Urban densification and housing typology for climate change mitigation

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Abstract. This paper investigates different urban growth and densification scenarios and their energy performance under climate change conditions using urban energy simulation. We developed an abstract urban growth model based on the West Campus neighborhood in downtown Austin, Texas. Four different scenarios were applied to an abstract population growth model, which were then tested from the current year to 2100 under both climate change and control (TMY) conditions. Our results show that all urban growth models perform similarly in terms of operational energy but differ radically in terms of carrying capacity and embodied energy.

1. Introduction
Buildings are responsible for 30-40% of global greenhouse gas emissions [1], and the residential sector represents 60% of total energy consumption [2]. The aim of this paper is to examine the impacts on operational energy in the urban environment amid two difficult pressures: population growth due to urbanization and increased temperatures due to climate change. To accomplish this, we superimpose a climate scenario for the 21st century as projected by the Intergovernmental Panel on Climate Change (IPCC) onto an abstract urban growth model in the West Campus neighborhood in Austin, Texas.

Building energy simulation at the urban scale is useful to obtain information about the potential energy behavior of cities [3]. However, there still exists a shortage of approaches that can model multitudes of urban-scale scenarios with many predictands and variables [4]. Using CitySim, a district-scale energy simulation engine [5], we parameterized our process, which increased computational efficiency while modeling many predictands and unique scenarios.

It was our goal to consider a diverse array of housing types, modeled with specific attentiveness to qualities that affect heat transfer and population density. Urban geometry is known to have a major effect on the comfort and energy profile of a city [6], and the complex profile of all the major housing types in West Campus was a primary consideration in the creation of the simulation models. In the next section, we introduce the modeling techniques and scenarios, before moving on to present the results and discuss their implications.

2. Methodology
2.1. Abstract urban growth model
The abstract urban growth and densification model supposes a continuation of the current pattern of single-family houses being redeveloped into various types of multi-family housing. The model is an abstracted section of the West Campus neighbourhood; street size, lot size and shading from surrounding buildings are all based off values that are present in West Campus. The model is made up of 70 plots, each of which have an area roughly equivalent to that of four single-family house lots. The initial 280 houses thus abstractly represent the 285 currently present single-family houses in West Campus, and each growth scenario represents an option for how they might develop during future densification. Our framework allows for each scenario to be accounted for in a parametric growth model, for which each ten-year step from 2030 to 2100 can be modelled and simulated.

2.1.1. Population growth and building types. Population growth is kept consistent in every scenario. The rate of growth that is used is a diagrammatic possibility based on a population growth function. The function itself is a natural growth function based on the real population of West Campus in 2017 [7] and a prediction by a market research group for Austin’s growth from the same year until 2046, putting the metro population at over 3.86 million people [8]. This figure is simplified in our model, which supposes that number being hit six years earlier, in time for 2040, which was a benchmark year for the model. While this population growth model is simplified, it is an acceptable abstraction, representing an extreme yet plausible case for metro population growth. From ten-year populations for populations for the entire metro area, populations for West Campus were taken based on the share of total metro population that resided in its census tracts in 2017. To determine the population values for the growth model itself, we assume that the modelled area takes in all new residents.

| Population       | 2017 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|------------------|------|------|------|------|------|------|------|------|------|
| Modeled area     | 840  | 7,440| 14,412| 23,614| 35,761| 51,795| 72,963| 100,899| 137,778|
| Modeled area growth (10 yrs) | 244.6%| 93.7%| 63.8% | 51.4% | 44.8% | 40.9% | 38.3% | 36.6% |

To allow the increase of population in the neighbourhood, we assume redevelopment with building typologies that allow for densification. Each of the four housing types were carefully designed to represent a different building type that exists in West Campus. As such, metrics such as ground area, building height, and surface-to-volume ratio (STV) are used in the model to be as close as possible to the mean values of all buildings of the corresponding type in the West Campus building stock. These metrics were measured from a 3D building database with building program information, which had been organized and used for an earlier study [9]. Table 2 shows these metrics for each type, along with illustrations of each type. The first three types are all commonplace in West Campus, the ‘Tower’ typology is introduced in this study.

| # Occupants (whole lot) | Envelope Type | Height (m) (# floors) | Ground Area (m²) | Lot Coverage |
|-------------------------|---------------|-----------------------|------------------|--------------|
| 3 (12)                  | Non-LEED      | 4.5 (1)               | 224              | 0.107        |
| 91 (182)                | LEED          | 12.4 (3)              | 850              | 0.395        |
| 776                     | LEED          | 26.7 (8)              | 2,720            | 0.633        |
| 2331                    | LEED          | 80.1 (24)             | 2,722            | 0.633        |
To diagrammatically illustrate change in envelope construction over time, a different material set (LEED) was used for the multi-family buildings than for the single-family houses (non-LEED) [9]. Each of the four different building types illustrate a great increase in overall population density. The occupancy values used in the model were derived from census data on the two tracts that make up the neighbourhood [7]. The occupancy of the single-family houses was taken from the mean single-family household size in West Campus, while the occupancy of multi-family buildings was taken from the mean apartment household size, as well as metrics of average apartment size in Texas. For each ten-year time step in a scenario, a certain amount of the single-family tiles is replaced by multi-family housing corresponding to the number of residents who are predicted to live there. Figure 1 shows this dynamic for the ‘all types’ model, which uses all three multifamily buildings types in succession. For the other scenarios, each type of multi-family housing was tested as individual options.

### Table 1. The four residential typologies studied with relevant metrics and attributes. Illustration by author J.B.

| FAR    | STV (\(\frac{L}{m}\)) |
|--------|-----------------------|
| 0.107  | 0.490                 |
| 1.186  | 0.304                 |
| 5.060  | 0.158                 |
| 15.181 | 0.092                 |

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### Figure 1. Concept showing abstract model within West Campus (left) and tiles being ‘redeveloped’ (centre through right).

#### 2.2. Simulation Workflow
We used CitySim, a large-scale urban energy simulation tool, to simulate each scenario. All models were created parametrically using Rhino 5 and Grasshopper, which allowed for the creation of growth models that adjusted to the population criteria. The geometric and material data were transferred from grasshopper into CitySim usable XML files using GHCitysim [9].

For the reference year climate, data was used reflecting the typical meteorological year (TMY3) representing an average of decades of data, mostly from the latter quarter of the 20th century. Regarding climate change, weather files for each simulated year were taken from Meteonorm. Meteonorm uses stochastic modelling, a method of statistical downscaling based on observations of local weather patterns as well as regional climate model data for future climate scenarios. For all future climate files in this study, data reflecting IPCC scenario A1b were used, reflecting a middling case in reduction of greenhouse gas emissions. Each full scenario was tested both under climate change (future weather data) and TMY3, so that the magnitude of climate change effects could be isolated and studied.

#### 3. Results

##### 3.1. Growth characteristics
As briefly discussed before, three of the scenarios suppose redevelopment using only one of the three types of multi-family housing. The other scenario, ‘all types’, explores the option of all three multi-family types being used, wherein denser housing buildings begin to be constructed when the neighbourhood has reached carrying capacity through the last type. It is worth keeping in mind that the ‘all-types’ scenario supposes a much shorter building life cycle than the other scenarios, with new multi-family buildings existing for an average of 20-30 years before being replaced by a larger building.
Figure 2. Character of housing growth scenarios: building stock (bar chart), neighbourhood population, and built area energy consumption.

Figure 2 provides a perspective on how each of the four scenarios alters the building stock and energy use density of the neighbourhood. The building stock in each case is represented as a bar graph in the background as total percentage of buildings. Solid and dashed lines represent operational energy use per unit ground area (as opposed to floor area). With this metric, increases indicate the presence of buildings that use more cooling energy for each square meter of urban ground area they occupy, which generally corresponds to building height and population density. For both the low-rise and mid-rise scenarios, the neighbourhood reaches a carrying capacity decades before 2100, as the housing type used cannot hold the supposed population without further densification.

3.2. Cooling Energy Use

3.2.1. Overall Patterns. As shown in figure 3 top row, the total operational energy use increased steadily decade by decade in each scenario, starting at around 3.77 GWh/year for the single-family only neighbourhood before rising above 55 GWh/year by 2100 (in the scenarios that can support densification that long). The ‘all-types’ scenario is used as a background on the other three scenarios and indicated as grey background. The highest noted neighbourhood energy use was the ‘all-types’ scenario in the year 2100, where cooling energy use topped at 57.73 GWh/year. The ‘all-types’ scenario underperforms against every other scenario from an operational energy standpoint. The ‘tower only’ scenario consumes slightly less energy than its counterpart in every scenario, but the difference adds up over time. Over the 82 years simulated in the study, the ‘tower only’ neighbourhood could save an estimated 170 GWh of cooling energy over ‘all types’.

Per-occupant energy use is shown in Fig. 3 bottom row and follows similar trends across all scenarios. Due to low-efficiency, low-density single-family houses, the starting load per occupant is around 4.49 GWh/year, before dropping in every scenario by 2030 to values at or below 1 GWh/year.
Even during climate change, the cooling load per occupant values continue to slowly and steadily decrease in each scenario by the decade, reaching their lowest near the end of the simulated timeframe. The lowest values observed are in simulated year 2100, with the ‘all types’ scenario at 417 kWh/year per occupant and the ‘tower’ scenario about 2% lower (409 kWh/year per occupant). Both of these scenarios, by 2100, cut energy use per occupant to a tenth of what it is in the starting suburban neighbourhood condition. Without climate change, these values are roughly halved. In TMY weather conditions, the average occupant in the 2100 ‘all types’ neighbourhood consumes 222 kWh per year in cooling energy, a number that is again roughly 2% lower in the ‘tower only’ scenario (217.9 kWh/year per occupant). Note that similar patterns in overall energy use are observed across all scenarios in both TMY (dashed) and climate change (solid) instances: Climate change acts as a multiplier to the cooling demand stresses created by population growth and urban densification.

3.2.2. Effects of Climate Change. In order to study the effects of climate change separated from population growth, we first ran each scenario in a control climate (TMY), keeping the population constant. The annual cooling load for climate change and TMY versions were then subtracted. Figure 4 shows this difference as a percentage increase in the climate change scenario over the TMY scenario.

![Figure 4. Energy use impact of climate change as percent increase in cooling load.](image)

Across all scenarios, the impact of climate change increases steadily every decade. By 2030, climate change in IPCC A1b exacerbates neighbourhood cooling load in all scenarios by over 40%. For the scenarios that accommodate densification to 2100, the cooling load in that year is over 87% more than the same scenarios in TMY.

3.2.3. Discrete Comparison of Growth Scenarios. As discussed in subsection 3.2.1, the ‘tower only’ scenario tended to have a slight edge over the ‘all types’ scenario up to and including the year 2100. The difference in performance across the ‘mid-rise only’, ‘tower only’, and ‘all types’ scenarios can be seen in figure 5, which compares overall cooling load in the former two scenarios as a percent increase or decrease from the latter.

Both scenarios measured against ‘all types’ here generally use less cooling energy, but not in a consistent or linear manner. In the A1b climate change setting, both scenarios become increasingly more efficient than the ‘all types’ scenario until a certain point, where energy savings become less and less pronounced as a percentage of total load values. Within the studied timeframe, the ‘tower only’ scenario is always more energy efficient than the other scenarios. In the TMY cases (lighter bars in figure 5), climate change has an observable effect of increasing the stratification between cooling load for the different scenarios, but that the patterns generally remain the same throughout.
4. Discussion & Conclusion

It is noteworthy that all three housing types perform similarly over the growth period. If buildable land and embodied energy were no object, all three housing types would be roughly equally viable options in terms of long-term operational energy savings. Thus, there are many ways to compare the different growth scenarios. We can group them into two general areas: a) extant differences of space, embodied energy, and social concerns, and b) measures that are assumed identical for all housing types by our model, which are not necessarily so in reality.

For a), there are some differences to be drawn from metrics such as lot coverage or overall building massing that define the urban texture created by each of the building types: the mid- and low-rise buildings could have more options for green space or courtyards compared to the towers, which would leave more space between buildings and allow space for streets, sidewalks or other transportation lanes to possibly be expanded. A major concern between scenarios that lie outside the realm of these simulations is embodied energy and rate of development, which would be much higher in the ‘all types’ scenario than in the similarly high-density ‘tower only’ scenario. Building life cycle decrease and embodied energy increase, as discussed in section 3.1, are relatively characteristic of the ‘all types’ scenario. Also, the ‘tower only’ scenario has the slowest rate of lot-by-lot redevelopment; it preserves the most single-family homes yet ends up being the most energy efficient scenario due to the high per-occupant efficiency of the tower buildings themselves. Embodied energy metrics have a place in answering a more incisive resource optimization question regarding these urban housing types, but in looking at operational energy and some basic planning concerns alone, the ‘tower only’ scenario is found to be the most efficient option for densification in West Campus.

For area b), in this paper, we considered housing types that increase population density by getting taller and/or taking up more ground area. Other options are available to increase density by using less space per occupant. For example, micro-unit buildings have been successfully implemented in Austin and urban planning could consider the use of space this way.

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