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The Environmental Impact of Tall vs Small: A Comparative Study

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Abstract

The concept of vertical living has been hailed as a solution to control fast growth and urbanization of cities worldwide. As super tall residential projects become more common and sustainability considerations become more necessary, their efficiency has been called into question. How do vertical residential developments compare with suburban homes? What are the environmental advantages and disadvantages of vertical communities? Is there a middle ground?

We present the results from an AS+GG study that compares the environmental performance of different housing typologies ranging from a 215 supertall building to single family residences, including several scales in between. Our samples comprise 2,000 residential units per type and include the infrastructure needed to support them. We analyzed land use, energy use, and lifecycle carbon emissions for each typology.

The results show that different typologies perform better depending on the parameter being assessed. We discuss these findings; assess overall performance, and present conclusions.

Keywords: Supertall, Energy, Land, Urban sprawl, lifecycle carbon

1. Introduction

At the beginning of 2014, the global population stood at over 7.1 billion people (USCB, 2014). The United Nations estimates that the global population will exceed 8 billion by 2025 and almost 11 billion by the turn of the next century (see Fig. 1). This will be accompanied by an increase in overall average population density from 51 people per sq. km in 2010 to 60 in 2025 and 147 by 2100 (UN, 2014a).

Urbanization, which is the growth or expansion of urban areas, has recently become the focus of a great deal of attention. In 2010, the global urban population exceeded 50% of the world's population, by 2025 it will reach 58% and by 2050 it will exceed 67% (UN, 2014b). In 1950, when the world's population was a mere 2.5 billion there were 83 cities with over a million people (compared to 12 in 1900). This number has risen to a present day total of more than 520, with 30 cities having more than 10 million and 12 having more than 20 million inhabitants (Brinkhoff, 2014). These staggering numbers are prompting planners and policy-makers alike to ask questions about the sustainability of city growth and try to understand how best it can be planned.

Urbanization occurs as a result of two processes - migration from rural areas and natural population growth. Migration from rural areas may occur as a result of a number of factors. Mechanization of agriculture means that fewer farm laborers are required and therefore there are fewer opportunities for employment on farms and in other agriculture related industries, forcing people to seek employment in urban areas (this phenomenon is known as rural flight). Often, people move to the cities simply for the economic benefits and career opportunities. Furthermore cities tend to have a greater range of education options for parents to choose from for their children as well as better healthcare and social facilities.

There are, however, some negative environmental effects associated with urbanization, the most prevalent known as urban sprawl. Sprawl is a complex socio-economic phenomenon, but one of its defining characteristics is an imbalance between the physical form of a city and the desires and needs of its population. These desires may include specific housing types, neighborhood structure, and the provision of services and/or available recreation space. Consequently, when a population cannot meet all of its needs in one location, it will migrate to other areas to meet those missing needs.

The concept of high density vertical living has been hailed as a solution to control the fast growth and urbanization of cities around the world. As supertall residential projects become more common and sustainability is regarded as a pressing issue for the built environment, the efficiency of such projects is often called into question. How efficient are supertall residential developments versus low-rise single-family residences? What are the environmental, social and economic benefits and/or disadvantages of vertical communities? Is there a middle ground?

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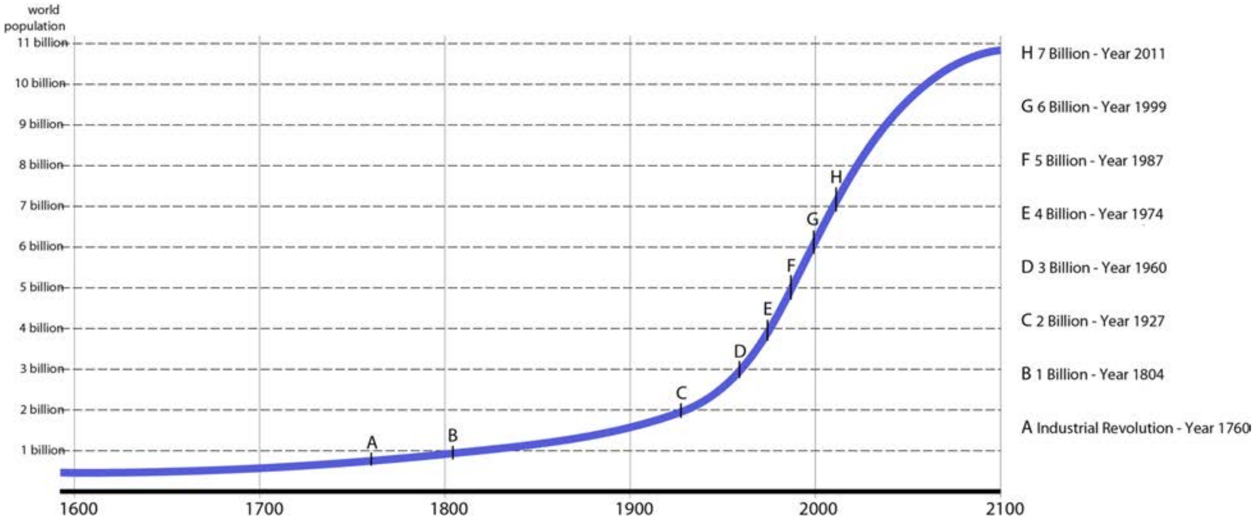


Figure 1. World population growth (Source: UN data).

This study was undertaken in order to compare the environmental performance of different urban and suburban residential building typologies ranging from supertall buildings graduating down to single-family residences. In all, nine different buildings were designed, divided into four broad categories based on their height and nature: supertall, high-rise, low-rise and single family homes.

Each typology was analyzed against a series of environmental indicators - land use, energy demand, transportation and life cycle carbon emissions.

2. Methods

2.1. Building Typologies

As described above, nine residential buildings were designed within 4 categories as described above. Each was designed for an ASHRAE climate zone 5 (such as Chicago) and was tested for constructability and compliance with Chicago's Building Code and ASHRAE 90.1 (2010). Each typology was designed using typical building materials and mechanical systems to allow for a better comparison of the different models.

The sample size for the study of each typology was 2,000 residential units, including the infrastructure needed to support them, creating nine hypothetical communities (see Fig. 2). The housing was designed following two distinct approaches: firstly, a market based unit size (based on a cross section of apartment and house sizes within the Chicago area), which was termed Tbase and secondly on a fixed unit size of 150 m^2, termed T150 (see Table 1). The two approaches allowed us to make relative comparisons of total energy demand (using Tbase) and energy use intensity (using T150).

2.2. Energy Use

Energy Models were constructed using Design Builder and run in Energy Plus for all the prototypes in the Density Study. This allowed the estimation of overall energy consumption as well as demand profiling for each typology. Buildings were modeled as part of prototype communities, to take into account the effect of overshadowing by neighboring structures, as would be in real life. To eliminate the influence of orientation, the energy models for each prototype were run in four cardinal directions with the mean result being considered for the discussions. These individual results were then extrapolated to represent 2,000 units and the totals have been compared.

2.3. Land Use

Communities were built for the Tbase typologies using ArcGIS. These communities included roads, sidewalks, water, waste water and stormwater distribution networks. The building structures as well as the infrastructure required to support them were included in the community models. Prototypes for each community type were designed based upon GIS data obtained from the City of Chicago and its western suburb of Naperville, IL. Road widths, sidewalks and alleyways were designed according to the relevant Chicago or Naperville code.

Infrastructure falling within the community boundary up to the entrance of each building was included in the GIS model. The infrastructure systems included potable water, stormwater and wastewater networks; electricity and telecommunications were not included.

2.4. Lifecycle Carbon

In order to estimate life cycle carbon emissions it was necessary to calculate the embodied carbon for each community. This included above grade infrastructure (roads, sidewalks etc.), utilities infrastructure (potable water, wastewater and stormwater) and the buildings.

For the embodied carbon calculations of the building

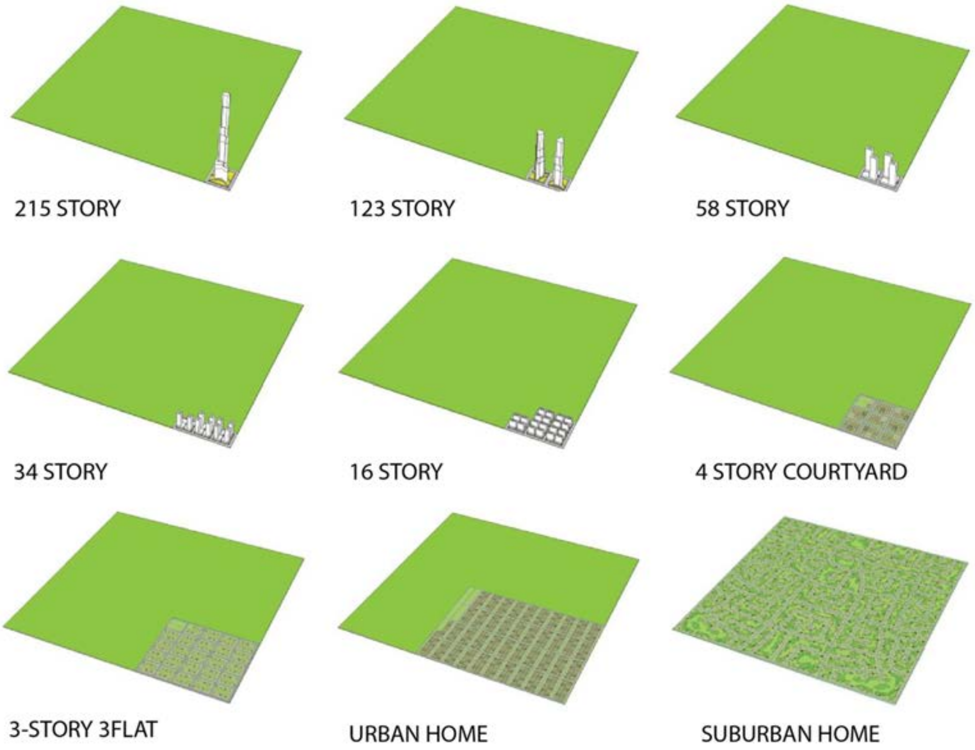
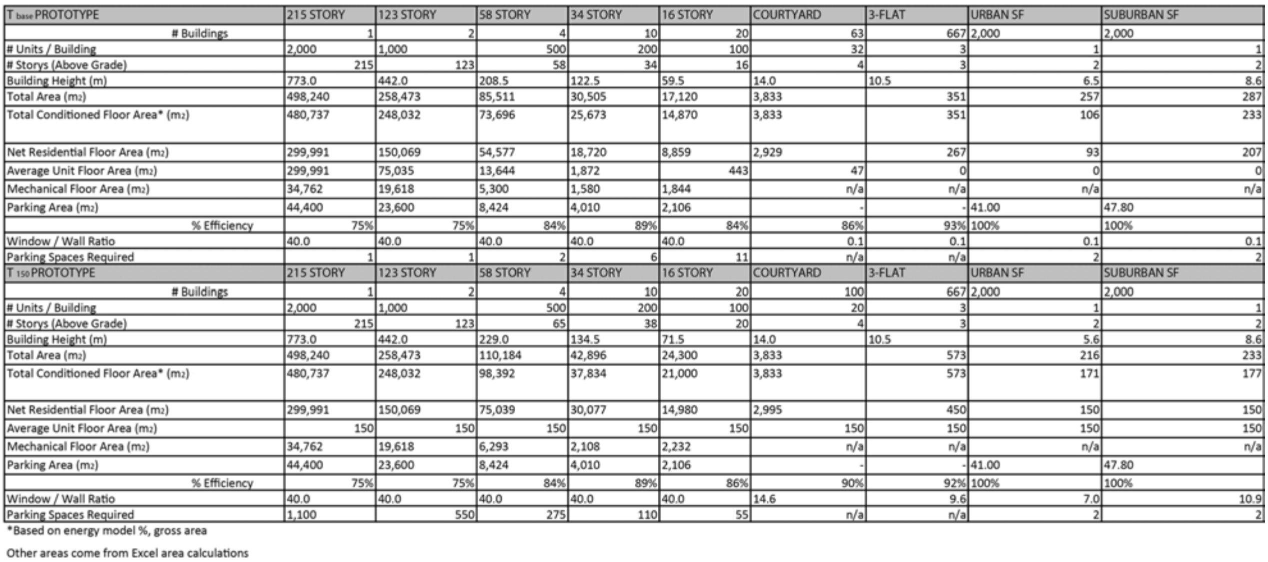


Figure 2. Community prototypes (Source: AS+GG).

Table 1. Community design parameters for the Tbase (market sized units) and T150 (150 m^2 units) typologies (Source: AS +GG)



T_{base} PROTOTYPE	215 STORY	123 STORY	58 STORY	34 STORY	16 STORY	COURTYARD	3-FLAT	URBAN SF	SUBURBAN SF
# Buildings	1	2	4	10	20	63	667	2,000	2,000
# Units / Building	2,000	1,000	500	200	100	32	3	1	1
# Storys (Above Grade)	215	123	58	34	16	4	3	2	2
Building Height (m)	773.0	442.0	208.5	122.5	59.5	14.0	10.5	6.5	8.6
Total Area (m$_2$)	498,240	258,473	85,511	30,505	17,120	3,833	351	257	287
Total Conditioned Floor Area* (m$_2$)	480,737	248,032	73,696	25,673	14,870	3,833	351	106	233
Net Residential Floor Area (m$_2$)	299,991	150,069	54,577	18,720	8,859	2,929	267	93	207
Average Unit Floor Area (m$_2$)	299,991	75,035	13,644	1,872	443	47	0	0	0
Mechanical Floor Area (m$_2$)	34,762	19,618	5,300	1,580	1,844	n/a	n/a	n/a	n/a
Parking Area (m$_2$)	44,400	23,600	8,424	4,010	2,106	-	-	41.00	47.80
% Efficiency	75%	75%	84%	89%	84%	86%	93%	100%	100%
Window / Wall Ratio	40.0	40.0	40.0	40.0	40.0	0.1	0.1	0.1	0.1
Parking Spaces Required	1	1	2	6	11	n/a	n/a	2	2
T_{150} PROTOTYPE	215 STORY	123 STORY	58 STORY	34 STORY	16 STORY	COURTYARD	3-FLAT	URBAN SF	SUBURBAN SF
# Buildings	1	2	4	10	20	100	667	2,000	2,000
# Units / Building	2,000	1,000	500	200	100	20	3	1	1
# Storys (Above Grade)	215	123	65	38	20	4	3	2	2
Building Height (m)	773.0	442.0	229.0	134.5	71.5	14.0	10.5	5.6	8.6
Total Area (m$_2$)	498,240	258,473	110,184	42,896	24,300	3,833	573	216	233
Total Conditioned Floor Area* (m$_2$)	480,737	248,032	98,392	37,834	21,000	3,833	573	171	177
Net Residential Floor Area (m$_2$)	299,991	150,069	75,039	30,077	14,980	2,995	450	150	150
Average Unit Floor Area (m$_2$)	150	150	150	150	150	150	150	150	150
Mechanical Floor Area (m$_2$)	34,762	19,618	6,293	2,108	2,232	n/a	n/a	n/a	n/a
Parking Area (m$_2$)	44,400	23,600	8,424	4,010	2,106	-	-	41.00	47.80
% Efficiency	75%	75%	84%	89%	86%	90%	92%	100%	100%
Window / Wall Ratio	40.0	40.0	40.0	40.0	40.0	14.6	9.6	7.0	10.9
Parking Spaces Required	1,100	550	275	110	55	n/a	n/a	2	2

*Based on energy model %, gross area

Other areas come from Excel area calculations

materials, the most significant (in terms of quantities) components of the constructions were analyzed: structures, building envelopes, insulation and interior partitions. Mechanical systems, wires and tubes, elevators, etc., were not included in the calculations. Quantities were taken from the building models described in the typologies section. The dimensions of the structural components were reviewed by structural engineers, who provided values for concrete strengths and reinforcement steel quantities.

The emissions factors for infrastructure and buildings were calculated using data from the Athena Institute, Bath ICE and the Concrete Pipeline Systems Association.

Transportation from place of manufacture to construction site was not accounted for in the study.

3. Results And Discussion

3.1. Energy Use

Energy consumption was considered in two ways-Total Energy Demand (TED, kWh/yr) and Energy Use Intensity (EUI, kWh/m2/yr). Figs. 3 and 4show the TED and EUI for the Tbase 2000 unit communities and Figs. 5 and 6 show the same data for the T150 communities. As the graph shows, the low-rise prototypes had six significant loads affecting their overall consumption: heating, cooling, interior lights, plug loads, fans and water heating. The high-rises had a total of nine loads (the other three being elevators, water pumps and heat rejection). Space heating and domestic water heating were the most energy intensive loads in almost all prototypes. Cooling became more significant in buildings with higher glazing ratios, where overheating occurs in summer.

In judging which of the Tbase buildings performs best, it is important to consider both EUI and TED as the unit sizes are different. In the T150 case, as the units sizes are the same in all typologies, the relationship between EUI and TED is constant.

The courtyard building was the most energy efficient of all the prototypes tested in both scenarios. A series of factors help explain these results: the high density of units, in a configuration where only two walls are exposed to the exterior, as well as a low glazing ratio. This helps contain the space heat in winter and reduce infiltration, as well as keep unwanted summer radiation out. The most significant load in this prototype was domestic water heating, because this value is not associated with environmental factors but with occupancy rates. Despite being a relatively dense prototype (with 32 or 20 units per building), the height still allowed it to operate with a simple system, not needing elevators or water pumping. Although not included in this prototype for the study, a single elevator would be required to allow disabled access up the building.

The high-rises (16 story, 34 story and 58 story) are much more interesting in terms of their performance; when looking at EUI (both scenarios) or TED in the T150 scenario the taller the building, the better it performs. Overall their energy consumption is greater than the low rise typologies, because these buildings have the added loads of water pumps and elevators, as well as higher loads for cooling, fans and, compared to some lower prototypes, higher lighting and plug loads as well.

The T150 suburban house performs reasonably well, on the other hand the market sized, Tbase suburban house would appear to perform very well in terms of EUI but because of its size (207 m^2 net residential area) the overall energy consumption is high.

In terms of energy use, the supertalls used the most energy out of all the prototypes. There are multiple factors associated with these results. First of all, these buildings depend on a series of spaces that are not residential units but account for around 30% of the total building area. Among these are the mechanical floors, the lobbies and amenities, and parking garages. These spaces are continuously illuminated and conditioned yet are not always occupied.

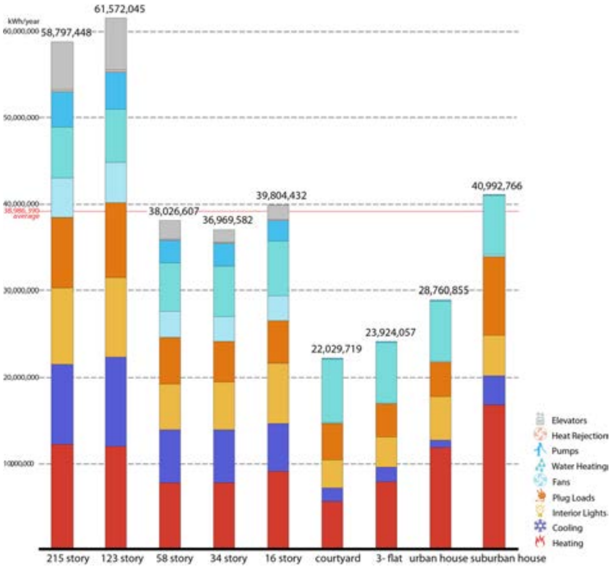


Figure 3. Total Community Energy demand for Tbase market sized units (Source: AS+GG).

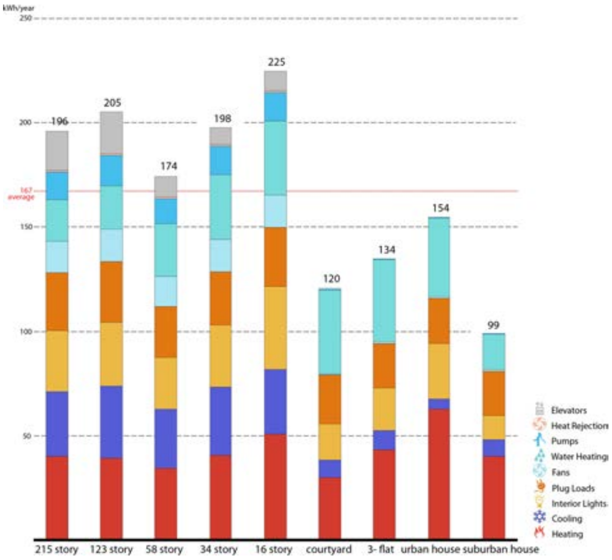


Figure 4. Energy Use Intensity for Tbase market sized units (Source: AS+GG).

Architecturally, higher glazing ratios commonly found on these kinds of buildings perform poorly compared to the high mass envelopes of the lower prototypes. This typically translates into higher infiltration rates, heat losses in winter and unwanted heat gain in summer. Another aspect to take into account is elevators. An efficient ver-

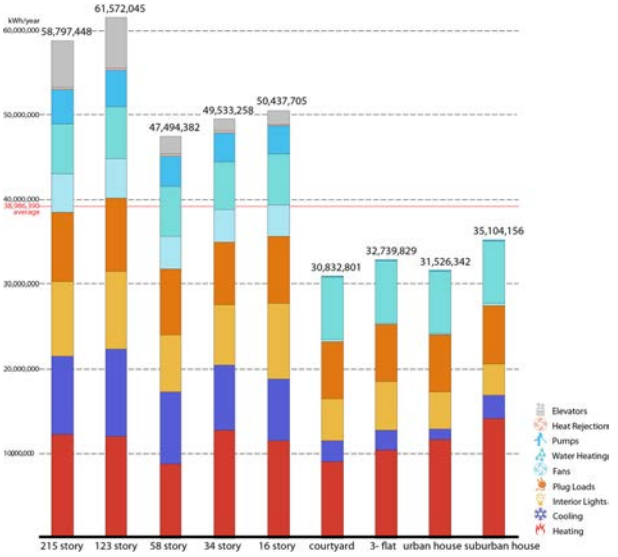


Figure 5. Total Community Energy demand for T150150 m^2 units (Source: AS+GG).

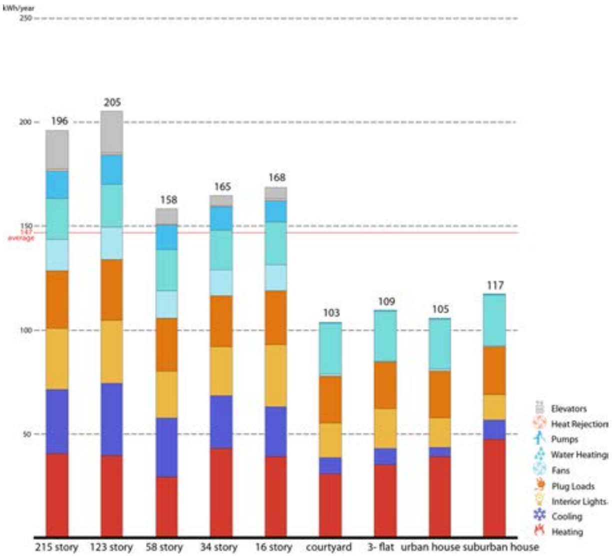


Figure 6. Energy Use Intensity for T150150m^2 units (Source: AS+GG).

tical transportation system is critical for the operation of supertall buildings, and it accounts for around 10% of the total energy consumption, compared to only four to six percent on other high-rises. Pumping energy also raises significantly, since water for mechanical systems and domestic uses needs to be pumped to higher elevations thus requiring more power.

An important aspect that was not accounted for in the study was the auxiliary energy required for the functioning of the smaller buildings. Auxiliary energy is considered to be any additional energy necessary for the operation of the prototypes that is not consumed within the building. Although systems like pumps and elevators are not part of these smaller buildings, other auxiliary systems replace these. For example, water distribution from the utility companies to these buildings at a certain pressure requires electricity. The potable water network in a suburban neighborhood of 2,000 single family homes is over 100 times longer than the one needed to supply one supertall building, resulting in increased auxiliary energy demand. Additionally it could be argued that the elevator energy demand, linking a residential unit almost directly to car-parking, replaces vehicle emissions associated with driving a car around a neighborhood (in the case of the two low-rise typologies).

3.2. Land Use

The study illustrates the extent to which the land use in lower rise communities is greater than that of high-rise communities; The Tbase suburban community occupies 110 times more land than a supertall tower housing the same number of units (see Table 2).

The land left undeveloped (see Fig. 2) in the high-rise and supertall developments could be used to mitigate the effects of the development. In an ideal scenario, the land could be left alone, which would preserve the natural habitat, protect wildlife and water sources and naturally sequester carbon. The land could also be used as farmland to support the demands of the growing population. For the purposes of this study, a scenario where 90% of the additional land is used to generate energy using Photovoltaic panels was considered. The NREL PVWatts calculator was used to estimate annual energy production assuming panel efficiencies of 18%, a Chicago weather profile and taking into account maintenance and shading packing factor. This analysis shows that the land difference between the Suburban Single family home typology is sufficient to meet the energy demands of all the other

Table 2. Land use of Tbase communities (Source: AS+GG)

T base PROTOTYPE	215 STORY	123 STORY	58 STORY	34 STORY	16 STORY	COURTYARD	3-FLAT	URBAN SF	SUBURBAN SF	SUBURBAN SF
Number of buildings	1	2	4	10	20	63	667	2,000	2,000	2,001
Total building footprint (m$_2$)	3,177	7,534	16,848	20,050	42,120	60,376	78,039	335,650	394,765	394,766
Total area required (m$_2$)	26,896	36,530	36,530	45,508	86,135	173,338	383,178	854,046	2,967,137	2,967,138
Land use as a % of suburban SF	0.91%	1.23%	1.23%	1.53%	2.90%	5.84%	12.91%	28.78%	100.00%	100.00%
Area compared to Suburban SF (m$_2$)	(2,940,241)	(2,930,607)	(2,930,607)	(2,921,629)	(2,881,002)	(2,793,799)	(2,583,959)	(2,113,091)	0	1
PV Power generation , 90% landuse (kWh/yr)	249,300,094	248,483,237	248,483,237	247,722,001	244,277,279	236,883,423	219,091,300	179,166,873	0	1

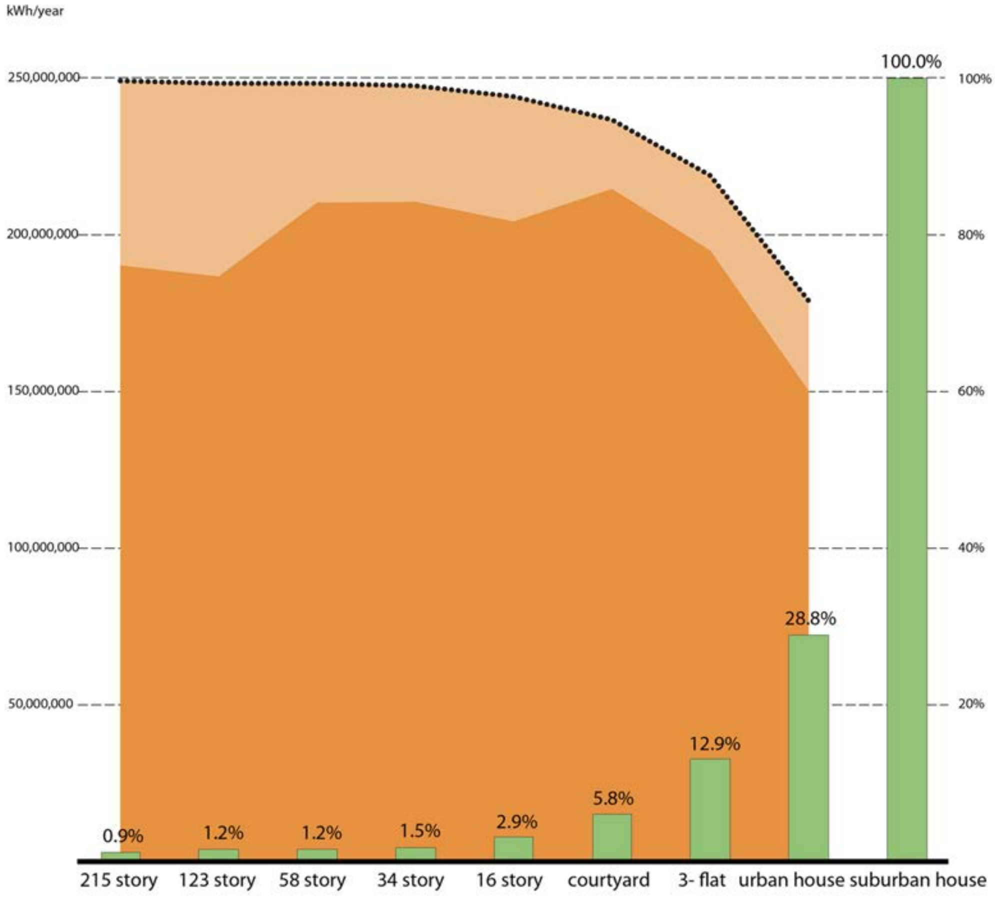
communities in the study (see Figs. 7 and 8). The best performing typology in both the Tbase and T150 scenarios is the 58 (65) story building, where the difference between energy generated on the unused land and energy consumption of the building is the highest, yielding a potential 238 GWh and 126 GWh of electricity per year in the Tbase and T150 scenarios respectively.

3.3. Life Cycle Carbon Emissions

The results of the Embodied Carbon EC analysis for Tbase are shown in Fig. 9. The EC of infrastructure directly correlates with land use. Spatially larger communities have greater lengths of roads and utilities to support the wider distribution of parcels, whereas taller buildings are confined to smaller plots with less external infrastructure. In these, some utilities move inside the buildings whereas other infrastructure (roads and sidewalks) is replaced by elevators and corridors.

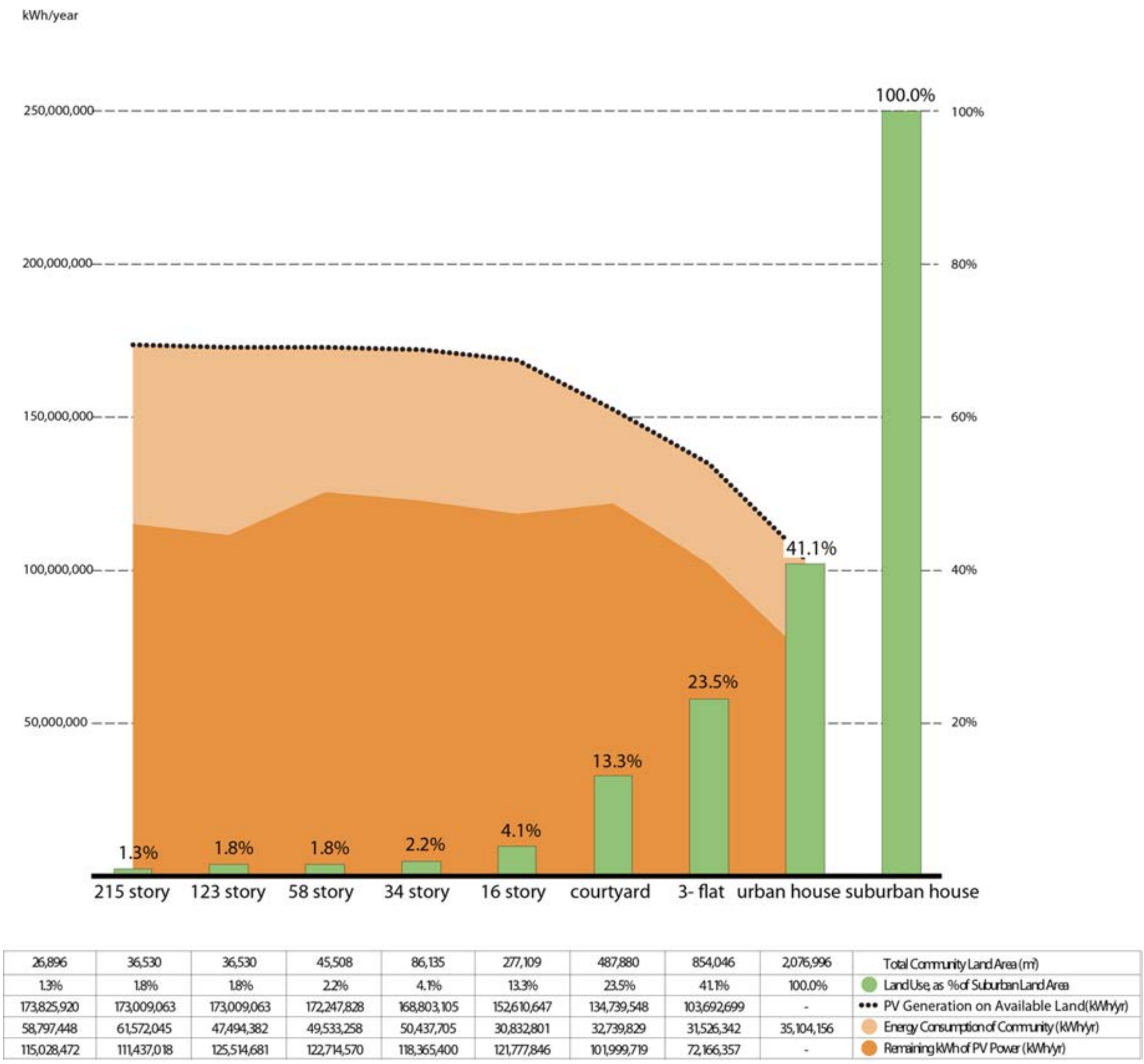
Regardless of community size (in terms of land area), the EC of buildings accounts for by far the greatest proportion of the communities' overall EC, with infrastructure accounting for only 0.15% in the supertall. However, it becomes more significant in the low rise typologies, rising from 3.7% in the courtyard community to 9.0% in the Suburban single family home community. The 213 story supertall community had a significantly higher embodied carbon than any other typology, primarily due to the amount of concrete and steel within the structure of the building. The typology that performed best in regards to embodied carbon was the 4 story courtyard building community.

The final element of the study was the estimation of lifecycle carbon emissions for the Tbase community. For this study, a 20 year period was used, as this represents a typical warranty period for photovoltaic systems. Although this is significantly less than the life expectancy of



26,896	36,530	36,530	45,508	86,135	173,338	383,178	854,046	2,967,137	Total Community Land Area (m²)
0.9%	1.2%	1.2%	1.5%	2.9%	5.8%	12.9%	28.8%	100.0%	● Land Use, as % of Suburban Land Area
249,300,094	248,483,237	248,483,237	247,722,001	244,277,279	236,883,423	219,091,300	179,166,873	-	••• PV Generation on Available Land (kWh/yr)
58,797,448	61,572,045	38,026,607	36,969,582	39,804,432	22,029,719	23,924,057	28,760,855	40,992,766	● Energy Consumption of Community (kWh/yr)
190,502,646	186,911,192	210,456,630	210,752,419	204,472,847	214,853,704	195,167,243	150,406,018	-	● Remaining kWh of PV Power (kWh/yr)

Figure 7. Analysis of land use, energy demand and energy production potential for the Tbase communities (Source: AS GG).



26,896	36,530	36,530	45,508	86,135	277,109	487,880	854,046	2,076,996	Total Community Land Area (m²)
1.3%	1.8%	1.8%	2.2%	4.1%	13.3%	23.5%	41.1%	100.0%	● Land Use, as % of Suburban Land Area
173,825,920	173,009,063	173,009,063	172,247,828	168,803,105	152,610,647	134,739,548	103,692,699	-	••• PV Generation on Available Land (kWh/yr)
58,797,448	61,572,045	47,494,382	49,533,258	50,437,705	30,832,801	32,739,829	31,526,342	35,104,156	● Energy Consumption of Community (kWh/yr)
115,028,472	111,437,018	125,514,681	122,714,570	118,365,400	121,777,846	101,999,719	72,166,357	-	● Remaining kWh of PV Power (kWh/yr)

Figure 8. Analysis of land use, energy demand and energy production potential for the T150 communities (Source: AS GG)

a high-rise building, 20 years is considered an acceptable time period for considering a major re-modelling and was therefore chosen as being appropriate for the purposes of this analysis.

The study included the embodied carbon, the operational carbon emissions and the amount of carbon offset by using the land saved (compared to suburban single family homes) for electricity generation from photovoltaics, as described earlier. This yielded a net relative carbon savings value (see Fig. 10) showing that the 58 and 34 story buildings provide the greatest overall net relative carbon saving, followed by the 16 story building and then the courtyard building.

3.4. General Discussion

The study reveals a number of interesting findings and direction for future study. In both the Tbase and T150 communities, the 4 story courtyard buildings had the lowest energy demand. However, in considering how energy demand across all typologies could be improved, this typology offers the least potential for improvement - the buildings already have a very low window to wall ratio (13.8%) and are well insulated in accordance with ASHRAE 90.1 energy standards. The taller buildings on the other hand offer the most potential for improvement - more efficient mechanical systems, vacancy and daylighting sensors, regenerative braking in the elevators, off peak thermal energy storage in basements, high performance glazing and reduction of the glazing ratios (from 40%) are just a few considerations that could be tested in the future. Moving to land use, when using the land area of the suburban single family home as a baseline, it is obvious that taller buildings will have a smaller footprint allowing the vacant land to be put to good use. For this study, using the

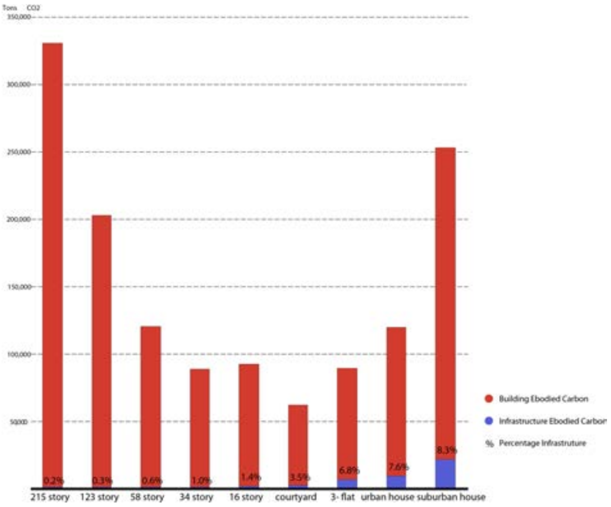


Figure 9. Embodied carbon of buildings and infrastructure for the Tbase communities (Source: AS+GG).

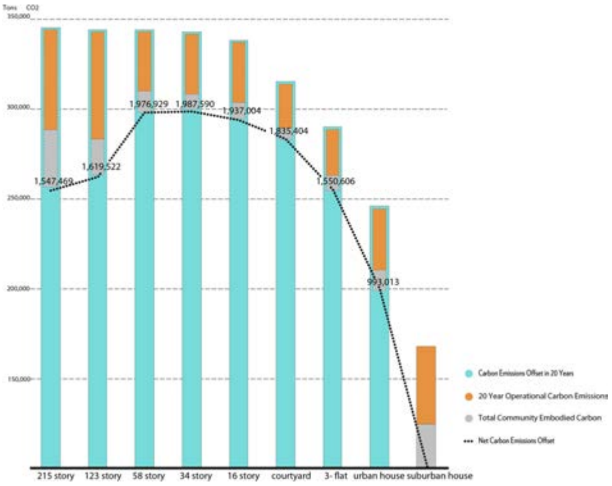


Figure 10. Lifecycle carbon analysis for the Tbase community (Source: AS+GG).

vacant land for power generation with photovoltaic was chosen - the study was conservative, assuming 90% of the land was used and that of that 90%, only 45% was covered with 18% efficient PV panels, to account for spacing and maintenance movement etc. Improvements in yield are clearly possible and could be considered as part of a future study. Secondly there are alternative uses for the land - loss of agricultural land, as mentioned in the introduction to the study is a global concern and is something that can be mitigated through building denser housing communities on marginal land. The net effect of using the vacant land for agricultural productivity or even carbon sequestration by natural systems is a subject for a future study.

Embodied carbon and lifecycle carbon emissions conclude this study, but to truly complete, it transportation should be further considered as improved connectivity with public transport and mass transit systems is typically thought of as one of the advantages of denser communities. For the present study, embodied carbon of infrastructure systems largely reflected land use, whereas as the embodied carbon of the buildings largely reflected the height of the individual buildings as far as the courtyard typologies before rising again through to the suburban single family homes. This is largely due to the relationship between structure and gross floor area being greater as buildings get taller. In the lower rise buildings, the choice of construction materials had a greater influence. Operational emissions were converted to CO2e using the grid emissions factor for Illinois. Clearly should the energy grid move over to cleaner forms of energy then operational emissions will become lower and embodied carbon will become more significant. Studying the impact of a reduced carbon grid and the effect of selecting low carbon construction materials is the subject of a future study.

Finally, taking into account operational emissions and potential carbon offsets through onsite energy generation, the communities that perform best overall are the high-rise buildings (58 and 34 story) with the taller buildings performing best.

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