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Impact of urban density and building height on energy use in cities

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Abstract

Compact cities have been attributed to lower per capita energy use. However, the complexity of relationships between the elements that constitute energy consumption in the urban system is poorly understood. Little or no research exist on the relation between energy costs of building taller, and transportation and infrastructure energy benefits of building denser. This study provides a theoretical assessment of how energy use is related to urban density in a densely populated area, to aid the development of sustainable cities and land-use planning. The paper builds a holistic parametric model to estimate the total urban energy use for space heating, embodied building energy, transportation energy, and road infrastructure energy, and how these relate to urban density. It does so by varying building height and other urban characteristics related to density, with the aim of identifying the most influential parameters with regard to energy consumption. The possibility of an optimal building height and urban density is also investigated. A much denser and taller city structure than what is normal in cities today appears to be optimal for low urban energy use. The most influential urban density indicators are found to be the dwelling service level (m^2/cap) and the building design lifetime. Transportation energy becomes increasingly important with a rise in population. Results indicate that depending on population and building lifetime there exists an optimal building height in the range of 7-27 stories. Climate is found to significantly influence the energy results. These preliminary findings are indicative of general trends, but further research and development of the model are needed to reduce uncertainties.

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Nomenclature

s	above ground story count
EE	initial embodied energy
FAPC	floor area per capita (usable floor area)
IPCC	Intergovernmental Panel on Climate Change
VBSA	variance-based sensitivity analysis

1. Introduction

Compact urban form is identified by the IPCC as an important sectoral climate mitigation measure [1], attributed to lower per capita energy use [2–7], mainly due to a reduction in transportation energy. Newman and Kenworthy [2] demonstrate that urban density is an important explicative factor of transportation energy use in big cities. The general trend of denser cities consuming less transportation energy per capita has been confirmed by others [8], and evidence suggests that the modal share of walking/cycling is higher in high-density communities [9]. Open space, i.e. the fraction of the urban area not built up, has also been identified as a significant variable in transportation energy [6]. A compact city structure, however, affects more than distances traveled and mode share. Studies claiming that higher urban density has energy benefits often only focus on one, and neglect other variables [7], while energy use of cities should be compared on a broad basis to be useful in planning [4].

Cities characterized by high density are housing more people within a certain area. This typically leads to a trend of building taller as to provide enough dwellings to house the population. The height of buildings is affecting mainly two aspects of the buildings' energy use. Firstly, the heat loss of buildings is dependent on its physical dimensions [10,11]. The greater the surface area the more heat is transferred to the environment. Both in hot and cold climates the envelope area to volume ratio should be as low as possible to minimize heat gain and heat loss. If each floor has a fixed footprint and volume, this also holds true for the envelope area to floor area ratio. The energy needed for heating and cooling per floor area, all else equal, can then be shown to be lower in tall buildings than in low structures due to a lower envelope area to floor area ratio. The heat loss to the ground and through the roof is divided by an increasingly larger floor area as the building reaches higher, while the surface wall area per story remains the same. The implication is that stacking more stories on top of each other is beneficial for minimizing heating and cooling energy load [12]. This is however a simplification since it is not taking into account the effect of daylighting and insolation, wind (higher wind speeds at higher altitudes) and humidity. Secondly, the embodied energy of buildings is generally increasing with building height. A few studies have examined this trend [13–15], but to our knowledge, no consistent comparison of how the embodied energy of buildings vary with height exist.

Urban economists provide one other viewpoint on urban density by pointing out significant economic benefits originating from increased scale and density, as the public services and infrastructure are shared more efficiently. [16,17]

A hybrid life-cycle assessment model by Norman et al. [5] compares energy in construction materials for residential dwellings, utility and road infrastructure, operation of buildings, and transportation. They show that building operations have the biggest energy reduction potential and that high urban density is less energy intensive. There is, however, a much greater energy benefit per capita than per m^2. This again suggests that the floor area per capita (FAPC) is an important determining factor. As their study demonstrates, building operational energy is one of the biggest urban energy consumers. In Europe, the residential sector alone accounted for 26.6% of the final energy consumption in 2005 and is one of the sectors with the highest potential for energy efficiency [18]. Of a building's energy demand, about 80-90% is operating- and 10-20% is embodied energy. This ratio is, however, changing as technologies for energy efficiencies are applied to reduce operational energy [19]. Several reports on world energy use show that cities consume up to 75% of global energy and account for 78% of anthropogenic carbon emissions