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The LCA of Tall Buildings: a Quick Pre-Design Assessment Tool

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Biography

Architect, PhD.
Dario is a research fellow at the IUAV University of Venice, Italy. His research activity if focused on the sustainable design of tall buildings, in particular of their service core. His activity is now centered on the lifecycle analysis of buildings, for the appraisal of alternative design solutions, materials, etc. through the use of an innovative methodology for the quantification of embodied energy based on Input/Output tables of economy exchange.
Dario is also co-chair of the CTBUH “Research, Academic and Postgraduate Working group” and CTBUH country representative for Italy.

Abstract

Tall buildings are always regarded as voracious energy consumers. This is true indeed, though important progresses have been achieved in the past 20 years. Innovative materials and upgraded technical solutions have reduced the running energy consumption of buildings consistently. On the other hand, little has been done to lower their embodied energy, that is the amount of energy required to produce and use the building materials the skyscraper is made of. Eventually, we can speculate that the embodied energy of tall buildings is even increased over the past few decades, as a consequence of the augmented complexity of structures and the multiplication of some parts of the buildings (double skin facades, extra insulation, etc.). This limits or even cancels the positive effects of some of the measures aimed at reducing the energy efficiency of tall buildings, worsening their Life Cycle Energy sustainability.
Indeed, it is difficult to verify the real efficacy of energy saving measures, because LCA analysis are difficult and time consuming. Also, they are not applicable to projects at the design stage and they can only be performed on completed structures.
This paper presents an alternative methodology for embodied energy quantification based on econometric procedures. As such, this methodology is easily applicable from the very early stages of design, thus allowing the quick assessment of design alternatives.

Keywords: Lifecycle Analysis, Embodied energy, Alternative sustainable design solutions.

The energy use of tall buildings

Tall Buildings have always been seen as important energy consumers. This can not be denied as some of their very unique features, or at least some distinctive aspects of their design that have become very common, cause an increase in their running energy consumption if compared to their low-rise equivalents: an office tower is very likely to consume more energy than a standard office building, and the same applies

for high-rise residences, hotel towers, etc. However, surveys show that only a marginal share of the overall energy consumption of a tall building is really a consequence of its height.
In the table below (Raman, 2001), typical values of energy consumption for a high rise building in New York are listed. The largest share of energy consumption, almost one fourth of the total, is caused by the use of office equipment (computers, printers, servers, etc.), whose energy consumption doesn't depend on whether they are employed in a high rise or a conventional building. The same applies for the production of hot water for domestic uses.

Table 1. Typical subdivision of the energy consumption of a tall building

Component	***% On the total***
Heating	20,6
Cooling	11,2
Evaporation towers	0,6
Moisture control	0,2
Domestic hot water	4,4
Ventilation/air pumps	17,8
Other pumps	0,9
Lighting	14,3
Office equipment	23,2
Lifts	6,6

Other aspects of energy consumption are only marginally affected by the height of the building directly, such as the HVAC expenses and lighting, even though height may have some impact (St Clair, 2010). While it can be acknowledged that the size of tall buildings generally limits an extensive use of natural ventilation (thus augmenting the needs for mechanical air handling), it is also true that the height of the building gives a benefit in terms of natural lighting, impacting positively on the electricity supplies of the tower.
The only voice of energy consumption that is directly connected to the fact that the building under consideration is a high rise building is the consumption of the lift system and, maybe, the "Other pumps" consumption. Lifts take an average of 5-10% of the whole consumption of the building, depending on its height, use and other parameters of traffic design: they need energy to be elevated, but they also cause drawbacks on the whole energy need of the building through the heat dissipation they produce because of their breaking system.
Accordingly, it can be said that most studies on the "sustainability" of tall buildings can be seen as studies on the "sustainability" of offices in general, or hotels, or residences.

The evolution of skyscrapers energy consumption

Previous studies of the author and colleagues (Oldfield, Trabucco and Wood, 2009), evidenced the existence of different "families" of skyscrapers that occurred at different times in the past, with one family evolving from the precedent one as a product of new technical features or as the consequence of external forces that affected the shape of the buildings, their appearance, etc. impacting on their running energy requirements.
Skyscrapers evolved in the last century following the introduction of new technical features, but also leading architectural innovation themselves. Until the end of the third generation period, the energy consumption of tall buildings have constantly increased as a consequence of the amelioration of indoor environmental conditions with the introduction of mechanical ventilation and air conditioning, increased lift performances, improved lighting, and so on

Table 2. Subdivision of the history of skyscraper history in five energy generations

Generation	Years	Notable examples	Specificities
1st	From the birth of tall buildings in 1885, to the 1916 Zoning Law	Woolworth, Equitable - New York; Monadnock - Chicago;	- compact shape - thick masonry walls - operable windows - gas lighting
2nd	From the 1916 Zoning Law to the development of the glazed curtain wall, 1951	Empire, Chrysler – New York; Palmolive – Chicago	- slender shape - appearance of air conditioning - larger windows

			- improved electric lighting
3rd	From the development of the glazed curtain wall, 1951, to the 1973 energy crisis	Lever House, Seagram, U.N. - New York; Sears Tower, Lake Shore Drive - Chicago; Fiat, Montparnasse -Paris	- "boxy" volume - fully glazed curtain walls - sealed windows - complete reliance on air mechanical ventilation
4th	From the energy crisis of 1973 to the present day	Aqua, Trump Tower - Chicago; Beekman, New York One Canary Warf, London Burj Khalifa, Dubai	- compliance to local energy codes - selective glazing - operable windows
5th	From the rise of an environmental consciousness in 1997 to the present day	Commertz bank – Frankfurt; 7th World Trade Center, 1 Bryant Park – New York; Palazzo Lombardia, Milan	- higher-than-average levels of energy efficiency - compliance to sustainable assessment tools - presence of "sustainable" features as solar shades, double skin façades, etc.

Energy efficient and zero energy tall buildings

The 1973 energy crisis brought a move toward more efficient buildings in general, and the trend involved also the design of tall buildings with lower running energy needs. The adoption of energy preservation building codes brought to a broad range of innovations aimed at reducing the energy needs of buildings, initially of their heating systems and from a broader perspective from the '80 onward.

Most initiatives consist in an improved design of the building envelope, so as to avoid excessive heat gain/loss, especially from glazed surfaces. While buildings of the fourth generation generally features conventional façade designs, where the performances of the glass panels installed are the most important characteristic aimed at the reduction of the heat exchanges between indoor spaces and the external environment, tall buildings from the 5th generation have much more complex façade designs. Buildings of this generation attain higher energy performances as a consequence of the use of multi-layered façades, solar shades, moving elements and the possibility to use natural ventilation to a certain degree.

In the last decade several proposals have been presented for zero energy tall buildings. Such buildings integrate highly energy efficient design principles with technologies for the on-site production of energy from renewable sources, notably wind and sun. The applicability of these devices in the urban context is arguable and limited to very specific cases. In fact, despite the large number of proposals that have been shown, at present there are only a handful of buildings that successfully integrate wind turbines or large photovoltaic systems and probably there is not a single skyscraper that is able to produce enough energy to fully compensate its own needs. In fact, such systems have proved to produce fewer energy than expected, especially when they are applied to tall buildings in dense urban settlements. In cities, dust, fog or shadows from other buildings limit the efficacy of photovoltaic technologies and the noise produced, the presence of induced wind gusts or the vibrations transmitted to the building prevent the full exploitation of wind turbines.

Consequences from a lifecycle perspective of "sustainable" design solutions

All such ameliorations of the energy efficiency of tall buildings have been achieved thanks to the addition of new materials, new components or entire new building elements. It is undisputable that strategies for the improvement of the running consumption of buildings have reached their goal in terms of on-site consumption but very little care has been paid to the lifecycle consequences introduced by such variations from the standard design.

Thought the overall benefits arising from the use of a coated glass panel or the introduction of thermal insulation in opaque walls are quite obvious, more attention has to be paid when conceiving complex double skin façades, sunshades or even more complex solutions. In fact, after a certain degree of energy efficiency has been achieved, it is much more difficult to reduce the energy consumption of the building further.

Of course the design of ever greener buildings is now a matter of fashion and a precise marketing strategy, however the topic of energy consumption should be addressed from a much wider perspective and also the production phase of the materials used in the project should be taken into account.

Life Cycle Assessment (LCA) is a tool that enables an overall quantification of the consequences caused and related to a human action, from an environmental point of view. LCA is a standardized procedure (described by ISO 14040 and 14044 norms) that was invented for industrial purposes for the management and the amelioration of production processes. Its use has then been extended to other purposes, such as the comparison of different products from an environmental point of view, though some problems on this may occur as it will be described later. If the only parameter of energy is assessed, an LCA is called LCEA, Life Cycle Energy Analysis.

In architecture, the quantification of the energy needs for the daily use of the building can be calculated as part of the design activity thanks to the use of specific software, and the expected results can then be assessed against data from the real building. On the contrary, it is much more complex to esteem the energy embodied in the building through the production of the materials it is made of, their transport to the building site and their installation. The embodied energy is a fundamental parameter to perform an LCEA analysis. Different studies (Treloar, Fay, Ilozor and Love, 2001), (Kofoworola and Gheewala, 2009) have tried to assess the embodied energy of tall buildings and they show that embodied energy represents a share of 15-30% of the total energy of a skyscraper over a 50 years lifespan.

Of course many factors affect this, such as the size of the building, the construction materials (especially its structural elements) and so on. However, it has to be noted that this results are likely to be conservative as the ISO-complying quantification procedure for embodied energy tends to neglect some aspects (such as those not-directly involved in the production process itself, but generated as a consequence of it). Studies suggest that embodied energy figures calculated with the methodology advised by ISO norms represent a value that is up to half the real embodied energy content of a good (Lengzen, 2001). Thus, it can be assumed that the embodied energy of a tall building represent 30 to 60% its lifecycle energy consumption and this share is likely to grow for the combined effect of an ever decreasing running energy consumption and the augmented complexity of buildings to achieve higher levels of energy efficiency.

This makes the problem of embodied energy in tall buildings even more important than how it as been regarded until now.

LCA as a design tool.

Therefore, it is important to address the problem of embodied energy from the early stages of a project, so as to avoid the use of design solutions, materials or components with a high embodied energy value. It would be beneficial to assess different designs of the same project with an LCEA analysis, in order to choose the most convenient design from a Life Cycle perspective.

Unfortunately, some major problems prevent the use of the LCA procedure for product comparisons, despite these are quite common in many fields, architecture in particular. For instance, it is not possible to decide whether its more "sustainable" the construction of a brick wall or a concrete wall or the use of a metal structure instead of a concrete beam. In fact, the quantification procedure of the energy embodied in a good is done according to ISO through the decomposition of its production process in smaller actions, and the quantification of the energy needed for that action to happen. The same procedure is repeated for the elements that are needed for that action to happen (ie: raw materials), and so on upstream. The problem, that makes results unreliable for comparisons, is the definition of the system boundary as it is impossible to repeat the process an infinite number of times and the analysis has to be cut somewhere. This results in an arbitrary decision of the inspector that makes two different LCAs not consistent one with the other as different boundaries may have been adopted (Treloar, 1998).

The problem of system boundary definition can be solved with the use of different accounting methodologies, such those that rely – or are based on – the Input/Output matrices that describe the exchanges happening within a Country's economy (Miller and Blair, 2009). The interest in such new methodology is now growing among the scientific community as shown by the results of a 6^{th} European framework research project (CALCAS, 2008). However, some drawbacks exist, and further research is needed to mitigate them. The IUAV University of Venice is carrying on a research project on the application of the Input/Output methodology for the LCEA analysis of tall buildings.

The following table lists the results obtained from a conventional LCEA analysis and with the adoption of the Input/Output methodology.

Table 3. Embodied energy of the structural elements for a 85 meter tall building

Building part	Building material	Quantity	Price €	EE LCA MJ	EE I/O MJ
Vertical structure	Concrete rck 30	1935 m^3	145.000	5.224.000	5.227.000

	Structural steel	540 T	1.231.000	13.176.000	17.189.000
Horizontal structure	Light concrete	2742 m³	548.400	3.836.000	4.354.000
	Rebars	786 T	414.300	19.335.600	19.730.000
Total embodied energy of the structural elements				**41.571.600**	**46.500.000**

LCA analysis of tall buildings

Regardless of the choice on the calculation methodology of embodied energy, tall buildings are a distinctive building typology that has specific construction features in addition to the usual building characteristics. These have a specific impact on the embodied energy of the skyscraper and specific design principles can help reduce the energy content of such building parts.

Structural system

The structural system has a very important impact on the LCEA of a tall building, especially for relatively high towers (Moon, 2008). This is the result of the combined effect of the increased quantity of structural materials and the typology of the structural materials themselves: steel, as most metals, is an energy intense building material while concrete, though not so energy intense per unit of mass, is needed in very large amounts, thus impacting seriously on the final embodied energy content of the building. The identification of the most suitable structural system can play an important role in the creation of a sustainable tower and also the shape of the building itself impacts seriously on the final result.

The widespread use of simulation software and innovative structural schemes have improved the efficiency of the structural systems conceived in the last few decades, if compared to those used in the first half of the twentieth Century.

Benefits in terms of sustainability can also arise from the adoption of dampers or other solution that may reduce the quantity of structural materials.

However, the picture is now getting more confused, as the relatively simple study of complex geometries (tilting or twisting buildings in particular) is now encouraging the design building with unusual shapes, resulting in an excessive use of structural materials.

Service core and lifts

The role of the service core in the embodied energy context requires a more detailed explanation: in order to do so, the importance of the efficient use of space in a tall building should be acknowledged. In fact, the total area of a skyscraper can be divided into Net Usable Area (NUA) and Service Area. The NUA is the part of the building that can be effectively dedicated to the purposes the skyscraper has been built for (office space, residential, institutional, hotel etc.), whereas the Service Area occupied by the service core is the space necessary to make the building functional, accessible and comfortable. In building practice the developer's objective is to maximize the NUA against the Gross Floor Area (GFA), thus maximizing the NUA/GFA ratio: the higher the ratio, the more efficient the use of space. If the amount of NUA required can be achieved with an efficient use of space, then the GFA of the building will be smaller than that obtained through a poorer design. Therefore, beside sound economic reasons, the efficient use of the built space can lead to important savings in terms of material use, and subsequently of embodied energy.

The NUA is between 90 - 75% of the GFA of a skyscraper and this value diminishes progressively as the height of the building increases (Trabucco, 2008). Though this is only an average figure, it can be considered a characteristic feature of tall building design. This means that the service core takes the corresponding 10 - 25% of the built surface and an equivalent share of embodied energy. By reducing this figure, the embodied energy of the whole building can decrease accordingly. For instance, estimations by the author on the 30 st. Mary Axe building in London (see note 14) shows that the embodied energy of a 40 story building can be as high as 1.500.000 GJ with a NUA/GFA ratio of 0,8. An increase of this figure to 0,85 can result in a building with the same NUA but much smaller, saving 75.000 GJ in terms of embodied energy and a corresponding decrease of surface-dependent running energy (lighting, HVAC, etc.). For reference, the annual energy consumption of the same building expressed in primary energy is of a different magnitude (roughly 28.000 GJ/year).

Facades

Facades, as stated before, are the most important feature to control the indoor environment and are responsible for a great deal of the overall energy efficiency of a tall building. However, the excessive marketing appeal of "sustainability" is leading to the design of excessively complex facades, whose benefits may not be so straightforward from an energy perspective. Additionally, some details that are conceived purely for aesthetic purposes can cause a negative impact, such as an excessive use of sun-shades: more and more often they are used for architectural purposes, rather than for environmental reasons or for light control, thus impacting negatively on the LCA of buildings. In fact, it should be remembered that any addition of material to the design of a building have a consequence not just in terms of cost, but also in term of sustainability as construction materials require enormous amounts of energy for their production.

Vertical greenery

Many design from the last decade have proposed the construction of sky gardens, green walls or roof top green areas, claiming a positive impact on the energy efficiency of the building. Despite their positive effects in terms of running energy is difficult to prove, it is easy to understand that they can cause a dramatic increase of the forces that structural system of the building have to withstand. Additionally, the simple adoption of the measures that are necessary for the plants to grow (additional layers of membranes, soil, watering system, etc.), by increasing the complexity of the tower, have a negative impact on its embodied energy, shifting, if not counterweighting at all the potential benefits of such natural elements on the energy consumption of the building

Conclusion

Embodied energy is a very important aspect of the sustainability of a tall building. LCA studies are important to describe the whole energy behavior of a tower, though ISO-compliant procedures have serious drawbacks that must be addressed. Difficulties are overcome by the use of an alternative accounting methodology, derived from the use of Input/Output matrices, that provides comprehensive results.

However, despite the methodology used, some elements in a tall building should be carefully designed, so as to keep the whole embodied energy content to a minimum, in particular the structural system and the service core of the building.

In general, it should be remembered that any addition to the building causes an increase of its embodied energy content, thus impacting negatively on its sustainability. Architects’ and engineers’ efforts should be aimed at a more attentive design inspired by a broader idea of sustainability.

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