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*Article*

# Life-Cycle Energy Implications of Downtown High-Rise *vs.* Suburban Low-Rise Living: An Overview and Quantitative Case Study for Chicago

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**Abstract:** It is commonly accepted that the concentration of people in high-density urban city centers, which are typically dominated by medium- and high-rise buildings located close to public transit systems, offers greater overall energy efficiency and lower life-cycle greenhouse gas emissions than lower-density expanded suburbs, which are dominated by low-rise single-family buildings and larger per-person automobile travel requirements. However, few studies have combined quantitative analyses of the life-cycle energy use of both buildings and transportation in both urban and suburban areas, especially in American cities. This work uses a variety of data sources to provide a quantitative comparison of the life-cycle energy consumption associated with residential life (including buildings, transportation, and supporting infrastructure) in prototypical downtown high-rises and suburban low-rises in and around Chicago, IL. We estimate that downtown high-rise living in Chicago, IL accounts for approximately 25% more life-cycle energy per person per year than suburban low-rise living, on average, contrary to some common beliefs (best estimates were ~141 and ~113 GJ/person/year, respectively). Building operational energy use was found to be the largest contributor of the total life-cycle energy in both the downtown high-rise and suburban low-rise cases, followed by vehicle operational energy.

**Keywords:** life cycle assessment (LCA); high-rise; energy; embodied energy; infrastructure; Chicago

## 1. Introduction

The U.S. population has continued to urbanize and suburbanize in recent decades. As a share of total population, the metropolitan population increased from 69% in 1970 to 80% in 2000 [1]. Within metropolitan areas, however, the population has mostly continued to suburbanize. From 1970 to 2000, the suburban population in the United States more than doubled, from 52.7 million to 113 million [2]. This phenomenon is especially highlighted in Chicago, IL, where there has been a large population shift from the city to the suburbs over the last half of the 20th century. According to the U.S. Census Bureau, the population of the City of Chicago peaked at 3.6 million in 1950 and contained approximately 70% of metropolitan area residents. By 2000, 2.9 million people in the City of Chicago made up only 36% of the region's population [3]. Actually, U.S. Bureau of the Census does not identify a location as "suburban" Metropolitan areas are divided into two classifications: (a) inside central city and (b) outside central city. Many researchers treat the latter areas as suburban, and they are so treated in this paper [3].

It is widely accepted that the concentration of people in high-density downtown city centers, which are dominated by medium- and high-rise buildings located close to a variety of public transit systems, offers greater overall energy efficiency and lower life-cycle greenhouse gas emissions than lower-density expanded suburbs, which are dominated by low-rise single-family buildings and larger per-person automobile travel requirements [4–7]. To account for the total life-cycle energy use and greenhouse gas emissions of a particular living area, one must consider both the embodied and operating energy consumed during all phases of the life-cycle of two key sectors: buildings and transportation. A number of studies have examined the energy use and/or greenhouse gas emissions associated with low-rise residential buildings (*i.e.*, single-family homes or small multi-family buildings) from a life-cycle perspective. A common finding for low-rise residential buildings has been that energy requirements for building operations tend to dominate overall life-cycle energy consumption compared to the embodied energy required for construction [8–11]. Unfortunately, very little data are available in the literature on either the embodied or operational energy use of high-rise buildings, which limits many direct comparisons of high-rise and low-rise buildings [12].

Further, many studies have explored the energy impacts of varied travel behaviors and have indicated that neighborhood characteristics such as density, levels of mixed land use, accessibility to public transit services, and the presence of pedestrian-friendly environments can contribute to a less car-dependent environment and lead to energy savings and reduced greenhouse gas emissions for transportation purposes alone [4,13]. For example, a study of 32 cities by Newman and Kenworthy concluded that there was a strong link between urban development densities and petroleum consumption [4].

However, few studies have combined quantitative analyses of the life-cycle energy use and/or greenhouse gas emissions of both buildings and transportation in both urban and suburban areas.

A few recent studies that have done so for cities such as Helsinki, Finland; Halifax, Canada; and Adelaide, Australia suggest that high-density urban areas may not actually lead to more energy- or carbon-efficient lifestyles [14–17], contrary to common beliefs. However, we are not aware of any similar comparisons in U.S. cities. Therefore, this work examines the life-cycle energy implications of downtown high-rise living compared to suburban low-rise living based on two distinct case studies in and around Chicago, IL using a variety of data sources and estimation methods. We specifically consider the following components of residential living: (1) the embodied and operational energy use of a prototypical code-compliant residential building of recent construction in each location (e.g., a high-rise in downtown Chicago, IL, and a low-rise residence in suburban Aurora, IL), (2) the embodied and operational energy for vehicle transport for multiple modes of transport including automobile, bus, train, and others based on average travel patterns in each location, and (3) the embodied and operational energy for transportation infrastructure for multiple modes of transport including automobile, bus, and train.

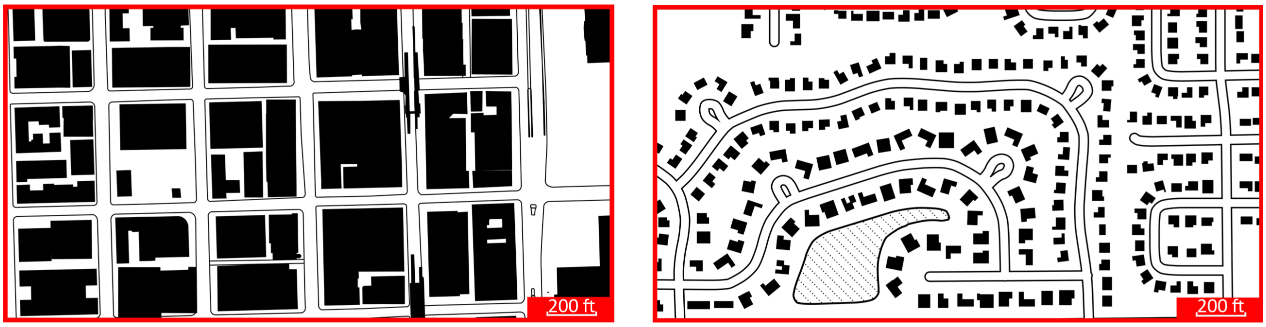
## 2. Case Studies

The research was based on two study areas in Chicago: Chicago Loop as a downtown high-rise case, and Aurora as a suburban low-rise case. Their geographic locations are shown in Figure 1.


**Figure 1.** Site locations and transportation systems including Chicago Transit Authority (CTA) train lines, Metra lines, and major highways.

Chicago has a long history at the forefront of skyscraper development. In the downtown Chicago Loop area, high-density residential communities and tall buildings dominate the housing type and all public transportation, including train lines and numerous bus lines, are easily accessible to a number of communities. Conversely, in Aurora, low-density residential communities and single-family homes dominate the housing type (single-family homes make up ~74% of homes in Aurora [18]). Aurora is the final stop of the Metra's Burlington Northern Santa Fe (BNSF) Line connecting to downtown Chicago, and also operates a Pace suburban bus system connecting to the surrounding cities, although most travel occurs via automobile. Figure 2 shows the distinctly different urban layouts of typical residential communities in the two study areas.

Table 1 outlines the basic characteristics of the two study areas with data culled from a variety of sources. Generally, the Chicago Loop area indeed has a higher population density, lower household (HH) size, and lower vehicle miles traveled (VMT) than Aurora.




(**a**) (**b**)

**Figure 2.** Urban layouts of typical residential communities in the (**a**) downtown Chicago Loop and (**b**) suburban Aurora.

**Table 1.** Basic characteristics of the two study areas.

| Basic Characteristics | Chicago Loop | Aurora |
|---|---|---|
| Urban Pattern | Downtown area | Suburb area |
| Population [18] | 28,614 | 198,726 |
| Distance to Downtown | Walkable | Avg. 50 miles |
| Avg. HH Size [18] | 1.6 | 3.2 |
| Avg. Floor Area Occupied per Person ($m^2$) * | 66 | 66 |
| Avg. Annual VMT per HH [18] | 6406 miles | 20,150 miles |
| Avg. Annual VMT per Person * | 4004 miles | 6297 miles |
| Public Transportation | All CTA Lines, All Metra Lines, and Multiple Bus Lines | Metra BNFT Line and Pace Buses |

Note: * Calculated by the authors. Specifically, there is no data available indicating the average floor area of either a unit of downtown high-rises in Chicago or a single-family house in Aurora. According to the US Census, the average floor area of a single-family house completed in Midwest in 2010 was 210 $m^2$ [19], and the average floor area of a multi-family unit completed in Midwest in 2010 was 106 $m^2$ [20], which is assumed to be representative of an average floor area of a unit in downtown high-rises.

## 3. Methodology

### *3.1. LCA Analysis: An Overview*

Life cycle assessment (LCA) involves quantifying environmental impacts throughout a product's life, from raw material acquisition through production, use, and disposal (*i.e.*, cradle-to-grave) [21]. By including the impacts throughout the product's life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. Therefore, the life-cycle energy of a particular building or transportation network can be expressed as the sum of embodied energy (EE) + operational energy (OE) +

demolition energy (DE) (Demolition energy is required to demolish a building and transport the waste materials to landfill sites and/or recycling plants). However, this study does not account for demolition energy due to the very limited data availability and relatively minimal contribution of the life-cycle energy in residential buildings [10].

Embodied energy (EE) is the energy consumed in all activities necessary to support a process, and comprises both a direct and an indirect component [22]. Embodied energy in buildings typically consists of two main elements: initial embodied energy (Initial embodied energy of a building is the energy incurred for initial construction of the building) and recurring embodied energy (Recurring embodied energy is the embodied energy in the materials used in the rehabilitation and maintenance of a building, since some of the materials used in building construction may have a life span). The building embodied energy analysis in this work only accounts for initial embodied energy due to the limited availability and reliability of data for recurring embodied energy in both low-rise and high-rise buildings. Compared to embodied energy, operational energy (OE) is an ongoing and recurrent expenditure of energy that is consumed to satisfy the demand for day-to-day operation process. The operational energy of a building is consumed to satisfy the demand for heating, cooling, lighting, ventilation, appliances, equipment, *etc.*

### *3.2. Research Scope and Analysis*

The research phases involve estimating the embodied and operational energy for the two case study buildings in Chicago and Aurora, vehicle embodied and operational energy, and transportation infrastructure embodied and operational energy via multiple modes of transport including automobile, CTA bus, Pace bus, school bus, CTA train, and Metra. Table 2 outlines the research framework including research phase, scope, and data sources, and the subsequent subsections describe our methods for gathering data for each outcome. Throughout the paper, source (*i.e.*, primary) energy is used for inputs and outputs to provide an equivalent comparison across all domains.

**Table 2.** Research phase, scope, and data sources.

| Research Phase | Research Scope | Data Sources |
|---|---|---|
| Building EE | Initial EE | Existing literature |
| Building OE | OE of the entire building facility | US DOE prototype building models |
| Transportation EE and OE | Vehicle and supporting infrastructure of automobile, CTA bus, Pace bus, school bus, CTA train, and Metra | US Census, 2011 American Community Survey, Chicago Metropolitan Agency for Planning (CMAP), Illinois Secretary of State, The Transportation LCA Database (tLCAdb) [23] |

#### 3.2.1. Building Operational Energy

Building operational energy (OE) varies with climate zone, envelope materials and thermal properties, vintage, equipment, occupancy, and many other parameters. We have relied on a comparison of prototypical code-compliant residential buildings of recent construction in each location, including a high-rise residential building in Chicago and a low-rise residence in Aurora. For simplicity, we use the U.S. Department of Energy's prototype single-family detached residential house [24] and high-rise apartment buildings [25] as case studies for each location (Table 3). We consider the annual operating energy for each building as the modeled source energy per conditioned building area reported from their original simulations. We gathered predicted operating energy use for four variations of the high-rise apartment building model (meeting ASHRAE Standard 90.1 version 2004, 2007, 2010 and 2013) and three variations of the single-family model (meeting International Energy Conservation Code (IECC) 2006, 2009, and 2012) to gain a broader representation of typical energy use in prototypical residences over the last 10 years or so. We should note that there is no Aurora-based low-rise residential prototype model from the U.S. Department of Energy (DOE), so the one located in Peoria, IL was chosen, which is the closest location to Chicago in this series of prototype models. These prototype buildings are primarily chosen to illustrate a common building type that is generally representative for each location and are not meant to take into account the wide variations in energy consumption of each building type typically observed across the building stock.

**Table 3.** Characteristics of the high-rise and low-rise residential prototype models.

| Characteristics | High-Rise | Low-Rise |
|---|---|---|
| Type * | High-rise apartment building | Single-family detached house |
| Location | Chicago, IL | Peoria, IL |
| Number of floors | 10 | N/A |
| Conditioned Building Area ($ft^2$) | 75,992 | 2,401 |
| Energy simulation program | EnergyPlus Version 8.0 | EnergyPlus Version 5.0 |
| Annual OE ($MJ/m^2$) | 1843 (STD 2004)<br>1802 (STD 2007)<br>1663 (STD 2010)<br>1559 (STD 2013) | 1246 (IECC 2006)<br>1187 (IECC 2009)<br>998 (IECC 2012) |

Note: * The function of high-rise models was relatively simple. Each floor has eight apartments except the ground floor, which included seven apartments and one lobby with equivalent apartment area. The single-family detached model with gas furnace heating system and unheated basement was chosen, because this is the most common type of single-family house in the Midwestern region of the United States [26]. In the statistics for new single-family houses completed in the United States, the other heating system types included electric resistance, oil furnace, and heat pump, and the other foundation types include slab, crawlspace, and heated basement.

As Table 3 shows, the prototypical high-rise buildings are predicted to consume more annual operational energy than low-rise buildings per conditioned floor area. The average OE across the four high-rise cases was 1717 $MJ/m^2$/year (standard deviation (SD) = 130) and 1143 $MJ/m^2$/year (SD = 130) across the three low-rise cases. The ratio of high-rise OE to low-rise OE was approximately 1.5, on average. In a comparison of high-rise *vs.* low-rise end use OE using the most recent code-built models (see Figure 3), it is clear that heating energy is much higher in the low-rise model compared to the high-rise model, as expected given a greater exposed enclosure area, but all other end uses are lower for a number of reasons (e.g., towers required more cooling, more fan energy, more lighting, and more water systems on an area-normalized basis than do low-rises).

The ratio of high-rise OE to low-rise OE being greater than 1 based on the digital prototype modes is also supported by data on existing buildings from the Building Performance Database (BPD), which is currently the largest publically available source of actual measured building energy performance data [27]. According to BPD, residential buildings containing five units or more consumed an average of 1678 MJ/m$^2$/year in Climate Zone 5A (Cool-Humid, represented by Chicago, IL) while single-family homes consumed only 889 MJ/m$^2$/year on average in the same climate zone (for a ratio of high-rise OE to low-rise OE of 1.89). Thus we consider these OE estimates appropriate for the analysis herein. We should note that we did not use data from the BPD because the sample sizes, when limited to Chicago alone, were too small to yield a meaningful comparison (There is no data available for residential buildings containing 5 units and more in Chicago, IL, so the data was collected from a larger area—5A Cool-Humid (Chicago, IL) climate zone. Specially, the sample was 17 for residential buildings containing 5 units and more, and 2497 for single-family houses).

Further, we also estimated OE on a per person basis using both the average floor area occupied per person and the average floor area of each home type (*i.e.*, 210 m$^2$ for a typical low-rise home and 106 m$^2$ for a typical high-rise unit, as reported in Table 1). In this manner, residents in the prototypical high-rise model are assumed to consume approximately 112.9 GJ/person/year (SD = 8.6) and residents in the low-rise home are assumed to consume approximately 75.9 GJ/person/year (SD = 8.6).

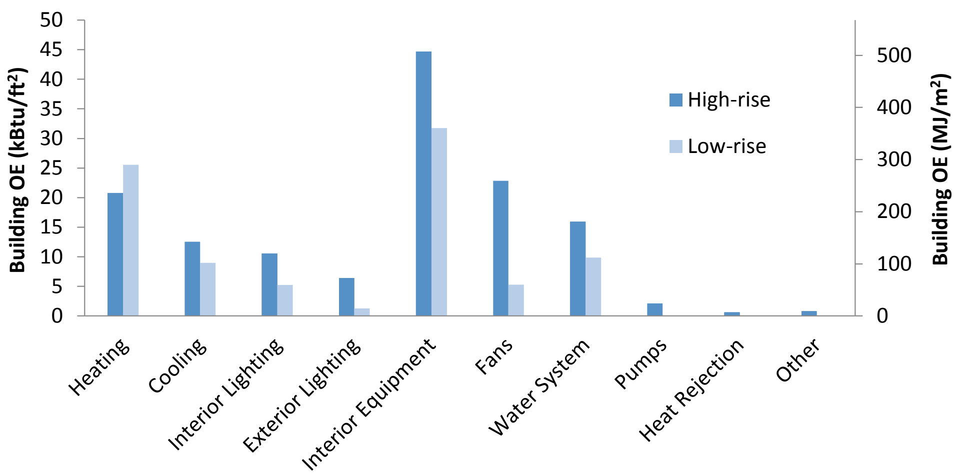



**Figure 3.** High-rise (STD 2013) *vs.* low-rise (IECC 2012) building end use operational energy (OE) for the U.S. DOE prototype building models.

### 3.2.2. Building Embodied Energy

Next, rather than undertaking a full assessment of the actual embodied energy in the two prototypical case study buildings, we instead conducted a literature review on building embodied energy (EE) in order to quantify typical values for each type of construction. Initial embodied energy mainly consists of the energy consumed in the acquisition, processing, and manufacturing of raw materials. Unlike operational energy, initial embodied energy varies primarily with respect to the type and quantity of building materials used, rather than climate zone or other operational factors. Also, embodied energy has typically been estimated as a much smaller contributor to the overall life-cycle energy consumption for residential buildings compared to operational energy use [8–11]. Therefore, we simply rely on the mean value of EE per floor area from the existing literature as a reasonable estimate for each building type herein. The information collected across published previous studies includes building type, height (number of floors), project location, structure, life cycle quantification method EE (kBtu/ft$^2$ and GJ/m$^2$) (EE analysis methods include process analysis, input-output (I-O) analysis and hybrid analysis [28–30]. A process analysis is defined as "the determination of the energy required by a process, and the energy required to provide inputs to the process, and the inputs to those processes, and so forth; I-O analysis as "the use of national economic and energy data in a model to derive national average EE data in a comprehensive framework"; and hybrid analysis as "the combination of process analysis and I-O analysis data" [30]. Hybrid analysis combines both process analysis and I-O analysis in order to reduce the errors that are typically found among both. Hybrid EE analysis methods typically include process-based hybrid analysis (total energy intensities derived using I-O analysis are applied to product quantities derived using process analysis) and I-O-based hybrid analysis (process analysis data is substituted into the I-O framework) [30], the EE literature includes various case studies across different countries, so the metrics they used vary. The authors converted all the Imperial and US customary units to SI units. However, both kBtu/ft$^2$ and GJ/m$^2$ units are presented in embodied and operational energy comparison charts for different audiences) and source.

Table 4 shows an overview of existing building EE literature for low-rise residential buildings and Figure 4 shows the estimated building EE from each study. Low-rise residential building EE is estimated to vary from as little as 2900 MJ/m$^2$ to as much as 15,200 MJ/m$^2$, with differences driven by a combination of differences in estimation methodology (e.g., I-O, I-O-based hybrid, or process) and the case study itself (e.g., different buildings use different structures and exterior walls, which require different levels of embodied energy). Overall, the average value of EE of these low-rise cases (1–2 stories) is approximately 7007 MJ/m$^2$ (SD = 3356). It is likely most appropriate to focus on estimates made using only similar estimation methods, but we use an average across all case studies given the relatively small sample sizes involved. Further, Figure 5 shows that there is no correlation between estimated EE and building height for the low-rise cases.

**Table 4.** Overview of literature on embodied energy (EE) of low-rise residential buildings.

| Case No. | Type | No. of Floors * | Location | Structure | Method | Source |
|---|---|---|---|---|---|---|
| 1 | Single-detached | 1 | Australia | Wood-frame | I-O-based hybrid | [31] |
| 2 | Single-detached | 1 | Australia | Wood-frame | Process | [32] |
| 3 ** | Single-detached | 1 | | | | |
| 4 | Single-detached | 1 | Sweden | Wood-frame | Process | [33] |
| 5 | Single-detached | 1 | Sweden | Wood-frame | | |
| 6 | Single-detached | 2 | Sweden | Wood-frame | | |
| 7 | Single-detached | 2 | Sweden | N/A | I-O | [34] |
| 8 | Single-detached | 1 | USA | N/A | I-O-based hybrid | [35] *** |
| 9 | Single-detached | 1 | USA | N/A | | |
| 10 | Single-detached | 1 | USA | N/A | | |
| 11 | Single-detached | 1 | USA | N/A | | |
| 12 | Single-detached | 2 | USA | N/A | | |
| 13 | Single-detached | 2 | USA | N/A | | |
| 14 | Single-detached | 2 | USA | N/A | | |
| 15 | Single-detached | 2 | USA | N/A | | |
| 16 | Single-detached | 2 | Australia | N/A | I-O-based hybrid | [36] |
| 17 ** | Single-detached | 2 | Australia | N/A | | |

**Table 4.** *Cont.*

| Case No. | Type | No. of Floors * | Location | Structure | Method | Source |
|---|---|---|---|---|---|---|
| 18 | Semi-detached | 2 | UK | Wood-frame | Process | [37] |
| 19 | Semi-detached | 2 | UK | Wood-frame | | |
| 20 | Semi-detached | 2 | UK | Masonry cavity wall | | |
| 21 | Single-detached | 2 | Canada | Wood-frame | I-O-based hybrid | [7] |
| 22 | Single-detached | 2 | USA | Wood-frame | Process | [9] |
| 23 ** | Single-detached | 2 | USA | Wood-frame | | |
| 24 | Semi-detached | 2 | Australia | Wood-frame | I-O-based hybrid | [30] |
| 25 | Detached | 2 | Sweden | N/A | Process-based hybrid | [38] |
| 26 | N/A | N/A | N/A | N/A | I-O | [39] **** |
| 27 | Single-detached | N/A | N/A | Wood-frame | I-O | [40] |

Note: * Number of stories above ground. ** The second case was an energy efficient model. *** The models developed in the research used four different exterior wall materials across five different sizes including 139, 186, 228, 279, and 325 $m^2$. Only the models with the size of 186 $m^2$ were included in this table since approximately 186 $m^2$ is considered a typical single-family house in the United States. **** The research was conducted using 25 houses as case studies, which ranged in size from 91 to 320 $m^2$ and varied in structure/material. The EE in the table was the mean value.

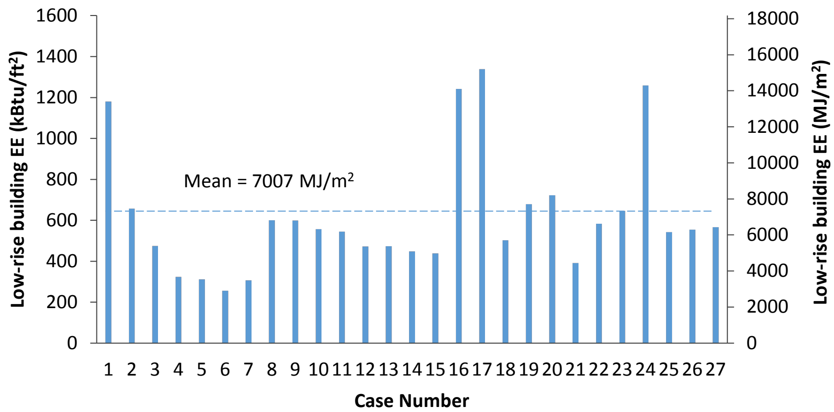



**Figure 4.** Embodied energy (EE) of low-rise building case studies in the literature.

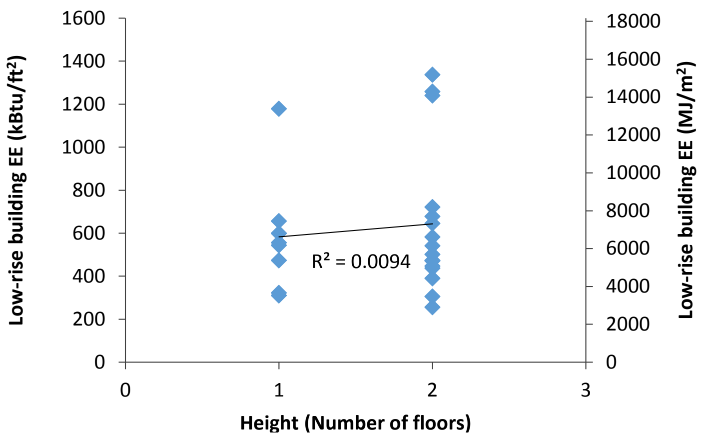



**Figure 5.** Correlation between embodied energy (EE) and building height for low-rise case studies in the literature.

Fewer published studies have estimated the embodied energy of tall buildings, largely due to the complexity of projects and limited data availability. However, one of the many criticisms leveled at tall buildings is the high quantities of structure and materials required to support, clad, and service them, coupled with energy intensive construction at height [41]. We surveyed the existing literature review and summarize several studies in Table 5. A number of estimation methods have been used in these cases as well. We should note that there are numerous definitions of what constitutes a "high-rise" or "tall building". The Council on Tall Buildings and Urban Habitat (CTBUH) considers 14 or more stories, or a height of more than 50 m (165 ft), as a reasonable threshold for defining a "tall" building, although they also claim that there is actually no absolute definition of what constitutes a tall building [42]. ASHRAE classifies a tall building as a building taller than 100 m (328 ft), which was increased from their previous reference of 91 m (300 ft) [43]. The National Fire Incident Reporting System (NFIRS) defines a "high-rise" building as having a height above ground of seven or more stories [44]. Due to the limited availability of published EE studies on high-rise buildings, we rely on the more conservative NFIRS definition of a tall building in order to gather as much data as possible from the literature.

**Table 5.** Overview of literature on embodied energy (EE) of high-rise buildings.

| Case No. | Type | No. of Floors * | Location | Structure | Method | Source |
|---|---|---|---|---|---|---|
| 1 | Office | 7 | Australia | Reinforced concrete | I-O-based hybrid | [45] |
| 2 | Office | 15 | Australia | Reinforced concrete | | |
| 3 | Office | 42 | Australia | Reinforced concrete | | |
| 4 | Office | 52 | Australia | Reinforced concrete | | |
| 5 | Office | 7–9 | Japan | N/A | I-O | [46] ** |
| 6 | Office | 8 | Japan | Steel reinforced concrete + Steel | I-O | [47] |
| 7 | Office | 8 | Japan | Steel reinforced concrete | | |
| 8 | Office | 18 | Japan | Steel | | |
| 9 | Office | 25 | Japan | Steel | | |
| 10 | Office | 31 | Japan | Steel | | |
| 11 | Residential | 15 | Canada | N/A | I-O | [7] |
| 12 | Education | 19 | China | N/A | Process-based hybrid | [48] |
| 13 | Office | 38 | Thailand | Concrete | I-O-based hybrid | [49] |
| 14 | Residential | 40 | Hong Kong | N/A | Process-based hybrid | [50] |
| 15 | Residential | 40 | Hong Kong | | | |

Note: * Number of stories above ground. ** Ten office buildings were examined in the study, including 8 seven-story buildings, 1 eight-story building, and 1 nine-story building. The building size varied from 1253 to 22,982 m$^2$. Six of the buildings were reinforced concrete structures, three were reinforced concrete and steel, and one was steel. The EE in the table was the mean value of these 10 buildings. The height was assumed to be seven floors in the correlation analysis between EE and building height shown in Figure 7.

The average value of estimated embodied energy of high-rise buildings (seven stories or higher) was found to be approximately 10,451 MJ/m$^2$ (SD = 3356) (see Figure 6), which is indeed higher than the average for low-rise residences (by approximately 50%). Interestingly, there was also a very weak correlation between EE and building height in these high-rise cases (see Figure 7).

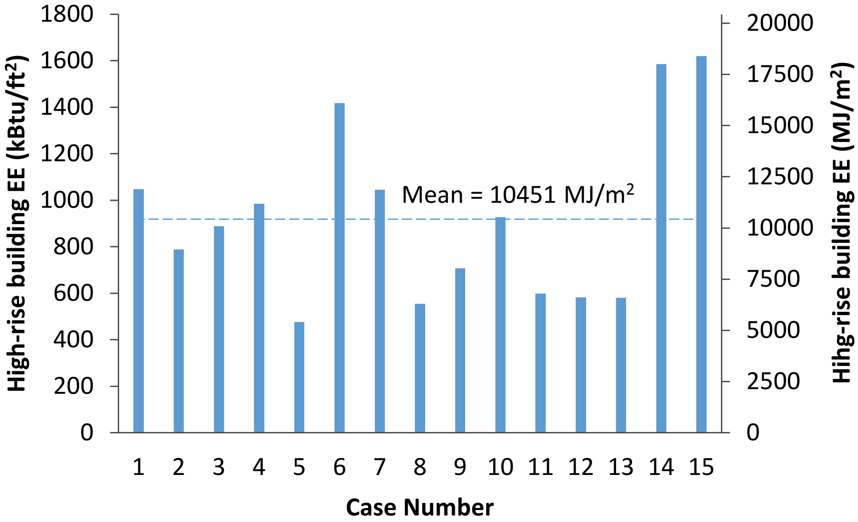



**Figure 6.** Embodied energy (EE) of high-rise building case studies in the literature.

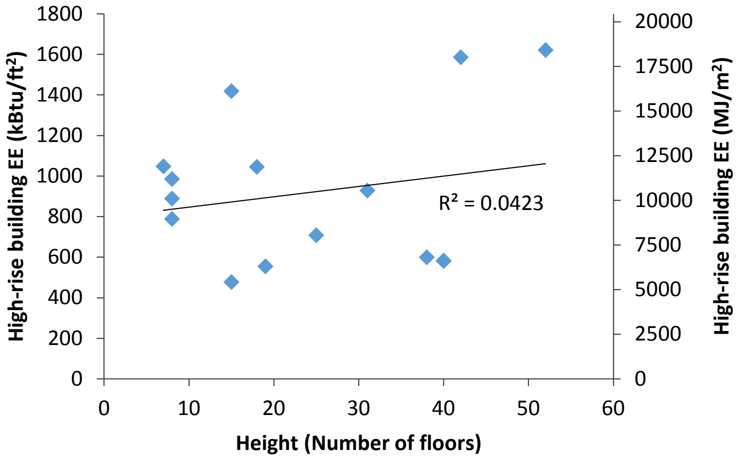



**Figure 7.** Correlation between embodied energy (EE) and building height for high-rise case studies in the literature.

For simplicity's sake, we took only the mean values from these data and, assuming population statistics from the Chicago Loop and Aurora (Table 1), used them to estimate the embodied energy (EE) for both types of construction. We estimate that the EE for the prototypical high-rise building would be approximately 687 GJ/person (SD = 278) and approximately 465 GJ/person (SD = 223) for the low-rise building. Thus, we assume that high-rise construction requires about 50% more EE per person than low-rise construction, on average. We also use the standard deviation as a measure of uncertainty in this parameter later in our analysis.

3.2.3. Transportation Embodied and Operational Energy

Next, we quantified the life-cycle energy requirements per person for transportation in the Chicago Loop and in Aurora based on a survey of mobility via different transportation modes including automobile, CTA/Pace/school bus, CTA train, and Metra. These publically available data are reported in the Chicago Regional Household Travel Inventory from the Chicago Metropolitan Agency for Planning (CMAP) [51]. Part of this transportation section was previously presented in a recent conference paper by the authors [52], but the data was updated in CMAP in March 2015 and changes are reflected here [18]. According to these data, the total mileage traveled per person by public transportation modes was calculated and shown in Table 6. Due to the limited open data about travel behavior via public transportation modes at the neighborhood scale, the study assumed that the share of total mileage of travel by mode in the Loop is the same as in the "Central Chicago" area, and Aurora is the same as the "Eastern Kane county" area in which Aurora is located.

**Table 6.** Annual mileage traveled per person (miles/person/year) by different transportation modes in the two study areas.

| Study Area | Automobile | CTA/Pace Bus | School Bus | CTA Train | Metra |
|---|---|---|---|---|---|
| Chicago Loop | 4004 | 764.8 | 24.1 | 572.6 | 144.2 |
| Aurora | 6297 | 7.3 | 103.2 | 0.0 | 574.9 |

Next, data from Table 6 were used with data from the transportation LCA database (tLCAdb) [23] to estimate the life-cycle embodied and operational energy use for each mode of transportation in each location for the average household. Table 7 outlines the system boundary of analysis with life cycle groupings and generalized life cycle components for each of the transportation modes. As Table 7 shows, the embodied energy of vehicle includes the energy consumed in vehicle manufacturing and maintenance process, and the embodied energy of infrastructure includes the energy consumed in the construction and maintenance process for the infrastructure.

For each component in a transportation mode life cycle, the average energy performance was calculated and then normalized on a per passenger-mile-traveled (PMT) basis, using estimates from the transportation LCA database (tLCAdb) [23]. Data on three typical categories of automobiles (sedan, SUV and pick-up truck) were available in the transportation LCA database (tLCAdb). The tLCAdb selected the most typical vehicles representing these three automobile categories—A sedan presented by Toyota Camry, an SUV presented by Chevrolet TrailBlazer, and a pick-up truck presented by Ford F-Series [53]. We used the data on sedan from tLCAdb to present the average automobile in our study. The travel modes have different life-cycle energy profiles, as shown in Table 8, which outlines the estimated energy usage per PMT of four different transportation modes including automobile, bus, CTA train, and Metra. The vehicle operational energy portion of each mode clearly consumes more operational energy than its embodied energy per PMT, but the infrastructure of each mode requires more embodied energy than operational energy per PMT. Further, the energy required for vehicle operation shares the largest portion in each mode, especially for automobile (OE makes up ~71.3% of total energy) and bus (OE makes up ~82.8% of total energy).

Based on the data in Tables 6 and 8, the average life-cycle energy associated with annual mileage traveled per person via different transportation modes across the two locations was estimated (shown in Table 9 and Figure 8). The results show that the average Aurora resident is estimated to consume approximately 28 GJ/person/year for transportation (vehicle + infrastructure), which is about 1.3 times greater than the estimate for the average Chicago Loop resident (approximately 21.2 GJ/person/year).

Intuitively, we estimate that Loop residents consume approximately 4.3 GJ/person/year for public transport, about 2.8 times greater than Aurora, but only 16.9 GJ/person/year for private transport, which is far less than the estimate of 26.5 GJ/person/year in Aurora.

**Table 7.** Life-cycle assessment of the system boundary. HVAC: Heating, ventilating, and air conditioning

| LCA Component | Automobile | CTA/Pace/School Bus | CTA Train/Metra |
|---|---|---|---|
| | | **Vehicle** | |
| Manufacturing | Manufacturing | Manufacturing | Manufacturing |
| Maintenance | Typical Maintenance Tire Replacement | Typical Maintenance<br>Tire Replacement | Routine Maintenance<br>Flooring Replacement |
| Operation | Propulsion | Propulsion<br>Idling | Propulsion<br>Idling<br>HVAC |
| | | **Infrastructure** | |
| Construction | Roadway<br>Parking | Roadway | Station<br>Station Parking<br>Track |
| Maintenance | Parking | Roadway | Station<br>Station Parking<br>Track |
| Operation | Roadway Lighting | Roadway Lighting | Station Lighting<br>Station Parking Lighting<br>Station Escalators<br>Station Train Control<br>Station miscellaneous |

**Table 8.** Assumptions of energy use per passenger-mile-traveled (MJ/PMT) for multiple transportation modes from tLCAdb.

| LCA Energy Component | Automobile | | Bus | | CTA Train | | Metra | |
|---|---|---|---|---|---|---|---|---|
| | Value | Percent | Value | Percent | Value | Percent | Value | Percent |
| Vehicle EE | 0.55 | 13.1% | 0.45 | 12.0% | 0.07 | 3.7% | 0.17 | 8.9% |
| Vehicle OE | 3.00 | 71.3% | 3.10 | 82.8% | 1.13 | 60.1% | 1.07 | 55.7% |
| Infrastructure EE | 0.62 | 14.7% | 0.19 | 5.1% | 0.62 | 33.0% | 0.42 | 21.9% |
| Infrastructure OE | 0.04 | 1.0% | 0.002 | 0.1% | 0.06 | 3.2% | 0.26 | 13.5% |
| Total life-cycle energy (MJ/PMT) | 4.21 | 100% | 3.74 | 100% | 1.88 | 100% | 1.92 | 100% |

Note: Data was calculated based on the transportation LCA database (tLCAdb) [23].

As Figure 8 shows, although the life-cycle energy for public transport for an average resident in the Chicago Loop is estimated to be greater than Aurora in each of the four categories, the total life-cycle energy required for auto transport in Chicago Loop is estimated to be far less than Aurora in each of the four categories, especially for vehicle operational energy use. The total life-cycle energy in Chicago Loop for transportation (vehicle + infrastructure) is approximately 75% of the total life-cycle energy in Aurora (approximately 21.2 compared to 28.0 GJ/person/year). This confirms the benefits of transit-oriented development (TOD) for reducing travel energy requirements, and also demonstrates that reducing automobile usage and new roadway construction is a key component in lowering the energy required for transportation purposes.

**Table 9.** Estimates of annual embodied and operational energy (GJ/person/pear) by vehicle and supporting infrastructure for all transportation modes across the two study locations.

| LCA Energy Component | Loop | | | | | Aurora | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Auto | Bus | CTA Train | Metra | Total | Auto | Bus | CTA Train | Metra | Total |
| Vehicle EE | 2.20 | 0.36 | 0.04 | 0.02 | 2.62 | 3.46 | 0.05 | 0 | 0.10 | 3.61 |
| Vehicle OE | 12.01 | 2.45 | 0.65 | 0.15 | 15.26 | 18.89 | 0.34 | 0 | 0.62 | 19.85 |
| Infrastructure EE | 2.48 | 0.15 | 0.36 | 0.06 | 3.05 | 3.90 | 0.02 | 0 | 0.24 | 4.16 |
| Infrastructure OE | 0.16 | 0.002 | 0.03 | 0.04 | 0.23 | 0.25 | 0 | 0 | 0.15 | 0.40 |
| Total life-cycle energy (GJ/person/year) | 16.86 | 2.95 | 1.08 | 0.27 | 21.16 | 26.51 | 0.41 | 0 | 1.10 | 28.02 |

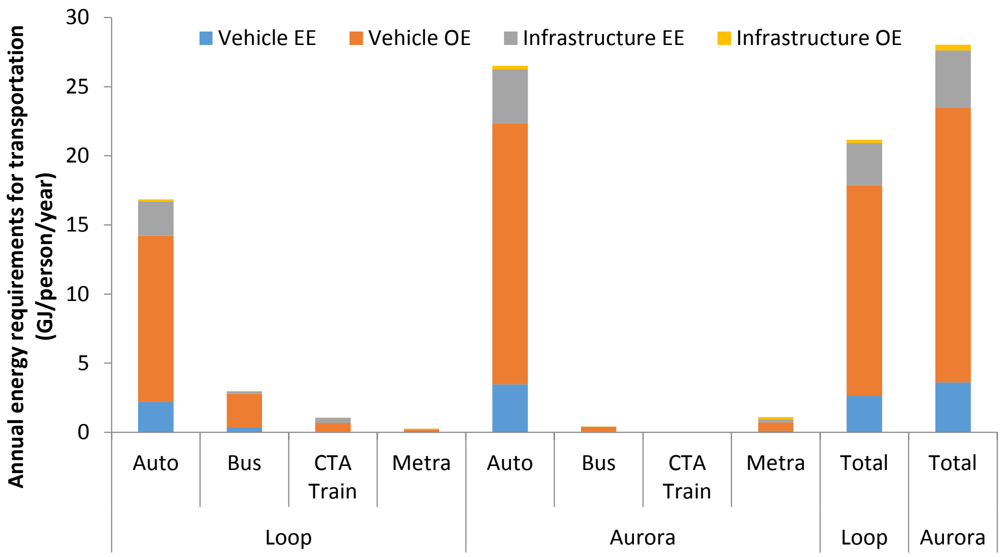



**Figure 8.** Estimated annual embodied and operational energy (GJ/person/year) for all transportation modes across the two study locations.

### *3.3. Overall Life-Cycle Energy Comparison of Downtown High-Rise vs. Suburban Low-Rise Living*

Finally, we combine the buildings and transportation energy data to make a direct comparison of the overall life-cycle energy requirements associated with typical residential life in the downtown high-rise and suburban low-rise locations. This involved summing the results of all six categories including building embodied energy, building operational energy, vehicle embodied energy, vehicle operational energy, infrastructure embodied energy, and infrastructure operational energy on a per-person per-year basis (e.g., GJ/person/year was used as the functional unit for an equivalent comparison).

In order to convert the one-time initial embodied energy required for building construction to an annualized value for comparison to the other measures, we assumed that the lifespan of high-rises is 100 years and that the lifespan of low-rises is 50 years. Although there is not much data available to verify this assumption, we consider these to be reasonable. For one, the American Housing Survey from the Oregon Department of Environmental Quality (DEQ) [54] reported that the service life of a non-residential wood structure was 51.6 years. This life span was adopted as a proxy for the lifespan of U.S. single-family homes because of the similarity between the non-residential wood structures and U.S. single-family homes in the use of wood as the dominant construction material [40]. It is more difficult to estimate the life span of a typical high-rise building, but 100 years is considered as a reasonable estimate based on the authors' knowledge of existing high-rise building construction around the world and in Chicago. Thus, it was calculated that high-rises account for approximately 6.9 GJ/person/year in initial embodied energy when annualized over its lifespan and the low-rises account for approximately 9.3 GJ/person/year.

As Figure 9 and Table 10 show, the average resident living in a typical Chicago downtown high-rise of recent construction is estimated to account for approximately 141 GJ/person/year in overall life-cycle energy use, while those in Aurora low-rises account for only 113 GJ/person/year, yielding a ratio of downtown high-rise to suburban low-rise of approximately 1.25 (*i.e.*, 25% greater for downtown high-rise living).

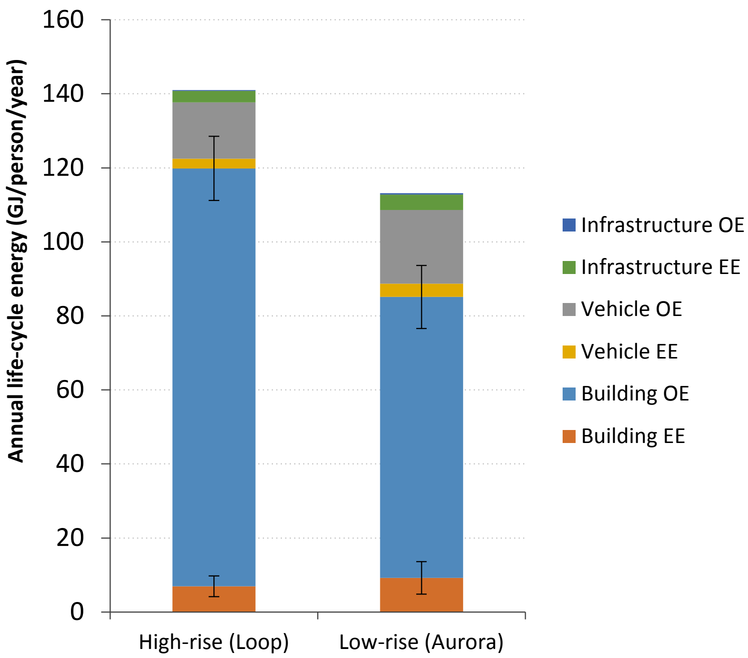



**Figure 9.** Annual life-cycle energy (GJ/person/year) associated with residential life in high-rises in the downtown Chicago Loop and low-rise residences in suburban Aurora, IL.

These data suggest that when accounting for building construction, building energy use, transportation infrastructure, and travel modes across these two locations, downtown high-rise living is estimated to account for approximately 25% more life-cycle energy use than suburban low-rise living based on the methods and best estimates of inputs used herein. This result is in conflict with some early studies by Norman *et al.* and Perkins *et al.* [7,55], but generally in line with others [15,16].

Interestingly, building operational energy use was estimated to be the largest contributor of the total life-cycle energy in both the downtown high-rise and suburban low-rise cases (even when accounting for uncertainty in building OE for these building types), followed by vehicle operational energy. Building OE accounted for approximately 80.1% and vehicle OE for 10.8% of the total life-cycle energy in the downtown high-rise scenario, while building OE accounted for 67.1% and vehicle OE for 17.5% of the total life-cycle energy in suburban low-rise scenario. Thus, the combined operational energy of building, vehicles, and infrastructure dominates the overall life-cycle energy usage in both downtown high-rise (91.1%) and suburban low-rise (85.0%) scenarios compared to relatively low values of embodied energy.

In comparison to previous studies, we should note that building operational energy, which has been widely confirmed as one of the largest contributors of the total life-cycle energy associated with residential life, did not account for as large of a portion of overall energy use in the studies by Norman *et al.* and Perkins *et al.* [7,55] as it did in our study. This difference drives most of the differences in findings between our study and theirs. This difference may be attributable in part to methodological differences in our studies (e.g., Norman *et al.* [7] used country-wide average data for specific building cases in Toronto and Perkins *et al.* [55] used data collected via interviews with residents).

**Table 10.** Annual life-cycle energy (GJ/person/year) associated with residential life in high-rises in the downtown Chicago Loop and low-rise residences in suburban Aurora, IL.

| **LCA Energy Component** | **High-Rises in Loop (Downtown)** | | **Low-Rises in Aurora (Suburb)** | |
|---|---|---|---|---|
| | Value | Percent | Value | Percent |
| Building EE | 6.9 | 4.9% | 9.3 | 8.2% |
| Building OE | 112.9 | 80.1% | 75.9 | 67.1% |
| Vehicle EE | 2.6 | 1.9% | 3.6 | 3.2% |
| Vehicle OE | 15.3 | 10.8% | 19.8 | 17.5% |
| Infrastructure EE | 3 | 2.2% | 4.2 | 3.7% |
| Infrastructure OE | 0.2 | 0.2% | 0.4 | 0.4% |
| Total life-cycle energy (GJ/person/year) | 141.0 | 100% | 113.1 | 100% |

## 4. Discussion and Conclusions

This work provides a quantitative comparison of life-cycle energy consumption associated with typical residential life in downtown high-rises and suburban low-rises in and around Chicago. The comparisons were made using a variety of data sources and estimation methods, but the findings of this study provide a reasonably complete understanding of overall life-cycle energy consumption by different residential types in terms of residents' life (building, transportation, and supporting infrastructure) in Chicago and surrounding suburbs. The key findings and conclusions are summarized below.

### *4.1. Building Embodied Energy*

Based on an extensive literature review, we estimate that high-rise residential buildings account for more initial embodied energy than low-rise residential buildings (on both per area and per person basis) due to the high quantities of structure and materials required for high-rise construction. However, if we assume that the life span of high-rises is longer, high-rises actually consume less initial embodied energy when annualized over their lifespan. Although this result was based on limited studies on high-rise embodied energy with a limited research scope and data availability, as well as the authors' assumptions on building lifespan, it still provides a reasonably complete understanding of the factors that contribute to building embodied energy, as well as a greater potential of tall building's embodied energy in terms of an even longer lifespan (According to CTBUH Skyscraper Center database, only four skyscrapers (taller than 150 m) have been demolished in the last 50 years: the Singer Building in New York (187 m), the Morrison Hotel in Chicago (160 m), the Deutsche Bank in New York (158 m) and the One Meridian Plaza in Philadelphia (150 m)). Moreover, the results herein also show that embodied energy in building construction is not a large contributor to overall life-cycle energy consumption. Building EE was estimated to account for only 4.9% of the overall annual life-cycle energy of downtown high-rises and only 8.2% of suburban low-rises on a per person basis. We should note that there was considerable variability in the values for building EE reported in Figures 4 and 6, so the mean values may not be the most suitable for our case study buildings in and around Chicago. As an estimate of the sensitivity of our results to this variation, if the upper ends of the ranges for both high-rise and low-rise building EE are used, building EE would account for 8.3% and 16.2% of the overall annual per-person life-cycle energy use of downtown high-rises and suburban low-rises, respectively. Similarly, if the lower ends of the reported ranges are used, building EE would account for only 1.8% and 3.5% of the overall annual per-person life-cycle energy use of downtown high-rises and suburban low-rises, respectively. While our building EE results are quite sensitive to this input parameter, building OE still dominates life-cycle energy use regardless of the assumption for building EE.

We should also note that we only consider initial embodied energy according to the limited availability and reliability of data for recurring embodied energy buildings. However, recurring embodied energy could be a major factor that increases the portion of embodied energy of the overall life-cycle energy from the perspective of a long-term lifespan of buildings, especially for tall buildings. Unfortunately, there are no data available for recurring embodied energy of tall buildings, as far as we are aware. The literature on embodied energy of low-rise buildings in this study shows that the ratio of recurring embodied energy to initial embodied energy in a 50-year lifespan ranges from 13.5% [38] to 94% [40].

### *4.2. Building Operational Energy*

Our results show that the prototypical high-rise building case study used herein was estimated to consume approximately 112.9 GJ/person/year in building operational energy while the low-rise model was estimated to consume only 75.9 GJ/person/year. This is contrary to the common belief that high-rises should be more energy efficient in the operation phase because of a smaller surface area of envelope per floor area for heat losses and gains and higher density occupancy. However, there are many other energy end uses in relatively densely populated high-rises that lead to higher energy requirements overall per area and per person. These data also demonstrate that building operational energy is the single greatest contributor of the overall life-cycle energy for both urban and suburban locations investigated herein. Building OE was estimated to account for approximately 80.1% of the overall annual life-cycle energy of downtown high-rises and 67.1% of suburban low-rises on a per person basis. This indicates that improving the energy efficiency of the building operation is the key to reduce the overall life-cycle energy usage in terms of the residents' lifestyle for these case studies.

We should also note that the residential prototype building cases in this study were relatively simplified digital models. The high-rise case only included one small lobby on the ground floor, but many residential tall buildings in cities actually include multiple larger-size common areas such as a package room, gym, party room, laundry, and others, which would tend to increase the estimate of operational energy. Therefore, residents who live in downtown high-rises might consume even more operational energy by sharing the energy usage by the common areas from this point of view. We also do not explore the wide variety of building operational energy use that exists beyond the averages used for the prototypical case studies. A case study on energy efficient construction would yield different results than the cases used herein, as would a case study on older vintage construction in each area.

*4.3. Transportation Embodied and Operational Energy*

The estimated life-cycle energy consumed by the downtown high-rise residents was estimated to be lower than for those who live in suburban low-rises in all transportation categories. Specifically, downtown high-rise residents were estimated to consume 2.6 GJ/person/year for vehicle embodied energy, 15.3 GJ/person/year for vehicle operational energy, 3 GJ/person/year for infrastructure embodied energy, and 0.2 GJ/person/year for infrastructure operational energy. Conversely, suburban low-rise residents consumed 3.6 GJ/person/year for vehicle embodied energy, 19.8 GJ/person/year for vehicle operational energy, 4.2 GJ/person/year for infrastructure embodied energy, and 0.4 GJ/person/year for infrastructure operational energy. Vehicle operational energy was estimated to be the second greatest contributor to the overall life-cycle energy in both locations, accounting for 10.8% of the overall annual life-cycle energy of the downtown high-rise case study and 17.5% of the suburban low-rise case study on a per person basis. Moreover, the total transportation sector (vehicle + infrastructure) was estimated to account for 15.0% of the overall annual life-cycle energy of downtown high-rises and 24.8% of suburban low-rises.

We should note that we did not explore the wide variety of automobile vehicle type and ownership that exists beyond the averages used for travel data. For example, suburban low-rise residents might tend to own larger automobiles than downtown high-rise residents, but we were unable to obtain this information from our data sources. The automobile data used for the transportation section in this work was based solely on a regular sedan type (representative of the average vehicle), but a study on different vehicle types and ownerships across the two residential locations would likely yield different results for both embodied energy and operational energy for vehicles and infrastructure. This should be taken into account in future work.

Overall, this paper provides a reasonably complete understanding of the average life-cycle energy consumption for downtown high-rise and suburban low-rise living in and around Chicago, IL. Future work should focus on improving limited public data availability, collecting actual energy and travel data from individual occupants, and accounting for other life-cycle environmental impact categories such as greenhouse gas (GHG) emissions and global warming potential (GWP).

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## Author Contributions

As the primary author, Peng Du initiated the study, performed the majority of the analysis, and wrote the main body of this paper. Antony Wood supervised the study and provided advice on the research scope and methodology. Brent Stephens contributed in editing and structuring the paper, advising on data analysis, and proofreading the manuscript. Xiaoyu Song contributed to the literature review and the initial process of data collection and analysis.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

1. Gomez-Ibanez, D.J.; Boarnet, M.G.; Brake, D.R. *Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and $CO_2$ Emissions*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2009.
2. University of Illinois at Chicago. *Metropolitan Decentralization in Chicago*; University of Illinois at Chicago: Chicago, IL, USA, 2001.
3. Giuliano, G.; Agarwal, A.; Redfearn, C. *Metropolitan Spatial Trends in Employment and Housing Literature Review*; University of Southern California: Los Angeles, CA, USA, 2008.
4. Newman, P.W.G.; Kenworthy, J.R. Gasoline consumption and cities. *J. Am. Plann. Assoc.* **1989**, *55*, 24–37.
5. Ewing, R.; Rong, F. The impact of urban form on U.S. residential energy use. *Hous. Policy Debate* **2008**, *19*, 1–30.
6. Nichols, B.G.; Kockelman, K. Urban Form and Life-Cycle Energy Consumption: Case Studies at the City Scale. In Proceedings of Transportation Research Board 94th Annual Meeting, Washington, DC, USA, 11–15 January 2015.
7. Norman, J.; MacLean, H.L.; Kennedy, C.A. Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. *J. Urban Plan. Dev.* **2006**, *132*, 10–21.
8. Cole, R.J. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. *Build. Environ.* **1998**, *34*, 335–348.
9. Keoleian, G.A.; Blanchard, S.; Reppe, P. Life-cycle energy, costs, and strategies for improving a single-family house. *J. Ind. Ecol.* **2000**, *4*, 135–156.
10. Ochoa, L.; Hendrickson, C.; Matthews, H.S. Economic input-output life-cycle assessment of U.S. residential buildings. *J. Infrastruct. Syst.* **2002**, *8*, 132–138.
11. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of buildings: An overview. *Energy Build.* **2010**, *42*, 1592–1600.

12. Optis, M.; Wild, P. Inadequate documentation in published life cycle energy reports on buildings. *Int. J. Life Cycle Assess.* **2010**, *15*, 644–651.
13. Lang, R. *Residential Density and Energy Conservation*; York University: Toronto, Canada, 1986.
14. Heinonen, J.; Junnila, S. A carbon consumption comparison of rural and urban lifestyles. *Sustainability* **2011**, *3*, 1234–1249.
15. Heinonen, J.; Junnila, S. Implications of urban structure on carbon consumption in metropolitan areas. *Environ. Res. Lett.* **2011**, *6*, doi:10.1088/1748-9326/6/1/014018.
16. Heinonen, J.; Kyrö, R.; Junnila, S. Dense downtown living more carbon intense due to higher consumption: A case study of Helsinki. *Environ. Res. Lett.* **2011**, *6*, doi:10.1088/1748-9326/6/3/034034.
17. Wilson, J.; Spinney, J.; Millward, H.; Scott, D.; Hayden, A.; Tyedmers, P. Blame the exurbs, not the suburbs: Exploring the distribution of greenhouse gas emissions within a city region. *Energy Policy* **2013**, *62*, 1329–1335.
18. Community Data Snapshots. Available online: http://www.cmap.illinois.gov/data/metropulse/community-snapshots (accessed on 10 August 2015).
19. Median and Average Square Feet of Floor Area in New Single-Family Houses Completed by Location. Available online: https://www.census.gov/construction/chars/pdf/medavgsqft.pdf (accessed on 10 August 2015).
20. Median and Average Square Feet of Floor Area in Units in New Multifamily Buildings Completed. Available online: http://www.census.gov/const/C25Ann/mfu_medavgsqft.pdf (accessed on 10 August 2015).
21. American National Standards Institute. *Environmental Management—Life Cycle Assessment—Principles and Framework*; ANSI/ISO 14040; American National Standards Institute: Washington, DC, USA, 1997.
22. Baird, G.; Aun, C.S. *Energy Cost of Houses and Light Construction Buildings*; New Zealand Energy Research and Development Committee: Auckland, New Zealand, 1983.
23. Transportation Life-Cycle-Assessment. Available online: http://www.transportationlca.org/index.php (accessed on 23 June 2015).
24. Building Energy Codes Program: Residential Prototype Building Models. Available online: https://www.energycodes.gov/development/residential/iecc_models (accessed on 5 July 2015).
25. 90.1 Prototype Building Models High-Rise Apartment. Available online: https://www.energycodes.gov/901-prototype-building-models-high-rise-apartment (accessed on 5 July 2015).
26. Characteristics of New Housing. Available online: https://www.census.gov/construction/chars/completed.html (accessed on 23 June 2015).
27. Building Performance Database. Available online: https://bpd.lbl.gov/ (accessed on 3 July2015).
28. Bullard, C.W.; Penner, P.S.; Pilati, D.A. Net energy analysis: Handbook for combining process and input-output analysis. *Resour. Energy* **1978**, *1*, 267–313.
29. Graham, J.; Owen, T.C.; Fay, R. Environmental assessment of rammed earth construction systems. *Struct. Surv.* **2001**, *19*, 99–106.
30. Treloar, G.J.; Love, P.E.D.; Holt, G.D. Using national input/output data for embodied energy analysis of individual residential buildings. *Constr. Manag. Econ.* **2001**, *19*, 49–61.

31. Crawford, R. An As-Occupied Life Cycle Energy Assessment of a Residential Building. In Proceedings of 46th Annual Conference of the Architectural Science Association, Gold Coast, Australia, 14–16 November 2012.
32. Myer, F.; Fuller, R.; Crawford, R.H. The Potential to Reduce the Embodied Energy in Construction through the Use of Renewable Materials. In Proceedings of 46th Annual Conference of the Architectural Science Association, Gold Coast, Australia, 14–16 November 2012.
33. Adalberth, K. Energy use during the life cycle of single-unit dwellings: Examples. *Build. Environ.* **1997**, *32*, 321–329.
34. Gustavsson, L.; Joelsson, A. Life cycle primary energy analysis of residential buildings. *Energy Build.* **2010**, *42*, 210–220.
35. Frijia, S. Energy Use and Greenhouse Gas Emissions in Residential Neighborhoods in the Southwest: A Built Environment Life-Cycle Assessment. Master's Thesis, Arizona State University, Phoenix, AZ, USA, August 2011.
36. Fay, R.; Treloar, G.; Iyer-Raniga, U. Life-cycle energy analysis of buildings: A case study. *Build. Res. Inf.* **2000**, *28*, 31–41.
37. Monahan, J.; Powell, J.C. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy Build.* **2011**, *43*, 179–188.
38. Thormark, C. A low energy building in a life cycle—Its embodied energy, energy need for operation and recycling potential. *Build. Environ.* **2002**, *37*, 429–435.
39. Pullen, S.F. Energy used in the construction and operation of houses. *Archit. Sci. Rev.* **2000**, *43*, 87–94.
40. Analysis of the Life Cycle Impacts and Potential for Avoided Impacts Associated with Single-Family Homes. Available online: http://www.epa.gov/wastes/conserve/imr/cdm/pdfs/sfhomes.pdf (accessed on 10 August 2015).
41. Oldfield, P. Embodied Carbon and High-Rise. In Proceedings of CTBUH 9th World Congress, Shanghai, China, 19–21 September 2012.
42. CTBUH Height Criteria. Available online: http://www.ctbuh.org/HighRiseInfo/TallestDatabase/Criteria/tabid/446/language/en-GB/Default.aspx (accessed on 10 August 2015).
43. Simmonds, P. *ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems*; American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA, USA, 2015.
44. High-Rise Building Fires. Available online: http://www.nfpa.org/research/reports-and-statistics/fires-by-property-type/high-rise-building-fires (accessed on 10 August 2015).
45. Treloar, G.J.; Fay, R.; Ilozor, B.; Love, P.E.D. An analysis of the embodied energy of office buildings by height. *Facilities* **2001**, *19*, 204–214.
46. Suzuki, M.; Oka, T. Estimation of life cycle energy consumption and $CO_2$ emission of office buildings in Japan. *Energy Build.* **1998**, *28*, 33–41.
47. Oka, T.; Suzuki, M.; Konnya, T. The estimation of energy consumption and amount of pollutants due to the construction of buildings. *Energy Build.* **1993**, *19*, 303–311.
48. Chang, Y.; Ries, R.J.; Lei, S. The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model. *Energy Build.* **2012**, *55*, 790–798.

49. Kofoworola, O.F.; Gheewala, S.H. Life cycle energy assessment of a typical office building in Thailand. *Energy Build.* **2009**, *41*, 1076–1083.
50. Chen, T.Y.; Burnett, J.; Chau, C.K. Analysis of embodied energy use in the residential building of Hong Kong. *Energy* **2001**, *26*, 323–340.
51. The Chicago Metropolitan Agency for Planning. *Chicago Regional Household Travel Inventory: Mode Choice and Trip Purpose for the 2008 and 1990 Surveys*; The Chicago Metropolitan Agency for Planning: Chicago, IL, USA, 2010.
52. Du, P.; Wood, A.; Stephens, B. Life Cycle Assessment of Urban *vs.* Suburban Residential Mobility in Chicago. In Proceedings of the ARCC 2015 Conference, Chicago, IL, USA, 6–9 April 2015.
53. Chester, M.V. *Life-Cycle Environmental Inventory of Passenger Transportation in the United States*; University of California: Berkeley, CA, USA, 2008.
54. A Life Cycle Approach to Prioritizing Methods of Preventing Waste from the Residential Construction Sector in the State of Oregon. Available online: http://www.deq.state.or.us/lq/pubs/docs/sw/ResidentialBldgLCA.pdf (accessed on 10th August 2015).
55. Perkins, A.; Hamnett, S.; Pullen, S.; Zito, R.; Trebilcock, D. Transport, housing and urban form: The life cycle energy consumption and emissions of city centre apartments compared with suburban dwellings. *Urban Policy Res.* **2009**, *27*, 377–396.