Sustainable tall buildings: toward a comprehensive design approach

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Abstract: This paper presents a comprehensive design approach to sustainable tall buildings development. It argues that the true efficiency and success of tall buildings are heightened by their overall relationship with their urban setting and infrastructure. Tall and supertall buildings are mini-cities and their social, economic, and environmental impacts extend throughout the neighbourhood and the city at large. A new sustainable approach should not only consider incorporating sustainable features, such as photovoltaic panels and wind turbines; but should also consider an overall approach that balances multiple issues, including the environmental, economic, social, construction, operational, and building’s functional adaptability for future market changes. This paper serves to illustrate this view by providing a detailed account on a comprehensive approach to sustainable tall buildings development. While there is an increasing pace of constructing tall buildings worldwide, currently, there are no sustainability assessment tools for tall buildings. It is hoped that this paper will serve as a foundation to develop such tools.

Keywords: energy; social ecology; green design; macro-scale; microenvironment.

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1 Introduction

Sustainability or sustainable development is increasingly making its way to the top of the agenda of many planning and urban design policies and regulations. Sustainability poses the central challenge to our age: how can we promote healthy and economically sound urban growth without hurting the environment and depleting natural resources (Beedle et al., 2007; Prieto, 2001). It aims at promoting positive urban development that meets the needs of today's generation without jeopardising the ability of future generations to meet their own needs. The idea has its origin from the most commonly accepted definition of sustainable development in the world today, published in Our Common Future – also known as the ‘Brundtland Report’ – in 1989, by the United Nation’s World Commission on Environment and Development. One of the issues that the report addressed is the unsustainable practices of modern cities that voraciously consume fossil fuels, emit vast quantities of carbon, and release toxic chemicals into water, ground, and air (WCED, 1987; McGeough et al., 2004; Lam, 2009).

Any assessment of the environmental impact of tall buildings should take into account the many aspects concerning the influence exerted by them on their own internal environments and their external surroundings (Beatley, 2009; Low et al., 2005). As a new tall building is inserted into a financial district or a residential neighbourhood, it creates a zone of influence impacting the natural and socio-economic conditions around it (Collins, et al., 2008). The taller the tower, the wider is the area of influence. A broader view is needed to tackle aspects in relation to long-term policies and management of urban growth, the number of added green jobs, dwelling units, areas taken for development, and social impact. In sustainability terms, the true values of tall buildings are heightened by their overall relationship with their urban setting and infrastructure (Stern, 2007; Pank et al., 2002; CTBUH, 2010a; Blustein and Rodger, 2001).

Most importantly, currently, there are a number of environmental assessment processes, design tools and key performance indicators for sustainability. However, none of them are specifically intended for evaluating high-rise construction. Examples of current evaluative tools include the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), the Civil Engineering Environmental Quality and Assessment Award (CEEQUAL), ARUP’s Sustainable Project Appraisal Routine (SPeAR), the DTI’s Movement for Innovation (M4i) indicators, and DETR’s (now DEFRA) ‘Quality of Life Counts’ indicators. This paper provides a comprehensive account of key issues that should be considered for achieving sustainable tall buildings. It is hoped that the provided review and discussions in this paper will serve as a base for developing assessment tools for sustainable tall buildings.

The past decade has witnessed an unprecedented construction of tall buildings worldwide. This is corroborated by the Council of Tall Buildings and Urban Habitat (CTBUH, 2009), which went even further in observing that the past decade has witnessed the completion of more skyscrapers than any previous period in history. This resurgence of tall buildings has led to the construction of higher buildings in greater numbers (Wood, 2011; CTBUH, 2010b). Therefore, there is an increasing need for sustainability research on tall buildings. Also, there is a need to develop tools that assess tall buildings on sustainability. This paper is meant to cater to these needs.
2 The larger sustainable context

2.1 Community life and social sustainability

Developments of tall and supertall buildings should not be isolated projects and should contribute to the social life and vitality of the city. Tall buildings contain their own community of residents and/or workers, but they are also part of the wider urban community. The dynamic relationship between these two communities must be considered. As an overall strategy, tall buildings should invest in the community’s socio-economic growth by providing opportunities for employment and social spaces. They should embrace mixed-use schemes (work, live, shop, and play), for they have the potential to augment vital social life, propel businesses, and support livable and safe communities. They can be instrumental in regenerating depressed residential neighbourhoods and communities and revive ‘social brownfields’, thereby contributing to social sustainability. A community is more than just its physical form – it is as much a social environment as a physical one. As a city has its ‘hard infrastructure’, which is the spine of the city allowing it to function, a community likewise has a ‘soft infrastructure’, the elements of which allow it to function.

2.1.1 Services

The sustainability of tall buildings hinges on their integration with the scheme of a broader range of services; the tower and the surrounding development must be mutually supportive. The functions of proposed tall buildings should complement and cater to local community needs. Likewise, existing community services should be potentially supportive of the services needed by tenants of proposed tall buildings. Multi-functional towers have the capacity to provide a concentrated wide range of services and activities that need to be tailored to match local needs. In particular, functions of the ground plane are expected to connect well with the surrounding neighbourhood and tie the tall and supertall buildings into their place. The possibility of creating 24-hour activities in a supertall building warrants careful examination. Therefore, a sustainability review of proposed tall buildings implies that their proposed functions will be compatible with existing functions and activities of the community.

2.1.2 Social ecology

Promoting a healthy and sustainable social ecology is meant to enhance community life, promote socio-economic opportunities, and support empowerment. It requires advocating on behalf of groups which have no access to power or expertise, and are fighting for equity and justice. Tall buildings can be viewed as neighbourhoods or mini-cities that house large numbers of people. The introduction of tall buildings into a neighbourhood will have a considerable impact on the social life of the existing community. Social connectivity, fit, and compatibility with the social make-up of the existing neighbourhood need evaluation. Social class, ethnic backgrounds, and lifestyle of the existing neighbourhood should match or complement that of the prospective tenants of the proposed tall buildings.

There have been examples in which tall buildings were aimed for the very top of the social scale for economic reasons, and as a result, these newly introduced buildings were
socially segregated from the rest of the neighbourhood. Rather than blending into the
neighbourhood they create social enclaves or ‘vertical gated communities’. Guthrie
(2008) has noted that many of today’s towers promote isolation rather than support
community life. These new towers function as private spheres separate from the rest of
the neighbourhood. By providing civic and outdoor spaces (e.g., community gardens),
activities in proposed buildings can support and integrate into the pre-existing local social
web of community interaction.

2.1.3 Green jobs

Sustainability values the economic dimensions of projects including the types, quality,
and number of green jobs generated and their impact on local conditions and renewal
programmes. It is important to check if the proposed businesses will be stable and make a
long-term contribution to the community, and assess the risks involved should the
business go bankrupt, move away, or simply not perform to expectation (Fodor, 1999). A
new tall building project can create many jobs during its construction and service life.
Employing local people fosters a stronger relationship between the new building project
and the local residents. Furthermore, employing experts and workers of the community
for the building construction will be beneficial to the local economy.

A few questions could be posed to assess the impact of such generated jobs on the
local environment. Would the proposed jobs complement or strain the local environment?
For example, it would be important to assess if the proposed tall building project will
employ local people so that travel distances are shortened. This is usually measured by
the vehicle miles travelled per person per year multiplied by the number of tenants, or
\[ VMT/\text{person/\text{year}} \times N, \]
where VMT is vehicle miles travelled and N is number of tenants. Green jobs should produce less pollution and use less local natural resources per worker
than regular jobs. Therefore, each job consumes less land, lesser quantities of water, and
fewer kilowatt-hours of electricity. Also, jobs are anticipated to use fewer hazardous
and toxic chemicals than existing businesses, and minimise waste products through
recycling, reuse, and the most efficient production practices. Further, jobs need to be
context-sensitive so as to exert minimal negative impacts on the community in terms of
traffic, noise, parking, aesthetics, and general livability (Fodor, 1999).

2.1.4 Adaptive reuse

Building a high-rise requires a large amount of materials and energy. Environmental and
financial costs are high for both demolishing old buildings and constructing new ones. A
sustainable approach lengthens the life of a building by designing it to be adaptive to the
future needs of the community. Adaptive reuse strategies are needed to successfully
respond to emerging needs, market trends, and uses so that they provide opportunities
and flexibility for better space utilisation, and economic gain. It is important that internal
arrangements facilitate flexibility for other uses over time, if the originally intended use
becomes obsolete or proves unprofitable (Gause et al., 1996).

2.2 Energy efficiency

A tall building demands a massive amount of energy in one concentrated location. Total
energy need prior to its deconstruction consists of embodied energy and operational
Sustainable tall buildings

Energy. Energy is also spent for deconstruction, which should be accounted for in the design process, and for which more research is needed.

2.2.1 Embodied energy

Sustainable tall buildings require that less energy be spent in their assembly. Embodied energy refers to all the energy required to extract, manufacture, and transport a building’s materials as well as that required to assemble and complete its construction. The distance travelled during construction by contractors, the design team, raw materials, recycled materials, and waste materials are all significant components of embodied energy. The embodied energy of materials used in the structural system of a tall building utilising steel and concrete is far greater than that of low-rise buildings, which generally employ wood, brick, stone, etc. Therefore, any efforts in reducing the amount of building materials will provide a significant reduction in embodied energy in tall buildings. Embodied energy in building materials can be discussed in terms of material strength, the location of material, and the processing history. As a rule, material selection should be considered as a function of strength, durability, availability, and energy efficiency.

2.2.2 Operational energy

Since tall buildings demand high levels of operational energy, they should be considered in the context of the wider development picture – for example, how the building’s energy supply systems can be integrated with the existing and future ‘low or zero carbon’ energy supply infrastructure. Operational energy consumption can be reduced by using solar, wind and geothermal sources of energy (see Section 3.3 below). Proposed tall buildings may consider the opportunities to tie in with local energy service provision so as to look beyond the renewable opportunities available on-site. Integration of tall buildings with third party energy centres based on renewable energy sources should be considered, where it is available. The development may also consider the opportunities to tie in with the citywide network of district heating systems or the citywide combined heat and power (CHP) network.

CHP is the simultaneous production of power, heat, and, sometimes, chilled water for air-conditioning. CHP avoids transmission losses because electricity is generated close to the point of use. The simultaneous production of electricity and heat in a useable form enables substantial thermal efficiencies and reduces CO₂ production. CHP plants, therefore, have lower fuel requirements and lower costs in comparison to conventional energy supplies. These systems are particularly effective in urban areas with compact layouts. Sustainable solutions can also consider harnessing excreted heat from tall buildings for use elsewhere in the city. Sharing the heat and power across the city has the potential to reduce overall energy use, greenhouse gas emission, and cost (Toderian, 2008). Energy spent on maintenance and repairs should also be included in operational energy. A sustainable tall building should be designed keeping this in mind to minimise the energy consumption. Further, energy analysis could examine if a building can take advantage of adjacent natural resources, such as the water of lakes and rivers.
2.2.3 Deconstruction

When buildings deteriorate with age or lack of maintenance, they reach their end stage of service life. An energy-related topic that is not discussed much and, for which little or no research has been conducted, is the deconstruction of tall buildings. Deconstruction is often viewed in terms of material reuse and recycling. However, a large amount of energy is spent during the deconstruction of a tall building. Deconstruction is the process of taking a building apart into its constituents in such a way that they can be more readily reused or recycled later. In addition to the reuse and recycling potential of its materials, it involves energy consumption. Deconstruction should be considered in the early design phase of a tall building in terms of energy consumption and other potential benefits. For example, use of prefabricated components and reversible connections using bolts will contribute to achieving the goals of sustainability in design. Unlike a monolithic concrete structure, precast, as well as modular structural assembly, should be considered whenever possible.

2.3 Transportation

Sustainability has provided new ways to evaluate transportation and land use plans. One of the new evaluation measures of the proposed plans is to quantify the generated CO2 emission. The proposed locations of towers in relation to commercial offices, retail services, and schools impact people’s choices of travel route and mode of transport. Simply put, when services are located within walking distances, people walk rather than drive; and therefore, no additional CO2 is generated. When services and jobs are located very far, for example, 80+ km (50+ mi) or so, less people are willing to travel and hence less CO2 is produced. However, placing activities at medium-range travel distance encourages people to use cars and therefore much higher amounts of CO2 are generated (Headicar and Echenique, 2010).

Reducing the need to use automobiles is an essential principle in evaluating new tall building projects. Tall building development supports sustainable mobility when the site is in proximity to public transport and mass transit, and when it supports environmentally clean modes of transportation, such as bicycling and walking. A tall building development at a site which increases the use of private transport is less sustainable than one that is close to public transport nodes and encourages their use by the occupant. Public transport has a much lower negative impact on society than the private automobile since it is less polluting per capita, more energy efficient, more socially cohesive, and cheaper. Clearly, transportation nodes located within close distance from tall buildings are highly desirable (Cervero, 2009). Wide sidewalks, inviting streetscapes and other design elements that encourage people to walk to nearby conveniences and mass-transit stations should be provided. Walking in particular should be emphasised since it is healthy, clean, and the most reliable form of transportation. In cold climates, protected walking environments and indoor residential connections are desirable.

The impact of the tall building development on services, delivery hours, and freight should also be assessed. Cities that have incorporated tall buildings without consideration for the large human, vehicular, and freight traffic they generate have major congestion, pollution, and parking problems, which downgrade the quality of city life and increase overall carbon output. Since tall buildings increase density, it is important to take measures to prevent the problem of overcrowding. This problem can be potentially
mitigated by clustering tall building development near open spaces, such as parks, gardens, public squares, and tree-lined streets that lend a green and inviting feel to the community.

3 Sustainable design features, technologies, and strategies

Buildings exert a profound impact on the environmental and economic aspects of cities (USGBC, 2011). The building sector ranks as the largest energy consumer and greenhouse gas emitter in a country. It can be predicted that in the future a large fraction of the country's built environment will be either new or renovated (Aarden, 2006). In response to this growing global awareness, builders, planners, and architects are advocating green structures and communities by implementing methods and materials for sustainability and efficiency. Today, we witness a paradigm shift in designing tall buildings that emphasise the use of green and sustainable building materials and technologies. The newest skyscrapers in many cities embody sustainable design, incorporating key environmental and quality-of-life aspects into their design and construction (Foster et al., 2008).

3.1 Site

Site has a profound influence on sustainability. This has been amply recognised by USGBC in formulating the LEEDS criteria for certification. Usually, site analysis is part of a schematic design of any building including the tall building.

3.1.1 Site selection

A primary goal of site selection for a development is to avoid taking up any farmland, countryside, or wetlands, and should not be part of a leap-frog development. Sustainable strategies may be employed by converting abandoned urban lots into vibrant architectural spaces, redeveloping older buildings, and choosing new sites that are close to existing communities and infrastructure. The proposed development should also minimise impact on ecosystems and waterways.

3.1.2 Site development

A tall building development is viewed as one component of a larger watershed plan that improves a region’s water quality by reducing polluted storm water entering rivers and streams. The development incorporates a system of storm water treatment onsite to reduce impervious surfaces so that storm water can infiltrate to recharge groundwater and surface water. This will, in turn, minimise the quantity of water that is eventually piped to streams and rivers. The proposed development can also reduce erosion, light pollution, the heat island effect, and construction-related pollution.

3.1.2.1 Landscaping

Appropriate landscaping not only beautifies a site but also helps in improving water management by absorbing and filtering water and delaying, and even preventing,
flooding events. Native landscaping should be encouraged because it supports the local ecology by attracting a variety of birds, butterflies, and other animals. Once established, native plants usually do not need fertilisers, herbicides, pesticides, or watering, thus benefiting the environment and reducing maintenance costs. Trees and green plantations around tall buildings can reduce CO₂ in the environment as well.

3.1.2.2 Permeable pavement

Porous or permeable pavement has multiple advantages, including reducing impervious areas, recharging groundwater, improving water quality, and reducing the need for detention basins.

3.1.2.3 Swales

Depressed land areas between slopes called swales have several advantages that include the reduction of peak flows, the removal of pollutants, the promotion of runoff infiltration, and lower capital costs. When combined with trees, they can help in reducing soil runoff recharging ground water, and in creating rich and green landscapes.

3.1.2.4 Stormwater management

Building tall on a small footprint potentially increases pervious land surfaces that can absorb excessive rainfall and reduce surface runoff, particularly important in areas where climate change predictions are forecasting increasingly severe storms and rainfalls.

3.2 Sustainable architecture

It is very important that architects and engineers take a comprehensive and integrated approach for building design that simultaneously considers the wide range of issues, such as lighting, ventilation, energy, building materials, etc. following the tenets of sustainable architecture (Wood, 2009). Green design should also be tailored to meet the requirements and challenges of the specific site. Ideally speaking, a zero-energy, zero-waste, and carbon neutral tall building is the ultimate goal for sustainable tall buildings. The closer a designer can approach this goal, the more sustainable the building will be.

3.2.1 Passive energy design

Of major impact on a building’s energy consumption is the fundamental early decision that building designers make in respect to size, form, shape, skin, and the location of cores, etc. – all relative to the specific site context and natural environment.

3.2.1.1 Daylighting

Required energy for lighting accounts for a large portion of the fuel bill for tall buildings, and can be greatly reduced by the use of natural daylight. Due to required setbacks and height above neighbouring buildings, high-rise buildings are less constrained than low-rise buildings by land plot shape and street layout in terms of maximum daylight
advantage. Tall buildings often have large transparent curtain walls. Useful daylight penetrates about 3–6 m (10–20 ft) inside a building from the windows, and shallower floor plates maximise the use of daylight. The width of the building, height of the ceiling, height and width of the windows, geographic location, and orientation of the building in relation to the seasonal paths of the sun across the sky all have a significant impact on daylight provision (Arend et al., 2011).

There is a fine balance between maximising glazing in the façade of a building to harness daylight and minimising the heat transmission properties which influence thermal comfort conditions and heating/cooling loads. Adopting a glazed area of 25% to 30% of the exterior building surface is an optimum value with 50% being a practical limit. For example, Ken Shuttleworth, architect for such noteworthy tall buildings as the abundantly glazed Swiss Re Tower in London, while he was employed at Foster and Partners, believes that façade design is on the frontline of change (Wood, 2008). He argues that due to environmental considerations, the all-glass tower model has to be altered so that a sizable proportion of the building is not glazed. Shuttleworth used only 50% glazing for the Kite Tower at Leeds, UK, that he designed.

3.2.1.2 Natural ventilation

Wind can be utilised to provide natural ‘free’ ventilation and cooling rather than using mechanical air-conditioning, which requires considerable energy. By allowing air into and through the internal spaces of the building, natural air conditioning can be achieved. Fresh air can also create a healthier internal environment and raise the comfort level and productivity of occupants. Building occupants get the opportunity to regulate fresh air coming into the building, helping them to adjust the airflow as required.

3.2.2 Façade technology

Tall buildings with transparent glazed curtain walls allowing sunlight to penetrate lead to higher heat gain and heat loss, thereby increasing their cooling and heating loads. To manage sunlight appropriately, innovative window systems have been developed to include elements which both maximise and minimise light. External solar shading can be added to lower sections of windows, while higher sections may reflect sunlight on to the ceiling plane. Different types of glass and applicable films are also available to enhance the performance of lighting, and heat gains and losses in the work space.

Among the prevailing façade engineering solutions are the use of double skins (two layers of glass separated by an air space), occasionally triple skins, and façades with natural ventilation systems. These façades can accommodate ventilation that is either continuous or controlled. Continuous ventilation maintains a constant connection between the surrounding environment and an air gap enclosed by the outer skin. This air gap has a constant air supply and an exhaust opening that remains always open. In case of controlled ventilation, openings in ventilation systems can be regulated by dampers which allow a modification of the temperatures within the air gap (Behr, 2001). The premium paid in increased embodied energy of materials involved in improving the thermal insulating properties of façades is often paid back in reduced energy consumption over the life of the building.
3.2.3 Artificial lighting systems

Lighting control systems and energy-efficient lamp technologies can be integrated with daylight to provide reductions in overall consumption. Automatic lighting systems and internal space sensors can allow control of electric lighting that leads to higher utility efficiencies. Daylighting with continuous dimming of artificial lighting can account for 25-40% of energy savings for internal lighting. New technologies and innovative strategies are providing new lighting capabilities and energy saving designs. Re-lamping of existing tall buildings with energy-efficient lamps can potentially cut energy consumption and running costs. However, the cost of new fixtures and lamps will increase the initial cost and hence the life cycle cost benefits may not be obvious, although such benefits could be achievable if the cost of fixtures can be reduced.

3.2.4 Intelligent systems

Innovative building technologies, such as computer-based smart or intelligent building systems, can play a major role in managing the energy usage. The increasing reliance on computer technology and automated systems can be directed toward achieving a sustainable functioning of skyscrapers. The building management system (BMS) is a centralised control system used to manage the operations of various building systems, such as fire protection, security, communication, elevators, HVAC systems, etc. The component of the BMS that deals with energy-related services is controlled by the building energy management system (BEMS), also known as the energy management and control system (EMCS).

3.2.5 Building materials

Sustainable tall building development encourages using local materials in order to support the local economy and reduce travel distances. Construction requires a very large percentage of raw materials and a high-rise building will likely use more materials in construction than an equivalent usable area low-rise building. Depending upon its location, a tall building will consume steel amounting to about 150 kg/m² (30 lb/sq ft) of gross floor area, whereas a low-rise building might use one-half of that (Guthrie, 2008). More material means more energy used in production and transportation, more consumption of natural resources, more waste, and more CO₂ emission. Locally sourced materials, aggregates from waste processes, and off- or on-site prefabrication can all contribute to a reduction in the use of new and raw materials as well as reducing cost, energy use, and most importantly, the need for landfills.

Use of ‘green’ materials can play an important role for savings in operational energy. For example, wood, concrete, and masonry, whether used for structural or non-structural applications, can save more energy through their thermal mass than aluminium or steel. Further, use of energy for repair and maintenance also adds to operational energy. Thermal mass of a material is defined as its ability to absorb, store, and release heat when needed. The most energy is saved when significant reversals in heat flow occur within a wall during the day. Mass has the greatest benefit in climates where large temperature fluctuations occur above and below the balance point of the building. Thermal mass in buildings will improve the performance in most climates. Research on buildings in the Gulf region indicates that the heavyweight building has a peak load of 40% less than the lightweight building (Guthrie, 2008). Building materials vary in the way they absorb and
dissipate that heat energy by their thermal mass characteristics. Concrete buildings have a higher thermal mass than steel buildings and naturally lend themselves to nighttime heat purges and their fire resistance permits the structure to be exposed.

3.2.5.1 Economics of scale

Refinements of design, such as repetitive floor plans and modular structural member sizes, can offer major savings in materials. Procurement of large quantities can lead to more efficient production and cheaper unit costs. Sustainability benefits can also be derived during the construction process through modern methods of manufacture and off-site fabrication. Such processes can considerably contribute to the construction programming and economic viability of tall buildings, especially where repeating elements allow for reductions in waste and improvements in constructability, tolerances, logistics, and on-site safety.

3.2.5.2 Structural optimisation

Any saving in structural materials via construction methods and structural design is significant in that it prevents the waste of precious natural resources and reduces the embodied energy – two important goals of sustainability. Structural material selection (steel, concrete, or composite steel-concrete) by designers, and scheduling, as well as means and methods of construction, can have considerable effect on a building’s construction time and cost. Tall structures should be designed to resist the forces of nature due to gravity, i.e., resulting from the vertical live and dead loads as well as lateral loads due to wind and earthquakes. For tall buildings, steel and concrete are preferred materials because of their high strength-to-volume ratio, acceptable behavioural characteristics, and possible effective structural planning strategies to minimise material consumption. The shape and profile of a tall building determine its performance in wind.

3.2.5.3 Climate change

Sustainable building materials should be selected to minimise their impact on global warming and ensure that they can adapt to anticipated climate changes. Both steel and concrete used for tall buildings are fossil fuel-intensive materials, and concrete has a higher rate of carbon emission compared to steel. Detailed studies on LCA based on accurate data collection with regard to climate change are still lacking. Some buildings, however, are already being designed so that they will be able to cope with future climate change. In this regard, the European Commission has identified the future market opportunity for climate-adaptive buildings.

3.2.5.4 Recycled materials

Many construction materials are available that were once something else. More and more interior and finish materials are being produced from recycled every-day goods such as carpet (polyester), carpet cushion, reprocessed and consolidated latex paints, gypsum wallboard, flowable fill, structural fibreboard, laminated paperboard, and modular threshold ramps. Other such items are non-pressure pipe, railroad grade crossing surfaces, floor tiles, patio blocks, and shower and restroom partitions. The 58-story Comcast
Center in Philadelphia provides a good example of making use of recycled materials. After deconstructing the pre-existing 9-story building, developers recycled and then utilised 90% of the demolished building in the new structure.

### 3.2.6 Building’s end-of-life scenario

The building end-of-life stage is reached when a building has deteriorated beyond repair and requires demolition. There is a direct relationship between the physical design features of a building and what can be done with it and its components when it reaches its end-of-life stage. Therefore, the design and building materials should consider the deconstruction process so as to achieve a more environmentally beneficial end-of-life scenario. The process of the disassembly of structures for reusing components and building materials for other projects can significantly reduce the solid waste burden the construction industry imposes on the environment. Through deconstruction, natural resources are saved, employment and training opportunities are created, and local businesses are developed that use the materials diverted from landfills. Deconstruction can supply useful materials to building material yards, recycling centres, and remanufacturing enterprises, creating new job opportunities and local revenue. Because tall buildings are massive in scale, their large amounts of materials can be put to beneficial use when they are deconstructed.

### 3.2.7 Core design

Cores are crucial to the viability of tall buildings since they provide a path for building services, vertical transportation, and a means of escape; as well as contributing to the structural stability of a building. It is the core where much of the systems’ integration takes place. Single core arrangement is most common in tall buildings. From sustainability point of view, dual cores, however, are preferable for tall and supertall buildings for several reasons. Dual concrete cores provide the opportunity to place them near perimeter so that they provide additional thermal mass for energy efficiency and added lateral stiffness against building sway in high winds. Also, when double cores are placed near the perimeter, they may allow natural daylight and ventilation to the elements within and near the cores such as stairways, elevators areas, and lobbies. In addition, two perimeter cores allow a second path of escape during fire. When single cores are employed, they should be placed at the centre of the building so that they strategically serve the buildings and provide efficient circulation. For tall buildings in hot climates, the cores can be positioned to maximise the benefits of natural daylighting, while reducing solar gain by shielding. In cold climates, the cores can be positioned to protect from the cold winter winds. In terms of the monetary value invested in tall buildings, the service core usually commands the highest relative investment. Therefore, it is desirable that the core is arranged with the greatest level of compactness and efficiency possible to maximise usable floor space and reduce construction costs and energy consumption. Whether a single or double core will be employed depends on the size, geometry, and functions of the building. More research is needed on this issue (Trabucco, 2008).
3.2.8 Vertical transportation

Vertical transportation by elevators and escalators impacts efficiency in energy consumption and people movements. Vertical transportation generally accounts for about 5% to 10% of the building energy consumption. Sustainable tall buildings should take advantage of the recent technological solutions that maximise efficiency and minimise energy usage of lifts. For example, a ‘regenerative elevator’ is being proposed whereby energy captured by descending cars is used to help power ascending ones. Further, design configurations can improve efficiency of the net-to-gross floor area ratio. Such as, the double-decker elevators in the Petronas Towers in Kuala Lumpur double efficiencies of single-decker elevators. The use of variable speed gearless elevators with intelligent programming and energy recovery can also reduce energy consumption by as much as 50%.

3.2.9 Vertical landscaping

Vertical landscaping is aimed at improving air quality, ambience, amenity space, visual quality, ecology, storm water management, energy conservation, air cleaning, and mitigating urban heat island effects, to name a few. Among the prevailing green elements for vertical landscaping are sky gardens, sky courts, green roofs, green terraces, waterfalls, vertical green walls, and continuous ramps of vegetation around a building. Green roofs increase energy efficiency (from cooling in the summer and added insulation in the winter), provide longer roof membrane life span, improve fire resistance and sound insulation, increase marketability, and improve the ability to turn wasted roof space into various types of amenity space for building occupants. Green roofs filter particulate matter from the air, retain and cleanse storm water, and provide new opportunities for biodiversity preservation and habitat creation. They generate aesthetic benefits and help reduce the ‘urban heat island effect’ – the overheating of cities in the summer which contributes to air pollution and increased energy consumption. Life cycle costing indicates that green roofs cost the same or less than conventional roofing, while also contributing significant social, environmental, and economic benefits for both the public and private sectors.

3.2.10 Water conservation

Fresh water is a valuable natural resource and tall buildings have a major responsibility to conserve water by reducing use, and collecting and recycling grey water to utilise for toilet flushing, irrigation, and other purposes. Therefore, it will be increasingly advantageous to devise systems that minimise water consumption and waste water discharge through new approaches in services design. The opportunity to do this is greater in residential buildings than in office buildings. The design of recycling systems should ensure that the energy used in pumping and treating water does not negate the water saving in the overall sustainability equation. There are practical considerations and simple water conservation techniques that apply to high-rise building design (Yeang, 2007).
3.2.10.1 Rainwater collection

Rainwater can be collected from building roofs and façades, treated, and then used in flushing toilets, urinals, washing machines, and outside tap use. This volume of water is kept out of the stormwater management system, thereby reducing flooding risk. The size of the storage tank is determined by considering the amount of water available as a function of roof area and local average rainfall.

3.2.10.2 Recycled water

Grey water recycling is another process in which water from bath, shower, and hand wash basins are reused in landscaping, or utilised in a heating and cooling system, toilets, washing machines, and outside tap or other creative ways. In tall buildings, recycling grey water can make a significant difference in the amount of wastewater that is displaced into city sewer systems.

3.3 Renewable energy

Future tall buildings are poised to become ‘zero energy’ or even ‘positive energy’ so that in the course of a year they generate as much energy or even more than they use and supply excess energy to the city’s power grid. Tall buildings offer a great potential for harnessing solar and wind energy. Thus, future tall buildings have the potential for acting as ‘batteries’ to produce energy.

3.3.1 Photovoltaics

Photovoltaic (PV) technology converts solar energy to electricity and is increasingly in demand. Given tall buildings’ skin area-to-volume ratio, they have a great potential to employ PV, and tall buildings have taken great steps in integrating PV in their design. The geographic location makes a difference on efficiencies and electrical output of PV as shown in Table 1. For example, if PV panels were to be placed on a building in London, they would only generate half the energy of the same PV panels placed on a building in Delhi. New environmental computer programmes are helping in optimising PV integration into buildings. PV panels on the rooftop should be tapered according to the optimal tilt. If PV panels were applied on buildings’ sides that face the sun, the façade’s profile could embrace tapered forms to maintain the optimal angle. However, this may create a design challenge and new forms and geometries need to be explored. In the case of employing a double skin façade (two layers of glass separated by an air space), the solution is plausible by making the external skin jagged so that PV panels meet the optimal tilt, while the internal skin could remain vertical. The resulted space between the two skins could serve to improve the thermal performance of the building. Dynamic mechanical solutions that rotate solar panels to maintain optimal angles with the sun path are also possible. Interestingly, while architects explore new forms and geometries that cater to solar issues, they may arrive at new exciting architectural expressions denoting ‘green aesthetics’ (Al-Kodmany, 2010).
Table 1  Indicators of output for mono-crystalline panels used in major cities

<table>
<thead>
<tr>
<th>City</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Optimum tilt</th>
<th>Output KWH/m²/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delhi</td>
<td>28°35’N</td>
<td>77°12’E</td>
<td>30°</td>
<td>233</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>33°56’N</td>
<td>118°23’W</td>
<td>30°</td>
<td>233</td>
</tr>
<tr>
<td>Cape Town</td>
<td>33°54’S</td>
<td>18°32’E</td>
<td>30°</td>
<td>232</td>
</tr>
<tr>
<td>Mexico City</td>
<td>19°24’N</td>
<td>99°11’W</td>
<td>20°</td>
<td>205</td>
</tr>
<tr>
<td>Athens</td>
<td>37°58’N</td>
<td>24°43’E</td>
<td>30°</td>
<td>183</td>
</tr>
<tr>
<td>Melbourne</td>
<td>37°49’S</td>
<td>144°58’E</td>
<td>30°</td>
<td>182</td>
</tr>
<tr>
<td>Rome</td>
<td>41°54’N</td>
<td>12°29’E</td>
<td>35°</td>
<td>191</td>
</tr>
<tr>
<td>Oslo</td>
<td>59°56’N</td>
<td>10°44’E</td>
<td>45°</td>
<td>180</td>
</tr>
<tr>
<td>New York</td>
<td>40°42’N</td>
<td>74°01’W</td>
<td>35°</td>
<td>169</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>22°18’N</td>
<td>114°10’E</td>
<td>20°</td>
<td>156</td>
</tr>
<tr>
<td>Tokyo</td>
<td>35°41’N</td>
<td>139°46’N</td>
<td>30°</td>
<td>149</td>
</tr>
<tr>
<td>Geneva</td>
<td>46°12’N</td>
<td>06°09’E</td>
<td>30°</td>
<td>143</td>
</tr>
<tr>
<td>Berlin</td>
<td>52°27’N</td>
<td>13°18’E</td>
<td>35°</td>
<td>121</td>
</tr>
<tr>
<td>Moscow</td>
<td>55°45’N</td>
<td>37°34’E</td>
<td>40°</td>
<td>119</td>
</tr>
<tr>
<td>London</td>
<td>51°29’N</td>
<td>00°27’W</td>
<td>30°</td>
<td>111</td>
</tr>
</tbody>
</table>

Source: Pank et al. (2002)

3.3.2 Wind harnessing

Some cities enjoy wind speeds and patterns that qualify them to harness such wind for power generation, and planners should check on how much power can be generated out of a city’s wind pattern (Killa and Smith, 2008). If there is little wind to start with, employing turbines will not yield much power (Denoon et al., 2008). Urban cores often pose a significant challenge to the efficiency of wind turbines. Due to zoning regulations on FAR, height, etc., most tall buildings are likely to be of close height range. These buildings slow the wind near to the ground and increase wind turbulence, reducing the efficiency of wind turbines. It has been estimated that wind velocity within a city is half of what it is over open water and that, at the edge of a town, velocity is reduced by a third. There have been tall building examples where wind turbines are mounted atop the building, or incorporated in the building’s exterior or shells. Also, environmental computer software and Wind Map Resources help in optimising the location of tall buildings to harness wind power.

3.3.3 Biomass

Biomass is a renewable energy source, where biological materials derived from living, or recently living organisms, such as plant materials, wood, and animal waste are used as fuel. It can be used to power tri-generation systems (combined heating, cooling, and power production). Substantial amounts of biomass are ubiquitous in tall office buildings in the form of paper, most of which is used only briefly and trashed. The waste paper output would produce a significant amount of the system’s fuel required.
3.3.4 Geothermal energy

Geothermal energy is one of the most plentiful renewable energy resources. Since tall buildings most often are built deep into the ground, this form of energy can be extracted to support the functioning of the building. The Linked Hybrid in Beijing, China, employs 660 geothermal wells that descend about 100 m (328 ft) deep. The geothermal wells cool the complex in summer and heat it in winter, eliminating the need for boilers or electrical air conditioners.

3.4 Tall buildings and birds

Bird-building collisions are an unfortunate side effect of tall building development throughout the world; where hundreds of millions of birds perish each year from collisions with tall buildings. Approximately 98% of flying vertebrates (birds and bats) migrate at heights below 500 m (1,640 ft) during spring, with 75% flying below that level in fall. Today, many of the tallest buildings in the world reach or come close to the upper limits of bird migration paths. Birds are killed or injured as a result of clear and reflective glass – clear glass is perceived by birds as an unobstructed passageway and they attempt to fly through it; and reflective glass reflects sky, clouds, and nearby vegetation reproducing a perceived habitat familiar and attractive to birds. Consequently, prevailing modern all-glass tall buildings present serious hazards for birds. Further, artificial lighting confounds night-migrating species. Ironically, ‘building green’ promotes incorporating bird habitats in cities (since parks, vegetations, green roofs, and water surfaces invite birds) and requires incorporating plenty of glass to ensure daylight in buildings – a deadly combination for birds.

Fortunately, awareness and preventative measures are being taken by drafting bird-safe building guidelines and standards. New standards are reflected in the newer versions of LEED – an internationally-recognised green building certification system. In relation to tall buildings, these new standards deal with exterior glass choices and technology and nightlight considerations. Recommendations emphasise utilising etching, fritting, translucent, and opaque patterned glass, window films featuring artwork, and exterior and interior shading devices to reduce transparency and reflection. It is also recommended to incorporate windows with real or applied divided lights to break up large window expanses into smaller subdivisions. Further, rooftop obstacles, such as antennas and media equipment, can injure or kill birds and should be carefully designed.

3.5 New technologies

The ‘next generation’ sustainable tall building design will emphasise employing cutting-edge technologies such as nanotechnology. Nanotechnology provides extra strength materials which save space taken up by structural supports. Other materials include nanopaint, which can act as an air purifier and reduce pollution. When exposed to ultraviolet light, titanium dioxide (TiO₂) nanoparticles in paint break down the organic and inorganic pollutants that wash off in the rain. The nanoparticles also decompose air pollution particles, such as formaldehyde. Another application is the solar nanotechnology. Ultra-thin, amorphous silicon, organic and inorganic solar cells derived from nanocrystals can convert sunlight into electricity at a fraction of the cost of silicon-based solar cells. With nanotechnology, tiny solar cells can be printed onto
flexible, very thin light retaining materials, a less expensive alternative to silicon. Such technologies have great potential for future tall buildings.

4 Discussion

This paper argues for the need for embracing a holistic approach for achieving sustainable tall building development. The presented recommendations are meant to outline the many available possibilities and choices for promoting sustainable tall building development. On practical grounds, it is impossible to apply all the sustainable recommendations to a given project, and there are always trade-offs between different considerations. Therefore, planners and architects need to be provided with an evaluative account that considers the intricacy, inter-relatedness, and feasibility of applying these recommendations. Evaluation helps to assess the true value of sustainable features in different geographic and socio-economic contexts. Prioritising schemes based on economic and environmental conditions should also be developed so that choices and preferences are filtered and ranked. The following discussion is meant to serve these purposes. It centres on the three main dimensions of sustainability: economic, environment, and social.

4.1 Economic

Overall, tall buildings could potentially be a viable solution in dense urban environments where land is scarce and expensive. However, there are several economic disadvantages and depending on the context, alternative type of buildings such as mid-rises should be considered. Economically, tall building construction requires an extra premium because of their need for sophisticated foundations, structural systems to carry high wind loads, and high-tech mechanical, electrical, elevator, and fire-resistant systems. In addition, a large core area is needed to accommodate elevators and building services systems. Although mega-story skyscrapers provide more interior space than typical low-rise buildings on a given plot of land, they also cost more to significantly fortify them against the fierce natural forces of gravity, high wind, and earth tremors. Stronger structural systems are needed to withstand a stronger wind at higher altitude, and to carry larger loads. The high slenderness ratio makes the structural system more expensive. Vertical transportation, including elevators and stairways, is needed for daily and emergency use. While 70% of a skyscraper is usable space (the remainder being the building’s elevator core, stairwells, and columns), more than 80% of low-rise spaces are typically useable (Mann, 1992). Tall buildings also suffer from higher operational costs, such as elevator maintenance and emergency response preparedness. Also, in difficult economic times, towers simply may not generate enough sales or rental value to support the high quality of design, materials, and detailing. This situation risks producing low quality towers that maximise floor area at the expense of good design. Therefore, generally speaking, tall buildings rank low on the economic measure and unless there are compelling reasons for constructing them, other types of buildings should be considered.

However, it is important to note that the economics of building tall is ultimately a matter of local conditions and location. It can be the lowest-cost solution in a developed country in a location with other high-rises where the needed infrastructure and urban
services are in place with adequate capacity. Tall buildings fit in well where business and organisational structures are geared to large-quantity operations; where building materials are plentiful; and where there is an adequate force of skilled labour. Building tall could be the highest-cost solution when those factors do not exist; the negative impact of these missing resources must be considered carefully. Without great care in such situations, the cost of adjacent land could be pushed up to create higher costs per unit for structures yet to be built. Further, in some situations where land costs are low, as in smaller cities, tall buildings may be unprofitable because of anticipated high vacancy rates. Also to be considered is the general economic climate at the particular point in time (Yeang, 2008).

With the increasing economic uncertainty and market fluctuations, (e.g., the current global recession), building’s vacancy is a potential threat to tall buildings’ success. In response, mixed-used themes are preferred for ability to cater to changing needs and hence ensure a minimum level of building occupancy. Also, adaptive reuse should be encouraged so that tall buildings could cater to changing needs, market fluctuation, and new functional uses. Consequently, mixed-used schemes and adaptive reuse consideration enable tall buildings to reduce the impact of economic uncertainty and market changes. Furthermore, economic downtown may discourage employing green design features because they require additional initial costs. In this regard, architects should carefully evaluate the market conditions and recommend the most plausible and affordable sustainable features. At the same time, they should keep in mind the most critical issues pertaining sustainable tall building development. For example, tall buildings continue to be a major energy consumer. Therefore, any efforts that reduce their energy consumption and produce energy on-the-site should be stressed.

4.2 Environment

The geographic context and climatic conditions are critical to decide on the appropriate sustainable design method, techniques, and features. For example, employing green design through passive systems will be greatly influenced by the local climate. Strong winds or driving rain on the higher parts of very tall structures prevent employing operable windows. In other words, natural ventilation of offices will be harder to achieve in the taller high-rise buildings, due to increased wind speeds and noise at height, which prevent employing operable windows. In places that enjoy calm winds and moderate climate it is more plausible to apply passive systems. For example, Menara Mesiniaga in Selangor, Malaysia, a 16-sotry building by Ken Yeang, enjoys 100% natural ventilation via operable windows. Through articulation of the exterior surface and by partially opening the top of the building, via a louvered sunroof, the whole building, from stairways and central cores, lobbies, to the toilet areas, is naturally ventilated. Potentially, in colder climates mechanical ventilation systems can be more economical than naturally ventilated solutions due to the ability to recover heat from the exhaust air to preheat the fresh air (Abel, 2003).

In areas that experience excessive rain, the role of tall building development in mitigating surface run-off problems should be highlighted. This could be achieved, as mentioned earlier, through careful design of building facades, green roof, rainwater collection system, and employing impervious surfaces throughout the site. In contrast, areas that suffer from drought and water restrictions, water conservations and recycling techniques (such as rainwater collection, low flow wash hand basins, dual flow WC’s, dry urinals, grey water recycling) should be emphasised. Depending on the degree of
water scarcity these options should be stressed or relaxed. For example, a blackwater recycling system may be favoured over grey water recycling system to conserve more water. Blackwater systems recycle everything that goes down the drains including toilet water, fecal matter, and urine; while grey water systems recycle water of limited activities such as laundry, dishwashing, and bathing. In the same manner, applying green roofs for a large number of tall buildings in downtowns should be stressed in order to reduce urban heat island effect and reduce the required energy to cool buildings in summer times.

The key to having a net zero CO$_2$ building is the ability to create the required energy on-the-site. This is greatly influenced by the geographical location as well as specific site constraints. Depending on the context, tall buildings may enjoy unrestricted solar access, and PV can be used as a cladding system and as an energy producer simultaneously. However, the geographic location makes a difference in the harnessed energy. For example, if a solar array were to be placed on a building in London, UK, this would only generate half the energy of the same collector area situated in Damascus, Syria. The same applies to generating domestic hot water from solar plate exchangers or evacuated tube solar thermal collectors. On practical grounds, tall buildings’ roof areas are small compared to the overall building surface area, and therefore harnessing solar energy by PV panels placed on the rooftop is limited. Tall buildings in dense urban context can also suffer from over shading problem. Large portions of buildings’ facades are likely to be in shade – and therefore, applying solar PV is less productive. Harnessing wind power also could be limited to high-rises in dense urban areas. It has been estimated that wind velocity within a city is half of what it is over open water and that, at the edge of a town, velocity is reduced by a third.

Overall, current technologies for harnessing solar and wind power continue to be relatively less robust than desired. The produced energy continues to be marginal. For example, the Bahrain World Trade Center in Bahrain, Manama, viewed as a leading example in employing wind turbines, produces only 10% to 15% of the building’s needed energy. Collectively, given the limitations of harnessing solar and wind power in dense urban cores – since tall buildings block sun and wind from each other – combined with technological shortcomings, currently tall buildings have little chances to achieve zero net energy by only using onsite renewable technologies.

4.3 Social

Society and culture play a key role in accepting or rejecting tall building development altogether. In societies where living in a high-rise is the norm, local culture will have no problem with adding new tall buildings. People who were born and reared in tall buildings usually have no problem continuing to live in that environment. In contrast, people in some traditional societies who have been living for centuries in low-rise buildings may initially feel uncomfortable with living in high-rises until they become adjusted to the new lifestyle.

By and large, there is a noticeable shift from low-rise living to high-rise living. Many rural immigrants who lived for long in low-rises are accepting high-rise living in cities. In the USA, there is a renewed interest in living in city cores and pursing high-rise living. This is remarkable since residential high-rises were largely stigmatised after demolishing public housing high-rises, such as the Pruitt-Igoe housing project in St. Louis in 1972.
Such negative past experiences have been ingrained in the minds of a generation of planners and architects as well as the public. The demolition occurred in response to strong residential dissatisfaction and high levels of criminal activity. In China, however, high-rise residential blocks were accepted for long decades. Today, there is an increased desire toward high-rise living: it is regarded as aspirational symbolising a higher social class (Griffiths, 2011).

Indeed, the type of social community created in the high-rise is different from that found in the low-rise (Al-Kodmany, 1995). Therefore, urban planners and architects should pay attention to the socio-psychological impacts of living in high-rise housing (Normoyle and Foley, 1988). While high-rise housing may be desirable for single people and couples, it may be less desirable for a family with children. For example, mothers often are concerned about losing eye contact with their children at play on the ground floor (Aregger, 1967). Some sociologists argue that the environment of tall buildings can make inhabitants feel claustrophobic by creating a rat-cage mentality. It is argued that low-rise living is closer to nature and facilitates a stronger community-oriented social life. As structures grow taller and taller, tenants become out of touch with the city life below.

5 Conclusions

This paper attempted to present a comprehensive approach to sustainable tall buildings development. Any assessment of the environmental impact of tall buildings should take into account the many aspects concerning the influence exerted by them on their own internal environments and their external surroundings. A comprehensive approach should assess the impact on infrastructure, longevity of the building and its components in primary use and re-use, and contribution to the community at large. Other wider-context issues may address how a tall building’s energy supply systems can be integrated with the existing and future ‘low or zero carbon’ energy supply infrastructure. Sustainable design also should consider the location in relation to transportation so that travel distances and associated greenhouse gas emissions are reduced.

Environmental issues such as indoor quality, natural light, casting shadow, etc. are all interconnected and do impact the building itself, the site, and the neighbourhood. Sustainable tall buildings can not only ensure indoor air quality but can also contribute to outdoor environment. New technologies are enabling tall buildings to function as air filters to their neighbourhoods, for example, Bank of America in Manhattan, New York. The building’s embodied energy and the construction process may impact the neighbourhood and the city for transporting construction materials. Residents’ demography, profile, and lifestyle have profound social impacts on not only the building, but the community as a whole. Further, tall buildings have the potential to reconnect the community with nature.

It is intended that the presented comprehensive design approach for tall buildings will serve as basis for creating evaluative sustainable design tools. As explained earlier, currently, there are a number of environmental assessment processes, design tools and key performance indicators for sustainability (e.g., BREEAM, LEED, CEEQUAL, ARUP, SPEAR, M4i, and DEFRA). However, none of them are specifically intended for
Sustainable tall buildings assessing tall building development. Tall and supertall buildings are special projects of great significance: they are costly and their environmental, socio-economic, infrastructure, transportation and visual impacts are immense. Consequently, these projects deserve special sustainability assessment tools. This paper provided a comprehensive account of important sustainability issues that concern tall buildings development. It is hoped that the provided research will serve as groundwork for developing sustainability assessment tools for tall buildings.

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Sustainable tall buildings


