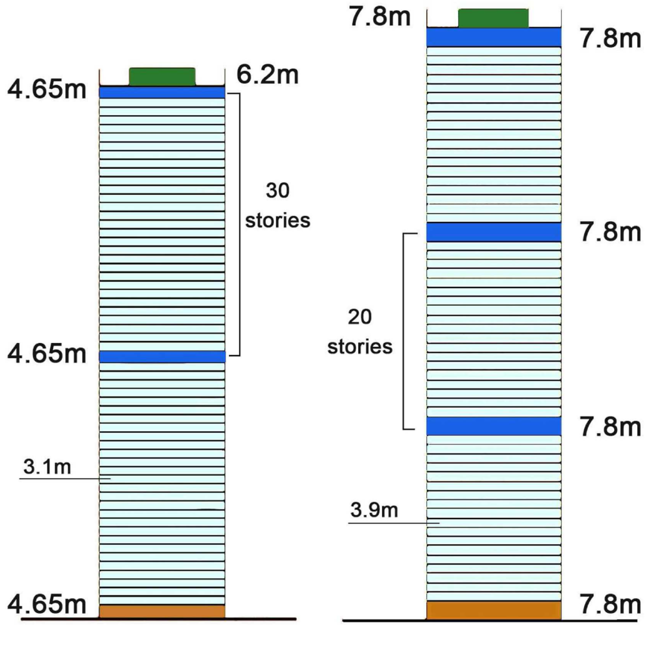

Fig. 3. Typical tall building height calculator according to CTBUH. (a) Left: Residential 60 stories 206.15 m high. (b) Right: Office 60 stories 273 m high.

is estimated at 7.8m, with a typical floor being 3.9 m high (2.7 m office space and 1.2 m plenum). Every 20 stories there is a mechanical floor 7.8 m high and the roof mechanical level is estimated at 7.8 m high. The office towers simulated in this study keep this analogy of 20 stories between mechanical floors. As a result, the estimated height of a 100 m tall office tower is 101.4 m [7.8 m + (3.9 m x 20m) + 7.8 m +7.8 m = 101.4m]. The simulated office towers in this study have a final height of 101.4 m (20 usable floors), 187.2 m (40 usable floors), 273 m (60 usable floors) and 358.8 m (80 usable floors) (Fig. 3b).

The structure of the reference models is reinforced concrete core (RC) with reinforced concrete shear walls. For buildings up to 100 m high and more, the construction of concrete walls cast on site with an external finish layer (plaster, stone rendering, sheet metal or other), is the most common construction method in Israel. The thickness of the shear walls is estimated in the simulations to be an indicative 300 mm thick. No structural analysis has been made at this stage on the lateral stiffness of concrete in relation to height [63,64]. Rather, the study focuses on the changes in the U-values of walls with the addition of different types of insulation, and their effects on building energy performance.

The design of the typical floor layout is based on the layout of a typical building in Israel and is positioned on a north-south axis. The floor plan consists of four thermal zones located SE, SW, NE and NW (Fig. 4a,b). All zones have in total the same floor area (115m^2) and each zone has the same window to wall ratio (WWR 15%), in order to evaluate better the effect of orientation on energy consumption. For both building uses the windows ratio is re-designed according to SI 5282 building codes. However in the office tower simulations are also performed with high WWR and comparisons are made between high WWR and window-to-floor ratio (WFR) specified in SI 5282. A number of studies have focused on the relationship between windows ratio and energy performance [65–68].

In regards to natural day-lighting requirements, both the office and residential models have been designed in accordance with the requirement set in SI 5282 Energy Rating of Buildings for 5 m depth of windows to usable floor space. This requirement refers to the offices, but for the purposes of comparison between the two building uses, the models use the same floor plan layout (not the windows ratio). Fig. 5 shows the simulated (e.g. office) plan layout. The hatched area indicates circulation area within the offices, while the central rectangle marked with diagonals as X is the core of the building. Internal heat gains are calculated for four people per zone for the residential option and 10m^2 of office space per person for

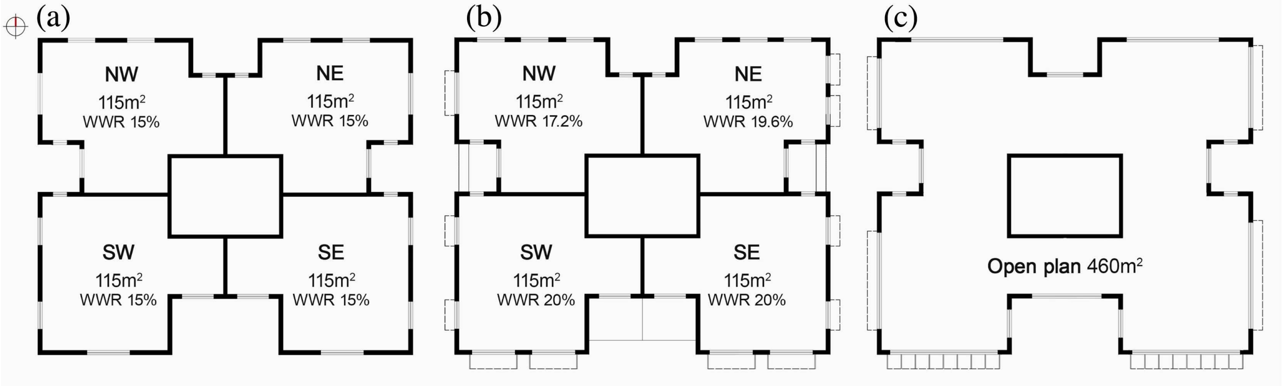

Fig. 4. (a) Left: typical four zones floor plan; (b) Middle: typical residential floor plan with IGBS, shading devices and balconies. (c) Right: typical office open plan layout with IGBS and shading devices.

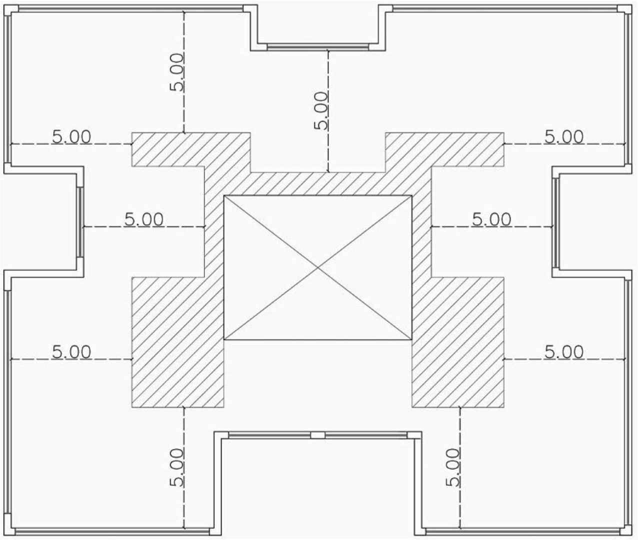

Fig. 5. Office and residential typical floor plan layout with the requirement set in SI 5282 Energy Rating of Buildings for 5 m depth of windows to usable floor space.

Table 5
Thermal properties of office building envelope (scenarios A–F).

Mass Wall Insulation (SOUTH) U-value 1.02 [W/m²K]	Mass Wall Insulation (N/E/W) U-value 0.54 [W/m²K]	Ext. Window double Low-E Spec Selection Tint 6 mm/13 mm Air U-value 1.626 [W/m²K]
19 mm gypsum board	19 mm gypsum board	LoE SPEC SEL TINT 6 mm
Extruded polystyrene 15 mm	Extruded polystyrene 40 mm	Air 13 mm
300 mm heavyweight concrete	300 mm heavyweight concrete	Clear 6 mm
F07 15 mm stucco	F07 15 mm stucco	SHGC: 0.292 V.T.: 0.408

the office. An activity and occupation schedule is used to simulate the behaviour of the occupants for both options.

The design optimized the thermal performance of the structure by meeting requirements of the mandatory standard (SI 1045) and the improved voluntary one (SI 5282) (Fig. 5) for Israel. The thermal properties of the different construction scenarios are shown in Tables 4 and 5. For the advanced glazing option, the use of low emissivity tinted glazing is considered an appropriate choice for the climatic conditions of Tel Aviv, by reducing incoming heat and thus cooling energy, without compromising natural light transmission. The benefits of this type of glazing, as opposed to the clear glass one, can be seen in Table 8.

4. Simulation results

4.1. Residential: simulation data for the envelope scenarios at different heights

Table 6 presents the cumulative changes in energy efficiency between the different envelope scenarios for a 100 m tall residential structure at ground and top floor. The U-values of the different

Table 4
Thermal properties of residential building envelope (scenarios A – G).

Mass Wall U-value 2.16 [W/m²K]	Mass Wall Insulation U-value 1.02 [W/m²K]	Mass Wall Israel GBS >0.55 U-value 0.54 [W/m²K]	Exterior Window U-value 2.67 [W/m²K]	Ext. Window Dbl LoE Spec Sel Tint 6 mm/13 mm Air U-value 1.626 [W/m²K]	Ext. Window Dbl LoE Spec Sel Tint 6 mm/13 mm Air U-value 1.333 [W/m²K]
19 mm gypsum board	19 mm gypsum board	19 mm gypsum board	Clear 6 mm	LoE SPEC SEL TINT 6 mm	LoE SPEC SEL TINT 6 mm
300 mm heavyweight concrete	Extruded polystyrene – 15 mm	Extruded polystyrene – 40 mm	Air 13 mm	Air 13 mm	Arg 13 mm
F07 15 mm stucco	300 mm heavyweight concrete	300 mm heavyweight concrete	Clear 6 mm	Clear 6 mm	Clear 6 mm
	F07 15 mm stucco	F07 15 mm stucco	SHGC: 0.703 V.T: 0.781	SHGC: 0.292 V.T.: 0.408	SHGC: 0.292 V.T.: 0.408

Table 6
Residential Tower: five scenarios of the building envelope at 100 m high at ground and top floors. (H) indicates heating requirements and (C) cooling in kWh/m^2/year.

<100 m High		7.75 m (GF)							97.65 m						
Envelope options		A	B	C	D	E	F	G	A	B	C	D	E	F	G
SW 115 m^2	H	7.52	3.18	2.76	1.77	0.83	1.09	**2.49**	8.83	3.89	3.57	2.36	1.14	1.62	**3.47**
	C	25.2	29.0	17.6	20.8	22.3	20.9	**14.9**	24.3	28.1	16.9	19.9	21.2	18.2	**13.1**
SE 115 m^2	H	7.53	3.17	2.73	1.73	0.80	1.05	**2.47**	9.15	3.80	3.52	2.31	1.16	1.67	**3.45**
	C	24.3	28.6	17.2	20.4	21.8	20.4	**14.8**	23.5	27.0	16.5	19.8	21.6	18.7	**13.1**
NW 115 m^2	H	13.8	7.75	5.24	4.60	2.70	2.82	**3.64**	14.9	8.43	6.03	5.38	3.33	3.79	**4.79**
	C	21.2	25.0	15.7	16.9	18.2	17.7	**14.7**	20.0	23.8	14.5	15.6	17.0	15.9	**12.9**
NE 115 m^2	H	13.9	7.76	5.11	4.37	2.58	2.69	**3.64**	14.9	8.46	5.90	5.14	3.17	3.68	**4.82**
	C	20.2	23.4	15.3	17.5	18.8	18.2	**14.8**	19.0	22.3	14.1	16.3	17.6	16.3	**13.1**

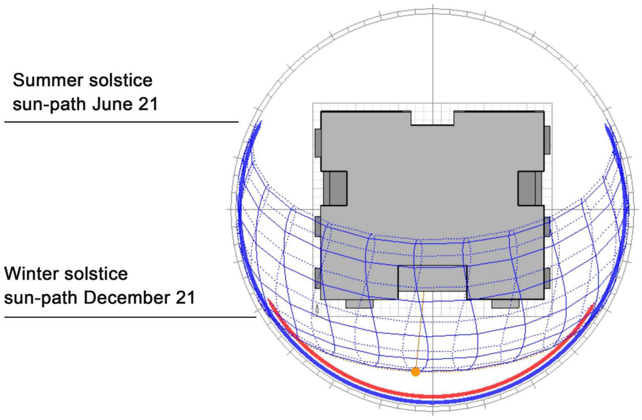

Fig. 6. Top view of tower displaying annual sun path with shading devices on south, east and west elevations.

constructions are presented in Table 4. The improvements in the building envelope are as follows:

- Scenario A: Energy consumption of reinforced concrete (RC) structure with double clear glazing 6 mm/13 mm air-gap, infiltration 0.9ACH (SI 1045).
- Scenario B: Addition of insulation: extruded polystyrene (XPS) – 15 mm/Thermal conductivity factor, λ: 0.029 W/mK. U-value dropped from 2.16 W/m^{2}K to 1.02 W/m^{2}K. Heating energy dropped a significant 57% for SW and SE zones, and 44% for NW and NE, while cooling energy has increased by 15% for SW and SE zones and 18% for NW and NE.
- Scenario C: Replacement of windows with low-emissivity, spectrally selective, tinted double-glazing (LoE Spec Sel Tint 6 mm/13 mm air/clear glass 6 mm), infiltration 0.6ACH. The reduction in ACH from 0.9 to 0.6 is based on an assumption that changing window systems from clear-glass, double clear glazing to LoE Spec Sel, including improved sealants and frames, will reduce infiltration. High cooling loads now reduced by 39% for SW and SE, and 37% for NW and NE. Heating reduced by a 13% for SW and SE zones, and a 32% for NW and NE. Table 8 shows the differences in the transmitted solar radiation between first and second choice in glazing type.
- Scenario D: Incorporation of SI 5282 window-to-floor ratio WFR (Table 11) (Fig. 4b). The 15% WWR that applied to all zones increased to 20% for SW zone, 20% for SE zone, 17.2% for NW zone and 19.6% for NE zone, to reflect the WFR specifications per zone. The increase of windows ratio in the SW and SE zones reduced heating by 35%, while cooling showed a 18% increase. In NW and NE zones, heating reduced by 12%, and cooling increased by 8%.
- Scenario E: Incorporation of SI 5282 for U-value of walls (Table 11). U-value decreased from 1.02 W/m^{2}K to 0.54W/m^{2}K. Heating energy reduced by 53% in SW and SE zones, and a 41% in NW and NE zones. Cooling increased by an approximate 8% in all zones.
- Scenario F: Incorporation of balconies 3 m deep x 4 m wide (South elevation) and 2 m deep x 4 m wide (West and East elevations) and a glass door per apartment. Windows ratio was preserved according SI 5282. Energy consumption for cooling reduced slightly for all zones; SW and SE a 6%, and for NW and NE 3%. Heating increased for SW and SE by a 31%, and for NW and NE a 7%.
- Scenario G: Incorporation of shading devices (Fig. 9), configured with the Ecotect 'Shading design wizard'. The shading devices were positioned on the south, east and a west elevation (Fig. 6). The optimum shading design for the south elevation is a horizontal shade with vertical fins on either side of the window, and

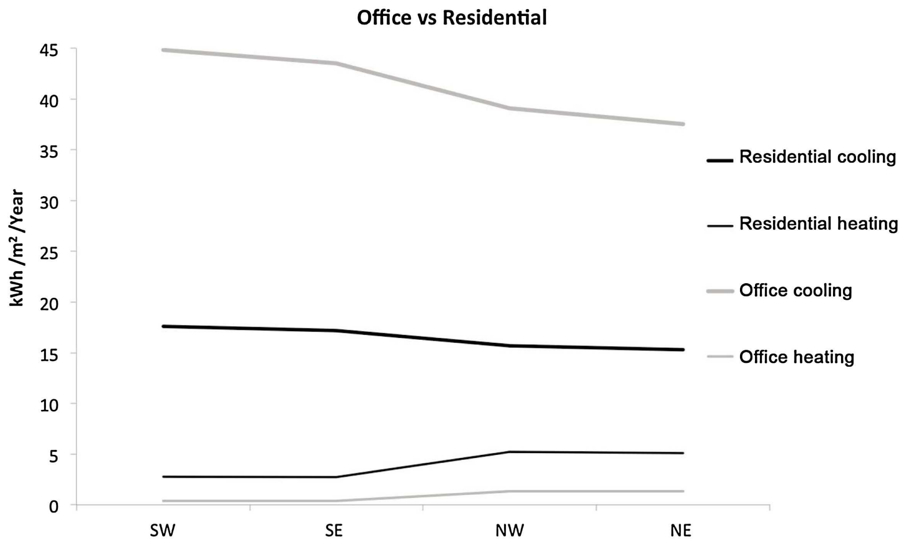

Fig. 7. Comparison of heating and cooling needs between residential scenario C and office scenario A. The model configuration is the same, but the internal heat gains and occupancy schedules differ according to building use.

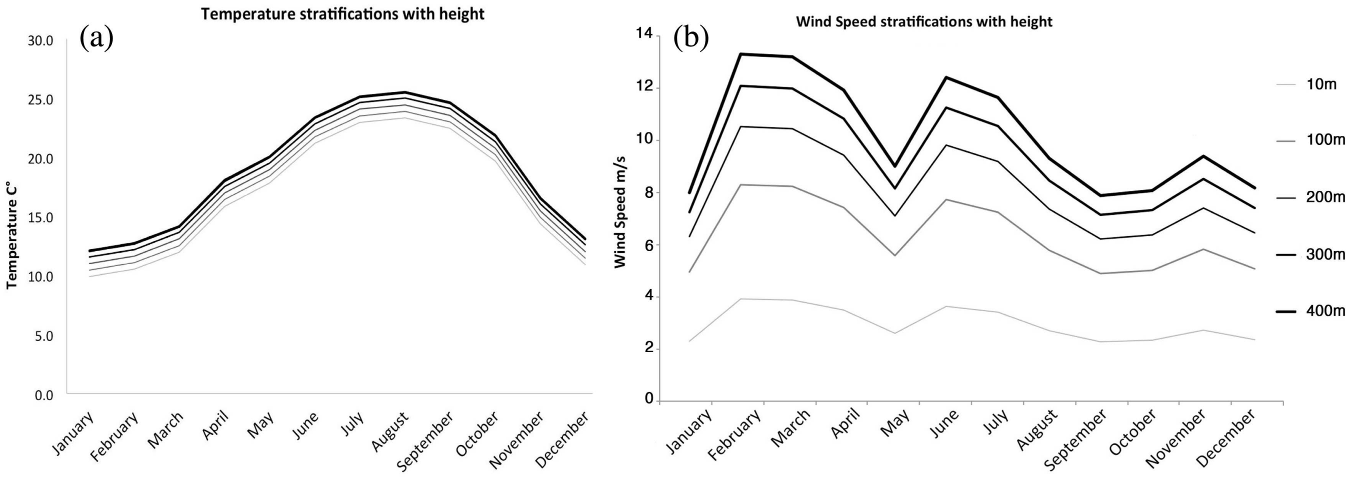

Fig. 8. (a) Temperature variation at building tops; (b) Outdoor wind speed at building tops.

for the east and west elevations a 45° angle shading that blocks 50% of the window, due to the low angle sun on these elevations. Cooling energy dropped by a further 28% on SW and SE zones and 17% on NW and NE, while heating energy increased 2.5 times for SW and SE, and 1.5 times for NW and NE, however still quite low in comparison with the cooling loads.

4.2. *Office: simulation data of the envelope scenarios at different heights*

Table 9 presents the cumulative changes in energy efficiency between the difference envelope scenarios for a 100 m tall office tower at ground and top floor. The U-values of the different constructions are presented in Table 5. The changes in the building envelope are as follows:

- Scenario A: Energy consumption of RC structure with 15 mm extruded polystyrene (XPS) – insulation, with low-emissivity, spectrally selective, tinted double-glazing (LoE Spec Sel Tint 6 mm/13 mm air/clear glass 6 mm), infiltration 0.6ACH. The first scenario of the office tower uses the residential model of scenario C and changes the internal heat gains (people, lights, devices, schedules) to reflect that of an office building. The changes in heating and cooling energy between the residential and office model at this stage are presented in Fig. 7. Heating energy decreased in the office tower by 7 times for the SW and SE zones and 4 times for NW and NE. The already higher cooling loads, in comparison to heating, increased by almost 2.5 times (e.g. 17.6 kWh/m^2/year <44.8 kWh/m^2/year).
- Scenario B: Increased the WWR from 15% to 35% to reflect the higher glazing areas used currently in office building design. Cooling requirements became especially high (< 34%) for the SW and SE zones, and for the NW and NE zones increased by 19%. No substantial changes in heating occurred.
- Scenario C: Further expansion in the WWR from 35% to 85%. Cooling energy amplified by an additional 68% for the SW and SE, with heating advancing by half, however still quite low in comparison with the cooling loads. In the NW and NE zones cooling showed a 46% increase and heating a 30% increase.
- Scenario D: Change of floor plan layout to 1 thermal zone (open plan) to reflect most current office building layouts (Fig. 4c). The average of the four apartments of C is relatively close to D, e.g. Heating energy: $\sim$1.17 relative to 1.39 kWh/m^2/year, and Cooling energy: $\sim$83.2 close to 82.7 kWh/m^2/year.

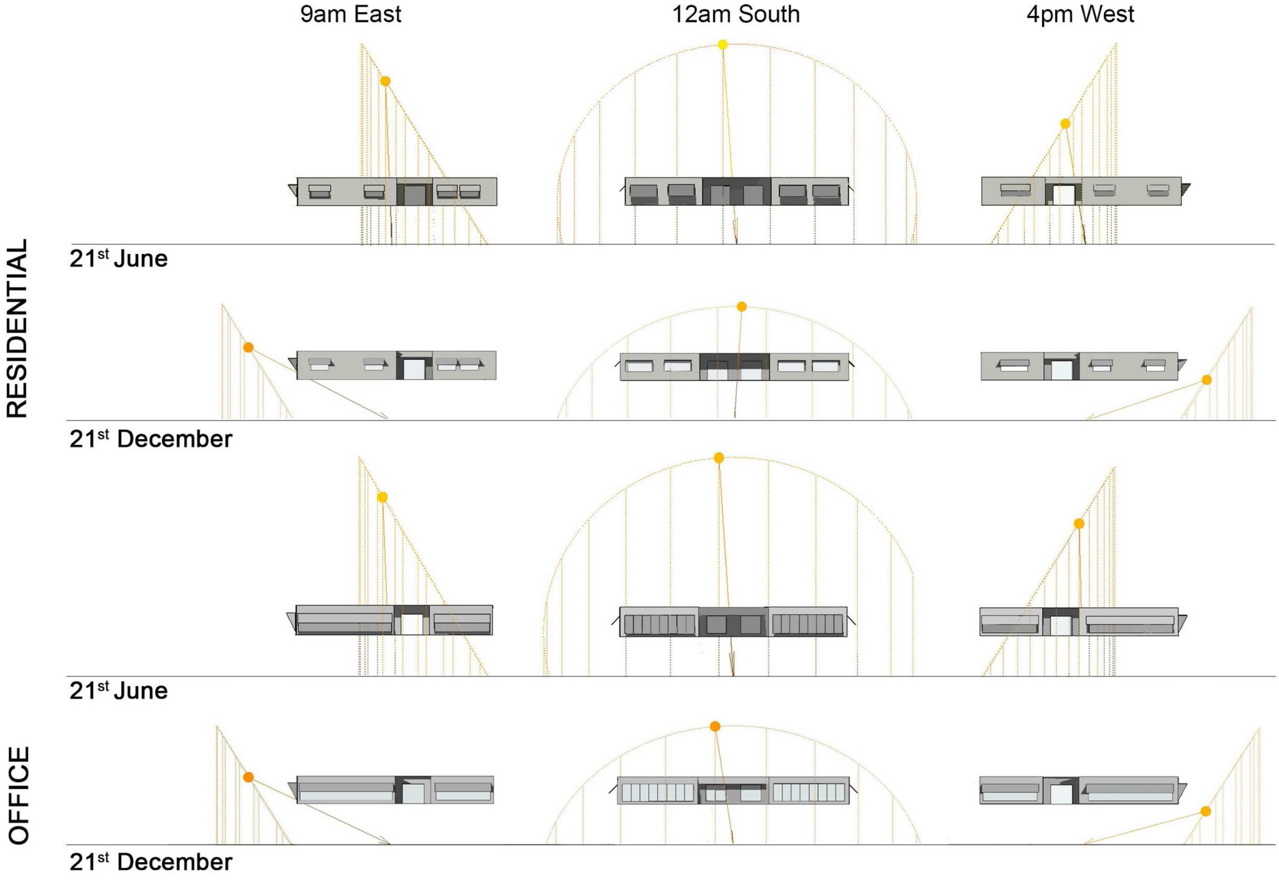

Fig. 9. Shading devices on east, south and west elevations for the residential (top) and office (bottom) towers at 9am, 12am and 4pm for the 21st of June (summer solstice) and 21st of December (winter solstice).

- Scenario E: Incorporation of SI 5282 for U-value of walls and WFR (Table 11). The WFR was estimated according to the lowest ratio (%) described in Table 11 for the purposes of comparison between the residential and office towers. Heating and cooling energy dropped in relation to the previous scenario. Heating reduced by a 70% (e.g. 1.39 W/m^2 K > 0.41 W/m^2 K), and cooling by 19% (e.g. 82.7 W/m^2 K > 67.1 W/m^2 K). The lower energy needs of this scenario, in comparison with the previous ones, is a combination of the WFR specifications and the reduced wall U-value for the East, West and North elevations, from 1.02 W/m^2 K to 0.54 W/m^2 K (Tables 5 and 11).
- Scenario F: Incorporation of shading devices (Fig. 9), configured with the Ecotect 'Shading design wizard'. The shading devices were positioned on the south, east and a west elevation (Fig. 6). The south elevation uses a horizontal shade with vertical fins every 1m. Cooling energy reduced by a further 30% (e.g. 67.1 W/m^2 K > 46.6 W/m^2 K), while heating increased by almost 2.5 times, however still quite low.

The advanced envelope scenarios are then simulated at approximately 200m, 300m, and 400 m high for each building use designed according to CTBUH high-rise typical construction. Fig. 8 shows the dry bulb temperature drop (a) and wind acceleration (b) from ground to 400 m high, a height in skyscraper construction that is considered a threshold in today's urban environments. The effect on energy consumption of these environmental variables in relation to height is seen in Table 7 for the residential tower and Table 10 for the office one. In both models, cooling energy reduced considerably from ground floor to top. In the office tower, cooling loads became 34% lower at the highest point, while in the residential tower a 45% reduction was observed.

Nevertheless, heating also became an issue at higher altitudes. In the office model, heating energy became almost four times bigger, from 0.94 kWh/m^2/year to 3.44 kWh/m^2/year, while in the residential model the increases were 3 times more (e.g. SW: 2.49 kWh/m^2/year < 7.38 kWh/m^2/year). In summary, even though the reductions in cooling energy are much greater in comparison to the increase in heating, for the Mediterranean climate of Tel Aviv, heating energy becomes also an issue at higher altitudes, especially for the residential tower. Further investigations on the envelope design of the two building uses in relation to the different heights could provide better results on energy performance.

5. Conclusion

The typology of the skyscraper is becoming ubiquitous as a response to population increase and urbanization, however the research on its energy efficiency does not move at a similar pace. Furthermore, a universal design of skyscraper development does not seem applicable in this environmentally aware era. This paper discussed two the reference models, a residential and an office one, located in Tel Aviv, representing a hot humid climate. Comparisons were made in relation to heating vs. cooling loads for each building use, as well as between the two models, and the differences that occurred on heating and cooling loads from ground to top.

For the Mediterranean climate of Tel Aviv cooling energy was observed to be much higher in relation to that for heating. The cooling vs. heating loads were 97% more for the office model at 11.7 m high, e.g. 46.6 kWh/m^2/year vs. 0.94 kWh/m^2/year (Table 10), and

Table 7
Residential Tower: Energy consumption reductions between ground floor and 400 m high. (H) indicates heating requirements and (C) cooling in kWh/m^2/year.

ZONES	WWR IS 5282		7.75 m	97.65 m	195.30 m	292.95 m	390.60 m
SW **115 m^2**	WWR: 20%	H	2.49	3.47	4.29	5.90	7.38
	S: 9.40%	C	14.9	13.1	11.9	9.75	8.07
SE **115 m^2**	WWR: 20%	H	2.47	3.45	4.27	5.95	7.43
	S: 9.40%	C	14.8	13.1	11.8	9.72	7.90
NW **115 m^2**	WWR: 17.2%	H	3.64	4.79	6.00	7.68	9.16
	N: 7.30%	C	14.7	12.9	11.6	9.59	8.14
NE **115 m^2**	WWR: 19.6%	H	3.64	4.82	6.00	7.76	9.54
	N: 7.30%	C	14.8	13.1	11.7	9.72	8.20

Table 8
Comparison of solar radiation energy between the two glazing types.

Ground Level	Surface Window Transmitted Diffuse Solar Radiation Energy [kWh] Annual Sum							
	SW zone		SE zone		NW zone		NE zone	
	South 3.6 m^2	West 2.4m^2	South 3.6 m^2	East 2.4m^2	West 3.6 m^2	North 2.4m^2	North 2.4 m^2	East 3.6 m^2
Dbl. Clr.	1055	658	1055	652	987	530	530	978
Low-E Spec Sel. Tint	190	102	190	100	281	151	151	279

Table 9
Office Tower: five scenarios of the building envelope at 100 m high at ground and top floors. (H) indicates heating requirements and (C) cooling in kWh/m^2/year.

kWh/m^2/year														
<100 m High Envelope options			11.7 m (GF)						85.8 m					
			A	B	C	D Open plan	E Open plan	F Open plan	A	B	C	D Open plan	E Open plan	F Open plan
SW 115 m^2		H	0.40	0.32	0.64	1.39	0.41	**0.94**	0.82	0.64	0.96	1.94	0.68	**1.44**
		C	44.8	60.1	101.	82.7	67.1	**46.6**	40.4	55.6	95.1	82.6	59.5	**40.9**
SE 115 m^2	Open plan 460 m^2	H	0.38	0.30	0.60				0.79	0.60	0.89			
		C	43.5	57.8	99.2				39.9	53.3	93.5			
NW 115 m^2		H	1.36	1.34	1.80				1.88	1.82	2.24			
		C	39.1	46.7	68.3				35.4	42.6	64.9			
NE 115m^2		H	1.33	1.27	1.65				1.80	1.71	2.01			
		C	37.5	44.5	64.6				34.7	41.4	62.5			

Table 10
Office Tower: Energy consumption reductions between ground floor and 350 m high. (H) indicates heating requirements and (C) cooling in kWh/m^2/year.

OPEN PLAN		11.7 m	85.8 m	171.60 m	257.4 m	343.2 m
460m^2	H	0.94	1.44	1.99	2.64	3.44
	C	46.6	40.9	37.1	33.7	30.9

Table 11
Green Building Standards, SI 5282: Energy Rating of Buildings. Note: Low-E Glazing.
G3: Uglass = 1.8 / Uframe = 3.5 / SHGC = 0.6 / Daylight trans. = 0.6
G4: Uglass = 1.8 / Uframe = 3.5 / SHGC = 0.5 / Daylight trans. = 0.5

Residential		
Window-to-floor ratio (WFR) % 20% max. relative area of windows per apartment		Wall heat transfer coefficient (W/m^2 K)/U-value
Main elevation	Other elevations	
N = 12%, E/W = 8% S = 20%	E = 10% W = 5%	0.55
Office		
Window-to-floor ratio (WFR) %	Window (W/m^2 K)/U-value	Wall heat transfer coefficient (W/m^2 K)/U-value
S = **23**–35, N = **23**–27 E = **23**–32, W = **18**–27	N/E = G3 S/W = G3 or G4	N/E = 0.6 S = 1.2 W = 0.6

for the residential tower at 7.75 m high were observed to be 83% more, e.g. SW: 14.9 kWh/m^2/year vs. 2.49 kWh/m^2/year (Table 7). The energy needs of office and residential towers are also described in the graphs of Fig. 10. The bold differences in heating and cooling energy between the two uses, due to variances in internal heat gains and WFR, suggest the requirement for a different envelope treatment between them, a requirement that IS 5282 is pursuing, however still on a voluntary basis. Its application is yet to be seen in the current and future construction, as well as in retrofitting. The importance of shading devices was especially pronounced in

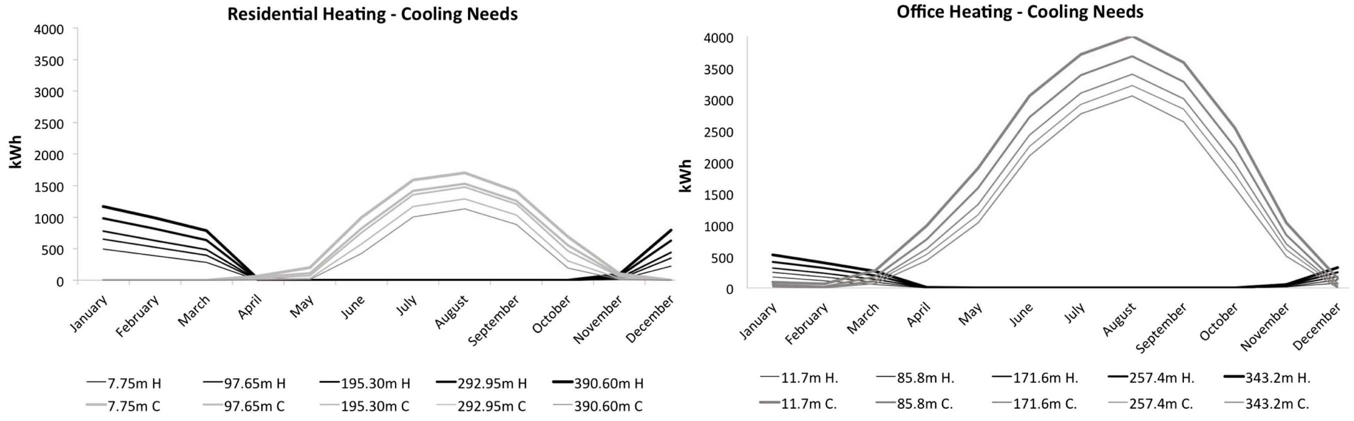

Fig. 10. Comparison of heating and cooling needs between residential scenario G and office scenario F.

the simulations, with cooling energy decreasing by an approximate 30%, both for the office tower and the residential towers.

The simulations also revealed the importance of the changing microclimate with height on energy performance for the typology of the skyscraper. The results showed that, as a norm, cooling energy decreased, while heating energy increased, with cooling loads, though, accounting for the higher values. However, especially in the example of the residential tower, while cooling loads were increased to begin with, heating energy also amplified its impact in the total energy use intensity (EUI) of the tower, by increasing to 3 times more from 7.75 m to 390.6m high. Further studies on heating and cooling loads between the subsequent heights, in relation to building use, will provide information on design alterations of the building envelope with altitude for energy efficiency. The above considerations stand in contrast to the current practices of curtain wall design of most high-rise building facades, including many residential ones.

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